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Memorandum

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Memo date	25/09/2018
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Project number	ENAUABTF20484AA
Memo Subject	SGP Stage 1 CSG WMMP: Groundwater modelling technical memorandum

1. Introduction

A significant body of numerical groundwater modelling relating to the Surat Gas Project (SGP) has been undertaken during the past five years. The primary purpose of this memorandum is to present the modelling basis (groundwater and surface water-groundwater interaction) for which predictions of impacts and monitoring/management measures will be prepared for the SGP Stage 1 Coal Seam Gas (CSG) Water Monitoring and Management Plan (Stage 1 CSG WMMP).

The models considered most relevant for the development of the Stage 1 CSG WMMP are:

1. The Arrow SREIS Groundwater Model (GHD, 2013) based on the OGIA 2012 Groundwater Model (QWC, 2012)
2. The CDM Smith Condamine Alluvium Model (CDM Smith, 2016) based on the Central Condamine Alluvium Model (KCB, 2012).
3. The CDM Smith (2016) upper and middle Condamine River Integrated Quantity and Quality Model (CDM Smith IQQM).

The key outputs from these models, which are described in more detail in Section 2, have been assessed and presented in Sections 4 and 5. Together, these models address Approval Conditions 13a, 13b and 13d. Approval Conditions 13(c), 13(f), 13(j) and 13(p) are also reliant on or underpinned by groundwater modelling and are to be separately addressed in other memoranda, and the WMMP.

This memorandum includes:

- To address Approval Condition 13(d), a distillation of the key findings of the Supplementary Report to the EIS (SREIS) (Coffey, 2013) and CDM Smith report '*Section 13(b)*' (CDM Smith, 2016) describing groundwater and surface water modelling as relevant to the Stage 1 CSG WMMP.
- A summary of the impact predictions in relation to groundwater and surface water, including the predicted impacts indicated by IQQM modelling in CDM Smith (2016).

- Relevant modelling figures and data that will underpin the development of management and monitoring objectives.
- Discussion regarding the changes in conceptualisation and model design of the 2016 OGIA model, and the implications such changes have to the assessment of impacts due to CSG production.
- An analysis of the results of the OGIA 2016 Groundwater Model through comparison with the results from the OGIA 2012 Groundwater Model, as required under Approval Condition 13(a).

Whilst not all content within this memorandum will be included in the Stage 1 CSG WMMP report, it is required for the purpose of establishing a common understanding and underlying basis.

2. Background

2.1. Previous modelling

Since completion of the EIS, the OGIA developed an independent numerical groundwater model referred to as the **OGIA 2012 Groundwater Model** (QWC, 2012) that included CSG proponents' predicted cumulative drawdown, and underpinned the Surat Cumulative Management Area (CMA) Underground Water Impact Report (UWIR). WaterMark (2012) presented a method and results of uncertainty analysis and predictive modelling completed on the OGIA 2012 Groundwater Model. Analysis was completed using the null space Monte Carlo (NSMC) and subspace methods.

The **Central Condamine Alluvium Model** (CCAM) is a numerical model originally developed by KCB (2012) and now managed and updated by Department of Natural Resource, Mines and Energy (DNRME). The purpose of the CCAM is to model groundwater processes in the Condamine Alluvium.

At the time of preparation of the SREIS, the OGIA 2012 Groundwater Model was adopted by Arrow to revise the groundwater impact predictions based on Arrow's current Field Development Plan (FDP). This version of the OGIA 2012 Groundwater Model is referred to as the **Arrow SREIS Groundwater Model** (Appendix 4 of the SREIS) and was used to support the supplementary groundwater assessment, and will provide the main basis for regional impact prediction underpinning the Stage 1 CSG WMMP. This model included uncertainty analysis based on the field development plan for the SREIS (GHD, 2013). It included a calibrated model and a set of uncertainty analysis modelling predictions using the NSMC method. This uncertainty analysis involved the generation of 200 model predictions based on statistically generated parameter sets. The 200 predictions were ranked in an increasing order from lowest to highest predicted drawdown. Predictions beyond the 5th and 95th percentiles were treated as outliers. Predictions based on the calibration realisation were used in determining the groundwater impacts.

The CCAM was used in tandem with the Arrow SREIS Groundwater Model to enable predictions of CSG impact (drawdown) in the Condamine Alluvium for the SREIS. This was achieved by removing water volumes equivalent to the predicted changes in vertical groundwater flux between the Great Artesian Basin (GAB) and Condamine Alluvium from the Arrow SREIS Groundwater Model.

2.2. Recent modelling

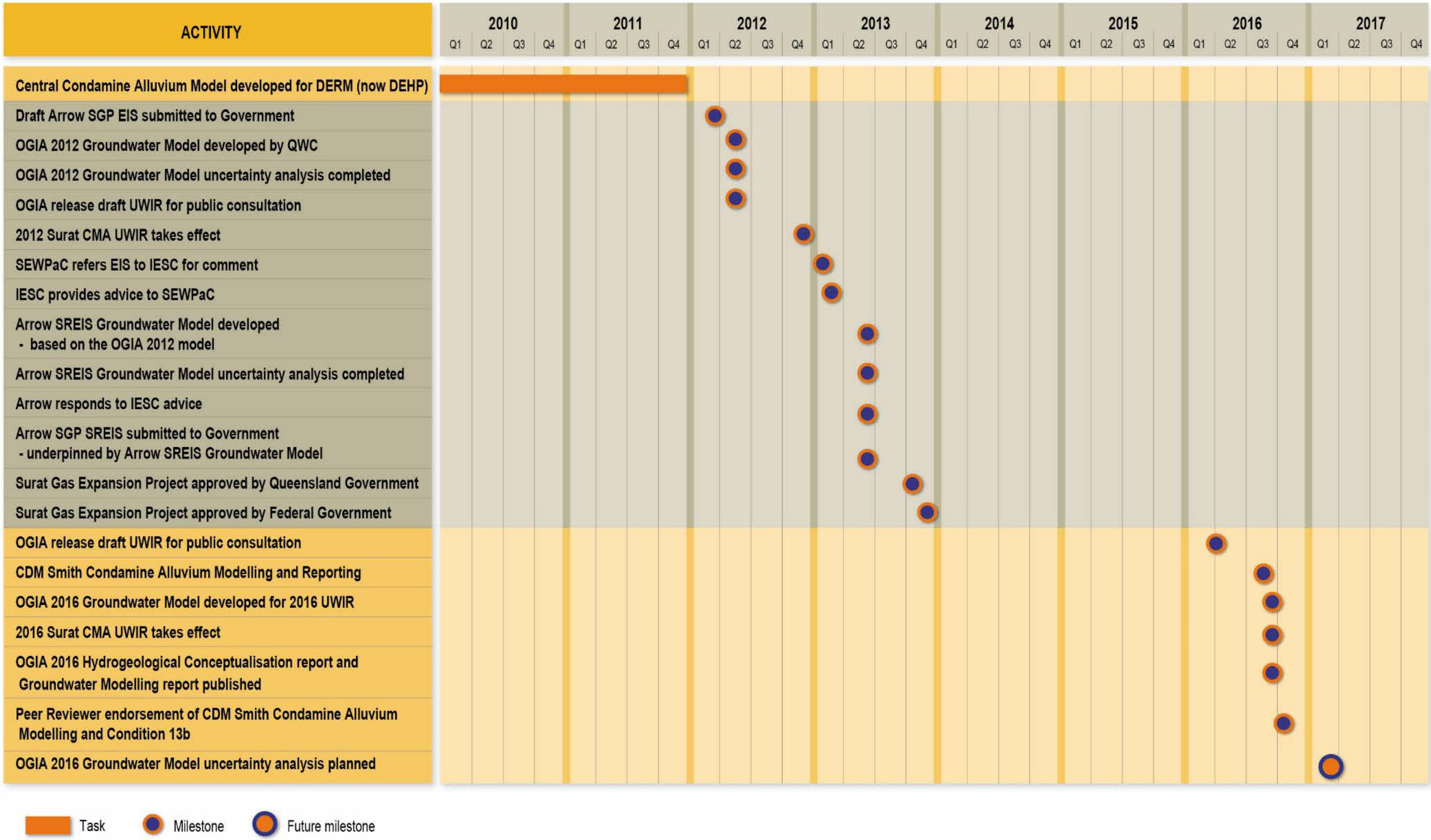
A significant body of further modelling work to consider groundwater-surface water interactions has been undertaken. This further modelling has been peer-reviewed and accepted as a basis for achieving the requirements of the EPBC 2010/5344 Approval Conditions, specifically including Condition 13(b).

The **CDM Smith Condamine Alluvium Model** (CDM Smith, 2016) is a numerical model based on the CCAM to enable predictions of drawdown in the Condamine Alluvium due to CSG production. The model predicted impacts were used as inputs to the Condamine River **Integrated Quantity and Quality Model** (IQQM) which is a hydrological modelling tool used for planning and evaluating water resources, developed by the NSW Department of Primary Industries. This enabled the evaluation of impacts on river flows and users that may result from CSG induced drawdown. The IQQM simulations relevant to this memorandum are detailed in CDM Smith (2016).

The OGIA released a new groundwater model in 2016 (the **OGIA 2016 Groundwater Model)** to inform the Surat CMA 2016 UWIR. The draft UWIR was released for comment on 22nd March 2016, with the final version released in September 2016, together with the supporting groundwater modelling report. The Chief Executive of Department of Environment and Science (DES) approved the Surat CMA 2016 UWIR with conditions and a take-effect date of 19 September 2016.

The OGIA 2016 Groundwater Model is a regional numerical groundwater model developed for the purpose of predicting regional water levels and pressures in response to groundwater extraction from petroleum and gas production. In this sense, it is analogous to the OGIA 2012 Groundwater Model, however uses revised modelling code and has adopted other changes, as described in Section 5.

Schematic 1 presents an overview of the approvals and modelling milestone timeline to date.



coffey A TETRA TECH COMPANY	Date: 04.11.2016 Project: ENAUABTF20484AA File Name: 20484AA_M01_F001_GRA	Arrow Energy Surat Gas Project WMMP	arrow energy go further	SGP approvals and modelling development overview	Schematic No: 1

3. Methodology

A range of documents were reviewed and/or referenced in the development of this memorandum. Key reviewed documents are summarised in Table 3.1.

Table 3.1: Documents reviewed

Reference	Title/ Comment
CDM Smith, 2016.	Surat Gas Expansion Project – CSG WMMP Section 13(b). Report prepared for Arrow Energy, August 2016, by CDM Smith describing integrated groundwater-surface water modelling
Coffey Environments, 2013.	Supplementary Groundwater Assessment. Appendix 4 to the Arrow Energy Surat Gas Project Supplementary Report to the EIS, June 2013.
Department of Natural Resource Management (DNRM), 2016a.	Underground Water Impact Report for the Surat Cumulative Management Area, September 2016. Office of Groundwater Impact Assessment.
GHD, 2012.	Surat Cumulative Management Area Groundwater Model Report
GHD, 2013.	Arrow Energy Surat Gas Project Groundwater Modelling Report. Report prepared for Arrow Energy, June 2013.
Herckenrath D, Doherty J, and Panday, S. 2015	Incorporating the effects of gas in modelling the impact of CBM extraction on regional groundwater systems. Journal of Hydrology 523 (2015) pp. 587-601.
Department of Natural Resource Management (DNRM), 2016b.	Groundwater modelling report for the Surat Cumulative Management Area, September 2016. Office of Groundwater Impact Assessment.
Queensland Water Commission (QWC), 2012.	2012 Underground Water Impact Report for the Surat Cumulative Management Area.
Simons, M, Podger, G & Cooke, R 1996,	IQQM – A hydrologic modelling tool for water resource and salinity management, Environmental Software, DOI: 10.1016/S0266-9838(96)00019-6 January.

4. Modelling results supporting Condition 13(d)

This section provides a review of the results of modelling undertaken and presents a summary of the modelling results, to demonstrate that the work undertaken to date addresses Approval Condition 13(d).

4.1. Simulation of impacts to Surat Basin formations

CSG extraction under the SGP requires groundwater abstraction from the Walloon Coal Measures, which will lead to depressurisation of this formation and in other GAB formations that have connectivity with the Walloon Coal Measures. In addition, this depressurisation can lead to potential changes in flux to the Condamine Alluvium, and hence affect groundwater-surface water interaction with the Condamine River system.

For the SREIS, the Arrow SREIS Groundwater Model was used to model regional impacts. Flux change predictions from this model to the Condamine Alluvium were then used as inputs to the more detailed CCAM to model Condamine Alluvium drawdown, at a better resolution than provided by the Arrow SREIS Groundwater Model. Uncertainty analysis was also undertaken to enable an understanding of the predictive uncertainty of the model[1].

Four predictive scenarios were simulated using the Arrow SREIS Groundwater Model:

1. Non CSG Case - this scenario modelled non-P&G industry extraction only from 1995 onward;

2. Base Case - this scenario modelled current and proposed CSG water extraction associated with the GLNG, QCLNG and APLNG Projects and other petroleum activities from 1995 onward (Arrow coal seam gas activities were excluded);

3. Cumulative Case - this scenario modelled current and proposed water extraction from all petroleum and gas activities from 1995 onwards. Extraction associated with the GLNG, QCLNG, APLNG and Arrow Surat Gas Projects was included in addition to non-P&G extraction; and

4. Substitution Case - this scenario was run to quantify net impacts on groundwater levels in the Condamine Alluvium with and without 'virtual injection' via substitution to existing licensed allocations.

The predicted Arrow only impacts were calculated by determining the difference between the Base Case and Cumulative Case predictions.

Groundwater extraction from coal seam gas production in the Arrow SREIS Groundwater Model was handled using the MODFLOW EVT package, consistent with the 2012 OGIA approach. The OGIA EVT input files were revised to provide consistency with Arrow's current FDP at the time, which has reduced extractions (702 GL) compared with the 2012 OGIA modelling (717 GL).

4.1.1. Key findings

The Arrow SREIS Groundwater Model simulated a water production with a peak extraction rate of 140 ML/d anticipated between 2021 and 2024. It is noted that the primary purpose of the model was

[1] Uncertainty analysis comprised simulation of 200 separate realisations of the OGIA 2012 Groundwater Model and interpreted using a statistical approach whereby the 5th and 95th percentiles of head at each grid cell were computed (GHD, 2012). Mean and median values were also computed, and contours of the 95th percentile, median, mean and 5th percentile were produced.

to predict drawdown impacts under depressurisation scenarios, rather than water flows. This is because simulated water production rates are affected by the effects of dual-phase flow (i.e. gas and water) which cannot be fully accounted for in the model.

Field development planning tools (based on reservoir modelling) for Arrow's current FDP have indicated that actual total water production expected for the duration of the SGP will be approximately 510 GL, which is lower than the 702 GL as modelled.

4.1.2. Predicted impacts

Arrow Only Case

Great Artesian Basin (GAB) aquifer drawdown

The maximum predicted drawdowns in the main GAB aquifers in the Surat CMA (Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone) as a consequence of Arrow's current FDP only and based on the calibrated model are shown in Figures 1 to 4.

Predicted hydrographs for proposed extraction blocks were extracted for the calibration case, and plots showing drawdowns at each location for the Springbok Sandstone, Walloon Coal Measures, Hutton Sandstone and the Precipice Sandstone are included in Appendix 4 of the SREIS. The hydrographs indicate that time lags between extraction in the Walloon Coal Measures and impacts in the adjacent aquifers increase with vertical separation.

Peak impacts in the Springbok Sandstone is up to 10 m and typically occurs at 20 years after peak impact in the Walloon Coal Measures. Peak impacts in the Hutton Sandstone is approximately 8 m and typically occurs at 75 years after peak impact in the Walloon Coal Measures. Drawdown impacts to the deeper Precipice Sandstone are less than 0.7 m and of limited extent.

Condamine Alluvium aquifer drawdown

The maximum predicted Arrow related drawdown in the Condamine Alluvium aquifer (based on the calibrated model) indicated drawdown of up to 0.5 m in central parts of the Condamine Alluvium. However, this maximum drawdown was only evident in a small proportion (<10%) of the Condamine Alluvium, and drawdown was typically less than 0.18 m across the remainder of the alluvium.

Condamine Alluvium flux changes

Existing interlayer flux into the Condamine Alluvium (i.e. under non-CSG development conditions) comprises upward flow from the Walloon Coal Measures. Therefore flux changes resulting from coal seam water production cause a small reduction in the existing upward flux, which remains predominantly upward from the Walloon Coal Measures to the Condamine Alluvium, with only minor exception.

Predicted flux changes to the Condamine (presented in the SREIS) indicated relatively minor impacts peaking at between 1.25 and 2.8 ML/d.

Cumulative Case

Total modelled water extraction from current and proposed coal seam gas projects to be operated by Arrow, Santos, QGC and Origin within the Surat CMA indicated a peak extraction of around 550 ML/d in 2015.

Great Artesian Basin (GAB) aquifer drawdown

The maximum predicted drawdown based on the calibrated model case in the main GAB aquifers in the Surat CMA (Springbok Sandstone, Walloon Coal Measures and Hutton Sandstone) as a consequence of cumulative impacts of coal seam gas projects are shown in Figures 5 to 8.

Predicted hydrographs for proposed extraction blocks were extracted for the calibration case, and plots showing drawdown at each location for the Springbok Sandstone, Walloon Coal Measures and the Hutton Sandstone are included in Appendix 4 of the SREIS.

Cumulative maximum impact drawdown (50th percentile case) in the Springbok Sandstone is up to 15 m, and for the Hutton Sandstone is up to 15 m. Cumulative maximum impact drawdown (50th percentile) in the Precipice Sandstone is up to 5 m but of limited areal extent.

Condamine Alluvium aquifer drawdown

The maximum predicted cumulative impact in the Condamine Alluvium (calibrated model) indicates drawdown of up to 0.9 m near Dalby. Drawdown of less than 0.24 m is typical across the remainder of the Condamine Alluvium. Predicted cumulative drawdown in the Condamine Alluvium is therefore higher than that for the Arrow only case.

Condamine Alluvium flux changes

Cumulative predicted flux changes to the Condamine (presented in the SREIS) indicated relatively minor impacts peaking at between 1.8 and 3.8 ML/d.

The flux change as a result of cumulative water extraction to the Condamine Alluvium was 79 GL over a 100 year modelled period for the calibrated model, and 101 GL over a 100 year period for the maximum impact realisation.

4.1.3. Summary of predicted impacts due to Arrow FDP

Table 4.1 provides a summary of the predicted drawdown impacts in the key aquifers for the Arrow FDP scenarios, based on the calibrated model (refer also to Figures 1 to 4).

Table 4.1: Arrow only drawdown (Time of maximum drawdown in years from 1995)

Key Aquifers	SREIS			
	Average Drawdown (m)	Maximum Drawdown (m)	Time of Maximum Drawdown[1]	Year of maximum drawdown
Condamine Alluvium	<0.18	0.5	105	2100
Springbok Sandstone	<2	10	50	2045
Walloon Coal Measures	<50	350	30	2025
Hutton Sandstone	<5	8	105	2100
Precipice Sandstone	-	0.7	110	2105

Condamine Alluvium (shallow groundwater system)

Modelled Arrow only drawdown in the Condamine Alluvium (without mitigation through substitution) peaks at 0.5 m and is typically less than 0.18 m (in the calibrated model). The greatest drawdown was predicted to occur along the western extent of the Condamine Alluvium (Appendix 4 of the SREIS).

