# Appendix F

## Groundwater impact assessment

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# Narrabri Gas Project
# Groundwater Impact Assessment

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# Narrabri Gas Project Groundwater Impact Assessment

October 2016

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# Executive Summary

## Groundwater Modelling

A numerical groundwater model has been developed in MODFLOW-SURFACT using the Groundwater Vistas interface. Considerable stratigraphic data were available to construct the model layers and provide a relatively high confidence level in the model geometry. The model has been assessed against model confidence level criteria from the Australian Groundwater Modelling Guidelines (Barnett *et al.* 2012) and is considered to be fit for purpose for predicting potential regional impacts on groundwater and surface water from proposed water extraction from deep Permian Age coal seams in the Gunnedah Basin. The numerical model is judged to have a confidence level of Class 1 based on the criteria established in the guidelines.

Predictive simulations have been conducted for three volumes of water production for the project over 25 years: Base Case simulated water production of 37.5 GL; Low Case simulated water production of 35.5 GL; and High Case simulated water production of 87.1 GL. The Base Case is the estimate of water production being used as the basis for the project construction and design concept (referred to here as the Narrabri Gas Project). The simulations of water production are based on a target for peak gas production of 200 terajoules per day.

The predictive simulations adopt values of hydrogeological properties that are considered to be appropriate for strata within the boundary of the groundwater model. The adopted values are based on: review of available field studies; previous groundwater modelling; and current knowledge of the groundwater sources of the Gunnedah-Oxley Basin, the overlying portion of the Great Artesian Basin (GAB) and the Upper and Lower Namoi alluvium.

Potential cumulative drawdown impacts of the Narrabri Gas Project and the Narrabri Coal Mine Stage 2 Longwall Project have been simulated. Potential cumulative impacts of the six other existing or approved coal mines are assessed to be negligible and are not simulated in this GIA.

The results of the groundwater modelling show that:

- Intentional depressurisation and drawdown of hydraulic head in the target coal seams occurs rapidly, but vertical propagation of drawdown into overlying and underlying strata is impeded (attenuated in magnitude and delayed in time) by thick aquitard sequences. Lateral propagation of drawdown into formations immediately bordering the depressurised coal seams is also impeded by the lateral extent of the Bohena Trough.

- Drawdown of hydraulic head in the Pilliga Sandstone of the GAB is attenuated in magnitude and delayed in time relative to the predicted impacts in the target coal seams, with the predicted maximum value of drawdown in the Pilliga Sandstone not exceeding 0.5m.

- Negligible potential impacts to the Namoi alluvium are predicted as a result of the Narrabri Gas Project. The maximum predicted drawdown of the water table within the Namoi alluvium is undiscernible and significantly less than the existing seasonal variation of the water table in the alluvium.

- Predicted cumulative drawdown impacts of the Narrabri Gas Project and the Narrabri Coal Mine Stage 2 Longwall Project are dominated by the effects of groundwater inflow to the coal mine, with relatively minor contributions to cumulative drawdown from the Narrabri Gas Project. Maximum drawdown in the Pilliga Sandstone and at the water table due to the coal mine occurs approximately 50 years in the future, which is 150 to 200 years in advance of predicted maximum drawdown due to the Narrabri Gas Project.

In general, the modelling results show that after depressurisation of the target coal seams has taken place, the characteristically small hydraulic conductivity of the deep basin strata act to impede groundwater replenishment from overlying groundwater sources, which prolongs the localised impacts in the deep coal seams and hosting strata for hundreds of years, but thereby attenuates the impacts in the overlying high-valued groundwater sources.

On the basis of the groundwater modelling results, the environmental values of the GIA study area, as defined by the extent of the Gunnedah Basin Regional Model, are not expected to be adversely affected due to the small and gradual predicted impacts on drawdown in the Pilliga Sandstone, and negligible predicted impacts at the water table in the Namoi alluvium.

### Predicted Subsidence

The probable worst case range of subsidence at depth within the target coal seams and their hosting strata due to depressurisation of the coal seams is predicted to be 137 mm to 205 mm of vertical compaction within the project area. This magnitude of compaction at depth is likely to cause negligible settlement and subsidence at ground surface due to the large depth below ground surface of the target coal seams and the presence and thickness of structurally competent rock formations within the overburden.

The risk of impacts to sub-surface infrastructure and groundwater resources due to potential subsidence at depth arising from the project is assessed to be low to very low. The associated risk of impacts on surface infrastructure and surface water resources due to differential settlement and subsidence at ground surface is assessed to be very low.

### NSW Aquifer Interference Policy

In relation to the minimal impact considerations of the NSW Aquifer Interference Policy (AIP) it is concluded that:

- For the **Gunnedah-Oxley Basin Groundwater Source**, intentional depressurisation of the target coal seams and their immediate host strata would constitute aquifer interference under the AIP. The predicted impacts to the Gunnedah-Oxley Basin Groundwater Source may exceed the minimal impact consideration under the AIP; however, this groundwater source has a relatively low value due to high salinity and subsequent lack of usage by existing or reasonably foreseeable third party users. In addition, the volume of water that would be extracted under a Water Access Licence (WAL) is well within the sustainable diversion limits (maximum usage cap) of the targeted water source. Therefore, depressurisation effects would be considered negligible on existing water users targeting this water source.

- For the **GAB Southern Recharge Groundwater Source**, no impacts on hydraulic head or water supply works in the Pilliga Sandstone exceeding 0.5 m drawdown are predicted as a consequence of the Narrabri Gas Project. No impacts on hydraulic head exceeding 0.5 m drawdown are predicted at GDEs located within the area that is potentially impacted by the project. The predicted maximum induced flow rate from the Southern Recharge Groundwater Source is 0.06 GL/y (1.8 L/s).

- For the **Upper and Lower Namoi Groundwater Sources**, no impacts on water table elevation or water supply works in the Namoi alluvium exceeding 0.5 m drawdown are predicted as a consequence of the Narrabri Gas Project. The predicted maximum induced flow rates from all Water Sharing Plan reporting areas of the Upper and Lower Namoi Groundwater Sources are less than 0.01 GL/y (0.3 L/s).

### Environment Protection and Biodiversity Conservation Act

In relation to the Water Trigger of the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) it is concluded that:

- For the **Gunnedah-Oxley Basin Groundwater Source**, based on the Commonwealth Significant Impact Guidelines 1.3 (Commonwealth 2013) predicted changes to hydraulic head in the basin may be classified as significant due to the long-term duration of depressurisation (approximately 1500 years) and the regional extent of depressurisation (an area greater than 1800 $km^2$). Notwithstanding these criteria, the Gunnedah-Oxley Basin Groundwater Source within the project area has a relatively low value due to high salinity, and there are no known groundwater users abstracting water from the coal seams or surrounding host rocks. On balance of these considerations, potential impacts to the GOB from the project are unlikely to be considered as significant. Furter to these considerations, the volume of water that would be extracted under a Water Access Licence (WAL) is well within the sustainable diversion limits (maximum usage cap) of the targeted water source. Therefore, depressurisation effects would be considered negligible on existing water users targeting this water source.

- For the **GAB Southern Recharge and Surat Groundwater Sources**, predicted impacts are unlikely to be considered as significant due to: predicted drawdown less than 0.5 m in the Pilliga Sandstone as a consequence of the Narrabri Gas Project; minor induced change in groundwater storage in the GAB (approximately 0.05 GL/y maximum rate of storage change); and minor induced groundwater flow within the GAB.

- For the **Upper and Lower Namoi Groundwater Sources**, predicted impacts are unlikely to be considered as significant due to: predicted water table drawdown less than 0.5 m in the Namoi alluvium as a consequence of the Narrabri Gas Project; negligible induced change in groundwater storage in the Namoi alluvium (less than 0.01 GL/y maximum rate of storage change); and insignificant induced change to groundwater flow in the Namoi alluvium.

### Risk mitigation and monitoring

Thirteen of the sixteen risks identified in the risk assessment are assessed to have the lowest possible residual risk score of 1 (very low risk) and the remaining three risks are assessed to have residual risk scores of 2 (low risk).

The three potential impacts with low residual risks (i.e., the highest-ranked risks identified in the assessment) are assessed as follows:

- Drawdown in existing groundwater bores - decline of water levels in existing deep groundwater bores screened below the Pilliga Sandstone aquifer that would materially affect the water supply from the bores is assessed to be possible but the potential consequences are considered to be minor and manageable. Mitigation would be achieved through the Water Monitoring Plan, which is designed to detect if adverse impacts on the pressure in existing bores is going to occur before those impacts are realised, and implementation of make good options if water supply from an existing bore is materially affected by depressurisation from the project.

- Drawdown of hydraulic head at GDEs - potential damage to GDEs caused by long-term decline of hydraulic head at the location of GDEs is classified as a major consequence under the criteria of the project risk matrix; however, these potential impacts are assessed to be unlikely, resulting in a medium risk score. Maximum drawdowns in the source aquifers for GDEs are predicted to be less than 0.5 m and are small compared to existing and expected future variation of water pressure in the source aquifers due to natural variation in climate patterns and variation in other extractive use patterns. None of the GDEs identified in the GDE impact assessment meet the definition of a high-priority GDE in NSW, and none support MNES defined under the EPBC Act.

- Induced groundwater flows between groundwater sources - depressurisation of deep coal seams for coal seam gas production is almost certain to induce very small rates of groundwater flow from overlying groundwater sources as the water extracted from the coal seams is replaced by downward flow through the overlying thick aquitard sequences. This replacement of the extracted water will take place naturally and very slowly over hundreds of years as the pressure in the coal seams recovers. The consequence of such small induced changes in the inter-formational flows in hydrostratigraphic units above the coal seam targets are assessed to be negligible.

| Risk / Issue | Cause | Potential Impact | Possible Mitigation Measures | Consequence | Likelihood | Risk Rating |
|---|---|---|---|---|---|---|
| Subsidence at depth due to compaction within target coal seams and their hosting strata | Depressurisation of coal seams and gas desorption from the matrix | Damage to sub-surface infrastructure due to differential settlement | ▪ Implement make good protocols | II. Minor | D. Unlikely | 1 |
| | | Fracturing and alteration of hydraulic connections between aquifers and aquitards | ▪ No direct action | I. Negligible | D. Unlikely | 1 |
| Subsidence at ground surface due to settlement of compacted strata and overburden | Depressurisation of coal seams and gas desorption from the matrix | Damage to surface infrastructure due to differential settlement | ▪ Implement make good protocols | I. Negligible | E. Remote | 1 |
| | | Alteration of flow paths in rivers and wetlands | ▪ Implement surface control structures if appropriate | I. Negligible | E. Remote | 1 |
| Induced aquifer connectivity via vertical groundwater leakage in coal seam gas wells | Drilling and well installation | Inter-formational groundwater flow and resultant change in water quality of groundwater | ▪ Drilling, completion and rehabilitation of CSG wells in compliance with the NSW Code of Practice for Coal Seam Gas Well Integrity<br>▪ Implementation of the project Water Monitoring Plan, which includes groundwater pressure and quality monitoring<br>▪ Adoption of petroleum industry standards and guidelines for drilling and well completion. | II. Minor | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical groundwater leakage in conventional gas wells | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | ▪ Rehabilitation of Santos' conventional gas wells in compliance with the NSW Code of Practice for Coal Seam Gas Well Integrity<br>▪ Implementation of the project Water Monitoring Plan, which includes groundwater pressure and quality monitoring | II. Minor | D. Unlikely | 1 |

| Risk / Issue | Cause | Potential Impact | Possible Mitigation Measures | Consequence | Likelihood | Risk Rating |
|---|---|---|---|---|---|---|
| Induced aquifer connectivity via activation of vertical groundwater leakage in coal mine core holes | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | ▪ Implementation of the project Water Monitoring Plan, which includes groundwater pressure and quality monitoring | I. Negligible | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical flow in groundwater bores | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | ▪ Groundwater bores do not intersect the coal seam targets or immediately overlying strata.<br>▪ Significant impact on vertical groundwater flux would require an improbable number of leaking bores<br>▪ Santos' groundwater monitoring bores will be completed in accordance with the Minimum Construction Requirements for Water Bores in Australia. | I. Negligible | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical groundwater in fault zones | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | ▪ Implementation of the project Water Monitoring Plan which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head | III. Moderate | E. Remote | 1 |
| Drawdown in existing groundwater bores | Water extraction from coal seams | Reduced access and availability of groundwater for existing uses | ▪ Implementation of the project Water Monitoring Plan which includes an early detection system to detect un-anticipated drawdown of hydraulic head<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water supply to the owners of impacted bores | II. Minor | C. Possible | 2 |
| Drawdown of hydraulic head at GDEs | Water extraction from coal seams | Damage or destruction of GDEs | ▪ Implementation of the project Water Monitoring Plan, which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head | IV. Major | D. Unlikely | 2 |
| Induced groundwater flows between groundwater sources | Water extraction from coal seams | Reduced availability of groundwater sources for existing uses | ▪ Implementation of the project Water Monitoring Plan which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water supply to the owners of impacted bores | I. Negligible | A. Almost certain | 2 |

| Risk / Issue | Cause | Potential Impact | Possible Mitigation Measures | Consequence | Likelihood | Risk Rating |
|---|---|---|---|---|---|---|
| Induced changes in groundwater quality | Water extraction from coal seams and associated induced groundwater flows | Change in water quality for existing uses | ▪ Implementation of the project Water Monitoring Plan<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy<br>▪ Induced downward flows have potential to cause freshening but not deterioration of deep groundwater sources, which currently have low value due to high salinity<br>▪ Induced downward flows means there is no pathway for deterioration of shallow groundwater sources | I. Negligible | B. Likely | 1 |
| Reduction of base flow to rivers | Water extraction from coal seams and associated induced groundwater flows | Reduction of low rivers flows and decline or loss of riparian GDEs | ▪ Minor to negligible impacts on water table elevation in river alluvium are predicted hundreds of years after coal seam gas production has ceased<br>▪ Implementation of the project Water Monitoring Plan, which includes an early detection system to detect un-anticipated or premature drawdown<br>▪ | IV. Minor | E. Remote | 1 |
| Induced gas flow in existing groundwater bores | Water extraction from coal seams and associated depressurisation | Deterioration of existing groundwater uses and potential exposure to fugitive gas emissions | ▪ Implementation of the project Water Monitoring Plan<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water quality and supply to the owners of impacted bores. | II. Minor | E. Remote | 1 |
| Visual amenity of rivers and streams | Water extraction from coal seams and associated induced drawdown of water table | Degradation of community values | ▪ Minor to negligible impacts on water table elevation in river alluvium are predicted hundreds of years after coal seam gas production has ceased<br>▪ Implementation of the project Water Monitoring Plan, which includes an early detection system to detect un-anticipated or premature drawdown | IV. Minor | E. Remote | 1 |

(Risk rating provided in Table 7-3)

# 1 Introduction

## 1.1 Overview

The proponent is proposing to develop natural gas in the Gunnedah Basin in New South Wales (NSW), southwest of Narrabri (refer Figure 1-1).

The Narrabri Gas Project (the project) seeks to develop and operate a gas production field, requiring the installation of gas wells, gas and water gathering systems, and supporting infrastructure. The natural gas produced would be treated at a central gas processing facility on a local rural property (Leewood), approximately 25 kilometres south-west of Narrabri. The gas would then be piped via a high-pressure gas transmission pipeline to market. This pipeline would be part of a separate approvals process and is therefore not part of this development proposal.

The primary objective of the project is to commercialise natural gas to be made available to the NSW gas market and to support the energy security needs of NSW. Production of natural gas under the project would deliver economic, environmental and social benefits to the Narrabri region and the broader NSW community. The key benefits of the project can be summarised as follows:

- Development of a new source of gas supply into NSW would lead to an improvement in energy security and independence to the State. This would give NSW gas markets greater choice when entering into gas purchase arrangements. Potential would also exist for improved competition on price. Improved competition on price would have flow on benefits for NSW's economic efficiency, productivity and prosperity.

- The provision of a reduced greenhouse gas emission fuel source for power generation in NSW as compared to traditional coal-fired power generation.

- Increased local production and regional economic development through employment and provision of services and infrastructure to the project.

- The establishment of a regional community benefit fund equivalent to five per cent of the royalty payment made to the NSW Government within the future production licence area. If matched by the NSW Government, the fund could reach $120 million over the next two decades.

## 1.2 Description of the Project

The project would involve the construction and operation of a range of exploration and production activities and infrastructure including the continued use of some existing infrastructure. The key components of the project are presented in Table 1-1, and are shown on Figure 1-1.

The project is expected to generate approximately 1,300 jobs during the construction phase and sustain around 200 jobs during the operational phase; the latter excluding an ongoing drilling workforce comprising approximately 100 jobs.

Subject to obtaining the required regulatory approvals, and a financial investment decision, construction of the project is expected to commence in early 2018, with first gas scheduled for 2019/2020. Progressive construction of the gas processing and water management facilities would take around three years and would be undertaken between approximately early/mid-2018 and early/mid-2021. The gas wells would be progressively drilled during the first 20 or so years of the project. For the purpose of impact assessment, a 25-year construction and operational period has been adopted.

**Table 1-1 Project infrastructure components**

| Component | Infrastructure or Activity |
|---|---|
| Major Facilities | |
| Leewood | ▪ a central gas processing facility for the compression, dehydration and treatment of gas<br>▪ a central water management facility including storage and treatment of produced water and brine<br>▪ optional power generation for the project<br>▪ a safety flare<br>▪ treated water management infrastructure to facilitate the transfer of treated water for irrigation, dust suppression, construction and drilling activities<br>▪ other supporting infrastructure including storage and utility buildings, staff amenities, equipment shelters, car parking, and diesel and chemical storage<br>▪ continued use of existing facilities such as the brine and produced water ponds<br>▪ operation of the facility |
| Bibblewindi | ▪ in-field compression facility<br>▪ a safety flare<br>▪ supporting infrastructure including storage and utility areas, treated water holding tank, and a communications tower<br>▪ upgrades and expansion to the staff amenities and car parking<br>▪ produced water, brine and construction water storage, including recommissioning of two existing ponds<br>▪ continued use of existing facilities such as the 5ML water balance tank<br>▪ operation of the expanded facility |
| Bibblewindi to Leewood infrastructure corridor | ▪ widening of the existing corridor to allow for construction and operation of an additional buried medium pressure gas pipeline, a water pipeline, underground (up to 132 kV) power, and buried communications transmission lines |
| Leewood to Wilga Park underground power line | ▪ installation and operation of an underground power line (up to 132 kV) within the existing gas pipeline corridor |
| Gas Field | |
| Gas exploration, appraisal and production infrastructure | ▪ seismic geophysical survey<br>▪ installation of up to 850 new wells on a maximum of 425 well pads<br>  o new well types would include exploration, appraisal and production wells<br>  o includes well pad surface infrastructure<br>▪ new well types would include exploration, appraisal and production wells<br>▪ installation of water and gas gathering lines and supporting infrastructure<br>▪ construction of new access tracks where required<br>▪ water balance tanks<br>▪ communications towers<br>▪ conversion of existing exploration and appraisal wells to production |
| Ancillary | ▪ upgrades to intersections on the Newell Highway<br>▪ expansion of worker accommodation at Westport<br>▪ a treated water pipeline and diffuser from Leewood to Bohena Creek<br>▪ treated water irrigation infrastructure including:<br>  o pipeline(s) from Leewood to the irrigation area(s)<br>  o treated water storage dam(s) offsite from Leewood<br>▪ operation of the irrigation scheme |

## 1.3 Project Location

The project would be located in north-western NSW, approximately 20 kilometres south-west of Narrabri, within the Narrabri local government area (LGA) (see Figure 1-1).

The project area covers about 950 square kilometres (95,000 hectares), and the project footprint would directly impact about one per cent of that area.

The project area contains a portion of the region known as 'the Pilliga'; which is an agglomeration of forested area covering more than 500,000 hectares in north-western NSW around

Coonabarabran, Baradine and Narrabri. Nearly half of the Pilliga is allocated to conservation, managed under the NSW *National Parks and Wildlife Act 1974*. The Pilliga has spiritual meaning and cultural significance for the Aboriginal people of the region.

Other parts of the Pilliga were dedicated as State forest, and set aside for the purpose of 'forestry, recreation and mineral extraction, with a strategic aim to "provide for exploration, mining, petroleum production and extractive industry" under the *Brigalow and Nandewar Community Conservation Area Act 2005*. The parts of the project area on state land are located within this section of the Pilliga.

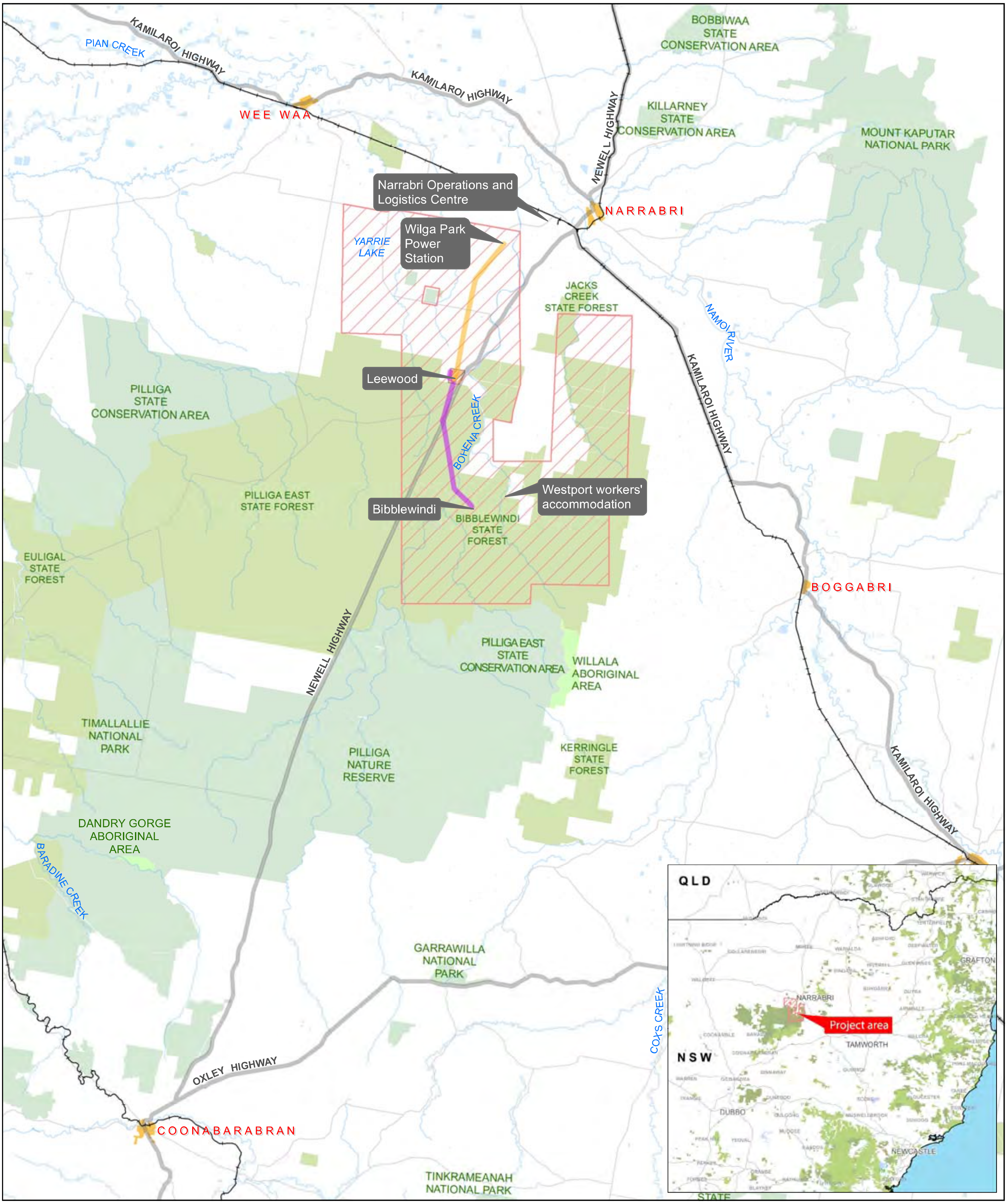
The semi-arid climate of the region and general unsuitability of the soils for agriculture have combined to protect the Pilliga from widespread clearing. Commercial timber harvesting activities in the Pilliga were preceded by unsuccessful attempts in the mid-1800s to establish a wool production industry. Resource exploration has been occurring in the area since the 1960s; initially for oil, but more recently for coal and gas.

The ecology of the Pilliga has been fragmented and otherwise impacted by commercial timber harvesting and related activities over the last century through:

- the establishment of more than 5,000 kilometres of roads, tracks and trails
- the introduction of pest species
- the occurrence of drought and wildfire.

The project area avoids the Pilliga National Park, Pilliga State Conservation Area, Pilliga Nature Reserve and Brigalow Park Nature Reserve. Brigalow State Conservation Area is within the project area but would be protected by a 50 metre surface exclusion zone.

Agriculture is a major land use within the Narrabri LGA; about half of the LGA is used for agriculture, split between cropping and grazing. Although the majority of the project area would be within State forests, much of the remaining area is situated on agricultural land that supports dry-land cropping and livestock. No agricultural land in the project area is mapped by the NSW Government to be biophysical strategic agricultural land (BSAL) and detailed soil analysis has established the absence of BSAL. This has been confirmed by the issue of a BSAL Certificate for the project area by the NSW Government.




LEGEND
- Project area
- Leewood
- Urban
- State forest
- Parks and reserves
- Aboriginal areas
- Lakes and dams
- Watercourses
- Highways
- Major Roads
- Train line
- Leewood to Wilga Park infrastructure corridor
- Bibblewindi to Leewood infrastructure corridor

0 5 10 20
Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 55

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Narrabri Gas Project
EIS Technical Appendix

Job Number 21-22463
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Date 12 Mar 2015

Regional context and location of key infrastructure

Figure 1-1

C:\Users\AFoddy\Desktop\21_22463_KBM29.mxd [KBM: 221]

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Data source: NSW Department of Lands: DTDB and DCDB - 2012-13. Santos: Operational and Base Data - 2013. Created by: afoddy

# 1.4 Requirements of the Groundwater Impact Assessment

## 1.4.1 Commonwealth

The GIA has been prepared taking into consideration the Commonwealth's Department of the Environment EPBC Act policy statement *Significant Impact Guidelines 1.3: Coal Seam Gas and Large Coal Mining Developments-Impacts on Water Resources* (Commonwealth of Australia 2013). These guidelines provide criteria which assists in deciding whether the project is likely to have significant impacts on water resources. The significant impact guidelines cover a range of criteria including:

- **Value of a water resource** – consideration of the value of the water resource in determining whether the impacts of the proposed action are likely to be significant;
- **Changes to hydrological characteristics** – potential significant impacts on the hydrological characteristics of a water resource as a result of the action;
    - Changes in water quantity, including timing of variations on water quantity
    - Changes in integrity of hydrological and hydrogeological connections
    - Changes in the area or extent of a water resource
- **Changes to water quality** – a significant impact on a water resource may occur as a result of the proposed action if there is a risk that the ability to achieve relevant local or regional water quality objectives would be materially compromised, there is a significant worsening of local water quality and/or high quality water is released into an ecosystem which is adapted to a lower quality of water;
- **Cumulative impacts** – must be considered with other developments, whether past, present or reasonably foreseeable;
- **Timing** – significance of impacts must be assessed in both the short and the long term; and
- **Scale** – significance of impacts on a water resource should be considered on each of a local, aquifer or catchment and regional scale.

## 1.4.2 New South Wales

A preliminary environmental assessment for the Narrabri Gas Project was submitted to the NSW Department of Planning & Infrastructure (DPI) on 31 March 2014. In response to the new application, the NSW Office of Water (now DPI Water) reviewed the supporting documents and made recommendations to the DPI, which now form part of the Secretary's Environmental Assessment Requirements (SEARS) for the project. The SEARS were subsequently updated and re-issued on 27 September 2016, including updated advice and recommendations from DPI Water. Table 1-2 is a list of the DPI Water's recommendations from the updated SEARS that are addressed as part of this GIA. Not all recommendations of DPI Water are addressed in the GIA.

### Table 1-2 Advice of DPI Water to NSW Department of Planning & Infrastructure

| In relation to water resources potentially affected by the project, the NOW has recommended that the Environmental Impact Statement be required to include: | | |
|---|---|---|
| Recommendation | Section | Comment |
| Assessment of any water licensing requirements (including those for ongoing water take post-closure). | 6.12 | Potential groundwater licensing requirements under the NSW AIP. |
| Details of water proposed to be taken (including through inflow and seepage) from each water source as defined by the relevant water sharing plan. This should include a description of the expected spatial and temporal pattern of water take (eg year on year), as well as a detailed site water balance outlining predicted annual water production for the life of the project | 6.8.1 | Indicative development plan for the gas field, and simulated rates of water production in time and space. |
| The identification of an adequate and secure water supply for the life of the project. Confirmation that water can be sourced from an appropriately authorised and reliable supply. This is to include an assessment of the current market depth where water entitlement is required to be purchased | - | Not considered in this report. |
| A detailed description of the produced water resulting from the project, including outlining the management, treatment and disposal methods to be implemented, and the final disposal pathway | 6.8.1 | Indicative development plan for the gas field, and simulated rates of water production in time and space. Produced water management is not considered in this report. |
| A detailed assessment against the NSW Aquifer Interference Policy (2012), using the NSW Office of Water assessment framework | 6.12 | Significance of predicted groundwater impacts in relation to the minimal impact considerations of the AIP. |
| Assessment of impacts on surface and ground water sources (both quality and quantity), related infrastructure, watercourses, riparian land, and groundwater dependent ecosystems, and measures proposed to reduce and mitigate these impacts | All | This groundwater impact assessment. |
| Proposed surface water and groundwater monitoring for the project | - | Not considered in this report. See the Water Monitoring Report (CDM Smith 2016c). |
| Detailed surface water and groundwater modelling to assess impacts of the project, undertaken in accordance with standards outlined in relevant National and State Guidelines. The EIS should also describe plan for ongoing validation calibration and development of the model. | 6.0 | Groundwater flow modelling and predictive simulations.<br>Future development of the groundwater modelling. |
| Consideration of relevant Federal and State policies and guidelines | 2.0 | Commonwealth and State legislative context. |
| Details of all relevant management plans to be developed for the project, including, but not limited to, water management plans, produced water management plan, monitoring plans, rehabilitation plans and erosion and sedimentation control plans. | 7.6 | Not considered in this report. Considered elsewhere in the EIS. |
| A description of how the proponent plans to stage development of the project, including the development of any plans, models, infrastructure, and monitoring requirements. | - | Not considered in this report. Considered elsewhere in the EIS. |
| A table outlining where each element of the Secretary's Environmental Assessment Requirements is addressed in the Environmental Impact Statement." | 1.5.2 | This table, for this report.. |
| Specifically in relation to groundwater assessment, the NOW has recommended that the EIS needs to include adequate details to assess the impact of the project on all groundwater sources including: | | |
| Recommendation | Section | Comment |
| Works likely to intercept, connect with or infiltrate the groundwater sources | 7.0 | Considers potential sub-surface impacts of drilling, excluding surface works (e.g. well pads and pipelines). Other surface works (e.g. storage ponds, creek crossings) and managed surface water releases are not considered in this report. |

| | | |
|---|---|---|
| Any proposed groundwater extraction, including purpose, location and construction details of all proposed bores and expected annual extraction volumes | 6.8.1 | Indicative field development plan including Design and simulated rates of water production for. |
| A description of the flow gradients and physical and chemical characteristics of the groundwater source (including connectivity with other groundwater and surface water sources) | 4.0<br><br>5.0 | Description of the existing environment including hydrology.<br>Conceptual hydrogeology. |
| Sufficient baseline monitoring for groundwater quantity and quality for all aquifers and GDEs to establish a baseline incorporating typical temporal and spatial variations | 3.1<br>5.0 | Data collation and review.<br>Conceptual hydrogeology. |
| The predicted impacts of any final landform on the groundwater regime | - | Not considered in this report. |
| The existing groundwater users within the area (including the environment), any potential impacts on these users and safeguard measures to mitigate impacts | 4.8<br><br>7.4 | Current water extraction and entitlements.<br>Potential groundwater impacts and mitigation measures. |
| An assessment of the quality of the groundwater for the local groundwater catchment. | 5.7 | Groundwater quality. |
| An assessment of the potential for groundwater contamination (considering both the impacts of the proposal on groundwater contamination and the impacts of contamination on the proposal) | 7.4 | Groundwater risk assessment potential impacts and mitigation measures. |
| Measures proposed to protect groundwater quality, both in the short and long term, so that remediation is not required. | 7.4 | Groundwater risk assessment potential impacts and mitigation measures. |
| Protective measures for any groundwater dependent ecosystems (GDEs) | 7.4<br>App. B | Groundwater risk assessment and Groundwater Impact Assessment (Appendix B). |
| Proposed methods of the disposal of waste water and approval from the relevant authority | - | Not considered in this report. |
| The results of any models or predictive tools used | 6.9 | Groundwater modelling results. |

## 1.5 Role of the GIA within the Project Assessment

The GIA has been prepared as part of the Environmental Impact Statement (EIS) for the Narrabri Gas Project within the context of the environmental assessment requirements of the NSW and Commonwealth Governments (Section 1.4). Other supporting documents to the GIA, which also form part of the project EIS include the Water Baseline Report (CDM Smith 2016b) and the Water Monitoring Plan (CDM Smith 2016c).

The GIA follows a rigorous assessment procedure that has been undertaken using the best hydrogeological data and water information available at the time of preparing the EIS. The predictions of potential impacts on the groundwater sources in the project area, and their dependent systems are based on the results of detailed groundwater modelling conducted for the GIA.

The Water Monitoring Plan (WMP) will support management of the NGP operations by providing water-related data for ongoing risk-based assessment of the efficacy of proposed water management strategies and mitigation measures in relation to existing and future uses of water resources in the project area. The WMP recognises that the predictions of the potential effects of the project on water resources, such as the predictions in this GIA are not static and may potentially change over time due to differences between the indicative field development plan and the realised field development, as well as improvements in the water-related information for the project that is gathered as part of the water monitoring program and through field investigation and development activities.

Geological and hydrogeological data that are gathered as part of the project field operations and groundwater monitoring program will be used to audit the modelling predictions in the GIA and, if necessary, will be used to improve the groundwater model and the existing predictions. Within this context, the GIA has been prepared together with the Water Monitoring Plan to achieve ongoing improvement in the modelling predictions over the life of the project as warranted.

## 1.6 GIA History and Scope of Work

An earlier numerical groundwater flow model for the project was developed by Golder Associates. The model was then refined by Halcrow Limited (Halcrow) and converted from MODFLOW-2005 to MODFLOW-SURFACT. This improved the re-wetting of dry cells within the model, enabling the model to recover following depressurisation. The numerical groundwater flow model and associated GIA has undergone a number of independent review processes during the study development phase.

More recently, NTEC Environmental Technology (now CDM Smith) was sub-contracted by Halcrow to developed a numerical groundwater flow model for Santos' future Gunnedah Coal Seam Gas Project. The Gunnedah Basin Regional Model (GBRM) covers a larger area than the earlier Project model and is suitable for future assessment of potential cumulative groundwater impacts from possible concurrent development of this Project and Gunnedah Coal Seam Gas Project. For this reason the GBRM is used in this GIA.

### 1.6.1 Existing and Supporting Studies

Table 1-3 provides a summary of previous studies undertaken for the project and surrounding region that are relevant to this GIA.

**Table 1-3 Other studies relevant to the GIA**

| Report Title | Brief Summary |
|---|---|
| Project Specific Studies | |
| Narrabri Gas Project Preliminary Environmental Assessment, March 2014 (GHD 2014) | Provides a broad description of the proposed development, reviews the applicable legislative framework, and identifies potential environmental and social issues associated with construction and operation of the proposed development. |
| Narrabri Gas Project: Subsidence Assessment – Appendix G of this GIA | An assessment of the potential for sub-surface and surface subsidence due to proposed depressurisation of the target coal seams for the project. |
| NGP Water Baseline Report (CDM Smith 2016b) | A statement of the groundwater and surface water datasets that constitute the baseline monitoring for the project. |
| NGP Water Monitoring Plan (CDM Smith 2016c) | Establishes the proposed water monitoring strategy and provisional water monitoring network for the project. |
| Groundwater Dependent Ecosystems (Springs) Risk Assessment Report (Eco Logical 2016b) | Identifies and characterises surface GDEs within the project area that may be dependent on surface expression of groundwater (potential Type 2 GDEs) based on NSW DPI Water's *Risk assessment guidelines for groundwater dependent ecosystems*. |
| GDE Impact Assessment (CDM Smith 2016a) - Appendix B of this GIA | Supplemental study to Eco Logical's GDE (Springs) Risk Assessment with expanded focus on sub-surface GDEs that may be reliant on sub-surface expression of groundwater (potential Type 3 GDEs) and adopting approaches defined in the GDE Tool Box. |
| Regional Studies | |
| Aquaterra, Narrabri Coal Mine Stage 2 Longwall Project Hydrogeological Assessment, 2009 | The report details the outcomes of a groundwater assessment undertaken for the Narrabri Coal Mine Stage 2 Longwall project. |

| Report Title | Brief Summary |
|---|---|
| Schlumberger Water Services, Namoi Catchment Water Study Independent Expert Phase 1 Report, November 2010<br><br>Schlumberger Water Services, Namoi Catchment Water Study Independent Expert Phase 2 Report, August 2011<br>Schlumberger Water Services, Namoi Catchment Water Study Independent Expert Phase 3 – Reference Manual, January 2012<br><br>Schlumberger Water Services, Namoi Catchment Water Study Independent Expert Final Study Report, July 2012 | The study included the construction of a numerical groundwater model used to assess the potential impact of various mining and coal seam gas activities on the water resources of the Namoi Catchment. |

### 1.6.2 Namoi Subregion Bioregional Assessment

Bioregional assessments (BAs) are one of the key mechanisms to assist the Independent Expert Scientific Committee (IESC) in developing advice to the federal Minister for the Environment on potential water-related impacts of coal seam gas and large coal mining developments. The Namoi subregion bioregional assessment is one of four subregion BAs that constitute the Northern Inland Catchments bioregion.

The project area of the NGP lies entirely within the area of the Namoi subregion BA.

The Namoi subregion BA is compiling existing information and will provide new scientific information about the potential impacts of coal and coal seam gas development in the Namoi subregion, including potential impacts on water within the central and eastern parts of the subregion. The assessment will also examine the cumulative impacts for surface water and groundwater across the Namoi river basin.

At the time of preparing this GIA, published products from the Namoi subregion BA include:

- Context statement for the Namoi subregion (Product 1.1) (Welsh et al 2014);
- Coal and coal seam gas resource assessment for the Namoi subregion (Product 1.2) (Northey et al. 2014);
- Description of the water-dependent asset register for the Namoi subregion (Product 1.3) (O'Grady et al 2015a) –
    - Water-dependent asset register and asset list for the Namoi subregion on 15 January 2015 (O'Grady et al 2015b);
- Current water accounts and water quality for the Namoi subregion (Product 1.5) (Pena-Arancibia et al 2016);
- Data register for the Namoi subregion (Product 1.6)

References to the Namoi subregion BA are made mainly within Sections 4 and 5 of the GIA., which contain contextual information and conceptualisation of the hydrogeology and water sources within the GIA study area.

### 1.6.3 Scope of Work

- Data collection, literature review and gap analysis, inclusive of -
    - Geological data
    - Existing ESG exploration programme borehole data
    - Existing ESG well test work and formation evaluation data
    - Existing regional coal mining exploration borehole data
    - Relevant water management records
    - Groundwater quality data
    - Regional groundwater literature and relevant coal mining-related groundwater studies
- Characterisation of the groundwater environment, including identification of environmental values associated with groundwater resources in consultation with other relevant specialists
- Review of applicable legislation regulatory requirements associated with the project, including the minimal impact considerations of the NSW Aquifer Interference Policy, and the significant impact guidelines of the Commonwealth EPBC Act
- Development of the hydrogeological conceptual model
- Development of a numerical groundwater flow model, and predictive modelling of the potential impacts of the project on groundwater resources
- Synthesis of the field development plan and associated water production for incorporation into the predictive groundwater modelling
- Preparation of a GIA report including -
    - Analysis of potential risks to groundwater resources and associated water users and groundwater dependent ecosystems (GDEs) associated with the development of the project
    - Assessment of the groundwater impacts of the project (e.g. drawdown, inter-aquifer depressurisation, groundwater quality and recharge), including assessment of post gas production recovery of groundwater levels and groundwater quality
    - Risk assessment and risk mitigation and management measures to avoid or mitigate the potential impacts of the project
    - Limitations of the numerical groundwater model

## 1.7 Structure of Report

The report is structured as follows:

- **Section 1, Introduction** – introduces the proposed development and the proponent, and describes the project area.
- **Section 2, Legislative Context** – outlines the relevant Commonwealth and State legislation relevant to the GIA.

  **Section 3, Groundwater Impact Assessment Methodology** – describes the methodology undertaken to assess potential groundwater impacts and their risks.
- **Section 4, Regional Context** – provides an overview of the existing environmental values of the study area that are relevant to the GIA.
- **Section 5, Conceptual Hydrogeological Model** – outlines the development of the conceptual model of the hydrogeology of the study area.
- **Section 6, Numerical Groundwater Flow Modelling** –describes the development of the numerical groundwater flow model and the results of predictive model simulations and sensitivity analyses.
- **Section 7, Risk Assessment** – describes the risk assessment undertaken for the GIA, including the potential impacts of water extraction from the target coal seams.
- **Section 8, Summary and Conclusion** –provides a summary of the GIA and its conclusions.
- **Section 9, References.**

# 2 Legislative Context

The project is permissible with development consent under the *State Environmental Planning Policy (Mining, Petroleum and Extractive Industries) 2007*, and is identified as 'State significant development' under section 89C(2) of the *Environmental Planning and Assessment Act 1979* (EP&A Act) and the *State Environmental Planning Policy (State and Regional Development) 2011*.

The project is subject to the assessment and approval provisions of Division 4.1 of Part 4 of the EP&A Act. The Minister for Planning is the consent authority, who is able to delegate the consent authority function to the Planning Assessment Commission, the Secretary of the Department of Planning and Environment or to any other public authority.

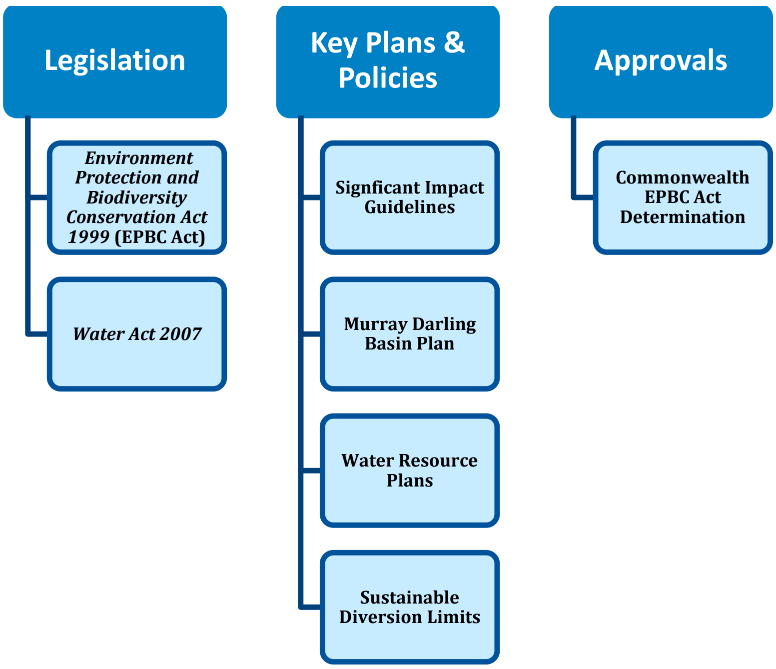
The project is also a controlled action under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. The project was declared to be a controlled action on 5 December 2014, to be assessed under the bilateral agreement between the Commonwealth and NSW Governments, and triggering the following controlling provisions:

- listed threatened species and ecological communities;
- a water resource, in relation to coal seam gas development and large coal mining development;
- Commonwealth land.

Commonwealth and NSW water and environmental legislation, and related policies and plans, relevant to groundwater and surface water resources and coal seam water management activities within the vicinity of the project are identified and discussed within this section.

## 2.1 Commonwealth

The following key Commonwealth environmental and planning legislation, policies, plans and approvals are considered relevant to the project, and are discussed within this section:



### 2.1.1 Environment Protection and Biodiversity Conservation Act 1999

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) provides a legal framework to protect and manage listed Matters of National Environmental Significance (MNES). The EPBC Act is administered by the Commonwealth Department of the Environment (DotE) [formerly the Department of Sustainability, Environment, Water, Population and Communities (DSEWPaC)].

The EPBC Act establishes a process for environmental assessment and approval of proposed actions that have, or are likely to have, a significant impact on MNES. Proponents refer projects to DotE initially for determination on whether a project is a controlled action or not a controlled action. If the referral is deemed to be a Controlled Action, then it is likely to have a significant impact on MNES and must be undertaken in accordance with the project specific tailored guidelines.

Under the EPBC Act, the following MNES are protected:

- World Heritage Properties;
- National Heritage Places;
- Ramsar wetlands of international importance;
- The Great Barrier Reef Marine Park (GBRMP);
- Listed threatened species and communities;
- Migratory species protected under international agreements;
- Nuclear actions (that may have significant impacts on the environment);
- The Commonwealth marine areas; and
- A water resource in relation to coal seam gas development and large coal mining development.

The final category of water resources as an MNES for coal seam gas and large coal mining developments was incorporated in June 2013 when the EPBC Act was amended via the *Environment Protection and Biodiversity Amendment Act 2013* (the Amendment Act). A water resource is the definition applied under the *Water Act 2007* (Commonwealth) and refers to groundwater and surface water, and includes organisms and ecosystems that contribute to the physical state and environmental value of the water resource. Applicable projects require federal assessment and approval under the EPBC Act if they are likely to have a significant impact on a water resource.

Actions that are likely to have a significant impact on a MNES are subject to the assessment and approval process. The EPBC Act Policy Statement *Significant Impact Guidelines 1.1: Matters of National Environmental Significance* (2013) define the criteria used against which an 'action' may be judged as having (or not having) a significant impact. If the project is determined to be a controlled action then approval is required under the EPBC Act.

The project has been referred to DotE and has been declared a controlled action by the DotE that will require assessment and approval under the EPBC Act before it can proceed. The DotE has identified the following controlling provisions within the Act:

- Listed threatened species and communities (sections 18 & 18A);

- A water resource in relation to coal seam gas development and large coal mining development (section 24D); and
- Commonwealth land (sections 26 & 27A).

The GIA has been prepared also to address the EPBC Act policy statement *Significant Impact Guidelines 1.3: Coal Seam Gas and Large Coal Mining Developments-Impacts on Water Resources* (2013) which states that “An action is likely to have a significant impact on a water resource if there is a real or not remote chance or possibility that it will directly or indirectly result in a change to:

- the hydrology of a water resource, and
- the water quality of a water resource,

that is of sufficient scale or intensity as to reduce the current or future utility of the water resource for third party users, including environmental and other public benefit outcomes, or to create a material risk of such reduction in utility occurring.”

Criteria that are to be considered when assessing the significance of an impact in relation to the EPBC Act water trigger are given in Table 2-1, and further elaboration is contained in the guidelines.

**Table 2-1 Considerations for significant impact under the EPBC Act water trigger**

| Criterion | Consideration |
|---|---|
| Value of a water resource | The utility of the water resource for all third party uses, including<br>• provisioning services (e.g. use by other industries and as drinking water)<br>• regulating services (e.g. climate and coastal systems)<br>• cultural services (e.g. recreation, tourism, science and education)<br>• supporting services (e.g. maintenance of ecosystem function) |
| Changes to the hydrological characteristics of a water resource | Changes of sufficient scale or intensity as to significantly reduce the current or future utility of the water resource for third party users, including<br>• changes in water quantity<br>• changes in the integrity of hydrological or hydrogeological connections<br>• changes in the area or extent of a water resource |
| Changes to the water quality of a water resource | Changes resulting in<br>• a compromised ability to achieve relevant local and regional water quality objectives<br>• significant worsening of local water quality<br>• release of high quality water into an ecosystem adapted to a lower quality water |
| Cumulative impacts | Impacts from existing actions and other reasonable foreseeable future actions<br>• not limited to coal seam gas development and large coal mines<br>• not limited to the project area |
| Timing | Variation of an impact over time, including<br>• short term and long term<br>• beyond the life of the action |
| Scale | Spatial extent of an impact, including local, aquifer/catchment and regional scales |

### 2.1.2 Water Act 2007

The *Water Act 2007* (Commonwealth) regulates the management of the water resources of the Murray Darling Basin (MDB), and establishes an independent Murray-Darling Basin Authority (MDBA) with the functions and enforcement powers needed to ensure that MDB water resources are managed in an integrated and sustainable way. A key function of the MDBA includes the preparation of a Basin Plan (outlined in the Section 2.1.3 below).

### 2.1.3 Murray Darling Basin Plan

The Murray Darling Basin Plan (the Basin Plan) is guided by the *Water Act 2007*, which specifies the measures the Basin Plan must contain to guide management of the water resources of the MDB. The objective of the Basin plan is to achieve a healthy working Basin, which will include a healthy environment, strong communities and a productive economy through integrated management of the water resources of the MDB. A key feature of the Basin Plan is the recommendation that the health of the Basin be improved by setting a long-term environmentally sustainable level of water take from its rivers of 10,873 GL/year and a volume of 3,334 GL/y for groundwater.

The key policy responses introduced as part of the Basin Plan include water resource plan areas, water resource plans, and sustainable diversion limits (SDLs).

#### Water Resource Plans

Under the Basin Plan, the Commonwealth and State Governments will cooperate in the development of water resource plans that include the Basin Plan requirements. Water resource plans will set out arrangements to share water for consumptive use. They will also establish rules to meet environmental and water quality objectives that take into account potential and emerging risks to water resources.

Under the Basin Plan, water resource plans, while not proposed to directly regulate land use planning or the management of other natural resources will likely require a range of management and monitoring requirements on the use of water resources that have the potential to impact on surface water and groundwater in a water resource plan area. The development and implementation of individual water resource plans under the *Water Act 2007* will not alter the need for Santos to meet relevant state water approvals, licensing and management requirements.

The Basin Plan puts forward the new limits on water that can be taken from the MDB, known as long-term average SDLs and transitional arrangements to support their implementation. The SDLs refer to the amount of water available for consumptive purposes (drinking water, industry, irrigation, agriculture, etc.) after environmental needs have been met. This is described in the *Water Act 2007* as the 'environmentally sustainable level of take'.

#### Sustainable Diversion Limits for Surface Water

The Project is located within the Namoi catchment, which represents approximately 3.8 % of the total MDB. Current average water availability is 965 GL/year and 37 % of this water is consumed through surface water diversions (260 GL/year) and stream flow losses induced by groundwater use (99 GL/year). In the Namoi catchment, the proposed reduction in current surface water diversions under the SDL proposal is 72 GL/year to 94 GL/year (the current diversion limit is 508 GL/year).

#### Sustainable Diversion Limits for Groundwater

There are a number of regions where proposed groundwater SDLs require reductions from current diversion limits (Murray-Darling Basin Authority 2012). The Namoi region has the highest level of groundwater development in NSW and one of the highest levels of groundwater extraction in the MDB. Groundwater use in the region is 15.2 % of the MDB total. Four groundwater-related SDLs exist and are listed in Table 2-2, along with the proposed reduction in current diversion limit within the Namoi alluvium.

The proposed SDLs mean that allocations for surface and groundwater consumptive purposes will be lower than the current extraction limits in the Namoi region, and existing surface water and groundwater extractors may face shortfalls in their water availabilities.

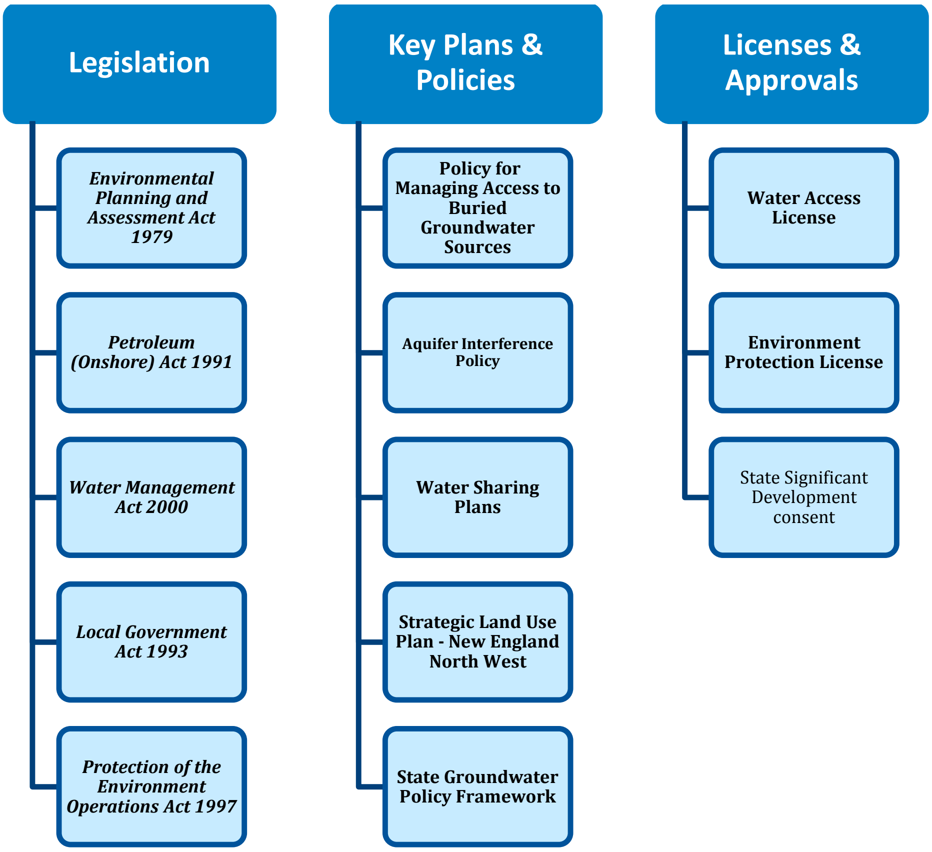
**Table 2-2 Proposed groundwater SDL reductions**

| Region | SDL Area | [1,2]Current SDL (GL/year) | [2]Proposed Reduction in Current SDL [%] | [2]Proposed Reduction in Current SDL [GL/y] |
|---|---|---|---|---|
| Namoi | Lower Namoi Alluvium | 88.3 | 12.8 | 11.3 |
| Namoi | Upper Namoi Alluvium | 123.4 | 22.2 | 27.4 |
| NSW GAB | Surat Shallow* | 15.5 | - | - |
| Eastern Porous Rock | Gunnedah-Oxley Basin MDB | 114.5 | - | - |

Sources: [1]Murray Darling Basin Plan 2012 (Schedule 4); [2]Murray-Darling Basin Authority (2012, Appendix C)
*The *Water Act 2007* excludes groundwater of the GAB from the definition of MDB resources - Murray Darling Basin Plan 2012 (Schedule 1, Item 9)

## 2.2 State

The following key NSW environmental and planning legislation, policies and plans are considered relevant to the project and are discussed within this section:



### 2.2.1 Environmental Planning and Assessment Act 1979

The main purpose of the *Environmental Planning and Assessment Act 1979* is the proper management, development and conservation of natural and artificial resources for the purpose of promoting the social and economic welfare of the community and a better environment. Under this Act development consent is required for coal seam gas projects. Approval under this Act requires an assessment of environmental impacts and the applicant must produce an Environmental Impact Statement. Section 79C outlines the matters that must be considered when granting development consent, including environmental impacts on groundwater.

### 2.2.2 The Petroleum (Onshore) Act 1991

The *Petroleum (Onshore) Act 1991* applies only to onshore exploration and production of oil and gas. It addresses issues relating to environmental protection and compensation, creates exploration and production titles, and allows for the following approvals to be granted:

- Exploration licences;
- Assessment leases;
- Production leases; and
- Special prospecting authorities.

### 2.2.3 Water Management Act 2000

The *Water Management Act 2000* (NSW) dictates how both surface and groundwater resources are managed in NSW. Its main objective is to ensure the future and present supply of water sources at a state level, and protect, develop and restore water resources in the region. It controls the extraction of water, how water can be used, the construction of works such as dams and weirs and the carrying out of activities on or near water sources.

The primary mechanism the Act provides for in managing the State's water resources are Water Sharing Plans (WSP). The *Water Management Act 2000* will generally apply to surface and groundwater sources in areas where a WSP is in place (as outlined in Section 2.2.4 below). In areas where there is no WSP the *Water Act 1912* (NSW) applies. A number of WSPs apply to the [1].GIA study area An amendment to the *Water Management Act 2000* requires new mining and petroleum exploration activities that take more than three megalitres per year (ML/y) from groundwater sources to hold a water access licence.

An approval is required under the Act where any aquifer interference activity (discussed further in Section 2.2.5.1) causes:

- The removal of water from a water source; or
- The movement of water from one part of an aquifer to another part of an aquifer; or
- The movement of water from one water source to another water source, such as:
    - From an aquifer to an adjacent aquifer; or

[1] Defined by the extent of the Gunnedah Basin Regional Model (GBRM) described in 6

- From an aquifer to a river/lake; or
- From a river/lake to an aquifer.

### 2.2.4 Water Sharing Plans

Water Sharing Plans (WSPs) are statutory documents currently used to manage water resources in NSW. They establish the rules for sharing water between different water users (including the environment) and between different types of users. WSPs also set rules for water trading and dealing with access licences and access regimes for the extraction of water from groundwater and surface water systems. WSPs set out the overall limit on surface and ground water that can be extracted from the source and the circumstances in which access licences can be granted. WSPs relevant to the GIA study area are outlined below.

Figure 2-1 shows the relationships between stratigraphic units, WSPs and defined water sources within the project area, which are depicted in a schematic cross section through the Bohena Trough (Gunnedah Basin) and the on-lapping portion of the GAB and the Namoi alluvium.

#### NSW Great Artesian Basin Groundwater Sources 2008

The *Great Artesian Basin WSP* covers all water contained in all rocks of Cretaceous and Jurassic Age at a depth of more than 60 metres below ground level within the NSW portion of the Great Artesian Basin (GAB). The basin has been divided into five groundwater sources: the Eastern and Southern Recharge Groundwater Sources in the non-artesian eastern fringes of the basin, and the Surat, Warrego and Central Groundwater Sources in the artesian western part of the basin.

This Project is within the Southern Recharge Groundwater Source of the GAB; however, the Permian strata that underlie the GAB, and from which the coal seam gas extraction is targeted are excluded from the application of this WSP. Nonetheless, the project has the potential to affect the groundwater resources addressed under this WSP in two ways, which have been assessed in this GIA:

- Induced vertical leakage of groundwater from the overlying GAB formations due to vertical propagation of depressurisation effects from the Permian coal measures; and
- Inter-aquifer leakage via wells and bores completed through the GAB formations into the underlying Permo-Triassic formations due to improper construction techniques.

#### NSW Murray-Darling Basin Porous Rock Groundwater 2011

The *Porous Rock Groundwater WSP* covers porous rock water bearing strata within the MDB not already included in other WSPs. In particular, this WSP establishes the framework for licensing and allocation of groundwater resources within the Gunnedah-Oxley Basin porous rock formations, and sets limits on the long-term abstraction rates. Coal seams within the Gunnedah-Oxley Basin contain the primary water sources that would be targeted by the project.

#### NSW Murray-Darling Basin Fractured Rock Groundwater 2011

The *Fractured Rock Groundwater WSP* has designated water management areas in the fractured rock groundwater sources of the MDB. These cover basalts and fold belts that have groundwater flow due to the fractures within the rock. Three water sources within this WSP fall within the Namoi catchment, which is at or beyond the limits of the model domain surrounding the project area. These water sources are associated with the fractured rocks of the Lachlan Fold Belt (buried groundwater source) and the Liverpool Ranges Basalt and Warrumbungle Basalt (outcropped groundwater sources).

### NSW Upper and Lower Namoi Groundwater Sources 2003

The upper and lower Namoi WSP covers the upper and lower Namoi Groundwater Sources including all water contained in the unconsolidated alluvial groundwater sources associated with the Namoi River and its tributaries. These strata are present at surface within the GIA study area, generally towards the north and east of the project area. The current WSP aims to reduce the Available Water Determinations (AWD) for supplementary water access licences as well as reducing the extraction limit. This is in response to the observed decline in groundwater levels in the Upper and Lower Namoi alluvium.

### NSW Great Artesian Basin Shallow Groundwater Sources 2011

The *Great Artesian Basin Shallow* WSP covers groundwater resources associated with the alluvial formations and all other formations to a maximum depth of 60 m below the surface of the ground which overlie the NSW GAB formations and are not included in any other WSP (within the boundaries of the NSW Upper and Lower Namoi Groundwater Sources 2003 WSP). Of the sources identified, the GAB Surat Shallow Groundwater Source extends across the north-western quarter of the GIA study area. This WSP allows for granting of water access licences as part of a controlled allocation order made in relation to unassigned water in this water source.

### Upper Namoi and Lower Namoi Regulated River Water Sources 2016

The Namoi and lower Namoi Regulated River WSP applies to two water sources – the Upper Namoi including the regulated river sections between Split Rock Dam and Keepit Dam and the Lower Namoi including the regulated river sections downstream of Keepit Dam to the Barwon River, including the regulated sections of the Gunidgera/ Pian system. While not directly relevant to the project, this WSP would only apply if coal seam gas extraction or coal seam water management activities were found to have an impact on these surface water sources.

### Namoi Unregulated and Alluvial Water Sources 2012

The *Namoi Unregulated and Alluvial Water Sources WSP* 2012 comprises 23 unregulated water sources upstream and downstream of Keepit Dam, as well as four alluvial groundwater sources to the east of the Namoi River catchment outside of the GIA study area. This WSP regulates access to all unregulated surface waters.

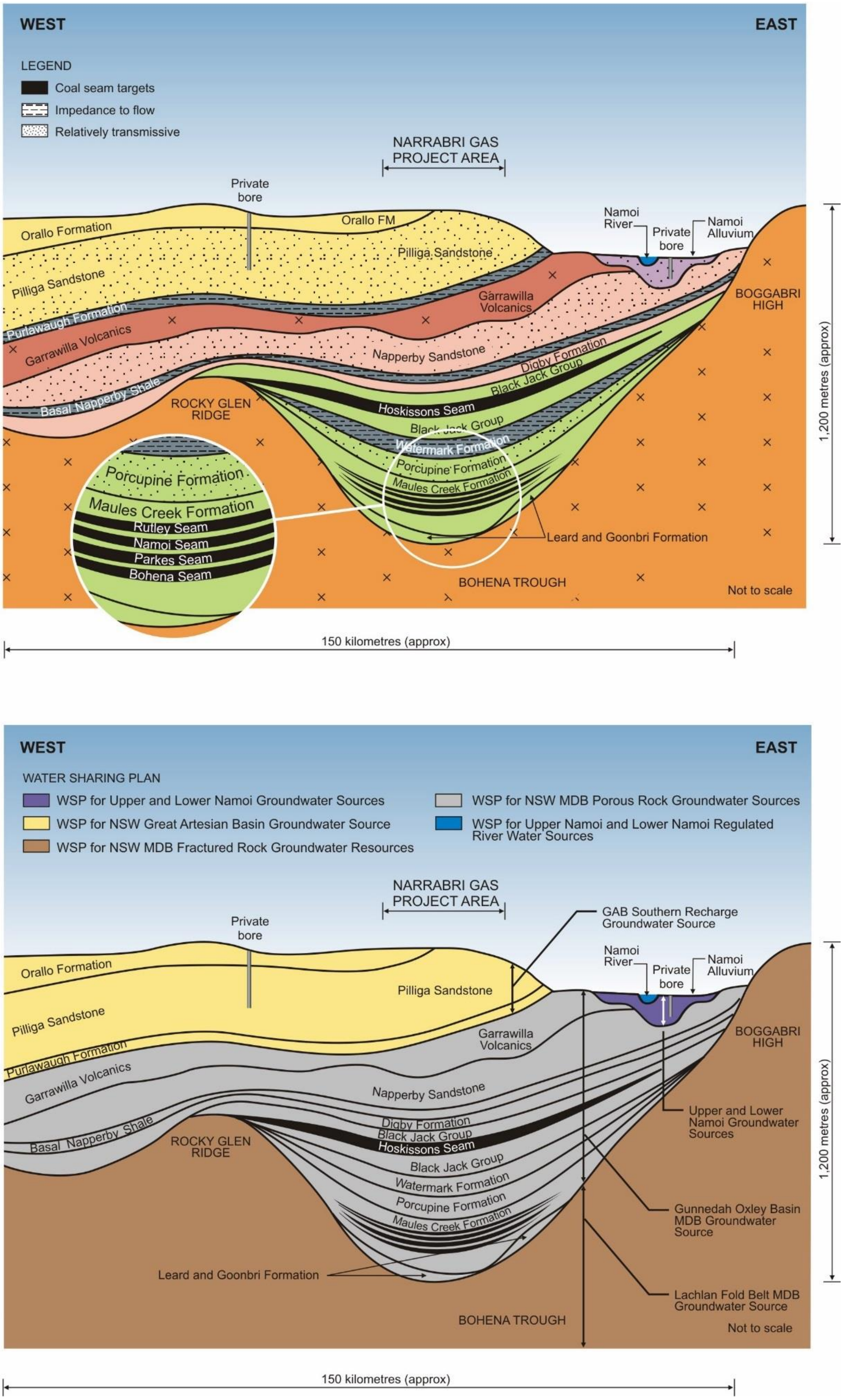



**Figure 2-1 Project area schematic showing lithology and WSPs**

### 2.2.5 NSW Strategic Regional Land Use Policy

The *NSW Strategic Regional Land Use Policy* was introduced in 2012 with the aim of managing potential conflicts between activities including coal seam gas and high quality agricultural land. The Policy has introduced a range of measures which affect coal seam gas projects including:

- The Gateway Process - This process introduces an additional level of assessment for coal seam gas proposals on biophysical strategic agricultural land (BSAL). The process necessitates a scientific assessment of the impacts of mining and coal seam gas production proposals on BSAL and its associated water resources. This includes a comprehensive assessment of potential aquifer impacts from the Minister for Primary Industries and the Commonwealth Independent Expert Scientific Committee; and

- Coal Seam Gas Exclusion Zones: Exclusion zones have been provided around existing residential areas in all Local Government areas of the State.

A number of additional statutory documents have been introduced to support the *NSW Strategic Regional Land Use Policy*. Those documents of particular relevance to groundwater are the:

- NSW Aquifer Interference Policy; and

- New England North West Strategic Regional Land Use Plan.

#### 2.2.5.1 NSW Aquifer Interference Policy

The purpose of the NSW Aquifer Interference Policy is to explain the water licensing and approval processes and requirements for aquifer interference activities under the *Water Management Act 2000*, and other relevant legislative frameworks. The Policy has been developed to ensure equitable water sharing between various water users and proper licensing of water taken by aquifer interference activities such that the take is accounted for in the water budget and water sharing arrangements.

The Policy adopts the definition of an aquifer interference activity from the *Water Management Act 2000*, which includes any of the following:

- The penetration of an aquifer;

- The interference with water in an aquifer;

- The obstruction of the flow of water in an aquifer;

- The taking of water from an aquifer in the course of carrying out mining, or any other activity prescribed by the regulations; and

- The disposal of water taken from an aquifer (for example, as a consequence of mining or coal seam gas activities).

The Policy specifies that the volume of water taken from a water source(s) as a result of an activity needs to be predicted prior to project approval and that project approval will not be granted unless the Minister is satisfied that adequate arrangements are in force to ensure that no more than minimal harm will be done to a groundwater source or its dependent ecosystems. Minimal impact considerations defined in the Policy for highly productive and less productive groundwater sources are listed in Table 2-3.

As parts of the project will be classified as aquifer interference activities, consideration will be given to the Aquifer Interference Policy.