Springbok Sandstone (intermediate groundwater system)

Modelled Arrow only drawdown predictions for the Springbok Sandstone is expected to be less than 10 m, with maximum impact to the west of Dalby in 2045, and a reduced impact in the area west of Cecil Plains in 2075 (Appendix 4 of the SREIS).

Walloon Coal Measures (coal seam gas groundwater system)

Modelled Arrow only drawdown predictions for the Walloon Coal Measures is indicated to be less than 50 m in most areas. In the more central-westerly areas, where the coal seam formation is relatively deep, the drawdown is predicted to be up to 350 m with maximum impact to the west of Cecil Plains in 2025 (Appendix 4 of the SREIS).

Hutton and Precipice Sandstones (deep groundwater system)

Modelled Arrow only drawdown predictions for the Hutton Sandstone is indicated to reach 8 m with maximum impact between Dalby and Cecil Plains in 2100 (Appendix 4 of the SREIS).

Maximum impact in the Precipice Sandstone is expected to be less than 0.7 m in drainage area DA5 southwest of Chinchilla in 2105, with impacts generally less than 0.3 m in other areas, but extended for longer periods of time.

4.2. Simulation of impacts to Condamine Alluvium and Condamine River

As described in Section 4.1, depressurisation of the Walloon Coal Measures due to CSG production has a potential influence on the water balance of the adjacent Condamine Alluvium aquifer, as modelled for the SREIS. Based on the requirement of Approval Condition 13(b) (addressed separately in CDM Smith, 2016), additional modelling has been undertaken to further assess this influence, and to quantify the impact that flux changes to the Condamine Alluvium may have on surface water flow to the Condamine River.

4.2.1. Integrated groundwater-surface water modelling

To assess this, an integrated groundwater-surface water modelling approach was undertaken by CDM Smith (2016).

Under this approach, the OGIA 2012 Surat CMA groundwater model was used to simulate potential impacts of Arrow’s proposed action (based on the SREIS FDP) on the rate and distribution of vertical groundwater flux between the Surat Basin and overlying Condamine Alluvium (CDM Smith, 2016). Predictions of changes in vertical groundwater flux established from this model were then used as inputs to the **CDM Smith Condamine Alluvium Model** to assess the effects of CSG development on groundwater levels in the Condamine Aquifer.

The predicted groundwater level impacts in the Condamine Alluvium were in turn used as inputs to the **CDM Smith IQQM** model to assess the potential impacts of CSG development under the SREIS FDP on the availability of surface water in the Condamine River.

The actual potential for a drawdown in groundwater level to impact flow in the Condamine River system is dependent on the relationship between river bed elevation and watertable depth. Figure 9 (after CDM Smith, 2016) illustrates this interpreted relationship.

The additional simulations are detailed in CDM Smith (2016). Key findings are summarised below for both the CCAM area and the total Condamine Alluvium footprint area. The area of alluvium in the CCAM where connection to underlying strata of the Surat Basin was simulated encompasses 5,321 km^2, representing approximately 90% of the footprint area of alluvium (5,904 km^2) as represented in the Surat CMA Groundwater Model. This difference is due to minor differences in conceptualisation of the extent of the Condamine Alluvium.

4.2.2. Key findings

Water production volumes and rates: existing and proposed CSG development

Based on 90% of realisations, predicted Arrow volumetric extraction is between 653 GL and 755 GL, with a median extraction of 710 GL over 65 years (11 GL/y). The predicted Arrow maximum rate is between 124 ML/d and 151 ML/d, with a median value of 138 ML/d.

Change in net vertical flux to Condamine: all operators

Table 4.2 details changes in net volumetric and vertical flux to the Condamine Alluvium footprint area and Central Condamine Alluvium Model area based on 90% of realisations over a 3,000-year simulation period.

Table 4.2: Net changes to Condamine Alluvium

	Volumetric change (GL)[1]		Max flux change (ML/d)[2]	
	Range	Median	Range	Median
All CSG operators				
Condamine Alluvium footprint area	465 - 608	537	1.79 – 3.57	2.36
Central Condamine model area	384 - 508	445	1.64 – 2.99	2.11
Arrow contribution				
Condamine Alluvium footprint area	264 - 341	303	not computed	not computed
Central Condamine model area	216 - 292	256	not computed	not computed

1 Volumetric change = reduction in flow volume over 3,000 year simulation period, between the Walloon Coal Measures and the Condamine Alluvium.
2 Flux change = reduction of flow rate between the Walloon Coal Measures and the Condamine Alluvium
Source: CDM Smith (2016)

4.2.3. Predicted impacts

Predicted change in flux to the Condamine Alluvium

The maximum rate of Arrow water production in the Surat CMA Groundwater Model, under the SREIS FDP, occurs around the same time (between year 2023 and 2024) for the high, median and low case realisations[2], however depressurisation in the Walloon Coal Measures takes time to propagate through to the base of the Condamine Alluvium. The simulated maximum change in net (vertical) flux at the base of the alluvium (a reduction in flow to the Condamine Alluvium) occurs 29 to 45 years after the maximum Arrow water production (between year 2052 and 2069 depending on the realisation).

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[2] Three simulations out of the 200 NSMC realisations of the Surat CMA Groundwater Model were run with the CCAM to predict impacts to the Condamine River. These simulations were selected based on the predicted change in net vertical flux volumes at the base of the Condamine Alluvium, and defined as the high, median and low cases (5%, 50% and 95% probability of exceedance in 200 realisations, respectively).

It is of note that the predicted maximum change in flux at the base of the Condamine Alluvium due to Arrow water production is greater for the median case (2.67 ML/d) than for the high case (2.11 ML/d) even though the corresponding maximum in water production for the median case is smaller. This is caused by the distribution and magnitudes of hydraulic conductivities in this realisation creating a more direct connection between the Surat Basin consolidated formations and the Condamine Alluvium.

The three realisations (high, median and low) reported in this section were ranked based on the total impact from all existing and proposed CSG water extraction on the Condamine Alluvium, not only Arrow. Table 4.3 summarises changes in Condamine flow components.

Table 4.3 Predicted changes to flow components in the CCAM due to Arrow water production

Prediction	High case		Median case		Low case	
	ML/d	Year	ML/d	Year	ML/d	Year
Max Arrow water production rate	138	2023	128	2023	123	2024
Max reduction in g/water flux to Condamine Alluvium	2.11	2054	2.67	2052	1.34	2069
Max reduction in net g/water flux to Condamine River	0.12	2146	0.13	2146	0.09	2137

Source: CDM Smith (2016)

In summary the predicted maximum changes in total groundwater flux to the Condamine River due to Arrow water production is 0.12 ML/d, 0.13 ML/d and 0.09 ML/d for the high, median and low case realisations. Figures 10 and 11 illustrate the predicted spatial distribution of flux changes for the high and median cases, whereas Figures 12 and 13 illustrate the predicted spatial distribution of flux changes for all realisations.

Analysis of the results shows that more than 75% of the model river cells experience no discernible change in groundwater flux over the simulation period because they are 'disconnected' from groundwater (Figures 14 and 15). Therefore the rates of leakage from these river cells are constant and largely independent of the watertable level changes. Most of the predicted impact on the Condamine River due to Arrow CSG water production occurs in river cells located downstream of Warra Town Weir with maximum changes in groundwater flux of between 0.001 ML/d and 0.004 ML/d. Impacts of less than 0.001 ML/d are also predicted just upstream of Talgai Weir, Yarramalong Weir, Cecil Plains Weir and Chinchilla Weir (Figures 16 and 17).

The predicted impacts are of very small magnitude and considered negligible.

Predicted drawdown due to CSG development in the Condamine Alluvium

The predicted values of maximum drawdown (the largest values of drawdown in each model cell over the period of the simulation) occur at different times within the simulation period and at different locations within the Condamine Alluvium.

Figures 18 and 19 illustrate the predicted maximum drawdown timing at the watertable due to Arrow production for the high and median cases, and Figures 16 and 17 present the distributed change in groundwater flux to the Condamine River due to Arrow production for the high and median cases.

Figure 14 shows the simulated depth to groundwater along the Condamine River, and Figure 15 presents the predicted Arrow contribution to all-time maximum drawdown (high case) for the Condamine River system.

Maximum drawdown is predicted earliest in several small areas on the western edge of the Condamine Alluvium between year 2100 and 2300 (Figures 18 and 19). More generally, the maximum drawdowns in the alluvium are predicted to occur after year 2300, which is around 275 years after the simulated maximum in water production.

The largest predicted value of maximum drawdown in a model cell due to Arrow water production is approximately 1.1 m for the high and median case realisations, and approximately 0.8 m for the low case realisation.

4.3. Simulated impacts to Condamine River water users

An integrated water quantity and quality simulation model (IQQM) has been implemented in several regulated river systems in Australia for water resources management planning, including the Condamine-Balonne system. IQQM comprise several modular components that include an instream water quantity module and a groundwater quantity and quality module (Simons *et al*, 1996).

River systems are represented in IQQM by a series of nodes connected with links, which allows the model to be configured to simulate any river system (Simons *et al*, 1996). Flow and routing is calculated along links at specified time-steps, which may be between one hour and one day.

In Queensland, IQQM data sets are developed and maintained by the DNRME. The data sets encapsulate licensing information, so that the model can be used to manage water allocations. IQQM models used by DNRM for the area defined by the extent of the Condamine Alluvium groundwater model are:

- Upper Condamine model:
  - Starts at Killarney Weir.
  - Finishes at Cecil Plains Weir gauge 422316A on the Condamine River, and at the Lone Pine gauge 422345A on the North Condamine River (the northern anabranch).
  - Includes 8 supply storages.
- Middle Condamine model:
  - Starts at Cecil Plains Weir and Lone Pine gauges, where outflows from the Upper Condamine model are passed through as inflows to the Middle Condamine model.
  - Finishes at Beardmore dam headwater gauge 422212B.
  - Includes 17 regulated storages.

Groundwater interaction is not explicitly simulated in the IQQM, however stream transmission losses were included and estimated by comparing recorded and simulated flows at a downstream gauge (CDM Smith, 2016). Flow losses can be attributed to groundwater recharge and infiltration during periods of overland flooding, flow breakout around the downstream gauge, and uncertainty in the measurements and water extraction estimates.

The Resource Operation Plan (ROP)[3] scenario was provided with each IQQM model, and used as the base case to assess the potential impacts of CSG production on surface water resources. The ROP scenarios include full entitlements, and allocations that existed at the time the two models were developed are assumed to be fully utilised.

The environmental flow objectives (EFO) performance indicators for the Condamine and Balonne Water Resource Plan (Queensland Government, 2004) provide a basis for assessing the performance of the Water Resource Plan, and are adopted for the purpose of quantifying impacts to river flows. Water Resource Plans also contain water allocation security objectives (WASOs) which are a key measure within water resource plans for protecting the availability of water under a water allocation.

To investigate potential impacts to Condamine River flows, IQQM was used to simulate flow reduction due to the ROP basecase, and due to Arrow's FDP. IQQM model details and application are provided in Section 7.7 of CDM Smith (2016).

4.3.1. Key findings

Flow reduction due to ROP

In the Upper Condamine, only one EFO reporting site (IQQM node K at Cecil Plains Weir) is located within the extent of the Central Condamine Alluvium groundwater model. The basecase simulations indicate that the pre-development mean annual flow at this node was reduced by 30% due to ROP water allocation.

In the Middle Condamine, only one EFO reporting site on the Condamine River (IQQM node J at the upstream limit of Chinchilla Weir) is located within the extent of the Central Condamine Alluvium Model. Nodes I and H are located further downstream on the Condamine River and were considered as part of the study to look at potential impacts further downstream. The basecase simulations indicate that the pre-development mean annual flow at these EFO nodes was reduced by 29-37% due to ROP water allocation (Table 4.4).

[3] An ROP describes the rules and requirements to achieve the water resource objectives from the Water Resource Plan. The ROP for the Condamine and Balonne River system was published in 2008 and revised in 2015 (DNRM 2015).

Table 4.4 Simulated mean annual flow at Condamine River nodes I, J, K and H

Section	Node	Pre-development flow (ML/year)	ROP scenario flow (ML/year)[1]	Flow reduction*
Upper Condamine	K	267,608	188,544	30%
Middle Condamine	I	555,433	376,428	32%
	J	440,462	278,276	37%
	H	589,925	416,428	29%

1: Assumes all water allocations are utilised

<u>Condamine River flow reduction due to Arrow SGP</u>

IQQM was used to simulate the impact of the change in groundwater flux to the Condamine River, as predicted by the CCAM groundwater model. Based on predicted drawdown, the CCAM shows that impacts to the Condamine River are predicted to occur almost entirely along reaches between Warra Town Weir and Chinchilla Weir (Figures 16 and 17). These reaches are located within the Middle Condamine IQQM domain. No drawdown impacted reaches are predicted for the Upper Condamine IQQM domain.

To evaluate the impacts on river flows, an additional node has been included in the IQQM Middle Condamine ROP model, to remove up to the predicted maximum change in groundwater fluxes to the Condamine River when water is available in the system. To ensure a conservative assessment, the maximum change in groundwater flux based on the CCAM was used for the assessment (0.13 ML/d).

To assess the predicted impacts, EFO performance indicators were reviewed at three reporting nodes located downstream of the river reach where the simulated groundwater loss occurs. The results for the three simulations are compared to the base case ROP scenario.

The results show that performance indicators are achieved for all three cases and the predicted maximum impact is negligible, with only the number of low flow days at Node J reporting an increase of 0.1% (from 112.5% to 112.6%). All other performance indicators are unchanged relative to the ROP basecase.

Daily flow duration curves that compare the ROP basecase with the High, Medium and Low CSG scenarios at Nodes J, I and H are provided in CDM Smith (2016) (Figures 7-51, 7-52 and 7-53).

4.3.2. Predicted impacts

The potential impacts of groundwater drawdown on surface water users were assessed against the associated Water Allocation Security Objectives (WASO). WASOs are performance indicators are defined for a water allocation group as follows:

- The annual volume probability:
    - For taking un-supplemented water, the percentage of years in the simulation period in which the volume of water that may be taken by the group is at least the total of the nominal volumes for the group, and
    - For taking supplemented allocations, the average annual volume of water that may be taken by the group in the simulation period as a percentage of the total of the nominal volumes for the group.

- The 45% annual volume probability:
  - The percentage of years in the simulation period in which the volume of water that may be taken by the group is at least 45% of the total of the nominal volumes for the group.

Note that “supplemented water” means water supplied under a resource operations licence or other authority to operate water infrastructure.

All WASO performance indicators were checked for users downstream of the loss node. There were no reductions in the performance indicators except at IQQM node 184 (Brigalow Town Water Supply). At this node, the Annual Volume Probability decreased by 0.3% for the high, median and low cases.

5. Condition 13(a)

To provide an ongoing basis for regional groundwater impact prediction, the OGIA has developed a new regional numerical groundwater model to support the Surat CMA 2016 UWIR. This model (OGIA 2016 Groundwater Model) replaces the previous model that provided the groundwater impact predictions for the Surat CMA 2012 UWIR (QWC, 2012) and upon which the Arrow SREIS Groundwater Model (GHD, 2013) and CDM Smith (2016) model were based.

To address Approval Condition 13(a), this section provides a discussion regarding the changes in conceptualisation and model design of the OGIA 2016 Groundwater Model, and a comparison of the drawdown with the Arrow SREIS Groundwater Model. The implications of these on long-term fluxes between aquifers (and therefore potential impacts on groundwater - surface water interaction and GDEs) are discussed. This summary comparison of the two models is necessarily made in the context of the impact prediction for the Arrow Stage 1 CSG WMMP.

5.1. Introduction

The Arrow SREIS Groundwater Model has been described briefly in Sections 2 and 3 of this document.

The OGIA 2016 Groundwater Model is described in the ‘Underground Water Impact Report for the Surat Cumulative Management Area’ (DNRM, 2016a) and also the ‘Groundwater modelling report for the Surat Cumulative Management Area’ (DNRM, 2016b). This model has been used to generate impact predictions to underpin the Surat CMA 2016 UWIR.

More specifically, the Surat CMA 2016 UWIR model is designed for regional cumulative impact assessment to:

- Define the immediately affected area (IAA) for each consolidated aquifer present within the model domain—that is, the area where water pressures are predicted to decline by more than 5 m within 3 years.
- Define the long-term affected area (LAA) for each consolidated aquifer present within the model domain—that is, the area where water pressures are predicted to decline by more than 5 m at any time in the future.
- Identify potentially affected springs—that is, springs where the water pressure in aquifers underlying the sites of these springs is predicted to decline by more than 0.2 m at any time in the future.
- Predict the rate and volume of water movement between formations.

- Estimate the quantity of groundwater that is expected to be extracted as a result of P&G developments in the Surat CMA.

The model is not designed to be used to directly predict water pressure or water level variations at a local scale.

5.1.1. Model domain and discretisation

The domain of the Arrow SREIS Groundwater Model covers an area of 547.5 km x 661.5 km. The model comprises 441 rows and 365 columns. The model domain is discretised into cells of 1.5 km x 1.5 km areal extent, 19 layers deep, for the purpose of simulating flow of groundwater within the Surat Basin sequence and overlying alluvial formations within the Surat CMA. The model includes Bowen Basin formations including Moolayember, Clematis and Rewan formations. The Blackwater Group and other undifferentiated Permian sediments of the Bowen Basin are also represented.

The domain of the OGIA 2016 Groundwater Model covers an area of 460 km × 650 km encompassing the entire Surat CMA. The model domain is discretised into cells of 1.5 km × 1.5 km areal extent, 32 layers deep, for the purpose of simulating flow of groundwater within the Surat Basin sequence and overlying alluvial formations within the Surat CMA, and within the CSG-producing Bandanna and Cattle Creek formations of the Bowen Basin. Bowen Basin units such as Moolayember, Clematis and Rewan formations are included.

5.1.2. Modelling platform

Arrow SREIS Groundwater Model: Modelling was undertaken using the MODFLOW-SURFACT modelling code, a proprietary MODFLOW variant that also includes a more sophisticated well simulation package (the Fracture Well (FWL4) package) which was seen as advantageous.

The OGIA 2016 Groundwater Model: Modelling was undertaken using the MODFLOW-USG groundwater modelling code. This code version utilises an unstructured grid, as compared with the rectilinear grid utilised in other versions of MODFLOW. MODFLOW-USG was initially released by the United States Geological Survey (USGS). It is noted that the version used for the OGIA 2016 model is a modified version of MODFLOW-USG.

5.1.3. Upscaling of properties

A stratigraphic unit that is assigned to an individual model layer is comprised of a layered sequence of individual lithologies, and the medium represented by an individual model cell can therefore include facies such as sandstone, shale and coal whose individual hydraulic properties are very different. To account for this, upscaling is required to represent hydraulic properties at the coarse model scale, and in such a manner that Darcy's law and conservation of mass are preserved when applied at the model cell scale. To account for this, a process for parameter upscaling has been applied to the OGIA 2016 Groundwater Model.

Upscaling involves statistical generation of model parameters sets from probability distributions of the parameters, to enable hydraulic properties of formations to be represented in a manner that reflects their bulk properties.