**Table 2-3 Minimal impact considerations of the Aquifer Interference Activities**

| Alluvial Water Sources | Porous and Fractured Rock Water Sources |
|---|---|
| Less than 10% cumulative variation in the water table relative to "post-water sharing plan" variation 40 m from any:<br>(a) high priority groundwater dependent ecosystem; or<br>(b) high priority culturally significant site;<br>listed in the schedule of the relevant water sharing plan; or<br>Less than 25% cumulative variation in the water table relative to "post-water sharing plan" variation 40 m from any:<br>(a) high priority groundwater dependent ecosystem; or<br>(b) high priority culturally significant site;<br>listed in the schedule of the relevant water sharing plan if appropriate studies demonstrate to the Office of Water's satisfaction that the activity will not prevent the long-term viability of the dependent ecosystem or significant site.<br>A maximum of 2 m cumulatively at any water supply work unless make good provisions apply. | Less than 10% cumulative variation in the water table relative to "post-water sharing plan" variation 40m from any:<br>(a) high priority groundwater dependent ecosystem; or<br>(b) high priority culturally significant site;<br>listed in the schedule of the relevant water sharing plan; or<br>Less than 25% cumulative variation in the water table relative to "post-water sharing plan" variation 40m from any:<br>(a) high priority groundwater dependent ecosystem; or<br>(b) high priority culturally significant site;<br>listed in the schedule of the relevant water sharing plan if appropriate studies demonstrate to the Office of Water's satisfaction that the activity will not prevent the long-term viability of the dependent ecosystem or significant site.<br>A maximum of 2 m cumulatively at any water supply work unless make good provisions apply. |
| A cumulative pressure head decline of not more than 40% of the "post-water sharing plan" pressure head above the base of the water source to a maximum of 2 m, at any water supply work unless make good provisions apply. | A cumulative pressure head decline of not more than 2m, at any water supply work unless make good provisions apply. |
| Any change in the groundwater quality must not lower the beneficial use category of the groundwater source beyond 40 m from the activity.<br>No increase of more than 1% per activity in long-term average salinity in a highly connected surface water source at the nearest point to the activity.<br>Redesign of a highly connected surface water source that is defined as a "reliable water supply" is not an appropriate mitigation measure to meet the above criteria.<br>No mining activity to be within 150 m laterally from the top of high bank or 100 m vertically beneath (or the three dimensional extent of the alluvial material - whichever is the lesser distance) of a highly connected surface water source that is defined as a "reliable water supply". | Any change in the groundwater quality must not lower the beneficial use category of the groundwater source beyond 40 m from the activity. |

### 2.2.5.2 Strategic Regional Land Use Plan – New England North West

The *New England North West Strategic Regional Land Use Plan (2012)* covers part of the project area. The purpose of the plan is to provide a framework to support growth, protect the environment and respond to competing land uses, whilst preserving key regional values over the next 25 years.

The Plan introduces a gateway assessment process for resolving potential land use conflict between coal seam gas activities, including coal seam water management, and existing agricultural land. Under the gateway process, a panel of independent experts assesses coal seam gas development proposals on or within 2 km of strategic agricultural land against criteria covering issues, such as soil and groundwater source impacts, impacts on critical industry clusters, and the overall public benefit of the proposal. If a proposal does not pass the gateway, it cannot proceed to the development application stage.

An Agricultural Impact Statement is required for all state significant mining and coal seam gas development applications that may impact agricultural resources and all exploration activity requiring approval under Part 5 of the *Environmental Planning and Assessment Act 1979*.

### 2.2.6 NSW Groundwater Policy Framework 1997

The main role of the Groundwater Policy Framework is to ensure that the groundwater resources of the state are appropriately maintained and to ensure that sustainability of groundwater resources and their ecosystem support function are given explicit consideration in resource management decision making. The Groundwater Policy Framework has been constructed with the aid of two NSW policies:

- NSW Groundwater Quality Protection Policy 1998 – provides guidance on how to manage and protect groundwater quality against pollution; and
- NSW State Groundwater Dependent Ecosystems Policy 2002 – provides guidance on how to protect ecosystems which rely on groundwater and where possible the ecological processes and biodiversity of these dependent ecosystems.

### 2.2.7 NSW Policy for Managing Access to Buried Groundwater Sources

The Policy for Managing Access to Buried Groundwater Sources sets out a framework for how access to water will be managed in groundwater sources that are partly or fully buried. It outlines the limits to access water from storage in porous rock groundwater sources and also the licensing and approval requirements for the take of water from all contributing water sources.

Although not clearly stated, this Policy appears to provide a general and strategic document for access to groundwater, whilst specific water sharing details are contained within the WSPs discussed above.

## 2.3 Legislative Requirements Summary

Groundwater development as a resource or as incidental water requires a licence or an authorisation from DPI Water (formerly NSW Office of Water). Table 2-4 summarises the legislative requirements relevant to groundwater management within the GIA study area.

**Table 2-4 Legislative requirements relating to groundwater**

| Legislation | Driver | Requirements for the Project |
|---|---|---|
| Murray Darling Basin Plan under the *Water Act 2007* (Commonwealth) | The Basin Plan will establish limits on the quantities of surface water and groundwater that can be accessed from "Basin water resources" in each sustainable diversion limit (SDL) area (see section 2.1.3. | Portions of the Upper and Lower Namoi alluvium and Gunnedah-Oxley Basin are considered to be MDB water resources.<br>Santos may be required to demonstrate that the project development will not result in, or significantly increase the rate of, inter-aquifer transfer from the Namoi alluvial groundwater sources to the underlying Gunnedah-Oxley Basin. |

| Legislation | Driver | Requirements for the Project |
|---|---|---|
| WSPs for the NSW Great Artesian Basin Groundwater Sources 2008, and NSW Great Artesian Basin Shallow Groundwater Sources 2011 under the *Water Management Act 2000* | Incorporates the principles of the State Groundwater Policy. The WSP Policy is a framework designed to establish objectives and principles for groundwater management. | Portions of the Pilliga Sandstone in the GIA study area are considered to be part of the GAB water resource.<br>Santos may be required to demonstrate the project development will not result in, or significantly increase the rate of, inter-aquifer transfer from the Pilliga Sandstone groundwater source to the underlying strata. |
| WSP for the Upper and Lower Namoi Groundwater Sources 2003 under the *Water Management Act 2000* | The vision for this Plan is ecologically sustainable groundwater sources that provide an assured supply of quality groundwater for the social and economic benefit of the people in the Namoi Valley. | Portions of the Upper and Lower Namoi are present at the surface in the GIA study area.<br>Santos may be required to demonstrate that the project development will not result in, or significantly increase the rate of, inter-aquifer transfer from the Upper and Lower Namoi groundwater sources to the underlying strata. |
| WSP for the NSW Murray-Darling Basin Fractured Rock Groundwater Sources 2011 under the *Water Management Act 2000* | Provide for healthy and enhanced water dependent ecosystems and equitable water sharing among users. | Santos may be required to demonstrate that the Narrabri Gas Project development will not result in, or significantly increase the rate of, inter-aquifer transfer from fractured rocks within the region of the GIA study area. |
| WSP for the NSW Murray-Darling Basin Porous Rock Groundwater Sources 2011 under the *Water Management Act 2000* | Provide for healthy and enhanced water dependent ecosystems and equitable water sharing among users. | Santos will be required to apply for a water access license to cover the anticipated groundwater extraction volumes during coal seam gas production, or to purchase existing water access licenses and annual entitlements if there is insufficient unassigned water available. |
| NSW Aquifer Interference Policy and Regulation | This Policy defines aquifer interference and identifies considerations to be addressed in assessing potential impacts of the proposed activities to key water-dependent assets. | Santos will be required to demonstrate whether the proposed project activities will result in exceedance of the minimal impact considerations and that sufficient mitigation and management measures will be adopted where impacts are identified.<br>Santos will be required to consider potential aquifer interference resulting from drilling, appraisal, and extraction activities carried out in the coal seam gas field. |
| *Water Management Act 2000* | A water licence is required to take water. Where applicable, there may be a requirement to carry out groundwater monitoring and reporting on the results of the monitoring program. | Santos will be required to obtain a water access licence for the abstraction of coal seam water, allocated according to the relevant WSP(s) |

# 3 Groundwater Impact Assessment Methodology

Data and literature related to the environmental, geological, hydrological and hydrogeological conditions of the GIA study area have been collated from a number of sources and analysed to assist in the development of the GIA. Most recently, exctensive contextual information for the region has been complied and published as part of the context statement for the Namoi subregion bioregional assessment (Welsh et al. 2014).

The potential impacts associated with depressurisation caused by extraction of water from the target coal seams are assessed directly in this study through numerical modelling.

The GIA also considers potential impacts on aquifers that are associated with induced flows of groundwater and hydrocarbons via pathways within geological faulting and via compromised well integrity. These inclusions in the GIA rely on supporting studies commissioned by Santos for the project EIS.

## 3.1 Data Collation and Review

Data used in this assessment are summarised in Table 3-1 and include:

- Geological core hole and bore data;
- Water type curves reflecting reservoir characteristics;
- Drill stem test (DST) measurements;
- Geophysical surveys;
- Geological and topographical mapping, including stratigraphic surfaces;
- Local and regional bore records, including groundwater levels and groundwater quality;
- Other field data or reports in the vicinity of the project and surrounds; and
- Other supporting studies undertaken for the project, as listed in Table 1-3 (Section 1.6.1).

**Table 3-1 Available data sources**

| Data | Source | Comment |
|---|---|---|
| Geological Core hole and Bore Data Records | Santos | Bore completion details and geophysical logs (not interpreted) |
| | Santos | Stratigraphic bore logs (interpreted) |
| | Santos | Production bore drilling, geophysical and strata logs (interpreted) |
| | Santos | Depth and thickness of relevant coal seams |
| | [1]NOW & NSW - DPI | Water bore and basic groundwater information, and geological logs |
| Water type curves | Santos | Water type curves have been developed based on performance of the current and historic pilot well activity and reflect a range of reservoir characteristics in the production of water from the coal seam. Water type curves are the primary data source of induced output fluxes (simulations) in the groundwater model |
| Geophysical surveys | Santos | Interpreted geological cross-sections with geophysical logs |
| Geological Mapping | Santos | Mapped isopach for relevant coal seams. Some depth to strata data. |
| | Santos | Generalised geological column for Gunnedah Basin |

| Data | Source | Comment |
|---|---|---|
| | NSW - DPI | Coalfield Map: NSW Government DPI, Gunnedah Coalfield (North) Regional Geology (Scale: 1:100,000) (Edition 1, 1998) |
| | NSW - DPI | Geological map: Mapsheet ID: SH5512; NARRABRI (edition 1st ed. 1971); |
| | SRK | Gunnedah Bowen Study SEEBASE |
| | NSW - DPI | DIGS Database |
| Topographical | Santos | Topographical map files for Narrabri area |
| | CGIAR CSI | SRTM 500 m |
| Study Area | Santos | Proposed study area map |
| Local and Regional Bore Information | [1]DPI Water | NSW State groundwater bores in ESRI shapefile format |
| | Santos | Santos bore audit giving location, elevation and coal seam gas bore use/status |
| | Santos | Exploration core hole and petroleum bore groundwater quality |
| | Santos | Exploration core hole and petroleum bore groundwater levels |
| Hydrogeological Testing | Santos | Santos bore density and porosity results |
| | Santos | Santos bore drill stem test (DST) results |
| Groundwater quality | Santos | Coal seam gas and petroleum groundwater analysis: anion/ cation analysis |
| | NOW | Groundwater quality monitoring |
| Regional Information | Various | Namoi Catchment Water Study (SWS 2010) |
| | | Narrabri Coal Mine Stage 2 Longwall Project Hydrogeological Assessment (Aquaterra 2009) |
| | CSIRO | Water Availability in the Namoi –Murray-Darling Basin Sustainable Yields Report Project (CSIRO 2007a) |
| Climatic Conditions | BoM | Temperature, rainfall and evaporation - weather station data |

[1]DPI Water was formerly the NSW Office of Water (NOW)

### 3.1.1 Geology and Stratigraphy

Geological and stratigraphical data within the GIA study area have been sourced primarily from geological and geophysical logging undertaken by Santos to assess the coal seam gas resource in the Narrabri area. Further regional information has been sourced from published reports and datasets, which mainly focus on the shallow alluvial groundwater system associated with the Namoi River and the GAB.

The majority of geological data held by Santos pertain to the deeper strata of the Gunnedah Basin within the project area. These data are supplemented with published data or anecdotal information where available.

### 3.1.2 Groundwater Levels

Data on water table elevation and hydraulic head within the GIA study area have been acquired from the DPI Water's (formerly NOW) PINNEENA database, and through the project Water Baseline Report.

Other sources of groundwater information include:

- Santos core holes and appraisal bores – Santos monitors groundwater levels across the project area in core holes and pilot production bores;
- Namoi Catchment Water Study, Phase One to Four (SWS 2010, 2011, 2012a, 2012b);
- Water Availability in the Namoi – A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project (CSIRO 2007a); and

- Narrabri Coal Mine Stage 2 Longwall Project – Hydrogeological Assessment (Aquaterra 2009).

### 3.1.3 Surface Water Flow

The project Water Baseline Report includes review of DPI Water's stream flow data for Namoi River and Bohena Creek. Flow duration curves have been prepared for five flow gauges along the Namoi River between Boggabri and Mollee Weir (approximately 10 km downstream of Narrabri) and one flow gauge on Bohena Creek at Newell Highway.

### 3.1.4 Groundwater Quality

Data on groundwater quality within the GIA study area are available from DPI Water's (formerly NOW) PINNEENA database, and specific water quality data collected for the project are described in the project Water Baseline Report.

Groundwater investigations for the Water Baseline Report include sampling and chemical analysis of groundwater in the shallow alluvial sources, GAB aquifers and Gunnedah Basin strata. Chemical analyses of most groundwater samples have included electrical conductivity (EC), pH, total dissolved solids (TDS), temperature, and major and minor ions. Other analytes of interest for the GAB and Gunnedah Basin groundwater samples have included organic compounds, nutrients and dissolved methane.

### 3.1.5 Surface Water Quality

Santos is currently undertaking a programme of surface water sampling within the Namoi Catchment, comprising surface water sampling analysis within the project area. The purpose of the water quality programme is to characterise the baseline water quality within the Namoi catchment and to identify locations for on-going monitoring to assess potential impacts of the proposed coal seam gas activities on the surface water systems in the GIA study area. Surface water sampling locations have been selected within the Narrabri region, with up to nine monitoring events undertaken at each site to date.

## 3.2 Development of the Hydrogeological Conceptual Model

A hydrogeological conceptual model has been developed to encapsulate the current understanding of the groundwater systems of the GIA study area. The conceptual model is a simplified representation of the key features of the groundwater systems that has been built based on the interpretation of available data and information. The conceptual model forms the basis for establishing the environmental values of groundwater and provides the framework for assessing and managing potential groundwater related impacts due to the project. An important part of the conceptualisation is the consideration of past, present and future states of groundwater within the context of the proposed coal seam gas development.

## 3.3 Groundwater Modelling and Prediction of Potential Impacts

A regional-scale numerical groundwater flow model of the Gunnedah Basin has been developed for the GIA based on the hydrogeological conceptual model described above. The groundwater model is used to predict the potential impacts on groundwater sources within the GIA study area due to water extraction from the coal seams that will be targeted for coal seam gas production. Simulations of water extraction from the coal seams provide regional-scale predictions of depressurisation and drawdown of hydraulic head within the Gunnedah Basin and the associated induced flows between groundwater sources and hydrostratigraphic units.

# 4 Regional Context

Regional contextual information contained in this section of the report is tailored toward understanding the groundwater and connected surface water systems of the region within the context of the GIA. More detailed descriptions of the regional environment can be found in the publications referenced throughout this section.

Most recently, and post-dating earlier drafts of the GIA, water-related information for the region has been compiled and published for the context statement for the Namoi subregion bioregional assessment (Welsh et al. 2014; see Section 1.6.2). Although the study areas for the Namoi subregion and this GIA differ in their geographic extents, the NGP area is fully encompassed by both study areas. Thus, the context statement for the Namoi subregion bioregional assessment contains similar information to contextual information in the GIA (based on similar or same information sources) which may vary in detail due to the geographical extent being considered, and the methods applied to interpret and present these information sources.

The context statement for the Namoi subregon is identified as valuable information for the NGP that compliments the assessment in this GIA. In general, no attempt has been made to reproduce synthesis in the context statement for the Namoi subregion, beyond acknowledging the value of this information, providing references to the context statement where relevant, and checking for consistency between the studies.

## 4.1 Topography and Drainage

The Project located within the Namoi catchment which represents approximately 3.8% of the total Murray-Darling Basin (MDB). The Namoi catchment is bounded to the east by the Great Dividing Range, to the north by the Gwydir catchment, to the south by the Castlereagh, Macquarie and Hunter catchments and to the west by the Barwon-Darling catchment, as shown in Figure 4-1.

The Project area is predominately within the Lower Namoi sub-catchment on gentle north-northwest facing valley slopes. The flat open floodplain of the Namoi River is situated to the north and west of the project, with steep to undulating, mostly vegetated land to the east and south. The Warrumbungle Ranges occur approximately 112 km to the south and the Mount Kaputar National Park occurs approximately 50 km to the northeast. Elevations within the project area range from approximately 400 m Australian Height Datum (AHD) in the southeast down to approximately 250 mAHD in the northwest.

The Lower Namoi sub-catchment commences at Narrabri which is considered to be the start of the true riverine zone of the Namoi catchment due to the increased frequency of lagoons, the low gradient of the channel and the development of several anabranches and effluent channels (NSW Office of Water 2011). The lower Namoi is regulated by two major weirs downstream of Narrabri – Mollee Weir and Gunidgera Weir.

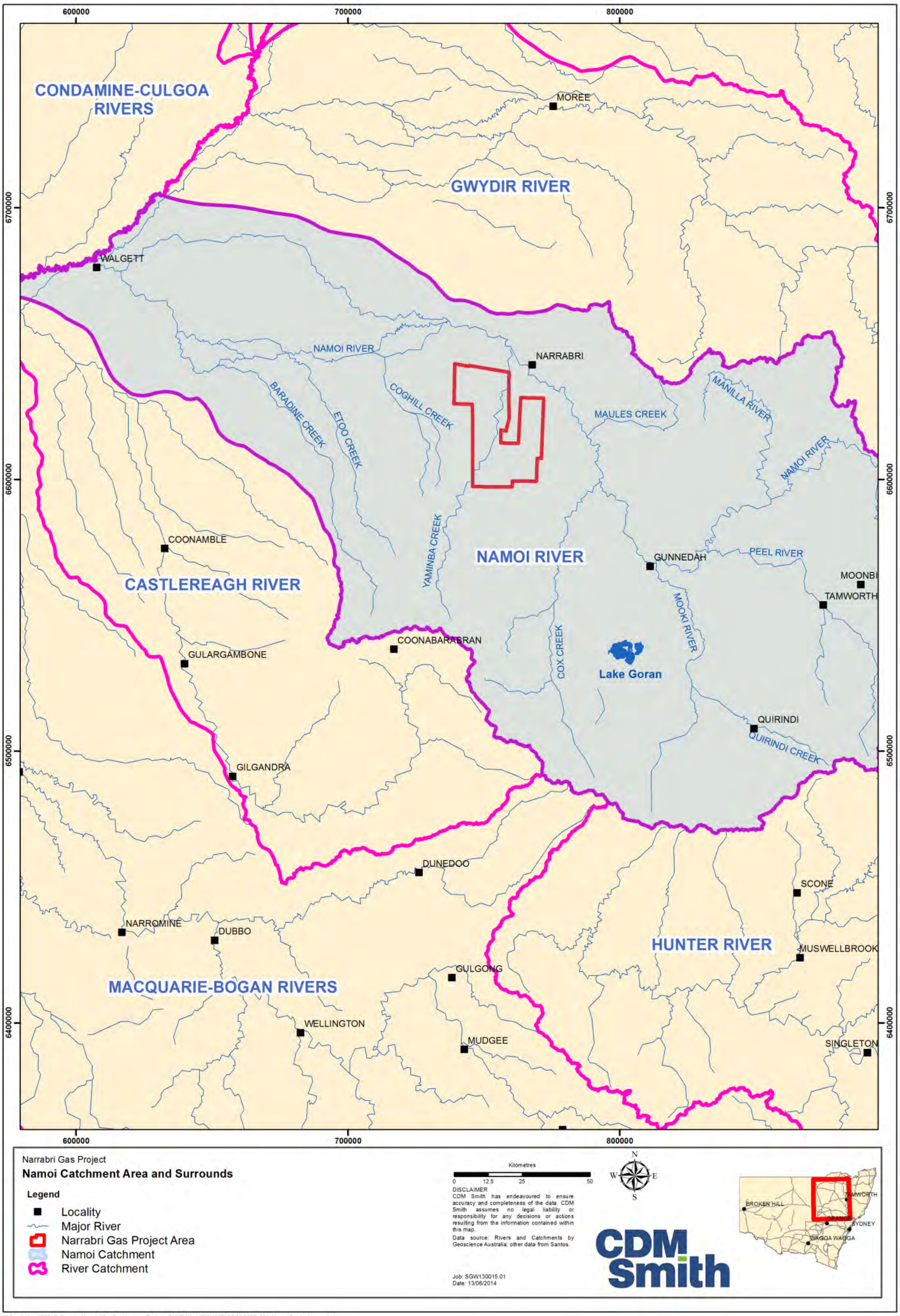



**Figure 4-1 Namoi catchment area and surrounds**

## 4.2 Land Use

The central and southern portion of the project area is predominantly woodland vegetation associated with the Pilliga East, Pilliga West and Bibblewindi State Forests. This area of forest is classified as *Eucalyptus Crebra* dry open forest. In the northwest of the project area the dominant land use is dryland agriculture and plantations.

Outside od State forest, there is a range of land uses within the GIA study area. Data from Australian Land Use and Management (ALUM) Classification (ABARES 2011) was utilised to assess the current land uses within the Namoi Catchment shown in Figure 4-2 and summarised in Table 4-1. The context statement for the Namoi subregion bioregional assessment (Welsh et al. 2014) considers ABARES land use data for 2012, and contains additional more general information on the human geography of the region, including population statistics.

**Table 4-1 Land use in the Namoi catchment**

| Namoi Catchment Land Use | Area [$km^2$] | Proportion of Namoi Catchment [%] |
|---|---|---|
| Grazing | 4,287 | 32.6 |
| Dryland cropping and horticulture | 1,901 | 14.4 |
| Forestry | 1,881 | 14.3 |
| Native landscapes | 1,858 | 14.1 |
| Conservation | 1,953 | 14.8 |
| Irrigation | 811 | 6.2 |
| Residential | 282 | 2.1 |
| Industrial | 22 | 0.2 |
| Lakes, rivers, dams | 148 | 1.1 |
| Wetland | 10 | <0.1 |
| Mining | 8 | <0.1 |
| Total | 13,161 | 100 |

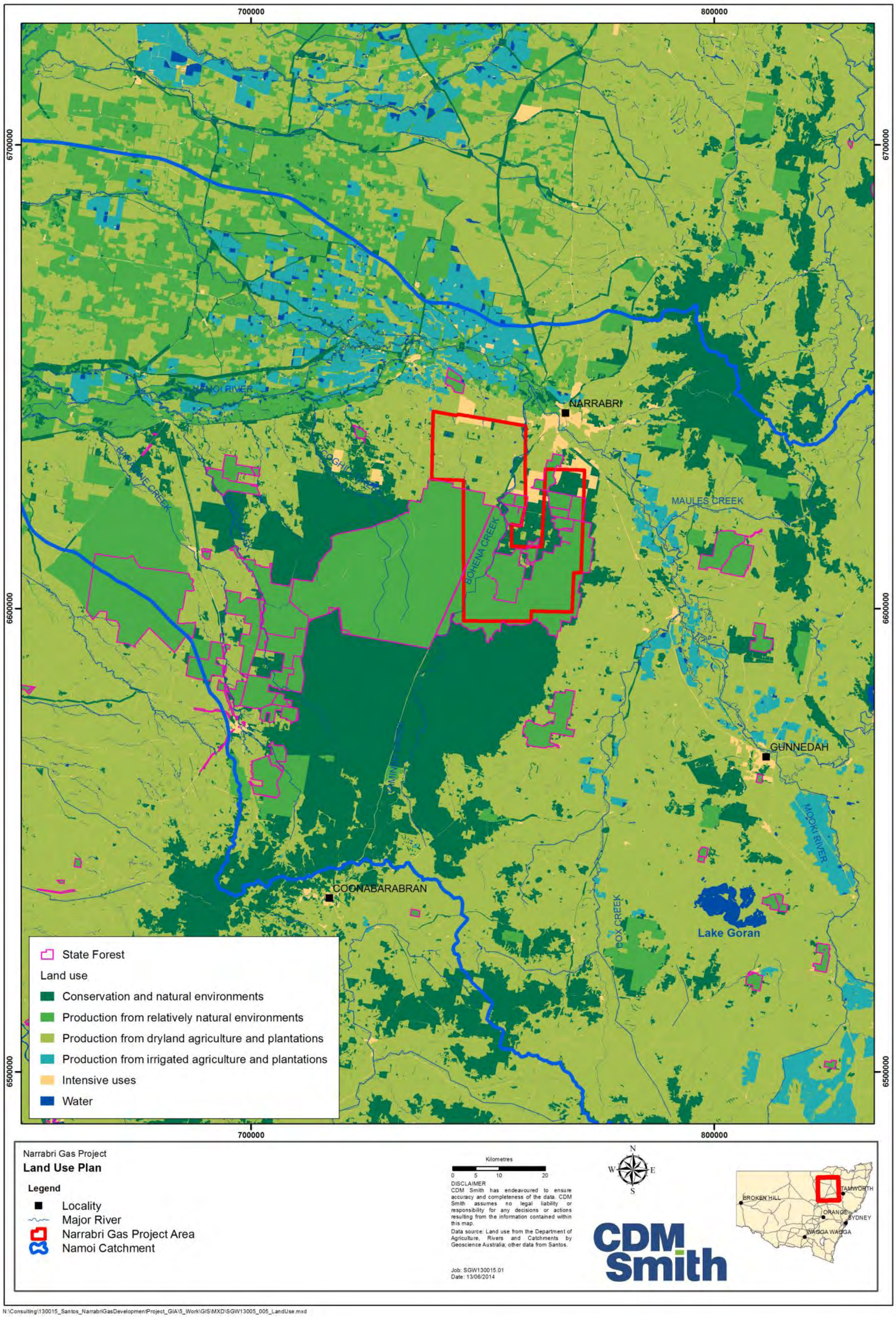



**Figure 4-2 Regional land use**

## 4.3 Climate

The climate of the region is generally described as cool to temperate, with hot summers and cool winters. Welsh et al. (2014) identified three key climate groupings across the region, varying from Temperate in eastern parts, Subtropical centrally within the region, and Grassland in western parts. Climatic statistics for the Narrabri Bowling Club (Bureau of Meteorology (BoM) site No. 054120) and Tamworth Airport (BoM site No. 055054) can be seen in Table 4-2 and are illustrated graphically in Figure 4-3.

The average daily maximum temperature at the Narrabri Bowling Club ranges from 35.3°C in January to 17.0°C in July. Potential evaporation (PE) at Tamworth Airport reflects the seasonal variation of temperatures, with the largest mean potential evaporation experienced during winter months from November to March, and smallest mean potential evaporation experienced during June and July. Annual average potential evaporation at Tamworth Airport is approximately 1,971 mm (5.4 mm/d).

While the mean annual rainfall at Narrabri Bowling Club is 646 mm/y, there is considerable variation across the region. Figure 4-4 shows that the distribution of annual rainfall across the the Namoi catchment varies from a maximum of around 1300 mm/y in the eastern Barwon Highlands to around 400 mm/y in the western-most part of the region. Rainfall is generally higher during the summer, with the highest average monthly falls occurring between December and February. The region's average annual rainfall has remained relatively consistent over the past 50 years and at a level slightly higher than the preceding 50 years (CSIRO 2007a).

The distribution of potential evapotranspiration across the region is shown in Figure 4-5 and varies from a maximum of around 700 mm/y in the eastern highland areas to a minimum of around 450 mm/y in the western-most margin of the region. Thus, there is a broad tendency for rainfall excess (i.e., rainfall greater than potential ET) in the eastern higlands, and for a small rainfall deficit within the western fringe of the region.

**Table 4-2 Local historical climatic conditions**

| **Mean Rainfall [mm]** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Narrabri Bowling Club – Site #054120 | | | | | | | | | | | | | |
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Mean | 80.2 | 73.9 | 53.6 | 38.2 | 48.9 | 50.9 | 44.9 | 37.4 | 39.1 | 51.2 | 59.9 | 67.7 | 646.0 |
| **Monthly Mean Temperature [°C]** | | | | | | | | | | | | | |
| Narrabri Bowling Club – Site #054120 | | | | | | | | | | | | | |
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Mean Max (°C) | 35.3 | 33.9 | 31.3 | 26.8 | 21.6 | 17.6 | 17.0 | 19.4 | 23.3 | 27.7 | 31.8 | 34.5 | 26.7 |
| Mean Min (°C) | 19.4 | 18.6 | 16.3 | 11.7 | 7.4 | 4.9 | 3.4 | 4.6 | 7.5 | 11.7 | 15.3 | 18.0 | 11.6 |
| **Average Monthly Potential Evaporation Rates [mm/d]** | | | | | | | | | | | | | |
| Tamworth Airport – Site #055054 | | | | | | | | | | | | | |
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
| Mean | 8.6 | 8.1 | 6.9 | 4.6 | 2.9 | 2.0 | 2.1 | 3.0 | 4.4 | 6.0 | 7.6 | 8.7 | 5.4 |

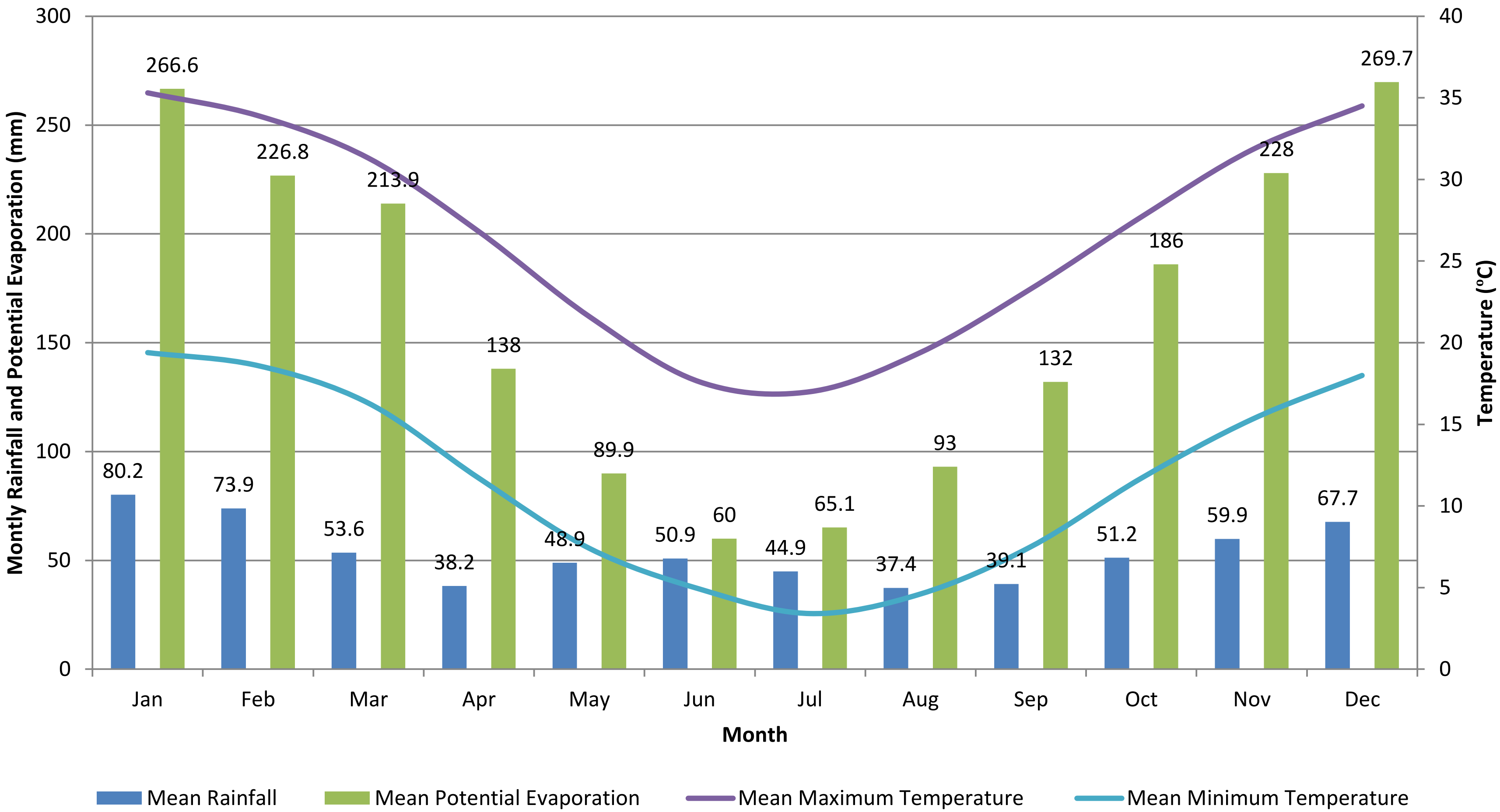



**Figure 4-3 Climate curves and rainfall histogram**

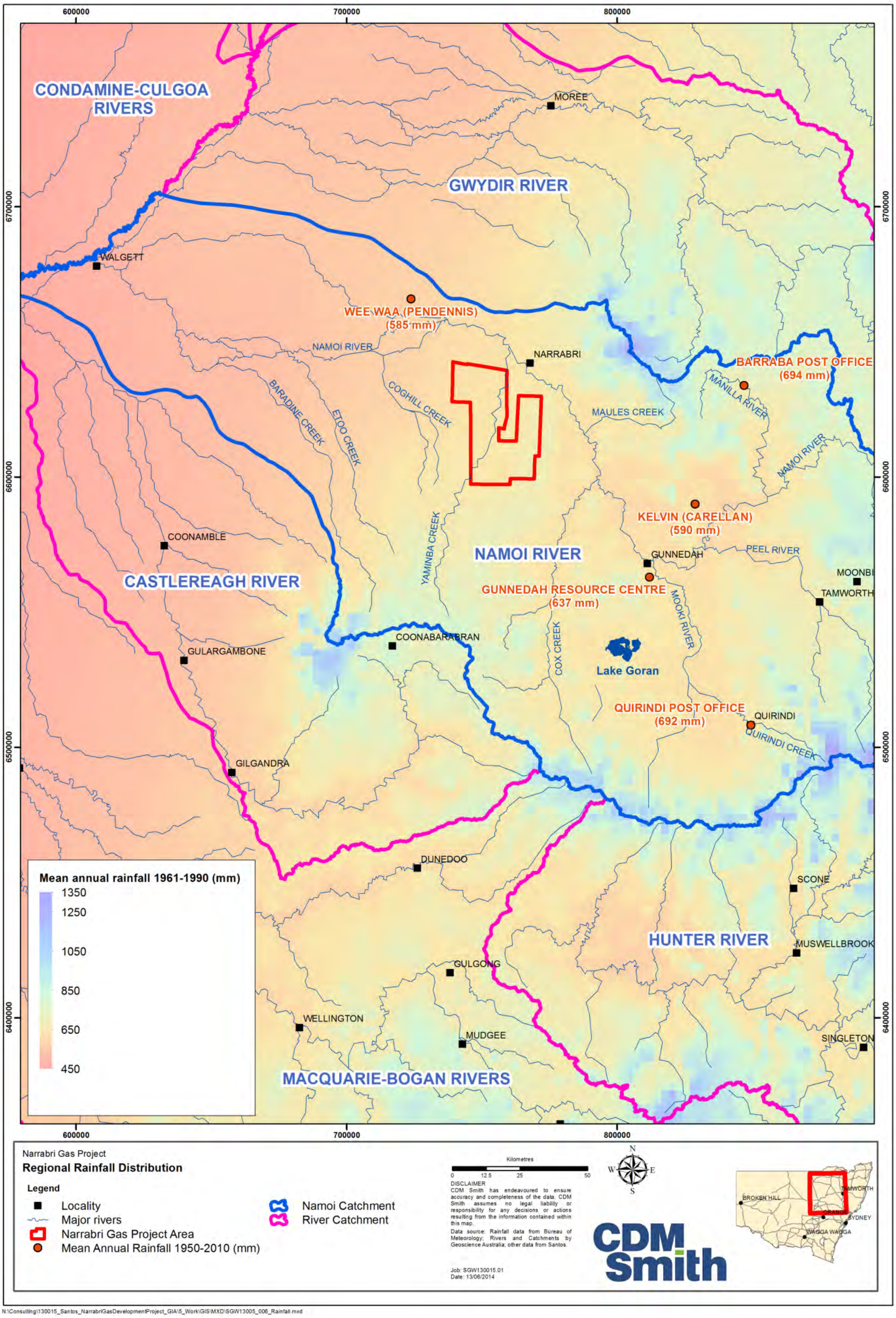



**Figure 4-4 Regional rainfall distribution**

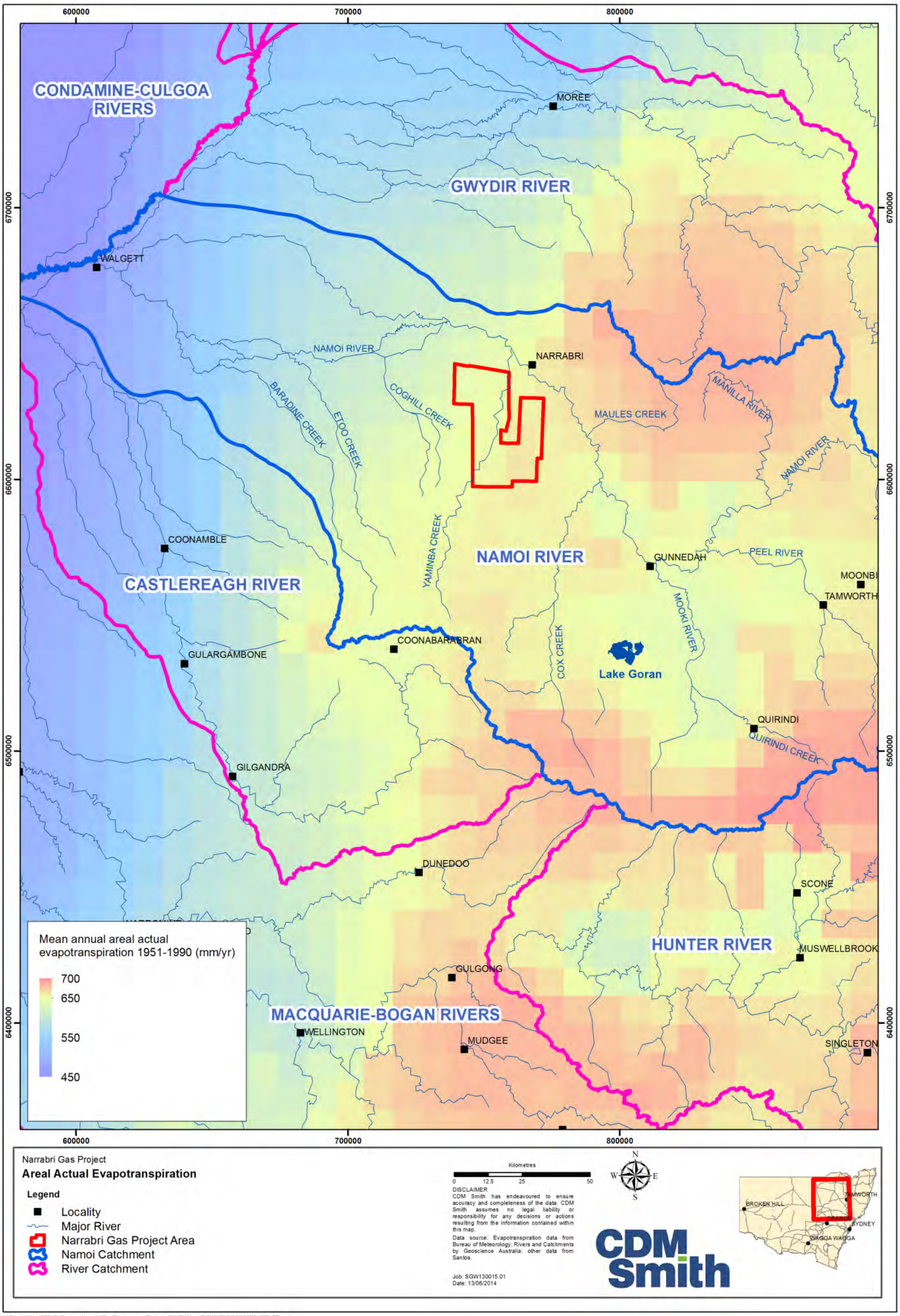



**Figure 4-5 Areal actual evapotranspiration**

# 4.4 Hydrology

## 4.4.1 Catchment Hydrology

A general synthesis of surface water hydrology across the region can be found in the context statement for the Namoi subregion bioregional assessment (Welsh etal. 2014)

For the GIA, daily stream flow records obtained from the PINNEENA database have been analysed to characterise the flow regimes based on Hedman and OsterKamp (1982) and Hewlett (1982). These classifications are applied by assessing stream gauge data recorded for each surface water system and calculating the percentage number of days in which stream flow exceeded 1 ML/d, which is used to define minimum flow in the surface water systems.

The major surface water systems within the GIA study area are characterised under the following categories:

- Perennial: stream flow exceeded 1 ML/d greater than 90% of the time;
- Intermittent: stream flow exceeded 1 ML/d between 10% and 90% of the time; and
- Ephemeral: stream flow exceeded 1 ML/d less than 10% of the time.

Figure 4-6 illustrates the stream gauges selected for the above analysis in the Namoi catchment and the derived results. The Namoi River is a perennial surface water system, while the majority of the tributaries, including Bohena Creek, flow intermittently.

Streams below Narrabri make little or no contribution to the Namoi River (such as Pian Creek, Baradine Creek and Bohena Creek for example).

Table 4-3 shows the flow statistics for the gauges analysed within the Namoi catchment.

Figure 4-7 depicts the median daily flow (the flow that is exceeded 50% of the time) in the different reaches assessed for the Namoi catchment. The figure shows that only the Peel River and main Namoi reaches have over 100 ML/d for 50% of the time, while the other watercourses do not contribute significantly to the Namoi River flow volume.

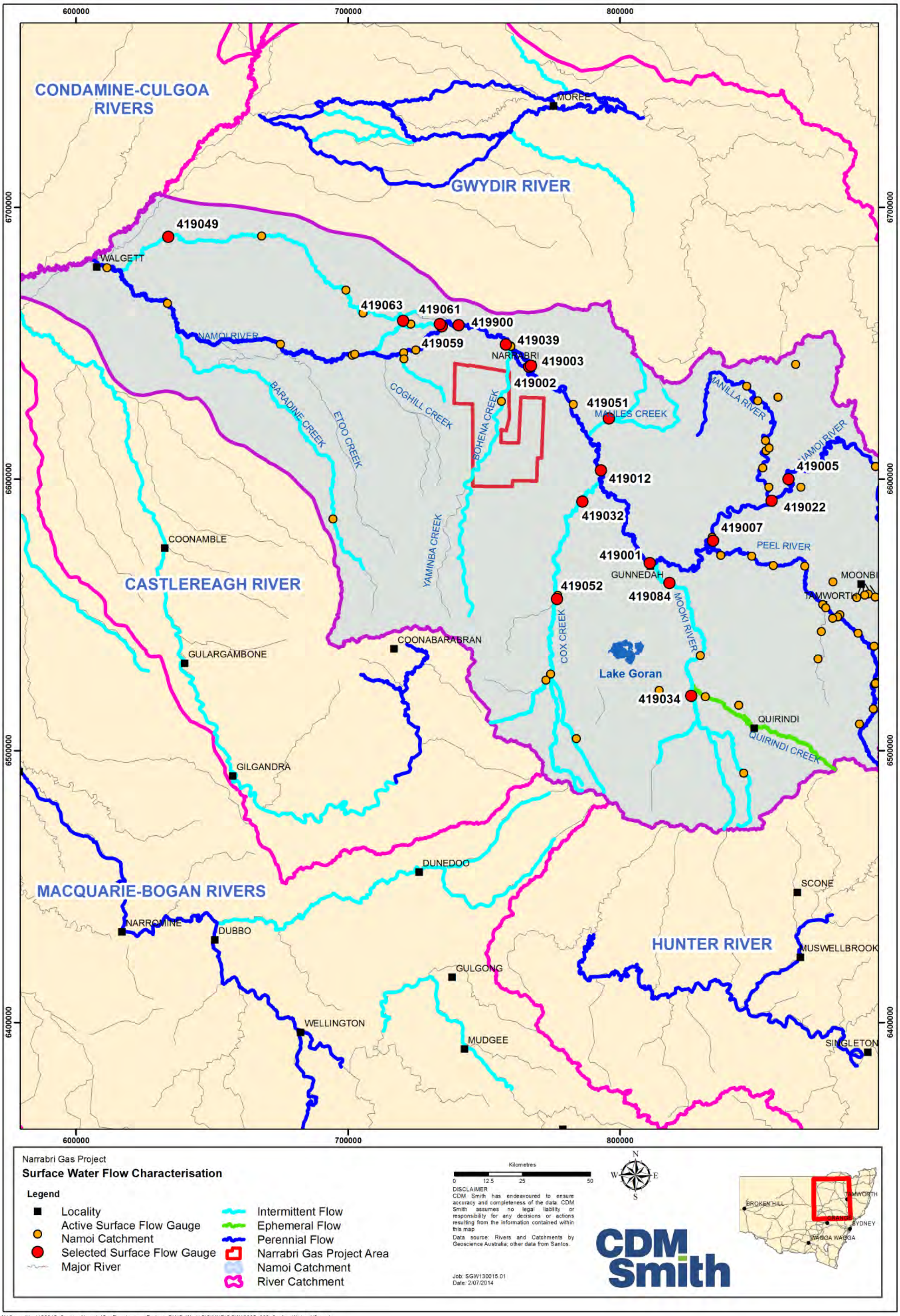



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**Figure 4-6 Surface water flow characterisation**

**Table 4-3 Flow statistics for the Namoi catchment**

| Location | Station No. | Median Flow [ML/d] | Average Flow [ML/d] | Average Min Flow [ML/d] | Average Max Flow [ML/d] | Surface Water Catchment Area [km²)] |
|---|---|---|---|---|---|---|
| Namoi at Gunnedah | 419001 | 520 | 1704 | 547 (Apr) | 3,480 (Jan) | 17,10 |
| Namoi at Narrabri | 419002 | 1.7 | 787 | 321 (Apr) | 1,270 (Jul) | 25,100 |
| Narrabri Ck at Narrabri | 419003 | 616 | 1550 | 618 (Apr) | 3,191 (Feb) | 25,120 |
| Namoi at North Cuerindi | 419005 | 150 | 566 | 183 (Apr) | 1,013 (Sep) | 2,510 |
| Namoi D/S Keepit Dam | 419007 | 101 | 738 | 143 (Apr) | 1,997 (Jan) | 5,700 |
| Namoi River at Boggabri | 419012 | 325 | 1619 | 452 (May) | 3,011 (Feb) | 22,600 |
| Namoi River at Manilla | 419022 | 205.0 | 794 | 240 (Apr) | 1,289 (Sep) | 5,180 |
| Coxs Ck at Boggabri | 419032 | 0 | 199 | 8.79 (Mar) | 487 (Jul) | 4,040 |
| Mooki at Caroona | 419034 | 7.3 | 199 | 21.6 (Mar) | 431 (Jul) | 2,540 |
| Namoi River at Mollee | 419039 | 567 | 2021 | 833 (Apr) | 4,012 (Jan) | 28,200 |
| Pian Creek at Waminda | 419049 | 3.7 | 238 | 50 (Oct) | 497 (Aug) | Unknown |
| Maules at Avoca East | 419051 | 8.2 | 51.5 | 19.6 (Oct) | 96.6 (Sep) | 663 |
| Cox Ck at Mullaley | 419052 | 0 | 172 | 17.1 (Dec) | 800 (Jan) | 2,370 |
| Namoi DS Gunidgera weir | 419059 | 228 | 1324 | 656 (Oct) | 2,141 (Aug) | 28,500 |
| Gunidgera Ck DS Regulator | 419061 | 125 | 319 | 125 (Apr) | 679 (Feb) | Unknown |
| Gunidgera-Pian cutting at Merah North | 419063 | 22.4 | 93.0 | 28.4 (May) | 216 (Jan) | Unknown |
| Mooki at Rouvigne | 419084 | 0.3 | 353 | 7.47 (May) | 1064 (Nov) | 6,600 |
| Bohena Ck at Newell highway | 419905 | 0 | 127 | 8.89 (Jun) | 267 (Nov) | 2,000 (estimated) |

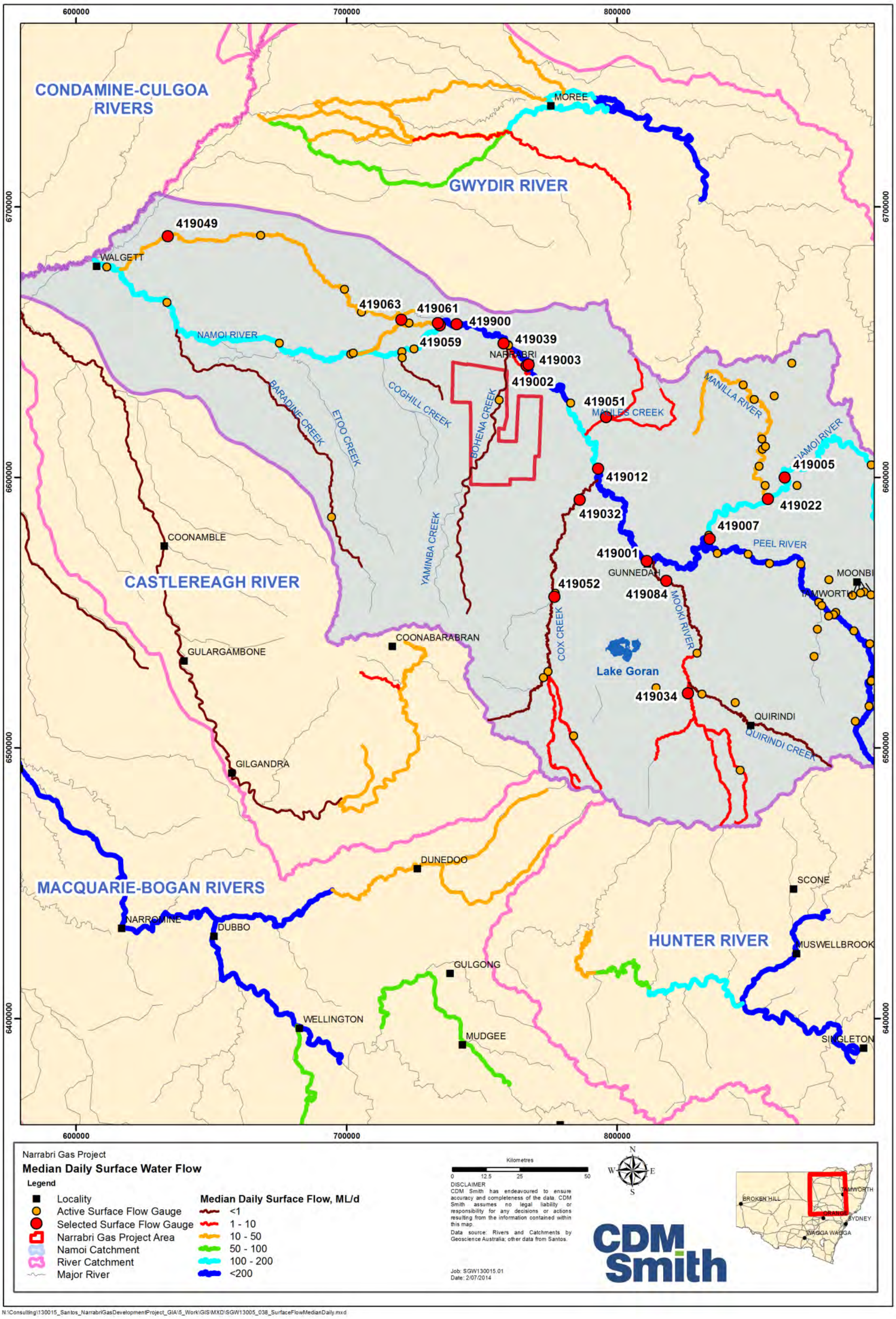


**Figure 4-7 Median daily surface water flow**

### 4.4.2 Catchment Setting

There are five major sub-catchments in the Namoi catchment:

1. Lower Namoi sub-catchment;
2. Middle Namoi sub-catchment;
3. Mooki sub-catchment;
4. McDonald / Manilla sub-catchment; and
5. Peel sub-catchment.

The GIA study area covers large portions of the Middle and Lower Namoi and Mooki sub-catchments, as shown in Figure 4-8.

#### 4.4.2.1 Lower Namoi sub-catchment

The Lower Namoi sub-catchment commences at Narrabri and is regulated by two major weirs downstream of Narrabri: Mollee Weir and Gunidgera Weir.

Pian Creek is the largest tributary of the Namoi River in the Lower Namoi sub-catchment and is regulated to supply irrigation water to properties along its length (NSW Office of Water 2011). Water generally enters Pian Creek only when the Namoi River is in flood. Water is now diverted into the system from the Namoi River via Gunidgera Weir into Gunidgera Creek, and then into Pian Creek.

In the northern primarily flat areas of the sub-catchment, large areas are utilised for irrigated cropping including cotton, dryland agriculture and grazing.

To the southwest of Narrabri is a large area of land with low elevation that includes Bohena, Coghill, Etoo and Baradine Creeks and many other minor water courses. The headwaters of the tributaries are generally located in forested conservation areas (Pilliga Forest) while the unforested areas of the sub-catchments are utilised predominately for sheep and cattle grazing and dryland cropping.

The lower reaches of the Namoi, below Baradine Creek, are characterised by multiple channels, with dryland agriculture and lagoons adjacent to the river (Green and Dunkerley 1992).

The Project area lies predominately within the Lower Namoi sub-catchment with the majority of the project area draining towards the north via two small creeks, namely Bohena Creek (running southeast to northwest) and Jacks Creek, draining the north-eastern part of the project area.

#### 4.4.2.2 Middle Namoi sub-catchment

The middle Namoi sub-catchment consists of several major tributaries including Bullawa and Maules Creek in the north-east and Cox's Creek in the south. The Cox's Creek catchment covers around 9% of the Namoi catchment area, while Maules Creek catchment represents around 1% (NSW Office of Water 2011). The upper reaches of the Bullawa and Maules Creek are located in the Mt Kaputar National Park and are characterised by steep slopes. The mid slope areas of the sub-catchments are utilised for grazing while the lower slopes are used for dryland and irrigated cropping.

Cox's Creek rises at the western end of the Liverpool Ranges and flows in a northerly direction towards the Namoi River. Both dryland and irrigated cropping are prominent on the more fertile plains of the sub-catchment.

Flooding, erosion and salinisation are also an issue in the Cox's Creek area of the middle Namoi sub-catchment.

#### 4.4.2.3 Mooki sub-catchment

The Mooki River catchment covers around 9% of the Namoi catchment area (NSW Office of Water 2011). The headwaters of the Mooki River lie in the Liverpool Ranges at elevations greater than 1,000 m Australian Height Datum (mAHD) and its confluence with the Namoi River occurs at approximately 300 mAHD.

Lake Goran is located in the centre of the Mooki sub-catchment, with many streams draining to this internal drainage basin. The steeper slopes and upper catchments are used for light grazing or reserved for state forest while the lower areas of the catchment are used for summer and winter cropping. Flooding, erosion and salinisation management issues are common in the lower areas of the catchment.

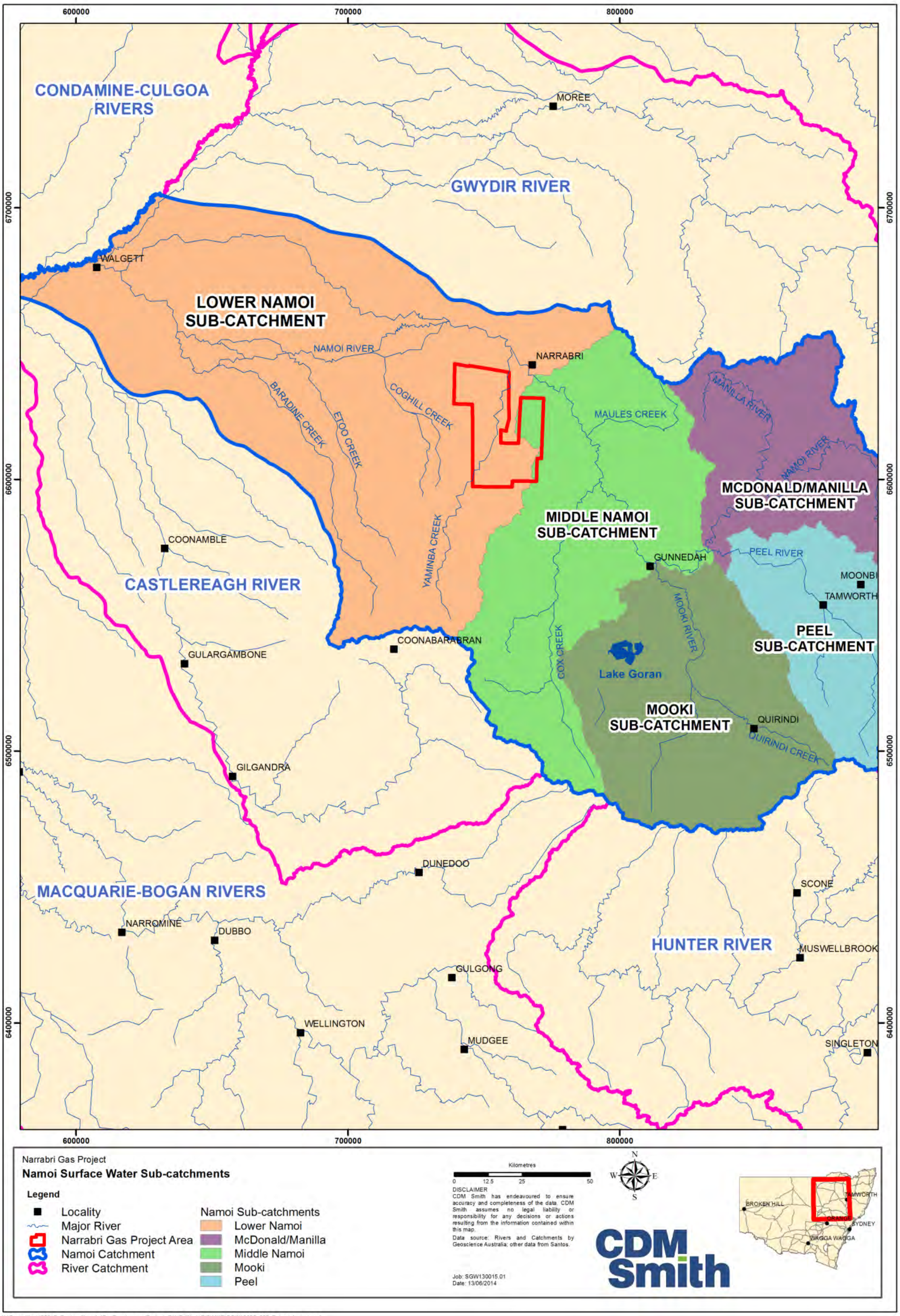


Figure 4-8 Namoi surface water sub-catchments

## 4.4.3 Groundwater

Groundwater resources in the GIA study area are highly developed within the areas occupied by the alluvial sediments of the Narrabri, Gunnedah and Cubbaroo formations. Extraction occurs primarily from the alluvial aquifers associated with the main rivers and their major tributaries, although a large number of smaller scale abstractions also occur from the consolidated (porous) and fractured rock aquifers.

CSIRO (2007a) found that the Namoi catchment accounted for 15% of all groundwater use in the Murray-Darling Basin and had the highest level of groundwater development in NSW. It was estimated that there were more than 18,000 groundwater bores in the Namoi catchment, which were licenced to provide 343,000 megalitre per year (ML/y) (Green *et al.* 2011a). Of this entitlement, 95% was utilised for irrigation purposes, with the remainder used for industrial, stock and domestic water.

## 4.4.4 Surface Water– Groundwater Interaction

Groundwater-surface water interaction can be described in the following ways:

- Streams gain water from inflow of groundwater through the streambed (a gaining stream);
- Streams lose water to groundwater by outflow through the streambed (a losing stream); and
- They do both at different locations and times (a gaining and losing stream).

Additionally, surface water systems may be connected or disconnected to the groundwater system. A connected surface water system is defined as having a length of river in direct contact with the underlying transmissive unit through a zone of saturated material or by a narrow unsaturated zone (Bouwer and Maddock 1997). A disconnected surface water system is characterised by the presence of an unsaturated zone between the surface water system and the underlying transmissive unit.

### 4.4.4.1 Namoi Catchment

A number of studies have been undertaken to assess the surface water-groundwater connectivity and interaction within the Namoi Catchment. The study outcomes indicate that river reaches located in the steeper, upland regions, generally in the east of the Namoi River catchment, were gaining reaches, while low relief areas were identified as connected and losing to the groundwater system (Ivkovic 2006). Downstream reaches of the catchment between Wee Waa and Walgett were identified as disconnected losing reaches (CSIRO 2007a).

Figure 4-9 show the surface water-groundwater interaction across the Namoi Catchment as identified from the Ivkovic (2006) study.

### 4.4.4.2 Mooki Sub-catchment

The Ivkovic (2006) study illustrates that the upland tributaries of the Mooki River are connected and gaining while the main channel of the Mooki River is variably gaining and losing.

### 4.4.4.3 Middle Namoi Sub-catchment

The Namoi River is connected to the underlying Narrabri alluvium and is typically losing, though may change to gaining with water level changes (Ivkovic 2006).

Cox's Creek varies from connected and gaining in the upper reaches to variably gaining-losing in the middle section of the creek system to disconnected in the lower section of the creek system (Ivkovic 2006).

Maules Creek is mainly ephemeral though has a perennial section that is exclusively controlled by surface-groundwater interactions (Anderson & Acworth 2009).

Studies indicate that groundwater abstraction in this region largely enhances recharge from rivers and streams to the underlying transmissive units (Anderson & Acworth 2007).

#### 4.4.4.4 Lower Namoi Sub-catchment

The Pian Creek and Namoi River in the Lower Namoi sub-catchment are disconnected from the underlying alluvial groundwater source and lose water through the intervening unsaturated zone (Ivkovic 2006).

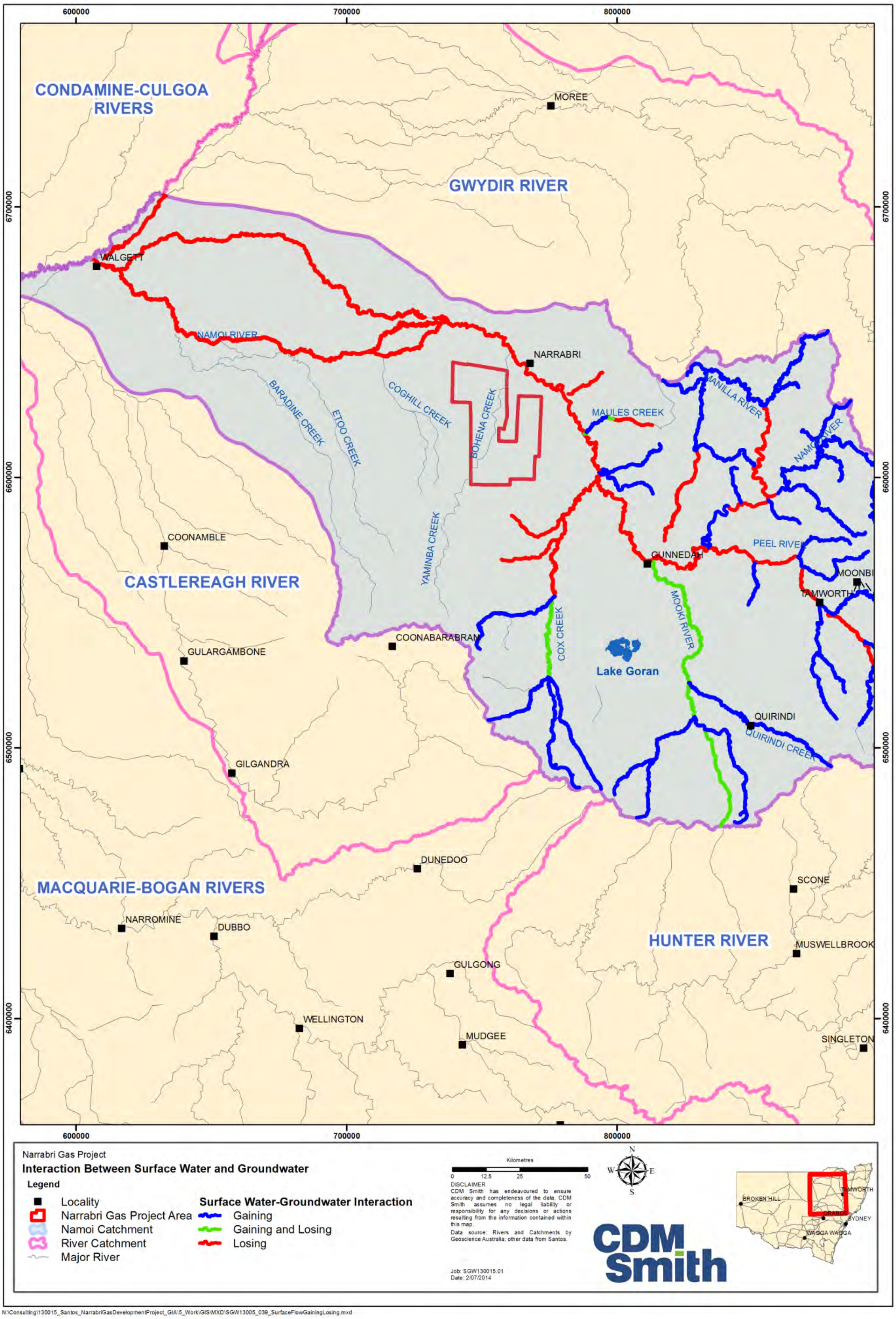


**Figure 4-9 Interaction between surface water and groundwater**

# 4.5 Geology

## 4.5.1 Regional Context

The geology of the region is well studied and has been described in detail, including the seminal studies of Tadros (1993, 1995). The available geological information for the region was most recently overviewed as part of the context statement for the Namoi subregion (Welsh et al. 2014) inclusive of the the basin history, structural framework and stratigraphy.

### 4.5.1.1 Sedimentary Basins

The NGP is located within both the Permo-Triassic Gunnedah Basin (containing the target coal seams for coal seam gas development) and the overlying Jurassic-Cretaceous Surat Basin. The Gunnedah Basin covers an area of over 15,000 km$^2$ and forms the central part of the Sydney-Gunnedah-Bowen Basin system. The Project area is located near the northern and western boundaries of the Gunnedah Basin as shown in Figure 4-10.

Overlying the Gunnedah Basin is the Coonamble Embayment of the Surat Basin, which itself forms the western province of the Great Artesian Basin (GAB). Groundwater sources forming the eastern and southern fringes of the Coonamble Embayment comprise the southern-most recharge (intake) beds for the GAB.

Generally, the stratigraphy of the Gunnedah Basin consists of up to 1,200 m of marine and non-marine Permian and Triassic sediments (Tadros 1995) that rest unconformably on Early Permian and older basement rocks (Russell and Middleton 1981). The Permian sediments represent a major coal province in Eastern Australia (Othman 2003; Hamilton *et al.* 1988; Tadros 1993).

The Gunnedah Basin is contiguous with the Sydney Basin in the south and Bowen Basin in the north, and collectively these basins form the Permo-Triassic foreland basin system of Eastern Australia. The system extends from the township of Bowen in northern Queensland to Sydney on the central coast of NSW. The Gunnedah Basin extends from Moree and Cryon in the north to Muswellbrook and Dubbo in the south, and from Gunnedah in the east to approximately Wingadee and Coonamble in the west. Strata of the Gunnedah Basin outcrop on the eastern side of the basin within a relatively thin zone extending between Quirindi in the south and Edgeroi in the north (Tadros 1993).

The Coonamble Embayment of the Surat Basin contains mostly Jurassic clastic sedimentary strata and lower Cretaceous marine beds (Exon 1976) extending over the western part of the Gunnedah Basin. The basal sequence of the Surat Basin (Garrawilla Volcanics) outcrops mainly within the central part of the Gunnedah Basin around Mullaley and Coonabarabran.

The Jurassic Oxley Basin, a lateral equivalent of the Surat Basin, extends across the southern half of the Gunnedah Basin, and corresponds broadly with the extent of Pilliga Sandstone east of Coonabarabran (Figure 4-10). A topographic high on the floor of the Jurassic strata has given rise to a groundwater divide extending from around Ballimore in the south, northwards through Coonabarabran. Incident rainfall to the south east of this line recharges the Pilliga Sandstone of the Oxley Basin, whilst that falling to the north-west recharges the Pilliga Sandstone of the GAB Surat.