For the OGIA 2016 Groundwater Model, a set of initial parameters was developed that reflects, as much as possible, the current state of geological knowledge throughout the CMA (DNRM, 2016a). The uncertainties with these estimates were also characterised and the initial estimates were revised during model calibration. The main components of the approach was:

- Initial values of hydraulic conductivity for each of six lithology types identified in geophysical logs were derived from expert knowledge, literature and permeability analyses based on petrophysical log data.
- These initial values were then input to a stochastic permeability model and calibrated (or 'conditioned') through comparison with the available hydraulic parameter data at three different scales. This conditioning procedure provided estimates of all parameters used in the permeability models, as well as estimates of the uncertainties associated with these parameters.
- Once calibrated, these values were then used to populate numerical permeameters - detailed 21 km by 21 km numerical models of each stratigraphic unit and covering the full extent of the 12 stratigraphic units modelled—to derive spatially variable formation-scale horizontal and vertical hydraulic conductivity based on 20 different possible realisations of the highly heterogeneous lithology observed in each area.

The output from this process provided a set of initial hydraulic conductivity parameters.

It is noted that it is likely that the application of various upscaling methods can have a large influence on model predictions. Upscaling was vertically averaged in the Walloon Coal Measures. Hence, the model parameters for layers representing this formation are a hybrid of the coal and interburden.

5.1.4. Calibration

Calibration of the OGIA 2012 Groundwater Model was undertaken using the model-independent parameter estimation package, PEST. Calibration of the OGIA 2016 Groundwater Model was also undertaken using PEST.

Construction, calibration and deployment of the OGIA 2016 Groundwater Model relied heavily on software developed by the OGIA personnel. Mention is also made of some of the tasks performed by these programs. Particular attention is paid to the handling of regional faults.

Parameters adjusted through calibration included:

- Hydraulic conductivity – horizontal
- Hydraulic conductivity – vertical
- Storage and specific yield'
- Recharge
- General Head Boundary characteristics
- Fault core and damage zone width
- Additional parameters in coal measures:
  - enhanced K in cells where CSG wells have been installed
  - dual domain transfer rate (DDFTR)

5.2. Technical differences with the OGIA 2012 Groundwater Model

5.2.1. Stratigraphy

Differences in the stratigraphy represented by the OGIA 2016 Groundwater Model primarily relate to further layer refinement in the Walloon Coal Measures, and other strata. According to DNRM (2016b) "*By increasing the number of layers represented in the model, there was less need to agglomerate stratigraphic units into single model layers*". In the OGIA 2016 Groundwater Model the Rolling Downs Group has been separated into model layers for the Upper Cretaceous sediments and the Wallumbilla

Formation, and individual model layers have also now been used to represent the Bungil Formation and the Mooga Sandstone.

A number of stratigraphic units are represented by multiple model layers in the OGIA 2016 Groundwater Model. This includes:

- The Walloon Coal Measures, Bandanna Formation and Cattle Creek Formation - now represented using a minimum of three layers (six layers for the Walloon Coal Measures).

Reasoning is stated as allowing more accurate representation of aquifer geometry in key areas such as the Condamine Alluvium, where coal seams subcrop beneath other aquifer layers, as well as allowing for improved simulation of vertical gradients induced by CSG extraction.

In addition:

- The Springbok Sandstone and Hutton Sandstone have each been subdivided into two layers.

Reasoning is stated that this accommodates vertical variation of hydraulic properties within these units, based on geophysical log interpretations that show differences in lithology and hydraulic properties in the upper and lower parts of these formations.

In summary, the OGIA 2016 Groundwater Model encompasses a slightly smaller model domain, but similar stratigraphy under an alternative layer representation. Both models include the major Surat Basin Formations, together with underlying southern Bowen Basin strata, and extend into the Clarence-Moreton Basin. The change in model domain area is reported to better align this boundary with the Helidon Ridge, a subtle structure which is now thought to form a groundwater divide between the Surat and Clarence-Moreton basins in hydrostratigraphic units corresponding to basal Jurassic sequences (DNRM, 2016b).

5.2.2. Representation of faulting

A total of 16 regional faults are afforded explicit representation in the OGIA 2016 Groundwater Model (DNRM, 2016b). In the model, fault plane and damage zone properties are represented in a manner whereby cross-fault and near-fault properties are modified using software specifically developed to implement this representation.

As described in DNRM (2016b), software has been developed by the OGIA personnel that enables a modeller to nominate the width of a fault and the width of the damage zone associated with a fault. A complex procedure is described, whereby the cross-fault hydraulic resistance at any point within the fault plane is obtained by summing the resistances of entrained lithologies at that point. The resistance of each entrained lithology is calculated as its entrained thickness divided by its vertical hydraulic conductivity. This cross-fault resistance is introduced to the model using the MODFLOW-USG horizontal flow barrier (HFB) package for model layers that are thick enough for their continuity to be preserved across the fault. MODFLOW-USG does not support HFB between cells that do not belong to the same layer; so this option is not available for cells that are juxtaposed across a fault entirely as a result of fault displacement.

Up-fault conductance is calculated through summation of entrained lithological conductances, and the conductance of each entrained lithology is calculated as its horizontal hydraulic conductivity times its entrained thickness. The vertical conductivity of the damage zone is calculated under the assumption that vertical hydraulic conductivity anisotropy within this zone has been reduced to 1.0 through catalysis.

No detail is provided in relation to actual fault zone hydraulic conductivities or actual conditions of faults, or behaviour under the compressive stress state within the Surat Basin. In this regard, it is considered appropriate to refer to previous investigations (Coffey, 2014) undertaken in relation to the hydraulic behaviour of faults in the Bowen Basin.

5.2.3. Uncertainty analysis

Arrow SREIS Model

The OGIA 2012 Groundwater Model, that formed the basis for the Arrow SREIS Groundwater Model, was subject to significant parameter uncertainty analysis. This uncertainty analysis involved the generation of 200 model predictions based on 200 statistically generated parameter sets, resulting in 200 different predictions of groundwater level impact. These simulations enabled results to be define in terms of high, median and low cases (5%, 50% and 95% probability of exceedance in 200 realisations, respectively).

The final calibrated parameters presented by the OGIA at the time were considered to be close to optimal, in terms of the modelled fit to the adopted calibration targets, however it is recognised that similar levels of fit could have been achieved using a range of different parameter sets.

In addition, as the analysis uses head and drawdown as calibration parameters, the uncertainty analysis may not accurately reflect flux uncertainty.

OGIA 2016 Groundwater Model

Uncertainty analysis has not been undertaken for the OGIA 2016 Groundwater Model. DNRM (2016b) report this model will be subjected to a similar process to the 2012 model in the future, and will likely include:

- Modification of the NSMC methodology to allow introduction of small-scale parameters (representing, for example, the effects of local faults and abandoned bores) to regional-scale parameter fields in order to support exploration of uncertainty at both local and regional scales.
- Endowment of parameters that pertain to processes such as CSG extraction not directly measurable (for example, those associated with the van Genuchten relationship which governs coal seam desaturation).
- Linear uncertainty analysis to calculate quantities which elucidate current sources of predictive uncertainty, and which suggest means through which this uncertainty can be reduced.

Section 7.3 of the Surat CMA 2016 UWIR states that new approaches to uncertainty analysis are being developed and will be applied, and that results will be provided in the first annual report on implementation of the Surat CMA UWIR 2016.

5.2.4. Modifications to USG code for the OGIA 2016 Groundwater Model

Extraction of water from a gas well represented in a typical groundwater model is problematic because gas wells commonly contain both water and gas simultaneously, and the relative proportions change over time. If a well is almost completely gas-filled, then conditions in the well approach that of uniform pressure rather than that of uniform head (DNRM, 2016b). In addition, the effective hydraulic conductivity of the coal seam changes as gas production commences, due to the effects of dual phase conditions.

MODFLOW-USG does not simulate dual phase flow, however DNRM (2016b) report it is capable of simulating water desaturation in response to reduction in pressure, implemented using a modified form of the van Genuchten equation that allows desaturation to commence at a user-specified pressure head (DNRM, 2016b). In the CSG context, this pressure normally coincides with the saturation pressure of the Langmuir isotherm that governs gas desorption, or the natural groundwater head, whichever is smaller (DNRM, 2016b).

Modifications have been made to the MODFLOW-USG source code by OGIA personnel '*to enhance its ability to simulate regional CSG impact*' (DNRM, 2016b). These include:

- **Derating of pumping**: As programmed in for the OGIA 2016 Groundwater Model, this allows derating of extraction from its prescribed value to commence if the head in the node falls to a level that is greater than the bottom of the cell or segment by 1% of the total thickness of the cell or length of the segment.

- **Descending drain methodology**: simulating water extraction from CSG wells using this method, as programmed in MODFLOW-USG, functions as follows: A single CSG well may tap multiple layers, and hence multiple MODFLOW-USG drains must be assigned to that well. The MODFLOW-USG drain boundary condition allows flow out of a model cell, but not into a model cell. The elevations of the drains are originally equated to the head in the highest model layer that is tapped by the CSG well, or the pressure head equivalent of the saturation pressure of the Langmuir isotherm that governs gas adsorption, whichever is lower. Once gas extraction commences from the well, all drains descend at the same rate, as set by the modeller and each layer-specific drain ceases its descent at a drain-specific elevation. This is normally the elevation of the centre of the model layer to which each drain is assigned plus the water head equivalent of the bottom hole pressure of the CSG well. However the elevation of the drain assigned to the bottommost layer descends to an elevation equal to that of the bottom of the well screen plus the water head equivalent of the bottom hole pressure. In the uppermost layer tapped by the CSG well, the terminal elevation of the pertinent drain is the top of the well screen plus the water head equivalent of the bottom hole pressure.

- **Hydraulic conductivity enhancement**: Alterations to implement the reading of a file containing horizontal cell hydraulic conductivities, which the extended drain package uses for calculation of conductance. The modified software calculates these conductivities through weighted averaging of hydraulic conductivities to reflect local lithological proportions. The conductance ascribed to a drain that occupies a particular cell is purported to be more representative of the transmissivity with which the well portion simulated by that drain is in contact (DNRM, 2016b). In the OGIA 2016 Groundwater Model, the conductance calculated in this way is modified by a user-supplied factor that is then adjusted through model calibration.

5.3. Comparison of results with OGIA 2012 Groundwater Model

5.3.1. Differences in flux to Condamine aquifer

The net reduction in flux to the Condamine Aquifer, as reported in the Surat CMA 2016 UWIR, is predicted to be 1,160 ML/year, compared with 1,100 ML/year for the Surat CMA 2012 UWIR.

DNRM (2016a) reports this to be in line with 2012 predictions, however when considering the overall reduced CSG development and 32% reduction in produced water volumes, for this to be in line with the 2012 OGIA modelling a reduced net loss of water would be expected, and therefore a smaller net reduction in flux to the Condamine Aquifer. As such, further investigation is warranted. Arrow will further investigate the changes in flux in the Stage 2 CSG WMMP and are committed to working with the OGIA to investigate the changes in flux.

5.3.2. Differences in predicted drawdown

Direct comparison of different model versions and approaches is difficult due to differences in the models, simulations, FDPs and presented outputs. In terms of drawdown, the Surat CMA 2016 UWIR presents modelled drawdown in relation to the Immediately Affected Area (IAA) and the Long-term Affected Area (LAA) of aquifers.

The IAA refers to areas where groundwater levels are predicted to fall by more than the trigger thresholds **within 3 years** of commencement of production. The LAA refers to the area within which water levels are predicted to fall, due to water extraction by petroleum tenure holders, by more than the trigger threshold **at any time** in the future. The trigger thresholds are specified in the Water Act as 5 metres for consolidated aquifers and 2 metres for unconsolidated aquifers.

Figures 20 and 21 provide a comparison between the 2012 and 2016 modelling of relative drawdown for the main Surat GAB aquifers.

The Surat CMA 2016 UWIR provides comments in relation to differences in predictions between the OGIA 2016 Groundwater Model and the OGIA 2012 Groundwater Model. General comment can only be made due to the different CSG production profiles between these two models, a factor that also applies to comparisons with the Arrow SREIS Groundwater Model. In this regard we note that the Arrow SREIS Groundwater Model represents a version of the OGIA 2012 Groundwater Model.

The following are general comments in relation to changes to LAAs in the Surat CMA 2016 UWIR when compared to the Surat CMA 2012 UWIR:

- The Walloon Coal Measures LAA extends further in the north-east and has contracted in the southwest. The extension towards the north-east is reported to reflect improved spatial understanding of variation in horizontal permeability within the formation. DNRM (2016a) states that horizontal permeability tends to be relatively high in the north-east where the coal is close to the surface, reducing with depth towards the south-west. The reduction in the area of planned CSG development is also a reported factor.
- The Springbok Sandstone LAA overlies the Walloon Coal Measures and is smaller than assessed in 2012. DNRM (2016a) states that this reflects the generally lower vertical permeability resulting from parameterisation and calibration of the new groundwater flow model.
- The Hutton Sandstone LAA is larger than assessed in 2012. DNRM (2016a) states that the Durabilla Formation aquitard is now considered to be less permeable than previously understood, and pressure reductions at the base of the Walloon Coal Measures are predicted to be higher.
- The Precipice Sandstone LAA, which was of very limited area for the 2012 model and confined primarily to locations west of Chinchilla, and west of Dalby, is no longer present in the 2016 model.

The following are general comments in relation to changes to IAAs:

- The Walloon Coal Measures IAA extent encompasses an area that is similar to that assessed in 2012, although less contiguous in the centre. The small IAA locality between Cecil Plains and Millmerran is no longer present.
- The Springbok Sandstone IAA extent encompasses a larger area to the south west of Chinchilla, than assessed in 2012. However the small IAA locality to the west of Dalby is no longer present.

5.3.3. Discussion of material differences

Based on this review, Coffey consider that direct comparison of the results of the OGIA 2016 Groundwater Model with the OGIA 2012 Groundwater Model should be interpreted carefully, for the following reasons:

- The version of numerical code (MODFLOW-USG) is relatively new, and even as unmodified may provide different results from other versions of widely tested and verified MODFLOW codes.

- Significant modifications have been made to the MODFLOW-USG code. The intention of these modifications to solve or address specific CSG related modelling factors is well placed, but nevertheless must be considered experimental.
- The OGIA 2016 Groundwater Model does not adopt a vertical hydraulic conductivity/depth relationship that accounts for the reduced hydraulic conductivity associated with near-surface conditions. This known feature of the Surat Basin coal measures arises due to the effects of weathering and stress. Fracture closure due to increased stress with depth results in reduce hydraulic conductivity. In addition, near surface weathering increases matrix permeability. The OGIA 2012 Groundwater Model accounted for this on a cell by cell basis using a depth-K relationship (GHD, 2012).
- Comparisons with earlier OGIA versions cannot be directly made due to the different water production profiles adopted.
- Increased Condamine flux change under a reduced FDP scenario for the OGIA 2016 Groundwater Model demonstrates a need for better understanding of the behaviour of the model.
- Ongoing development of the OGIA 2016 Groundwater Model should include comparison with earlier rectilinear grid MODFLOW versions as control versions. Accordingly, this would require identical water production profiles.
- In addition, the development and testing of experimental dual phase simulation should be made with model versions that don’t incorporate other experimental changes, otherwise it is difficult to distinguish the relative effects. Specifically this should include changing one element at a time and comparing the results with appropriate control versions.

In addition to the above, the OGIA 2016 Groundwater Model has not as yet been subjected to uncertainty analysis, which is a key factor in understanding how broad the range of potential predictive uncertainty might be, given the unverified nature of the model.

5.4. Comparison of results with Arrow SREIS Groundwater Model

Figure 22 shows the maximum cumulative impact 5m drawdown contours, based on the Arrow SREIS Groundwater Model calibration realisation. This represents an equivalent case output for comparison with the OGIA 2016 Groundwater Model.

The following are general comments in relation to changes to the LAAs in the Surat CMA 2016 UWIR when compared to the Arrow SREIS Groundwater Model:

- The Walloon Coal Measures LAA has contracted in the southwest and the reduction in the area of planned CSG development is likely the main contributing factor, however changes in the 2016 Walloon Coal Measures depth-permeability relationship is also likely to contribute.
- The Springbok Sandstone LAA overlies the Walloon Coal Measures and is approximately similar in area with the Arrow SREIS Groundwater Model. Additional drawdown is indicated north east of Cecil Plains, however the morphology has changed, and the LAA area between Tara and Jandowae has reduced. The area in the immediate vicinity of Miles has contracted also.
- The Hutton Sandstone LAA is larger than assessed in the Arrow model, probably due to the lower Durabilla Formation aquitard being assigned a lower permeability in the OGIA 2016 Groudnwater Model. The LAA area extends further north west of Miles and further south towards Tara. The LAA area in the vicinity of Cecil Plains and Dalby remains similar.
- The Precipice Sandstone LAA, which was of very limited area for the Arrow SREIS Groundwater Model and confined to small areas west of Chinchilla and Dalby is no longer present in the OGIA 2016 Groundwater Model.

Observations based on the comparison between the OGIA 2016 Groundwater Model and the Arrow SREIS Groundwater Model are similar to those made for the OGIA 2012 Groundwater Model. Accordingly the discussion of material differences in Section 5.3.3 above is considered to be equally relevant to the Arrow SREIS Groundwater Model comparison.

6. Conclusion

Based on the outcomes of this review, the Arrow SREIS Groundwater Model and CDM Smith integrated groundwater-surface water models are considered to be the most appropriate tools for the purposes of predicting groundwater and surface water impacts, developing monitoring and mitigation measures, and informing management decisions for the Stage 1 CSG WMMP.

Key reasons why the Arrow SREIS Groundwater Model is retained as the primary basis for assessing project-wide groundwater level and pressure changes in the Surat Basin, and for predicting flux changes to the Condamine Alluvium, include:

- The OGIA 2016 Groundwater Model contains significant changes in method to account for dual-phase flow near CSG wells that have not been rigorously verified in a regional scale predictive numerical groundwater model.
- The OGIA 2016 Groundwater Model utilises significant changes in conceptualisation, application and modelling technique. The predictive uncertainty associated with this model has not been tested.
- The Arrow SREIS Groundwater Model, and the OGIA 2012 Groundwater Model, were based on widely adopted and tested modelling methods, and were subject to extensive calibration and quantified uncertainty analysis using the widely accepted NSMC method.

On this basis, the Arrow SREIS Groundwater Model and the CDM Smith integrated groundwater-surface water model will be adopted as the basis for ongoing WMMP development. Table 6.1 provides a summary correlation of specific model uses and objectives with EPBC Approval Conditions that are specifically addressed by this memorandum.

Table 6.2 details other Approval Conditions that are reliant on or underpinned by groundwater modelling. The Arrow SREIS Groundwater Model and the CDM Smith integrated groundwater-surface water model will also be adopted as the basis for these other Approval Conditions, which are to be separately addressed in other memoranda, and the WMMP.

Arrow are committed to working with the OGIA to investigate the differences in flux reduction to the Condamine Alluvium aquifer between the 2012 and 2016 OGIA groundwater models, and will address this further in the Stage 2 CSG WMMP.