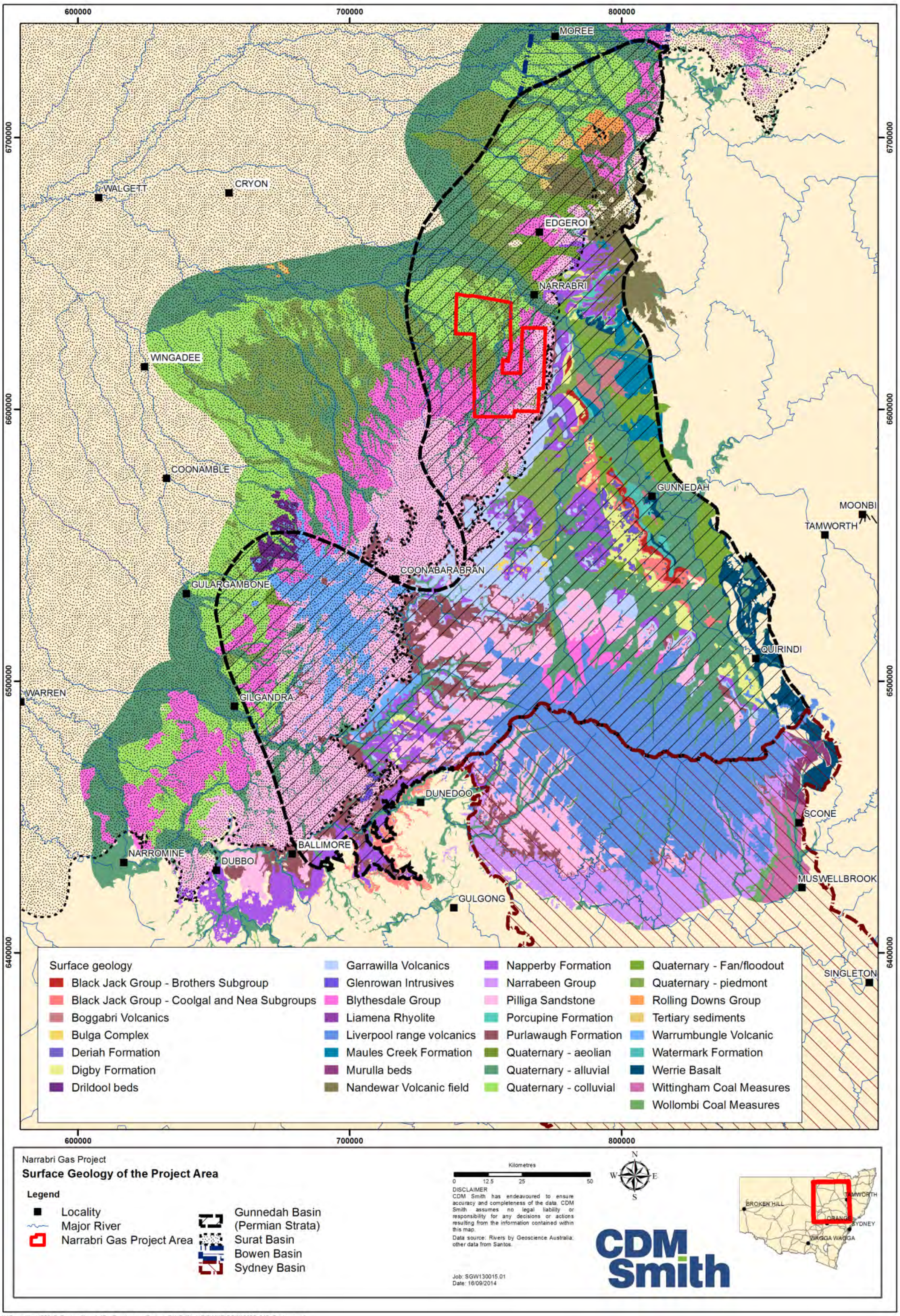


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**Figure 4-10 Regional surface geology**

#### 4.5.1.2 Macro-structure

The Gunnedah, Sydney and Bowen Basins overlie (onlap) the Lachlan Fold Belt (LFB) of the Tasman Orogen, which abuts the New England Fold Belt (NEFB) along its eastern margin. The NEFB lies to the east of the north-trending suture, which separates the terranes of the Hunter-Mooki-Goondiwindi Fault System (HMGFS). The basins are developed predominantly in the foreland setting of the Tasman Orogen, extending westwards from the HMGFS.

The Moree High and the Mt Coricudgy Anticline (axis defined between Rylstone and Muswellbrook) define the northern and southern extents of the Gunnedah Basin which is divided into three longitudinal sub-basins: from west to east they are the Gilgandra, Mullaley and Maules Creek Sub-basins.

The central Mullaley Sub-basin occupies the major part of the Gunnedah basin and is further sub-divided into four troughs. From north to south they consist of the Bellata Trough, Bohena Trough (encompassing the project area), Bando Trough and Murrurundi Trough.

The structural highs of the Gunnedah basin have significantly influenced sedimentation in the basin, both in the supply of material and thinning of strata and deterioration of coal quality during the Early Permian and through uplift and erosion; notably in the northern half of the Mullaley Sub-basin and the Maules Creek Sub-basin (Gurba *et al.* 2009).

The floor of the central part of the Gunnedah Basin comprises Early Permian igneous rocks of the Boggabri Volcanics and associated Werrie Basalt.

The Rocky Glen Ridge and much of the outcrop of the Boggabri Ridge comprise Early Permian silicic volcanics, including ignimbrites of the Boggabri Volcanics, whilst the extensive Mullaley Sub-basin is underlain predominantly by Early Permian mafic igneous rocks correlating with the Werrie Basalt (Tadros 1993). The top of the basal volcanic sequence is typically deeply weathered, indicating a pronounced unconformity (Tadros 1993).

### 4.5.2 Local Geological Setting

The local geology of the project area is characterised by unconsolidated alluvial and colluvial deposits overlying Jurassic Surat Basin strata, which in turn unconformably overlie indurated Permo-Triassic Gunnedah Basin sediments of the Bohena Trough, resting on Early Permian and older meta-volcanic basement rocks.

The Surat Basin strata present in the vicinity of the project area include the Blythesdale Group (Keelindi Beds), Pilliga Sandstone, Purlawaugh Formation and basal Garrawilla Volcanics. The Gunnedah Basin strata is locally present beneath the Surat sediments and include the Triassic Deriah, Napperby and Digby Formations overlying unconformably the Late Permian Black Jack Group, Middle Permian Millie Group and the Early Permian Bellata Group.

The structure of the Gunnedah Basin Permian sediments in the project area is defined largely by the shape of the Bohena Trough, with dips reflecting the draping of strata on the flanks of the structural highs forming the trough margins. Localised faulting may result in variations from this pattern. Permian strata in the northern part of the Mullaley Sub-basin in which the project area rests are largely confined to the Bohena Trough, terminating on the flanks of Rocky Glen Ridge in the west. Younger Triassic strata extend across Rocky Glen Ridge and onlap the Lachlan Fold Belt basement rocks in the west. Within the Surat Basin sequence, strata dips are typically toward the west or north-west, although locally the infilling and onlapping of strata mimic the geometry of the Bohena Trough, which has resulted in a local stratigraphical sub-basin.

Each stratum is described in further detail below from oldest to youngest. Table 4-4 indicates the indicative maximum and average thicknesses of selected key strata.

## 4.5.3 Basement Rocks

The basement of the Bohena Trough consists of Early Permian meta-volcanic rocks including the Boggabri Volcanics and Werrie Basalt. For the purposes of this GIA, the basement volcanic formations were the deepest stratigraphic units considered.

The Rocky Glen Ridge and much of the outcrop of the Boggabri Ridge consist of Early Permian silicic volcanics including ignimbrites of the Boggabri Volcanics, whilst the extensive Mullaley Sub-basin is underlain predominantly by Early Permian mafic igneous rocks correlating with the Werrie Basalt (Tadros 1993). The top of the basal volcanic sequence is typically deeply weathered, indicating a pronounced unconformity (Tadros 1993).

## 4.5.4 Bellata Group

The Bellata Group comprises an upward sequence of the Leard Formation, Goonbri Formation and Maules Creek Formation.

### 4.5.4.1 Leard Formation

The discontinuous Leard Formation comprises up to 18 m of alluvial (Thomson 1986) or colluvial flint pelletoidal claystone present as infills of basement topographic lows (Tadros 1993).

### 4.5.4.2 Goonbri Formation

The discontinuous Goonbri Formation consists of variably-lacustrine and prograding fluvial dark organic rich siltstones and coals, coarsening upwards through siltstones and sandstones. It is typically less than 100 m in thickness.

### 4.5.4.3 Maules Creek Formation

The Maules Creek Formation is present both sides of the Boggabri Ridge as onlapping alluvial-fluvial coal-bearing sediments overlying the Goonbri and Leard Formations. It is best developed east of the Boggabri Ridge, exceeding 800 m thickness, particularly approaching the Hunter-Mooki Fault. The formation contains approximately 50% lithic conglomerates and coarse sandstone, 40% claystone, siltstone and fine to medium grained sandstone and 10% coals (Tadros 1993).

The Maules Creek Formation has characteristics of low energy fluvial conditions in which the coal measures were deposited. Based on the percentage of quartz grains present in the sandstone, and the composition of some of the lithic rock fragments (phyllite-commonly derived from the Lachlan Fold Belt) a high percentage of westerly-derived sediment is interpreted for the sandstone portions, deposited in a transgressional, near-shore marine environment.

The basal sequence consists of carbonaceous claystone, pelletoidal clay sandstone and minor coal, transitioning into upward-fining cycles of sandstone, thinly bedded siltstone, sandstone and coal. Conglomerate is dominant towards the top of the formation. Coal seams in the Maules Creek Formation (primary target for coal seam gas development) occupy depths ranging from 500 to 1000 m below ground level (m BGL) with the seams terminating at depth against the flanks of the Bohena Trough. Prominent coal seams targeted for coal seam gas development include the Rutley, Namoi, Parkes and Bohena seams.

**Table 4-4 Indicative occurrence of stratigraphic units in the GIA study area**

| Formation | Lithology and Hydrogeological Classification | Thickness in Study Area [m] | |
|---|---|---|---|
| | | Maximum | Average |
| Bohena Creek Alluvium | Gravel and sand with clay lenses | 40* | 6* |
| Namoi Alluvium | Gravel and sand with clay and silt lenses | <150 | >100 |
| Blythesdale Group (Keelindi Beds) | Clayey to quartzose sandstone, subordinate siltstone and conglomerate | 50* | 30* |
| Pilliga Sandstone | Fluvial, medium to very coarse grained, quartzose sandstone and conglomerate. Minor interbeds of mudstone, siltstone and fine grained sandstone and coal. | 310 | 240 |
| Purlawaugh Fm | Fine to medium grained sandstone thinly interbedded with siltstone and thin coal seams, grading into mudstone with depth | 152 | 100 |
| Garrawilla Volcanics | Dolerite, basalt, trachyte, tuff, breccia | 100 | UK |
| Deriah Fm | Sandstone | UK | UK |
| Napperby Fm | Interbedded fine sandstone, claystone & siltstone | 232 | 164 |
| | Basal Napperby Shale | | |
| Digby Formation | Quartzose sandstone (Ulinda Ss) | 73 | 38 |
| | Lithic sandstone | | |
| | Lithic conglomerate (Bomera Conglomerate) | | |
| Trinkey Formation | Coal measures - siltstone, fine sandstone, tuffs, stony coal | UK | UK |
| Wallala | Conglomerate, sandstone, siltstone, minor coal bands | UK | UK |
| Breeza Coal | Coal and claystone | 184 | 137 |
| Clare Sandstone | Medium to coarse-grained quartzose sandstone; quartzose conglomerate | | |
| Hows Hill Coal | Coal | | |
| Benelebri | Claystone, siltstone & sandstone; fining up cycles; more sandy towards top | | |
| Hoskissons Coal | Potential target coal seam | | |
| Brigalow Fm | Fining-up sequence of medium to coarse-grained quartzose sandstone and siltstone | | |
| Arkarula Fm | Sandstone and siltstone | | |
| Melvilles Coal | Coal | | |
| Pamboola Fm | Sandstone, siltstone, minor claystone & coal | | |
| Watermark Fm | Marine siltstone, shales and sandstone | 21 | 11 |
| Porcupine Fm | Fining upward sequence of conglomerate and sandstone to mudstone | 203 | 128 |
| Upper Maules Creek Fm | Sandstone and conglomerate, siltstone, mudstone and coal | 182 | 125 |
| Rutley seam | Potential target coal seam | | |
| MC interburden | Sandstone and conglomerate, siltstone, mudstone | | |
| Namoi seam | Potential target coal seam | | |
| MC interburden | Sandstone and conglomerate, siltstone, mudstone | | |
| Parkes seam | Potential target coal seam | | |
| MC interburden | Sandstone and conglomerate, siltstone, mudstone | | |
| Bohena seam | Potential target coal seam | | |
| Lower Maules Creek Fm | Sandstone and conglomerate, siltstone, mudstone and coal | | |
| Goonbri Fm | Siltstone, sandstone and coal | UK | UK |
| Leard Fm | Flinty claystone | | |
| Werrie Basalt and Boggabri Volcanics | Rhyolitic to dacitic lavas and ashflow | ND | ND |
| | Tuffs with interbedded shale. Rare trachyte and andesite. Weathered basic lavas | | |

*Information provided by Santos; ND - not defined; UK - unknown

Outcrops of the Maules Creek Formation can be seen approximately 15 km to the east of the project area. It is likely that the coals are not continuous over these distances. Available seismic and well data indicate that the major coal seams onlap the basement rocks of Boggabri Ridge and do not continuously extend beyond the basin in the east. Within the centre of the sub-basin the Maules Creek Formation is up to 182 m thick.

The full thickness of the Maules Creek Formation, including the coal seams, onlap against the eastern flank of the Rocky Glen Ridge, with sediments of the Bellata Group not extending west of the Bohena Trough.

Maules Creek coals exhibit little or no face and butt cleat development. They do however have a series of master cleats and fractures that generally have a northeast-southwest fracture orientation in the project area (Golder Associates/Santos Limited pers. comm. 2009). The spacing of the “master cleats” is in the range of 10 to 300 mm. Fractures cross all coal lithotypes but do not penetrate the surrounding less transmissive units in the wellbores. The stress field is interpreted to be benign as limited caving or bore ovality is observed in exploration boreholes (Golder Associates 2011).

### 4.5.5 Millie Group

The Millie Group consists of the Porcupine Formation overlain by the Watermark Formation. The thickest sequence of the Watermark and Porcupine Formations is likely to be in the centre of the Bohena Trough and up to 225 m thick. The Millie Group onlaps against the eastern flank of the Rocky Glen Ridge and does not extend west of the Bohena Trough.

#### 4.5.5.1 Porcupine Formation

The Porcupine Formation consists of a single upward-fining unit comprising basal conglomerates fining upwards into sandstones and mudstones representing a Late Permian marine transgression. It varies in thickness from 0 to 10 m at the western margins of the Bohena Trough up to more than 60 m south west of Narrabri due to its mode of origin as a prograding delta fan originating from the adjacent Boggabri Ridge. The formation exhibits only very limited outcrop around Narrabri and north of Mt Kaputar.

#### 4.5.5.2 Watermark Formation

The lower part of the Watermark Formation comprises an upward-fining sequence of sandy siltstones to shale, whilst the upper part is split geographically into a lower shale (absent north of Boggabri) representing the maximum extent of the marine transgression and a widespread upper series of siltstone-sandstone and upward coarsening sequences representing marine regressions.

### 4.5.6 Black Jack Group

The Black Jack Group is characterised by diminishing marine influences and the dominance of deltaic swamps, giving rise to more than 500 m of lithic sandstones with coals (south of the project area around Quirindi). The group comprises the Brothers Sub-group at it base, including the Pamboola and Arkarula/Brigalow Formations; the Coogal Sub-group, including the Hoskissons Coal, Benelebri Member and Clare Sandstone Formation; and the uppermost Nea Sub-group, including the Wallala and Trinkey Formations.

The maximum thickness of Black Jack Group strata in the centre of the Bohena Trough is approximately 185 m, although the average thickness is likely to be around 140 m (Golder Associates 2011). The Black Jack Group thins out against the eastern flank of the Rocky Glen Ridge and does not extend west of the Bohena Trough.

#### 4.5.6.1 Pamboola and Arkarula / Brigalow Formations

The basal sub-group consists of the Pamboola and Arkarula/Brigalow Formations. The Pamboola Formation contains cyclical coal measure sequences including the Melvilles Coal Member, overlain by the bioturbated massive sandstone Arkarula Formation, which grades laterally in the west and north-west into the quartz-rich sandstone of the Brigalow Formation. The Arkarula Formation is up to 50 m thick in the northern Mullaley Sub-basin, whilst the Pamboola Formation is up to 90 m tick in the north of the Mullaley Sub-basin, thinning to zero m in the west.

#### 4.5.6.2 Hoskissons Coal Member, Benelebri Member and Clare Sandstone Formation

The Hoskissons Coal Member sequence consists of a series of interbedded siltstones and sandstones. The net sandstone within this interval is up to 19 m thick but its distribution is sporadic and not well developed within the project area. Deposition of the western derived quartzose sandstones was followed by very widespread coal swamp conditions depositing the 12 to 18 m thick Hoskissons coal seam that is readily correlated across the basin.

Hoskissons Coal is overlain by the medium-coarse grained quartz-rich Clare Sandstone, which is up to 95 m thick in the southeast of the Mullaley Sub-basin and south of the project area. The Benelebri Member comprises an interbedded silt and clay rich unit sporadically distributed within the Clare Sandstone. Outcrops of the Clare Sandstone form distinctive cliffs in the central Breeza-Curlewis area, whilst outcrops of the Hoskissons Coal follow a line from south-southeast of Narrabri to north of Quirindi.

#### 4.5.6.3 Wallala and Trinkey Formations

The uppermost strata of the Black Jack Group include the conglomeratic Wallala Formation in the east of the Mullaley Sub-basin (south of Boggabri) and fine-grained, tuffaceous sandstone of the Trinkey Formation, which is present comprehensively south of Narrabri.

### 4.5.7 Triassic Sediments

The Triassic strata consist of the Digby Formation, overlain successively by the Napperby Formation and Deriah Formation.

#### 4.5.7.1 Digby Formation

Tadros (1983) interprets the Early Triassic Digby Formation to rest unconformably on the Permian Black Jack Group while Beckett *et al.* (1983) suggest a conformable boundary. The formation is subdivided into three parts with a basal conglomerate derived from the New England Fold Belt, overlain by a lithic sandstone unit and topped by a quartzose sandstone unit. In the south of the Mullaley Sub-basin the three subdivisions of the formation are exhibited. Further northward the middle unit is absent, and north of Narrabri the upper unit is also absent, where the Napperby Formation rests directly on the basal Digby conglomerate.

Outcrops of the Digby Formation occur in discontinuous bands toward the east of the project area, with the nearest outcrop occurring approximately 10 km to the east. Geological records indicate that the Digby Formation thickens slightly toward the west but continues over the Rocky Glen Ridge and Narrabri High towards the north and west of the Bohena Trough. The Digby Formation is typically around 40 m in thick in the Bohena Trough.

#### 4.5.7.2 Napperby Formation

A basin-wide palaeosol horizon up to 1 m thick marks the unconformable base of this unit on the Digby Formation. The Middle Triassic Napperby Formation ranges in thickness from 25 m over the Rocky Glen Ridge to approximately 215 m in the central east of the Mullaley Sub-basin (Beckett *et al.* 1983). The formation is sub-divided into three parts including a predominantly mudstone basal member transitioning into a sandstone and mudstone middle member, topped by a predominantly sandstone member, and corresponding to progradation from lacustrine fan to fluvial facies (Tadros 1983).

The base of the unit is characterised by a dark grey claystone (Napperby Shale) 40 to 70 m thick directly overlying the Digby Formation and prevalent over the project area. The middle unit consisting of sandstone and claystone upward fining sequences is up to 55 m thick in the Narrabri area. The upper unit predominantly contains medium-grained, cross-bedded lithic sandstones ranging in thickness from 18 to 76 m.

The Napperby Formation outcrops in thin and discontinuous bands east of the project area. It is likely that the Napperby Formation thins over basement highs, with maximum thicknesses of up to 232 m near the centre of the Bohena Trough; however, it was found to be absent in exploration well Nyora No. 1 drilled 32 km west of Narrabri.

The Napperby Formation is overlain by the Deriah Formation in the north and northeast of the Mullaley Sub-basin and elsewhere is overlain by the Garrawilla Volcanics, Purlawaugh Formation and Pilliga Sandstone.

#### 4.5.7.3 Deriah Formation

The Deriah Formation rests unconformably on the Napperby Formation and is present mainly in the northern part of the Mullaley Sub-basin where it reaches a maximum thickness of 160 m. It comprises variously lithic sandstones, which in the in the upper part contain subordinate mudstones, coals and lavas up to 25 m thick, representing sandy alluvial fans, streams, lakes and swamp environments.

### 4.5.8 Jurassic–Cretaceous Rocks

#### 4.5.8.1 Garrawilla Volcanics

The Garrawilla Volcanics mainly consist of volcanic flows and pyroclastic deposits infilling relic topographical lows, and are therefore discontinuous across the region. They also occur as sills and plugs that have intruded into the surrounding host rock. Rock composition is generally described as both vesicular and non-vesicular alkali-olivine basalt, although includes of dolerite, trachyte, tuff and breccia have also been reported.

The volcanics are not widely proved in exploration wells, suggesting they are present in only limited areal extend beneath the project area. Nyora No. 1 exploration well proved the Garrawilla Volcanics lie directly over the Digby Formation approximately 32 km west of Narrabri.

#### 4.5.8.2 Purlawaugh Formation

The Purlawaugh Formation unconformably overlies the Garrawilla Volcanics except where the volcanics are absent north of Mullaley. At these areas it rests directly on the Napperby Formation or Deriah Formation (Beckett *et al.* 1983). In some locations where the Garrawilla Volcanics are absent the boundary between the Purlawaugh and Deriah Formations is unclear, and occurrences of the latter may have been reported as the former. It generally consists of thinly interbedded carbonaceous claystone and siltstone with minor thin coal seams. There can be abundant carbonaceous fragments with thin beds of flint and clay. There is a tendency for the Purlawaugh Formation to be sandy and silty in its upper half and to contain shale and mudstone in the lower half.

Purlawaugh Formation outcrops to the east of the project area as a thin band that is generally less than 1.5 km wide. Beneath the project area, the average thickness of the Purlawaugh Formation is around 100 m with a maximum recorded thickness of 152 m.

#### 4.5.8.3 Pilliga Sandstone Formation

Outcropping over the south-east of the project area are strata of the Jurassic Pilliga Sandstone Formation (known as the "Pilliga Sandstone") overlying the Purlawaugh Formation. The Pilliga Sandstone comprises gently dipping medium to coarse grained well sorted quartzose sandstones with conglomerates and minor thin siltstone/mudstone interbeds and coals extending up to at least 135 m north of Pilliga at Bellata 1 (Etheridge 1987) and 161 m west of Narrabri and 300 m in thickness in the south of the Coonamble Embayment (Tadros 1983) but averaging over 100 m. Minor interbeds of mudstone, siltstone, fine sandstone and coal may be locally present. Regionally, the formation dips gently westward reflecting the structure of the Coonamble Embayment; however, locally in the western part of the Bohena Trough, dips may be gently eastward due to minor subsidence within the heart of the Bohena Trough and Mullaley Sub-basin associated with a Tertiary compressional phase.

#### 4.5.8.4 Blythesdale Group (Keelindi Beds)

Overlying the Pilliga Sandstone across the majority of the project area (apart from the southwest corner) are strata referred to by Hawke and Cramsie (1984) as the Keelindi Beds. These sediments are Late Jurassic to Early Cretaceous age, containing off-white, coarse-grained, cross-bedded, well-sorted, porous, sandstone and conglomerate, interbedded with minor shale, siltstone and coal (Barnes *et al.* 2002). The Keelindi Beds are considered the lateral equivalent of the Orallo Formation, Mooga Sandstone and lowermost Bungil Formation of the Surat Basin to the west (Watkins and Meakin 1996) where they are collectively the Blythesdale Group (Keelindi beds). The group is understood to be approximately 30 to 50 m thick (AGE 2006) although the corehole and bore log data provided by Santos is inconclusive. URS (2012) has calculated the thickness in the project area to range from 0 to 88 m and averaging approximately 46 m thick.

### 4.5.9 Superficial Sediments

Within the Gunnedah Basin the superficial deposits principally consist of the Pliocene-to-recent unconsolidated deposits of the Gunnedah and overlying Narrabri formations (not formal stratigraphic names). The Gunnedah formation contains up to 115 m of Pliocene to Early-Pleistocene gravel and sand with minor clays. The overlying Narrabri formation consists of up to 70 m of extensive clays with minor channel sands and gravels.

The distribution of the Gunnedah and Narrabri formations is controlled by the existing major drainage patterns, with these sediments occupying the valley-fill bottom of the Namoi River and its tributaries. The combined thickness of the Narrabri and Gunnedah formations within the Gunnedah Basin is approximately 170 m (McNeilage 2006).

To the northwest beyond Narrabri, the Gunnedah formation is underlain by the Cubbaroo Formation consisting of Early-to-Late Miocene sand and gravel deposits with interbedded clays, infilling the pre-Miocene river channels downstream of Narrabri (Williams 1997).

Towards the west, north and east of the project area and beyond the immediate confines of the Namoi River floodplain, minor deposits of undifferentiated and unconsolidated alluvial and colluvial sediments have a limited occurrence and form localised surface cover over the sub-cropping Permo-Jurassic stratigraphy, with a thickness that locally can extend to several tens of metres. Those forming the channel infill along the Bohena Creek and tributaries are collectively known as the Bohena Creek Alluvium.

### 4.5.10 Structural Geological Controls

Compressional deformation is the dominant structural style in the Basement rocks of the Gunnedah Basin and was formed in response to periodic east-west compressive and left lateral strike slip movements along the main thrust. Four major phases of structural deformation are recognised:

- Foreland style deformation during inception of the Sydney Gunnedah Basin system. Early Permian Leard, Goonbri and Maules Creek Formation sediments unconformably overlie Boggabri Volcanics and Werrie Basalts. The main target coals were deposited during a quiescent period;
- Subsequent Late Permian east-west foreland basin compressional deformation is seen in parts of the northern Gunnedah Basin and was followed by major erosion. Seismic and well data in the northern Gunnedah Basin indicate a major angular unconformity between the Early Triassic Digby Formation and Permian sediments. Further south this appears to be represented by only a minor hiatus;
- Further east-west foreland basin compressional deformation during the Late Triassic culminated with folding, wrench and thrust faulting. Major erosion of Triassic and Permian sediments occurred at this time. This structural event represents the end of foreland basin development; and
- A Tertiary compressive phase associated with both intrusive and extrusive igneous activity (e.g. Liverpool and Warrumbungle Ranges in the south west and south east respectively) resulted in deformation of the Surat Basin sequence and accentuated structures formed in earlier tectonic phases.

There have been minor or no extensional stresses in the Bohena Trough, which displays a predominantly compressional regime. Analysis of core samples has not found evidence of extensional faulting in the trough (Golder Associates 2011).

### 4.5.11 Faulting

Information provided by Santos on major faulting in the project area , including fault types, their extents and probable ages (Figure 4-11) shows a relatively poor correlation between these results and the existing large-scale mapping of faults in the[2]OZSEEBASE datasets. Noting that the OZSEEBASE product was an inferred fault map based on features derived from several sources, including magnetic and gravity data.

Santos' investigations have identified four main phases of structural activity and faulting that are consistent with the above discussion of structural controls in the Gunnedah Basin:

- The Early Permian phase initiated the Gunnedah Basin as a discrete structural feature. The initial stage of this phase was marked by mechanical extension, rifting with normal faulting and

[2] http://www.frogtech.com.au/products/oz-seebas

in-fill with a thick sequence of volcanic rocks. Slowing of mechanical extension and replacement by passive thermal subsidence resulted in a subsequent stage of widespread sedimentation. In the project area, the Early Permian phase initiated the Bohena and Bellata Troughs and their in-fill with the Boggabri Volcanics and the Leard, Goonbri and Maules Creek Formations, including the Early Permian coals;

- The Middle Permian to Middle Triassic phase was marked by the development of the Gunnedah Basin as a foreland basin, and includes the most important phase of structuring and faulting. Extension and thermal subsidence ceased and was replaced by east-west compression associated with subduction. In the project area, the compressional forces resulted in differential subsidence, compressional anticlines and basin inversion, and the formation of reverse and thrust faults. Anticlines are generally bounded at depth by high angle reverse faults, which rarely extend higher than the Late Triassic unconformity. Listric faults formed on the crests of some of the larger anticlines (e.g. Wilga Park);

- The Jurassic-Cretaceous phase featured the formation of the Surat Basin through intra-cratonic sag. Sediment deposition occurred in association with slow, relatively even and laterally extensive subsidence with little deformation. No major unconformities are recognised within the Surat Basin sequence and deformation was limited to mild compression, which produced flexures above older faults. Within the project area, local structuring is characterised by drape over basement highs, subsidence caused by compaction above Permian and Triassic depocentres, and differential reactivation; and

- The Tertiary phase was marked by intrusive and extrusive igneous activity; uplift of eastern NSW with tilting and erosion of the Surat Basin sequence; and gentle folding of Jurassic rocks with very minor fault reactivation.

A far field tectonic event associated with the breakup of Gondwana during the Late Triassic to Early Cretaceous also affected eastern Australia. In the project area, this event is represented by the intrusive and extrusive rocks of the Garrawilla Volcanics. Many dykes, sills and lava flows were formed over this period, and small scale tensional normal faults may be associated with these events.

The investigation concluded that the majority of the faults in the project area are Permian to Triassic in age and mainly displace Permian and (to a lesser extent) Triassic strata. The amount of displacement is less than 100 metres. From the seismic data no evidence was found of large post-Jurassic age faults that displace Jurassic strata and extend into underlying Triassic and Permian strata. Where it is present, surface faulting and displacement in the Jurassic strata was found to be minor.

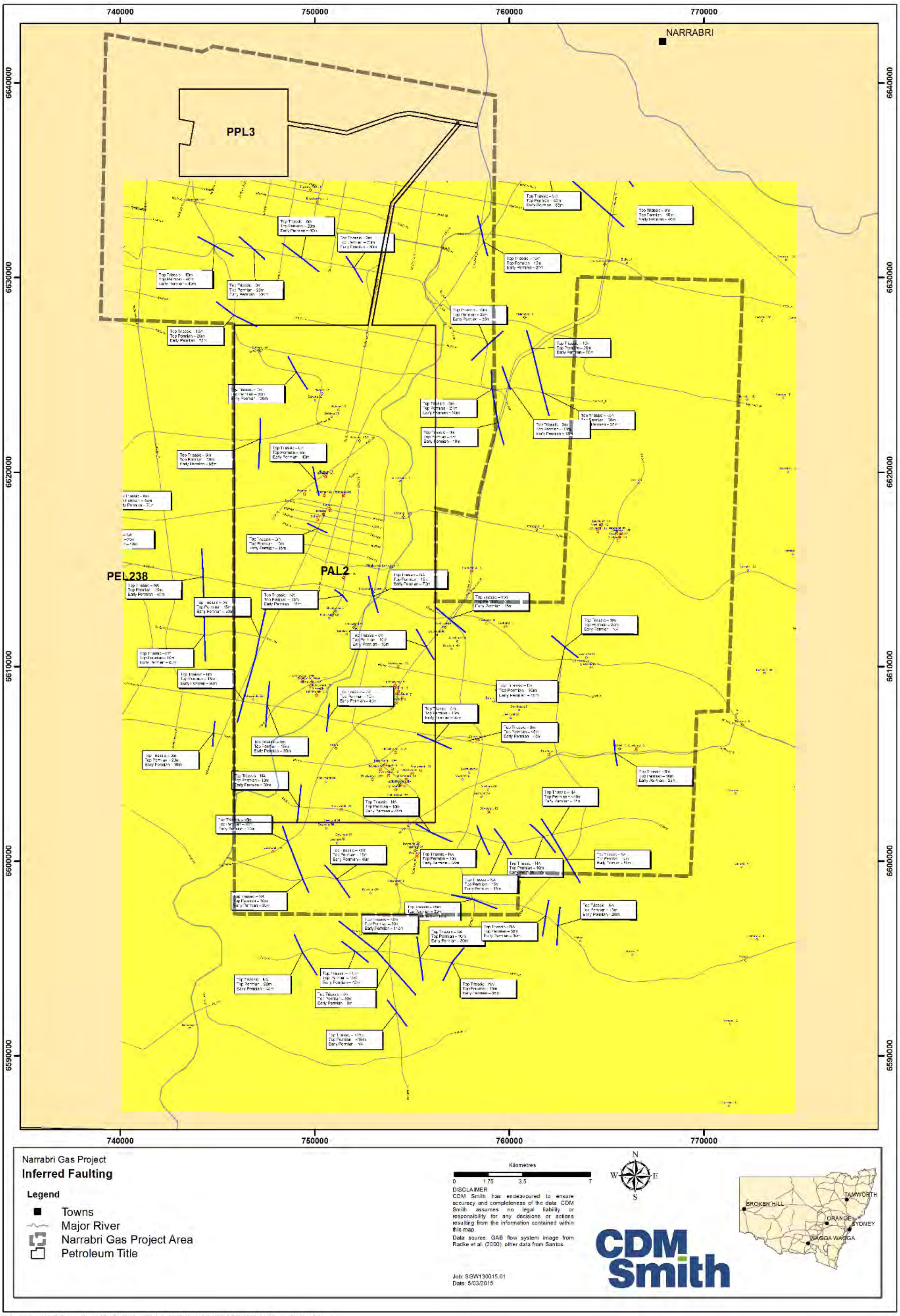


Figure 4-11 Inferred faulting across the project area

# 4.6 Surface Water and Groundwater Values

## 4.6.1 Groundwater Dependent Ecosystems

Evaluation of groundwater dependent ecosystems (GDEs) is conducted for the project through the GDE impact assessment included as Appendix B. The GDE impat assessment is undertaken in line with the current national framework for assessing the environmental water requirements of GDEs and utilises the GDE toolbox (Richardson et al. 2011). The GDE toolbox provides a starting point for investigating potential impacts on GDEs and is used as a framework to ensure that critical questions regarding risks to GDEs are addressed in the assessment. The assessment also follows DPI Water's GDE risk assessment guidelines (Serov et al. 2012) for all of the GDE types present in the study area.

Potential GDEs identified in the risk assessment are shown on the map in Figure 4-12.

Potential GDEs are classified into the three broad types defined by Eamus and Froend (2006) which are also recognised in the Namoi subregion bioregional assessment (Welsh et al. 2014):

- Type 1 GDEs - aquifers and stygofauna ecosystems referring to ecosystems that reside within the spaces of caves and aquifers;
- Type 2 GDEs - ecosystems dependent on the surface expression of groundwater, referring to ecosystems that are connected to groundwater that comes to the earth's surface, within wetlands, lakes, seeps, springs and river baseflow; and
- Type 3 GDEs - ecosystems dependent on the sub surface presence of groundwater, referring to ecosystems associated with terrestrial vegetation utilising the water table below the natural surface.

The study area for the GDE impact assessment is defined by the extent of maximum predicted depressurisation from the project exceeding 0.5 metres drawdown of hydraulic head (reported in Section 6.8 of the GIA) which is then projected vertically to the land surface and extended in size by a buffer zone of 5 km. The resulting GDE study area shown in Figure 4-12 covers an area of 3,946 $km^2$.

The GDE impact assessment found that potential Type 2 and Type 3 GDEs are present in the study area but no Type 1 GDEs with potential to be impacted by the project are present. Nine potential Type 2 GDEs that may be reliant on surface expression of groundwater are identified in the GDE impact assessment, and the Namoi River, Bohena Creek and Coghill Creek were identified in the GDE atlas as streams potentially receiving surface expression of groundwater.

Large areas of vegetation in the GDE atlas are mapped as having moderate potential for dependence on sub-surface expression of groundwater; however, detailed local vegetation mapping within the project area has shown that the distribution of potential Type 3 GDEs is much smaller than was estimated using the methodology of the GDE Atlas (refer to Figure 4-12). Vegetation communities with potential groundwater dependence are found to be concentrated in riparian areas, and include areas of:

- Rough-barked Apple – red gum – cypress pine woodland;
- Red gum – Rough-barked Apple with and without tea tree sandy creek woodland;
- Fuzzy Box Woodland (listed as endangered under the TSC Act); and

- A small area of Carbeen - White Cypress Pine – Curracabah – White Box tall woodland (listed as endangered under the TSC Act).

In relation to potential Type 2 GDEs that may be reliant on surface expression of groundwater, the assessment found:

- There are no known groundwater-dependent protected species or habitats in the study area;
- There are nine potential Type 2 GDEs considered likely to be dependent on groundwater;
- All potential Type 2 GDEs have low ecological values, mainly due to the absence of protected or important wetland species, and due to the heavily or moderately modified nature of the sites;
- None of the potential Type 2 GDEs meet the definition of a high-priority GDE in NSW, and therefore they fall outside of the minimal impact considerations of the NSW Aquifer Interference Policy;
- None of the potential Type 2 GDEs support Matters of National Environmental Significance (MNES) defined under the EPBC Act; and
- All nine potential Type 2 GDEs have water sources derived from either the Pilliga Sandstone aquifer or alluvial aquifers. At least two of the potential GDEs derive their water sources from pre-existing bores flowing freely to the land surface under artesian pressure.

In relation to potential Type 3 GDEs that may be reliant of the sub-surface expression of groundwater the assessment found:

- The Type 3 GDEs identified in the assessment are 'potential' GDEs based on absence of field data to verify if the vegetation communities access groundwater;
- Two vegetation communities listed as endangered under the TSC Act are identified as potential Type 3 GDEs within the project area; these being located predominantly in riparian areas of Bohena Creek and its tributaries; and
- Potential Type 3 GDEs source groundwater predominantly from the water table; however, they are also able to source soil water from rainfall recharge and surface flow events within alluvial settings.

Additional information and further analysis of the potential risks to GDEs from the project can be found in Section 7 and Appendix B of this report.

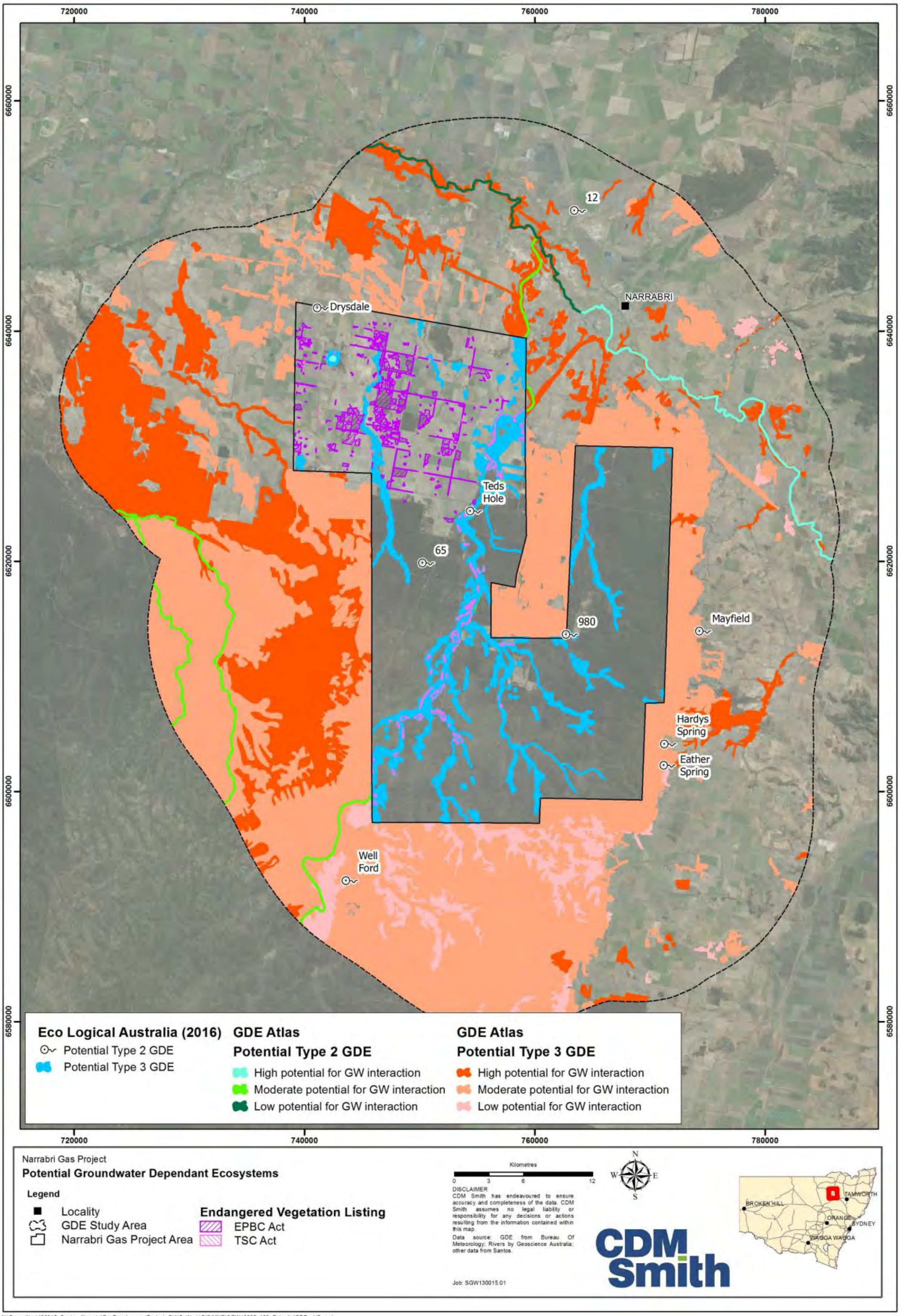


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**Figure 4-12 Potential groundwater dependent ecosystems**

### 4.6.2 Water Bearing Strata of the Murray Darling Basin

The Murray Darling Basin (MDB) is a surface water catchment incorporating the Murray Geological Basin, the Darling River Drainage Basin and the highland areas within the surface water catchments of the Murray and Darling Rivers.

The former Murray-Darling Basin Commission (now Murray-Darling Basin Authority) in *Introducing Groundwater to your Catchment* (URS 2007a) lists the main hydrogeological subsystems of the Namoi River catchment to be:

- Barwon Highlands: Fractured Palaeozoic and Mesozoic bedrock, basalts and upland alluvium located up steam of Narrabri;
- Gunnedah Subsystem: Coarse-grained river gravels and sands; major water supply for irrigated agriculture also located upstream of Narrabri (Upper Namoi Alluvium);
- Narrabri Subsystem: Shallow alluvial fan deposits associated with the Namoi River (Lower Namoi Alluvium); and
- Great Artesian Basin: Complex multi-layered system of water bearing sandstones confined by shales and mudstones, up to 2,000 m deep at its western extent and outcropping within the project area.

The formations of the Gunnedah-Oxley Basin are also considered to be groundwater sources within the MDB. The DPI Water has formally identified these formations as MDB groundwater sources in the *Water Sharing Plan for Murray Darling Basin Porous Rock Groundwater Sources 2011*. *The Water Act 2007* excludes groundwater in the GAB from the definition of the MDB water resources, as the GAB formations are considered to be hydraulically isolated from the underlying Gunnedah-Oxley Basin formations under natural conditions.

For the purposes of this assessment, the Gunnedah and Narrabri Subsystems are not differentiated and are referred to as the shallow alluvial groundwater source of the Namoi River. The GAB groundwater sources, irrespective of whether they are considered as part of the broader MDB groundwater catchment, are of particular interest to the project as they directly overlie the Gunnedah-Oxley Basin formations that are the subject of coal seam gas development, and they are the subject of greater water supply development than the Gunnedah-Oxley Basin formations. The Barwon Highlands are located outside of the GIA study area and are not considered further here. The remaining groundwater sources are dealt with in more detail below.

#### 4.6.2.1 Shallow Alluvium of the Upper and Lower Namoi

For the purposes of this assessment, the Gunnedah and Narrabri subsystems are referred to as the shallow alluvial groundwater sources of the Namoi River, divided into two separate systems: the Upper and Lower Namoi groundwater sources respectively.

Groundwater has been a major source of water for irrigation in this area since the 1970s and most abstraction has come from the Gunnedah Subsystem. The Gunnedah Subsystem sediments were deposited from streams draining the Barwon Highlands area to the east. In this catchment the Gunnedah Subsystem is overlain by the Narrabri Subsystem sediments and the two subsystems are hydraulically connected (URS 2007b).

Recharge to the groundwater source is mainly by rainfall, major overland flood events and the irrigation that takes place extensively in the area. Some recharge derives from normal river flows, and the volume and rate of this recharge is itself influenced by the pattern of groundwater pumping and the degree to which it induces additional losses from the river.

#### 4.6.2.2 Great Artesian Basin

The GAB groundwater sources within the GIA study area are generally associated with dual-porosity (fractured and porous) sandstone rocks (Cretaceous and Jurassic strata) which lie beneath the Lower Namoi Sub-catchment of the Namoi River Catchment. The groundwater source is not present in the Upper Namoi Sub-catchment, terminating towards the eastern margin of the site. The GAB is overlain by the Gunnedah and Narrabri Subsystem sediments that were deposited during the Tertiary period. The groundwater sources of the GAB are recharged from rainfall and surface water infiltration along the western side of the Great Dividing Range (GDR). The GIA study area takes in more than half of the southern recharge bed of the GAB, wherein the GAB units have outcrops that receive recharge directly from rainfall infiltration. The GAB consists of a complex multi-layered system of water bearing sandstones separated by predominantly shale and mudstone confining beds. Most rock units outcrop near the eastern margins of the Murray-Darling Basin, and dip to the west (URS 2007b).

#### 4.6.2.3 Gunnedah-Oxley Basin Strata

Underlying the Jurassic-Cretaceous GAB strata at great depth are the Permian strata targeted for coal seam gas extraction. They are not exploited as a groundwater source and are hydraulically separated from the overlying GAB groundwater sources by overlying Permian and Triassic strata. Smerdon and Ransley (2012) assessed the hydraulic connectivity of the basal GAB units directly overlying the Permo-Triassic strata and determined that these strata constituted an aquiclude throughout the region encompassing the project area. Hence the Gunnedah-Oxley Basin strata are confined in the project area, with the potentiometric head observed as being above ground level. Observed vertical hydraulic gradients in the project area (based largely on drill stem tests) are upwards and therefore groundwater is not likely to infiltrate downwards from overlying strata. Recharge is therefore likely to come from outcropping areas of these strata that lie to the east and to the far south of the project area.

### 4.6.3 Aquatic Ecosystems

An environmental audit of the Namoi Catchment has highlighted the following aquatic ecosystems that have the potential to be adversely impacted from changes in groundwater flow and disturbance from coal seam gas development:

- The Namoi region contains one wetland of national importance; Lake Goran (NSW005) which is adjacent to the Liverpool plains. The lake is the terminus of an internal drainage basin that does not connect to the Namoi River (although an conduit exists that allows the lake to over-spill to the Mooki River along Native Dog Gully at times of very high lake level); and

- The Namoi River system provides a wide range of aquatic habitats and is ecologically important. The floodplain downstream of Narrabri contains large areas of anabranches and billabongs. When flooded, these areas are considered to be important and research on similar rivers has established that they provide large amounts of organic carbon that is considered to be essential to the functioning of aquatic ecosystems.

These ecosystems occur within the GIA study area but are outside of the project area. Watercourses within the project area are ephemeral and considered unlikely to sustain viable aquatic ecosystems, with the exception of potential aquatic ecosystems supported by the recharge springs identified to the east of the project area.

# 4.7 Terrestrial Environment

The project area is located within the Brigalow Belt South Bioregion which extends from central Queensland south to northern New South Wales (NSW) and is characterised by a subhumid climate. The vegetation in the project area is predominantly composed of dry woodland vegetation associated with the Pilliga East and Bibblewindi State Forests. The Pilliga forest is classified within the Groundwater Dependent Ecosystem Atlas (Bureau of Meteorology 2012) as having moderate potential for groundwater interaction, which corresponds to the possible presence of groundwater and possible utilisation of groundwater by ecosystems.

The project area potentially supports 47 threatened fauna species, 9 migratory bird species, 10 threatened plants, and 4 threatened ecological communities as listed under NSW's Threatened Species Conservation Act 1995 (TSC) and/or the Commonwealth's EPBC Act. Vegetation communities in the project area are diverse and vary with slope, aspect and soil type, although the north-west region of the project area has relatively fertile soils where the native vegetation has been cleared for agricultural purposes.

Vegetation mapping for the project area (Figure 4-13) identified a total of twenty-two Plant Community Types totalling 80,519 ha of native vegetation. Four of the mapped Plant Community Types qualify as endangered ecological communities (with two of these endangered ecological communities being further divided by status under the EPBC Act and TSC Act due to condition) (Figure 4-14):

- Weeping Myall Woodlands (EPBC Act) / Myall Woodland in the Darling Riverine Plains, Brigalow Belt South, Cobar Peneplain, Murray-Darling Depression, Riverina and NSW South Western Slopes bioregions (TSC Act) - single small remnant located in the north-west of the Project area;
- Brigalow (Acacia harpophylla dominant and co-dominant) (EPBC Act) / Brigalow within the Brigalow Belt South, Nandewar and Darling Riverine Plains Bioregions (TSC Act) - located on the alluvial plains in the north-west of the Project area;
- Fuzzy Box Woodland on alluvial Soils of the South Western Slopes, Darling Riverine Plains and Brigalow Belt South Bioregions (TSC Act) – located on alluvial soils on the floodplain of Bohena Creek; and
- Carbeen Open Forest community in the Darling Riverine Plains and Brigalow Belt South Bioregions (TSC Act) – two small remnants located in the north-west of the project area.

General threats to these communities include vegetation clearing, fire, invasive weeds and inappropriate grazing regimes. Brigalow (Acacia harpophylla) and its associated species have a broad range of environmental tolerance (Butler 2007) which may allow some capacity to cope with changes in groundwater. Threats specific to the potential changes in water table elevation are assessed further in Section 6.11.2.

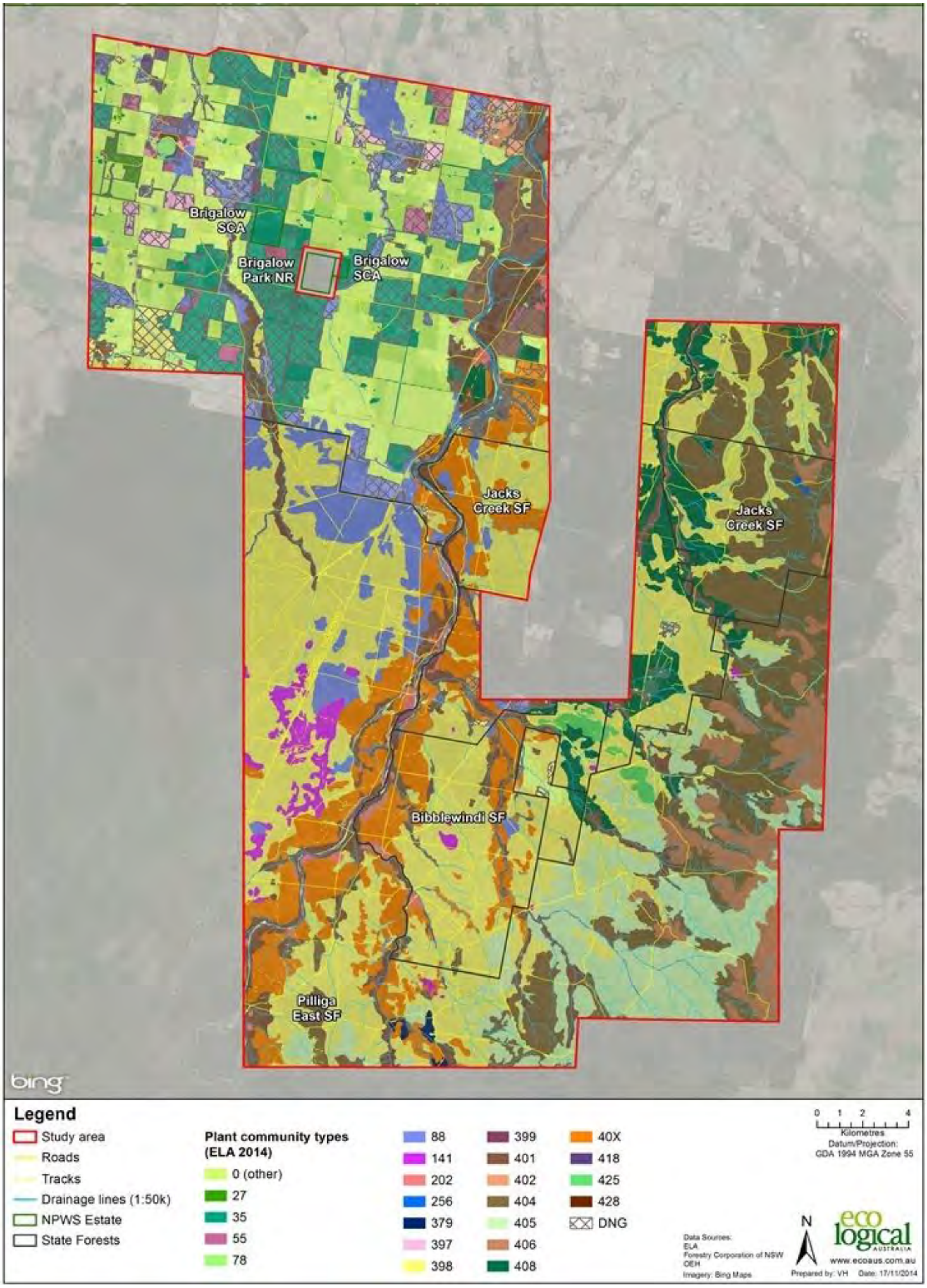



**Figure 4-13 Vegetation mapping: plant community types (source: Eco Logical)**

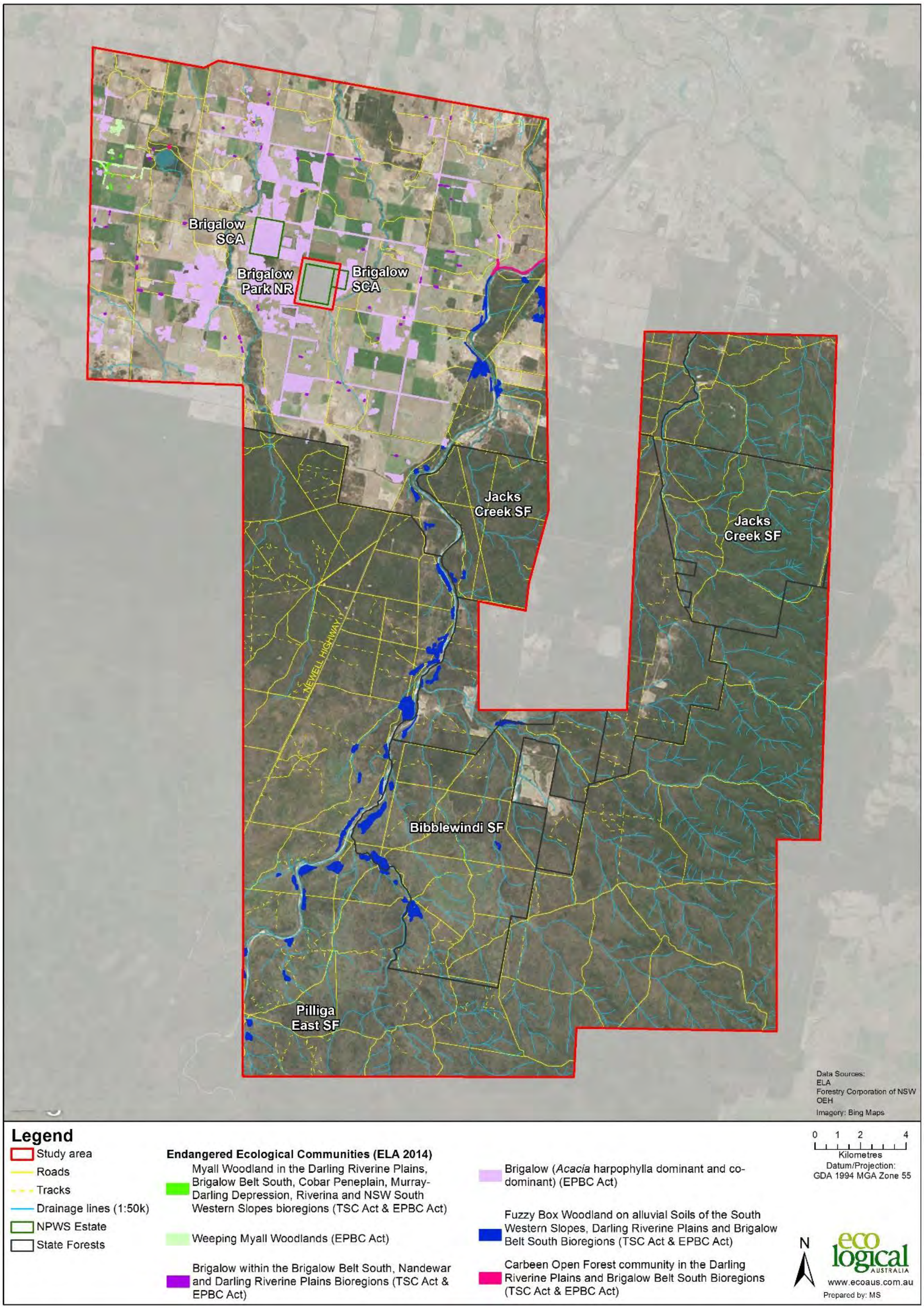



**Figure 4-14 Vegetation mapping: endangered ecological communities (source: Eco Logical)**

# 4.8 Existing Water Abstraction and Entitlements

The Namoi River and its associated alluvial groundwater sources and the Pilliga Sandstone of the GAB contain major water resources that are utilised for irrigation, potable water supply and livestock. Groundwater abstraction within some parts of the project area, and in close proximity to it, is limited by constraints on land use within the Pilliga East, Pilliga West and Bibblewindi State Forests (Section 4.2).

There is no known use of groundwater within the target coal seams of the Maules Creek Formation (Rutley, Namoi, Parkes and Bohena seams) or within coal seams within the Late Permian strata of the Black Jack Group.

Figure 4-15 shows the locations of groundwater bores registered in the PINNEENA (v.4.1) database. The locations are colour-coded by selected Groundwater Management Areas (GMAs) which include the Upper and Lower Namoi Alluvium, the Gunnedah and Oxley Basins, and the GAB Surat Basin. Although this information is not recorded for all bores within the database, the densities of registered bores in Figure 4-15 and the colour-coding of selected GMAs show intensive development of shallow groundwater sources within the Namoi alluvium, as well as the importance of the Pilliga Sandstone as a major regional aquifer.

## 4.8.1 Groundwater Abstraction

Analysis of the existing groundwater resource usage in the project area is based on the PINNEENA (v.4.1) groundwater database. The intended uses and water sources were reviewed for bores located within 30 km of the project area. Shallow groundwater sources within the alluvium and GAB are generally of good quality and are utilised for a diverse range of activities. Deeper groundwater in the Gunnedah Basin is less utilised due to its depth and inferior water quality, and is less accessible due to lack of transmissive strata.

Groundwater sources recognised in NSW Water Sharing Plans include:

- Shallow alluvial groundwater overlaying the GAB (Upper and Lower Namoi Groundwater Sources);
- Shallow groundwater within the Pilliga Sandstone of the GAB (Southern Recharge Groundwater Source); and
- Deeper groundwater within porous rocks of the Gunnedah-Oxley Basin, including the Permian and Triassic strata in the Bohena Trough (Gunnedah-Oxley Basin Groundwater Source).

Figure 4-16 and Figure 4-17 show registered groundwater bores in the vicinity of the project area. Within 30 km of the project area there are 4,682 registered bores in the PINNEENA database. The majority of these bores (approximately 97%) are less than 150 m deep and tap shallow groundwater sources in the alluvium and Pilliga Sandstone. Most of the bores deeper than 150 m (Figure 4-17) are identified as being within the Great Artesian Basin GMA, and are probably also screened within the Pilliga Sandstone, which is typically 150 to 300 m thick in the project area. Bores that are greater than 150 m deep and identified as being within the Gunnedah Basin GMA to the east and southeast of the project area are 150 to 270 m deep and possibly screened within the Garrawilla Volcanics or other Permo-Triassic strata with locally developed permeability.

Figure 4-18 and Figure 4-19 summarise the types of groundwater bores located within 30 km of the project area and the water sources they tap. These data show that around one-third (33%) of registered bores are used for stock watering, 23% for domestic uses and 23% for irrigation. Approximately 7% of licences are for “other” specified uses, 7% are for monitoring bores, and the remaining 7% are unknown uses.

Groundwater usage in the vicinity of the project area can be summarised as being mainly for stock, domestic and irrigation purposes (i.e. approximately 85% of known uses). The predominant water supply development has occurred within the Upper and Lower Namoi alluvium and Pilliga Sandstone of the GAB. Approximately fifteen bores within 30 km of the project area are identified as accessing deeper groundwater sources in the Gunnedah-Oxley Basin. These bores are located east of the project area and within the outcrop area of the Gunnedah-Oxley Basin, which is situated between the southern recharge beds of the Pilliga Sandstone and the Namoi alluvium.

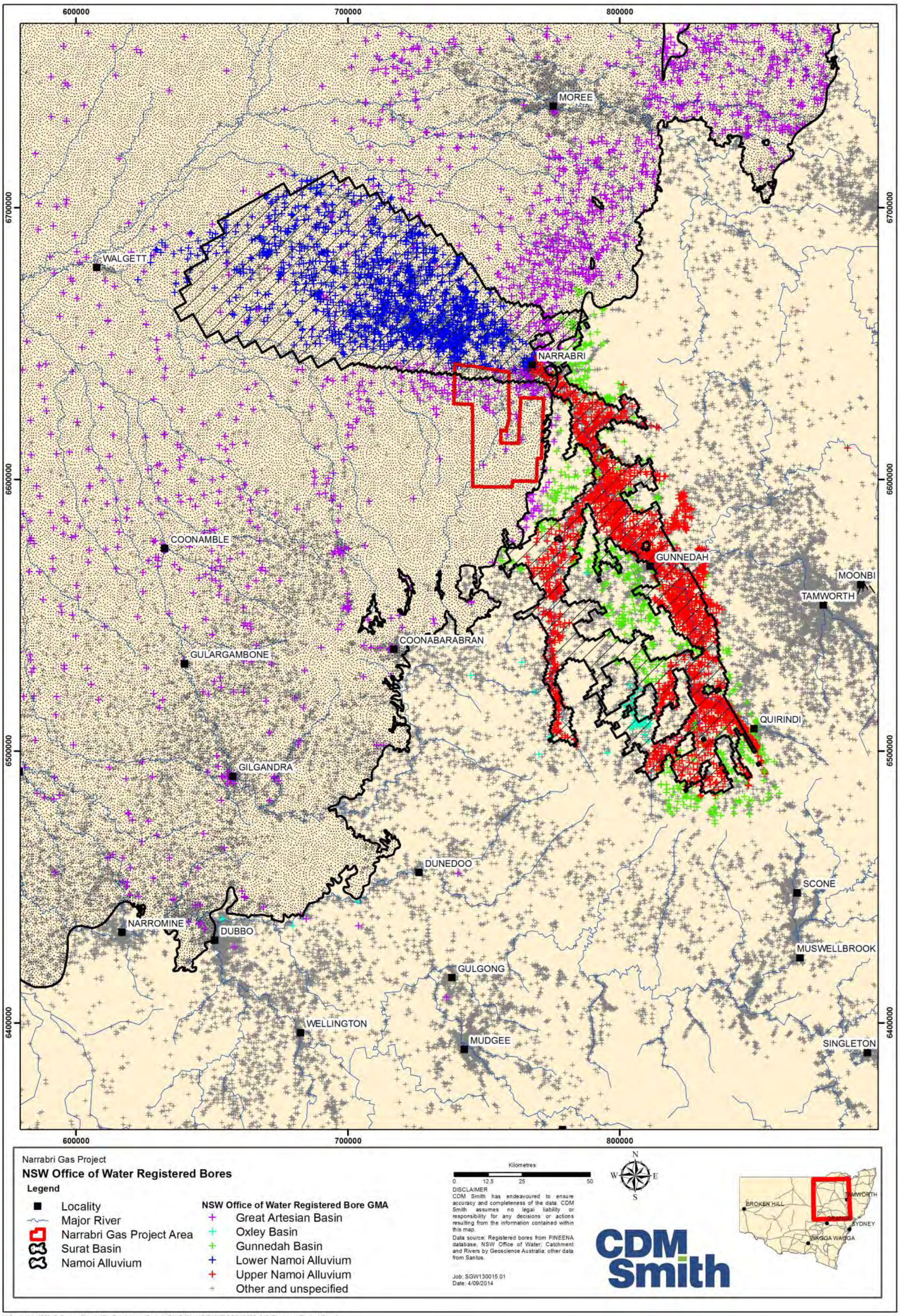



**Figure 4-15 DPI Water registered groundwater bores**

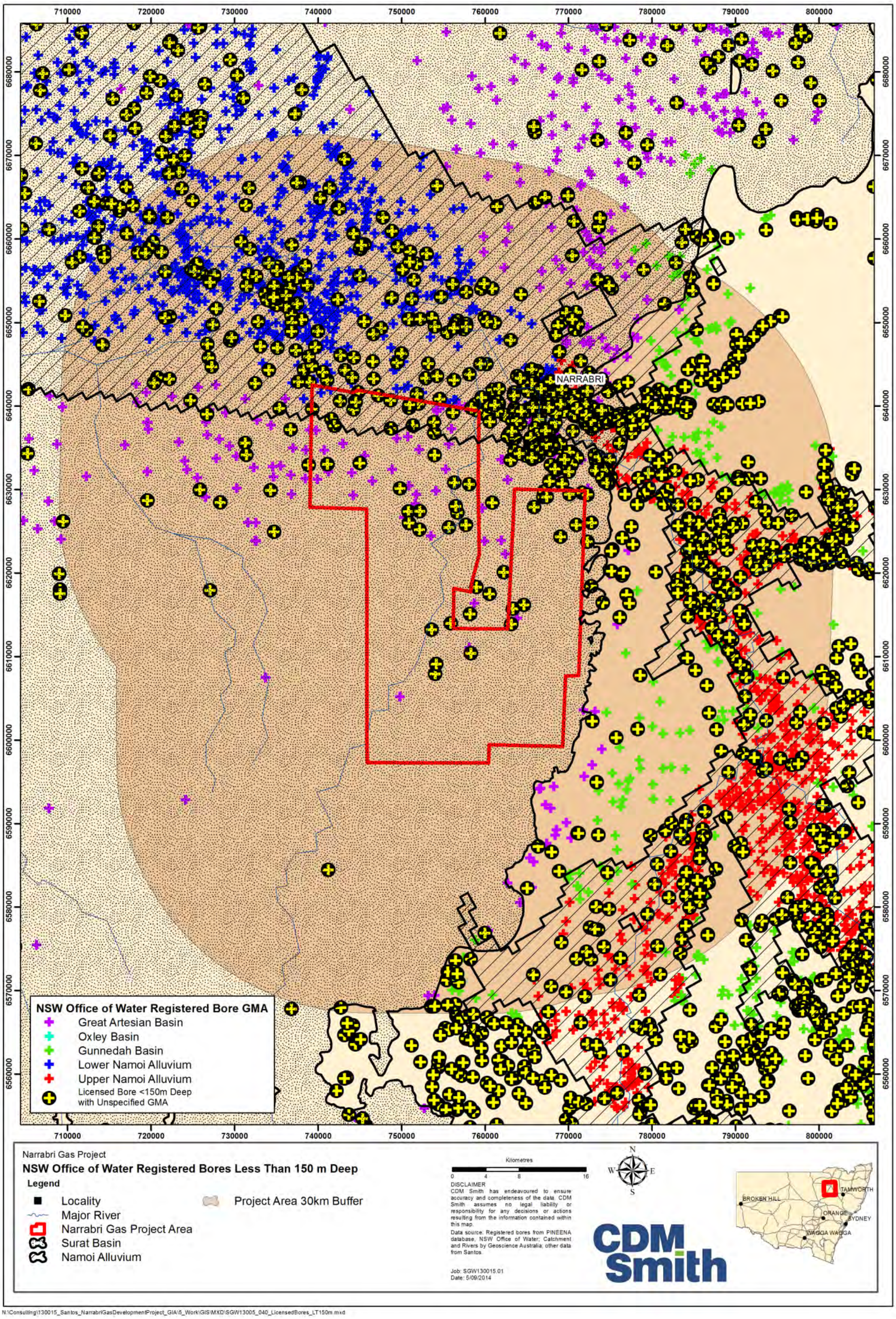



**Figure 4-16 Licensed groundwater bores less than 150-m deep**

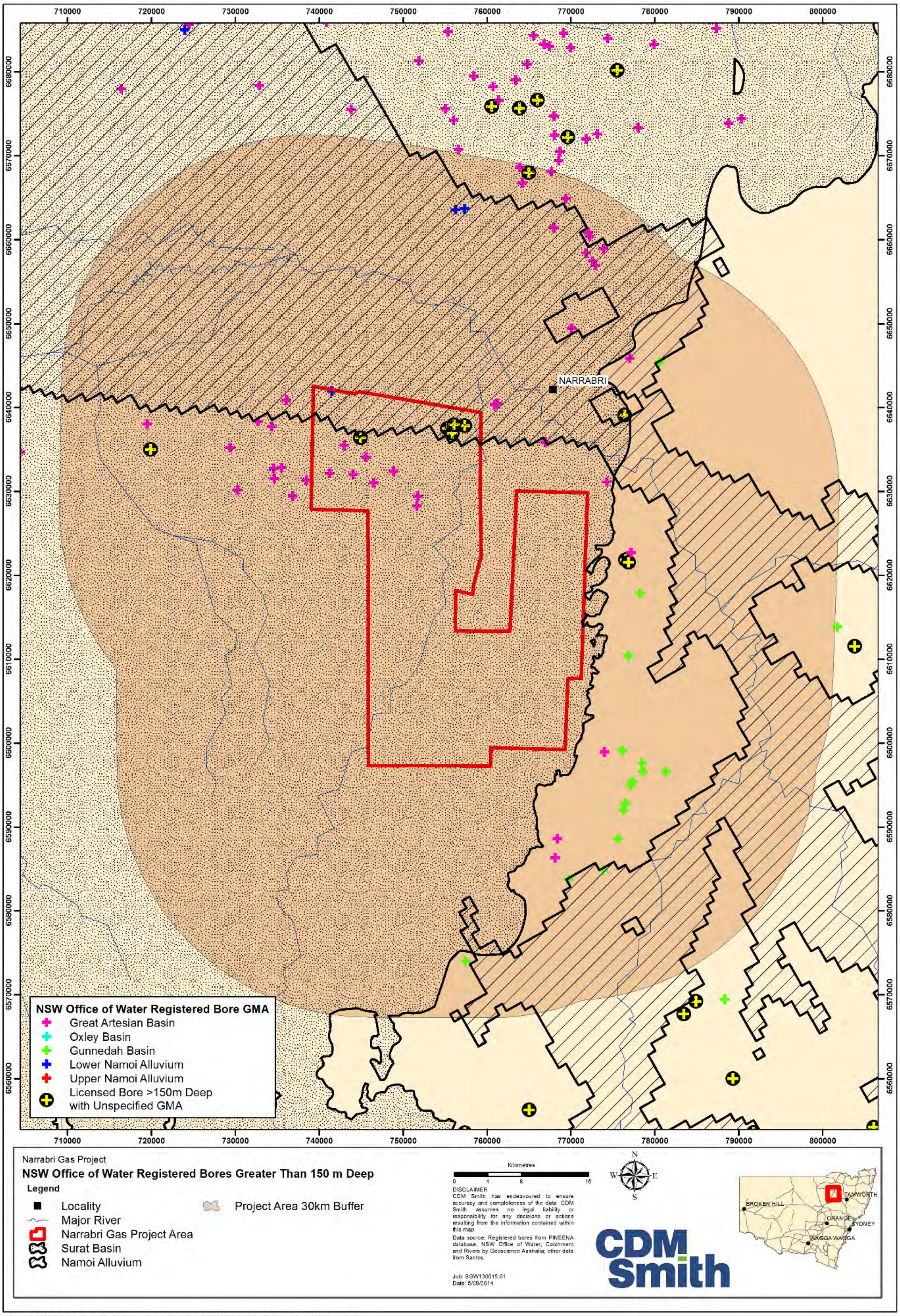



**Figure 4-17 Licensed groundwater bores greater than 150-m deep**

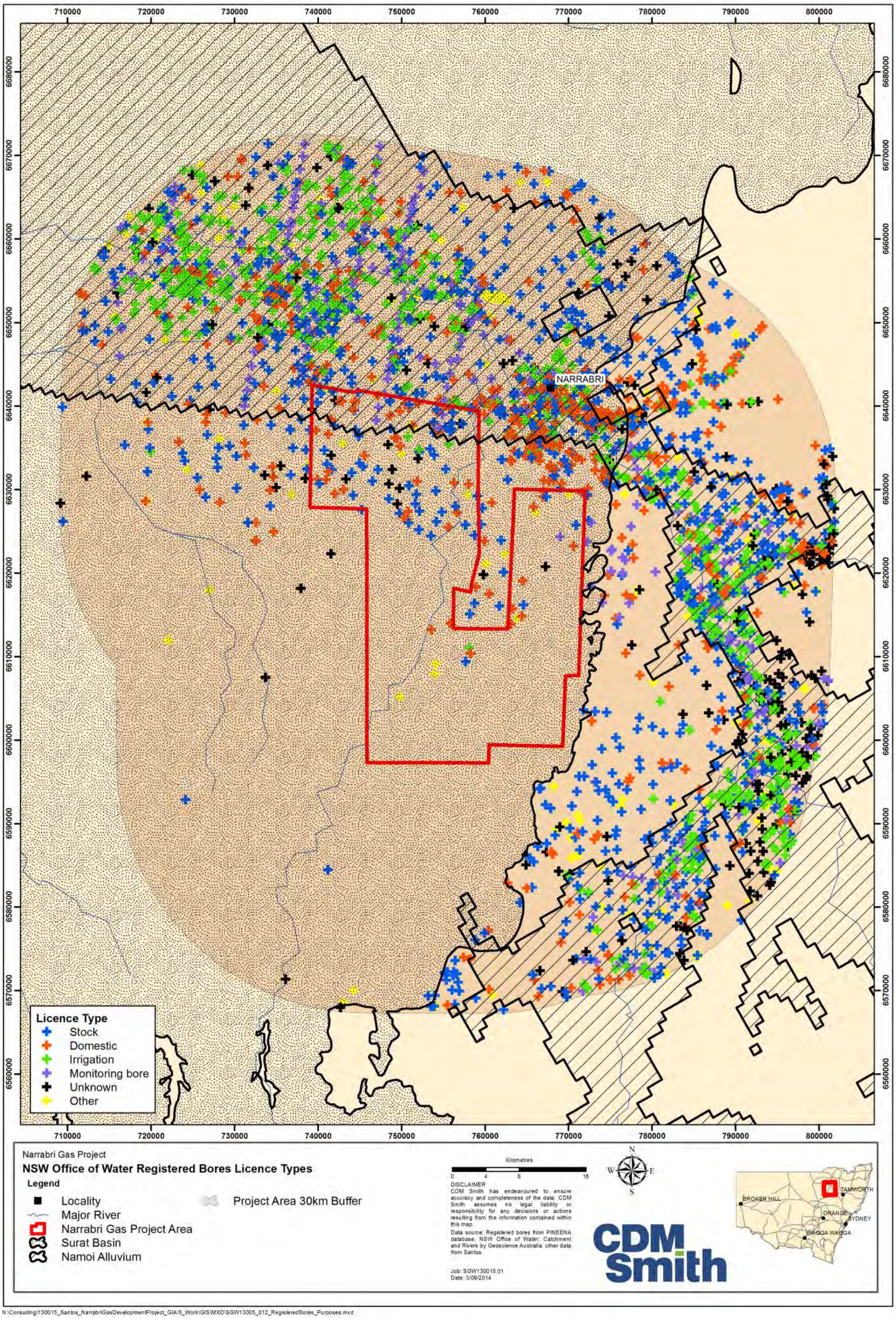



**Figure 4-18 Groundwater licences**

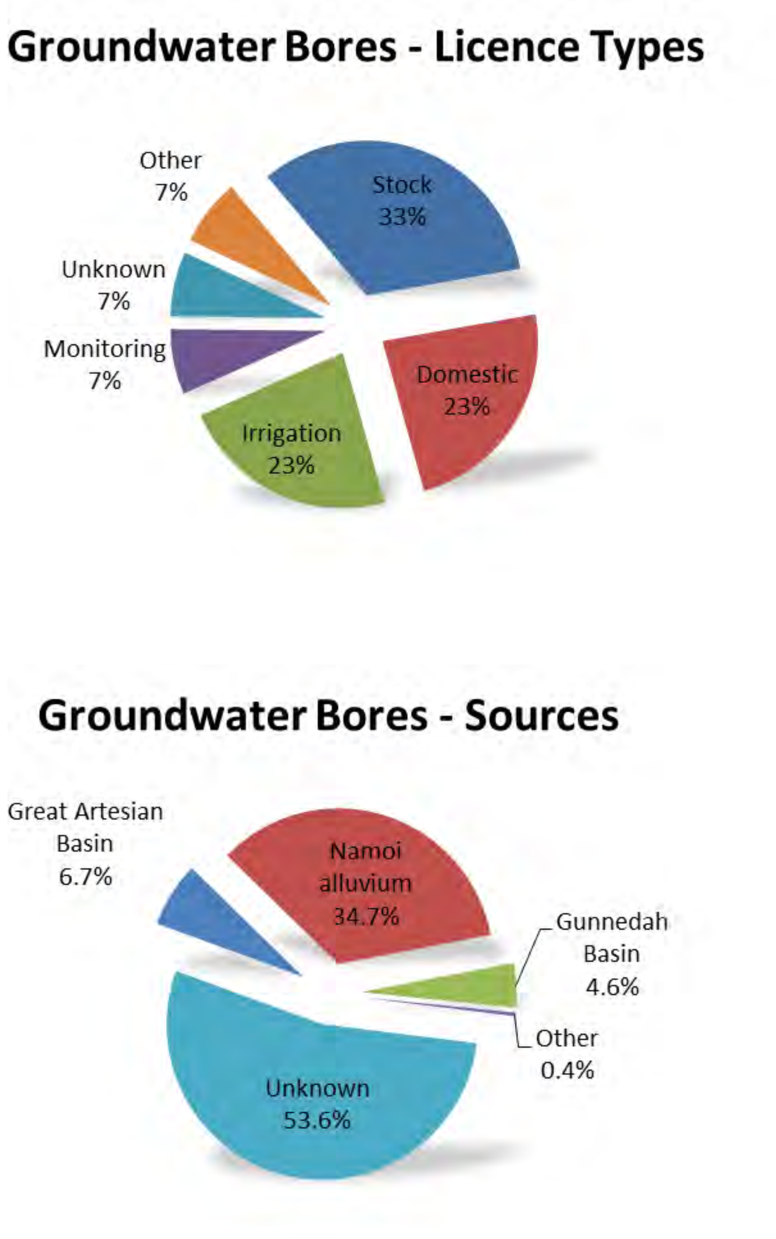



**Figure 4-19 Groundwater usage charts**

### 4.8.2 Water Licences

Water licences identified in NSW Water Sharing Plans and on the Water Register that are relevant to the GIA study area are listed in Table 4-5.

**Table 4-5 Groundwater source licences**

| Relevant Water Sharing Plan | Groundwater Source | Total Number of Licences Issued | Total Share Components Issued | LTAAEL* [ML/y] |
|---|---|---|---|---|
| NSW Murray-Darling Basin Porous Rock Groundwater Sources 2011 | Gunnedah-Oxley MDB | 142 aquifer<br>3 local utility | 23,109 aquifer<br>480 local utility | 205,640 |
| NSW Murray-Darling Basin Fractured Rock Groundwater Sources 2011 | Liverpool Ranges Basalt MDB | 12 aquifer | 422 aquifer | 19,075 |
| | Warrumbungle Basalt | 4 aquifer | 71 aquifer | 5,710 |
| NSW Great Artesian Basin Groundwater Sources 2008 | GAB Surat | 51 aquifer<br>10 local utility<br>1 Aquifer (TW) | 5,502 aquifer<br>3,318 local utility<br>25 aquifer (TW) | 35,097** |
| | Southern Recharge | 148 aquifer<br>9 local utility | 24,432 aquifer<br>3,066 local utility | 29,680 |
| Upper and Lower Namoi Groundwater Sources 2003 | Upper Namoi | 562 aquifer<br>9 local utility | 109,804 aquifer<br>6,280 local utility | 122,100 |
| | Lower Namoi | 213 aquifer<br>3 local utility | 81,586 aquifer<br>4,407 local utility | 86,000 |

Source: NSW Water Register, DPI Water 2016/17
*Long Term Annual Average Extraction Limit
** As at 30 June 2014 as advised by DPI Water on 27 July 2016

# 5 Conceptual Hydrogeological Model

This section describes the conceptualisation of the groundwater flow system within the GIA study area for the purpose of developing a clear understanding of the processes underpinning the regional hydrogeology and as a platform for developing a numerical groundwater flow model. The domain of interest is shown in Figure 5-1 as the GBRM (Gunnedah Basin Regional Model) boundary.

The conceptual model presented in this assessment adopts concepts from previous groundwater modelling within and near the GIA study area (Figure 5-1). Those studies include modelling of shallow alluvial sources within the Lower Namoi alluvium (Merrick 1999, 2000, 2001), the Lower Gwydir alluvium (Bilge 2002), the Upper Namoi alluvium (McNeilage 2006) and the Lower Macquarie alluvium (Bilge 2007). Conceptualisation of deeper groundwater sources also adopts ideas from groundwater investigation and modelling of the Great Artesian Basin (Radke *et al.* 2000; Welsh 2000, 2006) and recent modelling of the Gunnedah-Oxley Basin for the Namoi Catchment Water Study (SWS 2011, 2012a).

## 5.1 Hydrogeological Domain

The project area is located near the eastern edge of the Great Artesian Basin (GAB) where it onlaps the underlying Gunnedah Basin. The Hunter-Mooki Fault system forms the eastern extent of both basins within the GIA study area and is chosen as the eastern boundary of the hydrogeological domain. To the north, south and west of the project area, natural geological boundaries do not exist and artificial boundaries must therefore be established to define practical limits for the numerical groundwater flow modelling.

Previous groundwater modelling for the Namoi Catchment Water Study (SWS 2012a) predicted that cumulative groundwater impacts from concurrent development of the Narrabri and Gunnedah gas fields would extend north and south beyond the boundary of the Namoi Catchment after about 30 years, suggesting that regional boundaries for groundwater modelling should be located further away than in that study.

The northern limit of the hydrogeological domain in this assessment extends approximately to the northern limit of the Gunnedah Basin, which is around 70 km north of the project area. The boundary of the hydrogeological domain is aligned approximately with the direction of regional groundwater flow from east to west within the GAB and the northern limit of the Coonamble Embayment flow system within the GAB (Radke *et al.* 2000). A map of the GAB flow systems showing the Coonamble Embayment and Project location can be seen in Figure 5-2.

The northern boundary of the hydrogeological domain is positioned along the southern limit of the Lower Gwydir groundwater model domain (Bilge 2002) which was represented as a no-flow boundary for the Lower Gwydir alluvial groundwater source. The Lower Gwydir alluvium therefore lies directly north of the hydrogeological domain in this assessment and is not included in the modelling.

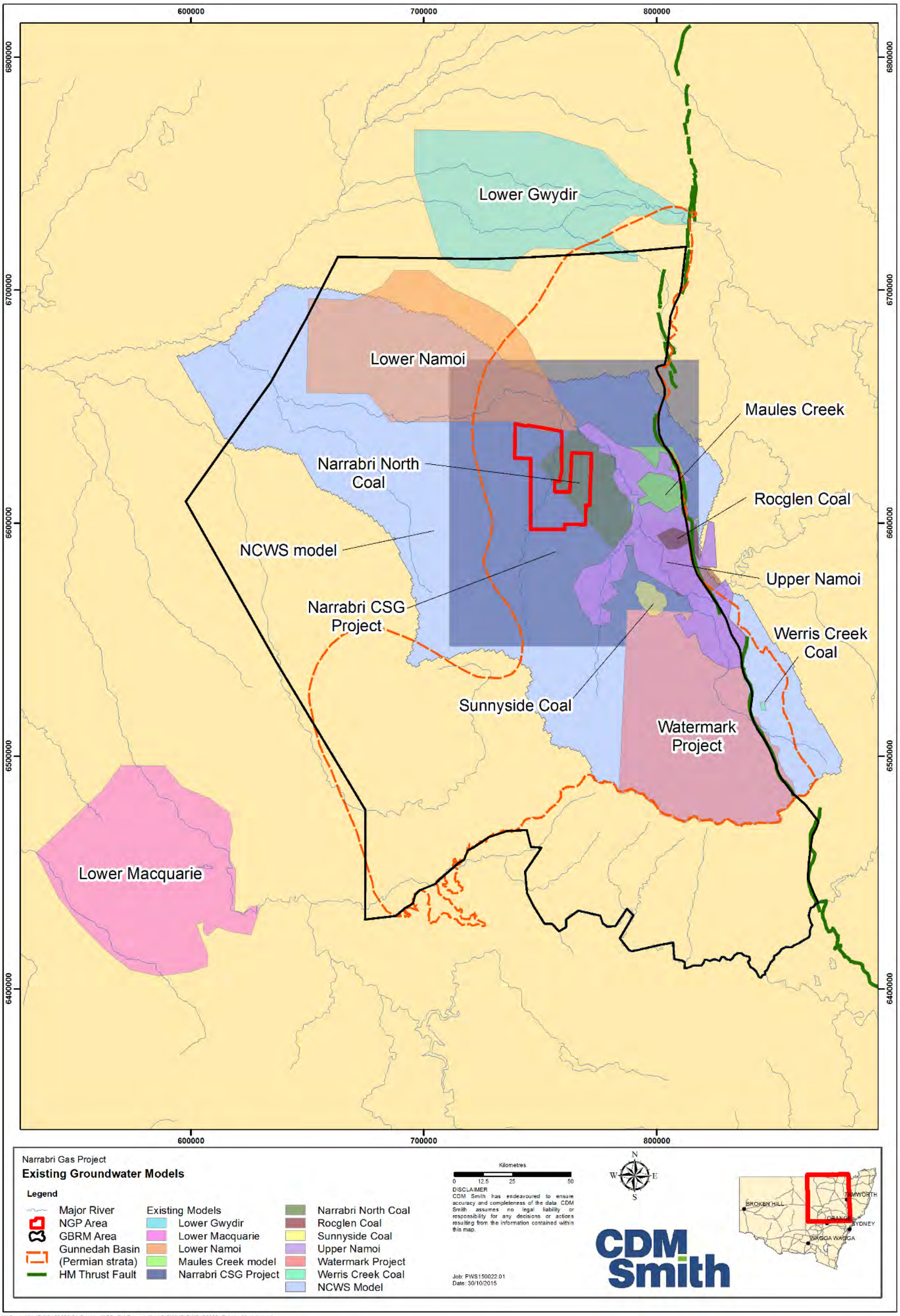



**Figure 5-1 Existing groundwater models in the GIA study area**

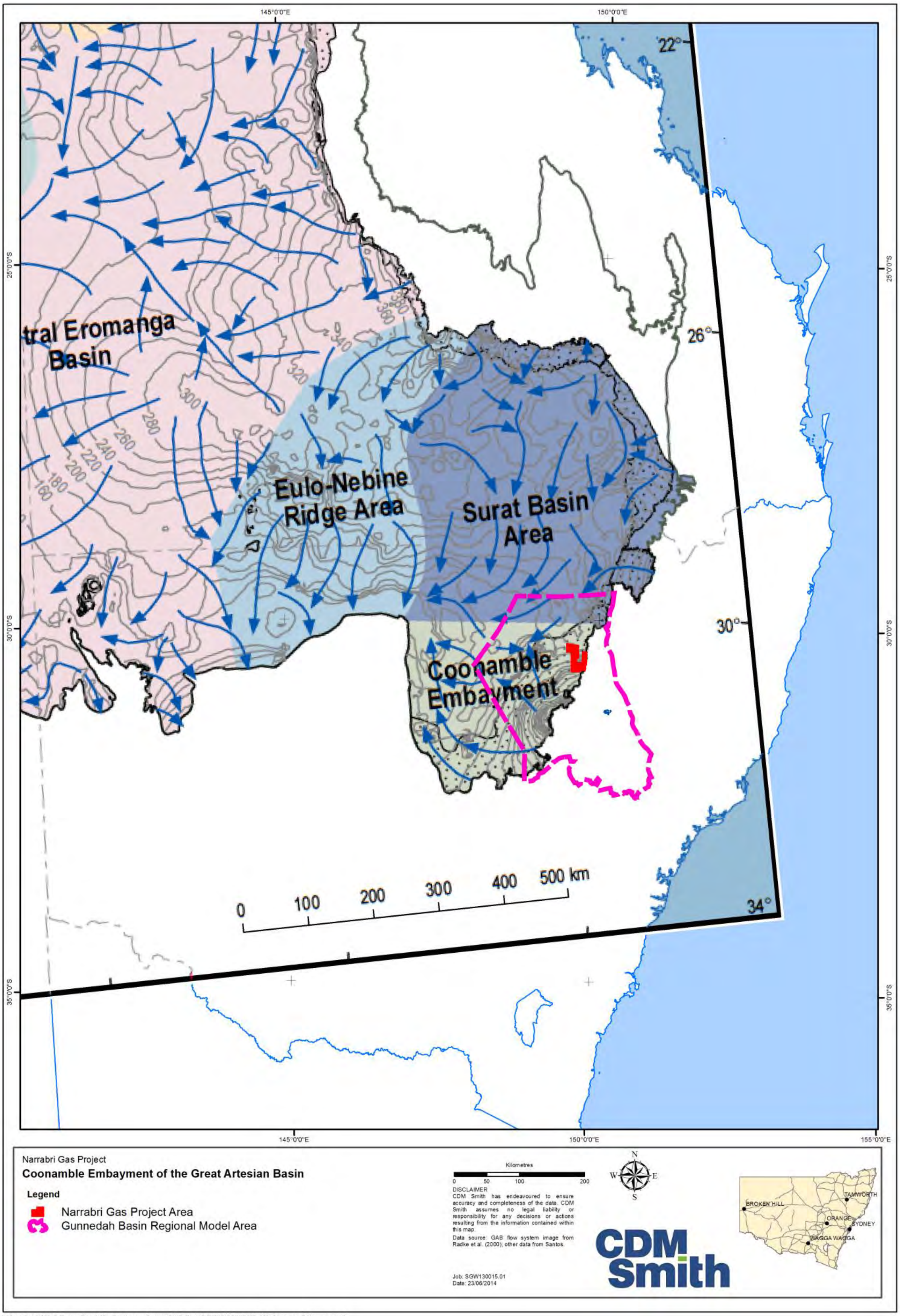



Figure 5-2 Coonamble Embayment of the Great Artesian Basin (after Radke *et al.* 2000)

The southern region of the hydrogeological domain extends into the Sydney Basin to the alluvial groundwater sources along the Goulburn and Hunter Rivers, approximately 160 to 200 km south of the project area. This choice for the southern boundary is based on the assumption that Permian and Triassic sediments are hydrogeologically continuous between the basins. Even though the southern extent of the Gunnedah Basin is commonly drawn along the ridge line of the Liverpool Ranges there is no evidence suggesting that the basin sediments are discontinuous or terminate beneath the range. The western portion of the boundary follows the margin of the Gunnedah Basin where it terminates along the outcrop of the Lachlan Fold Belt.

In the northwest of the GIA study area the hydrogeological domain is extended to the western limit of the existing Lower Namoi groundwater model domain shown in Figure 5-1 (Merrick 2001). The remaining section of boundary to the west and southwest of the project area follows the margin of the Gunnedah Basin in the southwest and then the direction of regional groundwater flow within the Coonamble Embayment. The overall distance from the project area to the western extent of the hydrogeological domain varies from around 110 to 180 km.

## 5.2 Hydrostratigraphy

The complex litho-stratigraphy of the GIA study area has been classified into hydrostratigraphic units denoting the significance or propensity of particular formations or groups of formations to transmit or inhibit the movement of groundwater. Table 5-1 illustrates the classification of the litho-stratigraphy into:

- Significant transmissive units (STU);
- Less significant transmissive units (LSTU);
- Probable negligibly transmissive units (PNTU); and
- Negligibly transmissive units (NTU).

The purpose of these definitions is to recognise the relative significance of hydrogeological properties to the response of the hydrogeological system to coal seam gas development. Under these definitions a very conductive and high-yielding stratum is be considered a STU and a low-yielding stratum is considered to be a LSTU. Leaky units and aquitards are considered to be PNTUs and NTUs.

Large head reductions within a stratum that yields relatively small flows, such as the target coal seam, may significantly alter the distribution of head within the hydrogeological domain. In this situation, potentially low yielding coal seams may be considered STUs because their transmissivity significantly influences the behaviour of subsurface flow and depressurisation.

The hydrostratigraphic units in Table 5-1 have been grouped according to the geological province and basin in which they occur, including the Namoi Province, comprising the Narrabri, Gunnedah and Cubbaroo formations; the Surat Basin, comprising Jurassic and Cretaceous units; and the Gunnedah Basin, comprising Permian and Triassic units. In addition, there are five volcanic sequences, including the recent Warrumbungle and Liverpool Range Volcanics, the Jurassic-Triassic Garrawilla Volcanics, and the Early Permian the Werrie Basalt and Boggabri Volcanics, which form the basement hydrostratigraphic units of the basin.

Figure 5-3 presents an east-west schematic cross-section through the Bohena Trough and illustrating the relationships between hydrostratigraphic units in a simplified way.

## Table 5-1 Hydrostratigraphic unit classification

| Province | Period/ Epoch | Division | Group | Sub-group | Formation | Lithology and Hydrogeological Classification |
|---|---|---|---|---|---|---|
| Namoi Alluvium Vocanics | Pleistocene | | | | Narrabri fm | Clay and silt with sand lenses |
| | Pliocene | | | | Gunnedah fm | Gravel and sand with clay lenses |
| | Miocene | | | | Cubbaroo fm | Gravel and sand with clay lenses |
| | | | | | Warrumbungle Vol | Basalt, dolerite |
| | Eocene | | | | Liverpool Range Vol | Basalt, dolerite |
| Surat Basin | Cretaceous | Middle | Blythesdale Gp (Keelindi Beds) | | Bungil Fm<br>Mooga Ss<br>Orallo Fm | Clayey to quartzose sandstone, subordinate siltstone and conglomerate |
| | | Early | | | Pilliga Ss | Fluvial, medium to very coarse grained, quartzose sandstone and conglomerate. Minor interbeds of mudstone, siltstone and fine grained sandstone and coal. |
| | Jurassic | Late | | | | |
| | | Middle | | | Purlawaugh Fm | Fine to medium grained sandstone thinly interbedded with siltstone, mudstone and thin coal seams |
| | | Early | Garrawilla Volcanics | | | Dolerite, basalt, trachyte, tuff, breccia |
| Gunnedah Basin | Triassic | Late | | | | |
| | | Middle | | | Deriah Fm | Sandstone |
| | | | | | Napperby Fm | Interbedded fine sandstone, claystone and siltstone |
| | | | | | | Basal Napperby Shale |
| | | Early | | | Digby Fm | Quartzose sandstone (Ulinda Ss) |
| | | | | | | Lithic sandstone |
| | | | | | | Lithic conglomerate (Bomera Conglomerate) |
| | Permian | Late | Black Jack | Nea | Trinkey Fm | Coal measures - siltstone, fine sandstone, tuffs, stony coal |
| | | | | | Wallala Fm | Conglomerate, sandstone, siltstone, minor coal bands |
| | | | | Coogal | Breeza Coal | Coal and claystone |
| | | | | | Clare Ss | Medium to coarse-grained quartzose sandstone; quartzose conglomerate |
| | | | | | Hows Hill Coal | Coal |
| | | | | | Benelabri | Claystone, siltstone and sandstone; fining up cycles; more sandy towards top |
| | | | | | Hoskissons Coal | Potential target coal seam |
| | | | | Brothers | Brigalow Fm | Fining-up sequence of medium to coarse-grained quartzose sandstone and siltstone |
| | | | | | Arkarula Fm | Sandstone and siltstone |
| | | | | | Melvilles Coal Mb | Coal |
| | | | | | Pamboola Fm | Sandstone, siltstone, minor claystone & coal |
| | | Middle | Millie | | Watermark Fm | Marine siltstone, shales and sandstone |
| | | | | | Porcupine Fm | Fining upward sequence of conglomerate and sandstone to mudstone |
| | | Early | Bellata | | Upper Maules Creek Fm | Sandstone and conglomerate, siltstone, mudstone and coal |
| | | | | | Rutley seam | Potential target coal seam |
| | | | | | Interburden | Sandstone and conglomerate, siltstone, mudstone |
| | | | | | Namoi seam | Potential target coal seam |
| | | | | | Interburden | Sandstone and conglomerate, siltstone, mudstone |
| | | | | | Parkes seam | Potential target coal seam |
| | | | | | Interburden | Sandstone and conglomerate, siltstone, mudstone |
| | | | | | Bohena seam | Potential target coal seam |
| | | | | | Lower Maules Creek Fm | Sandstone and conglomerate, siltstone, mudstone and coal |
| | | | | | Goonbri Fm | Siltstone, sandstone and coal |
| | | | | | Leard Fm | Flinty claystone |
| Basement | | | Werrie Basalt and Boggabri Volcanics (Basement) | | | Rhyolitic to dacitic lavas and ashflow |
| | | | | | | Tuffs with interbedded shale. Rare trachyte and andesite. Weathered basic lavas |

| | |
|---|---|
| Colour code key: | **STU** – Significantly Transmissive Unit |
| | **LSTU** – Less Significantly Transmissive Unit |
| | **PNTU** – Probable Negligibly Transmissive Unit |
| | **NTU** – Negligibly Transmissive Unit |

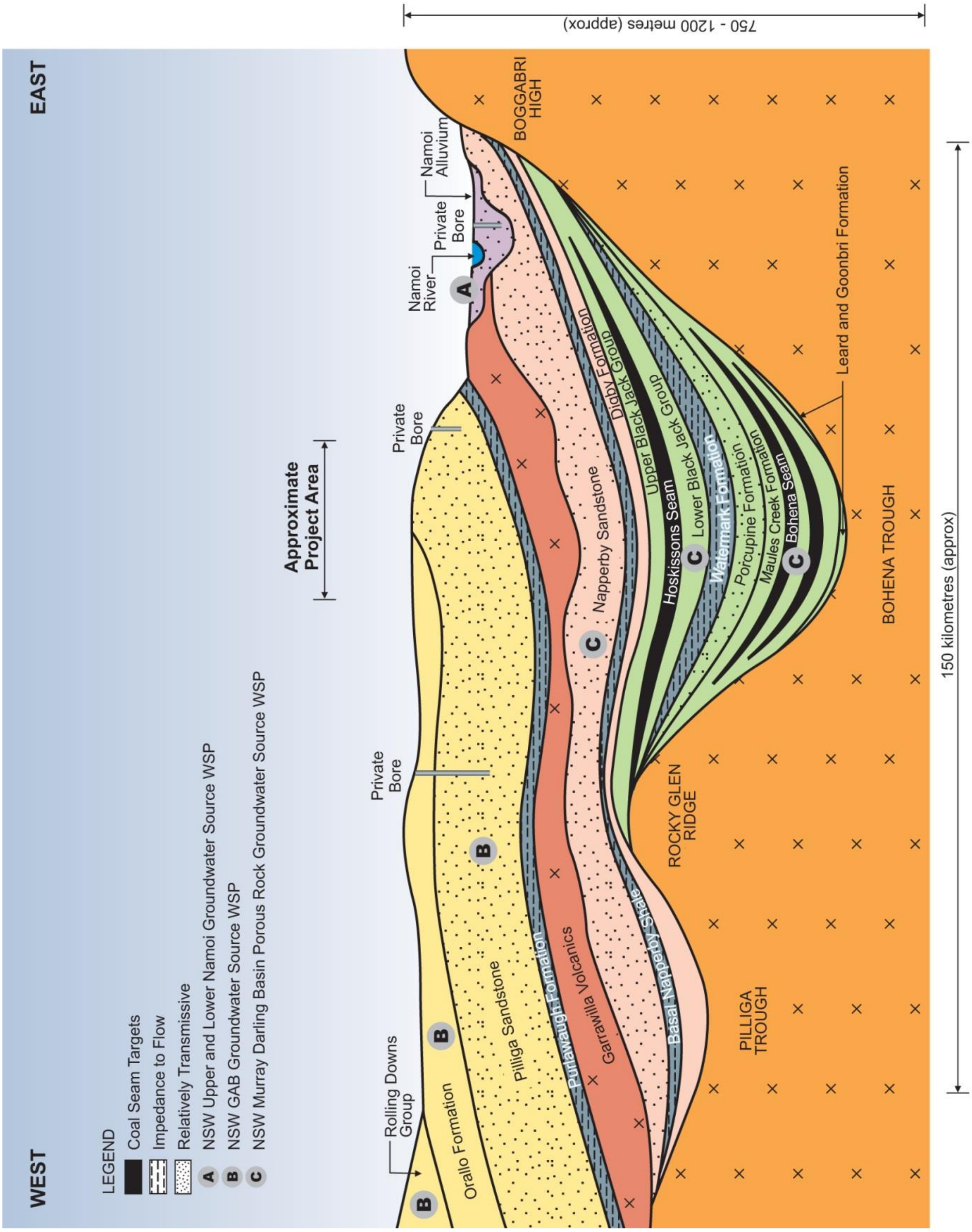



**Figure 5-3 Schematic hydrostratigraphy of Bohena Trough (Eco Logical 2016c)**

### 5.2.1 Namoi Alluvium

The principal significant transmissive units within the GIA study area are the Quaternary Narrabri and Gunnedah formations. These units contain a significant resource of readily accessible, good quality groundwater that is heavily utilised for irrigation, public water supply, private water supply and livestock.

The Gunnedah [3]formation consists of moderately well sorted gravel and sand with minor clay. The most productive groundwater sources of the Gunnedah formation are within palaeochannels that contain the coarsest sediments (Broughton 1994; McNeilage 2006). The lens-shaped sand deposits of the overlying Narrabri formation provide smaller yielding aquifers of low to medium salinity. Miocene gravel and sand of the Cubbaroo formation (underlying the Gunnedah formation) also provide productive groundwater sources where present. The Cubbaroo formation is considered to be a less significant transmissive unit.

Alluvial deposits are less prominent east of the Hunter-Mooki Thrust Fault within the New England Fold Belt. The most substantial deposits are within the incised Peel River valley in the south east of the Namoi catchment where groundwater in the alluvium is extensively utilised. Despite its large hydraulic conductivity, the limited extent of alluvium commonly results in sharply falling groundwater levels during dry spells.

### 5.2.2 Surat Basin Hydrostratigraphic Units

Hydrostratigraphic units of the Surat Basin include the Pilliga Sandstone, Purlawaugh Formation and Blythesdale Group (Keelindi Beds). The Pilliga Sandstone is a major regional aquifer and significant transmissive unit consisting of medium to very coarse grained sandstone and conglomerate with minor interbeds of finer grained sediments. Its lateral equivalent within the Oxley Basin also provides an important water resource within the southern part of the GIA study area.

The Purlawaugh Formation, which is positioned beneath the Pilliga Sandstone is considered to be negligibly transmissive due to the presence of predominantly fine grained sediments consisting of lithic to labile sandstone, with thin interbeds of siltstone, mudstone and coal.

The Blythesdale Group (Keelindi Beds) is positioned above the Pilliga Sandstone and is comprised of the Orallo Formation, Mooga Sandstone and Bungil Formation. The group contains numerous beds of fine-grained sediments that are considered collectively to be negligibly transmissive with respect to vertical groundwater flow through the group. Orallo Formation contains medium-grained, sub-lithic sandstone with interbedded siltstone and mudstone and minor coal. The Mooga Sandstone includes minor siltstone, shale and mudstone beds but is predominantly sandstone, and is generally classified as an aquifer within the Surat Basin. The Bungil Formation contains predominantly siltstone and mudstone with sub-dominant coarse-grained sandstone in some areas.

[3] The names of geological formations are capitalised when they are formal names. In the case of the Narrabri, Gunnedah and Cubbaroo facies in the Namoi Alluvium (see Table 5-1), these names are informal, and formation is not capitalised.

### 5.2.3 Gunnedah Basin Hydrostratigraphic Units

The Triassic Deriah Formation, Napperby Formation and Digby Formation are probable negligibly transmissive units and negligibly transmissive units capable of only minor groundwater yields.

Hydrostratigraphic units within the Late-Permian Black Jack Group are predominantly probable negligibly transmissive units. Apart from coal seams, the Clare Sandstone is the only hydrostratigraphic unit with potentially significant transmissivity within the Black Jack Group. Although it is considered to be a less significant transmissive unit the quality of groundwater in the Clare Sandstone is commonly affected by minor coals and can be unsuitable for use. The Clare Sandstone is not utilised as a significant groundwater source due to a combination of its depth below ground surface, unreliable water quality and the availability of alternative good-quality alluvial groundwater sources.

The Hoskissons Coal has significant transmissivity and is considered to be a significant transmissive unit within the context of potential future coal seam gas development. Estimates of hydraulic conductivity within the seam are several orders of magnitude greater than in the underlying and overlying hydrostratigraphic units.

Strata within the lower Black Jack Group (Brothers Sub-group) are considered to be probable negligibly transmissive units due to the combination of mixed lithology and cementation. The Melvilles Coal Member is understood to have similar hydrogeological properties to the Hoskissons Coal but is considered to be a probable negligibly transmissive unit in this assessment because it is not a recognised target for future coal seam gas development.

Middle Permian sediments of the Millie Group (Watermark and Porcupine Formations) are considered to be negligibly transmissive units due to the degree of cementation and their lithological characteristics.

The target coal seams within the Early Permian Maules Creek Formation include the Bohena, Namoi, Rutley and Parkes seams. In this assessment they are referred to collectively as the Early Permian coal seams and are considered to have significant transmissivity within the context of coal seam gas development. They are bounded above and below by the Maules Creek Formation, which is considered to be a negligibly transmissive unit. Interburden strata between the coal seams, consisting predominantly of sandstone, conglomerate and siltstone are thought to be probable negligibly transmissive units. The Goonbri and Leard Formations underlie the Maules Creek Formation and are considered to be negligibly transmissive units.

### 5.2.4 Volcanic Sequences

The Liverpool Range Volcanics consists predominantly of basalt and is considered to be a probable negligibly transmissive unit. A groundwater flow divide across the top of the range is likely to follow the surface water divide (SWS 2012a). The complex stream network in this area suggests that the hydrology is dominated by surface water runoff processes rather than infiltration and sub-surface flow processes.

To the west of the Liverpool Ranges the Warrumbungle Range outcrops prominently around Coonabarabran. The rocks consist predominantly of basalt and the formation is also considered to be a probable negligibly transmissive unit. The Garrawilla Volcanics form the basal unit of the Surat Basin sequence and is thought to be a less significant transmissive unit.

The Werrie Basalt and Boggabri Volcanics constitute the effective basement of the Gunnedah-Oxley Basin and are considered to be negligibly transmissive units on the basis of diagenetic mineralisation and the occurrence of shale interbeds.

### 5.2.5 Fractured Rock Aquifer East of the Hunter-Mooki Thrust Fault

The Hunter-Mooki Fault system forms the eastern margin of the Gunnedah-Oxley Basin. Small groundwater supplies are drawn from these rocks and the extent of individual water bearing horizons is understood to be limited both structurally and diagenetically. It is thought that the development of significant hydraulic conductivity is limited to shallow depth where jointing, fractures and bedding planes have been opened by the actions of weathering.

To the east of the Hunter-Mooki Thrust Fault, it is likely that the groundwater divide follows the surface water divide within the upland margins of the Namoi catchment and extending into the upper reaches of the Hunter catchment to the south-east and Macquarie catchment to the south (SWS 2012). The complex stream network indicates that the area is dominated by surface water runoff processes rather than groundwater infiltration. There are no significant transmissive units in these areas and groundwater flow is expected to be dominated by fracture flow within the shallow bedrock (SWS 2012a). It is unknown whether there is significant groundwater flow across the fault.

## 5.3 Hydrogeological Properties

Generally, there is a lack of published information describing the range and spatial distribution of hydrogeological properties of the deep consolidated strata within the Gunnedah Basin. Only limited data are available for strata within the vicinity of the project area, which relate predominantly to coal seam geology and reserve quantification. Drill stem tests (DSTs) have been undertaken almost exclusively on the coal seams.

Despite the absence of data at basin-scale, there are several detailed studies of formation hydrogeological properties conducted for colliery planning applications. These include groundwater impact assessments for mining in the Maules Creek Sub-basin (Boggabri, Maules Creek and Rocglen mines) and Mullaley Sub-basin (Narrabri, Sunnyside and Werris Creek mines) (see Figure 5-1).

Existing estimates of hydrogeological properties for stratigraphic units within the GIA study area are summarised in the tables and figures below. Appendix C contains a more detailed review of these studies.

The overview of test data in Table 5-2 is based on field investigations for the Narrabri Coal Mine Stage 2 Longwall Project (Aquaterra 2009). Hydraulic conductivity values were estimated for nine stratigraphic units between the Pilliga Sandstone (Late Jurassic age) and Pamboola Formation (Middle to Late Permian age) using falling head tests and petroleum well tests. The results are variable both within and between stratigraphic units. Obvious relationships between formation type and the estimates of hydraulic conductivity are not apparent.

**Table 5-2 Hydraulic conductivity measurements for the Narrabri Coal Mine (after Aquaterra 2009)**

| Hydrostratigraphic Unit | Hydraulic Conductivity, *K* [m/d] | Test Type |
|---|---|---|
| Pilliga Sandstone | 0.029–0.19 | Falling head |
| Purlawaugh Formation | 0.001–0.41 | Falling head |
| Garrawilla Volcanics | 0.047–0.11 | Falling head |
| Napperby Formation | 0.0006–0.09 | Falling head |
| Digby Formation | 0.063 | Petroleum well testing |

| Hydrostratigraphic Unit | Hydraulic Conductivity, *K* [m/d] | Test Type |
|---|---|---|
| Nea Sub-group (Upper Black Jack Group) | 0.14 | Petroleum well testing |
| Hoskissons Coal | 0.0086–0.013<br>0.00017–0.0025 | Falling head<br>Petroleum well testing |
| Arkarula Formation | 0.012–0.013 | Falling head |
| Pamboola Formation | 0.002–0.03 | Falling head |

The summary of hydrogeological properties in Table 5-3 is derived predominantly from existing groundwater modelling studies. The values of horizontal hydraulic conductivity adopted in these studies indicate that the alluvium, Pilliga Sandstone and target coal seams (Early and Late Permian) are generally considered to be more permeable with respect to the juxtaposing stratigraphic units; however, large variations in hydraulic conductivity and storativity are apparent within all units for which there are multiple estimates, with values typically ranging over several orders of magnitude.

Vertical hydraulic conductivity ($K_v$) of the strata overlying the target coal seams controls the rate of transmission of drawdown in the target seams to overlying aquifers, and is a critical parameter in the groundwater modelling and assessment of potential impacts. Figure 5-4 shows the vertical hydraulic conductivity values from Table 5-3 and provides a graphical comparison with typical ranges of values of hydraulic conductivity for different rock types from selected hydrogeological literature.

The following observations are made in relation to the compiled data:

- The existing ranges of values for $K_v$ that have been adopted in strata of the GAB and Gunnedah-Oxley Basin do not clearly distinguish between more and less transmissive units; for example, similar ranges of values for $K_v$ have been used in the Pilliga Sandstone (a major regional aquifer), the Permian coal seams (known water producing units) and strata considered to be aquitards (probable/negligibly transmissive units).
- The existing ranges of values for $K_v$ adopted for strata of the GAB and Gunnedah-Oxley Basin vary over almost four orders of magnitude from 1E-6 m/d to 4E-3 m/d.
- When considered within the context of the hydrostratigraphic unit classification (Table 5-1) there are some anomalies in the existing adopted values of $K_v$; for example, the Blythesdale Group (Keelindi Beds) has been assigned values of $K_v$ typical of a poor aquifer while it is generally considered to be an aquitard consisting of clayey sandstone, siltstone and conglomerate.
- The existing ranges of values for $K_v$ adopted for all strata of the GAB and Gunnedah-Oxley Basin are mainly typical of consolidated sandstones, and do not reflect literature values for aquitards containing shale, mudstone and siltstone, which are typically within the range 1E-8 to 1E-4 m/d.

The above observations have been taken into consideration in the choices for the hydrogeological properties made in this GIA, which are presented in the description of the groundwater modelling in Section 6.7.

It is relevant to emphasise that while review of existing estimates of hydrogeological properties is an essential task in the development of a groundwater model, the availability of estimates within large regional study areas is typically restricted to a few localised studies conducted for other development activities, which may or may not be related to coal seam gas development. As such, the results of such reviews (e.g., Table 5-2, Table 5-3 and Figure 5-4) should be interpreted carefully within this context. For example, taken in isolation, the compiled data in Table 5-3 and Figure 5-4 indicate that the Pilliga Sandstone and Purlawaugh Formation have similar hydrogeological properties, whereas it is known from experience and existing utilisation of groundwater sources in the region that the Pilliga sandstone is a major regional water supply aquifer and the Purlawaugh Formation is a relatively low to non-yielding formation that is not generally targeted for water supply. In this situation, it is reasonable to adopt a value of hydraulic conductivity for Pilliga Sandstone that is near the upper limit of the range of estimates in Table 5-3 (characteristic of a water supply aquifer) and to adopt a value of hydraulic conductivity for the Purlawaugh Formation closer to the lower limit of the range of estimates in the table.

A more detailed explanation of the approach used to interpret and assign hydrogeological properties of strata for the purposes of this GIA is provided in Section 5.3.1 below.

### 5.3.1 Interpretation of Hydraulic Conductivity Data

Whilst sandy lithologies exhibit grain sizes that vary over two orders of magnitude (from 1/16 mm to 2 mm according to the Wentworth scale) the vertical hydraulic conductivity of the same sand lithologies can vary across seven orders of magnitude from 1E-5 m/d to 1E+2 m/d (Table 5-3 and Figure 5-4). Common causes of large variation of hydraulic conductivity of a particular lithology include the presence of small proportions of platy clay impurities that inhibit vertical fluid flow; mixed grain sizes that diminish porosity; and mineralisation occupying the pore throats (the narrow passages between grains of sand that connect the larger pore spaces) which inhibits or blocks flow from pore to pore through the rock mass. The specific physical and diagenetic processes that formations have experienced contribute to the range of values of hydraulic conductivity that they exhibit.

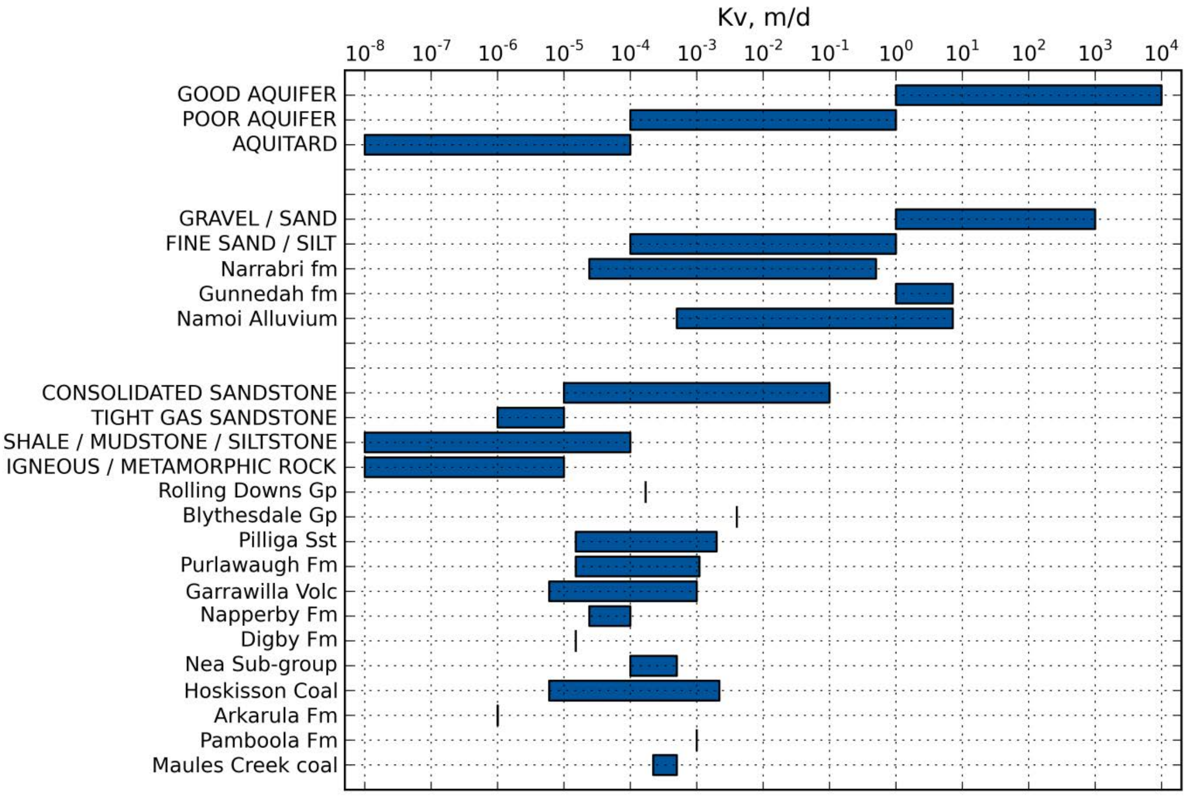
The majority of the Permo-Triassic strata present in the study area have sedimentary, diagenetic and tectonic histories that have contributed to characteristically low effective (connected) porosity and vertical hydraulic conductivity. Individual beds within formations may locally exhibit higher values of hydraulic conductivity but the combined influence of the beds with smaller values biases the effective average (bulk) hydraulic conductivity toward lower values. The overlying Jurassic to Cretaceous strata have experienced less influence from tectonic activity and diagenesis, and exhibit less induration and a greater propensity to store and transmit water. The youngest sediments occupying the present Namoi valley have yet to become consolidated and include very transmissive materials that form the most effective aquifers in the region.

Direct measurements have so far been made of the permeability of approximately 30 rock samples from the project area. These include three side-core samples recovered from one core hole in the Bando trough, representing the Triassic aged Napperby Formation and Digby Formation and the Permian aged Porcupine Formation, and 25 samples collected from the Cretaceous aged Orallo Formation and Jurassic aged Pilliga Sandstone and Purlawaugh Formation within the Bohena Trough. Additional measurements have been made indirectly by interpreting Drill Stem Tests (DSTs) performed almost exclusively on selected coal seams, and predominantly from the early Permian aged Maules Creek Formation in the Bohena Trough. Further indirect estimates have been derived from pumping tests conducted in newly-installed groundwater monitoring bores. Whilst these measurements collectively contribute to approximately 100 estimates of hydraulic conductivity and permeability, this represents only an initial position from which to conceptualise the hydrogeology of the entire study area and parameterise a numerical groundwater model.

**Table 5-3 Hydrogeological properties used in existing modelling studies**

| Hydrostratigraphic Unit | $K_h$ [m/d] | $K_v$ [m/d] | $S_y$ [1] | $S_s$ [1/m] | Source |
|---|---|---|---|---|---|
| Narrabri fm | 0.1 – 30 | - | 0.005 – 0.1 | - | 1 |
| | 0.09 – 86 | - | 0.02 – 0.1 | 1E-5 | 2 |
| | 7 | 6.3E-2 | 0.05 | 5E-4 | 3 |
| | 5 | 5E-1 | 0.05 | 5E-4 | 4 |
| | 0.008 – 6 | 2.4E-5 – 2.4E-4 | 0.1 | 4E-5 | 5 |
| | 0.008 – 86 | 2.4E-5 – 5E-1 | 0.005 – 0.1 | 1E-5 – 1E-4 | Summary |
| Gunnedah fm | 0.05 – 30 | - | - | 1E-7 – 5E-4 | 1 |
| | 8.3 | 2.4 | 0.05 | 5E-4 | 3 |
| | 0.09 – 86 | - | 0.01 – 0.1 | 1E-5 | 2 |
| | 10 | 1 | 0.05 | 5E-4 | 4 |
| | 8.6 – 31 | 3.5 – 7.2 | 0.1 – 0.15 | 1E-4 | 5 |
| | 0.05 – 86 | 1 – 7.2 | 0.01 – 0.15 | 1E-7 – 5E-4 | Summary |
| Namoi Alluvium | 0.26 – 5 | 5E-4 – 5E-3 | 0.1 | 5E-6 | 6 |
| | 22 - 26 | 3.5 – 7.2 | 0.1 | 1E-4 | 7 |
| | 0.26 – 26 | 0.0005 – 7.2 | 0.1 | 5E-6 – 1E-4 | Summary |
| Rolling Downs Gp | 0.05 | 1.7E-4 | 0.03 | 4E-6 | 9 |
| Blythesdale Gp (Keelind Beds) | 0.12 | 4E-3 | 0.03 | 4E-6 | 9 |
| Pilliga Ss | 0.004 – 0.27 | 1.5E-5 – 2E-3 | 0.001 | 5E-6 | 6 |
| Purlawaugh Fm | 0.004 – 0.02 | 1.5E-5 – 1.1E-3 | 0.001 | 5E-6 | 6 |
| Garrawilla Volcanics | 0.001 – 0.04 | 6E-6 – 1E-3 | 0.002 | 5E-6 | 6 |
| Deriah Fm | no estimates | no estimates | no estimates | no estimates | - |
| Napperby Fm | 0.08 – 1.5 | 6.2E-1 – 7.1E-1 | 0.1 | 1E-4 | 5 |
| | 0.001 – 0.012 | 1E-4 | 0.001 | 5E-6 | 6 |
| | 0.004 – 0.04 | 2.4E-5 | 0.001 | 5E-6 | 6 |
| | 0.001 – 0.04 | 2.4E-5 – 1E-4 | 0.001 | 5E-6 – 1E-4 | Summary |
| Digby Fm | 0.0005 – 0.04 | 1.5E-5 | 0.001 | 5E-6 | 6 |
| Trinkey and Wallala Fm | no estimates | no estimates | no estimates | no estimates | - |
| Nea Sub-group (Upper Black Jack Gp) | 0.0002 – 0.0004 | 1E-4 – 5E-4 | 0.1 | 1E-4 | 7 |
| Hoskissons Coal | 0.005 – 0.04 | 6E-6 | 0.001 | 5E-6 | 6 |
| | 0.33 – 3.3 | 2E-4 – 2.2E-3 | 0.2 | 1E-4 | 7 |
| | 0.13 – 3.3 | 2.2E-4 – 2E-3 | 0.2 | 1E-4 | 8 |
| | 0.005 – 3.3 | 6E-6 – 2.2E-3 | 0.001 – 0.2 | 5E-6 – 1E-4 | Summary |
| Brothers Sub-group (Lower Black Jack Gp) | no estimates | no estimates | no estimates | no estimates | 10 |
| Arkarula Fm | 0.0005 – 0.04 | 1E-6 | 0.005 | 5E-6 | 6 |
| Melvilles Coal Mb | no estimates | no estimates | no estimates | no estimates | - |
| Pamboola Fm | 0.04 | 1E-3 | - | - | 6 |
| Watermark Fm | no estimates | no estimates | no estimates | no estimates | - |
| Porcupine Fm | no estimates | no estimates | no estimates | no estimates | - |
| Maules Creek Fm | no estimates | no estimates | no estimates | no estimates | - |
| Maule Creek Coal | 0.054 | 5E-3 | 0.001 | 1E-5 | 3 |
| | 0.13-3.3 | 2.2E-4 – 2E-3 | 0.01 | 1E-4 | 8 |
| | 0.054 – 3.3 | 2.2E-4 – 5E-3 | 0.001 – 0.01 | 1E-5 – 1E-4 | Summary |

Sources: 1. Upper Namoi groundwater model (McNeilage 2006), 2. Maules Creek groundwater model (Giambastini 2009), 3. Maules Creek Coal Project groundwater model (AGE 2011), 4. Boggabri mine groundwater model, 5. Kahlua pilot test groundwater model (Golder Associates 2010), 6. Narrabri Coal Mine groundwater model (Aquaterra 2009), 7. Sunnyside Coal Project groundwater model (Geo Terra 2008), 8. Namoi Catchment Water Study (SWS 2012a), 9. APLNG groundwater model (Worley Parson 2010), 10. Estimates of hydrogeological properties in Golder Associates (2010) are from unrelated studies.




Capitalised categories are literature values (Bear 1972, Table 5.5.1; Freeze and Cherry 1979, Table 2.2; http://petrowiki.org/Rock_type_influence_on_permeability)

**Figure 5-4 Vertical hydraulic conductivity from Table 5-3 and selected hydrogeological literature**

Three non-coal sub-samples from the Bando Trough core individually contained approximately 15 mm to 20 mm of Napperby Formation, Digby Formation and Porcupine Formation, which are known to exhibit wide ranges of facies both laterally and vertically, and which constitute many 100s of billions of cubic metres of rock. The 25 samples from the Cretaceous and Jurassic strata consisted of the mixed lithologies of the Orallo Formation (coals, seat-earths, gravels, sandstones, siltstones and fireclays); fine sandstones, coarse sandstones, mudstones and ironstones of the Pilliga Sandstone; and shales, muddy sandstones and siltstones of the Purlawaugh Formation. Consequently, the values of permeability derived from these samples varied widely depending on the relative portions of lithology types captured in the core sub-samples of a few cubic centimetres. Within this context, the vagaries of such small sample sizes are not considered to provide adequate measurements of the true range or distribution of hydraulic conductivity of these formations at spatial scales relevant to regional-scale assessments.

The permeability values interpreted from drill stem tests (DSTs) provide a relatively abundant population of samples from which to derive the hydraulic conductivity of selected coal seams; however, spatial variation in cleating, mineralisation and other coal properties, together with the inclusion of non-coal roof or floor lithologies in the DST test zones diminish the overall value of these measurements for model parameterisation. Measurements of hydraulic head from the DSTs provide strong evidence of ‘over-pressure’ in the coal seams, which is consistent with groundwater being ‘trapped’ in the coal seams by hosting rock with very small hydraulic conductivity (see Section 5.4.2).

Aquifer pumping tests in newly-installed groundwater monitoring bores for Santos’ groundwater monitoring network have also provided valuable estimates of hydraulic conductivity in the Pilliga Sandstone and Orallo Formation.

Other disparate but supporting lines of evidence of distinctive differences in the hydrogeological properties of strata intersected by bores and core holes, include pronounced groundwater quality variations with depth and lithology; the varied spatial density of private groundwater extraction bores; local and regional concentrations of groundwater bores with larger extraction rates; differences in hydraulic gradients within different hydrostratigraphic units; the presence and locations of recharge springs and ephemeral creeks; and the predominance of lithotypes and diagenetic features in different formations.

Whilst not intended to be exhaustive, some of these lines of evidence are expanded briefly below:

- Observed water quality variations show that geologically old, highly saline, bicarbonate-rich waters ('sour waters') are 'locked' in the deep Permian rocks at the bottom of the Bohena Trough. Much fresher waters are found in shallower strata. Separating these easily distinguishable groundwater types are considered to be effective aquitards composed predominantly of platy clay particles pressed tightly together into shales and mudstones with very small vertical hydraulic conductivity. These lithologically distinct aquitards include the Purlawaugh Formation directly beneath the Pilliga Sandstone; the Garrawilla Volcanics beneath the Purlawaugh Formation; the basal shale of the Napperby Formation above the Digby Formation; the diagenetically-cemented Bomera Conglomerate at the base of the Digby Formation; numerous thin but spatially-extensive tuffs and thin mudstones and siltstones of the Trinkey and Wallala Formation at the top of the Permian sequence; the Benelebri Formation forming the roof of the Hoskissons Coal; the claystone of the Pamboola Formation; the dense black shales of the Watermark Formation; the thick middle sequence of shales within the Porcupine Formation; and the shale inter-measures segregating the coal seams of the Maules Creek Formation.

- The relative sparseness of groundwater extraction bores (Figure 4-15 to Figure 4-18) across the project area and wider extent of the Surat Basin provides evidence that the Pilliga Sandstone, whilst providing moderate groundwater yields, is not relied on regionally to provide large yields of good quality water. The largest concentration of bores occurs along the outcrop areas of the Pilliga Sandstone where weathering at the surface has increased its permeability and the sandstone receives fresh recharge from rainfall; thereby supporting larger groundwater extractions. Directly to the east of the outcrop of the Pilliga Sandstone, the density of bores decreases markedly in association with the presence at surface of much less permeable Permo-Triassic strata from which the extraction of economic quantities of water is generally not possible. The highest density of groundwater bores in the study area occurs within the Namoi alluvium, which contains sand and gravel lithologies that support the largest individual water extractions. On this basis, the distribution and density of groundwater bores throughout the study area, and the magnitude of existing extractions from these bores provide an effective proxy for groundwater yield, which can be considered to be a function of hydraulic conductivity.

In summary, Figure 5-4 illustrates that an extremely large range of values for hydraulic conductivity are reported in published literature, and a similarly large range of values has been reported for formations present in the study area. This large variability in local-scale measurements from across the study area renders much of the data irrelevant for regional-scale groundwater studies and parameterisation for regional-scale groundwater modelling. Instead, the broader lines of disparate hydrological, geological, chemical and hydrogeological evidence discussed above are considered to be more appropriate for characterising the permeability of the approximately 1 trillion cubic metres of strata beneath the project area.

# 5.4 Water Table and Hydraulic Head

## 5.4.1 PINNEENA Database

Time-varying water level data from 3,728 monitoring bores within the NSW Government's [4]PINNEENA (v.3.2) database were reviewed, including approximately 395,000 measurements of [5]hydraulic (groundwater) head. Data provided as depth to water were cross-referenced against the bore construction details to determine that 2,566 bores (69%) had known screen depths. A total of 347,474 water level measurements had been recorded in these bores.

Many bores registered within the PINEENA database do not have information indicating in which hydrostratigraphic unit the bore is screened (e.g., Figure 4-15 to Figure 4-17). Rather than omitting these bores from the analysis of hydraulic head, the recorded screen depth has been used as a surrogate to identify bores that most likely target shallow groundwater in the alluvium (less than 50 m deep) and bores that most likely target deeper groundwater sources in the GAB and Gunnedah Basin. This approach helps to reduce uncertainty about the reliability of alignment of well screens to aquifers in the database.

Table 5-4 summarises the spatial and temporal distribution of hydraulic head records. The tabulated summary is divided into "All Bores", including those within unknown screen depth, and "Bores with known screen depth". The data are ordered by "Number" with the "Year" column indicating the year when that number was recorded. For example, the first row of the table indicates that data were recorded for 1,960 bores in 2001—the largest number of bores monitored in a calendar year—while the largest number of water level readings was 13,843 in 1982, when fewer bores were measured on more occasions.

**Table 5-4 Hydraulic head data from the PINEENA database**

| All bores | | | | Bores with known screen depth | | | |
|---|---|---|---|---|---|---|---|
| Bores with data | | [1]Measurements | | Bores with data | | [1]Measurements | |
| Number | Year | Number | Year | Number | Year | Number | Year |
| 1,960 | 2001 | 13,843 | 1982 | 1,740 | 2001 | 11,952 | 1982 |
| 1,958 | 1999 | 13,587 | 1980 | 1,689 | 2000 | 11,540 | 1980 |
| 1,908 | 2000 | 12,946 | 1981 | 1,676 | 1999 | 11,103 | 1986 |
| 1,874 | 2003 | 12,218 | 1986 | 1,671 | 2003 | 11,092 | 1981 |
| 1,848 | 2002 | 12,071 | 1985 | 1,662 | 2002 | 11,015 | 2001 |
| 1,819 | 1998 | 12,062 | 1987 | 1,613 | 2007 | 10,988 | 1987 |
| 1,790 | 1997 | 11,711 | 2001 | 1,605 | 1998 | 10,970 | 2006 |
| 1,784 | 1993 | 11,693 | 2006 | 1,597 | 1997 | 10,851 | 1985 |
| 1,767 | 2007 | 11,567 | 2003 | 1,592 | 2008 | 10,781 | 2003 |
| 1,759 | 1988 | 11,402 | 2002 | 1,588 | 2009 | 10,717 | 2002 |

[1]includes multiple measurements in the same bore

Of the 2,566 bores with known screen depths, at least one negative depth to water measurement had been recorded in 228 bores, indicating potential artesian head (hydraulic head above ground surface elevation) at those locations. A total of 4,161 measurements were recorded in these potentially artesian bores, with the largest number occurring in 2001.

At unsurveyed monitoring bores, an estimate of ground surface elevation was made using SRTM (Shutter Radar Topography Mission) data (Jarvis et. al. 2008; version 4.1). The vertical error of the

[4] http://waterinfo.nsw.gov.au/pinneena/

[5] Hydraulic head (also called piezometric and potentiometric head) is the elevation to which water rises in a monitoring bore that is screened at depth. It is equal to the elevation of the screen plus the pressure head above the screen, measured in metres of water.

SRTM data is reported to be less than 16 m globally and is likely to be smaller in relatively flat terrain; however, the accuracy within the GIA study area is unknown. Bore screen depths and water level depth measurements were reduced to elevation estimates in mAHD (metres Australian Height Datum) using the bore elevations.

### 5.4.2 Drill Stem Test Data

Data describing groundwater pressure within the hard rock domain of the GIA study area are limited to those derived from [6]drill stem tests (DSTs) during exploration and drilling activities. These measurements are typically focussed on the coal seam pressures, while investigation of pressure in the bounding formations and interburden strata are not routine. Measurements are normally performed opportunistically during drilling and do not provide temporal trends; however, given minor utilisation of groundwater in the hard rock domain, it is likely that hydraulic head in the deep formations is relatively stable at contemporary time scales.

For the reasons discussed below, these data have not been used for the model calibration, or interpolation of initial conditions for the numerical modelling. This section describing the DST data is provided mainly for completeness, and as explanation for why DST measurements can differ from measurements of piezometric head using groundwater bores.

Results from 57 DSTs by Santos are summarised in Figure 5-6; the locations of the test sites are indicated in Figure 5-7. Figure 5-6 shows the measurements of formation pressure in units of kilopascals (kPa) as a function of the depth of the measurement below ground surface. The data are grouped according to measurements taken within the Early Permian Maules Creek Formation and measurements taken within the Late Permian Black Jack Group (including three measurements within the Digby Formation) The two other lines drawn on the graph indicate the hydrostatic gradients for fresh water and saltwater (with assumed seawater density 1025 kg/m$^3$). The two hydrostatic gradients indicate the potential pressure increase with depth due to the weight of water above. Hydrostatic pressure is greater for saltwater because it is heavier.

Visual inspection of Figure 5-6 indicates that the DST measurements of formation pressure are generally larger than the hydrostatic gradients for fresh water and saltwater. This overpressure can be explained either by the presence of fluids with much greater salinity and density or compression of the formation porosity at depth due to geological deformation. For this reason, the data are not directly suitable as calibration targets for a groundwater flow model that does not incorporate variable density flow and compressibility of the geological matrix. Maximum pressure head within a groundwater flow model that lack these processes (nearly all groundwater models neglect compressibility of the porous matrix) can only reflect the hydraulic potential of the water table or boundary conditions to the model. More generally, it is noted that to be consistent with these data a groundwater flow model should predict pressure head that is less than the DST measurements.

### 5.4.3 Groundwater Monitoring at Bibblewindi 9-Spot Pilot

The Bibblewind 9-Spot pilot is located within the southern portion of the project area as shown in Figure 5-8. The Bibblewind 9-Spot pilot wells target coal seam gas resources in Early Permian coal seams within the Maules Creek Formation. Other nearby pilots that also target gas in Early Permian

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[6] A drill stem test (DST) is a procedure for isolating and testing the permeability and productive capacity of a geological formation during the drilling of a well; the test yields measurements of the formation pressure at known depth, which can be converted to equivalent hydraulic head.

coal seams include Bibblewindi East, Bibblewindi West and, further away, Dewhurst North and Dewhust South.

Since 2015, the Bibblewindi 6 well (BWD6) within the Bibblewindi 9-Spot pilot has been used for collection of baseline monitoring data for the project. BWD6 provides measurements of hydraulic head in the Porcupine Formation, located immediately above the Maules Creek Formation at a depth of approximately 648 m below ground surface (Table 5-5). These data are summarised in Table 5-6 and the hydrograph for BWD6 can be seen in Figure 5-5.

**Table 5-5 Well details for BWD6**

| Well name | Owner | Target HSU | Water Source | Screened Interval, m BGL | |
|---|---|---|---|---|---|
| | | | | Top | Bottom |
| BWD6 | Santos | Porcupine Fm | GOB | Sensor depth | 647.7 |

To date, monitoring of hydraulic head in BWD6 has shown a relatively consistent groundwater pressure that does not appear to be influenced by historical water extraction at the Bibblewindi 9-Spot pilot and other nearby pilots. Historical water production for the pilots is summarised in Table 5-7, including approximately 198 ML of extraction from Bibblewindi 9-Spot at the location of BWD6 and 343 ML combined extraction from the other pilots.

On the basis of this evidence, depressurisation effects due to historical water production from Early Permain coal seams in the Maules Creek Formation have not yet propagated to the depth of BWD6 within the Porcupine Formation. The data provides supporting evidence that the Early Permian coal seams targets for the project are tightly confined and depressurisation effects within the seams due to water extraction are slow to propagate into overlying HSUs. This conclusion is consistent with 'over pressures' in the target coal seams that is evident from from drill stem tests (see Section 5.4.2).