Table 6.1 Summary of addressed Approval Conditions and associated model basis, outputs and objectives

Approval Condition	Model basis	Model outputs used for Approval Condition assessment	Approval condition assessment objectives
13(a) An analysis of the results of the most recent OGIA model (built or endorsed by OGIA), relevant to all of the project's tenement areas.	2016 OGIA Groundwater Model	Cumulative impacts: • IAA drawdown (Figure 20) • LAA drawdown (Figure 21) • Condamine Alluvium flux change	Analysis of the most recent OGIA model results relevant to the project tenement areas (2012 OGIA and Arrow SREIS models) Comparison of these results with the results from the 2012 OGIA Groundwater Model, and the results from the Arrow SREIS Groundwater Model (based on the 2012 OGIA Groundwater Model)
	2012 OGIA Groundwater Model	Cumulative impacts: • IAA drawdown (Figure 20) • LAA drawdown (Figure 21) • Condamine Alluvium flux change	
	Arrow SREIS Groundwater Model	Cumulative impacts: • Figure 7.7 in Appendix 4 of the SREIS • Condamine Alluvium flux change • SREIS GDE drawdown extents	
13(b) A fit for purpose numerical simulation to assess potential impacts on water resources arising from the action in the project area, subsequent surface water-groundwater interactions in the Condamine Alluvium and impacts to	Arrow SREIS Groundwater Model including uncertainty analysis	Cumulative impacts: • Predicted drawdown • Condamine Alluvium flux change Predicted calibration case drawdown in the Hutton, Springbok and WCM, at relevant future times, for the cumulative and Arrow only cases (refer SREIS figures)	Analysis of the most recent OGIA model results in relation to the Stage 1 CSG WMMP Comparison with the results from 2012 OGIA Groundwater Model To provide input for IQQM surface water

Approval Condition	Model basis	Model outputs used for Approval Condition assessment	Approval condition assessment objectives
dependent ecosystems.	CDM Smith Condamine Alluvium Model	Predicted drawdown in Condamine Alluvium (Figures 15, 18 and 19) Predicted Condamine Alluvium flux change – Arrow only case (Figures 10 and 11) Predicted flux change to the Condamine River – Arrow only case (Figures 16 and 17)	impact modelling To quantify surface water impacts arising from the action
	CDM Smith IQQM model	Predicted reduction in Condamine River flow due to drawdown in the Condamine Alluvium (Figures 16 and 17)	
13(d) An assessment of predicted project wide groundwater drawdown levels and pressures from the action, together with confidence levels.	Arrow SREIS Groundwater Model including uncertainty analysis	Predicted calibration case drawdown in the Hutton, Springbok and WCM, at future times as relevant to monitoring, for the cumulative and Arrow only cases (Figures 1 to 8)	Groundwater drawdown in the Walloon Coal Measures, and adjacent GAB formations that may be indirectly depressurised
	CDM Smith Condamine Alluvium Model	Predicted drawdown in Condamine Alluvium due to Arrow production at future times as relevant to monitoring for the high and median cases (Figures 18 and 19)	Groundwater drawdown in Condamine Alluvium due to changed flux from the Walloon Coal Measures

Note: Figures provided as indicative and typical. Timing of predictions to be considered in detail at the groundwater monitoring network and GDE technical memoranda stage.

Table 6.2 Other Approval Conditions reliant on groundwater modelling

Approval Condition	Model basis	Reliance on:	Relevant technical memorandum addressing condition
13(c) An assessment of potential impacts from the action on non-spring based GDEs through potential changes to surface groundwater connectivity and interactions with the sub-surface expression of groundwater.	CDM Smith Condamine Alluvium Model	Predicted groundwater drawdown and groundwater-surface water connectivity between the Condamine Aquifer and the Condamine River, at times relevant to monitoring	GDE and aquatic ecosystem impact memorandum, including cumulative impact assessment mapping.
	CDM Smith IQQM model	Predicted groundwater drawdown and groundwater-surface water connectivity between the Condamine Aquifer and the Condamine River, at future times as relevant to monitoring	
	Arrow SREIS Groundwater Model	Predicted groundwater drawdown in the surficial aquifers other than the Condamine Alluvium, at future times as relevant to monitoring	
13(f) A best practice baseline monitoring network that will enable the identification of spatial and temporal changes to surface water and groundwater. This will include a proposal for aquifer connectivity studies and monitoring of relevant aquifers to determine hydraulic connectivity (including potential groundwater dependence of Long Swamp and Lake Broadwater) and must also enable monitoring of all aquatic ecosystems that may be impacted by the action.	Arrow SREIS Groundwater Model	Cumulative drawdown and/or other model output will inform the locations for the identification of spatial and temporal changes to surface water and groundwater, monitoring of relevant aquifers to determine hydraulic connectivity, and monitoring locations for aquatic ecosystems that may be impacted. Aquifer connectivity studies have already been completed.	Groundwater monitoring network and program technical memorandum
	CDM Smith Condamine Alluvium Model		

Approval Condition	Model basis	Reliance on:	Relevant technical memorandum addressing condition
13(j) A groundwater early warning monitoring system 13(k) Early warning indicators and trigger thresholds, including corrective actions for both early warning indicators and trigger thresholds, for aquatic ecology and aquatic ecosystems.	Arrow SREIS Groundwater Model CDM Smith Condamine Alluvium Model	Cumulative model outputs such as drawdown and simulated hydrographs will provide a basis for design of the early warning system.	Triggers, limits and network indicators technical memorandum
13(p) A cumulative impact assessment based on the outputs of the OGIA model which integrates groundwater model outputs with known and potential GDEs and presents the outputs in map form. Contribute to investigations coordinated through the OGIA to assess hydrological and ecological characteristics of impacted GDEs.	Arrow SREIS Groundwater Model CDM Smith Condamine Alluvium Model	Cumulative groundwater drawdown in formations and relationship with known GDEs - for Surat formations such as the Walloon Coal Measures, adjacent GAB formations that may be indirectly depressurised, and the Condamine Alluvium aquifer. To consider SREIS GDE assessment drawdown extents.	GDE and aquatic ecosystem impact memorandum, including cumulative impact assessment mapping.

Note: Timing of predictions to be considered in detail at the groundwater monitoring network and GDE technical memoranda stage.

7. References

CDM Smith, 2016. Surat Gas Expansion Project – CSG WMMP Section 13(b). Report prepared for Arrow Energy, August 2016.

Coffey Environments, 2013. Supplementary groundwater assessment. Appendix 4 to the Arrow Energy Surat Gas Project Supplementary Report to the EIS, June 2013.

Coffey Environments, 2014. Fault hydraulic characteristics, well stimulation extent, and hydraulic connection between consolidated and unconsolidated media. In Appendix E of the Bowen Gas Project Supplementary EIS (Appendix A). April 2014.

Department of Natural Resource Management (DNRM), 2015. Condamine and Balonne Resource Operations Plan, December 2008, Amended July 2015 (revision 5), DNRM, Queensland.

Department of Natural Resource Management (DNRM), 2016a. Underground Water Impact Report for the Surat Cumulative Management Area, September 2016. Office of Groundwater Impact Assessment.

Department of Natural Resource Management (DNRM), 2016b. Groundwater modelling report for the Surat Cumulative Management Area, September 2016. Office of Groundwater Impact Assessment.

GHD, 2012. Report for Queensland Water Commission, QWC17-10 Stage 2, Surat Cumulative Management Area Groundwater Model Report.

GHD, 2013. Arrow Energy Surat Gas Project Groundwater Modelling Report. Report prepared for Arrow Energy, June 2013.

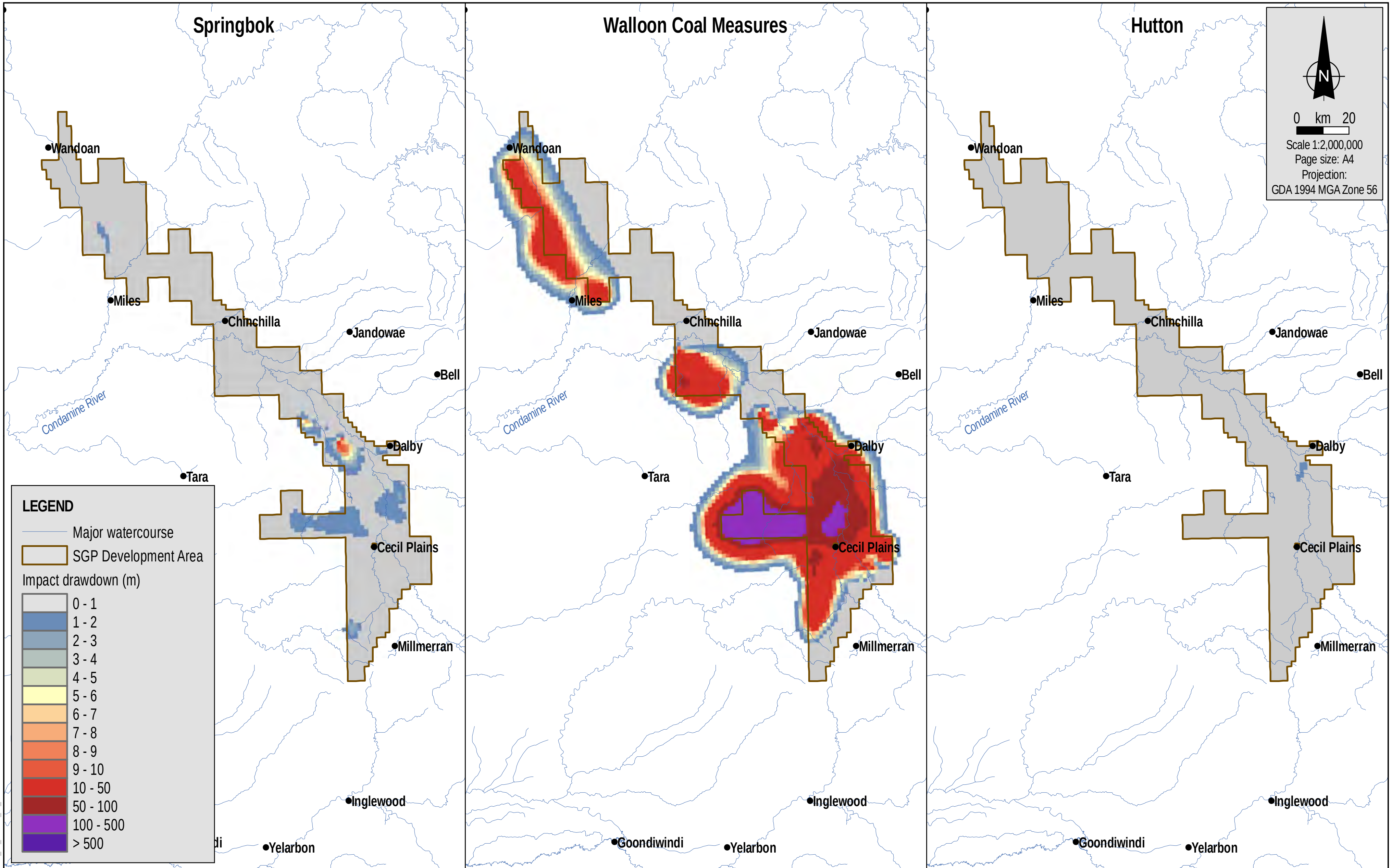
Herckenrath D, Doherty J, and Panday S, 2015. Incorporating the effects of gas in modelling the impact of CBM extraction on regional groundwater systems. Journal of Hydrology 523 (2015) pp. 587-601.

Queensland Water Commission (QWC), 2012. Underground Water Impact Report for the Surat Cumulative Management Area.

Simons, M, Podger, G & Cooke, R 1996, IQQM – A hydrologic modelling tool for water resource and salinity management, Environmental Software, DOI: 10.1016/S0266-9838(96)00019-6 January.

WaterMark Numerical Computing (2012). Predictive uncertainty analysis of the regional scale groundwater flow model for the Surat CMA.

Figures



MXD Reference: 20484AA_01_GIS012_v0_2

Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

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Date: 19.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F001_GIS

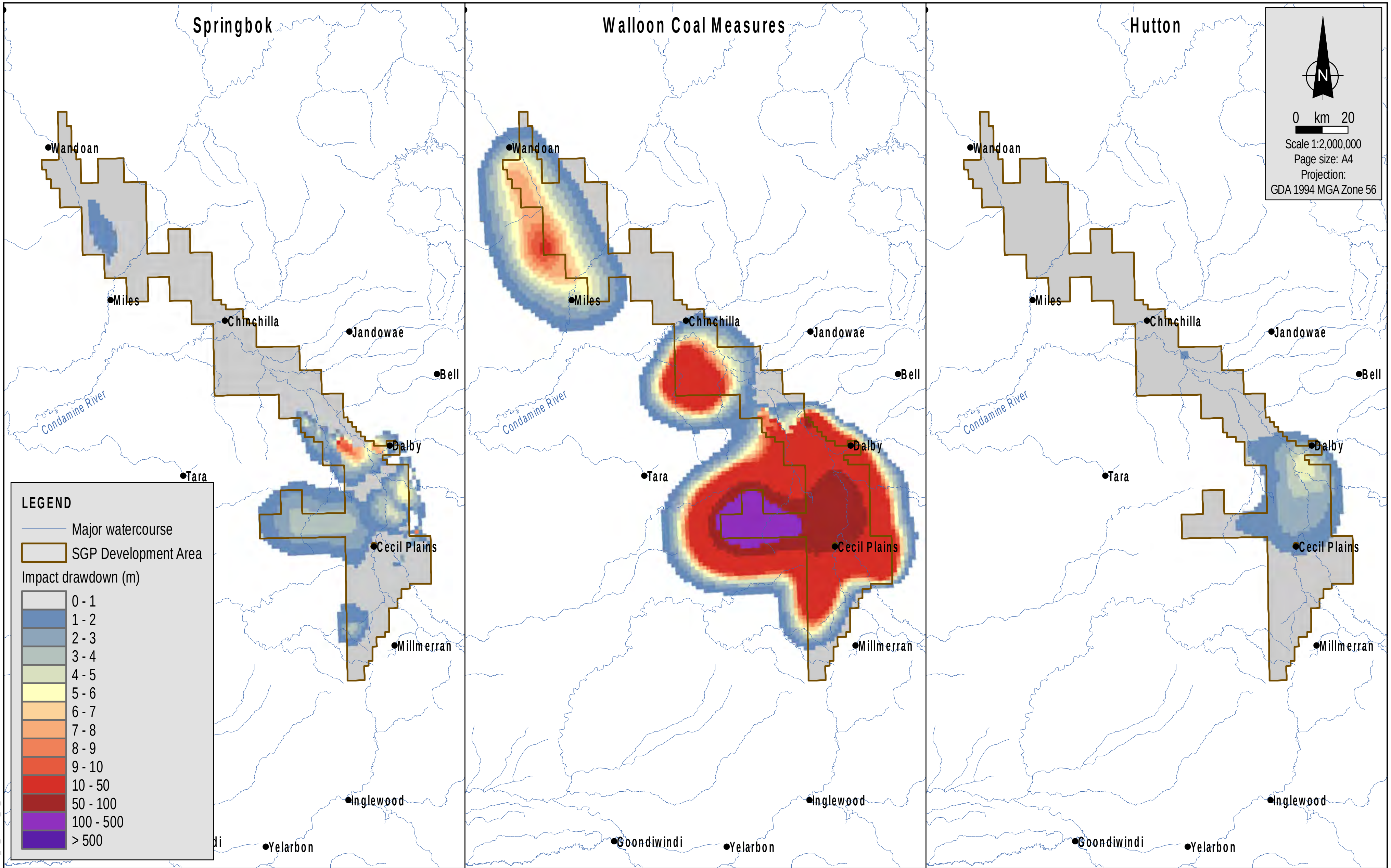
Arrow Energy

Surat Gas Project WMMP

arrow energy go further

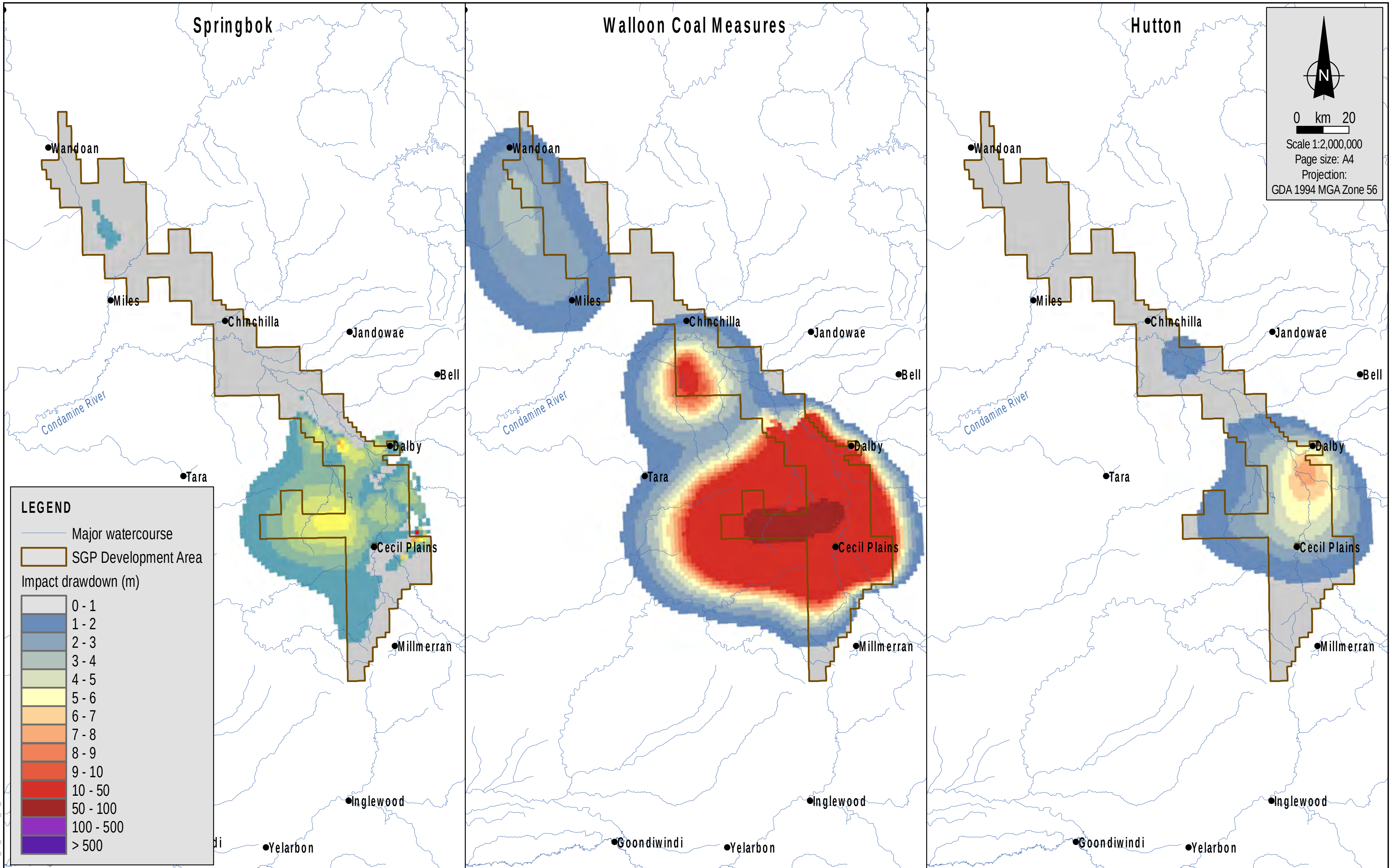
Calibrated Case predicted Arrow impact drawdown 2030