**Table 5-6 Summary of baseline hydraulic head data for BWD6**

| Well name | Owner | Target HSU | Water Source | Hydraulic Head, m AHD | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | No. of Records | Start Date | End Date | Min. | Max. | Mean | Median |
| BWD6 | Santos | Porcupine Fm | GOB | 427 | 5/15 | 6/16 | 354.2 | 369.7 | 362.3 | 362.6 |

**Table 5-7 Historical water production for Bibblewindi pilots**

| Pilot name | Owner | Target Coal Seam | Water Source | Date Range | Total Water Production, ML |
|---|---|---|---|---|---|
| Bibblewindi 9-Spot | Santos | Early Permian | GOB | 2000 - 2012 | 198 |
| Bibblewindi East | Santos | Early Permian | GOB | 2014 - 2015 | 152 |
| Bibblewindi West | Santos | Early Permian | GOB | 2014 - 2015 | 75 |
| Dewhurst North | Santos | Early Permian | GOB | 2014 - 2015 | 45 |
| Dewhurst South | Santos | Early Permian | GOB | 2014 - 2015 | 71 |

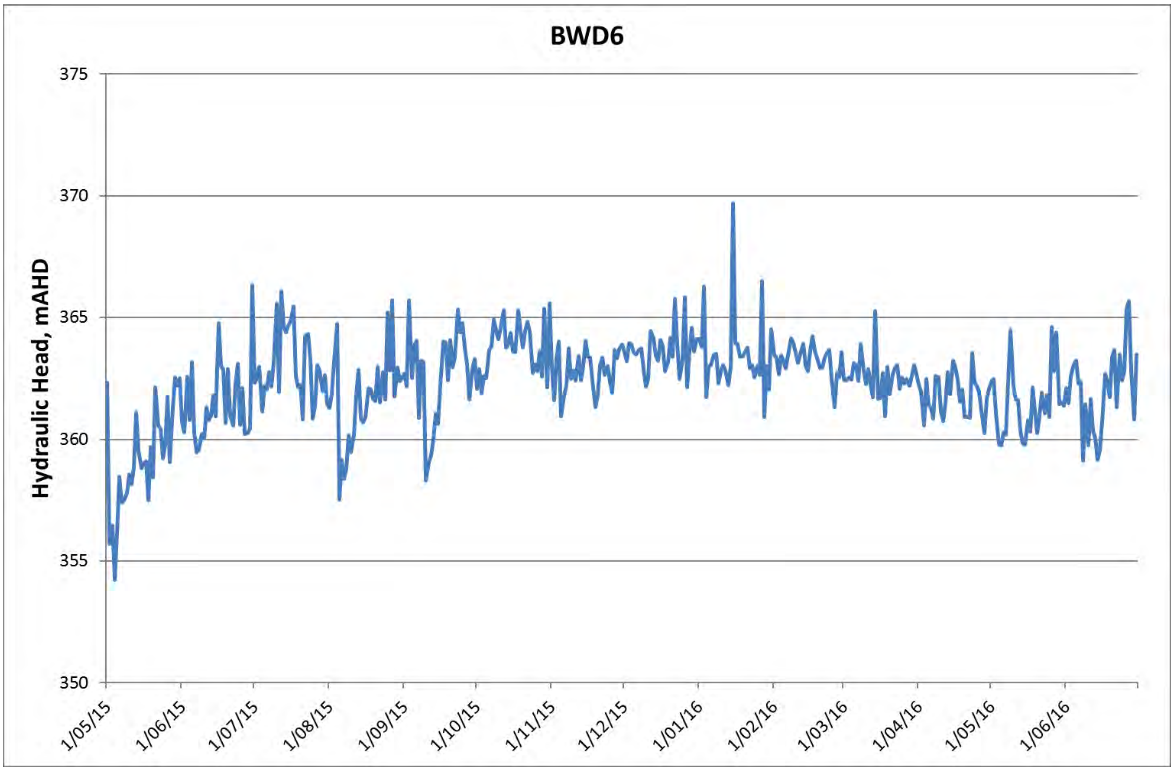



**Figure 5-5 Hydrograph for monitoring bore BWD6 (Porcupine Formation)**

### 5.4.4 Groundwater Flow Directions

Figure 5-9 shows a map of mean annual water table elevation in the year 2000 for monitoring bores with a screen depth of less than 50 m below ground surface. The water table contours are generated based on data from the PINNEENA v. 3.2 groundwater database (Section 5.4.1). Average values of water table elevation from 1015 bores were contoured in Surfer (v.10.7) using Kriging with 2 km × 2 km grid spacing; default linear variogram; point Kriging; no drift type; no search rules; and no breaklines (an explanation of these settings is available in Surfer help). In Figure 5-9 the contour lines are 'blanked' (not shown) in areas outside of the alluvium.

Relatively uniform water table gradients that follow the topography along rivers and valley floors occur in the alluvial aquifers. Water level measurements are sparse outside of the alluvium of the Gwydir, Namoi, Castlereagh and Macquarie River systems. Groundwater within the Upper Namoi Alluvium flows regionally in a north westerly direction following the course of the Namoi River. The alluvium narrows near the township of Narrabri before broadening into a substantial fluvial fan that forms the Lower Namoi Alluvium.

A corresponding map of mean hydraulic head in artesian bores for the period 1998 to 2001 is shown in Figure 5-10. The head contours are generated based on data from the PINNEENA v. 3.2 groundwater database (Section 5.4.1). Average values of piezometric head from 66 artesian bores were contoured in Surfer (v.10.7) using Kriging with 2 km × 2 km grid spacing; default linear variogram; point Kriging; no drift type; no search rules; and no breaklines.

The artesian data show regionally confined groundwater flow from southeast to northwest, which is generally consistent with existing interpretations of the regional flow direction within the Coonamble Embayment of the GAB (Figure 5-2). Hydraulic head in artesian bores beneath the Lower Namoi alluvium is above the water table elevation in the alluvium (below around 220 mAHD) indicating a tendency for upward leakage of artesian groundwater to the alluvium from the underlying GAB aquifer.

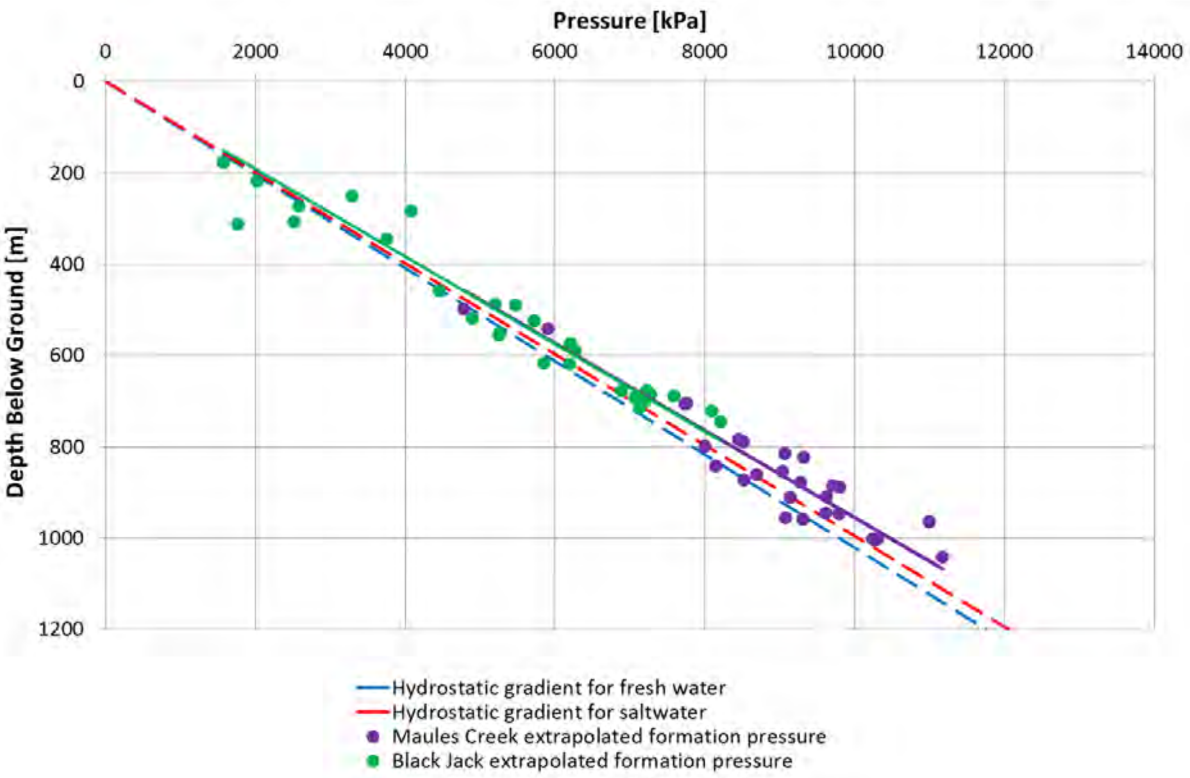



**Figure 5-6 DST pressure measurements in the Early and Late Permian target formations**

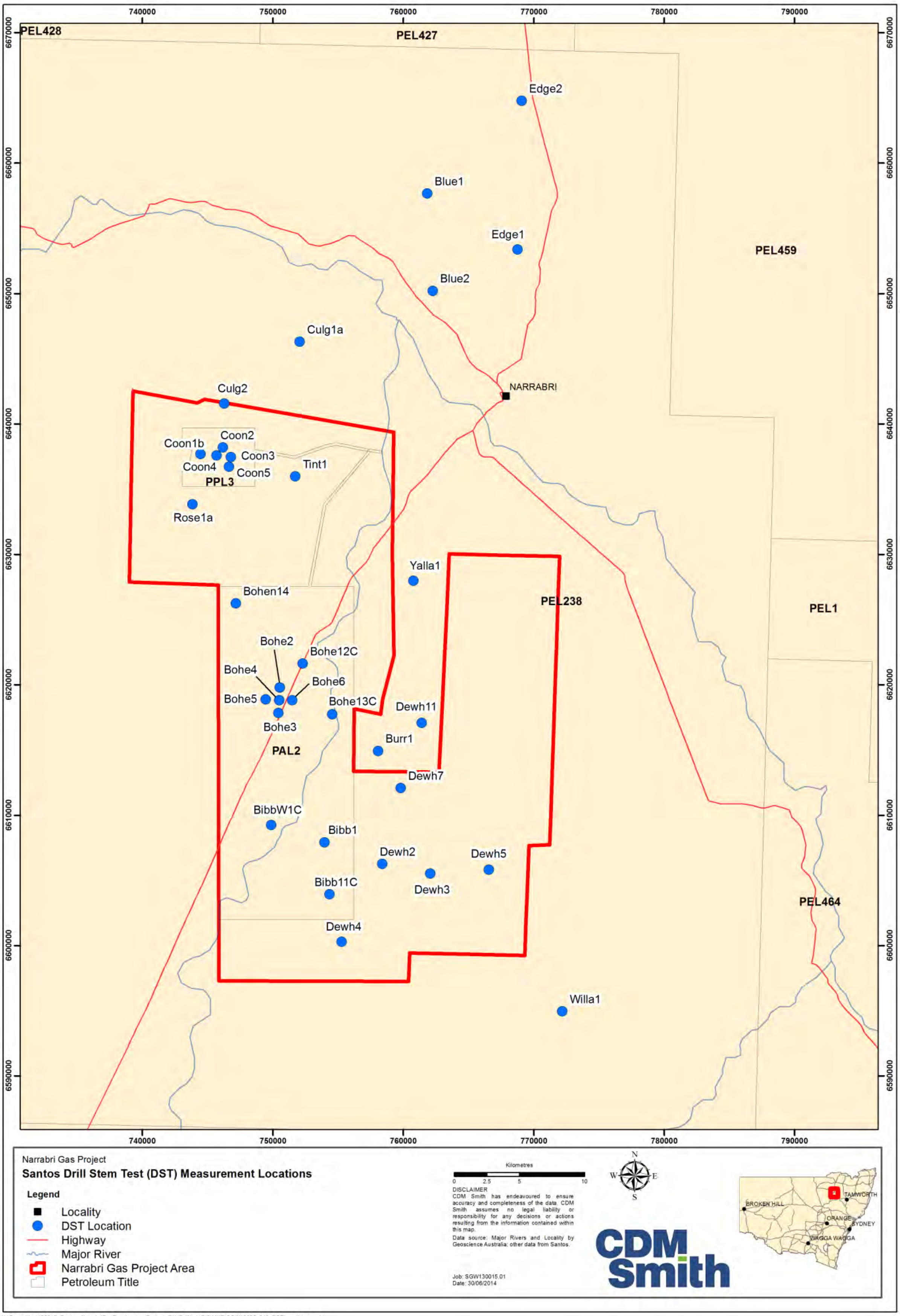



**Figure 5-7 Locations of Santos DST measurements**

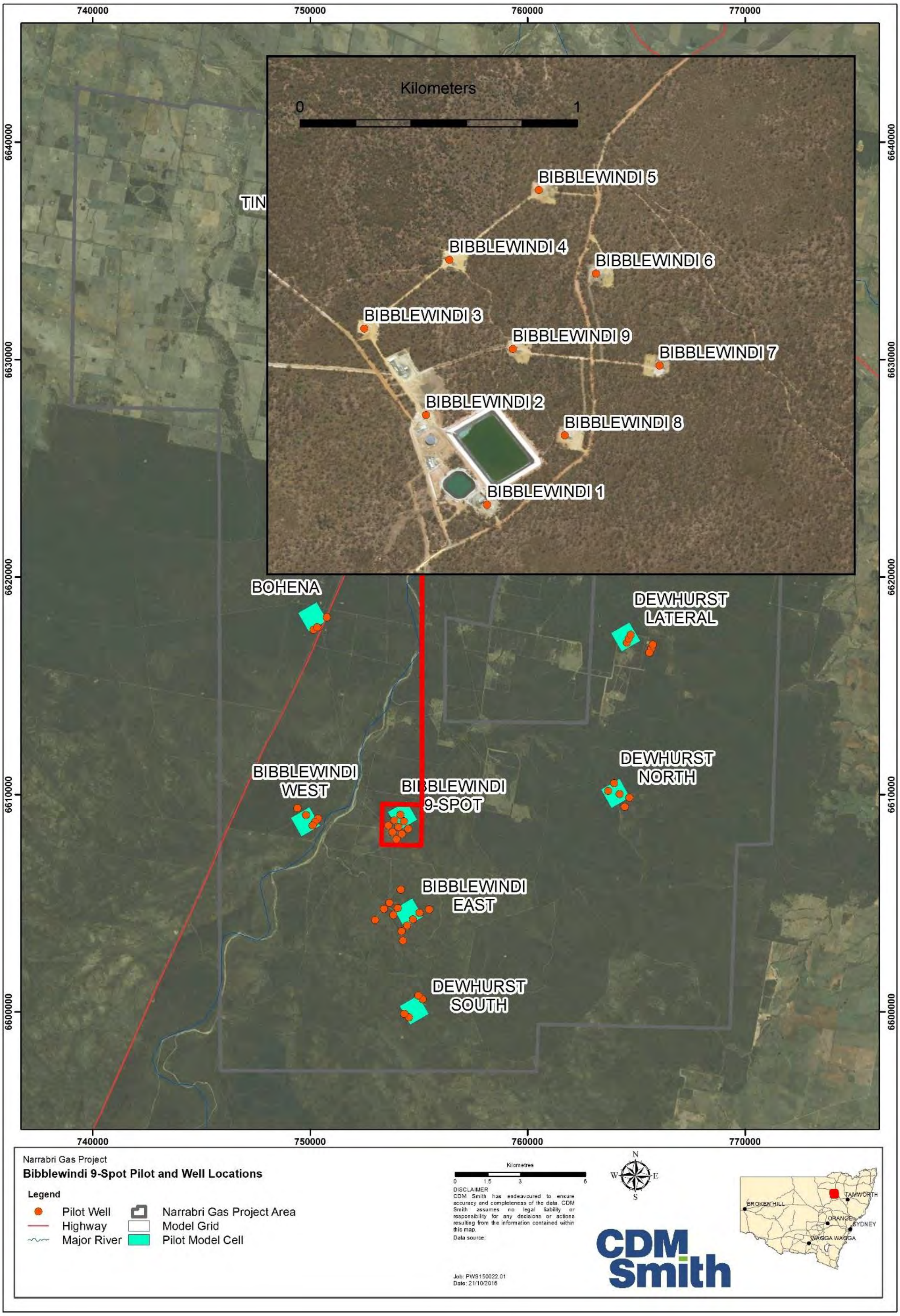



**Figure 5-8 Bibblewindi 9-Spot pilot and well locations**

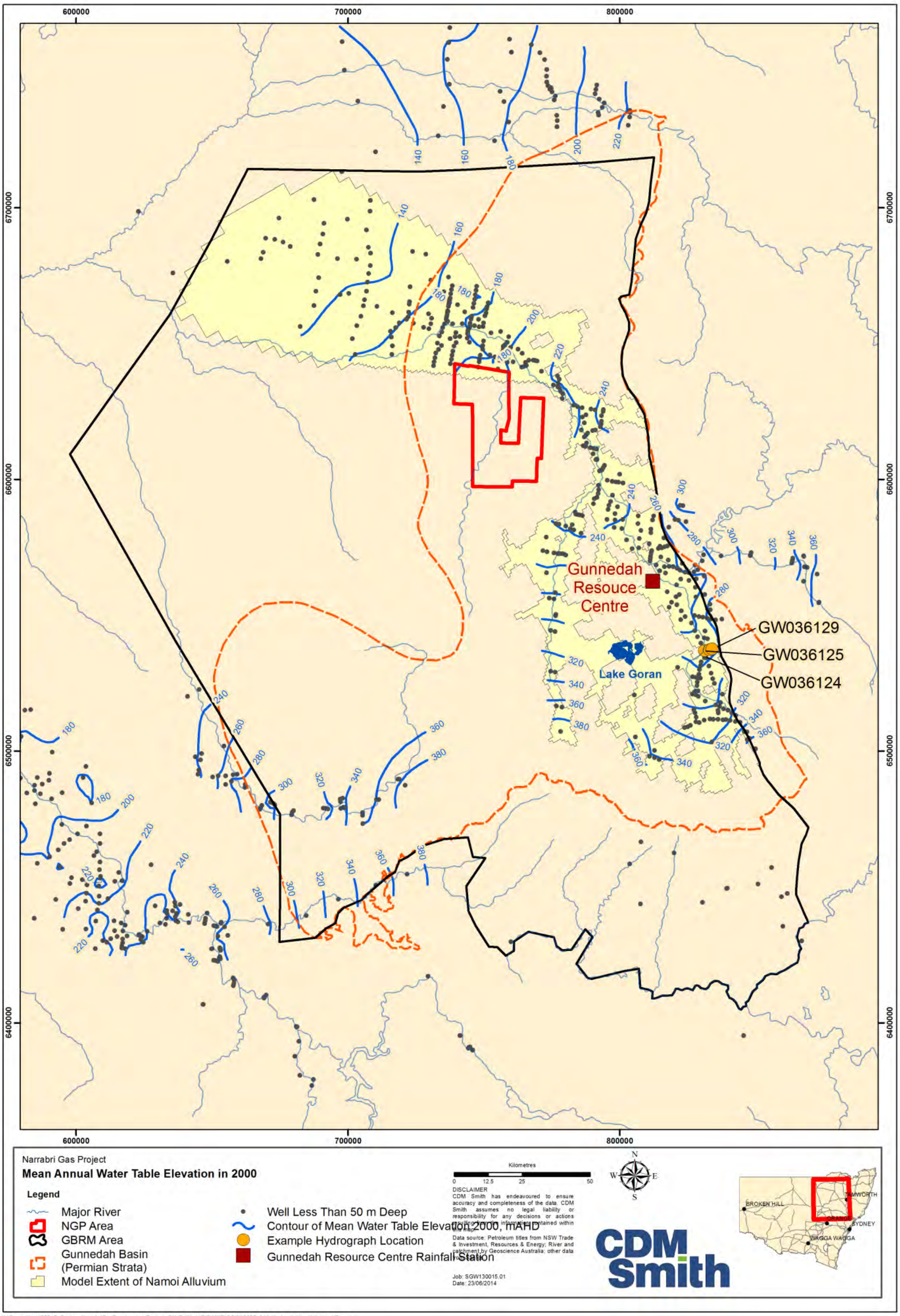



**Figure 5-9 Mean annual water table elevation for the year 2000**

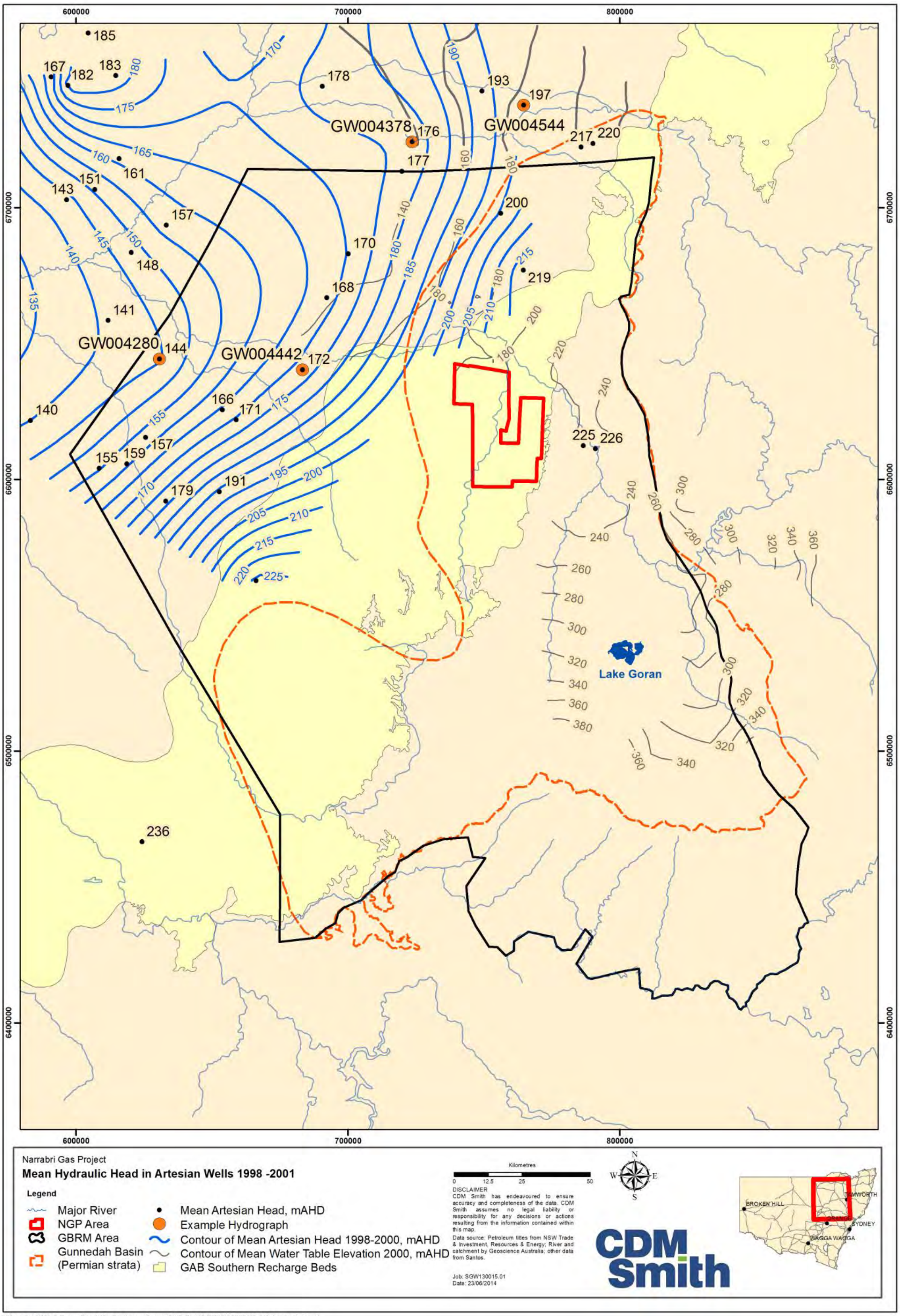


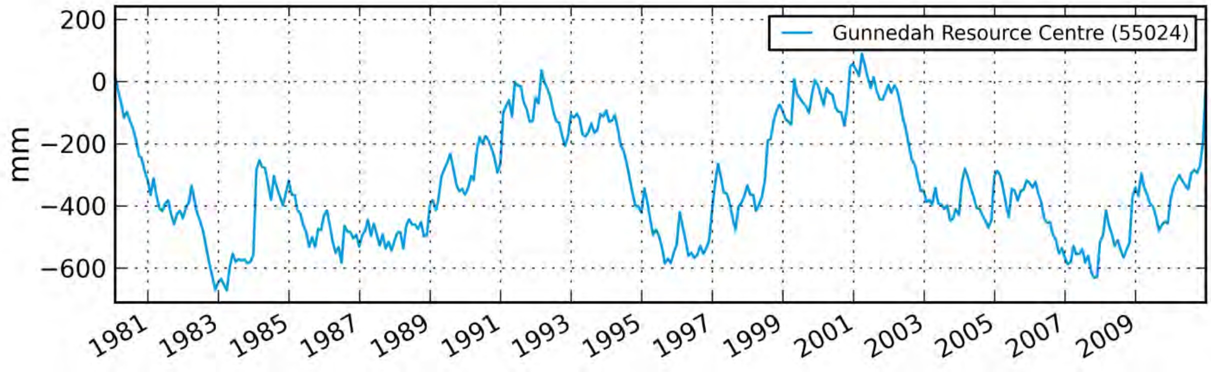

**Figure 5-10 Mean hydraulic head in artesian wells for years 1998-2001**

### 5.4.5 Bore Hydrographs

Example hydrographs in selected shallow alluvial bores and artesian bores are shown in Figure 5-11 and Figure 5-12; the bore locations are shown in Figure 5-9 and Figure 5-10. Annual water table fluctuations in shallow bores (Figure 5-11b) are consistent with regional rainfall cycles, which can be seen in the graph of cumulative deviation from mean (CDFM) rainfall at the Gunnedah Resources Centre (Station No. 55024) (Figure 5-11a). A declining trend in the water table elevation in shallow alluvial bores occurs from the mid-1990s and is probably in response to an increase in groundwater extraction also commencing in the mid-1990s (Section 5.5.3).

Hydrographs in artesian bores show a distinctive decline in hydraulic head within the GAB during the early-to-mid 1900s. This decline is followed by a period with relatively stable hydraulic head over the past 20 to 30 years. Stabilisation of artesian head is consistent with the timing of bore refurbishment works in the GAB and a reduction in the number of free flowing bores.

**a. Cumulative Deviation from Mean Rainfall**




**b. Example Well Hydrographs from the Upper Namoi Alluvium**

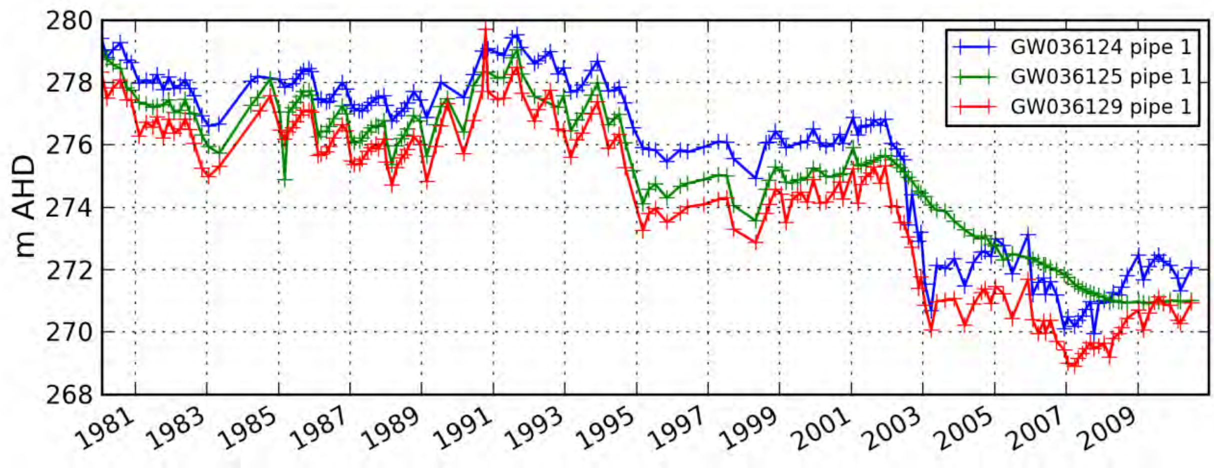



**Figure 5-11 Water table fluctuation and recent decline in the Upper Namoi Alluvium: (a) cumulative deviation from mean rainfall and (b) example bore hydrographs for years 1981 to 2011**

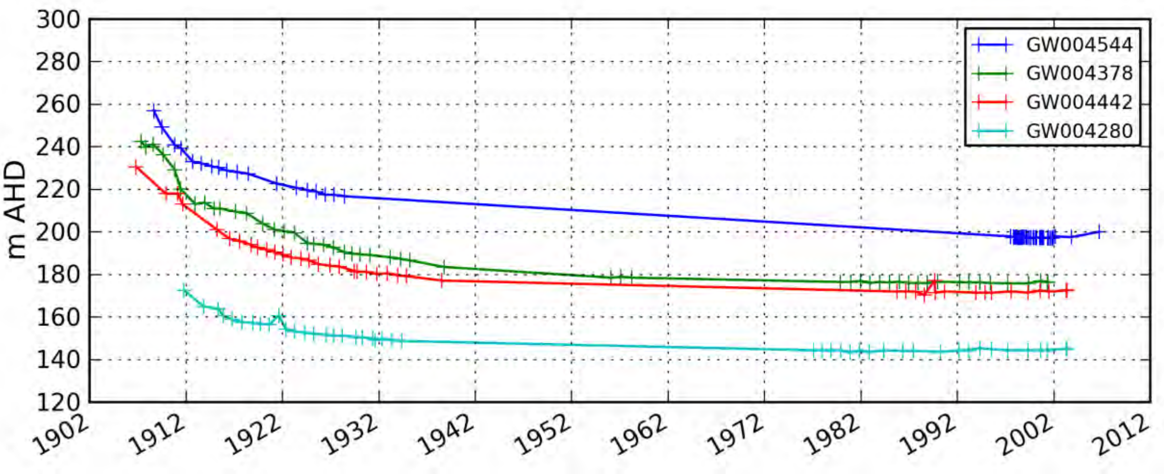



**Figure 5-12 Hydraulic head in selected artesian wells for years 1908 to 2008**

# 5.5 Groundwater Fluxes

## 5.5.1 Namoi Subregion Water Accounts

Product 1.5 of the Namoi subregion bioregional assessment (Pena-Arancibia et al. 2016) contains water accounts and water quality information that will be used in subsequent products in the bioregional assessment. The groundwater accounts were produced for the seven-year period spanning water years 2006-07 to 2013-14, and provide estimates of annual volumetric rates of groundwater inflows (recharge from rainfall) and groundwater outflows (extractions for consumptive use).

Estimates of groundwater recharge were taken from the NSW water sharing plans, or the associated background documents, including computed water budgets from DPI Water's existing groundwater models for the Upper and Lower Namoi alluvium (see Section 5.5.4). Groundwater use estimates were based on information obtained from the NSW Water Register.

## 5.5.2 Recharge Rates

Existing estimates of groundwater recharge rates within the GIA study area are summarised in Table 5-8. In the review of Australian groundwater recharge studies by Crosbie *et al.* (2010) the authors found that there have been comparatively few published recharge studies in NSW, with existing estimates being dominated by groundwater modelling studies, particularly within the inland alluvial areas.

Based on the Method of Last Resort (MOLR) developed for data poor areas, Leaney *et al.* (2011) estimated that groundwater recharge rates in the GIA study area are likely to vary from less than 1 mm/y up to approximately 20 mm/y (Figure 5-14).

Table 5-8 shows that a groundwater recharge rate of around 3% of the mean annual rainfall has generally been adopted for shallow groundwater sources within the Namoi alluvium. Estimates of groundwater recharge to outcrop units of the Gunnedah-Oxley Basin and GAB are generally smaller, with a regional value of around 1% of rainfall or less.

**Table 5-8 Existing estimates of groundwater recharge within the GIA study area**

| Location | Recharge type | Recharge rate estimate [mm/y] | Percent of 600 mm/y rainfall | Source |
|---|---|---|---|---|
| Namoi Alluvium | Rainfall | 20 | 3.3 | Golder Assoc. (2010) |
| | Rainfall | 58 | 10 | [1] Berhane (2001) |
| | Rainfall | 6 – 18 | 1 – 3 | McNeilage (2006) |
| | Irrigation | 30 – 72 | 5 – 12 | McNeilage (2006) |
| Liverpool Plains | Rainfall | 18 – 32 | 3 – 5.3 | Zhang (1997) |
| Lake Goran | [2]Inundated average | 28.5 | 4.8 | Zhang (1997) |
| | | 6 | 1 | Zhang (1997) |
| GAB Coonamble Embayment | Rainfall | 6 | 1 | [3]Wolfgang (2000) |
| | Rainfall | 0.2 – 1.1 | 0.03 – 0.18 | [3]Radke *et al.* (2000) |
| | Rainfall | 6 – 30 | 1 – 5 | [3]Kelett *et al.* (2003) |
| Triassic-Permian outcrops | Rainfall | 1 | 0.17 | Golder Assoc. (2010) |

[1]In Crosbie et al (2010), [2]Once every five years on average, [3]In Herczeg and Love (2007)

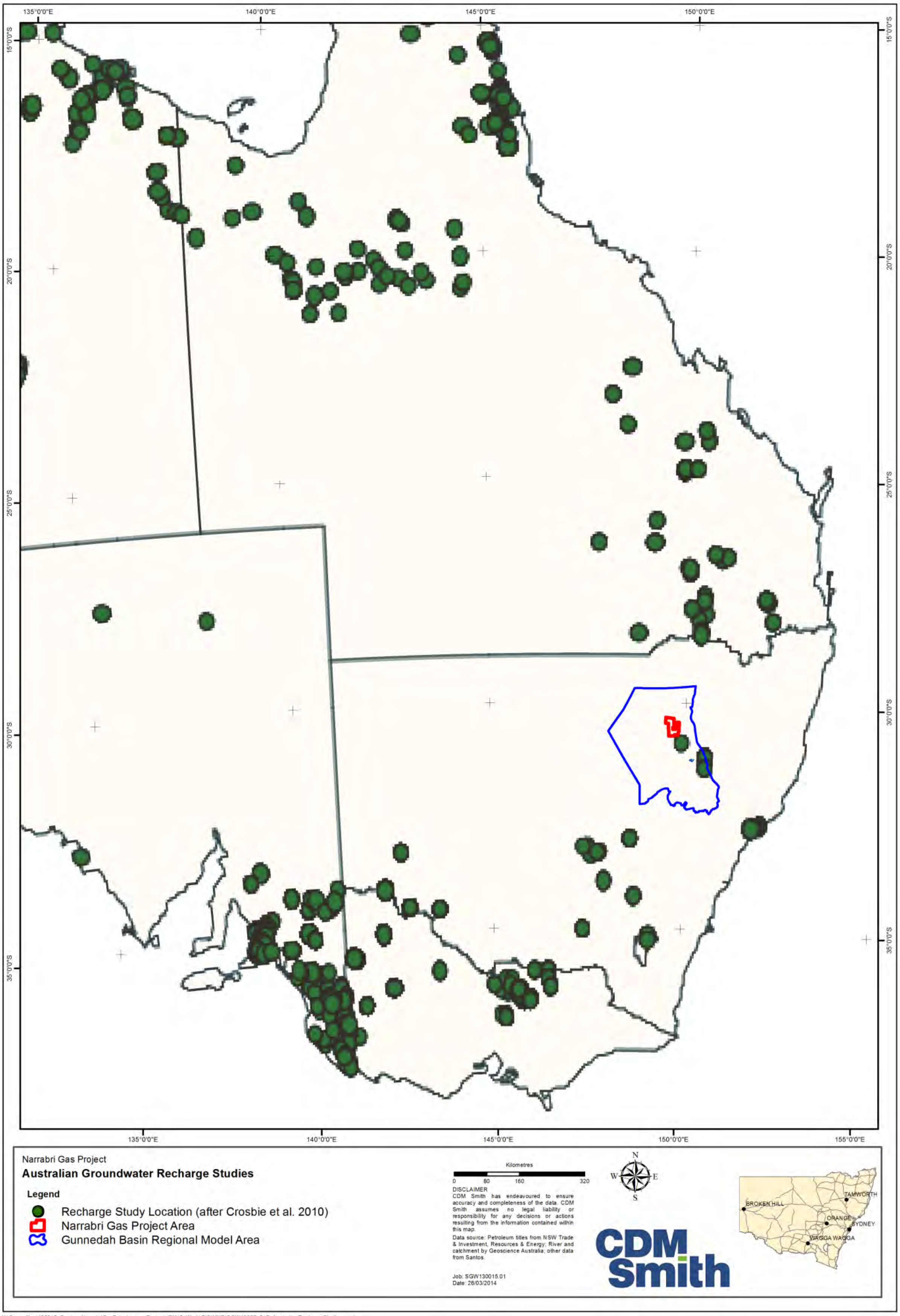



**Figure 5-13 Australian groundwater recharge studies (after: Crosbie *et al.* 2010)**

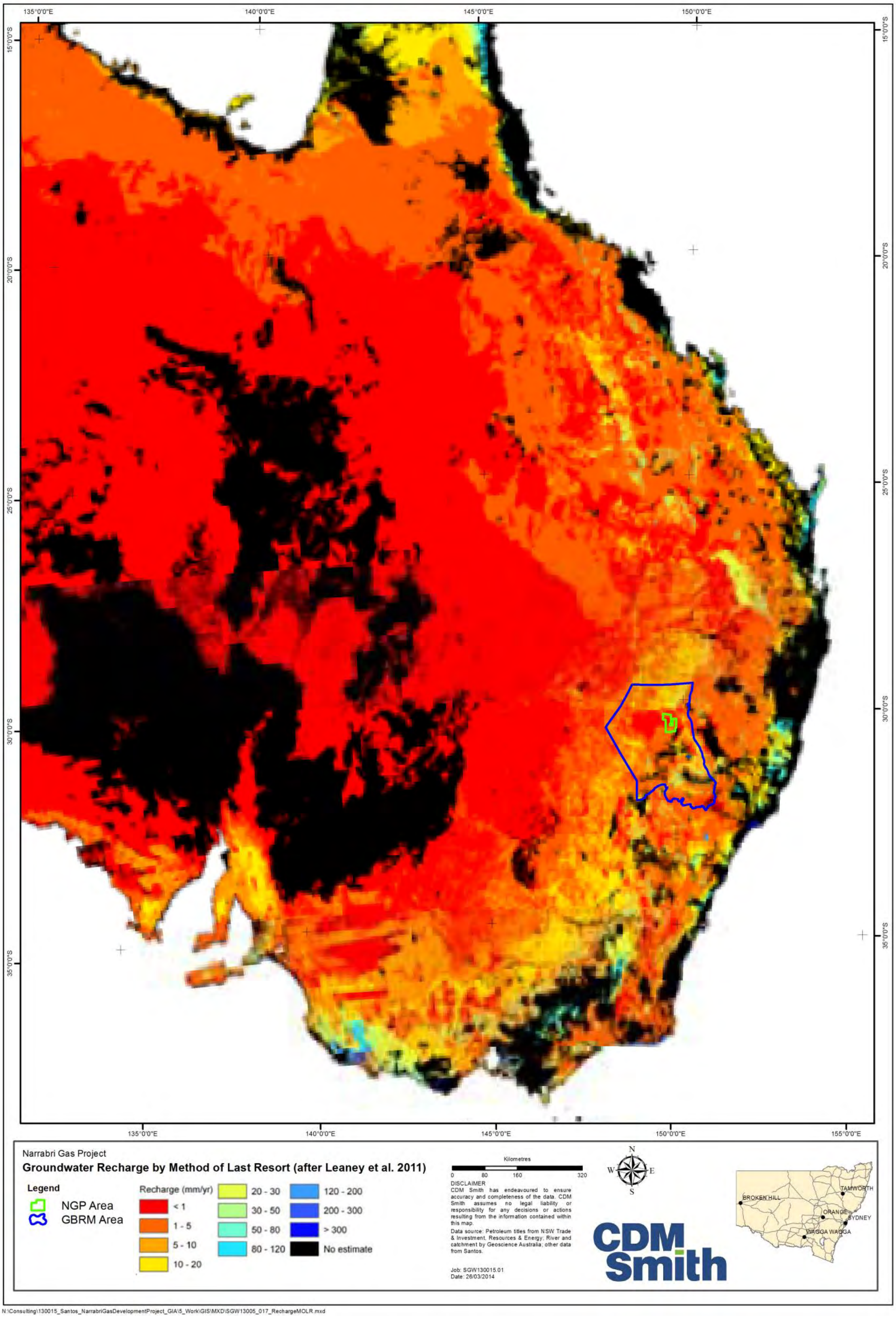



**Figure 5-14 Groundwater recharge estimation by MOLR (after Leaney *et al.* 2011)**

### 5.5.3 Groundwater Extraction

Groundwater extraction data from DPI Water contain annual groundwater extraction records for individual bores within the Upper Namoi Groundwater Management Areas (GMAs), the Lower Namoi GMA, the Gunnedah-Oxley Basin GMA and the Peel Valley GMA for the period 1984 to 2011.

A total of 933 bores have groundwater extraction records for the period 1996 to 2000. Of these bores, 920 are located within the portion of the Namoi Catchment contained within the GIA study area. The average extraction rate for 1996 to 2000 from these bores was approximately 148 GL/y; consisting of:

- 96 GL/y (65%) from the Upper Namoi GMAs;
- 49 GL/y (33%) from the Lower Namoi GMA;
- 1.7 GL/y (1%) from the Gunnedah-Oxley Basin GMA; and
- 1.3 GL/y (1%) from the Peel Valley GMA.

In comparison, annual groundwater extraction from the Castlereagh Alluvium in 2004–2005 was estimated to be approximately 2.6 GL/y (CSIRO 2008).

The annual groundwater extraction data for 1984 to 2011 from the Upper and Lower Namoi GMAs and the Gunnedah-Oxley Basin GMA are shown in Figure 5-15. The data indicate that there has been an overall increase in total extraction from the alluvium since the mid-1990s, including two periods of relatively larger extraction during 1992 to 1996 and 2001 to 2003. Groundwater extraction from the Gunnedah-Oxley Basin is comparatively much smaller.

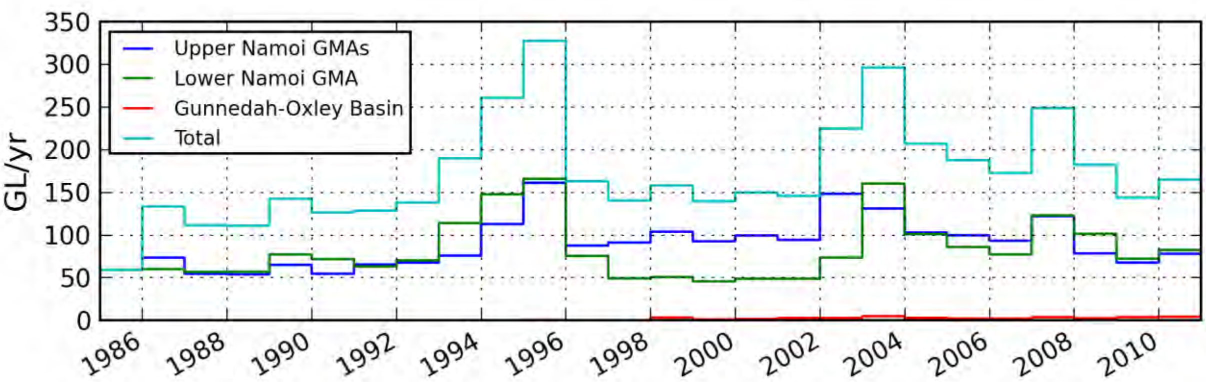



**Figure 5-15 Annual groundwater extractions from the Namoi alluvium and Gunnedah-Oxley Basin**

The Namoi subregion water accounts (Pena-Arancibia et al. 2016) estimated annual average groundwater use of:

- 79.5 GL/y from the Upper Namoi alluvium (groundwater management zones 1 to 11);
- 75.5 GL/y from Lower Namoi alluvium;
- 4.2 GL/y from the Gunnedah-Oxley Basin;
- 2.5 GL/y from the GAB Southern Groundwater Source; and
- 1.9 GL/y from the GAB Surat Groundwater Source.

### 5.5.4 Namoi Alluvium Water Balance

Previous groundwater modelling studies of the Lower Namoi alluvium (Merrick 2001) and Upper Namoi alluvium (McNeilage 2006) have led to estimates of the groundwater balances for these systems. Of particular interest to the GIA, the estimated annual inflows and outflows provide quantitative context for understanding the relative magnitude of anticipated coal seam water production within the Gunnedah Basin. Summaries of simulated water balances from studies by Merrick (2001) and McNeilage (2006) are given in Table 5-9. The Lower and Upper Namoi groundwater models were also used by CSIRO for groundwater assessments of the Namoi Catchment for the Murray-Darling Basin Sustainable Yields study (CSIRO 2007a). Summaries of the simulated water balances for Scenario A of that study "Historical climate and current development" are given in Table 5-10.

Total net inflow and outflow rates were estimated to be in the range 135 to 172 GL/y. Total simulated groundwater extraction from the Namoi alluvium varied from 135 to 154 GL/y, although data from DPI Water presented in the previous section indicate that annual extraction has been as large as 300 GL/y at times during the past twenty years.

**Table 5-9 Water balance results from the Lower and Upper Namoi groundwater models (after Merrick 2001 and McNeilage 2006)**

| Estimate | [1]Lower Namoi Groundwater Model 1980-1998 | [2]Upper Namoi Groundwater Model 1985-2001 | Combined Total Rates |
|---|---|---|---|
| **Period of Balance [y]** | **18.3** | **15** | **15-18.3** |
| | **Net inflow rate to model [GL/y]** | | |
| Rivers | 41.3 (57%) | 11 (17%) | 52 (38%) |
| Rainfall, irrigation and floods | 21 (29%) | 49 (78%) | 70 (52%) |
| Boundaries | 1.8 (3%) | 3.1 (5%) | 4.9 (4%) |
| Artesian | 7.9 (11%) | n.a. | 7.9 (6%) |
| Total net inflow | 72 (100%) | 63 (100%) | 135 (100%) |
| | **Net outflow rate from model [GL/y]** | | |
| Rivers | 1.6 (2%) | 9.0 (13%) | 11 (7%) |
| Extraction | 78 (94%) | 58 (86%) | 135 (91%) |
| Boundaries | 3.2 (4%) | 0.36 (1%) | 4 (2%) |
| Total net outflow | 82 (100%) | 67 (100%) | 150 (100)% |
| Loss | -10 | -3.5 | -13.5 |

[1]Adapted from Merrick (2001, Table 4.1), [2]Adapted from McNeilage (2006, Table 6.1)

**Table 5-10 Water balance results from the Lower and Upper Namoi groundwater models (after CSIRO 2007a)**

| Estimate | Lower Namoi groundwater model [1]Scenario A | Upper Namoi groundwater model [1]Scenario A | Combined total rates |
|---|---|---|---|
| **Balance period [y]** | **111** | **111** | **111** |
| | **Net inflow rate to model [GL/y]** | | |
| Rivers | 32 (40%) | 24 (33%) | 56 (36%) |
| Rainfall, irrigation and floods | 41 (51%) | 45 (62%) | 86 (56%) |
| Boundaries | 8 (10%) | 4 (5%) | 12 (8%) |
| Total net inflow | 81 (100%) | 73 (100%) | 154 (100%) |
| | **Net outflow rate from model [GL/y]** | | |
| Rivers | 6 (6%) | 2.4 (3%) | 8 (5%) |
| Extraction | 83 (85%) | 70 (94%) | 154 (89%) |
| Boundaries | 9 (9%) | 1.7 (2%) | 11 (6%) |
| Total net outflow | 98 (100%) | 74 (100%) | 172 (100)% |
| Loss | -17 | -0.8 | -18 |

[1]Historical climate and current development (CSIRO 2007a)

### 5.5.5 Coal Seam Gas Water Production

Existing estimates of coal seam gas water production for Australian basins are summarised in Table 5-11. The largest estimate of total water production is 1200 GL from 6000 anticipated coal seam gas wells for the Curtis LNG project in the Surat Basin. The other major gas fields have total anticipated water production volumes of order-of-magnitude 100 GL.

**Table 5-11 Estimates of coal seam gas water production for Australian basins (after SWS 2012a)**

| Project | Operator | Basin | No. of Wells | Water Production | | |
|---|---|---|---|---|---|---|
| | | | | Period [y] | Total [GL] | Peak Rate [GL/y] |
| Arcadia Valley | Santos | Bowen | - | 35 | 90 | 5.8 |
| Fairview | Santos | Bowen | 750 | 23 | 92 | 14 |
| Roma shallow | Santos | Surat | 1300 | 25 | 138 | 8.8 |
| Curtis LNG | QGC | Surat | 6000 | - | 1200 | 66 |
| Gloucester Stage 1 | AGL | Gloucester | 110 | - | - | 0.73 |
| Casino | Metgasco | Clarence-Moreton | 40 | 25 | 0.7 | 0.073 |

Figure 5-16 compares the estimates of historic groundwater extraction in the Upper and Lower Namoi alluvium (CSIRO 2007a) and the Base Case estimate of water production for the Narrabri Gas Project in this assessment (see Section 6.8.2). Over a period of 25 years, corresponding to the assessment period for the project, the total extraction from the Upper and Lower Namoi alluvium based on historic groundwater use over the same period of time is of order of magnitude 3500–4000 GL. In comparison, the simulated water production from the project is 37.5 GL, which is to be extracted from deep strata in the Gunnedah Basin. On this basis of this comparison, the simulated rates and volume of water production for the project are considered to be relatively small (approximately 2%) compared to the existing uses of shallow groundwater in the alluvial sources.

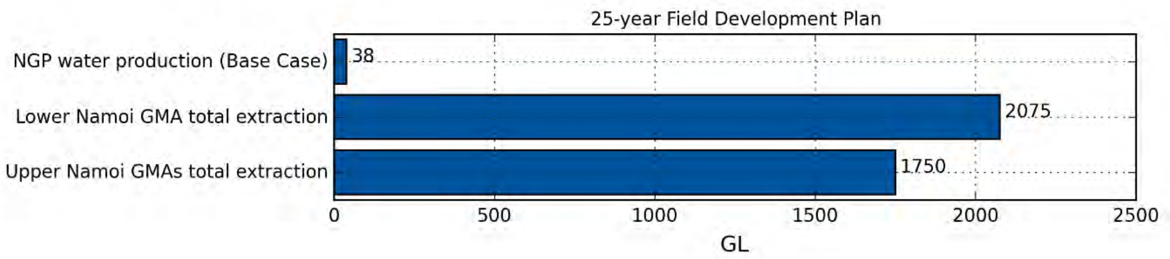



**Figure 5-16 Comparison of simulated water production for the Narrabri Gas Project and historical groundwater use in the Namoi alluvium (CSIRO 2007a)**

### 5.5.6 Existing and Approved Mine Dewatering

A summary of predicted drawdown of hydraulic head at existing and approved coal mines within the GIA study area is given in Table 5-12. The locations of the mines and the extent of drawdown predicted from previous groundwater modelling studies are shown in Figure 5-17. The Werris Creek mine is located outside of the GIA study area.

Groundwater impacts from underground mining operations at Narrabri North were predicted in an area above and to the northeast of the project area (Aquaterra 2009). Total inflow of 22.6 GL from the Hoskissons Coal to Narrabri Mine underground working was predicted for the 28-year mining period from 2012 to 2040 (see Section 6.9.4). Predictions of drawdown were made in the Hoskissons Coal, overlying units Napperby Formation and Garrawilla Volcanics, and at the water table. The contour of 1 m drawdown in the Hoskissons Coal was predicted to extend approximately 30 km within the seam at the end of mining, with the extent of drawdown decreasing in the overlying formations. Water table drawdown of 0.5 m at the end of mining was predicted in a relatively small area north of the underground operations adjacent to the Namoi alluvium.

The Tarrawonga, Boggabri, Maules Creek, Rocglen and Vickery coal projects are located in a cluster east of the project area within the Maules Creek Sub-basin. Effects from coal seam gas development are not expected in this region of the GIA study area due to sub-surface separation across the Boggabri Ridge.

The Sunnyside coal project and the Watermark Coal Project are located further away from the project area to the southeast. Depressurisation and drawdown at Sunnyside were predicted to be relatively small and localised compared to other mines in the region (GeoTerra 2008). Groundwater modelling for the Watermark Coal Project (AGE 2013) predicted that depressurisation greater than 1 m in Permian formations, with drawdown of 1-2 m in the overlying alluvial formations would be restricted to within approximately 4 km of the proposed open cut operations.

**Table 5-12 Predicted impacts of mine dewatering from existing groundwater assessments**

| Mine | Status | Start Year | Mining Period | Predicted Radius of Influence | Formation | Source |
|---|---|---|---|---|---|---|
| Narrabri North (Whitehaven) | Existing | 2010 | 29 y | 1 m drawdown contour 20 km to southwest and northwest and 10 km to south at end of mining; drawdown to east is limited by truncation of Hoskissons Coal | Hoskissons Coal | Aquaterra (2009) |
| | | | | 1 m drawdown contour 10 km to southwest and northwest at end of mining | Napperby Formation | |
| | | | | 1 m drawdown contour 5 to 8 km to west at end of mining | Garrawilla Volcanics | |
| | | | | 0.5 m drawdown 1 km to north at end of mining | Alluvium, colluviums, regolith | |
| Tarrawonga (Whitehaven) | Existing | 2006 | 8–10 y (possibly up to 23) | 2005 local scale model indicates 2 m drawdown contour extending 1 km outside of tenement to east and further to north (extending beyond model boundary) | Alluvium | RCA (2005) |
| | | | | 1 m drawdown contour 3 to 3.5 km from tenement boundary | Alluvium, regolith | Merrick & Alkhatib (2012) |
| Boggabri (Idemitsu) | Existing | 2006 | 21 y | 2 m drawdown contour of water table extending 4 to 5 km from site boundary to north and south but constrained to east and west | Alluvium | AGE (2010) |
| Rocglen (Whitehaven) | Existing | 2008 | 11–14 y | Predicted drawdown remains within project boundary | - | RCA (2007) |
| Werris Creek (Whitehaven) | Existing | 2005 | 15 y | 1 m drawdown contour extends 5 to 7 km from mine | Alluvium, Werrie Basalt | RCA (2010) |
| Sunnyside (Whitehaven) | Existing | 2009 | 5 y | Mine pits and drawdown restricted to an area of approximately 1 $km^2$ | Alluvium, Hoskissons Coal, | GeoTerra (2008) |
| Maules Creek (Whitehaven) | Existing | 2014 | 21 y | 1 m drawdown contour extends 5 to 7 km from mine | Gunnedah Formation (alluvium) | AGE (2011) |

| Mine | Status | Start Year | Mining Period | Predicted Radius of Influence | Formation | Source |
|---|---|---|---|---|---|---|
| Watermark Coal Project | Approved | NC | 30 y | 1 m drawdown at approximately 4 km from the Southern Mining Area in year 30 of mining | Permian formations | AGE (2013) |
| | | | | 1-2 m drawdown approximately 3.9 km from the Southern Mining Area in year 25 of mining | Alluvial formations | |
| Vickery Coal Project (Whitehaven) | Approved | NC | 30 y | Significant drawdown restricted to Maules Creek Formation; less than 1 m drawdown in Upper Namoi Alluvium | Regolith/ alluvium, Maules Creek Fm | Merrick & Alkhatib (2013) |

NC – not commenced

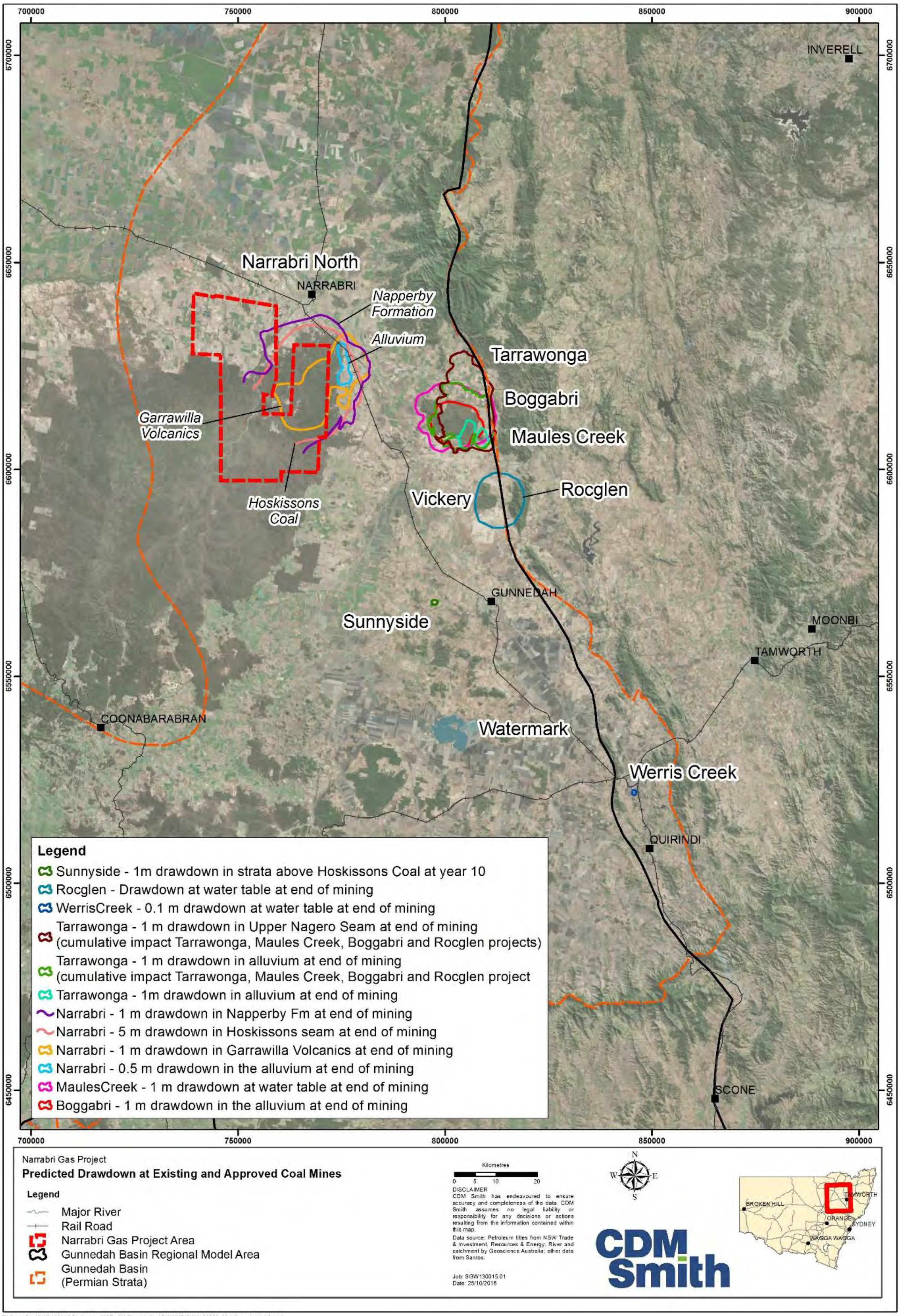



**Figure 5-17 Predicted drawdowns at existing and approved coal mines**

# 5.6 Groundwater Flow System

The GIA study area can be conceptualised as consisting of three connected hydrological systems with distinguishing spatial extents and hydrological regimes. A conceptual cartoon emphasising these distinctive hydrological scales can be seen in Figure 5-18.

From largest and least dynamic to smallest and most dynamic they consist of:

1. **Deep groundwater sources** - within Jurassic to Permian age hydrostratigraphic units, with hydrological response times of decades, centuries and possibly millennia;

2. **Shallow alluvial groundwater sources** - along river courses and streams with response times of weeks, months and years; and

3. **Surface water sources** - within rivers and streams, with hydrological response times of hours, days and weeks.

The primary source of recharge water to the system is from atmospheric precipitation, which imposes regional climate dynamics on surface water flows and groundwater levels. Daily variations of rainfall and evaporation in rivers and streams are damped within the alluvial groundwater systems, which typically exhibit seasonal and longer period cycles. The deep hydrostratigraphic units have much larger response times and follow multi-decadal cycles and longer climate trends.

River and stream flows occur in response to rainfall and runoff with connection to alluvial groundwater sources via exchanges across river and stream beds. Over annual time scales the daily and seasonal exchanges between rivers and alluvium are damped by the slower response of the groundwater system. On average there is either net percolation of surface water to the alluvium (net groundwater recharge) or net drainage of groundwater to the river (net groundwater discharge). River and stream reaches that contribute to net groundwater recharge are referred to as losing streams, while those receiving net groundwater discharge are referred to as gaining streams.

The direction of flow across the base of the alluvial deposits is controlled by the difference in hydraulic head between the alluvium and subcrop units, with an expectation of complex flow patterns. Net inflow across the base of the alluvium is generally anticipated at the margins of the alluvial deposits due to topographically controlled groundwater flow toward valleys. In contrast, beneath central parts of the alluvium, net outflow from the alluvium to deeper groundwater sources is hypothesised at locations where deep hydrostratigraphic units subcrop beneath the alluvium and hydraulic head in the alluvium is larger than in the Gunnedah Basin to the west. By these mechanisms the alluvium can act as both a discharge area for shallow local groundwater sources that fringe the alluvium and a recharge area for deep regional groundwater sources within the Gunnedah Basin and GAB.

Counter balancing groundwater flow from the deep hydrostratigraphic units back to shallow aquifers occurs in lower lying areas within the western part of the GIA study area, where artesian head occurs in the deeper units.

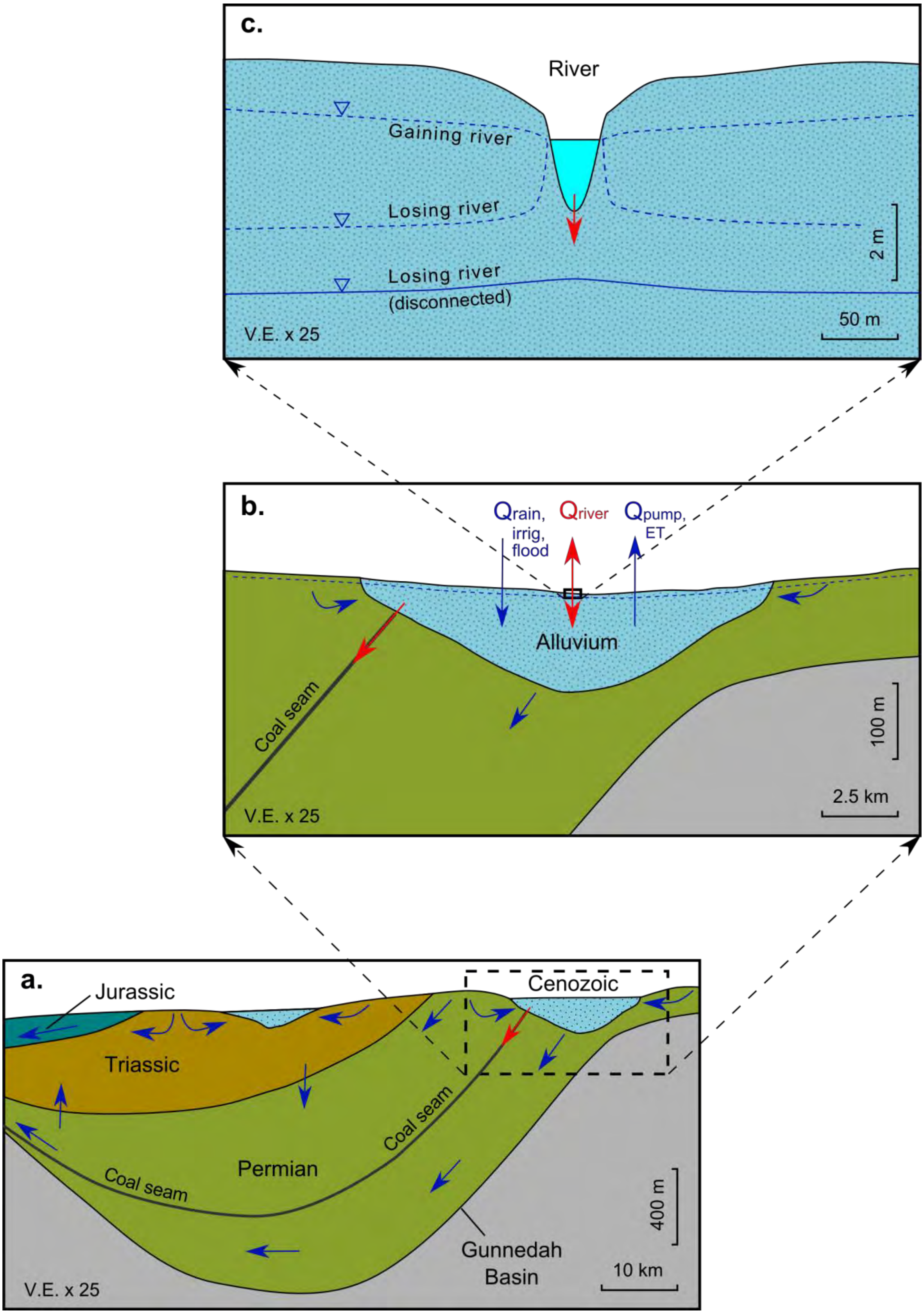



**Figure 5-18 Conceptualisation of hydrological scales and processes**

### 5.6.1 Current State

The hydrogeological domain contains unconfined alluvial groundwater sources and variably confined and unconfined groundwater sources within the GAB and Gunnedah-Oxley Basin. The shallow and deep groundwater sources are separated vertically by aquitard systems with potential for interaction across subcrop areas at the base of the alluvium.

The regional water table within the alluvial system is topographically controlled and generally follows the fall of the land surface along the river and stream valleys. Recharge to the alluvium is from rainfall infiltration, irrigation and episodic flooding.

Throughout most of the hydrogeological domain the river systems are losing stream flow to groundwater and are therefore a net source of groundwater recharge. Figure 5-19 shows an analysis of losing and gaining conditions along the Namoi River by CSIRO (2007a). In this analysis, the entire river within the Lower Namoi Groundwater Management Area (GMA) and around two-thirds of the river within the Upper Namoi GMA zones was classified as having net stream flow loss to groundwater. The remaining section of river, between the townships of Boggabri and Narrabri, was classified as having net stream flow gain from groundwater; however, it follows that a portion of the groundwater gained in this section of river is lost back to the alluvium further downstream within the Lower Namoi GMA.

Extraction from bores represents the largest removal of groundwater from alluvial sources. Pumping from the alluvium is estimated to be greater than 90% of the total discharge from the Lower Namoi (Merrick 2001) and greater than 85% of the total discharge from the Upper Namoi GMA zones (McNeilage 2006). CSIRO (2007a) found that the lower Namoi River has changed from a river that gained water from groundwater prior to development to a river that now loses considerable stream flow volumes to groundwater. Annual groundwater extraction is estimated to exceed total annual recharge in most years.

The inferred recharge area of the Permo-Triassic units within the Gunnedah Basin is located along the eastern margin of the basin where the units are exposed at outcrops and where they subcrop beneath Cenozoic sediments. The recharge area corresponds approximately to the extent of the Upper Namoi alluvium, where there is potential for groundwater in the alluvium to leak downward into the basin units across subcrop areas. Jurassic units within the GAB onlap the Gunnedah Basin from the west and it is expected that artesian pressures are present in the Permo-Triassic units where they underlie the GAB; particularly where the GAB has artesian pressure.

The regional distribution of hydraulic head and groundwater flow patterns within the Gunnedah Basin is mostly unknown due to a lack of measurements and investigation. Where both basins are present, it is expected that the patterns of hydraulic head distribution and groundwater flow in the Gunnedah Basin will broadly reflect the patterns within the GAB. A regional groundwater flow divide is expected within the Gunnedah Basin in the southeast of the GIA study area, representing the divide between groundwater drainage northwest toward the GAB and groundwater drainage southeast toward the Sydney Basin. It is likely that the location of the divide corresponds broadly with the location of the regional topographic divide defined by the Liverpool Ranges.