Figure No: 1



Source: SGP Development from Arrow Energy. Watercourses from DNRM. Predicted drawdown from GHD.	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F002_GIS	Arrow Energy Surat Gas Project WMMP	Calibrated Case predicted Arrow impact drawdown 2050	Figure No: 2

MXD Reference: 20484AA_01_GIS013_v0_2



Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

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Date: 19.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F003_GIS

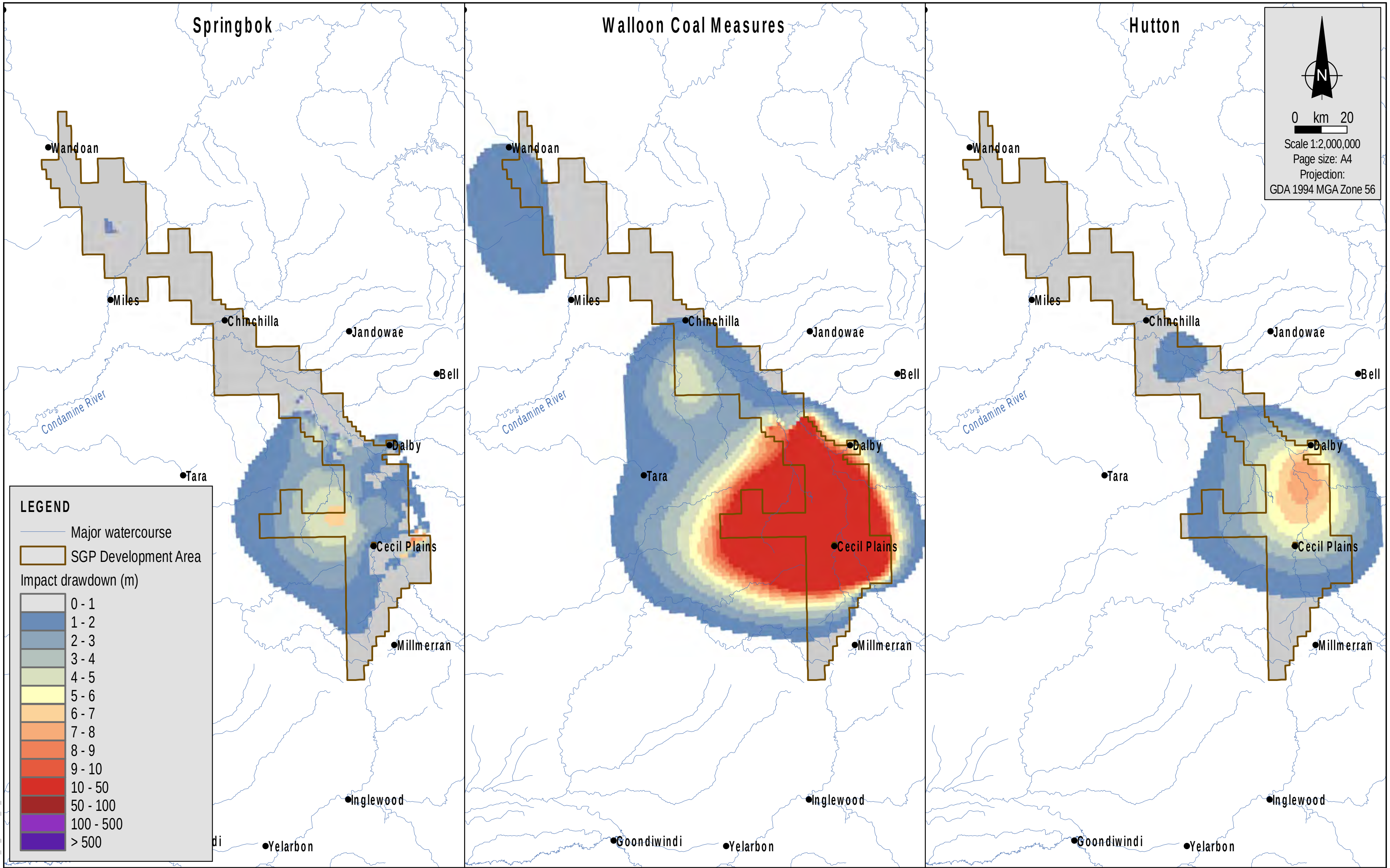
Arrow Energy
Surat Gas Project WMMP

arrow energy
go further

Calibrated Case predicted
Arrow impact drawdown 2094

Figure No: 3

MXD Reference: 20484AA_01_GIS014_v0_2



Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

coffey
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Date:
18.10.2016
Project:
ENAUABTF20484AA
File Name:
20484AA_01_F004_GIS

Arrow Energy

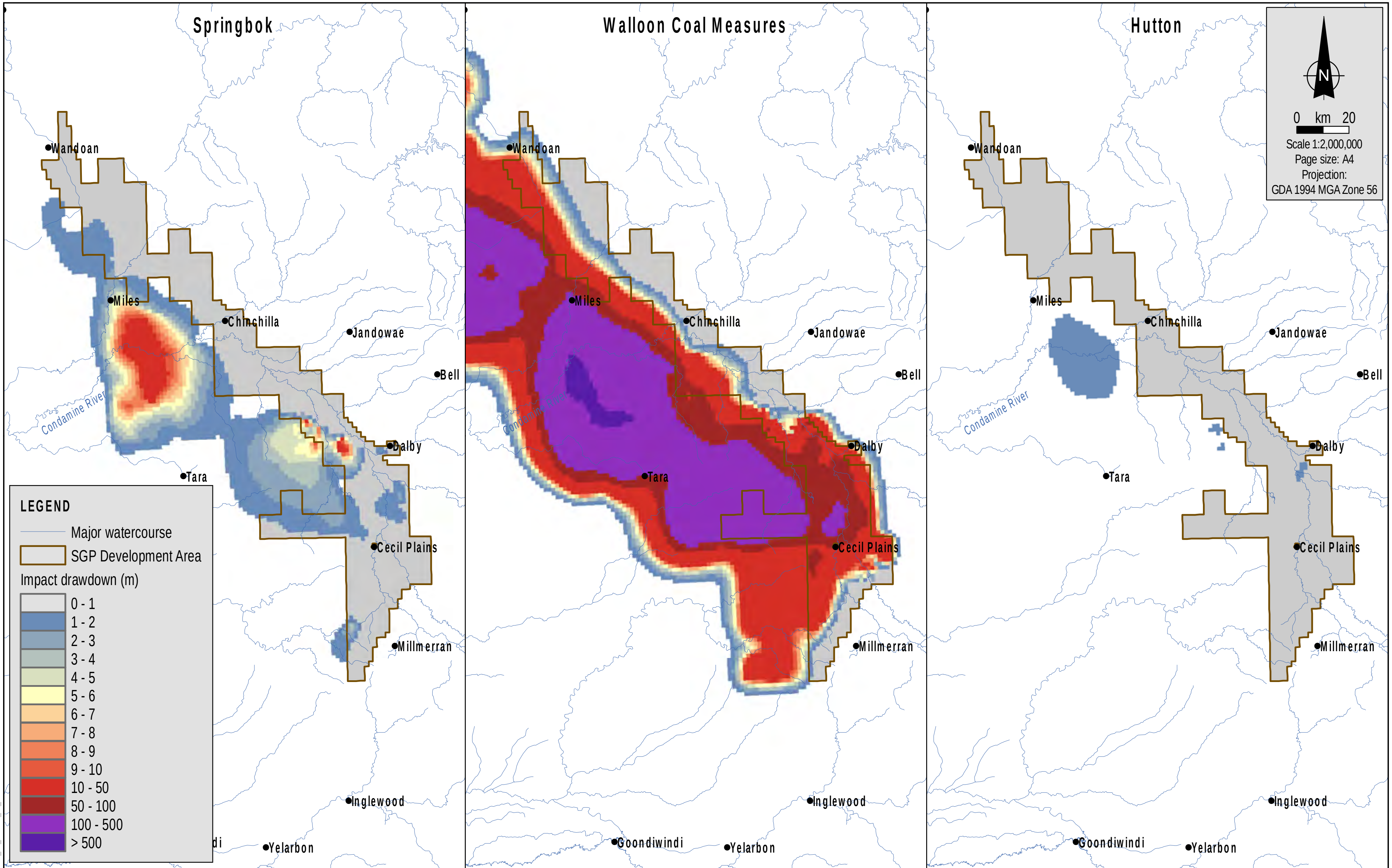
Surat Gas Project WMMP

arrow energy
go further

Calibrated Case predicted
Arrow impact drawdown 2154

Figure No:
4

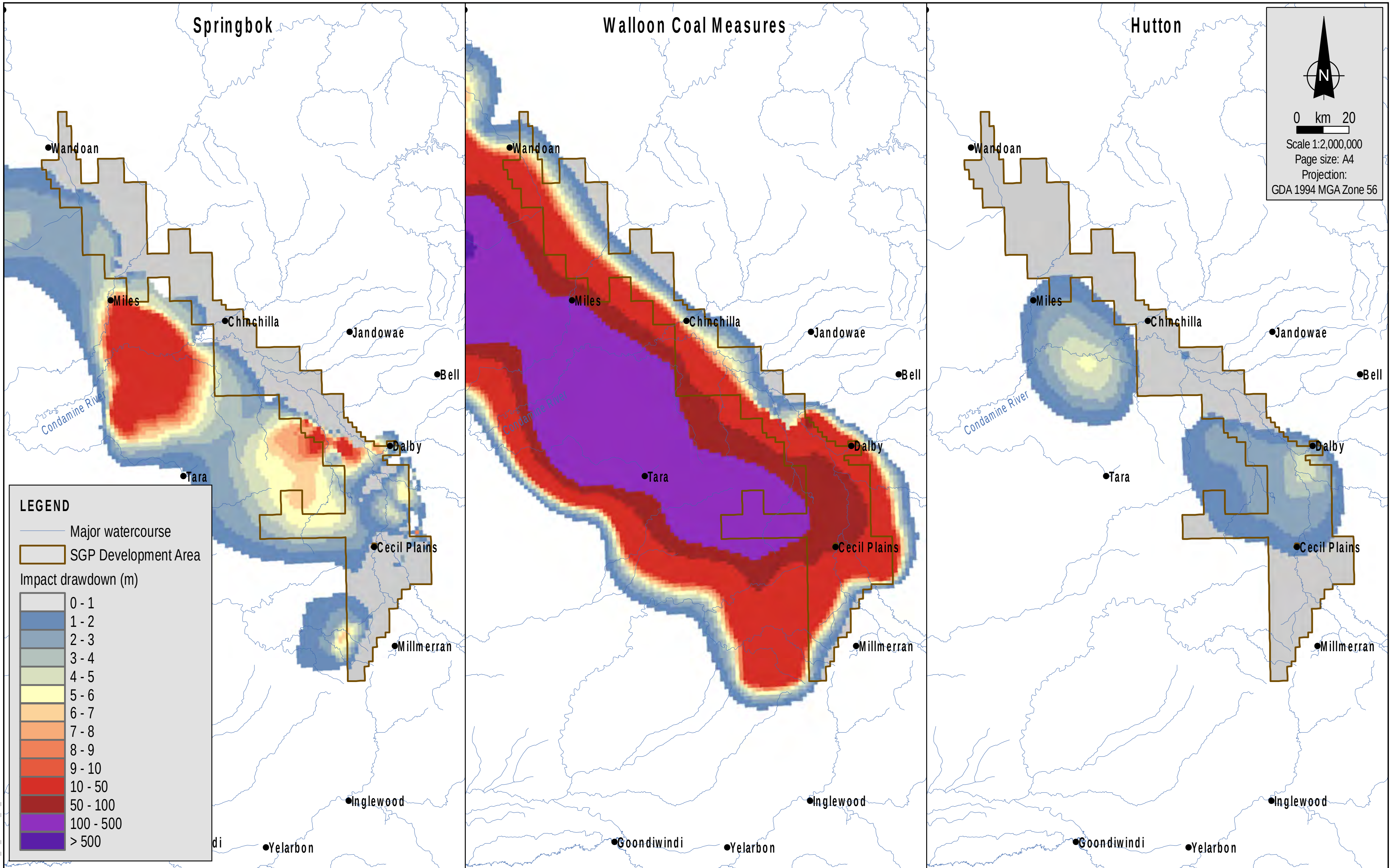
MXD Reference: 20484AA_01_GIS015_v0_2



Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

coffey A TETRA TECH COMPANY	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F005_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Calibrated Case predicted Cummulative impact drawdown 2030	Figure No: 5

MXD Reference: 20484AA_01_GIS016_v0_2



MXD Reference: 20484AA_01_GIS017_v0_2

Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

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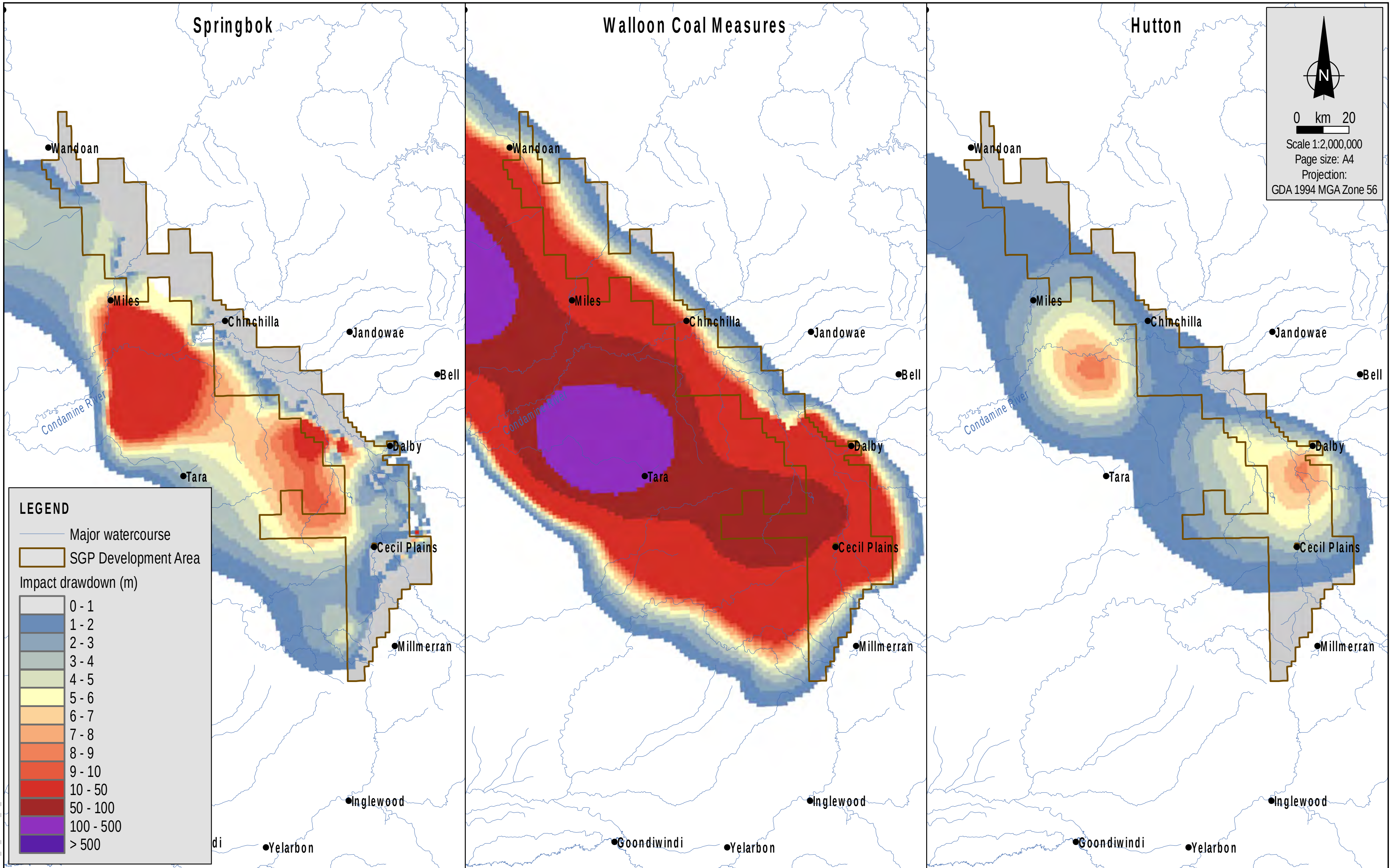
Date: 18.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F006_GIS

Arrow Energy
Surat Gas Project WMMP

arrow energy
go further

Calibrated Case predicted
Cummulative impact drawdown 2050

Figure No: 6



MXD Reference: 20484AA_01_GIS018_v0_2

Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

coffey
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Date:	19.10.2016
Project:	ENAUABTF20484AA
File Name:	20484AA_01_F007_GIS

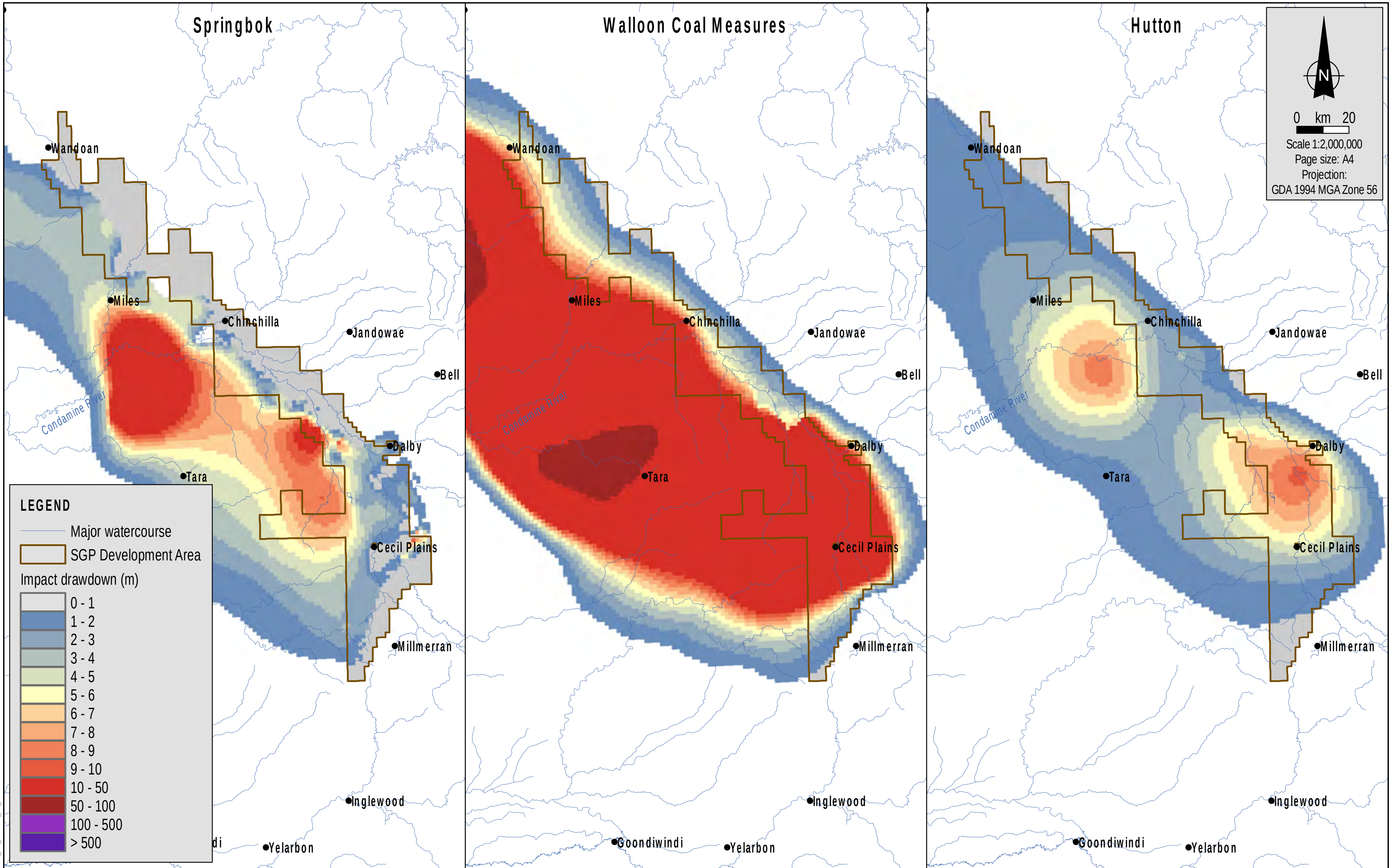
Arrow Energy

Surat Gas Project WMMP

arrow energy
go further

Calibrated Case predicted
Cummulative impact drawdown 2094

Figure No: 7



Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Predicted drawdown from GHD.

coffey
A TETRA TECH COMPANY

Date: 19.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F008_GIS

Arrow Energy

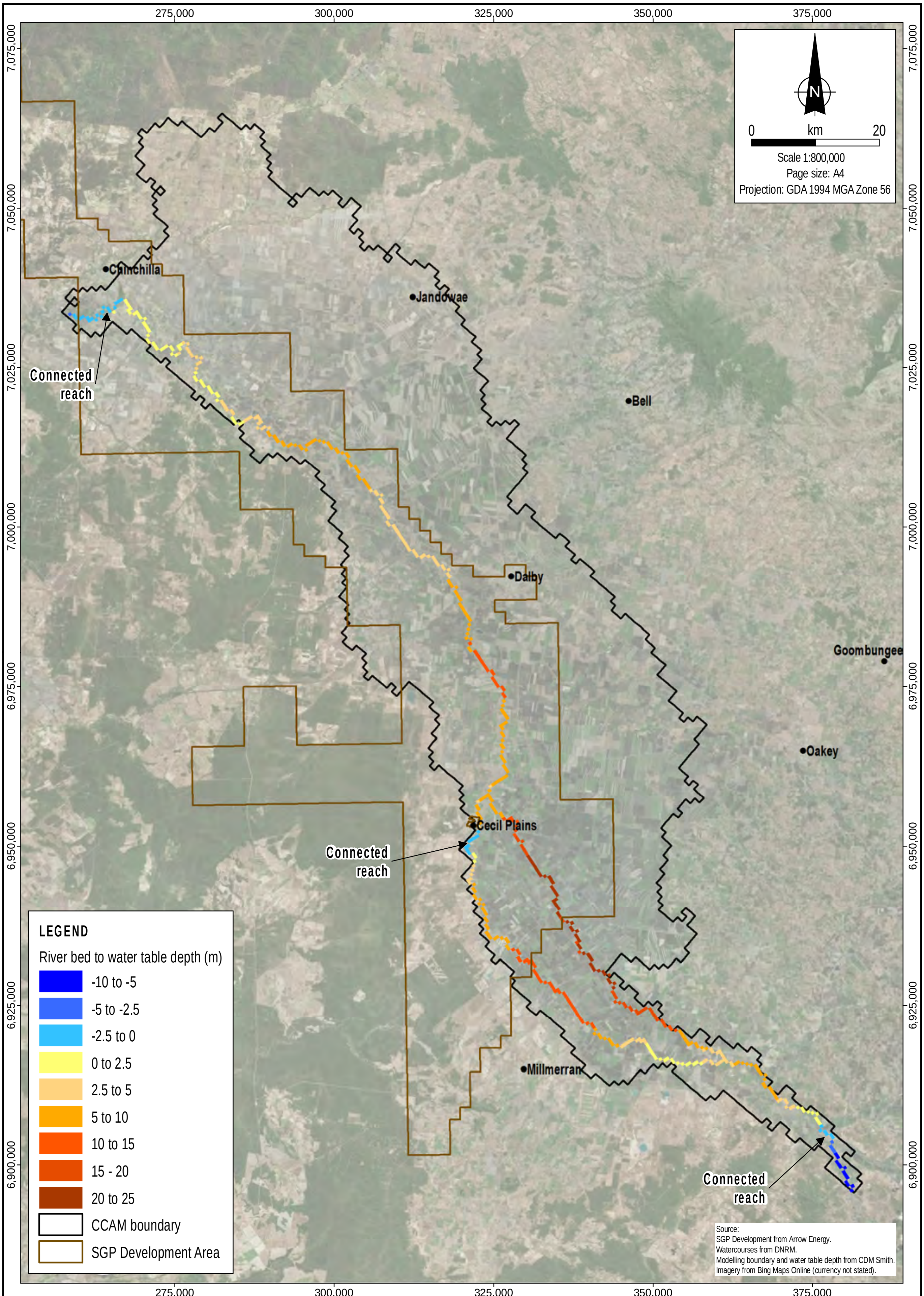
Surat Gas Project WMMP

arrow energy
go further

Calibrated Case predicted
Cummulative impact drawdown 2154

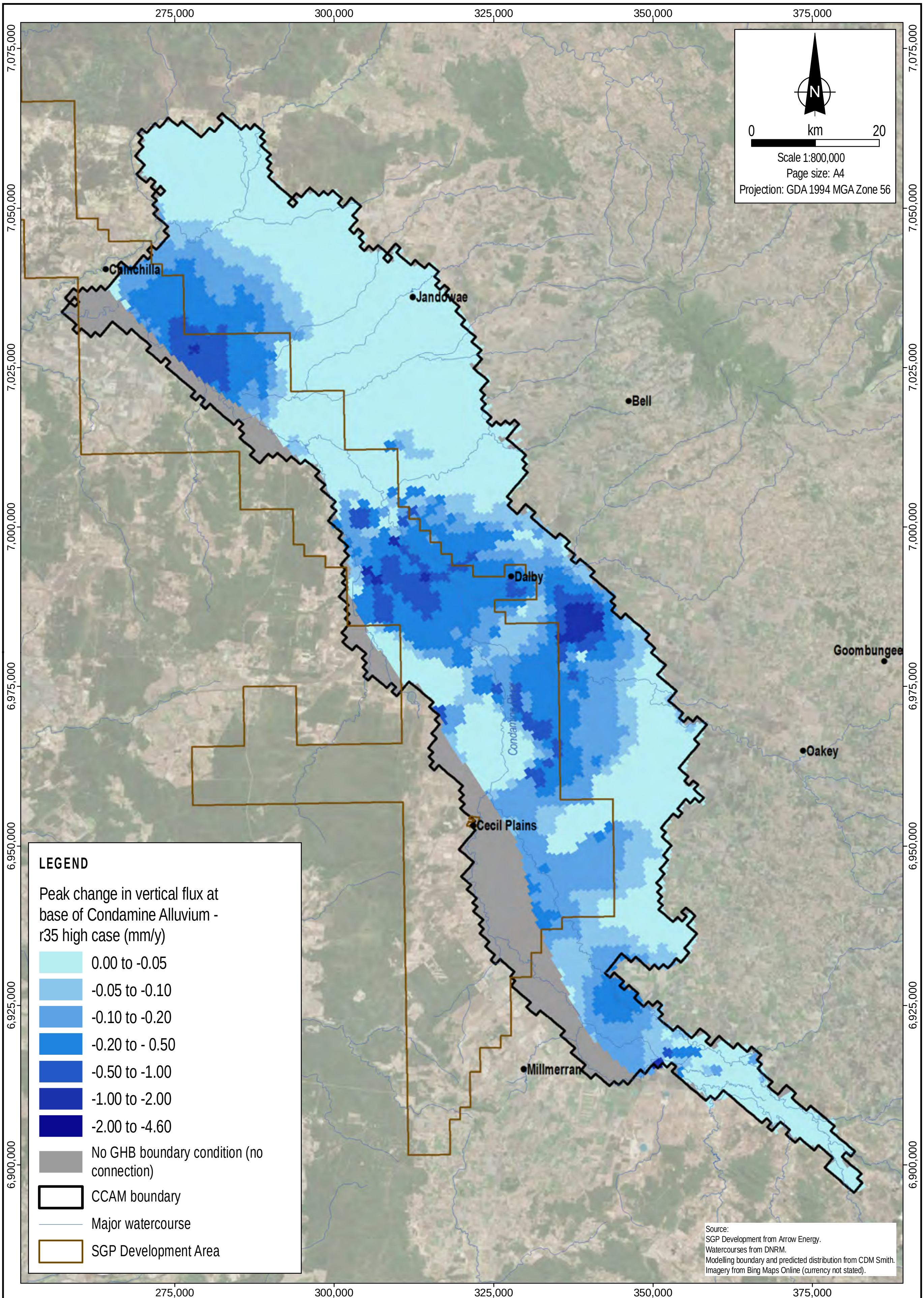
Figure No:
8

MXD Reference: 20484AA_01_GIS019_v0_2



MXD Reference: 20484AA_01_GIS001_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F009_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Representation of river bed to watertable depth in the CCAM	Figure No: 9



MXD Reference: 20484AA_01_GIS002_v0_2

coffey

Date: 19.10.2016

Project: ENAUABTF20484AA

File Name: 20484AA_01_F010_GIS

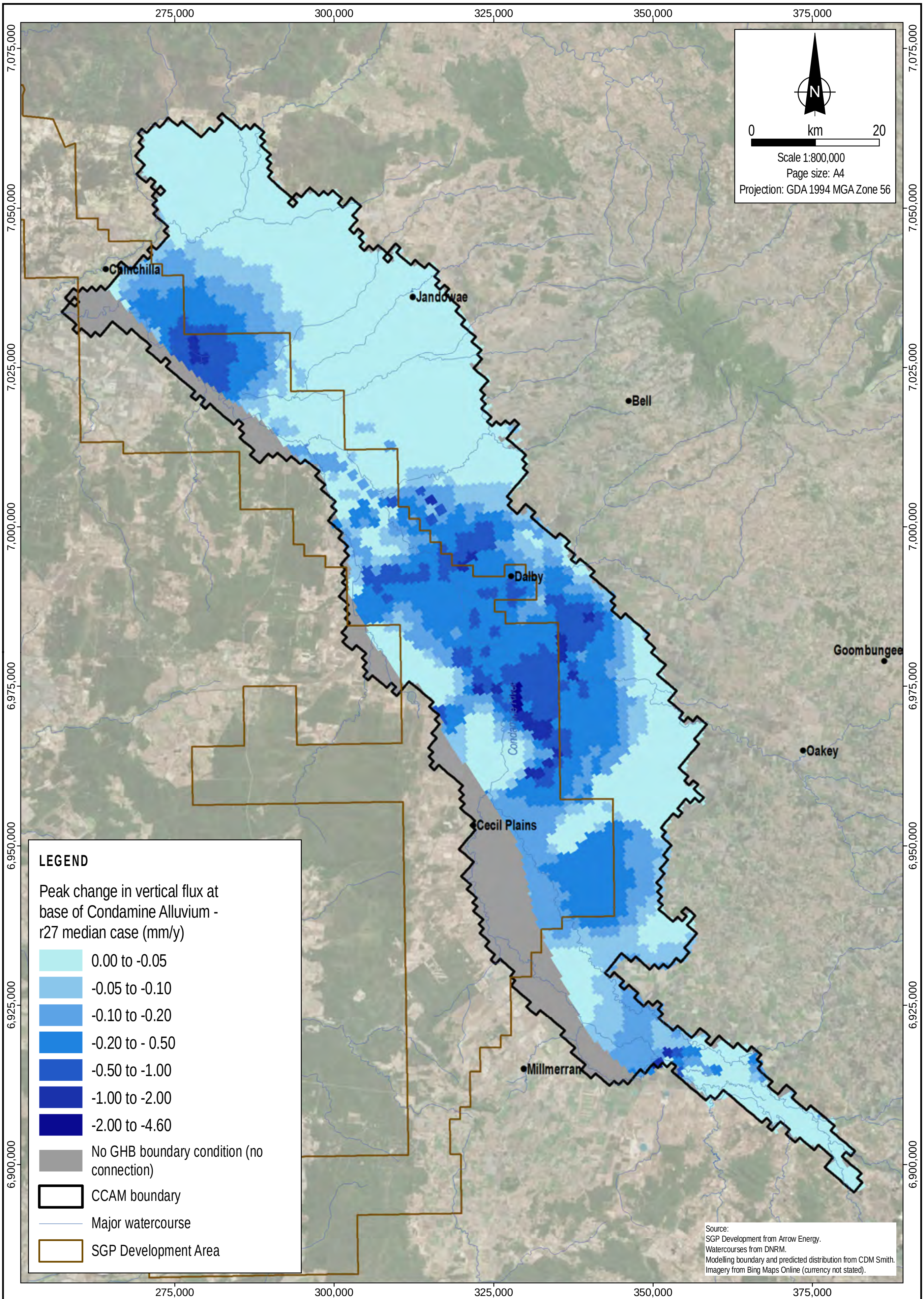
Arrow Energy

Surat Gas Project WMMP

arrow energy go further

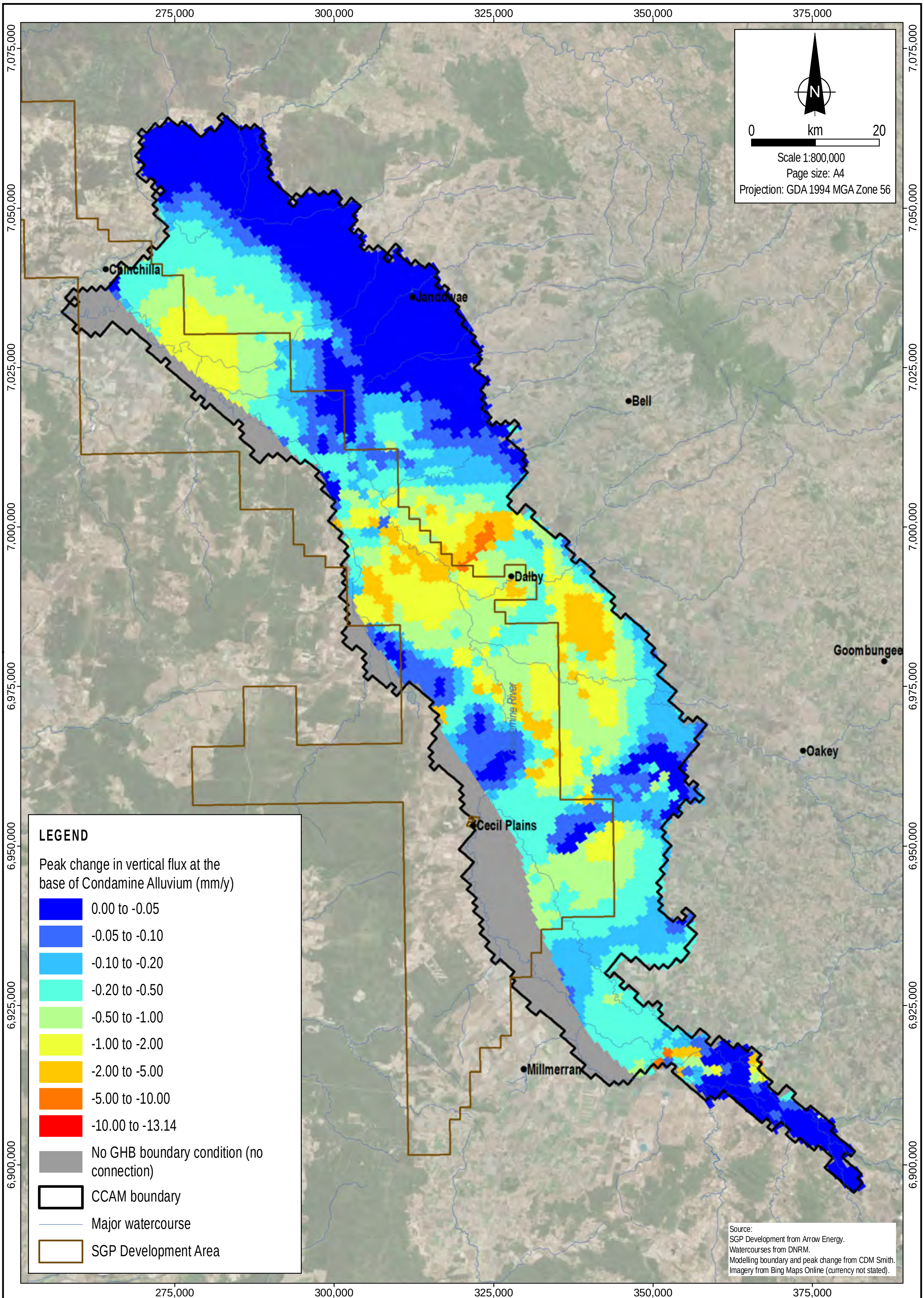
Predicted distribution of maximum change in flux at base of Condamine Alluvium due to Arrow production - high case

Figure No: 10



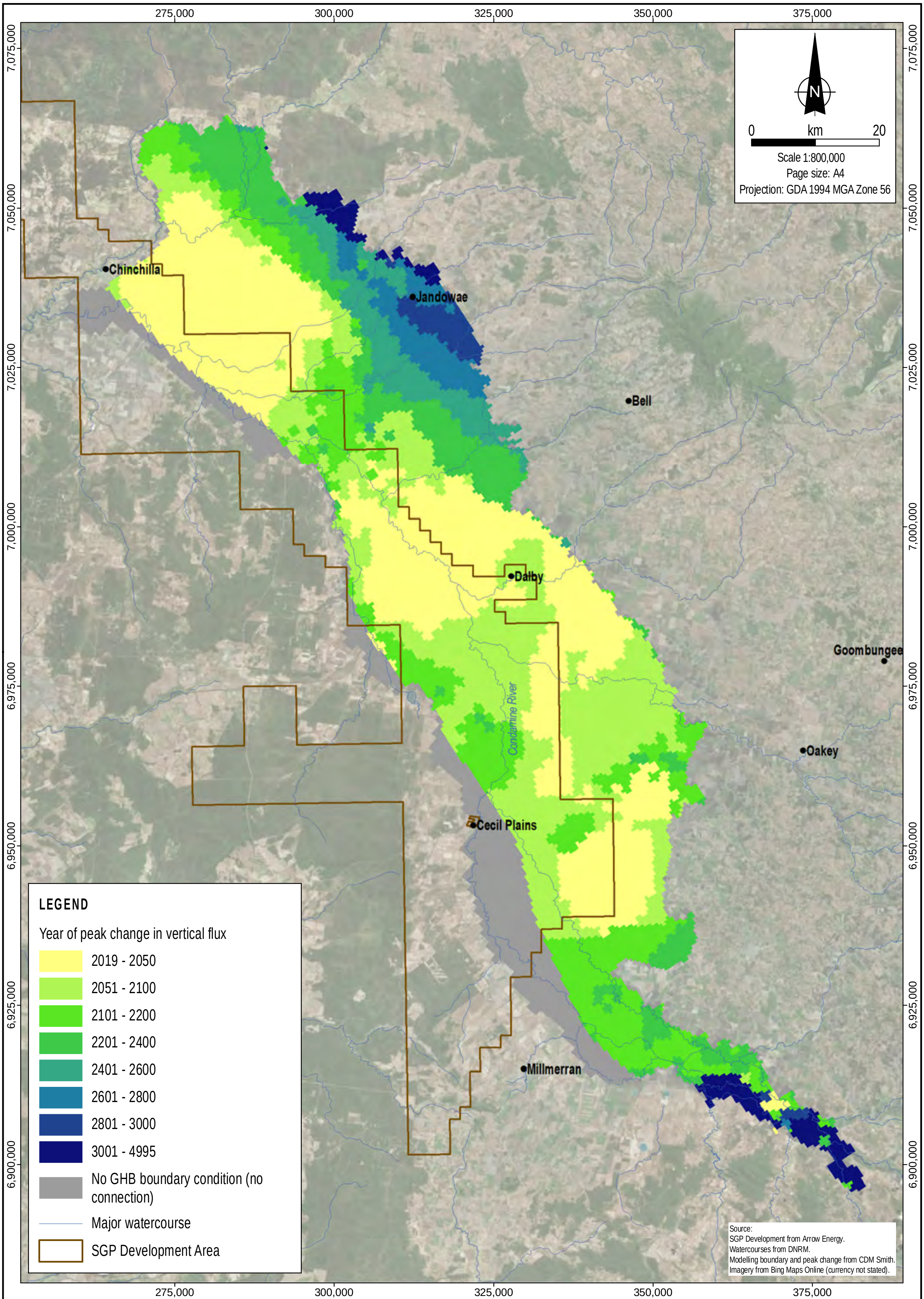
MXD Reference: 20484AA_01_GIS003_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F011_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted distribution of maximum change in flux at base of Condamine Alluvium due to Arrow production - median case	Figure No: 11