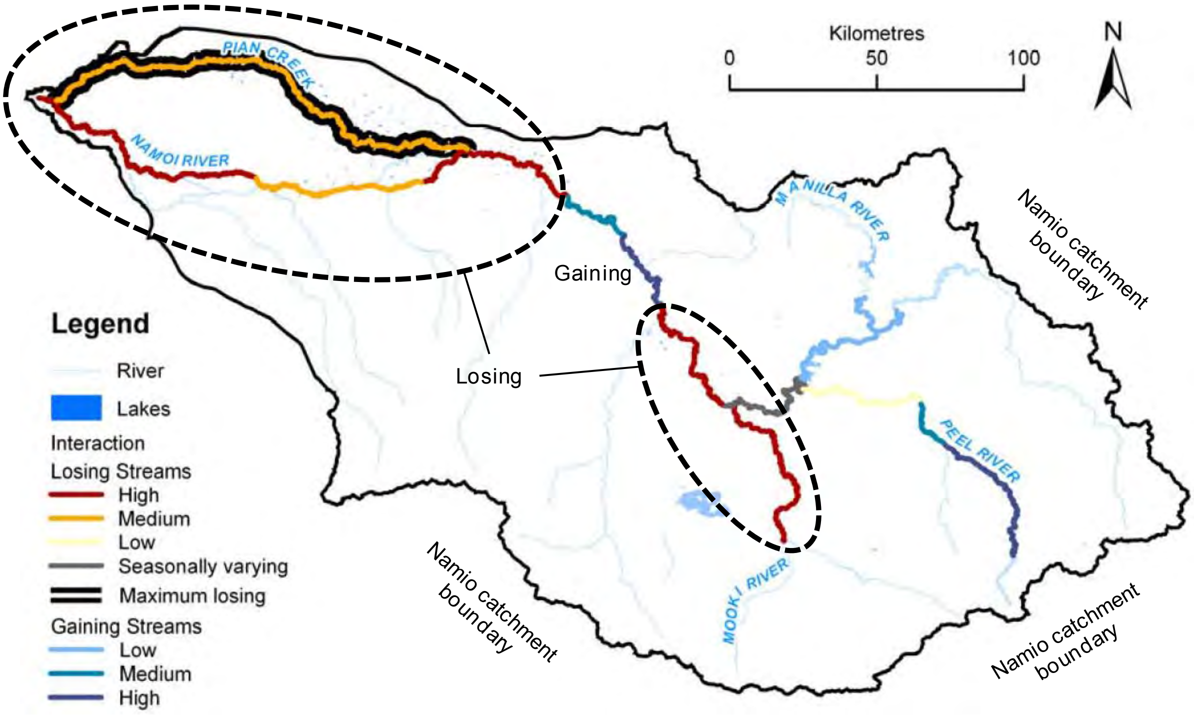



**Figure 5-19 Losing and gaining river reaches within the Namoi catchment (after CSIRO 2007a)**

## 5.6.2 Future State with Coal Seam Gas Development

Coal seam gas production is achieved by removing water to depressurise the target coal seams. The potential impact of water production during coal seam gas development depends on how much water is removed and the ultimate source for replacement of the water. It is possible to conceptualise four water balance adjustments that may occur to counter balance coal seam water production: a decrease in groundwater storage; a decrease in groundwater discharge; an increase in groundwater recharge, and a combination of these.

At the commencement of depressurisation of a coal seam all of the produced water must be derived from local storage. The zone of depressurisation that forms at extraction locations expands within the production seams and propagates into bounding and connected formations. Depressurisation does not mean that the formations are drained of water. Very locally, within a producing coal seam, the pore space becomes partly filled with gas, and this gas displaces the water that was previously stored; this is the source of the water produced as a by-product of gas production. Neighbouring units remain fully saturated with water; however, the pressure in the water and the hydraulic head are lower than before gas production.

Net groundwater inflow to the hydrogeological domain is affected by coal seam water production only if the induced change in hydraulic head extends to the region's boundary, including the water table and lateral boundaries that define its extent. Decline of hydraulic head adjacent to a recharge (source) boundary will increase the hydraulic gradient across the boundary and cause an increase in the rate of inflow. Alternatively, decline of hydraulic head adjacent to a discharge (sink) boundary will reduce the hydraulic gradient and decrease the rate of outflow. A sufficiently large decline in hydraulic head may cause a reversal of hydraulic gradient at the boundary and a change from outflow to inflow.

Change in net inflow to the hydrogeological domain in response to water removal from coal seams signifies that the impacts of coal seam water production are no longer contained completely within the domain. When this condition is reached a portion of the coal seam water production is counter balanced by the additional inflow and reduced outflow from boundaries; thus, the rate of release from formation storage reduces by the same amount and becomes less than the water production rate. As coal seam water production decreases over time, it must eventually become less than the net inflow rate across the boundaries, at which time the formation storage begins to recover. After coal seam water production ceases the induced change in net inflow across the boundaries is counter balanced completely by recovery of storage. For the groundwater system to fully recover, the total volume of water produced during coal seam gas development must ultimately be replaced by additional recharge and reduced discharge from the hydrogeological domain.

### 5.6.3 Significance of Faulting

The most recent study of faulting across the project by Santos is described in Section 4.5.11. Based on interpretation of seismic data, the study concluded that most faults in the project area are Permian to Triassic in age and mainly displace Permian and (to a lesser extent) Triassic strata; with typical vertical displacements of less than 100 m. No evidence of significant post-Jurassic age faulting extending into deeper Triassic and Permian age strata was found to be present, nor evidence of significant displacement of the Pilliga Sandstone. Where it is present, surface faulting in the Jurassic strata was assessed as minor. These findings were considered to be consistent with existing interpretation of the structural history of the Gunnedah Basin as a foreland basin.

The information provided by Santos noted that Triassic age faults showing lateral or transpressional movements are likely to contain smeared fault planes with some fault gouge, and that the minimum thickness of 30 to 50 m of argillaceous (clay composed) Triassic sediments overlying the Late Permian coals is likely to have annealled Triassic fault dislocations. Drill stem tests also suggest negligible pressure communication between Late and Early Permian coal seams.

Overall, the fault throws that have been observed are not large enough and pervasive enough to create the juxtpositioning of permeable formations that creates inter-connectivity where it did not already exist prior to faulting. Former erosional surfaces (discontinuities) that may create preferential flow paths between permeable formations (i.e., permeable beds sub-cropping beneath overlying permeable formations) are not found to be present in the project area.

### 5.6.4 Implications for Assessment of Groundwater Impacts

Within the context of predicting impacts of coal seam gas development spanning tens to hundreds of years, it follows from the above discussion that relatively short-lived fluctuations of water levels in rivers and shallow groundwater sources do not influence these predictions. For example, to predict potential interaction between the Early Permian coal seams and Upper Namoi alluvium over a period of several hundred years or more, it would be necessary to simulate the distribution of average water table elevation in the alluvium. Annual fluctuations about the mean would approximately sum to zero and could be neglected. In fact, the inclusion of relatively high-frequency, cyclic stresses in the modelling would make the detection of delayed and extended responses to coal seam gas development difficult to discern. Evidence of non-cyclic trends in water table observations would indicate climate change or other anthropogenic impacts, which are not the focus of this assessment.

The approach used to simulate coal seam gas development in the Gunnedah Basin in this assessment follows from the above rationale. Cyclic stresses and responses in streams and shallow groundwater sources are neglected so that changes in hydraulic head and groundwater flow are directly attributable to coal seam gas development. This is achieved by using head-dependent boundary conditions that allow inflow and outflow from the model domain to vary in response to change in hydraulic head induced by coal seam water production. Each model simulation can be likened to a regional scale 'slug test' in which a defined volume of water is removed from the target coal seams relatively quickly. Initially, all of the water removed is derived from formation storage. This is, followed by a longer period of storage recovery during which there is additional groundwater recharge and reduced discharge across the model boundary.

Other specific implications for modelling coal seam gas development in the Gunnedah Basin that follow from the preceding water balance discussion include:

- The locations for recharge and discharge boundaries are critical choices because they ultimately define where water can enter and leave the hydrogeological domain as well as the potential for water that is removed during coal seam gas development to be replaced;
- Initial drawdown of hydraulic head in response to prescribed water removal from coal seams will be controlled by the values of the formation storage coefficients, particularly within the coal seams and their bounding hydrostratigraphic units;
- The geometry and hydrogeological properties of the target coal seams and their bounding hydrostratigraphic units will control how the zone of drawdown expands after the commencement of coal seam gas production; and
- Connections between the target coal seams and alluvial units will control the potential magnitudes and locations of impacts on shallow groundwater sources in the alluvium.

Based on the assessment of faulting within the study area it will not be necessary to simulate individual faults as possible conduits for induced preferential flow under coal seam gas development.

# 5.7 Groundwater Quality

Data on groundwater quality within the GIA study area are available from the PINNEENA database and specific water quality data for the project are described in the project Water Baseline Report.

Groundwater investigations for the Water Baseline Report include sampling and chemical analysis of groundwater in the shallow alluvial sources, GAB aquifers and Gunnedah Basin strata. Chemical analyses of most groundwater samples have included electrical conductivity (EC), pH, total dissolved solids (TDS), temperature, and major and minor ions. Other analytes of interest for the GAB and Gunnedah Basin groundwater samples have included organic compounds, nutrients and dissolved methane.

A summary of the regional groundwater salinity and pH is provided in Table 5-13. Overall, the available data on groundwater quality show that:

- groundwater within alluvium is generally fresh (defined as less than 500 mg/L total dissolved solids (TDS)) to brackish (defined as 500 to 3500 mg/L TDS) and has an alkaline pH (approximately 8);
- groundwater in the Pilliga Sandstone is fresh to slightly brackish and has neneutral pH (approximately 7);
- groundwater in Permo-triassic strata of the Gunnedah-Oxley Basin tends to be brackish to saline (defined as 3500 to 10,000 mg/L TDS) and has alkaline pH (approximately 9); and
- groundwater within target coal seams is saline and has alkaline pH (approximately 8).

**Table 5-13 Regional groundwater quality**

| Hydrostratigraphic Unit | Mean EC [1] [µS/cm] | Equivalent TDS [2] [mg/L] | Mean pH |
|---|---|---|---|
| Namoi alluvium | 697 | 446 | 7.9 |
| Bohena Creek alluvium | 559 | 358 | 6.8 |
| GAB – Orallo Formation | 1030 | 659 | 7.4 |
| GAB – Pilliga Sandstone | 402 | 257 | 6.2 |
| GOB – Digby, Napperby and Purlawaugh Formations | 4,785 | 3,062 | 9.2 |
| GOB – Black Jack Group | 14,158 | 9,061 | 8.2 |
| GOB – Maules Creek Formation | 14,134 | 9,046 | 7.9 |

1. Electrical conductivity (source: Santos); 2. Total dissolved solids – an alternative measure of water salinity, converted from EC based on 1,000 µS/cm = 640 mg/L

## 5.7.1 Alluvium

The quality of alluvial groundwater is generally suitable for multiple uses. The pH of shallow groundwater is slightly alkaline with a range of 7 to 9. The alluvial groundwater is generally fresh to slightly brackish with a maximum TDS concentration of around 1500 mg/L. The water type of the Namoi alluvium is bicarbonate dominant with respect to anions, and sodium-potassium dominant with respect to cations. Chloride enrichment is not apparent. The dominance of bicarbonate and relative lack of evaporative minerals provide evidence of large recharge rates and rapid subsurface flow that does not permit the development of chloride type groundwater.

## 5.7.2 Pilliga Sandstone

Groundwater within the Pilliga Sandstone of the GAB is generally fresh to slightly brackish with a TDS range of around 80 to 800 mg/L, and is suitable for domestic, stock and irrigation purposes. The water types tend to be either bicarbonate or chloride dominant with respect to anions and to vary on a mixing line from no dominant type to sodium-potassium dominant with respect to cations.

### 5.7.3 Gunnedah Basin

Permo-triassic Age strata within the upper GOB contain groundwater that tends to be brackish to saline with a TDS range of around 500 to 6000 mg/L. Groundwater within the Black Jack Group and Maules Creek Formation that host the target coal seams is typically saline, with TDS values around two orders of magnitude larger than in the shallow alluvial groundwater sources and Pilliga Sandstone. Further information on water quality within the target coal seams is provided in Section 5.8.

## 5.8 Coal Seam Water Quality

The quality of water extracted from coal seams in the area is primarily dependent upon the local geology in the area of the gas well, and can be highly variable. Depending on local groundwater flow pathways towards each well, the quality of extracted water may remain consistent throughout the lifetime of the well or, more commonly, change over time. Observed variation of water quality over time is a likely consequence of induced groundwater flow from stratigraphically adjacent or structurally juxtaposed hydrostratigraphic units of differing water qualities.

As is common for Permian coal measures, the Black Jack Group and Maules Creek Formation contain groundwaters of sodium-bicarbonate type. The coals of the Black Jack Group have very low sulfur content (Jacobs 2014) and no appreciable sulfate occurs in the groundwaters. This contrasts with groundwaters in many other coal measures such as coals within the overlying GAB strata. A few samples of groundwater from the Maules Creek Formation exhibit minor sulfate content, which may arise from oxidation of sulfides in the coals.

The high bicarbonate concentrations reveal that calcite is saturated in solution. Carbonate minerals will continue to be dissolved as long as $CO_2$ and H are continuously generated through methanogenesis, which is significant in the Permian coal measures.

Summary statistics are separated for the Black Jack Group (Table 5-14) and Maules Creek Formation (Table 5-15). Both sequences of strata consist of several inter-bedded probable negligibly transmissive units and negligibly transmissive units, with the coal seams representing the significant transmissive units. While both sequences of strata reflect similar and high levels of salinity, particularly compared to other units in the sequence, groundwater from Maules Creek Formation exhibit slightly elevated sulfate and fluoride concentrations.

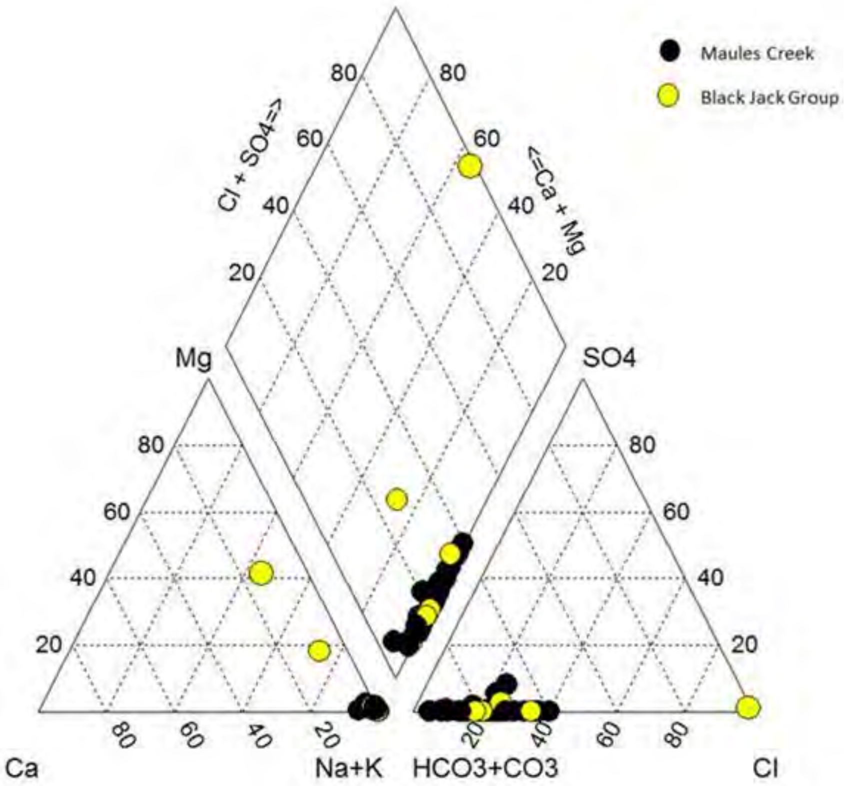



**Figure 5-20 Piper diagram for coal seam groundwaters**

**Table 5-14 Groundwater quality of the Black Jack Group**

| Parameter | Units | No. of Samples | No. of Detections | Minimum | Average | Maximum |
|---|---|---|---|---|---|---|
| *Physiochemical* | | | | | | |
| Electrical conductivity (EC) | µS/cm | 11 | 11 | 5310 | 14158 | 20200 |
| pH | | 11 | 11 | 7.5 | 8.2 | 9.1 |
| *Dissolved Anions* | | | | | | |
| Bicarbonate alkalinity as $CaCO_3$ | mg/L | 11 | 11 | 1300 | 9635 | 18243 |
| Carbonate alkalinity as CaCO3 | mg/L | 9 | 6 | 220 | 466 | 640 |
| Bromide | mg/L | 3 | 3 | 3.79 | 3.91 | 4.04 |
| Chloride | mg/L | 11 | 11 | 208 | 729 | 1350 |
| Fluoride | mg/L | 3 | 3 | 2.3 | 2.7 | 3.1 |
| Sulphate as $SO_4^{2-}$ | mg/L | 7 | 4 | 2.0 | 10.3 | 23.0 |
| *Dissolved Cations* | | | | | | |
| Calcium | mg/L | 10 | 10 | 0.8 | 5.9 | 14.0 |
| Magnesium | mg/L | 11 | 11 | 1.0 | 5.6 | 16.0 |
| Potassium | mg/L | 11 | 7 | 36 | 51 | 72 |
| Sodium | mg/L | 11 | 11 | 1300 | 4485 | 7540 |
| Total hardness as $CaCO_3$ | mg/L | 7 | 7 | 13.0 | 41.2 | 100.6 |
| *Nutrients* | | | | | | |
| Ammonia as N | mg/L | 3 | 3 | 5.90 | 6.06 | 6.28 |
| Nitrate as N | mg/L | 7 | 6 | 0.0 | 6.2 | 25.0 |
| Nitrite + nitrate as N | mg/L | 3 | 2 | 0.02 | 0.04 | 0.05 |
| Total Kjeldahl Nitrogen as N | mg/L | 3 | 3 | 5.7 | 6.9 | 8.2 |
| Total nitrogen as N | mg/L | 3 | 3 | 5.7 | 6.9 | 8.2 |
| Reactive phosphorous | mg/L | 3 | 3 | 0.15 | 0.56 | 0.84 |
| Total phosphorous as P | mg/L | 3 | 3 | 0.14 | 0.17 | 0.22 |
| *Total Metals (by ICP / MS)* | | | | | | |
| Aluminium | mg/L | 3 | 3 | 0.06 | 0.24 | 0.53 |
| Antimony | mg/L | 3 | 0 | ND | ND | ND |
| Arsenic | mg/L | 3 | 0 | ND | ND | ND |
| Barium | mg/L | 3 | 3 | 6.3 | 6.5 | 6.6 |
| Beryllium | mg/L | 3 | 0 | ND | ND | ND |
| Boron | mg/L | 3 | 3 | 0.31 | 0.34 | 0.36 |
| Cadmium | mg/L | 3 | 3 | 0.0003 | 0.0004 | 0.0005 |
| Chromium (total) | mg/L | 3 | 3 | 0.002 | 0.005 | 0.008 |
| Cobalt | mg/L | 3 | 0 | ND | ND | ND |
| Copper | mg/L | 3 | 2 | 0.002 | 0.008 | 0.013 |
| Iron (total) | mg/L | 4 | 4 | 0.20 | 2.10 | 5.28 |
| Lead | mg/L | 3 | 0 | ND | ND | ND |
| Lithium | mg/L | 3 | 3 | 0.91 | 1.16 | 1.29 |
| Manganese | mg/L | 3 | 3 | 0.003 | 0.027 | 0.066 |
| Mercury | mg/L | 3 | 0 | ND | ND | ND |
| Molybdenum | mg/L | 3 | 2 | 0.004 | 0.004 | 0.004 |
| Nickel | mg/L | 3 | 3 | 0.003 | 0.004 | 0.006 |
| Selenium | mg/L | 3 | 0 | ND | ND | ND |
| Silver | mg/L | 3 | 3 | 0.006 | 0.008 | 0.009 |
| Strontium | mg/L | 3 | 3 | 3.91 | 4.15 | 4.45 |
| Tin | mg/L | 3 | 1 | 0.002 | 0.002 | 0.002 |
| Uranium | mg/L | 3 | 0 | ND | ND | ND |
| Vanadium | mg/L | 3 | 0 | ND | ND | ND |
| Zinc | mg/L | 3 | 3 | 0.012 | 0.040 | 0.066 |

ND – no detection

**Table 5-15 Groundwater quality of the Maules Creek Formation**

| Parameter | Units | No. of Samples | No. of Detections | Minimum | Average | Maximum |
|---|---|---|---|---|---|---|
| *Physiochemical* | | | | | | |
| Electrical conductivity (EC) | µS/cm | 227 | 227 | 4980 | 14134 | 21700 |
| pH | | 227 | 227 | 6.2 | 7.9 | 9.3 |
| *Dissolved Anions* | | | | | | |
| Bicarbonate alkalinity as $CaCO_3$ | mg/L | 233 | 233 | 119 | 8010 | 14124 |
| Carbonate alkalinity as CaCO3 | mg/L | 140 | 82 | 23 | 614 | 4139 |
| Bromide | mg/L | 3 | 3 | 4.40 | 4.73 | 5.25 |
| Chloride | mg/L | 233 | 230 | 264 | 1401 | 3280 |
| Fluoride | mg/L | 52 | 52 | 3.0 | 5.7 | 10.8 |
| Sulphate as $SO_4^{2-}$ | mg/L | 195 | 159 | 0.3 | 68.9 | 1305.0 |
| *Dissolved Cations* | | | | | | |
| Calcium | mg/L | 192 | 192 | 1.8 | 18.4 | 162.0 |
| Magnesium | mg/L | 214 | 214 | 1.0 | 10.2 | 45.0 |
| Potassium | mg/L | 233 | 233 | 8 | 107 | 773 |
| Sodium | mg/L | 233 | 233 | 1200 | 4147 | 7360 |
| Total hardness as $CaCO_3$ | mg/L | 108 | 108 | 9.1 | 75.9 | 528.0 |
| *Nutrients* | | | | | | |
| Ammonia as N | mg/L | 3 | 0 | ND | ND | ND |
| Nitrate as N | mg/L | 122 | 64 | 0.2 | 5.0 | 30.0 |
| Nitrite + nitrate as N | mg/L | 3 | 3 | 0.04 | 0.37 | 0.83 |
| Total Kjeldahl Nitrogen as N | mg/L | 3 | 0 | ND | ND | ND |
| Total nitrogen as N | mg/L | 3 | 0 | ND | ND | ND |
| Reactive phosphorous | mg/L | 3 | 0 | ND | ND | ND |
| Total phosphorous as P | mg/L | 3 | 0 | ND | ND | ND |
| *Total Metals (by ICP / MS)* | | | | | | |
| Aluminium | mg/L | 3 | 3 | 0.11 | 0.43 | 0.95 |
| Antimony | mg/L | 3 | 2 | 0.001 | 0.002 | 0.002 |
| Arsenic | mg/L | 3 | 0 | ND | ND | ND |
| Barium | mg/L | 3 | 3 | 10.4 | 10.7 | 11.2 |
| Beryllium | mg/L | 3 | 0 | ND | ND | ND |
| Boron | mg/L | 3 | 3 | 0.18 | 0.22 | 0.26 |
| Cadmium | mg/L | 3 | 3 | 0.0002 | 0.0003 | 0.0003 |
| Chromium (total) | mg/L | 3 | 3 | 0.001 | 0.003 | 0.005 |
| Cobalt | mg/L | 3 | 1 | 0.002 | 0.002 | 0.002 |
| Copper | mg/L | 3 | 3 | 0.010 | 0.014 | 0.020 |
| Iron (total) | mg/L | 82 | 75 | 0.14 | 1.53 | 15.00 |
| Lead | mg/L | 3 | 3 | 0.002 | 0.006 | 0.009 |
| Lithium | mg/L | 3 | 3 | 2.85 | 2.98 | 3.19 |
| Manganese | mg/L | 4 | 4 | 0.017 | 0.071 | 0.200 |
| Mercury | mg/L | 3 | 0 | ND | ND | ND |
| Molybdenum | mg/L | 3 | 2 | 0.002 | 0.003 | 0.003 |
| Nickel | mg/L | 3 | 3 | 0.004 | 0.009 | 0.016 |
| Selenium | mg/L | 3 | 0 | ND | ND | ND |
| Silver | mg/L | 3 | 0 | ND | ND | ND |
| Strontium | mg/L | 62 | 59 | 0.29 | 1.88 | 7.00 |
| Tin | mg/L | 3 | 3 | 0.002 | 0.004 | 0.007 |
| Uranium | mg/L | 3 | 0 | ND | ND | ND |
| Vanadium | mg/L | 3 | 0 | ND | ND | ND |
| Zinc | mg/L | 3 | 3 | 0.048 | 0.105 | 0.214 |

ND – no detection

# 6 Numerical Groundwater Flow Modelling

A numerical groundwater flow model was developed to assess the potential impact on groundwater levels and groundwater flows of the project. The numerical model was developed based on the conceptual model presented in 5. This section presents a summary of the construction and calibration of the model, as well as predictive simulations and uncertainty analysis.

The groundwater model for the project has been designed based on the guiding principles and concepts of the Australian Groundwater Modelling Guidelines (Barnett *et al.* 2012) and the recommendations of the Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development in relation to modelling groundwater impacts of coal seam gas extraction (Commonwealth of Australia 2014a).

## 6.1 Modelling Objectives

The modelling objectives define the purpose of a numerical model and guide its design and implementation. They are related to the larger project objectives. The objectives of this groundwater flow model are to:

- Estimate changes in hydraulic head in the target coal seams, and head and water table elevations in connected hydrostratigraphic units due to the proposed coal seam gas field development activities;
- In areas where drawdown is predicted, estimate the recovery time for hydraulic head to return to pre- coal seam gas development levels;
- Identify and quantify the potential groundwater loss or gain in each Water Sharing Plan zone due to intra- and inter-formational flows; and
- Identify those landholders who may potentially be impacted by coal seam gas activities and quantify the predicted impacts;

These model objectives are essential to fulfilling the overall objectives of the GIA for the project, in that they predict and quantify the long-term effects of changes associated with the coal seam gas activities.

## 6.2 Model Confidence Level Classification

The degree of confidence with which a model's prediction can be used is a critical consideration. Several factors are typically considered in order to determine a model confidence level classification. The Australian Groundwater Modelling Guidelines (Barnett et al. 2012) define a system to classify the confidence level for groundwater models based on the following factors:

- Available data;
- Calibration procedures;
- Calibration and prediction consistency; and
- Level of stress (hydraulic stress in the model).

Models are classified as Class 1, 2 or 3 in order of increasing confidence. The numerical groundwater model developed for the Narrabri Gas Project complies with many of the Class 3 criteria from the modelling guidelines, as well as some Class 2 and 1 criteria. Table 6-1 identifies characteristics of the groundwater model that comply with each the confidence level criteria from the modelling guidelines.

**Table 6-1 Assessment of confidence criteria from the Australian Groundwater Modelling Guidelines**

| Model Characteristic | Classification Indicator from the Australian Groundwater Modelling Guidelines | Confidence Level Class |
|---|---|---|
| Data | Numerous bores have been utilised across the model domain with which to determine the stratigraphy and accurately define the spatial distribution and geometry of aquifers and other rocks. | 3 |
| | Rainfall and other climatic data have been obtained for local weather stations extending back greater than 50 years. | 3 |
| | Groundwater head observations are available but may not provide adequate coverage throughout the model domain. | 2 |
| | Reliable metered groundwater (and surface water) extraction data is not available but the inverse method of net recharge estimation does not explicitly require these data. | 2 |
| | Good quality and adequate coverage of digital elevation model to define ground surface elevation. | 3 |
| | No available records of metered groundwater extraction. | 2 |
| | Reliable land-use and soil mapping data available. | 3 |
| | Aquifer testing data to evaluate hydrogeological properties of aquifers and rocks are of limited availability in strata hosting the target coals seams. | 2 |
| Calibration | Scaled RMS error and other calibration statistics are acceptable in parts of the model domain with observed data, but this excludes deep strata hosting the target coals seams. | 2 |
| | Model is calibrated to hydraulic head, though only in parts of the model domain. | 2 |
| | Validation is not undertaken because there is not adequate redundancy in data availability. | 2 |
| Prediction | Predictive model time frame far exceeds that of calibration. | 1 |
| | Transient predictions are made when calibration is in steady state only. | 1 |
| | Level and type of stresses in the predictive model are outside the range of those used in the transient calibration. | 2 |
| Key Indicators | Key calibration statistics are acceptable (though do not apply to the entire model domain) | 2 |
| | Mass balance closure error is less than 0.01% of total; and total water extraction in each simulation is checked and confirmed against the simulated water production profiles. | 3 |
| | Model parameters consistent with conceptualisation. | 3 |
| | Appropriate model computational methods used with appropriate spatial discretisation to model the problem. | 3 |
| | The model has been reviewed and deemed fit for purpose by an experienced, independent hydrogeologist with modelling experience. | 3 |
| | Model predictive timeframe is more than 10 times longer than calibration period. | 1 |
| | Stresses in predictions are more than 5 times higher than those in calibration. | 1 |
| | Transient predictions made but calibration in steady state only. | 1 |
| Examples of Uses | Prediction of impacts of proposed developments in medium value aquifers (GAB Water Sharing Plans) | 2 |
| | Evaluation and management of medium risk impacts. | 2 |
| | Predicting long-term impacts of proposed developments in low-value aquifers (Gunnedah-Oxley Basin Water Sharing Plans) | 1 |
| | Understanding groundwater flow processes under various hypothetical conditions. | 1 |
| | Developing coarse relationships between groundwater extraction locations and associated impacts. | 1 |

In general, models will not fit entirely into one confidence level class, because determining the most appropriate class depends upon multiple factors.

Considerable data are available in the GIA study area to describe stratigraphy and the broad structural arrangement of the model geometry, lending high confidence to model geometry. There are fewer locally-derived measurements of hydrogeological properties to constrain the model parameters. Likewise, there are fewer groundwater head data in hydrostratigraphic units hosting the target coal seams, and these measurements are not widely distributed and neither spatially nor temporally extensive.

It is emphasised, here, that the confidence classification scheme in the modelling guidelines does not allow for a Class 2 to 3 confidence level for large regional-scale models with very long response times, and in which the strata targeted for development are previously unstressed.

In general terms the model is considered to be capable of providing appropriate physically-based predictions of relative responses to hydraulic stresses and is therefore fit for purpose in terms of providing an appropriate platform with which to assess the potential impacts of coal seam (produced) water extraction.

## 6.3 Selection of Numerical Modelling Code

Several well-respected modelling codes are available for simulation of large or basin-scale groundwater flow. They roughly fall into two categories: finite element (FE) and finite difference (FD) codes. Finite element codes excel at accurate representation of complex geometry but can have difficulties accurately quantifying internal fluxes such as those to and from a water sharing plan area. Finite difference codes are restricted to representing geometry with 3D quadrilateral prisms, but provide accurate accounting of internal flows. Because one of the modelling objectives specifically relies upon accurate flux forecasting, a finite difference code was selected for this modelling project.

The most commonly used groundwater FD code is MODFLOW, developed by the United States Geological Survey (McDonald and Harbaugh 1988). The latest version was released in 2005. Commercially developed variations on the public-domain MODFLOW are also available, which may have capabilities lacking in MODFLOW itself.

Another requirement of the code is the ability to handle physical situations likely to occur in modelling coal seam gas groundwater depressurisation. The extraction of water associated with coal seam gas could in principle cause lowering of the water table, in areas where zones of depressurisation interact with the water table. This dewatering can result in model cells becoming 'dry'. Once dry, the model cells in MODFLOW 2005 do not 're-wet' in the same way as the porous materials that are being simulated and they may remain 'dry' when groundwater conditions suggest otherwise. MODFLOW-SURFACT™ (SURFACT) was developed and is maintained by HydroGeoLogic Inc. (HydroGeoLogic 1998), specifically to handle issues associated with re-wetting of dry cells more effectively than the standard MODFLOW 2005 code.

Additional modifications available in SURFACT to address recognised limitations of MODFLOW include more accurate tracking of the water table and additional robust solver packages (HydroGeoLogic 1998, Panday and Huyakorn 2008). The requirement of MODFLOW to retain laterally continuous model layers can result in numerous thin and mostly dry cells that can be problematic in areas where the water table extends across multiple layers, particularly in areas of steep topographic gradient. SURFACT is better able to simulate these conditions and provides better numerical stability than MODFLOW 2005.

For these reasons, SURFACT (version 4) was chosen as the most appropriate numerical package for this modelling project. Groundwater Vistas version 6 (ESI 2011) was used as graphical user interface to pre- and post-process numerical modelling data. In addition, custom-designed scripts were written in Python and ArcGIS™ to perform additional pre- and post-processing tasks.

# 6.4 Model Design and Construction

## 6.4.1 Gunnedah Basin Regional Model (GBRM)

The active model domain corresponds to the GBRM extent shown in Figure 5-1. The domain extends over approximately 53,200 km$^2$ within which the project area (957 km$^2$) is positioned centrally and to the northeast. The extent of the model domain was selected based on structural and hydrogeological aspects of the region, and the distance from the project area to the boundaries was extended beyond the anticipated area of impacts to groundwater.

The geological structure of the Mullaley Sub-basin is dominated by the basement highs of the Boggabri Ridge and Rocky Glen Ridge, the Hunter-Mooki Thrust Fault and the inclined strata infilling the sub-basin. The Early Permian targets for coal seam gas development in the Maules Creek Formation onlap the Boggabri Ridge at great depth and dip westward. Hydraulic impacts arising from depressurisation of coal seams are unlikely to propagate significantly eastward beyond the sub-crop of the Maules Creek Formation. Consequently, the eastern domain boundary along the Hunter-Mooki Thrust Fault is geographically closer to the project area.

Towards the west, Permo-Triassic strata extend across the Rocky Glen Ridge and may interact hydraulically with the unconformably-overlying GAB southern intake beds, consisting of the Pilliga Sandstone and successively overlying strata. A natural hydrogeological boundary does not exist in this area and therefore an appropriate boundary beyond the likely zone of predicted impact has been selected to coincide with the extent of the Gunnedah Basin in the southwest and the Namoi River at Walgett in the northwest (110 to 180 km west of the project area). The northern and southern boundaries also are not defined by hydrogeological features and have been chosen based on geological interpretation of basin extents. To the north the Gunnedah Basin extends into the Bowen Basin around Moree, approximately 150 km north of the project area, and to the south it passes into the Sydney Basin around Scone, approximately 80 km south of the project area.

Additional information about the types of the boundary conditions applied in the numerical modelling is given later in Section 6.4.3.7.

## 6.4.2 Leapfrog Geological Model

A geological model was constructed using [7]Leapfrog Hydro (v1.7) and is based on a combination of geological datasets supplied and obtained for the project. The primary sources of information used to develop the geological model are summarised in Table 6-2 and Figure 6-1. Twenty-nine stratigraphic units present within the GIA study area are represented by 13 layers in the geological model. The relationships between geological layers, hydrostratigraphic units and groundwater model layers are described below in Section 6.4.3.2.

Each geological layer in the Leapfrog Hydro model is represented by a three-dimensional volume that can be continuous or discontinuous within the geological model domain. The layer thicknesses

[7] http://www.leapfroghydro.com/hydro/

and the contact surfaces between layers are modelled by the software based on interpolation and extrapolation of the input data and the stratigraphic relationships between geologic units.

The interpolation algorithm used to generate the geological layers in Leapfrog Hydro is proprietary (FastRBF™) and subject to minimal user control within the Leapfrog Hydro interface. The chronology of the geological layers is defined according to Table 6-4 (Section 6.4.3.2) and the interpolation algorithm uses the settings in Table 6-3, which define the reference planes for adjusting the contact surfaces between layers. No other user settings available in Leapfrog Hydro version 1.7.

Figure 6-2 indicates the surface geology used to constrain the interpolation of input data and the resulting outcrop geology of the model. Particular care was taken to accurately represent the existing surface geology map in the area of the Upper Namoi alluvium where the Black Jack Formation and Hoskissons Coal outcrop.

The locations of selected cross-sections through the geological model are shown in Figure 6-3 and the cross sections are shown in Figure 6-4 and Figure 6-5 (drawn with a 20:1 vertical exaggeration). Thicknesses of the geological model layers are contoured as isopachs in Figure 6-6 to Figure 6-8.

The geological model was constructed as the basis for developing the numerical groundwater flow model. Faults are omitted from the geological model on the basis of recent assessment of the potential for faults to provide preferential pathways for leakage of water and hydrocarbons between coal seam targets within the Gunnedah Basin and the overlying shallow groundwater sources in the Surat Basin and Namoi alluvium (see discussions in Sections 4.5.11 and 5.6.3). Based on the current interpretation of faulting within the study area it is thought that individual faults are unlikely to act as conduits for induced preferential flow under coal seam gas development, and therefore they do not need to be specifically represented in the groundwater flow model.

**Table 6-2 Sources of data for the geological model**

| Type of Data | Description | Source |
|---|---|---|
| Drilling logs | DIGS Database<br>Gunnedah Basin formation tops | Department of Primary Industries NSW<br>Santos |
| Stratigraphic surfaces | Upper Namoi groundwater model<br>Lower Namoi groundwater model<br>Gunnedah Bowen Study SEEBASE | McNeilage (2006)<br>Merrick (2001)<br>SRK (2010) |
| Outcrop geology | GIS files | Santos |
| Ground surface | SRTM 500m digital elevation model | [1]CGIAR CSI |

[1]Consultative Group for International Agricultural Research (CGIAR) - Consortium for Spatial Information (CSI)

**Table 6-3 Leapfrog Hydro interpolation settings**

| [8]Reference Plane Location | Values | Explanation |
|---|---|---|
| Dip | 0 | Dip of the reference plane used by the interpolation algorithm |
| Dip Azimuth | 0 | Dip of the reference plane |
| Pitch | 0 | Pitch of the reference plane |
| In Plane | 1 (isotropic) | In-plane anisotropy relative to the reference plane |
| Out of Plane | 1 | Out-of-plane anisotropy relative to the reference plane |

[8]These settings were used for all layers of the geological model

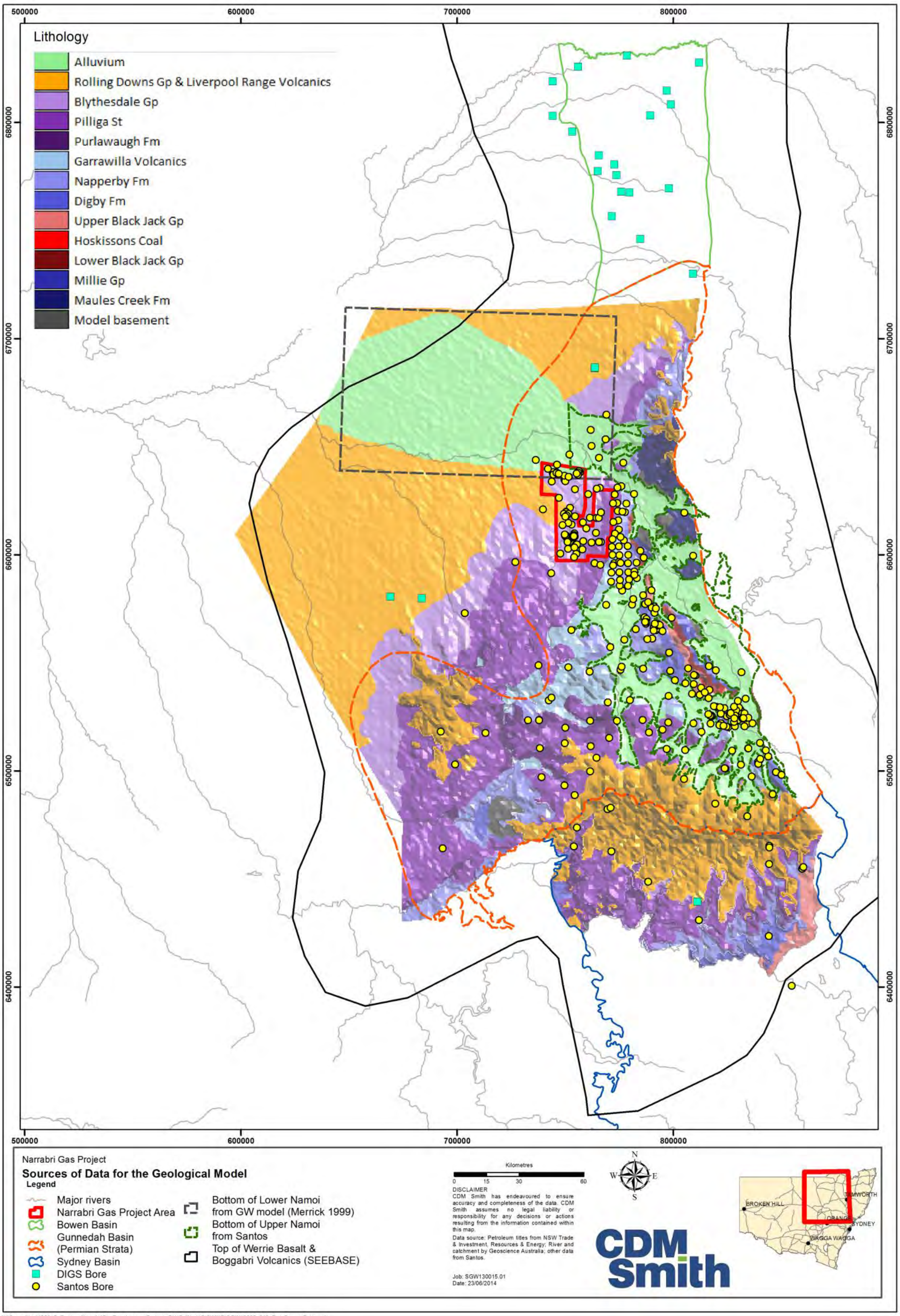



**Figure 6-1 Sources of data for the geological model**

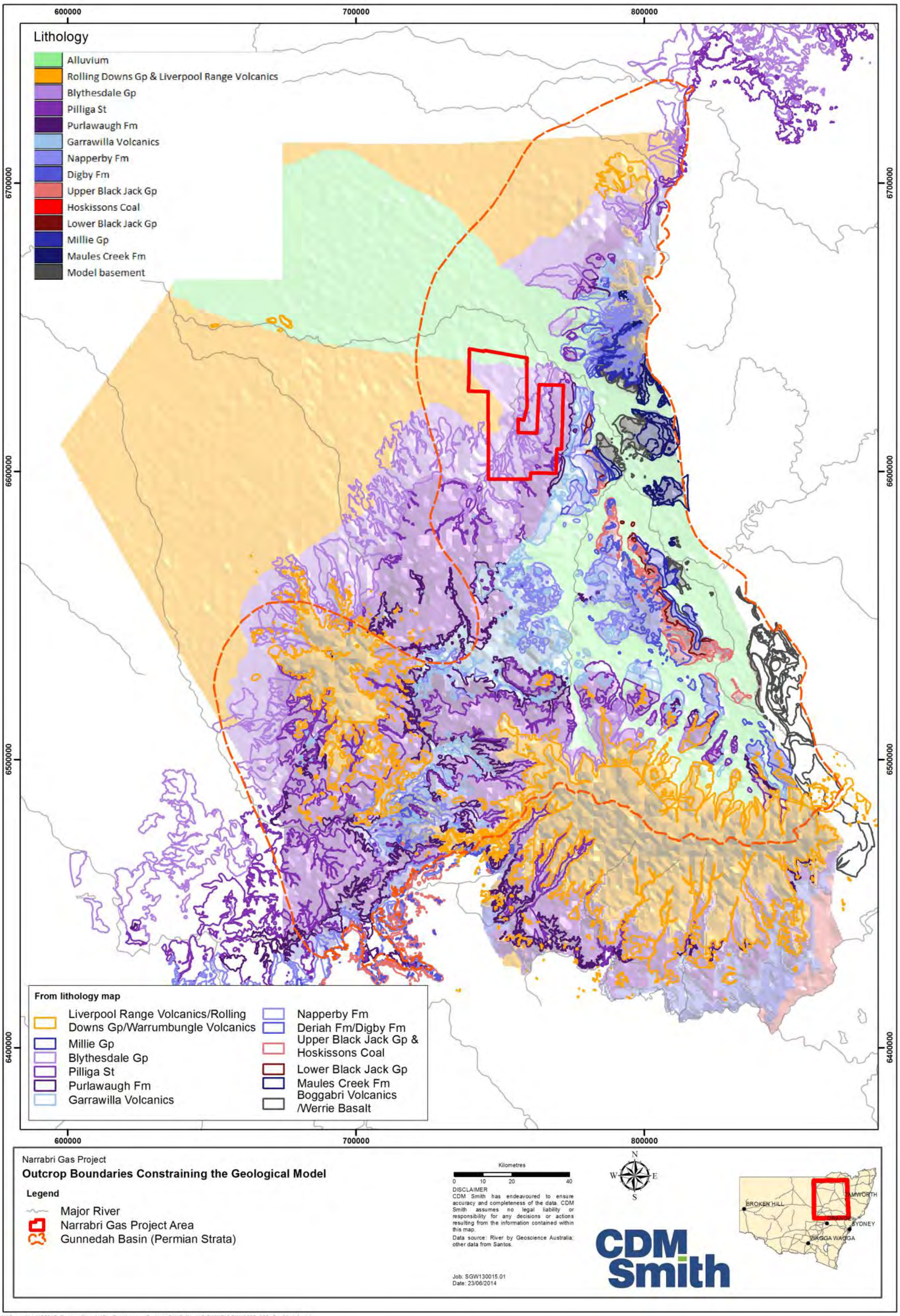



**Figure 6-2 Outcrop boundaries constraining the geological model**

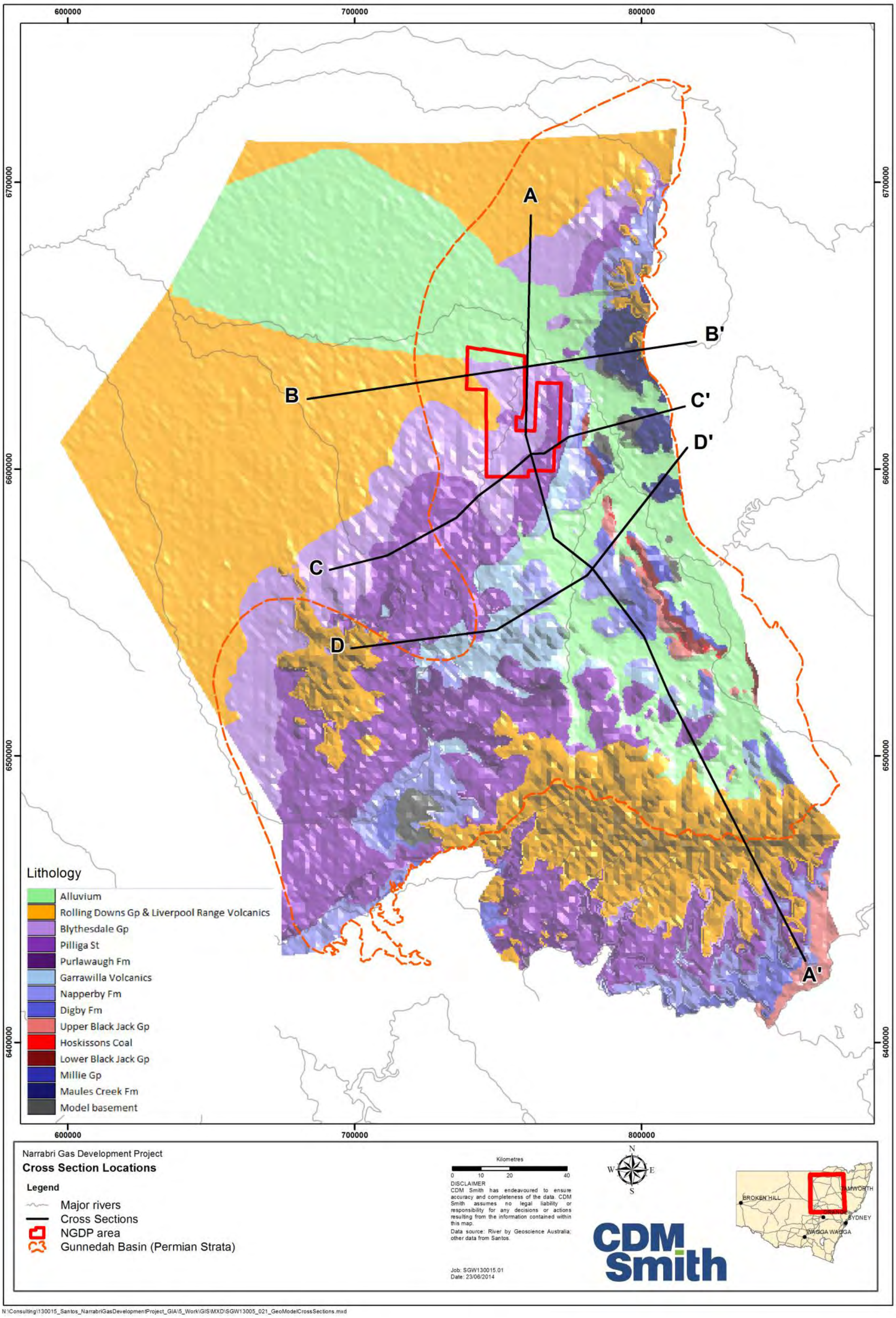



**Figure 6-3 Locations of cross sections**

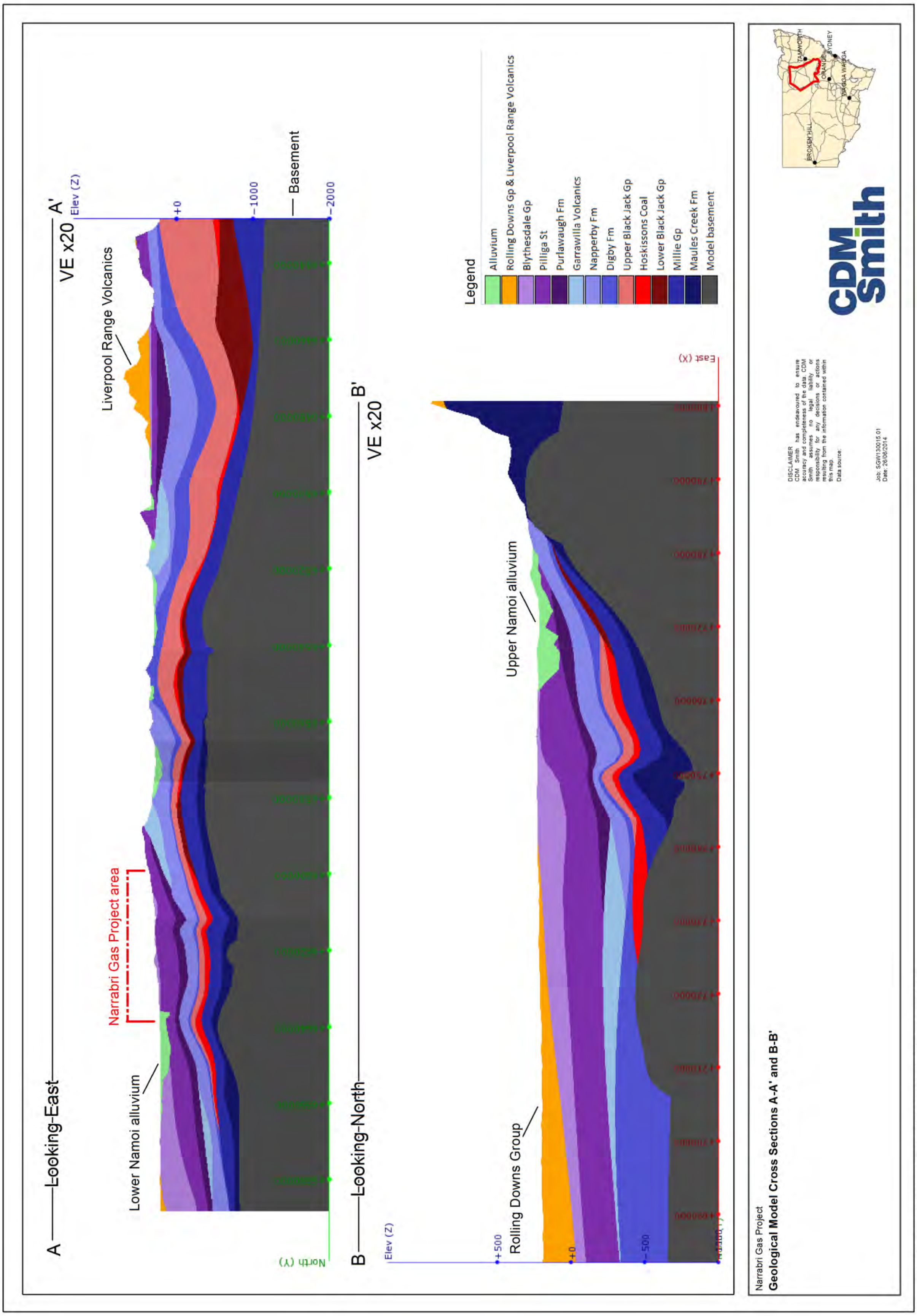



**Figure 6-4 Geological model cross sections A-A' and B-B'**

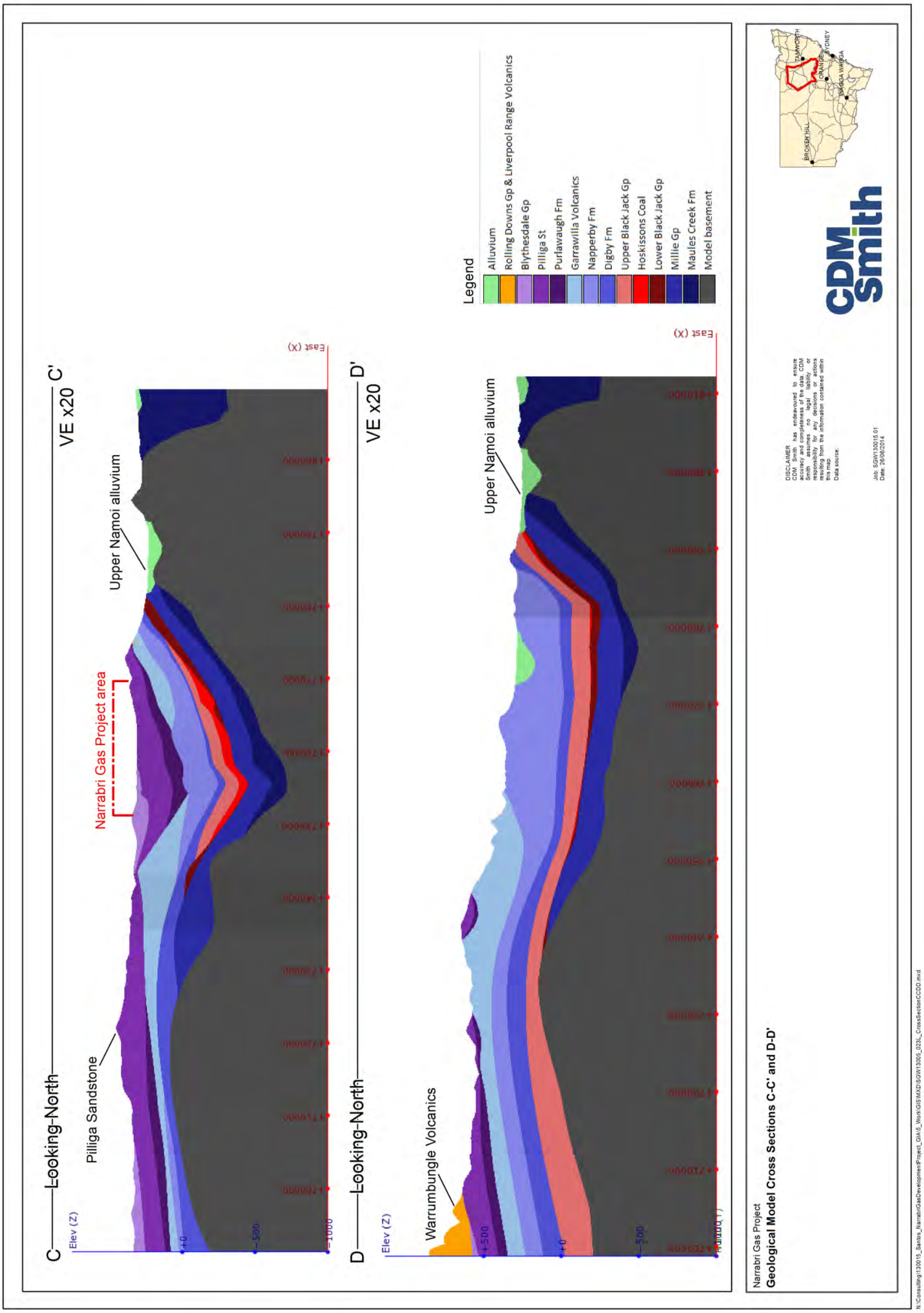



**Figure 6-5 Geological model cross sections C-C' and D-D'**

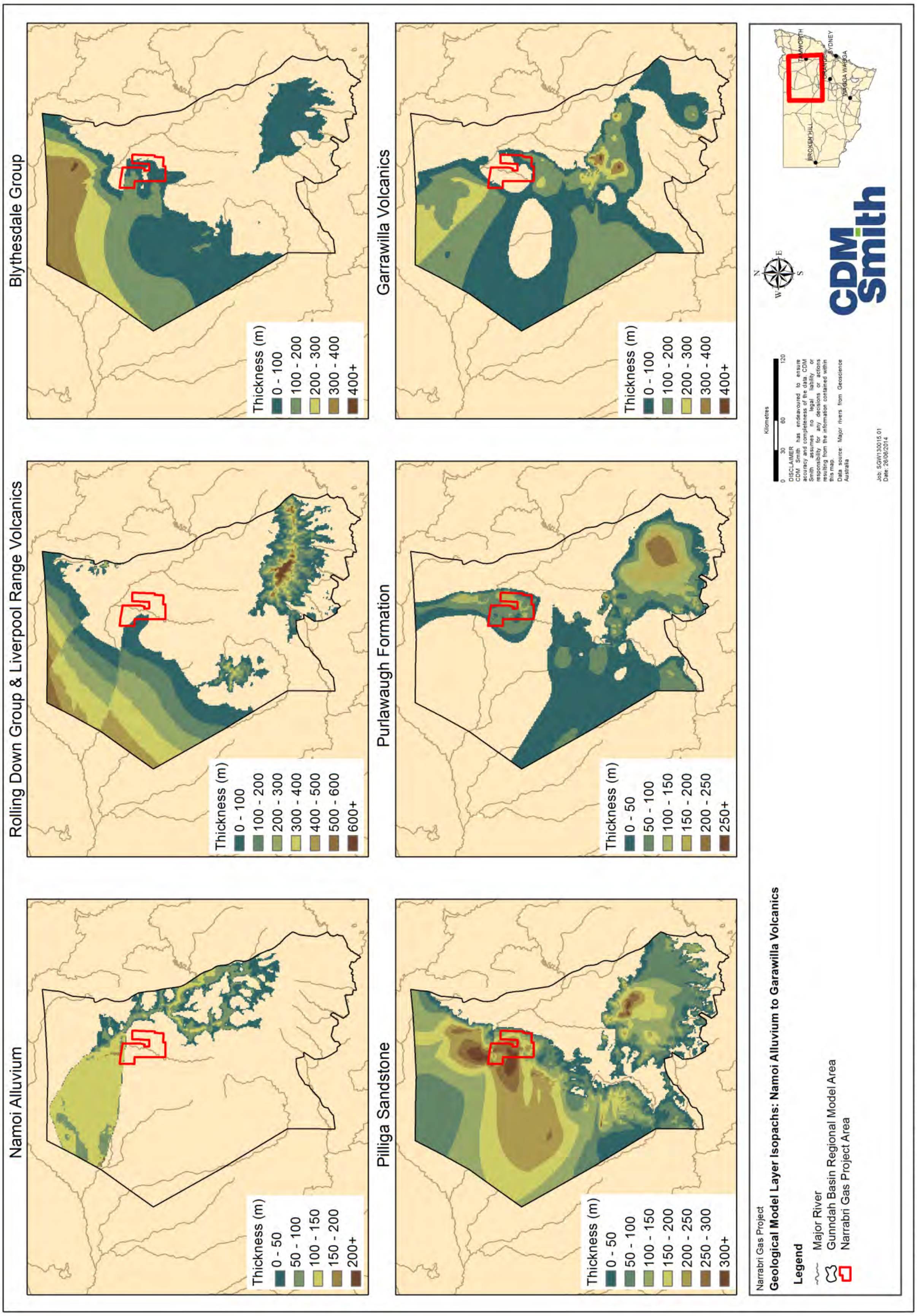



**Figure 6-6 Geological model layer isopachs: Namoi alluvium to Garawilla Volcanics**

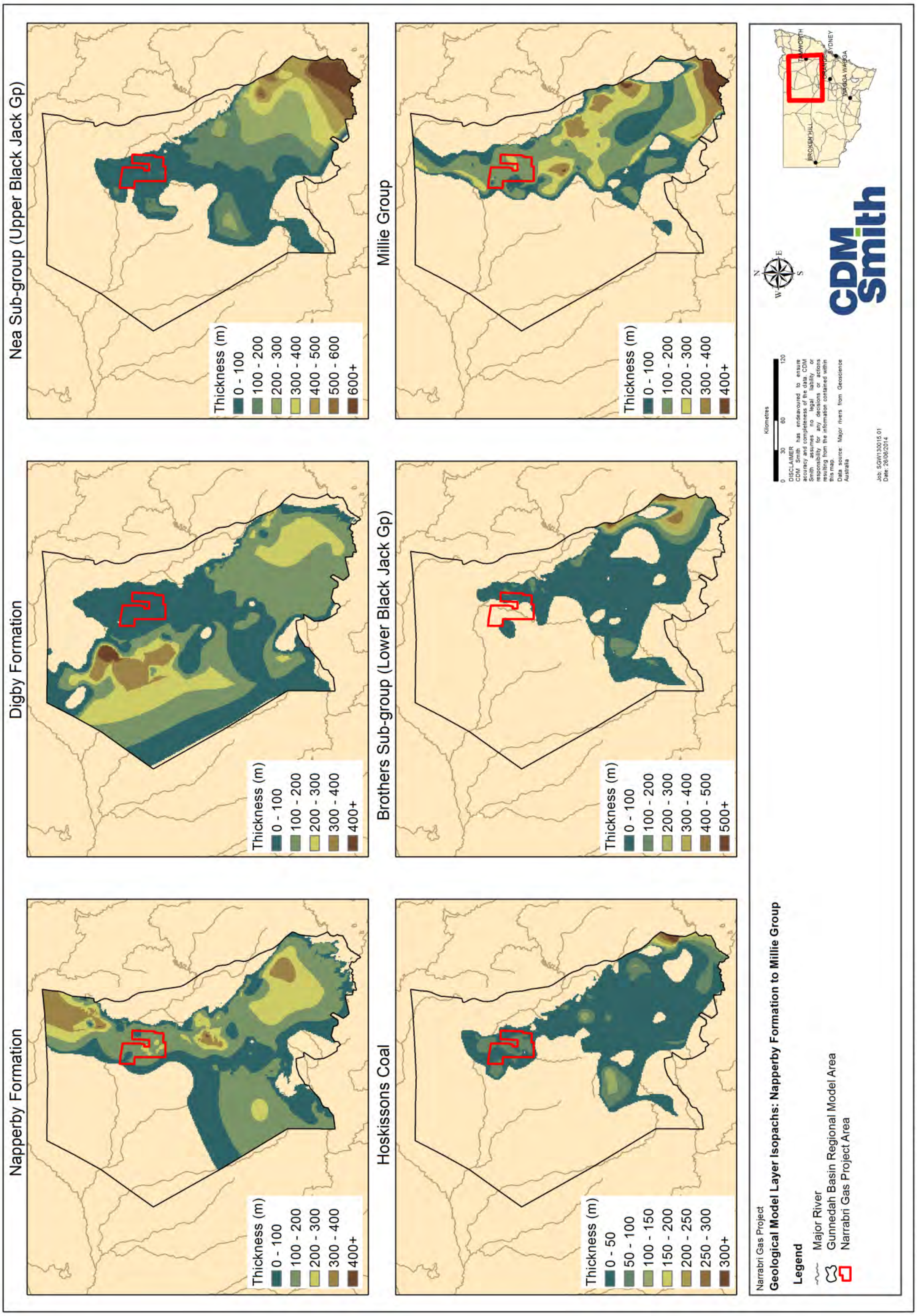



**Figure 6-7 Geological model layer isopachs: Napperby Formation to Millie Group**

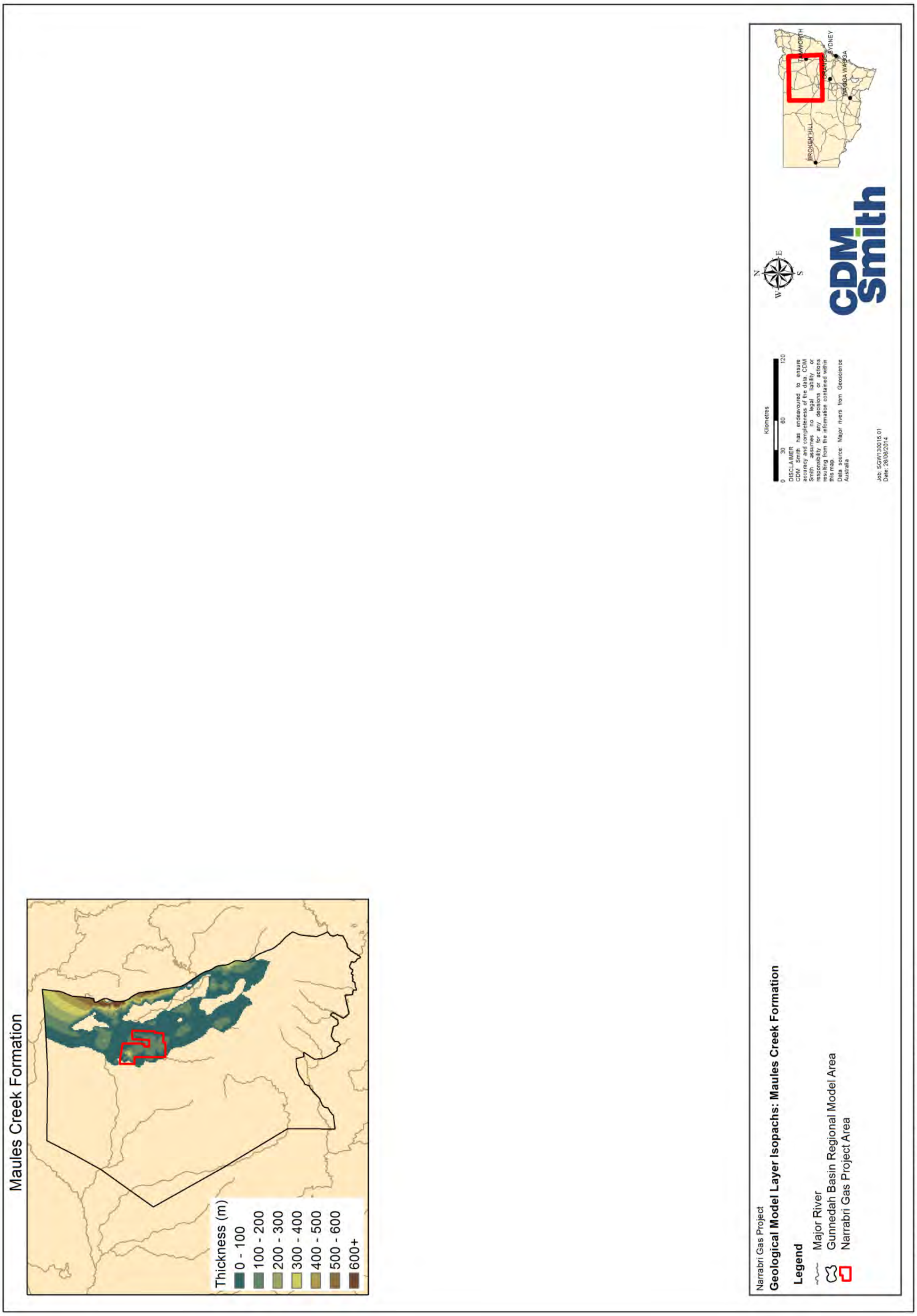



**Figure 6-8 Geological model layer isopachs: Maules Creek Formation**

### 6.4.3 MODFLOW-SURFACT Model

#### 6.4.3.1 Model Grid

The model grid shown in Figure 6-9 was generated in Leapfrog Hydro and then exported to Groundwater Vistas. The rows and columns are rotated by -30 degrees relative to due north so that the columns are approximately parallel with the regional alignment of the Upper Namoi alluvium and exposed Permo-Triassic units. The southwest corner of the grid is located close to Yearinan at 711000 mE and 6547000 mN, whilst the northeast corner is close to Rocky Creek at 818000 mE, 6670000 mN. The total number of cells is 719,712 (29,988 cells per layer) consisting of 126 columns, 238 rows and 24 layers, with a total of 539,592 active cells (22,483 cells per layer). Local refinement is introduced along the Upper Namoi alluvium and in the areas surrounding the project area and Santos' proposed future Gunnedah Coal Seam Gas Project area. The minimum row and column spacing is 1 km (1 km$^2$ minimum cell area) and the maximum is 5 km (25 km$^2$ maximum cell area). The total area of active cells is 53,219 km$^2$.

Selected cross-sections through the model grid are shown in Figure 6-10 and Figure 6-11, with the cross-section lines indicated in Figure 6-9.

#### 6.4.3.2 Model Layers

The relationships between stratigraphic units, geological model layers, hydrostratigraphic units and SURFACT model layers are indicated in Table 6-4. The initial grid exported from Leapfrog Hydro consisted of 13 geological layers, which were simplified in Groundwater Vistas by grouping them into 9 hydrostratigraphic units, consisting of 4 transmissive units and 5 intervening aquitards. Each of the five aquitards was subsequently divided into several model layers with identical hydrogeological properties to provide numerical resolution necessary for representing vertical hydraulic gradients expected above and below the target coal seams. After subdivision, 24 model layers were used in the final model. A description of the method used to sub-divide the aquitards is given below.

#### 6.4.3.3 Vertical Discretisation of Aquitards

A decline of hydraulic head in coal seam gas target coal seams by hundreds of metres leads to variations in hydraulic gradients (curvature in hydraulic heads) in the aquitards overlying and underlying target seams, particularly near the interfaces of these units. Appropriate numerical representation of the curvature of head within the aquitards and associated storage release and leakage to the coal seams from the aquitards requires suitable vertical discretisation.

The commonly adopted practice of using a single model layer per aquitard is considered to be inappropriate in this situation because it implies a constant hydraulic gradient in the aquitard and almost immediate release of storage throughout the full thickness of the aquitard in response to head decline in an adjacent aquifer. Previous work undertaken by NTEC Environmental Technology has shown that using four model layers for each aquitard can significantly improve the representation of curvature in heads across an aquitard and the associated release of storage and vertical flow within the aquitard. It is further reasoned in this assessment that aquitards adjacent to coal seam gas target coal seams should have thinner layers at the interface with the seam where the vertical hydraulic gradient is largest during coal seam gas production.

Within the above context the following approach is adopted for this assessment:

- The aquitards directly overlying and underlying the Hoskissons Coal (hydrostratigraphic units 4 and 6 in Table 6-4 are sub-divided into six layers with the layer thicknesses increasing away from the coal seam. The percentage contributions of each layer to the total thickness of the aquitards is 2.25%, 5.25%, 17.5% and 25% for each of the remaining three layers.

- The Maules Creek Formation is sub-divided into two layers above and below the Early Permian coal seams (hydrostratigraphic unit 8 in Table 6-4). In both cases the layer closest to the coal seam contributes 30% to the total thickness and the remaining layer contributes 70%.
- The Cretaceous aquitard (hydrostratigraphic unit 2 in Table 6-4) does not contact coal seam gas bearing coal seams and therefore is split into four model layers contributing equally to the total thickness of the aquitard.

#### 6.4.3.4 Representation of the Late Permian Coal Seam Targets

The Early Permian coal seam targets include the Bohena, Namoi, Parks and Rutley seams. In the numerical model they have simplified representation as a single hydrostratigraphic unit with total thickness and lateral extent equal to the combined thicknesses and lateral extents of the individual seams. The layer of the groundwater model representing the Early Permian coal seams is approximately mid-depth within the Maules Creek Formation and is assigned hydrogeological properties representing the coal seams. Elsewhere, the layer is assigned a thickness of 0.5 m and the hydrogeological properties of the Maules Creek Formation. This method of representing the bulk characteristics of multiple seams using a single model layer is considered to be a reasonable approach in large-scale regional modelling in which the local geometries of the coal seams are defined at sub-grid scales.

#### 6.4.3.5 Namoi Alluvium Subcrop Units

Physical connections between shallow groundwater sources in the Namoi alluvium and groundwater in the Gunnedah Basin are determined primarily by the subcrop patterns of the basin units beneath the alluvium. Similarly, in the groundwater modelling, the connection between the alluvium and Gunnedah Basin is determined by the subcrop patterns of the model layers representing the Gunnedah Basin beneath the model layer representing the Namoi alluvium. Figure 6-12 shows the subcrop patterns resulting from the model grid design and layering described in the preceding sections. Most of the Upper Namoi alluvium is underlain by model layers representing Early Permian to Jurassic age sediments. They include the Early-to-Late Permian aquitard sequence (HSUs 6 and 7 in Table 6-4), Hoskissons Coal (HSU 5) and the Late Permian to Jurassic age aquitard sequence (HSU 4). Direct connection of the Namoi alluvium with the Maules Creek Formation and Hoskissons Coal occurs to the southeast of the project area. Connection between the Maules Creek Formation and alluvium on the western side of the Boggabri Ridge occur within the Upper Namoi GMA zone 4, and direct connections between the Hoskissons Coal and alluvium occur within GMA zones 2 and 4 near the confluence of the Namoi River and Cox's Creek, and further south within GMA zones 7 and 8.

#### 6.4.3.6 Representation of Faulting

As discussed in Sections 4.5.11, 5.6.3 and 6.4.2, the current geological evidence indicates that Permian to Triassic age faulting in the Gunnedah Basin is unlikely to provide conduits for preferential flow of water and hydrocarbons between the target coal seams and shallow groundwater sources in the overlying Surat Basin and Namoi alluvium. Faulting is therefore neglected in the groundwater modelling in this assessment.

**Table 6-4 Correlation between geologic basins, geological ages, stratigraphic units, geological model layers, hydrostratigraphic units (HSU) and numerical model layers**

| Basin | Period | Stratigraphic Unit: Group | Stratigraphic Unit: Sub-group | Stratigraphic Unit: Formation | Geological Model Layer | HSU | Model Layers |
|---|---|---|---|---|---|---|---|
| | Cenozoic | | | Narrabri (informal) | 1 | Aquifer | 1 |
| | | | | Gunnedah (informal) | | | |
| | | | | Liverpool Range Volcanics | 2 | Aquitard | |
| Surat GAB | Cretaceous | Rolling Downs Gp | | Wallumbilla Fm | | | 2 |
| | | Blythesdale Gp (Keelindi Beds) | | Bungil Fm | 3 | | 3 |
| | | | | Mooga Ss | | | 4 |
| | | | | Orallo Fm | | | 5 |
| | Cretaceous / Jurassic | | | Pilliga Ss | 4 | Aquifer | 6 |
| | Jurassic | | | Purlawaugh Fm | 5 | Aquitard | |
| | | | | Garrawilla Volcanics | 6 | | 7 |
| Gunnedah | Triassic | | | Deriah Fm | 7 | | |
| | | | | Napperby Fm | | | 8 |
| | | | | Digby Fm | 8 | | |
| | Late Permian | Black Jack Group | Nea | Trinkey Fm | 9 | | 9 |
| | | | | Wallala Fm | | | |
| | | | Coogal | Breeza Coal Mbr | | | 10 |
| | | | | Clare Ss | | | |
| | | | | Howes Hill seam | | | 11 |
| | | | | Benelabri Fm | | | 12 |
| | | | | Hoskissons Coal (Late Permian coal seam targets) | 10 | Aquifer | 13 |
| | | | Brothers | Brigalow Fm | 11 | Aquitard | 14 |
| | | | | Arkarula Fm | | | 15 |
| | | | | Melvilles Coal Mbr | | | 16 |
| | | | | Pamboola Fm | | | 17 |
| | Middle Permian | Millie | | Watermark Fm | 12 | | 18 |
| | | | | Porcupine Fm | | | 19 |
| | Early Permian | Bellata | | Maules Creek Fm | 13 | Aquitard | 20<br>21 |
| | | | | Early Permian coal seam targets | 13 | Aquifer | 22 |
| | | | | Maules Creek Fm | 13 | Aquitard | 23<br>24 |
| | | | | Goonbri Fm | Model Basement | | |
| | | | | Leard Fm | | | |
| Base | | Basement | | Boggabri Volcanics | | | |
| | | | | Werrie Basalt | | | |

(Section 5.2 defines the relative transmissive context in which the terms aquifer and aquitard are applied in the table above)

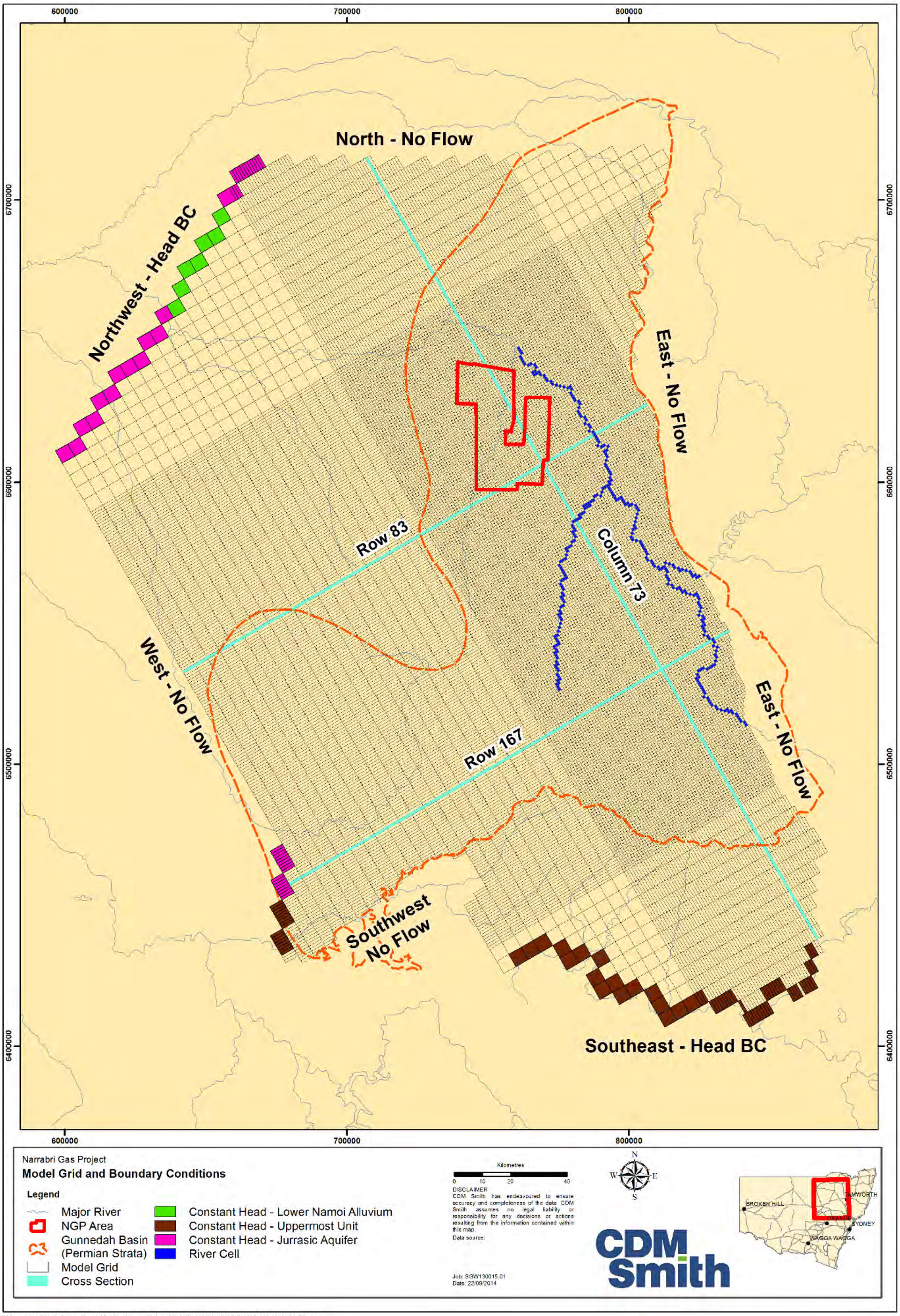



Figure 6-9 Model grid and boundary conditions

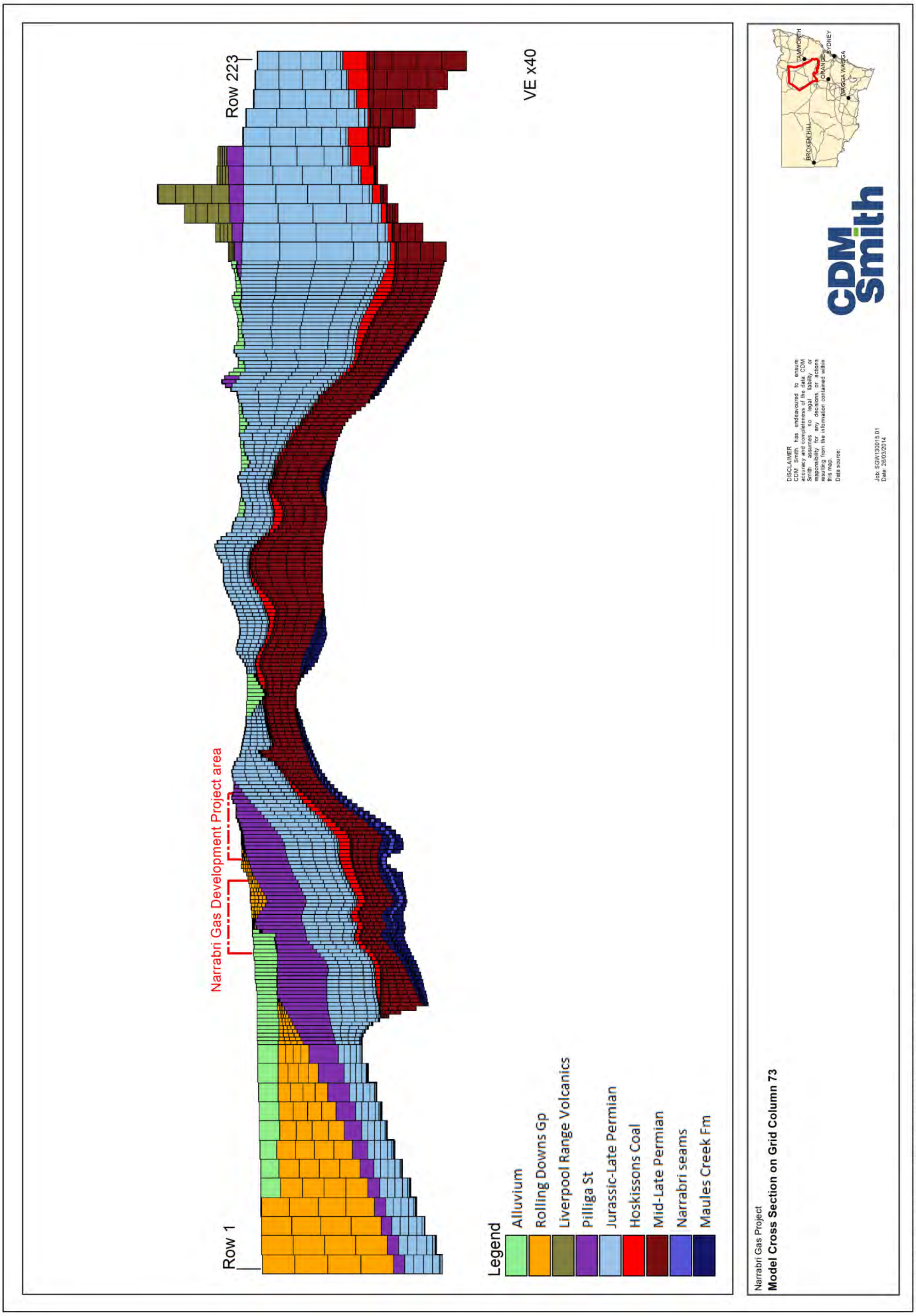



**Figure 6-10 Model cross section on grid column 73**

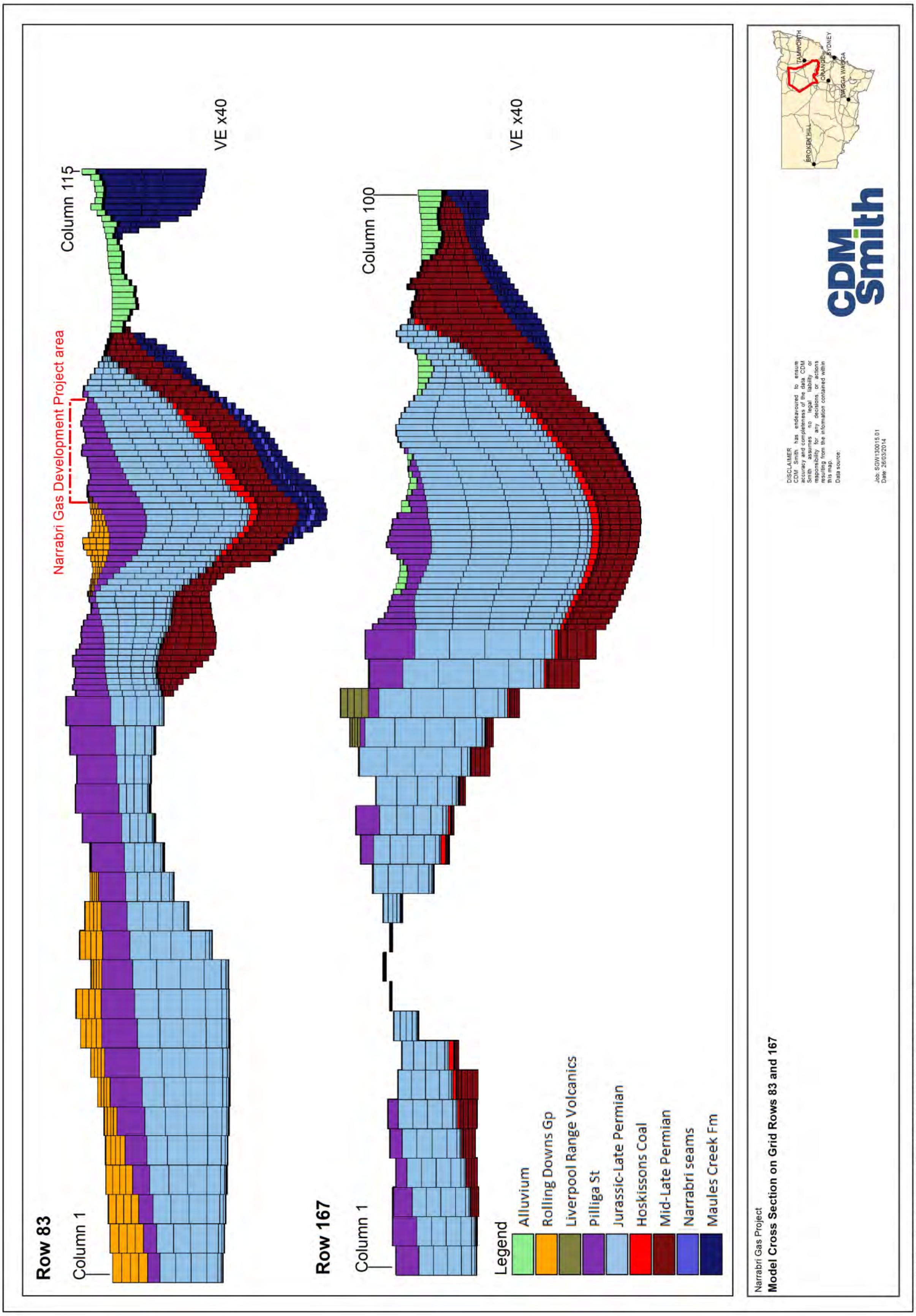



**Figure 6-11 Model cross sections on grid rows 83 and 167**

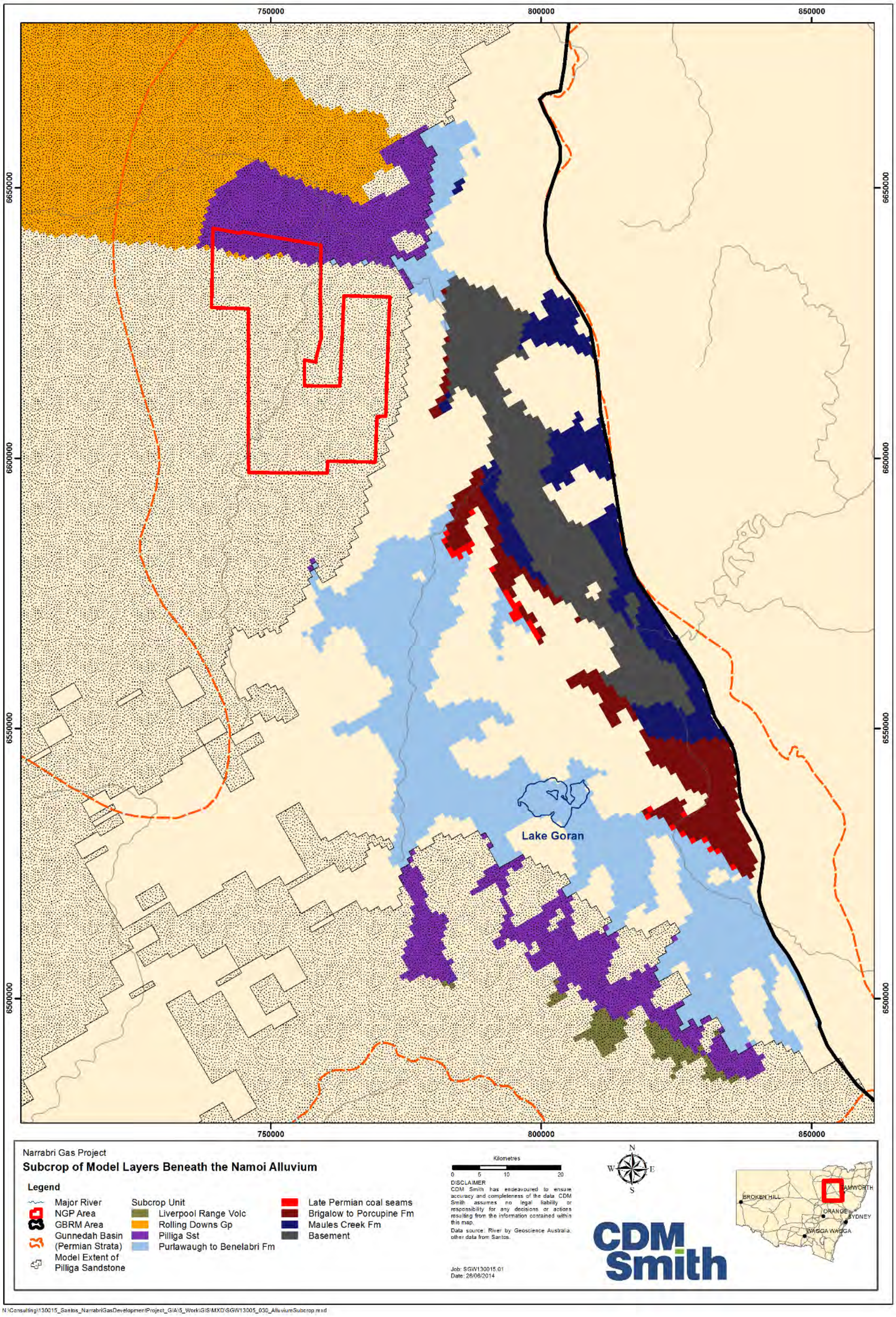



**Figure 6-12 Subcrop of model layers beneath the Namoi alluvium**

#### 6.4.3.7 Boundary Conditions

The limits of the model domain have been selected to ensure that the expected hydraulic impacts of coal seam gas development remain within the modelled extent, and to enable appropriate hydraulic conditions to be assigned at the model boundaries.

A summary of the boundary conditions assigned around the perimeter of the model domain is given in Table 6-5 and the corresponding boundary locations are shown in Figure 6-9. In Table 6-5, a boundary condition with zero prescribed flow is referred to as a no-flow (NF) boundary. Prescribed head boundaries are indicated as a (H) boundary, while (UNP) indicates that the particular HSU was not present in the model layer at the boundary edge.

Prescribed head conditions are used along two opposing segments of the boundary to allow regional groundwater outflow from the model domain to the GAB in the northwest and to the Sydney Basin in the southeast. A third section of the west boundary is also assigned constant head. No flow conditions are used along the remainder of the model boundary based on regional flow symmetry and the presence of structural controls. A brief rationale for these choices is provided in the following sections.

**Table 6-5 Model boundary conditions**

| Hydrostratigraphic Unit | Boundary Section | | | | | |
|---|---|---|---|---|---|---|
| | East | North | Northwest | West | Southwest | Southeast |
| Namoi alluvium (Cenozoic aquifers) | NF | UNP | H | UNP | UNP | UNP |
| Liverpool Range Volcanics | NF | UNP | UNP | UNP | UNP | UNP |
| Wallumbilla Formation to Orallo Fm (Cretaceous aquitards) | NF | NF | NF | NF | NF | UNP |
| Pilliga Ss (Jurassic aquifer) | UNP | NF | H | H / NF | NF | H |
| Purlawaugh Fm to Benelabri Fm (Jurassic-Late Permian aquitards) | UNP | NF | NF | NF | NF | H / NF |
| Late Permian coal seams | UNP | UNP | UNP | UNP | UNP | NF |
| Brigalow Fm to Porcupine Fm (Mid-Late Permian aquitards) | NF | NF | UNP | NF | UNP | NF |
| Maules Creek Fm (Early Permian aquitards) | NF | NF | UNP | UNP | UNP | NF |
| Early Permian coal seams | UNP | UNP | UNP | UNP | UNP | UNP |

NF – no flow boundary, H – prescribed head boundary [m AHD], UNP – units not present

***East Boundary***

A no-flow condition is adopted for all hydrostratigraphic units present along the eastern boundary of the model, which represents the eastern extent of the Gunnedah Basin along the Hunter-Mooki Fault system. The assumption of no flow across the boundary is conservative and neglects the possibility of groundwater exchange between the basin sediments and fractured rocks of the New England Fold Belt. The implication for predictive modelling is that water sources east of the Hunter-Mooki fault cannot contribute to coal seam water production or hydraulic head recovery in the Gunnedah Basin after coal seam gas production ceases.

***North Boundary***

A no-flow condition is adopted for all hydrostratigraphic units present along the northern boundary of the model, which corresponds approximately to the nominal northern limit of the Gunnedah Basin. The boundary is aligned with the regional flow direction within the Coonamble Embayment of the GAB (Radke *et al.* 2000) and with the southern limit of the Lower Gwydir alluvium, which is represented by a no-flow condition in the Lower Gwydir groundwater model (Bilge 2002).

Regional flow directions in the Permian coal seams are undetermined. A no-flow condition is adopted on the basis that lateral head gradients are likely to be similar to those within the overlying Jurassic aquifer. No-flow conditions are adopted for all aquitard units on the basis that similar hydraulic gradients are expected and laterals flow rates are smaller in these units.

The implication for predictive modelling is that water sources north of the boundary cannot contribute to coal seam water production or hydraulic head recovery after coal seam gas production ceases. This assumption is reasonable if hydraulic head change induced by coal seam water production does not extend to the boundary during a model simulation. Should this occur, inflow from the Bowen Basin would be prevented and drawdown of hydraulic head would be overestimated to some extent.

***Northwest Boundary***

The location and alignment of the northwest boundary is chosen to coincide with the western limit of the Lower Namoi groundwater flow model (Merrick 2001) and more generally with the curvature of head equipotentials in the GAB (Herczeg 2008).

For the shallow alluvial model layer a prescribed head boundary condition is adopted along the section of the boundary where the Lower Namoi alluvium is present; this is the same boundary condition used for the Lower Namoi groundwater model. Elsewhere along the boundary the shallow groundwater level is unknown and a no-flow boundary condition is adopted. This choice is not expected to influence the predictive simulations due to the large distance (approximately 200 km) from the project area. The implication for the predictive modelling is that there is potential for coal seam water production to reduce the rate of lateral outflow from the Lower Namoi alluvium.

A prescribed head condition is adopted for the Jurassic aquifer along the entire northwest boundary. In the absence of adequate hydraulic head measurements in other GAB units the same condition is also adopted for the deeper Triassic aquifers. No flow conditions are assumed for the other GAB units on the basis that lateral flow components are small. The implication for predictive modelling is a potential for coal seam water production to reduce groundwater outflow toward the Bogan River Spring Group discharge area. This will only happen if induced drawdown of hydraulic head extends several hundred kilometres to the boundary, which does not occur in this assessment.

***West Boundary***

The location and alignment of the west boundary coincides with the western extent of the Gunnedah Basin and the regional groundwater flow direction within the Coonamble Embayment of the GAB, which is generally northwest from the GAB recharge beds toward the Bogan River Spring Group discharge area (Radke *et al.* 2000).

Two boundary conditions are adopted to represent the observed shallow groundwater conditions along the west boundary. Prescribed head values are assigned along the south section of the boundary between the Talbragar River (a tributary of the Macquarie River) and Castlereagh River according to the observed hydraulic head (Figure 5-9). Shallow groundwater outflow occurs across this section of the boundary. A no-flow condition is assumed along the larger northern section of the boundary on the basis that the boundary follows the regional groundwater flow line, and based on the assumption that water table elevation is controlled by topographic fall in the direction of regional surface drainage within the Castlereagh River.

A no-flow boundary condition is adopted for all deep hydrostratigraphic units on the basis of either flow symmetry or extent of units. The implication for predictive modelling is that deep groundwater sources west of the boundary cannot contribute to coal seam water production or hydraulic head recovery after coal seam gas production ceases. The model results would be to some extent compromised if drawdown induced by coal seam water production extended to the model boundary; however, there is no depressurisation at the west boundary in this assessment.

***Southwest Boundary***

A no-flow condition is adopted for all hydrostratigraphic units along the portion of the model boundary corresponding to the southern limit of the GAB and Gunnedah Basin at the contact with the Lachlan Fold Belt. This condition is considered to be conservative and neglects the possibility of groundwater flow between the Gunnedah Basin and fractured rock of the Lachlan Fold Belt. The implication for predictive modelling is that water sources within the Lachlan Fold Belt cannot contribute to coal seam water production or recovery of hydraulic head in the Gunnedah basin after coal seam gas production ceases.

***Southeast Boundary***

The southeast model boundary is aligned with the Goulburn and Hunter Rivers. Prescribed head boundary conditions are assigned within the Jurassic aquifer based on the elevation of the valley floors and the assumption of a relatively shallow water table in the alluvial groundwater sources (referred to collectively as the Hunter Regulated River Alluvial Groundwater Source). In the absence of hydraulic head measurements, a no flow condition is assigned to all deeper units that are present along the boundary, including the Hoskissons Coal. The implication for predictive modelling is that water sources within the Sydney Basin cannot contribute to coal seam water production or recovery of hydraulic head in the Gunnedah Basin after coal seam gas production ceases.

#### 6.4.3.8 River-Aquifer Interaction

Assessment of surface water–groundwater interaction within the Namoi catchment by CSIRO (2007a) indicated that on average the Mooki and Namoi Rivers lose stream flow to groundwater over approximately 280 km within the Namoi catchment. The assessment found that the Namoi River gains stream flow from groundwater input over a relatively small reach of 50 km between the townships of Gunnedah and Narrabri (Figure 5-19). Previous detailed assessment of gaining and losing conditions within the Namoi catchment (Ivkovic 2006) similarly indicated that rivers in the Upper Namoi GMA zones are variably connected with gaining and losing sections, while rivers in the Lower Namoi GMA are disconnected losing systems.

In areas with disconnected stream flow the rate of leakage through the river bed is generally considered to be independent of groundwater level. This situation exists in the Lower Namoi GMA where disconnected leakage from the river to groundwater is incorporated into the estimate of net groundwater recharge at the water table, which is determined by the method described later in Section 6.4.4.

In the Upper Namoi GMA zones the MODFLOW River Package is used to simulate variable exchanges between the river and alluvial groundwater. The River Package provides a simplified representation of a river system by allowing the head in the river to be a specified input that is independent of head in the connected aquifer. The exchange flux between the river and aquifer is calculated during the model simulation based on the head difference and the supplied value of the river bed conductance.

The length of the river traversing each model cell is estimated using GIS tools and the ground surface elevation for each river cell is similarly extracted from STRM data. Locations of river cell determined by this procedure are indicated in Figure 6-9. Reach numbers and approximate values for river stage, river bottom elevation and river bed thickness for each river reach are adopted from the analysis conducted for the Upper Namoi groundwater model (McNeilage 2006). A summary for the five main sections of river between the confluences is given in Table 6-6. At locations where the river channels extend beyond the limit of the Upper Namoi model the reach numbers at those locations are continued further up river. The elevation of river stage in areas outside of the model is extrapolated based on the topographic gradient, such that the river stage varies parallel with ground surface. Average river widths are estimated from aerial imagery.

A uniform value of river bed hydraulic conductivity equal to 0.005 m/d is assigned for all six river reaches. This estimate is based on the average value used in the Upper Namoi groundwater model (McNeilage 2006).

**Table 6-6 River boundary conditions**

| River section | Channel Width [m] | Bed Thickness [m] | River Stage [mAHD] | River Bed Elevation [mAHD] |
|---|---|---|---|---|
| Namoi River: Bohena Ck to Coxs Ck | 30 - 30 | 2.0 – 2.5 | 207.0 – 235.0 | 203.5 – 231.5 |
| Namoi River: Coxs Ck to Mooki Rv | 30 - 15 | 2.5 – 2.0 | 235.0 – 255.5 | 231.5 – 252.0 |
| Namoi River: Hunter-Mooki Fault to Mooki Rv | 15 - 15 | 2.0 – 2.0 | 255.5 – 263.8 | 252.0 – 260.3 |
| Mooki River | 15 - 15 | 2.0 – 0.5 | 255.5 – 331.7 | 252.0 – 329.7 |
| Cox's Creek | 30 – 10 | 2.5 – 0.5 | 235.0 – 334.0 | 231.5 – 332.5 |

## 6.4.4 Groundwater Recharge within the Namoi Alluvium

The method used to assign groundwater recharge fluxes within the areal extent of the Namoi alluvium is described in Section 6.5.2. Net recharge fluxes, representing the net recharge due to rainfall, irrigation, flooding, evapotranspiration, and pumping are derived using a head-matching technique. The derived estimates of net recharge for each model cell within the alluvium can have negative values in areas where the shallow groundwater is at a high level of utilisation and the total discharge, including pumping, exceeds the total recharge.

These net groundwater recharge fluxes do not include groundwater exchange with the Namoi River channel, which is represented using the MODFLOW River Package (Section 6.4.8). Inclusion of river boundary conditions (a type of general head boundary condition) in the Namoi alluvium provides a mechanism for recovery of water table drawdown through increased recharge from the river channel. A more general discussion of the mechanisms within the groundwater model that will allow recovery of hydraulic head after cessation of coal seam water production can be found in Section 6.8.6.

A plausibility check against other independent estimates of water balance in the alluvium is fitting; however, it should be noted that all volumetric estimates of water balance over an area as large as the Upper and Lower Namoi alluvium (approximately 9300 km$^2$) are subject to uncertainty at the order-of-magnitude of that area.

For the values of the hydrogeological properties adopted in this assessment (see Section 6.6) the net recharge fluxes to the Namoi alluvium in Figure 6-13 sum to approximately -105 GL/y. Net leakage from the Namoi River is approximately 101 GL/y and, thus, the net water input to the alluvium in the modelling in this assessment is -4 GL/y. This can be cross checked against the independent estimate of -20 GL/y derived from Table 5-10 (CSIRO 2007a) which consists of net water inputs to the Upper and Lower Namoi alluvium from rivers, rainfall, irrigation and floods. The difference of 16 GL/y between these estimates over the 9,300 km$^2$ area of the Namoi alluvium is equivalent to a difference in uniform recharge rate of 1.7 mm/y. Although these estimates are not identical they are within the same order of magnitude and the difference is negligible within the context of the modelling in this assessment.

### 6.4.5 Groundwater Recharge outside of the Namoi Alluvium

A spatially-varying recharge rate is assigned to all areas outside of the Namoi alluvium based on the patterns of average regional rainfall and outcrop geology. The resultant distribution of groundwater recharge is shown in Figure 6-15.

The recharge rates Figure 6-15 are calculated as fixed percentages of annual average rainfall for the period 1976 to 2005, which varied from approximately 500 mm/y in the west of the GIA study area to approximately 1200 mm/y in areas of topographic highs in the east of the study area. The applied rainfall recharge percentages are: 2% in alluvial areas, 1% in areas where transmissive units outcrop (e.g. Pilliga Sandstone) and 0.1% in areas where aquitard units outcrop (e.g. Permo-Triassic units). A recharge rate of 0.15% of rainfall is applied over the areas of the Liverpool Ranges and Warrumbungle volcanics.

### 6.4.6 Evapotranspiration

Evapotranspiration at the water table is simulated using the MODFLOW Evapotranspiration (ET) Package. A constant potential evapotranspiration rate of 600 mm/y and extinction depth of 5 m are specified at all locations outside of the Namoi alluvium. The evapotranspiration rate is based on the Bureau of Meteorology 1975 to 2005 average areal actual evapotranspiration map and is not varied as part of the model calibration procedure.

Evapotranspiration within the area of the Namoi alluvium (excluded above) is included within the estimate of net groundwater recharge to the alluvium, as described in Sections 6.4.4 and 6.5.2.

### 6.4.7 Groundwater Extraction

Groundwater extraction from the Namoi alluvium is simulated indirectly as part of the method used to match water table elevation in the alluvium (see Sections 6.4.4 and 6.5.2). Negative estimates of net groundwater recharge occur where the total discharge of groundwater, including ground water pumping, is greater than the total recharge of groundwater. The distribution of net recharge estimated by this method can be seen in Figure 6-13 which also shows the locations of groundwater extraction bores from the PINNEENA database.

Existing groundwater modelling of the Upper and Lower Namoi alluvium (McNeilage 2006, Merrick 2001 and CSIRO 2007a) has shown that groundwater extraction from bores is by far the largest fraction of the total discharge from these water sources. The estimates of groundwater pumping from those studies vary from 86 to 94 percent of the total groundwater discharge from the Upper Namoi alluvium, and from 85 to 94 percent of the total groundwater discharge from the Lower Namoi alluvium.

Outside of the Namoi alluvium, the volume of groundwater extraction from bores in the Gunnedah-Oxley Basin is much smaller (see Section 5.5.3) and is not simulated in this assessment.

### 6.4.8 River–Aquifer Interaction

The method used to simulate interaction between surface water and groundwater in the Upper Namoi alluvium via the MODFLOW River Package is described in Section 6.4.3.8. The initial rates of water exchange between the river and alluvium are generated as initial conditions from the steady state model. The values of river stage and bed conductance used in assigning the river boundary conditions are not varied in this assessment, either between or during simulations.

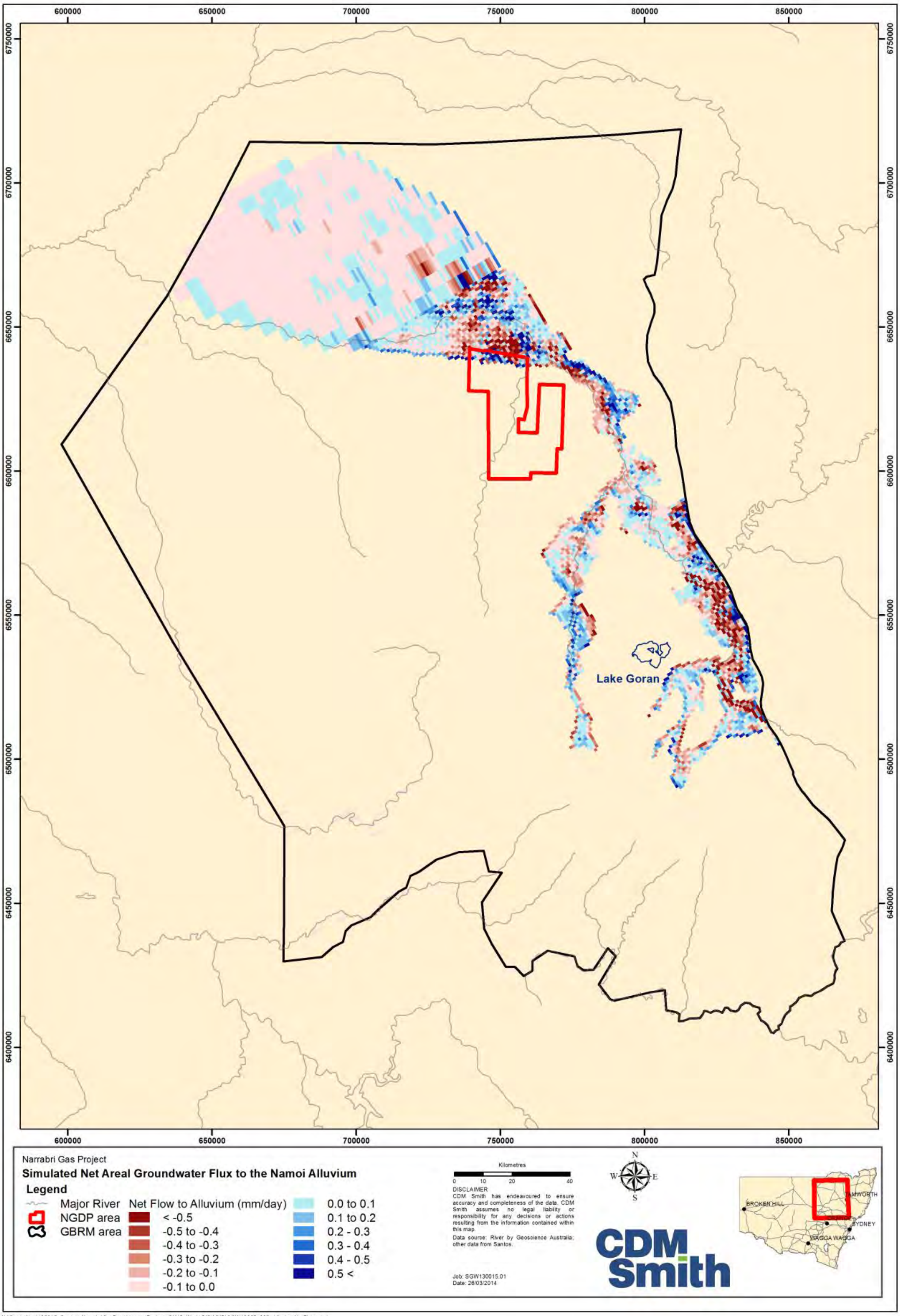



**Figure 6-13 Simulated net areal groundwater flux to the Namoi alluvium**

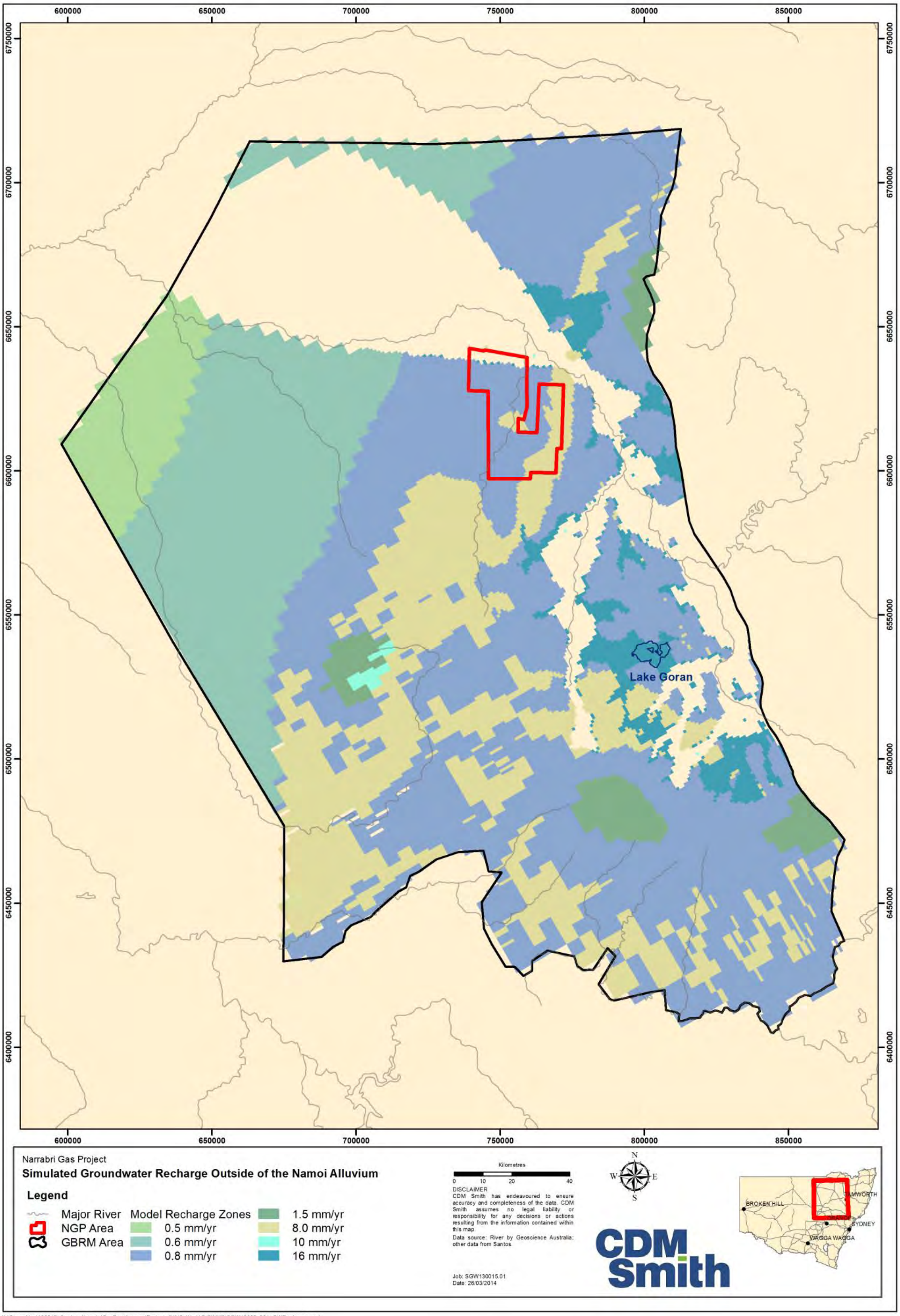



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**Figure 6-14 Simulated groundwater recharge outside of the Namoi alluvium**

## 6.5 Model Calibration

Model calibration normally involves changing values of model parameters within bounds until the model outputs fit historical measurements, such that the model can be accepted as a reasonable representation of the physical system of interest (Barnett *et al.* 2012, Sinclair Knight Merz 2013). Due to the absence of suitable historical measurements in the Gunnedah Basin, and the choice made in this assessment to represent the shallow alluvial system using average conditions, a modified approach to model calibration is necessary.

Modelling of proposed coal seam gas development in the Gunnedah Basin involves the simulation of regional scale changes in hydraulic head and groundwater flow over an area of approximately 50,000 $km^2$ in response to water extraction from coal seams at depths of hundreds of metres. Currently, there are no hydraulic head measurements within the target seams for coal seam gas development or their bounding hydrostratigraphic units that are suitable for conducting a transient model calibration.

Whilst a number of pilots have been conducted in PEL 238 for the appraisal of coal seam gas reserves, the measurements made during the pilots are typically focussed on the acquisition of coal and gas resource data and the testing protocols do not readily lend themselves to the derivation of hydrogeological characteristics. Further work is underway to optimise future pilot tests to obtain complementary data for hydrogeological analysis. The existing data are not suitable for extrapolation to, or calibration of, the numerical model due to the relative scale of the pilots and model grid. With minimum cell sizes of 1 km × 1 km, the model is effective at estimating the sub-regional impact on water resources of the proposed activities, sustained for the duration of the 25 year assessment period. However, the pilots are commonly operated for only weeks or months and stable water extraction rates are rarely maintained, such that the acquired target seam pressure data cannot be relied on to provide an appropriate representation of pressure within the broadly surrounding strata.

Observation data for the confined groundwater sources within the GIA study area are limited to sparse hydraulic head measurements, mostly within the GAB to the northwest of the project area. In contrast, there are a large amount of water table data for the shallow groundwater sources within the Namoi alluvium; however, these data are not useful for the purpose of estimating model parameters in the parts of the Gunnedah Basin where the coal seam gas development is proposed.

Within this context, the primary objective in this assessment is to establish a distribution of hydraulic head throughout the model that is suitable as an initial condition for the predictive simulations and which is consistent with the available hydraulic head information. The adopted approach attempts to match the simulated steady state hydraulic head to the available observations of hydraulic head; however, no attempt is made to estimate the model parameters as part of this process. Instead, a different set of initial conditions must be generated for each choice of the model hydrogeological properties. The choice of hydrogeological properties in this assessment is discussed in Section 6.6.

### 6.5.1 Selection of Calibration Data

The following factors were considered in choosing hydraulic head data that are suitable for producing initial conditions for transient predictive simulations:

- Groundwater extraction data indicate that the most recent period with relatively consistent extraction rates is 1996 to 2000 (Section 5.5.3). Hydraulic head observations at the end of this period are more likely to represent average conditions than measurements taken during periods of increasing or decreasing extraction.

- Artesian bores generally show stabilisation of hydraulic head during the past 30 years (Figure 5-12). Observations in around year 2000 fall within this period and should provide a reasonable initial condition for artesian head in the GAB.
- Statistical analysis of the available hydraulic head observations (Section 5.4.1) indicates that year 2000 has the second largest number of bores with measured head values.

On this basis, two sets of hydraulic head data are used for matching the model outputs and establishing initial conditions for transient simulations:

- Mean annual water table elevation in the Namoi alluvium for year 2000 is derived from 590 bores in the PINNEENA database that are shallower than 50 m deep and with hydraulic head measurements in year 2000 (see Figure 5-9); and
- Mean hydraulic head in artesian bores for the period 1998 to 2001 is derived from the 15 artesian bores within the GIA study area with hydraulic head measurements during 1998 to 2001 (see Figure 5-10).

### 6.5.2 Matching of Steady State Water Table Elevation in the Namoi Alluvium

Two approaches can be used to match the simulated hydraulic head in a groundwater model to the observations of water table elevation from groundwater monitoring. The first and most common approach involves systematic variation of the hydrogeological properties of the model to achieve an acceptable match between the simulated head and observational data, and often requires simultaneous variation of the groundwater recharge in the modelling.

The alternate less common approach involves imposing the observational data as prescribed head boundary conditions in the modelling and running the model to calculate the fluxes at the water table corresponding to those heads. The imposed prescribed head boundary conditions are subsequently replaced by prescribed flow boundary conditions with the flows set equal to the fluxes calculated in the previous step. This alternate approach does not require the hydrogeological properties of the model to be changed; however, it generates a unique estimate of the recharge fluxes at the water table for each choice of the model properties. When possible, the fluxes calculated by this method should be checked for consistency against independent estimates of groundwater recharge.

The second method of imposing a known water table elevation to estimate groundwater recharge at the water table is used in this assessment within the extent of the Namoi alluvium. The method is applied to produce estimates of net groundwater recharge based on mean annual water table elevation for year 2000 (Figure 5-9). This choice is based on the following considerations:

- It is impractical to implement local-scale distributions of hydrogeological properties from existing modelling of the Upper and Lower Namoi alluvium (e.g. McNeilage 2006; Merrick 2001) in a regional-scale groundwater model, or to simulate transient responses to short-term variations in rainfall, river flooding, irrigation and groundwater extraction;
- The focus of the modelling is to predict potential impacts of coal seam gas development on regional groundwater resources, such that additional effort dedicated to calibrating local scale responses far away from the proposed coal seam gas production areas is not expected to increase the confidence level of model predictions;

- Local-scale estimates of the hydrogeological properties of the alluvium in existing modelling studies were calibrated to local scale processes that are not represented in the GBRM;
- The spatial density of water table observations in the alluvium provides a high level of confidence in the interpreted water table surface; and
- The approach is suitable for producing average initial conditions in the alluvium that are appropriate for representing regional-scale exchanges of groundwater between the alluvium and underlying subcrop units of the Gunnedah-Oxley Basin.
- The resultant estimates of net groundwater recharge to the alluvium include groundwater pumping, which is not simulated directly. Thus, the net recharge rate can have negative values in areas where the aquifer has a high level of utilisation and total discharge exceeds total recharge.

A plausibility check to compare the net recharge fluxes calculated using this method against other independent estimates of water balance in the Upper and Lower Namoi alluvium is considered in Section 6.4.4.

Figure 6-15 shows a comparison of the simulated initial water table elevation and observed mean annual water table elevation for year 2000 in 590 shallow (less than 50 m deep) observation bores. The simulated values are produced using the method described above and the adopted estimates of model parameters in Table 6-7 (see Section 6.6 for a discussion of these values). As expected for this method, an almost exact match between the simulated and observed water table elevation is achieved for locations within the Namoi alluvium where the net recharge fluxes are applied. This result can be seen in the probability distribution of the head residuals (Figure 6-15b) which is centrally skewed and shows a disproportionate probability of very small head residuals compared to a normal distribution.

Several large discrepancies between the simulated and observed values (outliers) occur outside of the alluvium. These differences are generally caused by the lack of spatial resolution of the model (minimum cell size of 1 × 1 km up to 5 × 5 km) which cannot reproduce local variation of water table measurements within sub-grid scale topographic depressions and valleys. At these locations the model produces regionally-averaged estimates of water table elevation that tend to be above the local water table measurements within topographic lows.

The largest outliers (±25 to ±75 m) occur mainly in two locations that are relatively distant from the project area. One group of bores is located on the southern side of the Liverpool Ranges (near the southern boundary of the model) 150-200 km away from the project area; the depths of these bores correspond to the upper part of the Jurassic-to-Late Permian aquitard sequence in the geological model (Layer 7 of the groundwater model); however, they are more likely to be installed in the overlying Pilliga Sandstone (Layer 6). The other group of bores is located in the southwest of the model domain, approximately 160 km from the project area. Again, the depths of these bores correspond to the upper part of the Jurassic-to-Late Permian aquitard sequence in the geological models, whereas they are more likely to be installed in the overlying Pilliga Sandstone.

Figure 6-16 shows a sub-set of the results in Figure 6-15 for shallow (less than 50 m deep) bores located within 100 km of the project area (measured from a central location). Excluding bores more than 100 km from the project area also removes most of the large outliers. Fifteen (3.5%) of these bores have head residuals greater than 5 m and six (1.4%) have head residuals greater than 10 m.

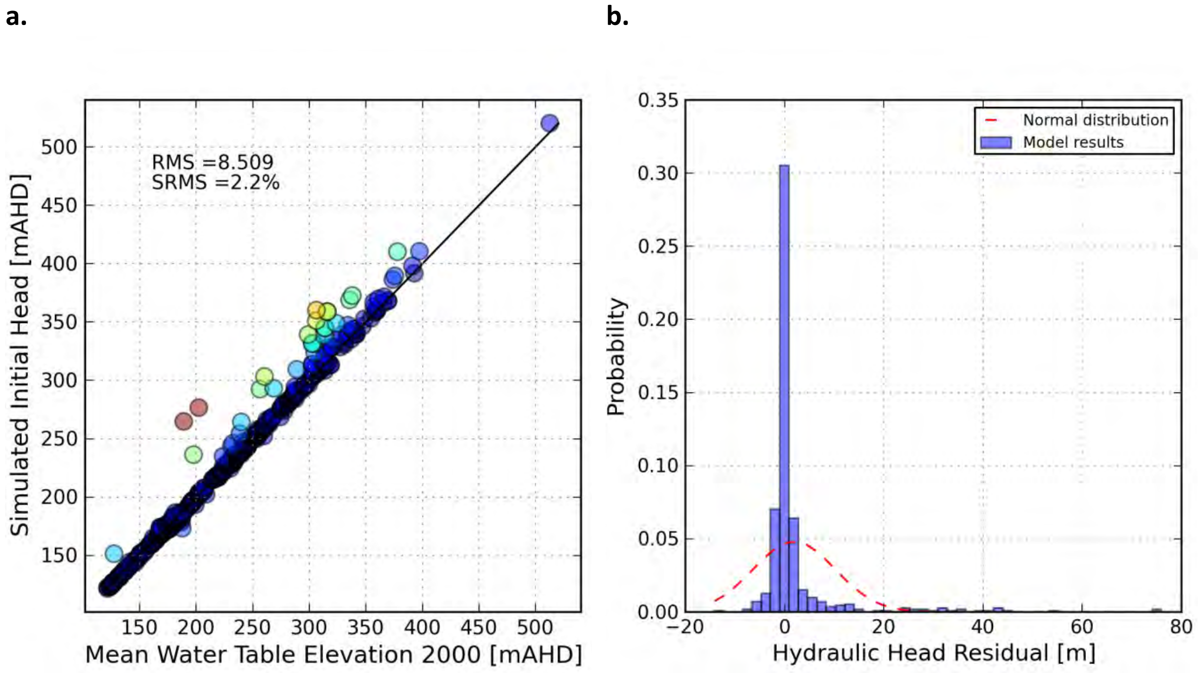


**Figure 6-15 Observed water table elevation and simulated initial head in bores less than 50 m deep: a. scattergram, b. probability distribution of hydraulic head residuals**

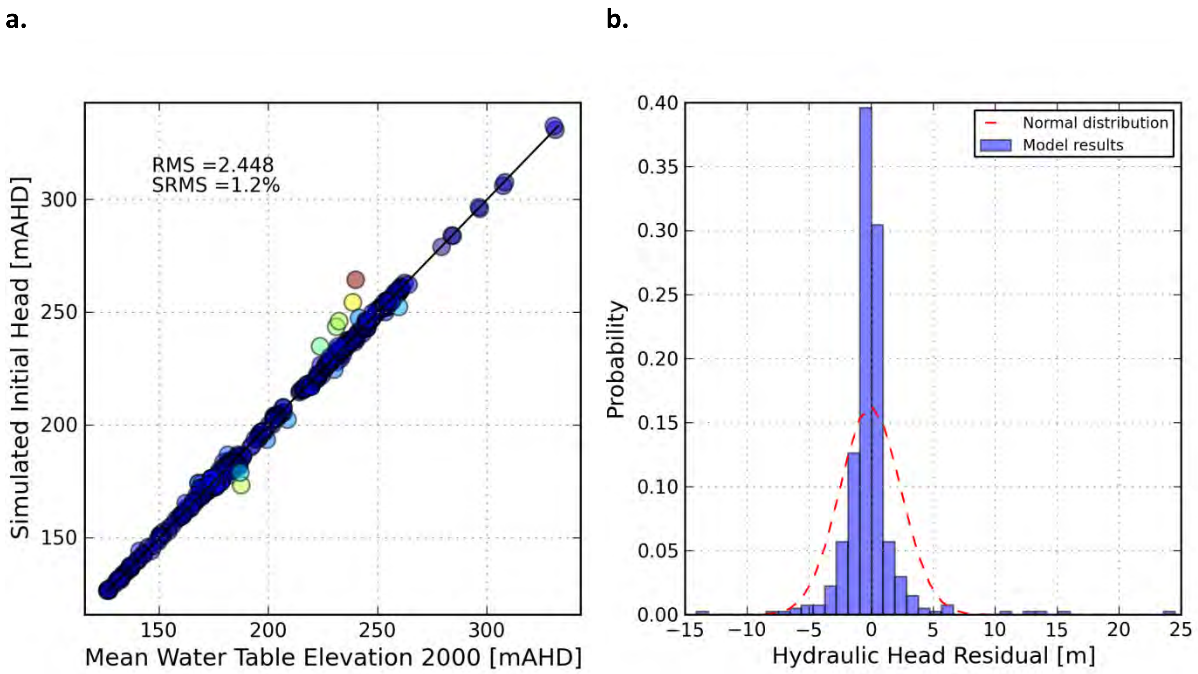


**Figure 6-16 Observed water table elevation and simulated initial head in bores less than 50 m deep and within 100 km of the project area (central location): a. scattergram, b. probability distribution of hydraulic head residuals**

## 6.5.3 Steady State Artesian Head

Figure 6-17 shows a comparison of simulated and observed hydraulic head in fifteen artesian bores available for the model calibration. These locations can be seen in Figure 5-10 and correspond to the area of artesian head within the GBRM area. The results are produced for the adopted estimates of model parameters in Table 6-7. A reasonable match between simulated and observed hydraulic head is achieved using uniform distributions of hydrogeological properties within the transmissive units and aquitards. No attempt is made to improve the match using spatially varying hydrogeological property distributions.

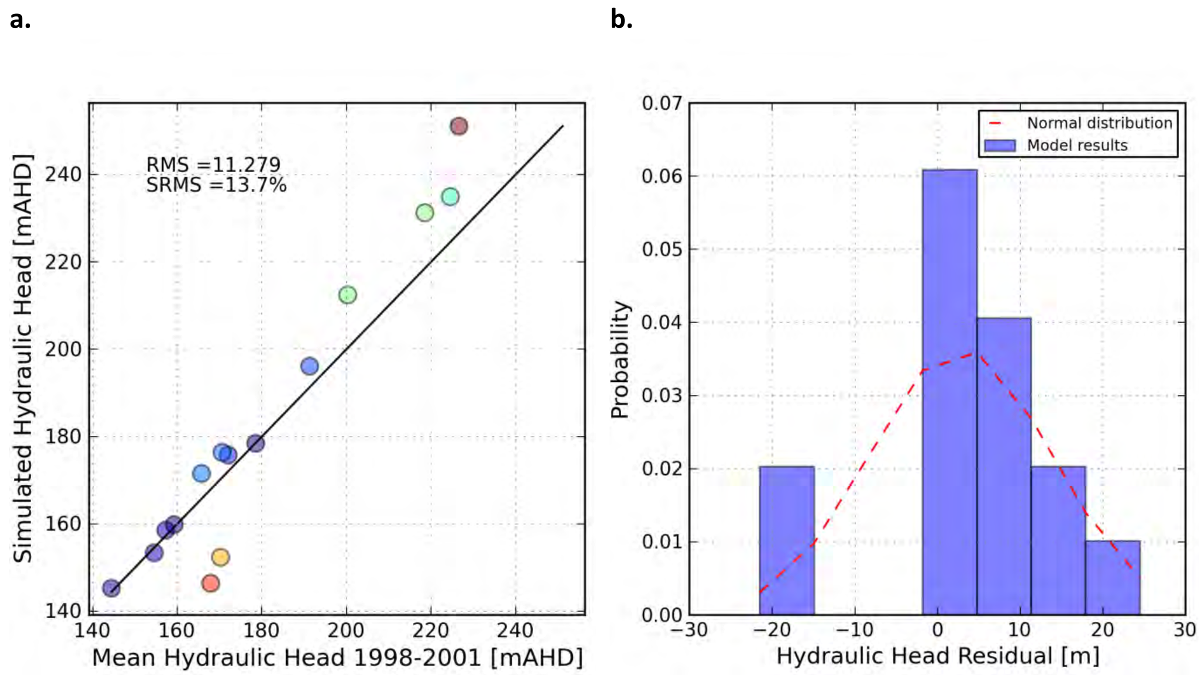


**Figure 6-17 Observed hydraulic head and simulated initial head at artesian wells: a. scattergram, b. probability distribution of hydraulic head residuals**

# 6.6 Steady State Water Balance

The water balance for the steady state model is shown schematically in Figure 6-18. The key features include:

- Simulated groundwater fluxes between hydrostratigraphic units deeper than the Jurassic-to-Late Permian aquitard (and minor aquifer) sequence are relatively small compared to fluxes within the Pilliga Sandstone and overlying units;
- Recharge enters the confined aquifer system predominantly through the recharge beds of the Pilliga Sandstone and by leakage beneath the Liverpool range volcanics; it is redistributed mainly by upward flow to the Namoi Alluvium and some downward flow into the Jurassic-to-Late Permian aquitard sequence; and
- Net fluxes to the Upper and Lower Namoi Alluvium (due to recharge, river leakage, evapotranspiration and pumping) are negative, which is consistent with a high level of allocation as discussed in Sections 5.5.4 and 6.4.4.

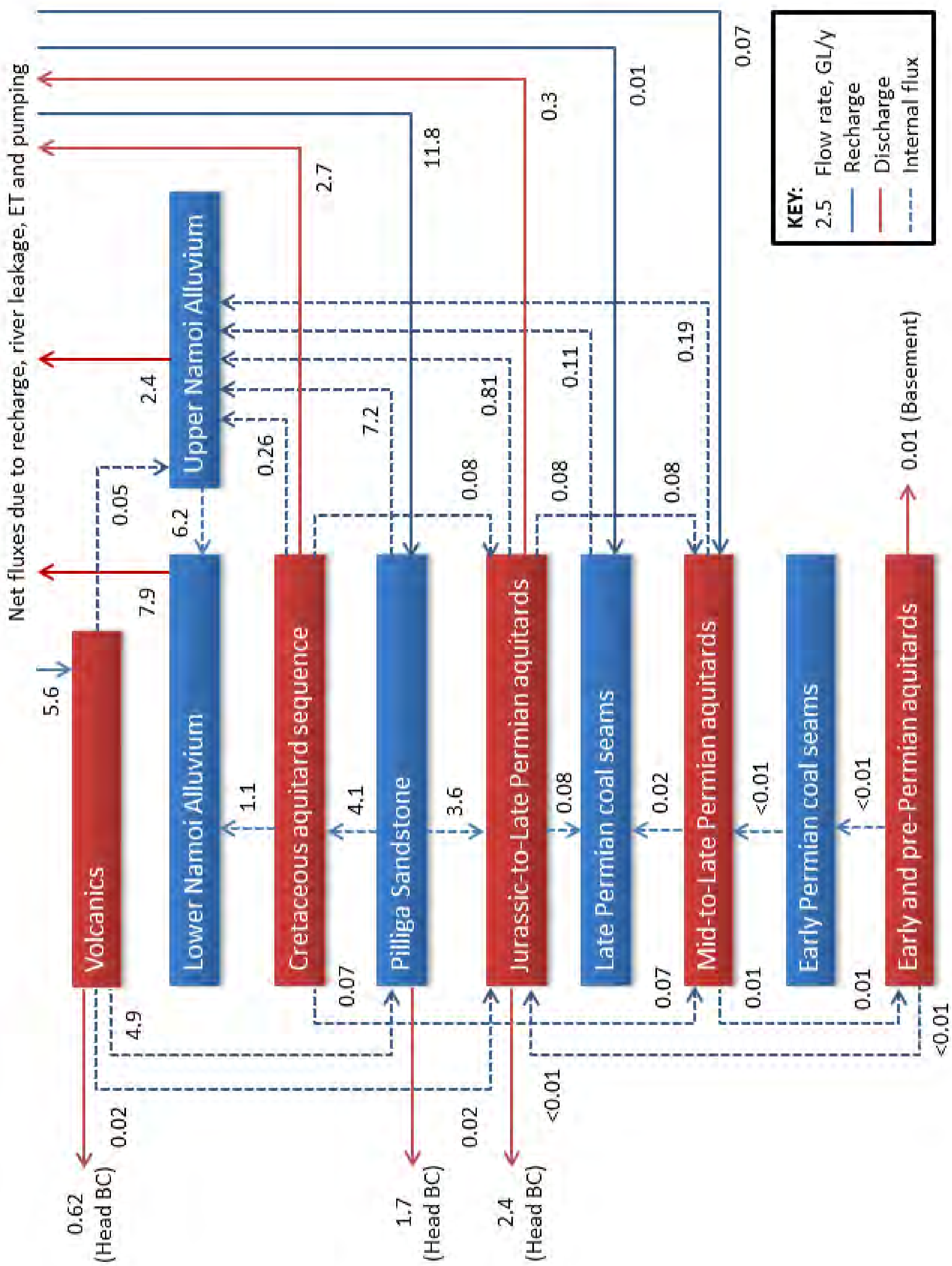


Figure 6-18 Water balance diagram for the steady state model

# 6.7 Adopted Hydrogeological Properties

The values of hydrogeological properties used for the predictive simulations in this assessment are given in Table 6-7. It can be seen in Table 6-7 that the adopted values of the hydrogeological properties are order-of-magnitude estimates, and are based on review of hydrogeological information relating to the Gunnedah Basin and the physical characteristic of rock types.

It has been noted in the past that very few physical parameters are known to vary over thirteen orders of magnitude as does hydraulic conductivity (e.g. Figure 5-4). Thus, an order-of-magnitude knowledge can be very useful (Freeze and Cherry 1979) and is considered appropriate in relation to application in a regional model of this magnitude. Discussion of the appropriateness of the adopted model parameter selections is made in Section 5.3.