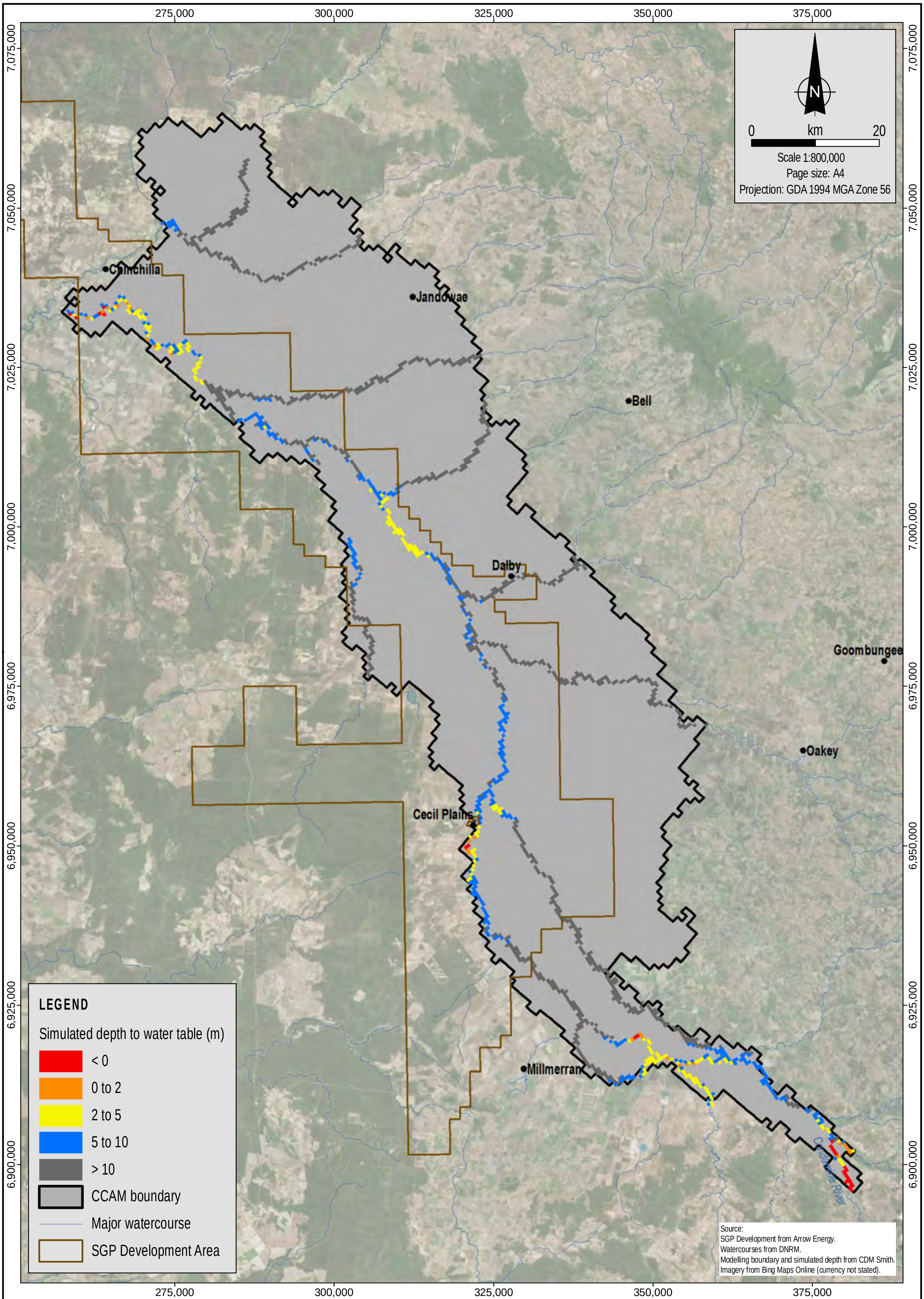
MXD Reference: 20484AA_01_GIS004_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F012_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted maximum change in flux at the base of the Condamine Alluvium due to Arrow production (all 200 realisations)	Figure No: 12



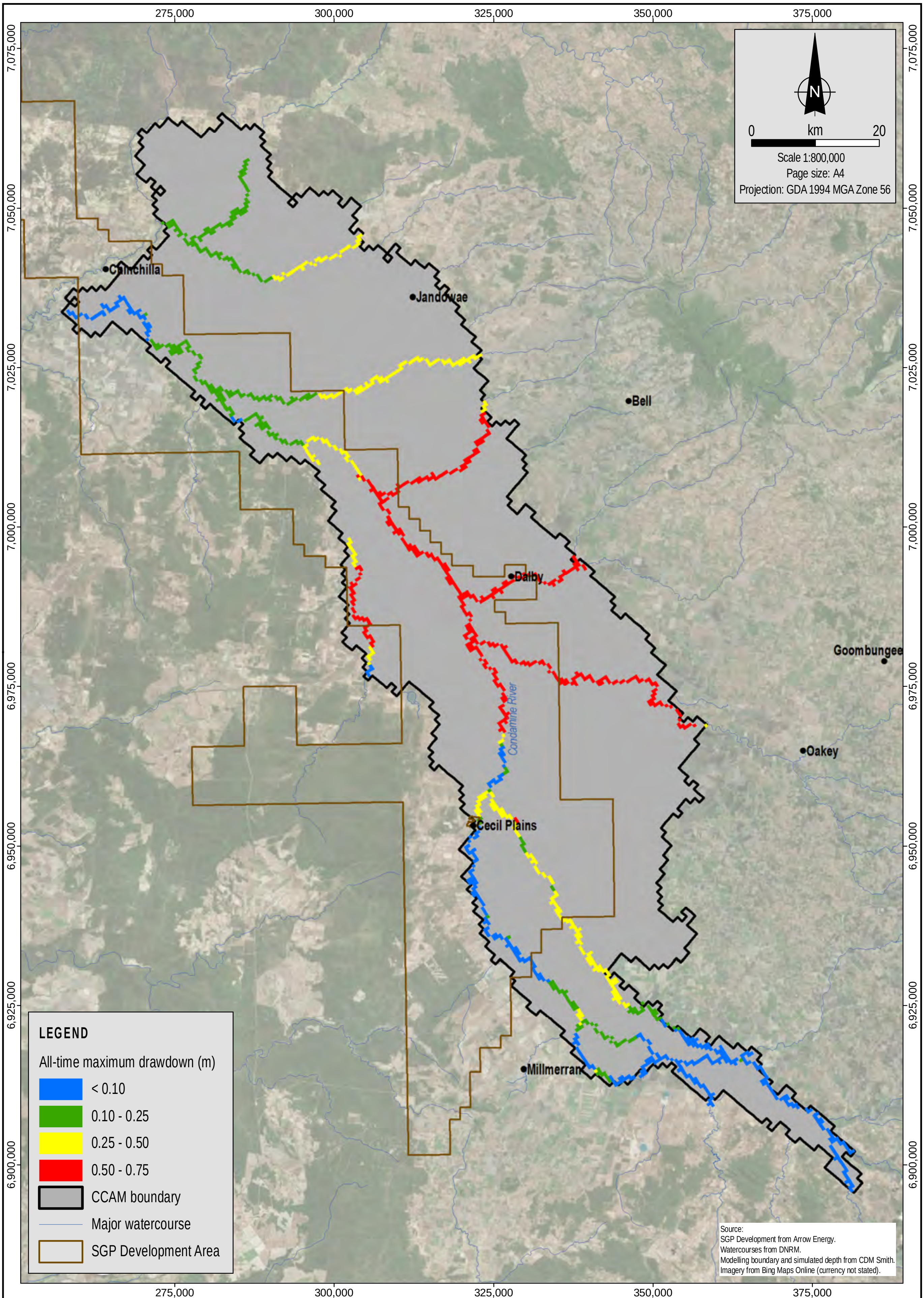
MXD Reference: 20484AA_01_GIS005_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F013_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted maximum flux change timing at base of Condamine Alluvium due to Arrow production (all 200 realisations)	Figure No: 13



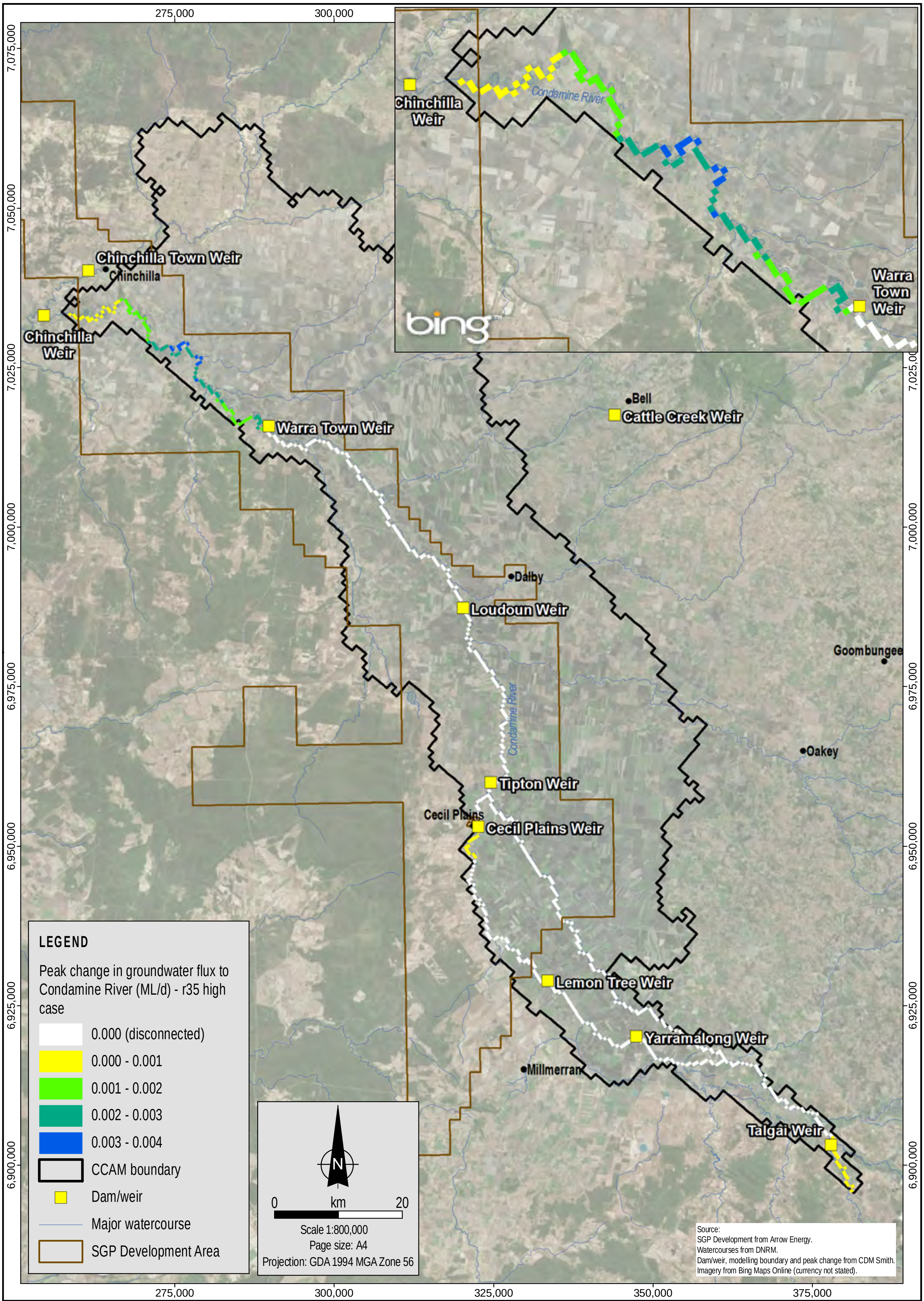
MXD Reference: 20484AA_01_GIS010_v0_2

Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F018_GIS	Arrow Energy Surat Gas Project WMMP	Simulated depth to groundwater along the Condamine River and its tributaries	Figure No: 14



MXD Reference: 20484AA_01_GIS011_v0_2

coffey	Date: 18.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F019_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted Arrow contribution to maximum drawdown (high case) along the Condamine River and its tributaries	Figure No: 15



MXD Reference: 20484AA_01_GIS008_v0_2

coffey

Date: 19.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F016_GIS

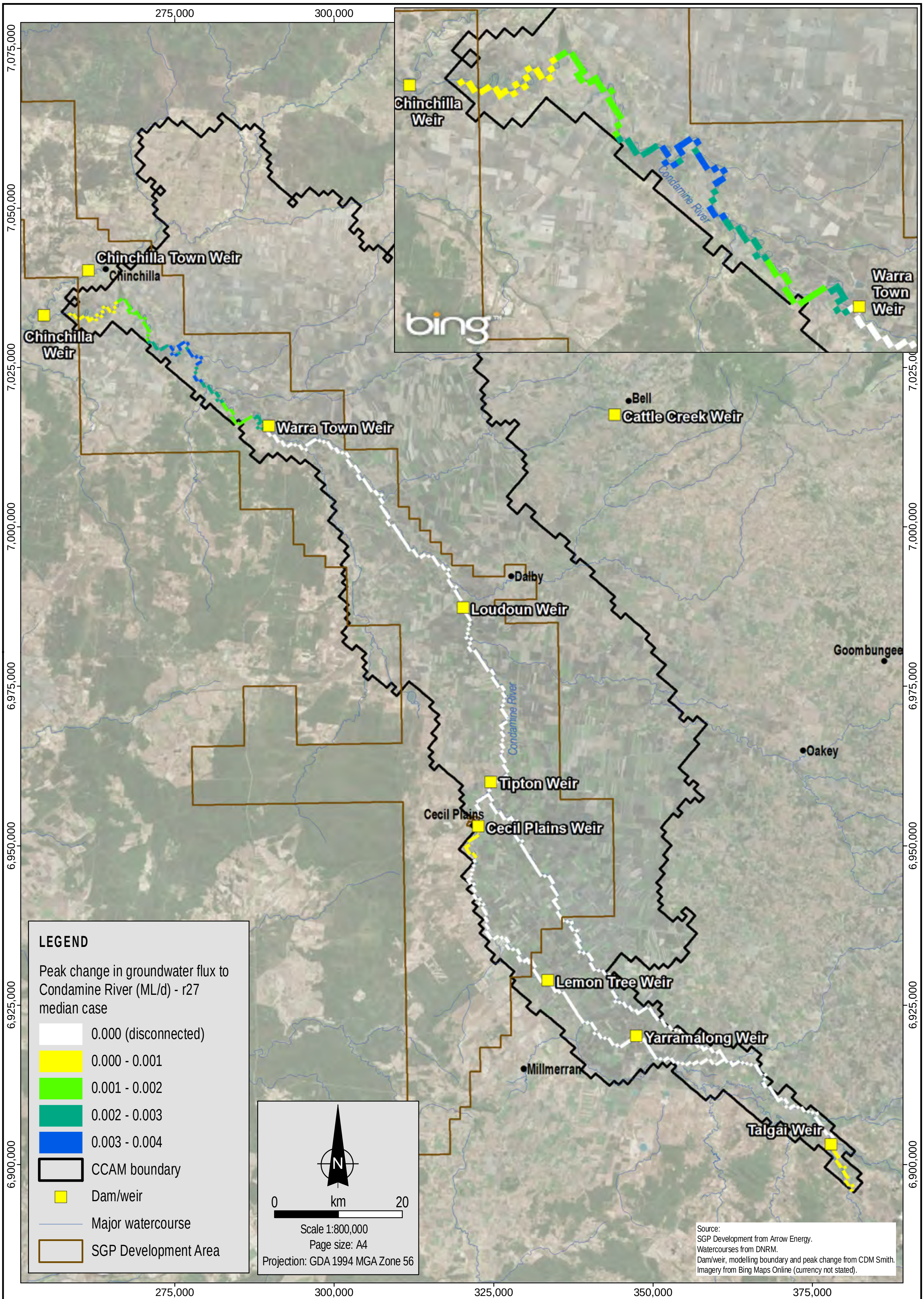
Arrow Energy

Surat Gas Project WMMP

arrow energy go further

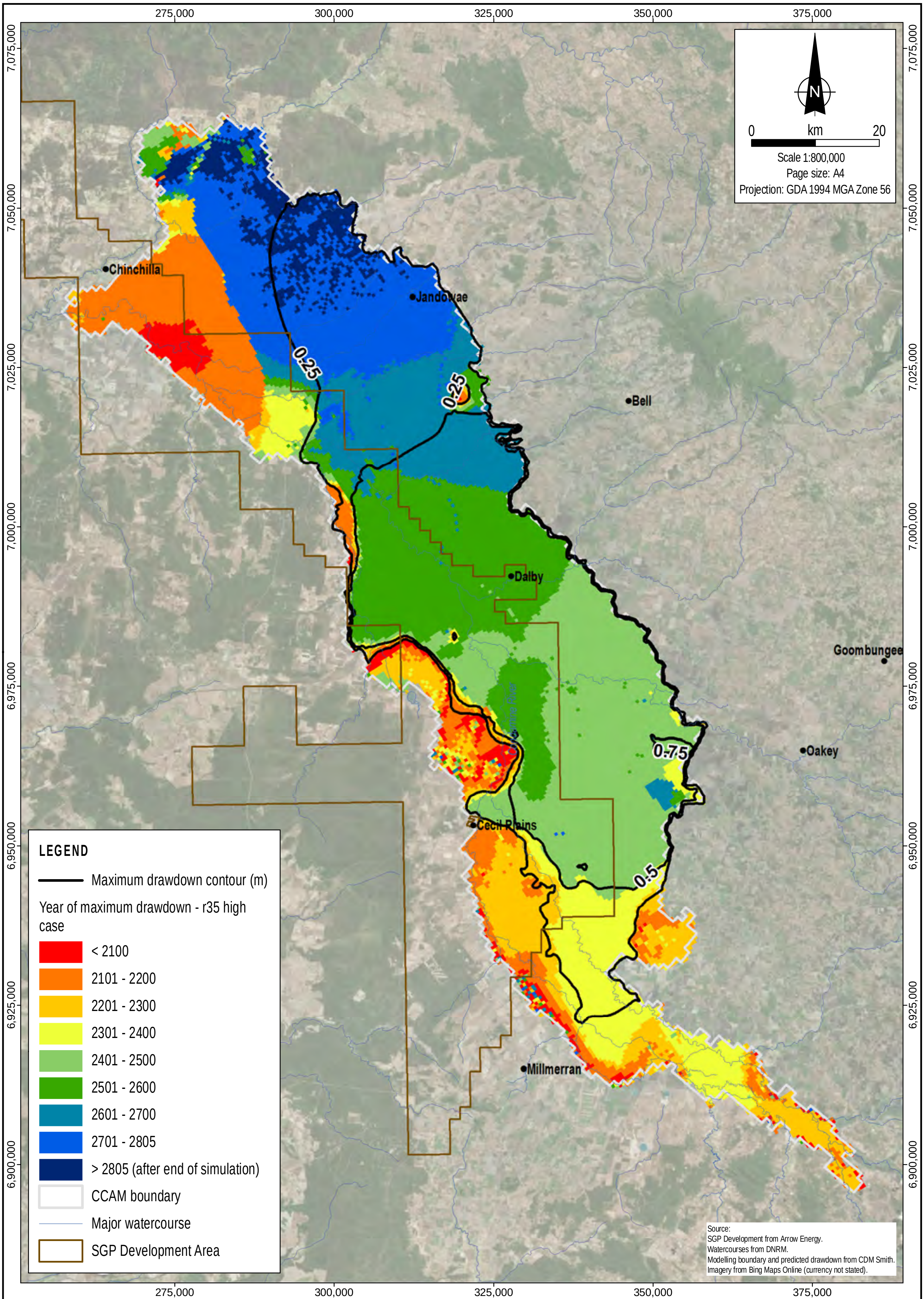
Distribution of maximum change in groundwater flux to the Condamine River due to Arrow water production - high case

Figure No: 16



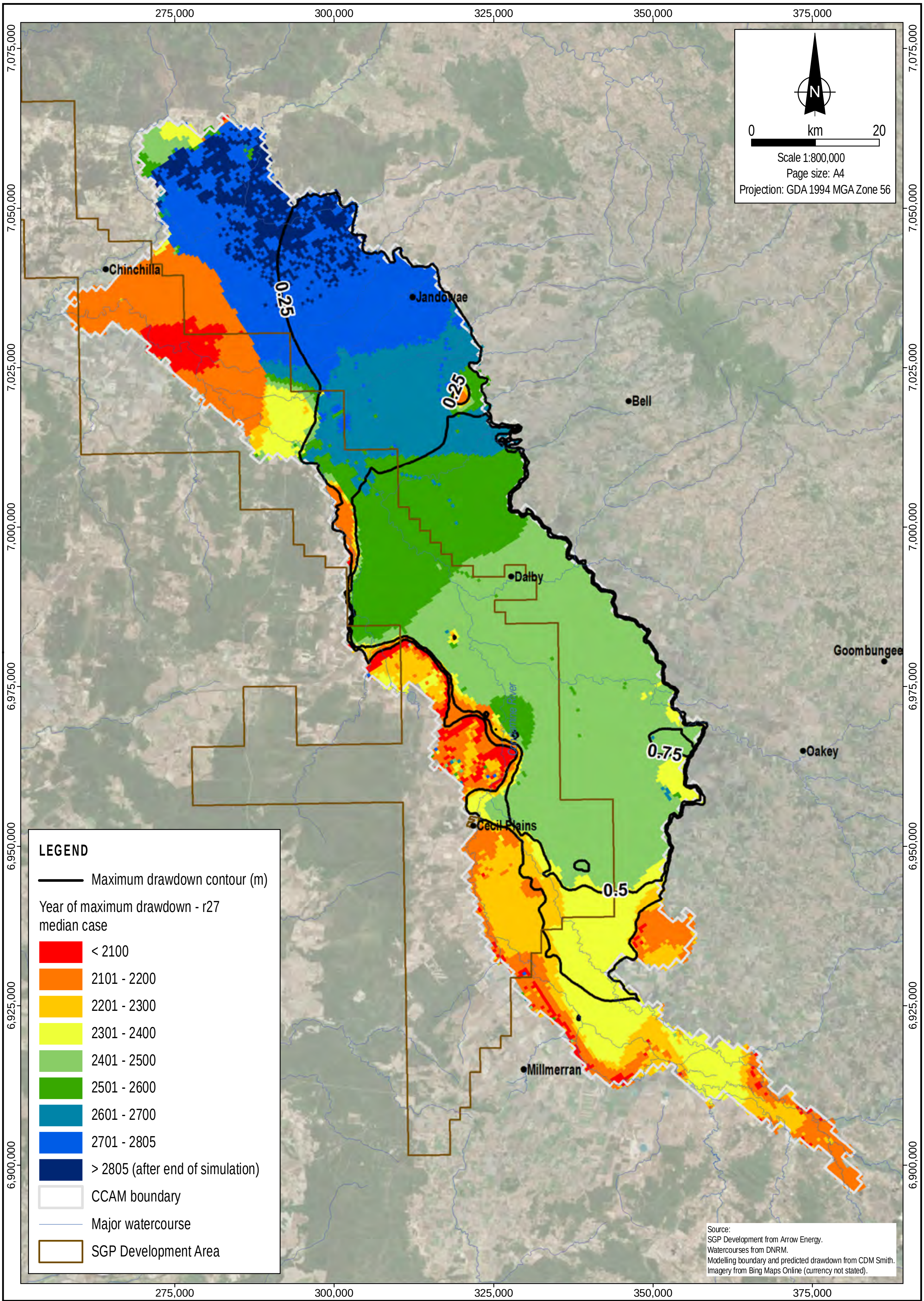
MXD Reference: 20484AA_01_GIS009_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F017_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Distribution of maximum change in groundwater flux to the Condamine River due to Arrow water production - median case	Figure No: 17



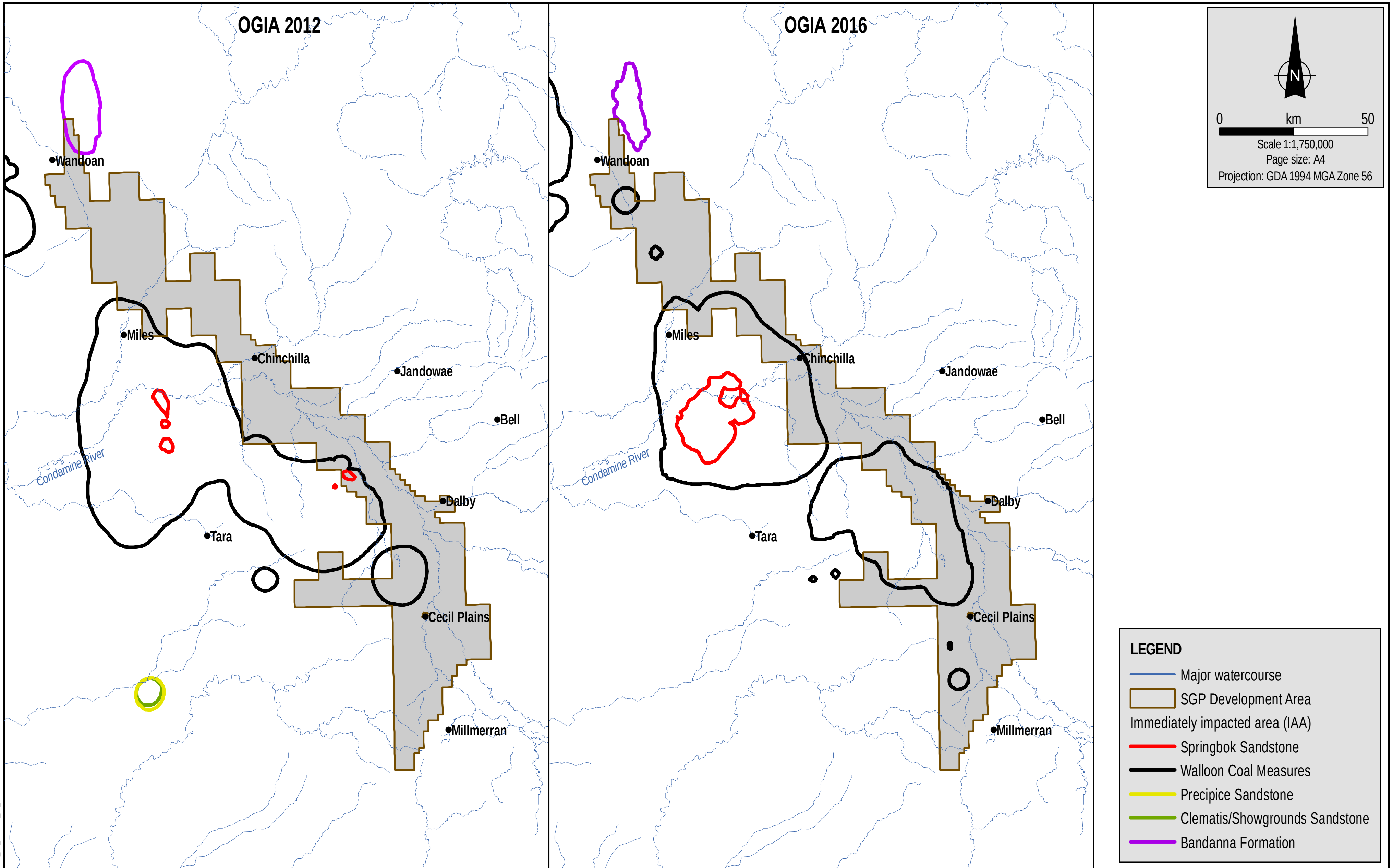
MXD Reference: 20484AA_01_GIS006_v0_2

coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F014_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted maximum drawdown timing at the watertable due to Arrow water production - high case	Figure No: 18



coffey	Date: 19.10.2016 Project: ENAUABTF20484AA File Name: 20484AA_01_F015_GIS	Arrow Energy Surat Gas Project WMMP	arrow energy go further	Predicted maximum drawdown timing at the water table due to Arrow water production - median case	Figure No: 19

MXD Reference: 20484AA_01_GIS007_v0_2



Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Immediately affected areas from OGIA.

coffey
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Date: 19.10.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F020_GIS

Arrow Energy

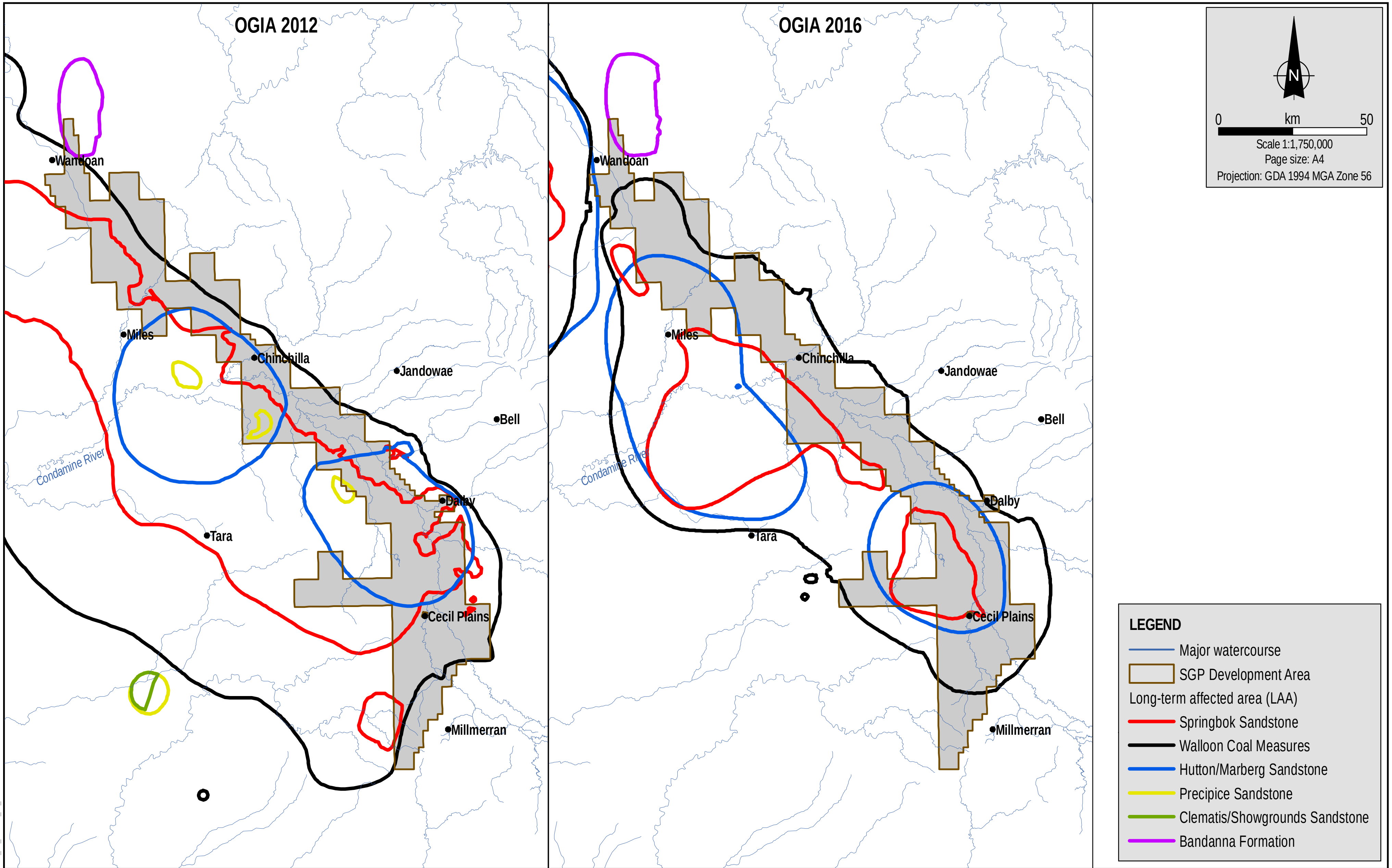
Surat Gas Project WMMP

arrow energy go further

OGIA UWIR 2012 and 2016 IAA comparison

Figure No: 20

MXD Reference: 20484AA_01_GIS020_v0_2



MXD Reference: 20484AA_01_GIS021_v0_2

Source:
SGP Development from Arrow Energy.
Watercourses from DNRM.
Immediately affected areas from OGIA.

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Date: 05.12.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F021_GIS

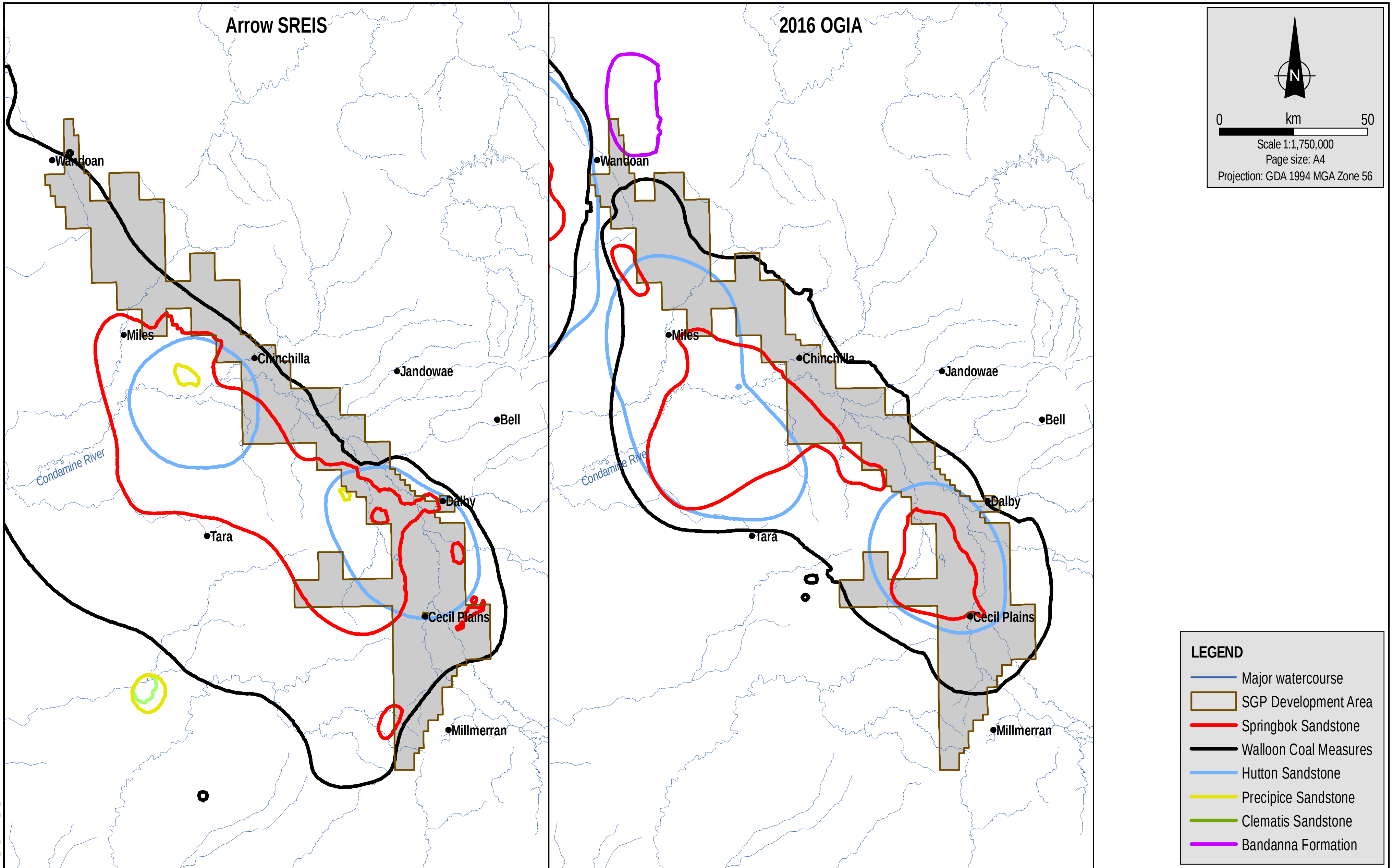
Arrow Energy

Surat Gas Project WMMP

arrow energy
go further

OGIA UWIR 2012 and 2016 LAA comparison

Figure No: 21



MXD Reference: 20484AA_01_GIS023_v0_2

Source:
SGP Development Area from Arrow Energy.
Watercourses from DNRM.
SREIS calibration realisation from GHD.
UWIR 2016 LAA contours from OGIA.

coffey
A TETRA TECH COMPANY

Date: 05.12.2016
Project: ENAUABTF20484AA
File Name: 20484AA_01_F022_GIS

Arrow Energy

Surat Gas Project WMMP

arrow energy
go further

Arrow SREIS and OGIA UWIR 2016 LAA comparison

Figure No: 22