**Table 6-7 Adopted hydrogeological properties**

| Hydrostratigraphic Unit | Model Layer | Hydrogeological Properties | | | |
|---|---|---|---|---|---|
| | | $K_h$ [m/d] | $K_v$ [m/d] | $S_y$ [-] | $S_s$ [1/m] |
| Namoi alluvium (Cenozoic aquifers) | 1 | 5E+0 | 5E-1 | 1E-1 | 1E-5 |
| Liverpool Range Volcanics | 1-5 | 1E-4 | 5E-6 | 1E-2 | 1E-5 |
| Wallumbilla Formation to Orallo Formation (Cretaceous aquitard sequence) | 2-5 | 1E-3 | 1E-5 | 1E-2 | 1E-5 |
| Pilliga Sandstone (Jurassic aquifer) | 6 | 1E-1 | 1E-2 | 1E-2 | 1E-5 |
| Purlawaugh to Benelabri Formations (Jurassic-to-Late Permian aquitards and minor aquifers sequence) | 7-12 | 1E-3 | 1E-5 | 1E-2 | 1E-5 |
| Late Permian coal seams (potential coal seam gas targets) | 13 | 1E-1 | 1E-2 | 1E-2 | 1E-5 |
| Brigalow to Porcupine Formations (Mid-to-Late Permian aquitard sequence) | 14-19 | 1E-3 | 1E-5 | 1E-2 | 1E-5 |
| Maules Creek Formation (Early Permian aquitards) | 20-21<br>23-24 | 1E-3 | 1E-5 | 1E-2 | 1E-5 |
| Early Permian coal seam (potential coal seam gas targets) | 22 | 1E-1 | 1E-2 | 1E-2 | 1E-5 |

## 6.7.1 Hydraulic Conductivity

The choice of values for hydraulic conductivity for each hydrostratigraphic unit effects the distribution and transmission of the simulated drawdown at the locations where water is extracted. The adopted values in Table 6-7 are based on the following rationale:

- Differences between the adopted values of horizontal and vertical hydraulic conductivity in each of the hydrostratigraphic units reflects anisotropy ratios ($K_v/K_h$) in the range 0.01–0.1;
- In the alluvium, the adopted values of hydraulic conductivity are based on the existing modelling studies of the Upper and Lower Namoi groundwater management areas (Table 5-3) and their related investigations;
- In the Pilliga Sandstone, the adopted values of hydraulic conductivity are based on existing modelling studies and their related investigations (Table 5-3) and typical literature values for consolidated sandstone in Figure 6-19;
- In the target coal seams, the adopted values of hydraulic conductivity are based on existing modelling studies and their related investigations (Table 5-3);

- The adopted values of hydraulic conductivity in the aquitard sequences are based partly on the existing modelling studies in Table 5-3; however, values at the low end of this range have been chosen based on;
    - the classification of hydrostratigraphic units and rock types in Table 5-1;
    - typical literature values for aquitards containing shale, mudstone and siltstone (Figure 6-19); and
    - the likely performance of the aquitards as effective seals above and below the target coal seams, and the associated implications of excessive leakage of water from the aquitards if they are not effective seals, which may counteract the potential to produce coal seam gas (see Section 6.8.3).

In Figure 6-19, it can be seen that the values of hydraulic conductivity adopted for the Namoi alluvium are consistent with sand and gravel aquifers; the adopted values for the Pilliga Sandstone and Permian coal seams are consistent with poor to good aquifers; and the values adopted for the aquitard sequence are consistent with the sediment types of consolidated sandstone, siltstone, mudstone and shale.

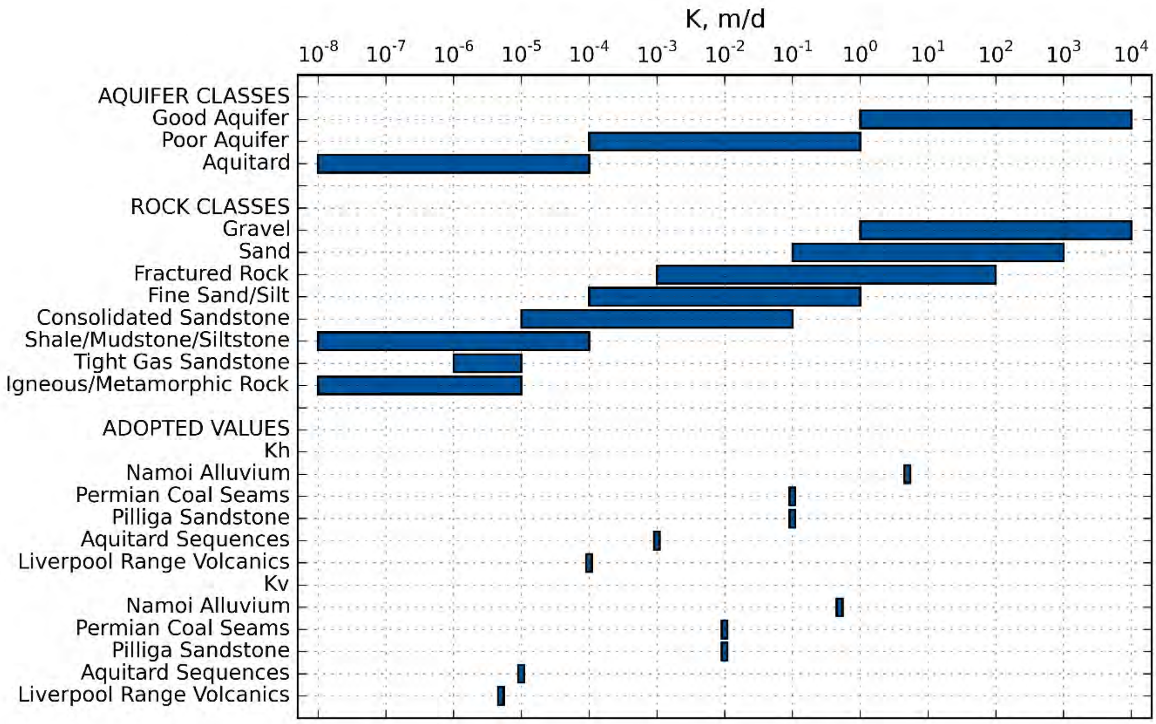


**Figure 6-19 Comparison of the adopted values of hydraulic conductivity and literature values**

## 6.7.2 Specific Storativity

The choice of values for specific storativity affects the magnitude of drawdown per unit volume of water taken from storage. Thus, when all of the extracted water is initially taken from storage in the target coal seams, the choice of value for specific storativity directly determines the magnitude of drawdown per unit volume of the simulated coal seam water production.

The adopted values of specific storativity are based partly on the existing modelling studies in Table 5-3 and influenced by the typical values of material compressibilities in Table 6-8.

### 6.7.3 Specific Yield

The choice of values for specific yield can affect the drawdown response at the water table because changes in water table elevation are associated with draining and filling of pore space.

- The adopted values of specific yield in the alluvium are based on the existing modelling studies of the Upper and Lower Namoi groundwater management areas (Table 5-3) and their related investigations; and

The adopted values of specific yield in other strata are based on existing studies (Table 5-3).

**Table 6-8 Typical material compressibilities (after: Kruseman and de Ridder 1991)**

| Material | Compressibility | |
|---|---|---|
| | $m^2/N$ | 1/m fresh water |
| Groundwater | 4.4E-10 | 4.3E-6 |
| Gravel | 1E-10 to 1E-8 | 1E-6 to 1E-4 |
| Sand | 1E-9 to 1E-7 | 1E-5 to 1E-3 |
| Clay | 1E-8 to 1E-6 | 1E-4 to 1E-2 |
| Rock, sedimentary | 1E-10 to 1E-8 | 1E-6 to 1E-4 |
| Rock, fractured | 1E-10 to 1E-8 | 1E-6 to 1E-4 |
| Rock, igneous & metamorphic | 1E-11 to 1E-9 | 1E-7 to 1E-5 |

## 6.8 Predictive Modelling

### 6.8.1 Historical Water Production from Pilot Wells

The model simulations in this GIA include the historical water production from conventional gas and coal seam gas pilot wells in the Gunnedah Basin. These data are summaries in Table 6-9 and Figure 6-20 shows the rates of water production for each of the pilot over time.

There are twelve pilots listed in Table 6-9, located across nine sites within the project area. The nine locations are shown on the map in Figure 6-21.

It can be seen that the historical water production from existing pilots spans a period of approximately 18 years, from 1998 to 2015. Total water production from all pilots over that period was approximately 1 GL.

**Table 6-9 Summary of historical water production from gas pilots**

| Pilot Name | Abbrev. | Type | Target | Date Range | Total Prod., ML | Representative Model Cell | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Row | Column | Layer |
| Bohena | BH | CSG | EP | 1998 – 2011 | 62 | 63 | 62 | 22 |
| Wilga Park | WP | CG | DF | 1999 – 2005 | 6.4 | 49 | 77 | 9 |
| Bibblewindi 9-Spot | BBD9S | CSG | EP | 2000 – 2012 | 198 | 73 | 61 | 22 |
| Bibblewindi East Lateral | BBDEL | CSG | EP | 2009 – 2012 | 261 | 77 | 59 | 22 |
| Bibblewindi West Lateral | BBDWL | CSG | EP | 2009 – 2013 | 123 | 71 | 57 | 22 |
| Dewhurst Lateral | DWHL | CSG | EP | 2011 | 0.3 | 71 | 74 | 22 |
| Tintsfield Lateral | TFDL | CSG | LP | 2011 – 2012 | 19 | 48 | 72 | 13 |
| Bibblewindi East | BBDE | CSG | EP | 2014 – 2015 | 152 | 77 | 59 | 22 |
| Bibblewindi West | BBDW | CSG | EP | 2014 – 2015 | 75 | 71 | 57 | 22 |
| Dewhurst North | DWHN | CSG | EP | 2014 – 2015 | 45 | 77 | 70 | 22 |
| Dewhurst South | DWHS | CSG | EP | 2014 – 2015 | 71 | 81 | 57 | 22 |
| Tintsfield | TFD | CSG | LP | 2014 – 2015 | 17 | 48 | 72 | 13 |

CSG – coal seam gas; CG – conventional gas; EP – Early Permian coal seams within Maules Creek Formation; LP – Late Permian coals seams within Black Jack Group; DF – Digby Formation

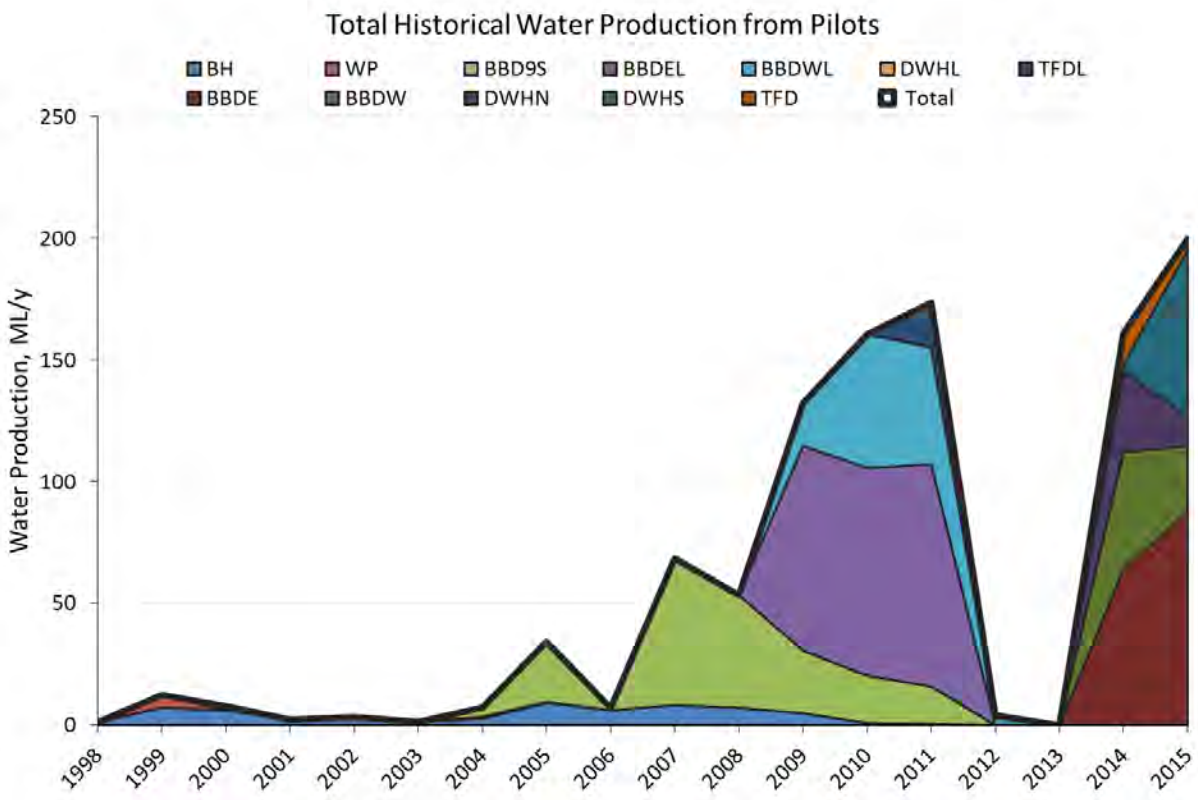


**Figure 6-20 Historical annual water production from gas pilots in the Gunnedah Basin**

Historical water production from the pilots is simulated in the modelling using pumping wells that extract water from the target strata at the annual rates shown in Figure 6-20. In each case, a model cell located closest to the producing wells is selected for locating the pumping well; the row, column and layer numbers of these cells are listed in Table 6-9 and their locations are shown in Figure 6-21.

### 6.8.2 Indicative Project Field Development Plan

The gas field development plan (FDP) considered in this assessment was developed by Santos for the purpose of assessing the potential impacts on groundwater resources of a target for peak gas production of 200 terajoules per day (TJ/d). At the time of preparing the GIA, the FDP is based on a maximum number of 425 sets of coal seam gas wells (850 wells in total) that primarily target Early Permian coal seams within the Maules Creek Formation of the Bohena Trough. The proposed gas extraction will be distributed across sixteen geodomains shown in Figure 6-22; for the purposed of the GIA the geodomains are referred to as Water Extraction Areas (WEAs). The 425 well sets will also target secondary coal seam gas reserves within the Late Permian sediments of the Black Jack Group.

While the groundwater modelling in the GIA adheres to the rates and volumes of forecast water production from the FDP, a final design for the FDP is not yet available. Thus, the geometries of the WEAs; the sequence of their development; the number, locations and order of development of the coal seam gas wells; and the WEA-specific water production profiles are all subject to change, and should be considered as indicative for the purposes of the GIA. All rates of forecast gas and water production are subject to future variations that may result from optimisation of the drilling schedule, constraints on gas and water production, and the scheduling and construction of project infrastructure and facilities.

For the purposes of the GIA, the FDP is considered to be continuous over a period of 25 years, with the water production commencing circa 2017 and ceasing circa 2042 (i.e. water production is considered to be zero from July 2042). Because the simulated depressurisation of the gas field occurs over a relatively short period of time compared to the amount of time predicted for depressurisation effects to propagate into overlying formations, the timing of the indicative FDP and the chronological sequence of WEAs is not considered to be critical with respect to predicted impacts in hundreds of years time.

Delineation of the WEAs and the proposed order of development in Table 6-10 is based on the current understanding of the coal seam gas reserves within the target strata. The water extraction rates for each WEA have been estimated from reservoir modelling by Santos that is based on a maximum rate of development of two well sets per month and an approximate spacing between well sets of 1 km.

The GIA considers three forecasts of water production:

- **Base Case scenario** – the water production profile that is being used as the base case for the project construction and design concept; consisting of total water production of **37.5 GL** over 25 years, with 35.6 GL (95%) contributed from Early Permian targets and 1.89 GL (5%) contributed from Late Permian targets;
- **Low Case scenario** – a forecast of water production that is based on a lower than expected value of porosity in the target coal seams, resulting in a lower than expected estimate of water production; consisting of total water production of **35.0 GL** over 25 years, with 33.3 GL (94%) contributed from Early Permian targets and 1.75 GL (6%) contributed from Late Permian targets; and
- **High Case scenario** – a forecast of water production that is based on a higher than expected value of porosity in the target coal seams, resulting in a higher than expected estimate of water production; consisting of total water production of **87.1 GL** over 25 years, with 82.5 GL (95%) contributed from Early Permian targets and 4.63 GL (5%) contributed from Late Permian targets.

The following sections provide additional information about the simulated water-production profiles for each of the above cases.

**Table 6-10 Order of the gas field development plan**

| Order of Development | Water Extraction Area | Number of Well Sets in Early Permian Targets | Number of Well Sets in Late Permian Targets |
|---|---|---|---|
| 1 | 1 | 69 | - |
| 2 | 9 | 50 | - |
| 3 | 4 | 26 | - |
| 4 | 2 | 37 | - |
| 5 | 12 | 47 | - |
| 6 | 14 | 33 | - |
| 7 | 3 | 12 | - |
| 8 | 11 | 36 | 36 |
| 9 | 13 | 24 | 24 |
| 10 | 7 | 26 | - |
| 11 | 5 | 24 | - |
| 12 | 17 | 7 | - |
| 13 | 10 | 12 | - |

| Order of Development | Water Extraction Area | Number of Well Sets in Early Permian Targets | Number of Well Sets in Late Permian Targets |
|---|---|---|---|
| 14 | 6 | 5 | - |
| 15 | 15 | 7 | - |
| 16 | 18 | 10 | - |
| | **TOTAL** | **425** | **60** |

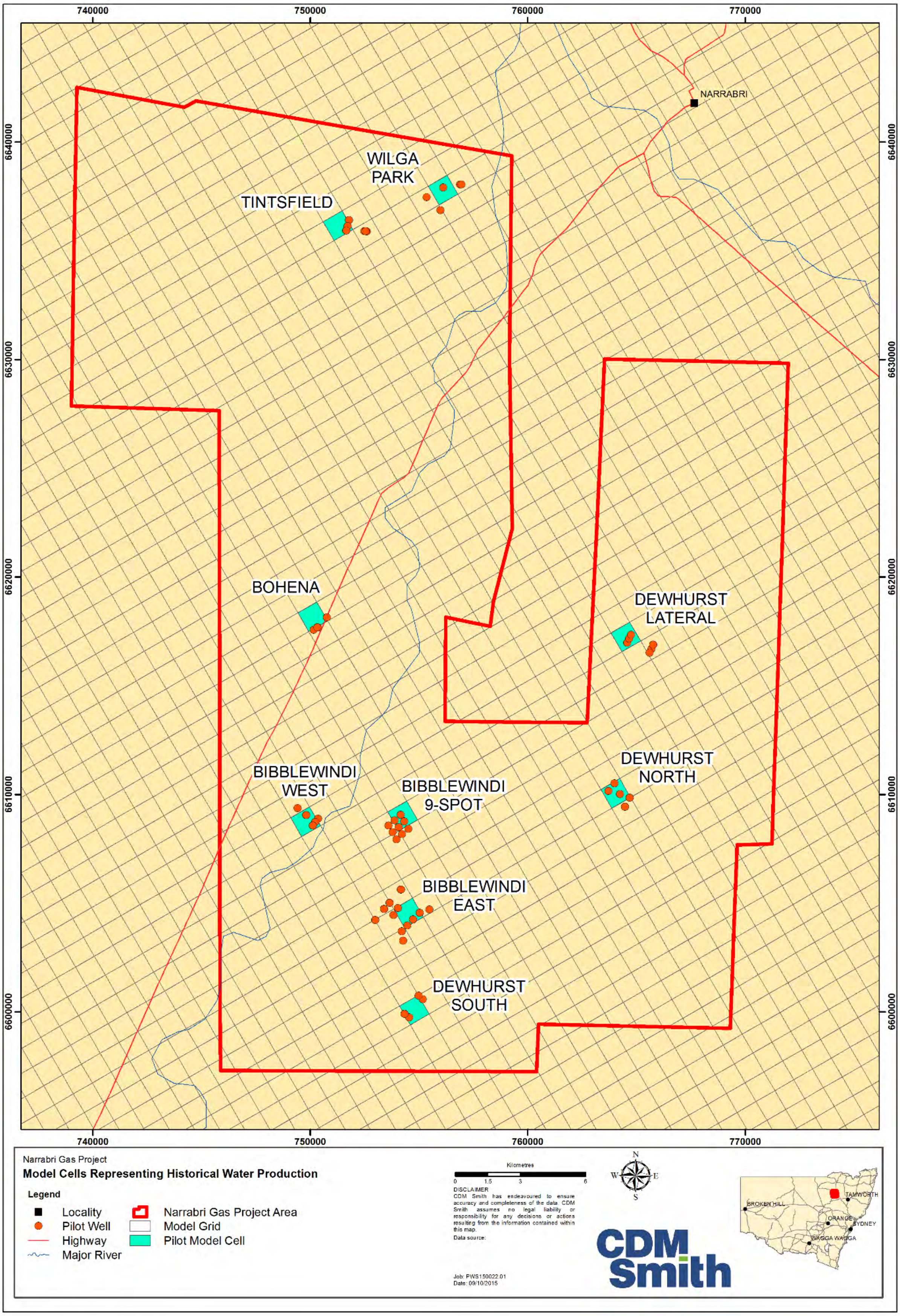


**Figure 6-21 Existing pilot locations and representative model cells**

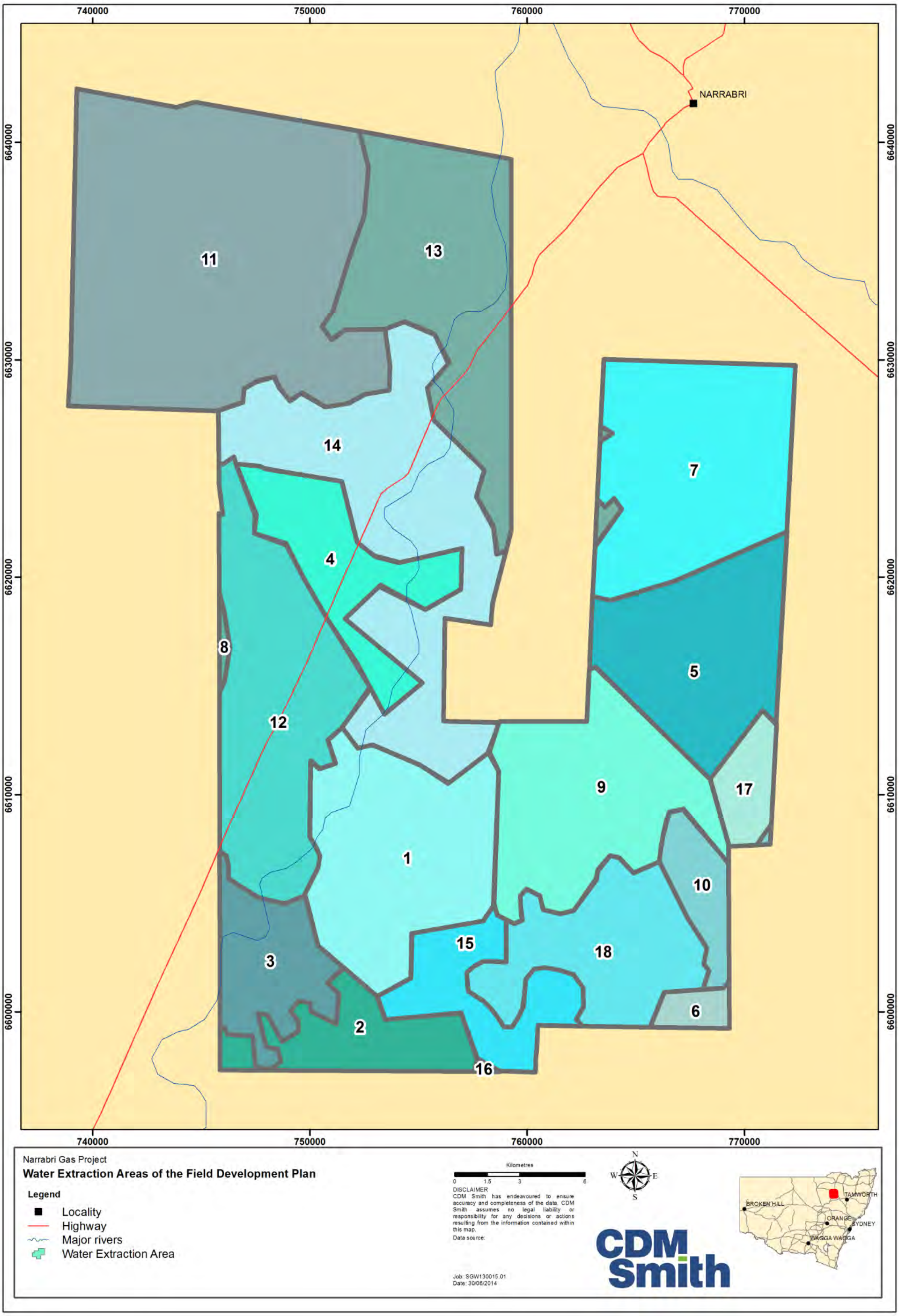


**Figure 6-22 Water extraction areas (WEAs)**

#### 6.8.2.1 Early Permian Coal Seam Gas Targets (Primary Target)

Simulated water production from the Early Permian coal seam targets is shown in Figure 6-23 to Figure 6-25 for the Base Case, Low Case and High Case scenarios, respectively. In the figures, the water production profiles for each of the sixteen WEAs are shown in stacked-area graphs that sum to the total annual rate of water production. Tabulated summaries of the maximum rates and the total volumes of water production for each WEA are also given in Table 6-11 below.

Simulated total water production over the 25-year FDP varies from 35.6 GL for the Low Case scenario up to 82.5 GL for the High Case. The maximum rate of water production in a year varies from 9.3 ML/y in year three for the Low Case scenario up to 19.6 ML/y in year three for the High Case.

Overall, the total simulated water production from Early Permian coal seam targets is approximately 95 percent of the total water production for the project over the 25-year FDP.

**Table 6-11 Summary of simulated water production from Early Permian targets**

| WEA | Base Case | | Low Case | | High Case | |
|---|---|---|---|---|---|---|
| | Maximum Rate, ML/d | Total Volume, GL | Maximum Rate, ML/d | Total Volume, GL | Maximum Rate, ML/d | Total Volume, GL |
| WEA 1 | 6.9 | 5.8 | 6.8 | 5.5 | 9.3 | 13.8 |
| WEA 9 | 4.3 | 4.2 | 4.2 | 4.0 | 7.1 | 10.0 |
| WEA 4 | 3.6 | 2.2 | 3.5 | 2.1 | 4.0 | 5.2 |
| WEA 2 | 4.5 | 3.1 | 4.5 | 2.9 | 6.4 | 7.4 |
| WEA 12 | 2.8 | 4.1 | 2.7 | 3.7 | 5.7 | 9.3 |
| WEA 14 | 2.5 | 2.8 | 2.6 | 2.6 | 4.0 | 6.5 |
| WEA 3 | 1.6 | 1.0 | 1.6 | 0.9 | 1.7 | 2.3 |
| WEA 11 | 2.6 | 3.0 | 2.7 | 2.8 | 4.2 | 6.9 |
| WEA 13 | 1.9 | 2.0 | 1.9 | 1.9 | 3.3 | 4.5 |
| WEA 7 | 2.5 | 2.1 | 2.6 | 2.0 | 3.8 | 4.9 |
| WEA 5 | 2.1 | 2.0 | 2.1 | 1.8 | 3.4 | 4.4 |
| WEA 17 | 0.7 | 0.6 | 0.7 | 0.5 | 1.3 | 1.3 |
| WEA 10 | 1.3 | 1.0 | 1.4 | 0.9 | 1.9 | 2.1 |
| WEA 6 | 0.7 | 0.4 | 0.7 | 0.4 | 0.9 | 0.9 |
| WEA 15 | 0.7 | 0.6 | 0.7 | 0.5 | 1.1 | 1.2 |
| WEA 18 | 1.3 | 0.8 | 1.4 | 0.7 | 1.8 | 1.7 |
| | TOTAL | 35.6 | TOTAL | 33.3 | TOTAL | 82.5 |

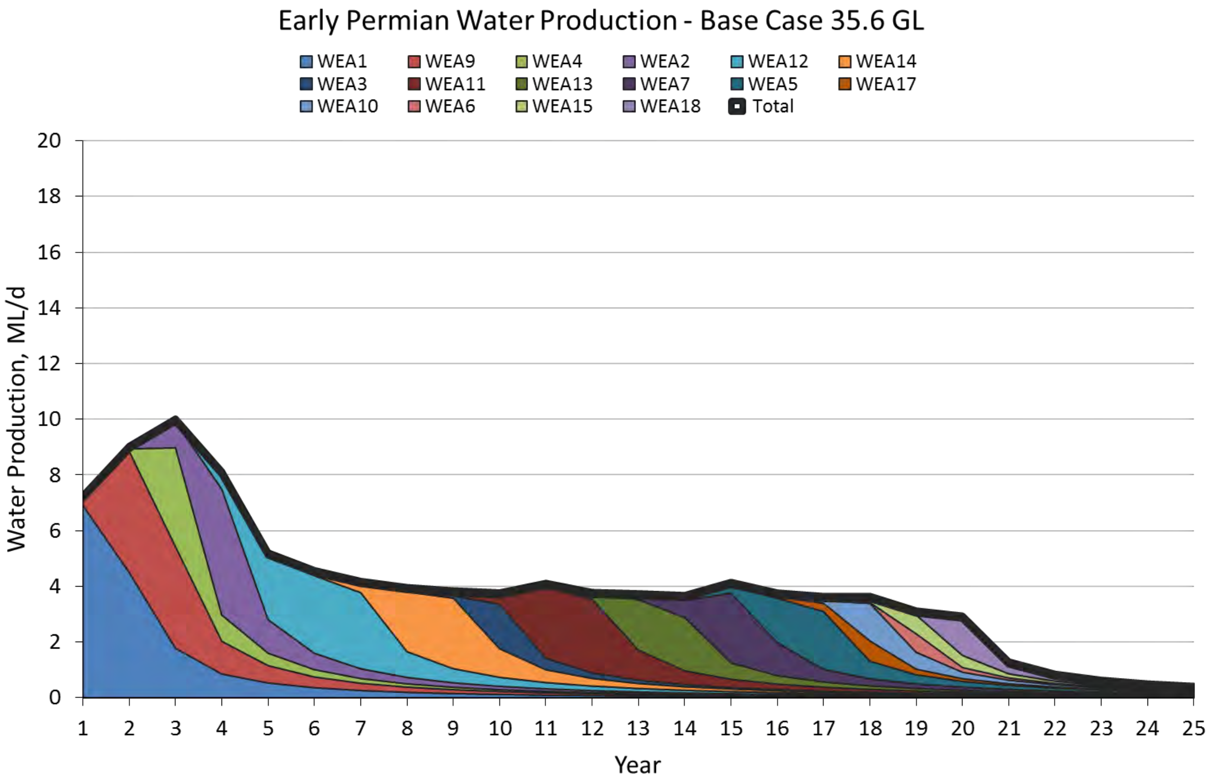


**Figure 6-23 Base Case scenario: simulated water production from Early Permian targets**

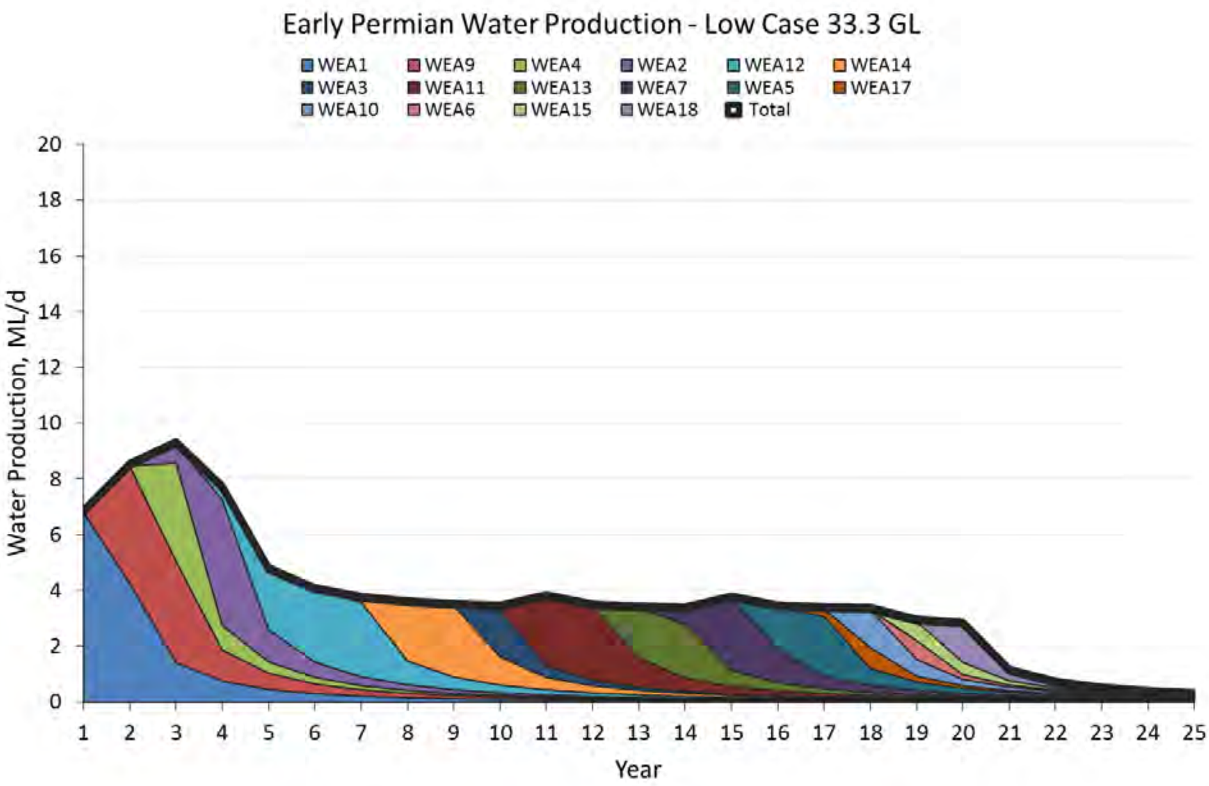


**Figure 6-24 Low Case scenario: simulated water production from Early Permian targets**

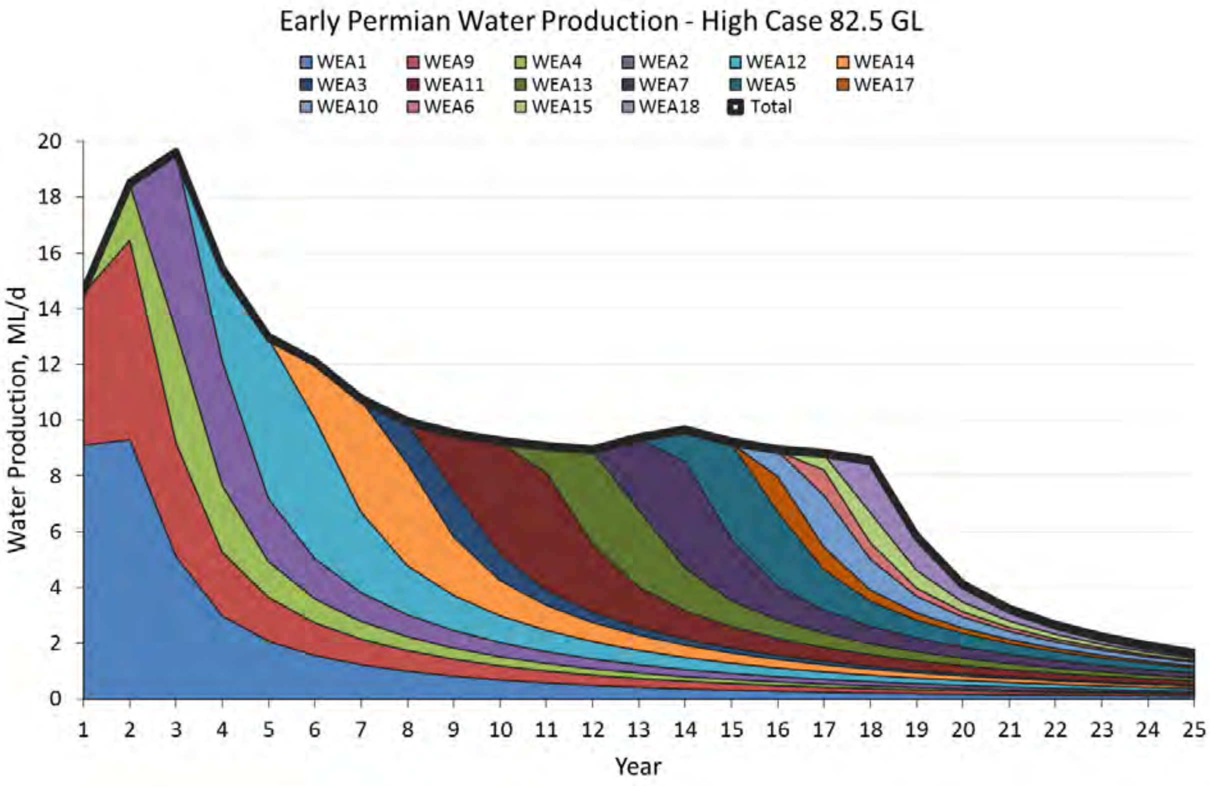


**Figure 6-25 High Case scenario: simulated water production from Early Permian targets**

### 6.8.2.2 Late Permian Coal Seam Gas Targets (Secondary Target)

Simulated water production from the Early Permian coal seam targets is shown in Figure 6-26 to Figure 6-28 for the Base Case, Low Case and High Case scenarios. Tabulated summaries of the maximum rates of water production and water production volumes are also given in Table 6-12.

Simulated total water production from the Late Permian targets over the 25-year FDP varies from 1.75 GL for the Low Case scenario up to 4.63 GL for the High Case. The maximum rate of water production in a year varies from 1 ML/y in year thirteen for the Low Case scenario up to 1.6 ML/y in year thirteen for the High Case.

Overall, the total simulated water production from Late Permian coal seam targets is approximately 5 percent of the total water production for the project over the 25-year FDP.

**Table 6-12 Summary of simulated water production from Late Permian targets**

| WEA | Base Case | | Low Case | | High Case | |
|---|---|---|---|---|---|---|
| | Maximum Rate, ML/d | Total Volume, GL | Maximum Rate, ML/d | Total Volume, GL | Maximum Rate, ML/d | Total Volume, GL |
| WEA 11 | 0.94 | 1.14 | 0.94 | 1.05 | 1.69 | 2.8 |
| WEA 13 | 0.67 | 0.75 | 0.68 | 0.7 | 1.45 | 1.83 |
| | TOTAL | 1.89 | TOTAL | 1.75 | TOTAL | 4.63 |

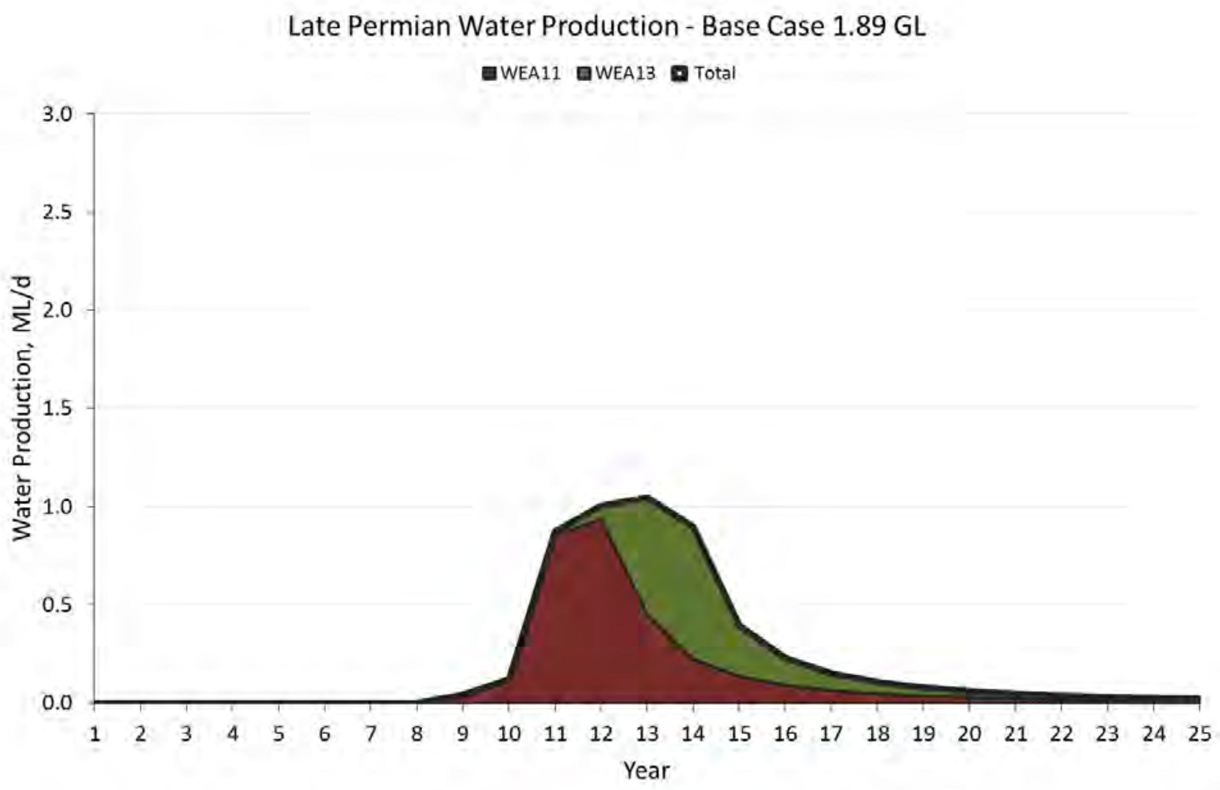


**Figure 6-26 Base Case scenario: simulated water production from Late Permian targets**

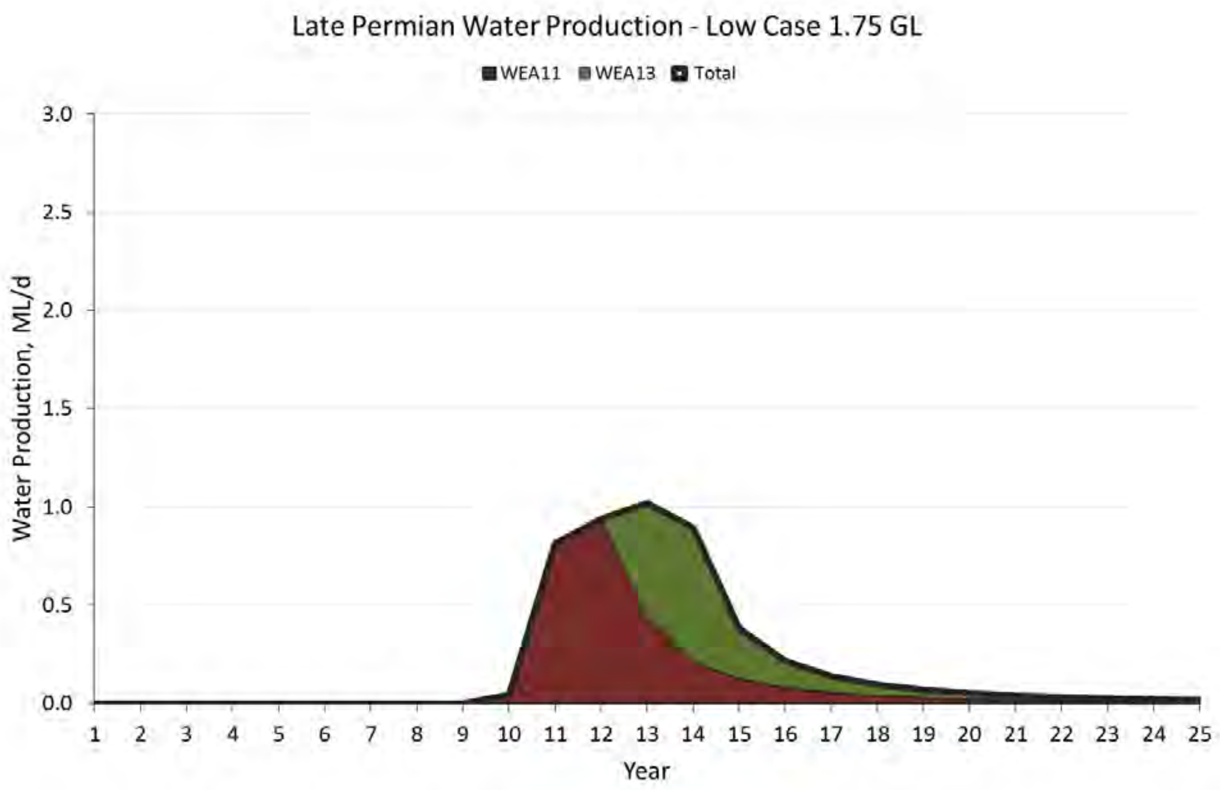


**Figure 6-27 Low Case scenario: simulated water production from Late Permian targets**

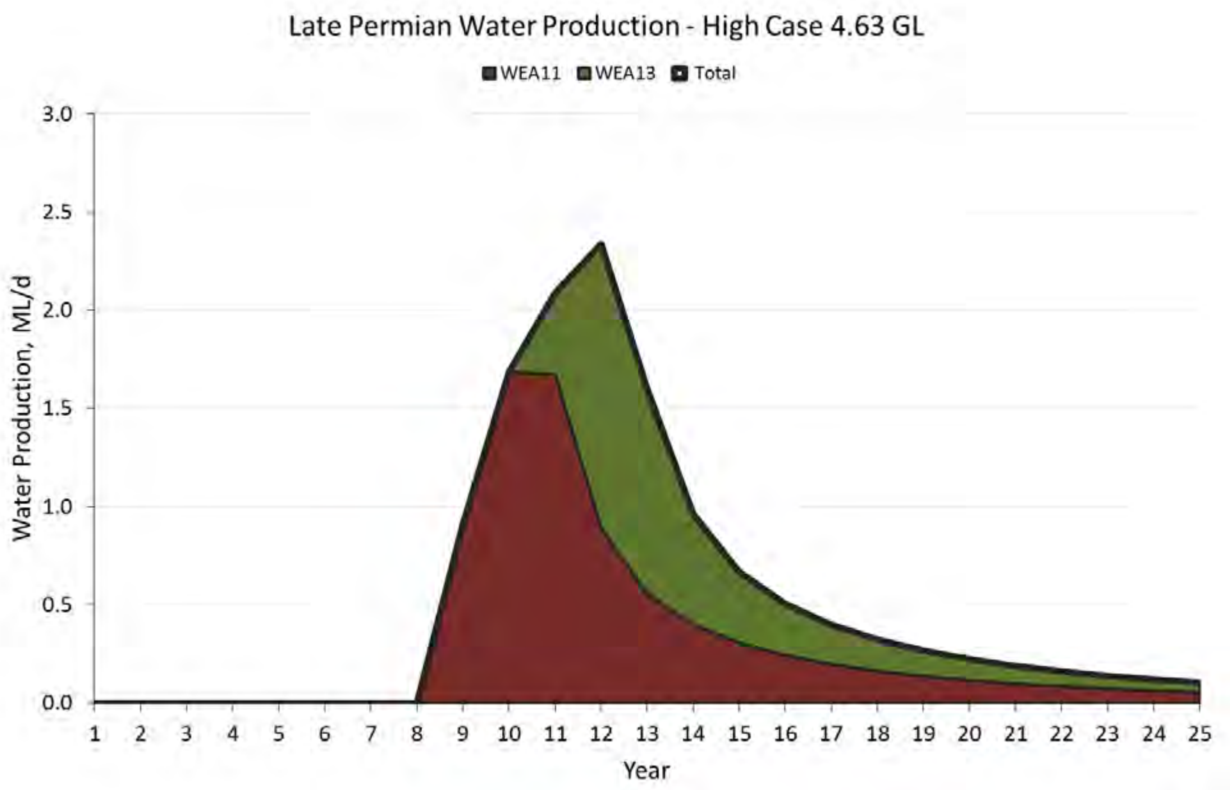


**Figure 6-28 High Case scenario: simulated water production from Late Permian targets**

#### 6.8.2.3 Total Simulated Water Production

The total simulated water production for the Base Case, Low Case and High Case scenarios is derived by summing the water production profiles for the Early and Late Permian targets for each of the WEAs. Graphs showing the resultant water production profiles are presented with the description of the model simulations in section 6.9.

### 6.8.3 Representation of Coal Seam Water Production

In this assessment the simulated rates of water production from the reservoir modelling by Santos are used as inputs to the groundwater modelling. Pumping bores are assigned within the model layers representing the coal seam gas targets and the rates and volumes of extraction from the pumping bores are set equal to the rates and volumes of water production in the reservoir modelling. The model cells from which water is extracted within each WEA can be seen in Figure 6-29. This approach was chosen to achieve consistency of water production between the groundwater modelling and reservoir modelling, and specifically to enable aquifer interference to be assessed based on the inter-formational flows induced by a specified water production profile.

In adopting this approach a choice has been made to exactly simulate the rate and volume of water production from the reservoir modelling in preference to the alternative of allowing the water production to be a result of the groundwater modelling. In the latter case, the water production in the groundwater modelling is independent of constraints on water production that may exist in the reservoir modelling, including the design considerations for pumping, conveying, treating and storing the produced water.

If hydraulic head, rather than flow, was used to specify the boundary conditions for the coal seam gas wells, then the groundwater modelling would generate varying estimates of the water production. This method could give a better match between simulated drawdown in the groundwater modelling and depressurisation in the reservoir modelling but, this improvement would come at the expense of considerable discrepancy in the respective estimates of water production. Strictly speaking, neither approaches for representing coal seam gas wells in groundwater models is ideal, and neither approach can achieve complete consistency with the reservoir modelling for both water production and drawdown. This difference occurs because the current generation of groundwater models and reservoir models are based on different physical processes and assumptions, different model boundaries and boundary conditions, and different spatial extents and scales.

When pumping bores are used to represent the simulated water production, such as in this assessment, the drawdowns predicted in the model cells containing those wells are expected to be smaller than the drawdowns needed to activate gas flow in the coal seam gas wells. This difference occurs because the simulated drawdowns at the pumping bores are averages over the areas of the model cells in which they reside. For example, in this assessment the volumetric rates of simulated water production and the resultant drawdowns at the coal seam gas wells are averages over the minimum cell area of 1 $km^2$.

Experience using regional groundwater models to predict potential impacts of coal seam gas development has shown that when the alternate approach of specifying hydraulic head in the coal seam targets is used, with head set equal to the depressurisation targets needed to produce gas, the simulated water production is substantially over estimated compared to the reservoir modelling. This excess of water production in the groundwater modelling often occurs because hydraulic head over the entire model cell must be lowered to the target pressure for coal seam gas production. In such cases, it may be more appropriate to specify a modified drawdown target for hydraulic head at the coal seam gas wells to reflect an average drawdown over the entire model cell.

In addition to a lack of local grid detail in regional groundwater models, the mechanisms for simulating the release of water from formation storage in the groundwater modelling are simplified compared to the reservoir modelling. In particular, dual-phase flow of gas and water, and desaturation and draining of pore space within the target coal seams are not simulated processes in the groundwater modelling. In contrast, reservoir models tend ignore, or neglect as being very minor, the leakage of water into the target coal seams from surrounding formations following depressurisation. Thus, the reservoir models infer that there are no impacts on hydraulic head outside of the target coal seams.

The inability to achieve consistency of both simulated water production and drawdown in reservoir models and regional groundwater flow models requires a choice in the groundwater modelling to either match fluxes or heads at the coal seam gas wells. In this assessment it is argued that a fundamental requirement of the groundwater modelling should be consistency of water production at the expense of loss of local detail in short-term drawdown at the coal seam gas wells. Over the long periods of time required for hydraulic head at the wells to recover (i.e. after water production ceases) it is further argued that longer-term patterns of drawdown in the groundwater modelling, particularly in strata overlying the coal seam targets, are likely to be reasonable representations of the distribution of drawdown expected after the localised impacts at the coal seam gas wells have dissipated. Pursuing this approach also ensures that accurate water accounting and water-balance checking can be conducted as part of the groundwater modelling, since the simulated extraction, the induced changes in groundwater storage, and the induced transfers of groundwater between water sources must add to the total simulated water production.

### 6.8.4 Stress Period Setup

A summary of the stress periods used for the predictive simulations can be seen in Table 6-13. A total of 47 stress period are used to represent the following periods:

- A pre-production period of 1 year (1997); to provide a check of the initial conditions;
- A 19-year period (1998 to 2016) of historical water production from gas pilots within the Gunnedah Basin; consisting of 19 stress periods of 1 year each;
- A 25-year period (2017 to 2041) of future water production based on the 25-year FDP; consisting of 25 stress periods of 1 year each; and
- A 1475-year period (2042 to 3517) of post-water production recovery; consisting of one stress period of 75 years, and a final stress period of 1400 years.

The minimum and maximum time step lengths during the production periods are approximately 59 days and 130 days, respectively. The minimum and maximum time step lengths during the recovery period are approximately 129 days and 3652 days, respectively.

The 1475-year recovery period ends 1500 years after the start of the 25-year FDP.

**Table 6-13 Stress periods for predictive simulations**

| Stress Period Number | Stress Period Length, y | Elasped Time, y | Time Steps Per Stress Period | Time Step Multiplier | Comment |
|---|---|---|---|---|---|
| 1 | 1 | 0 - 1 | 1 | 1 | Pre-production period |
| 2 - 20 | 1 | 2 – 20.5 | 4 | 1.3 | Historical water production |
| 21 - 45 | 1 | 21.5 – 45.5 | 4 | 1.3 | Future water production |
| 46 | 75 | 46.5 – 120.5 | 25 | 1.15 | Recovery period |
| 47 | 1400 | 121.5 – 1520.5 | 140 | 1 | Continuation of recovery period |

### 6.8.5 Initial Conditions

Initial conditions for all of the predictive simulations are generated from steady state model simulations. Within the area of the Namoi alluvium, the initial heads from the steady state simulations closely match the interpolated water table contours due to the inverse modelling method used to estimate the net recharge fluxes in the alluvium (Section 6.5.2).

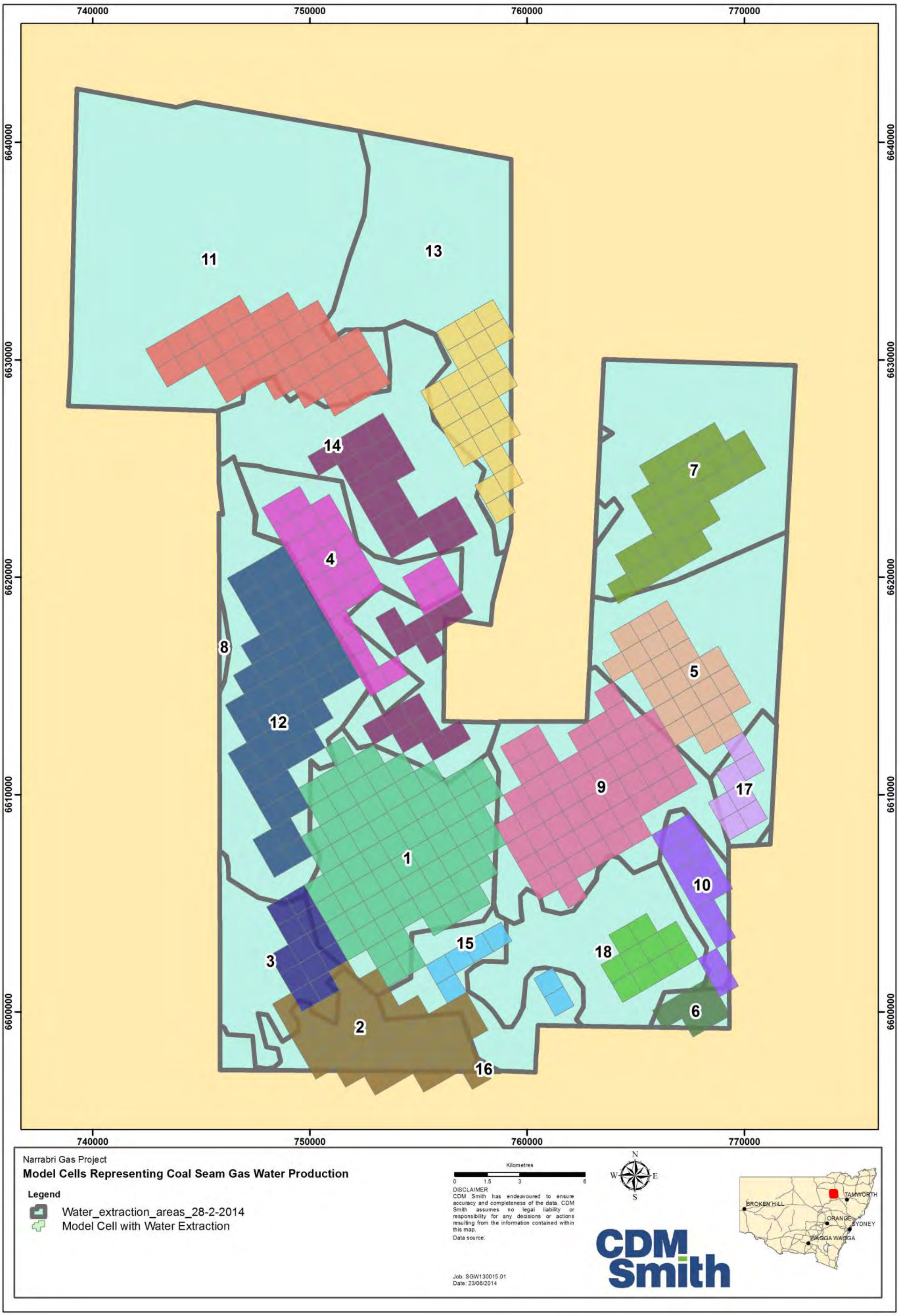


**Figure 6-29 Model cells representing coal seam simulated water production**

### 6.8.6 Recovery Mechanisms after Cessation of Coal Seam Gas Production

To simulate recovery of groundwater storage after coal seam gas production ceases the numerical groundwater model must include processes by which inflow and outflow from the model domain can vary in response to change in hydraulic head induced by depressurisation of the target coal seams. In general, this can happen where head-dependent boundary conditions are used. The following mechanisms for recovery of groundwater storage are incorporated into the predictive simulations in this assessment:

- **A decrease in evapotranspiration**; in model cells in which the water table elevation is above the evapotranspiration extinction depth (5 m) the rate of evapotranspiration is dependent on the water table elevation and can vary during transient simulations. Drawdown of the water table that is induced by simulated coal seam water production will decrease the evapotranspiration rate and thereby reduce the net outflow from the model in these cells.

- **An increase in recharge or a decrease in discharge to rivers**; potential for head-dependent variation of river recharge exists in river cells with water table elevation above the river bottom elevation (i.e., connected river reaches). Drawdown of the water table elevation in response to simulated coal seam water production will increase the recharge rate in losing sections or decrease the discharge rate in gaining section, thereby increasing net inflow or decreasing net outflow from the model in these cells.

- **A decrease of outflow at model boundaries**; if drawdown of hydraulic head extends to the regional model boundaries where fixed head boundary conditions are assigned then the rate of outflow from the model in these cells will decrease.

It follows from these considerations that the predicted rate of recovery of hydraulic head and storage in the model simulations will be most influenced by the model parameters that control the timing and distribution of depressurisation. For example, an increase in the horizontal hydraulic conductivity would provide more opportunity for depressurisation to reach the model boundary, whereas an increase in the vertical hydraulic conductivity would provide more opportunity for depressurisation to reach the water table.

### 6.8.7 Water Sharing Plan Reporting Areas (WSPRAs)

Table 6-14 identifies 21 areas that are used as the basis for reporting the simulated inter-formation flows between recognised groundwater sources. The extents of these areas are based on the groundwater source areas defined in four water sharing plans that cover the model area. Maps of the water sharing plan reporting areas (WSPRAs) used in this assessment are shown in Figure 6-30. A brief description of each is given below.

The Lower Namoi alluvium (Upper and Lower Namoi Groundwater Sources 2003) is divided into two WSPRAs representing vertical groundwater flux from the base of the alluvium to the Southern Recharge Groundwater Source and Surat Groundwater Source (NSW Great Artesian Basin Groundwater Sources 2008).

The Upper Namoi alluvium is southeast of the Lower Namoi alluvium and overlies the Gunnedah-Oxley Basin groundwater source (NSW Murray Darling Basin Porous Rock Groundwater Sources 2011). The Upper Namoi alluvium is sub-divided into eleven WSPRAs representing vertical groundwater flux from the base of the alluvium within the eleven Groundwater Management Area (GMA) zones located within the groundwater model domain.

**Table 6-14 Water Sharing Plan reporting areas (WSPRAs)**

| Water Sharing Plan | Groundwater Source | WSPRA | Description |
|---|---|---|---|
| Upper and Lower Namoi (2003) | Lower Namoi | 1<br>2 | Flux from base of alluvium to GAB Surat<br>Flux from base of alluvium to GAB Southern Recharge |
| | Upper Namoi | 3<br>4<br>5<br>6<br>7<br>8<br>9<br>10<br>11<br>12<br>13 | Flux from base of alluvium to GOB in GMA zone 1<br>" " " " GMA zone 2<br>" " " " GMA zone 3<br>" " " " GMA zone 4<br>" " " " GMA zone 5<br>" " " " GMA zone 6<br>" " " " GMA zone 7<br>" " " " GMA zone 8<br>" " " " GMA zone 9<br>" " " " GMA zone 10<br>" " " " GMA zone 11 |
| NSW MDB Fractured Rock (2011) | Liverpool Ranges Basalt | 14<br>15 | Base of basalt to Oxley Basin<br>Base of basalt to Gunnedah Basin |
| | Warrumbungle Basalt | 16 | Base of basalt to GAB Southern Recharge |
| NSW MDB Porous Rock (2011) | Gunnedah-Oxley Basin | 17<br>18<br>19 | Oxley Basin to Late Permian coal seam targets<br>Gunnedah Basin to Late Permian coal seam targets<br>Gunnedah Basin to Early Permian coal seam targets |
| NSW Great Artesian Basin (2008) | Southern Recharge | 20 | GAB Southern Recharge to Gunnedah Basin |
| | Surat | 21 | GAB Surat to Gunnedah Basin |

GAB – Great Artesian Basin, GOB – Gunnedah-Oxley Basin

WSPRAs 14 and 15 define the area of vertical groundwater flux from the base of the Liverpool Ranges Basalt groundwater source (NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011) to the Gunnedah-Oxley Basin groundwater source. These two WSPRAs represent the respective subcrop areas of the Oxley Basin and Gunnedah Basin.

WSPRA 16 defines the area of vertical groundwater flux from the base of the Warrumbungle Basalt groundwater source (NSW Murray Darling Basin Fractured Rock Groundwater Sources 2011) to the Surat groundwater source.

WSPRAs 17 and 18 define the area of vertical groundwater flux from the Gunnedah-Oxley Basin to the Late Permian coal seam targets from above. WSPRA 17 corresponds to the areal projection of the Oxley Basin onto the Late Permian targets and WSPRA 18 corresponds to the areal projection of the Gunnedah Basin onto the Late Permian targets.

WSPRA 19 defines the area of vertical groundwater flux from the Gunnedah-Oxley Basin to the Early Permian coal seam targets from above.

WSPRAs 20 and 21 define the area of vertical groundwater flux from the base of the Pilliga Sandstone, and provide an approximation of vertical groundwater flux from the Southern Recharge and Surat Groundwater Sources to the Gunnedah-Oxley Basin groundwater source.

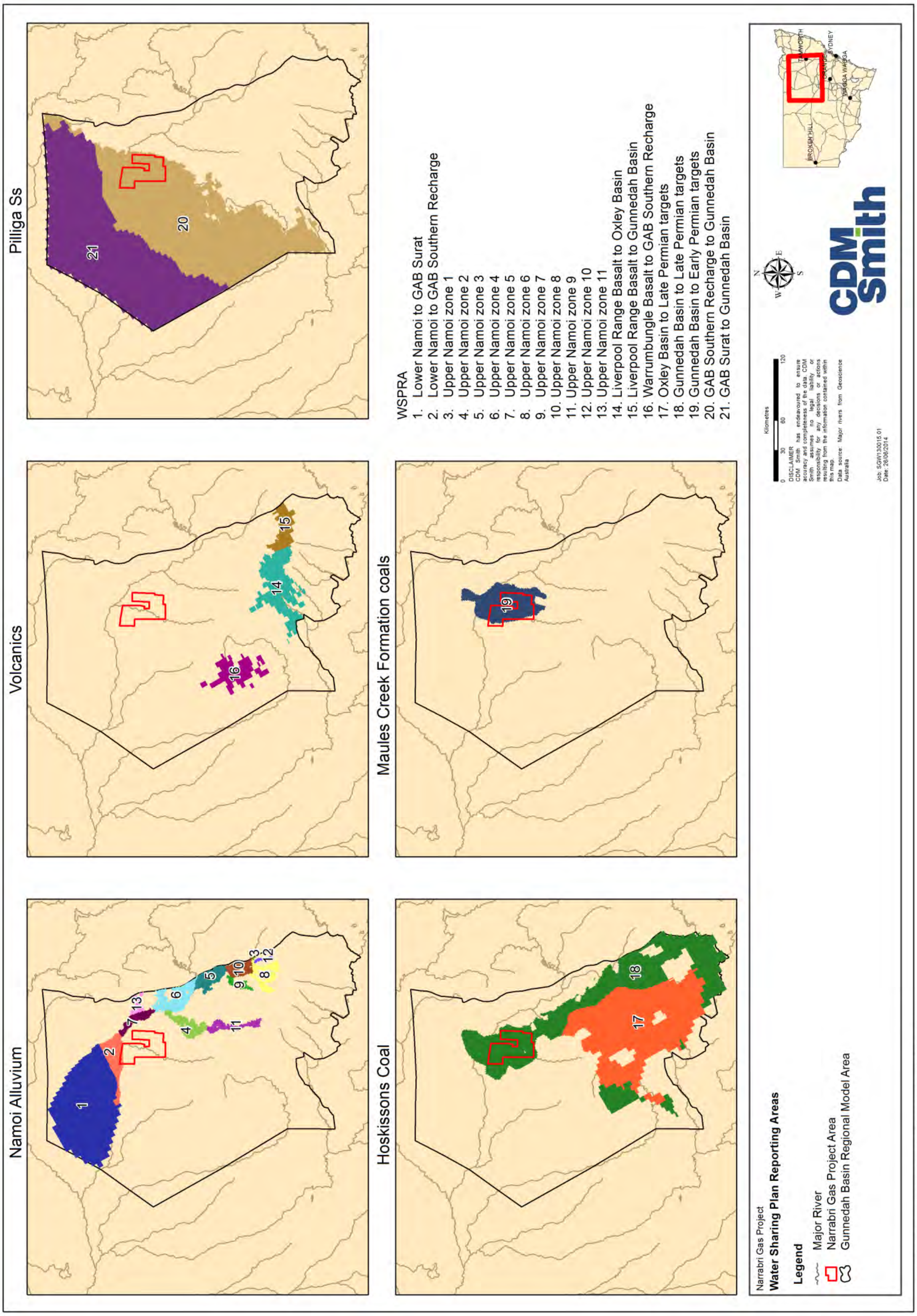


**Figure 6-30 Water Sharing Plan Reporting areas (WSPRA)**

### 6.8.8 Model convergence and Mass Balance

The head convergence criterion of the PCG5 solver package is set equal to 0.001 m for all transient predictive simulations in this assessment. The reported cumulative mass balance errors are less than 0.01%.

Total water extraction in each simulation is checked and confirmed against the simulated water production profiles to ensure that the correct pumping schedules are used.

Standard time stepping is used with variable time step multipliers. During the period of historical and future water production the model time steps vary from a minimum time step of approximately 59 days to a maximum time step of approximately 130 days. During the 1475-year recovery period the model time steps vary from a minimum of approximately 129 days to a maximum of 3652 days (10 years).

### 6.8.9 Modelling Outputs and Visualisation of Results

An effort has been made to produce outputs from the groundwater modelling—in the form of tables, maps and figures—that directly support the objectives of the GIA. It is possible that some of the outputs will be unfamiliar and therefore a brief description of each type of output is given in Table 7 2 below. These outputs appear in the results section (Section 6.9) of this report

**Table 6-15 Modelling outputs**

| Output Type | Title | Description |
|---|---|---|
| Tables | Summary of maximum predicted drawdown | A summary of maximum drawdown of hydraulic head and maximum drawdown of water table elevation. The reported values include **largest drawdown at any location**, which represents the largest value of drawdown within the hydrostratigraphic unit (HSU) at a location and over the entire simulation period, and **time to reach maximum drawdown**, which is the time range (to the nearest model time step) during which maximum drawdown occurs somewhere within the HSU. |
| | Summary of WSPRA groundwater fluxes | A summary of the rate of groundwater flux across the base of each WSPRA to the underlying WSPRA. The **initial flow rate** is the value of the flow rate prior to coal seam water production commencing and corresponding to the model initial conditions. The **maximum change in flow rate** represents the largest deviation of the flow rate from the initial value due to coal seam water production. The time of maximum change in flow rate is the time (to the nearest model time step) when this occurs. The **volume exchange due to coal seam water production** is the total volume of groundwater exchanged from one WSPRA to another during the entire simulation period as a result of coal seam water production. These do not sum to the total simulated water production. |
| | Induced storage releases (net takes) from WSP groundwater sources due to coal seam water production | A listing of the induced rates of storage release (net induced take of groundwater) due to coal seam water production from groundwater sources defined in NSW water sharing plans, at the time steps of the model simulation. |
| Bar charts | Maximum change in flow rates between WSPRAs | Plotted values of **maximum change in flow rate** from the base of each WSPRA to the underlying WSPRAs (from above Tables). |
| | Total volumetric exchange between WSPRAs | Plotted values of the **volume exchange due to coal seam water production** from the base of each WSPRA to the underlying WSPRAs (from above Tables). |

| Output Type | Title | Description |
|---|---|---|
| Time series graphs | Induced storage releases (net take) from WSP groundwater sources due to coal seam water production | Time variation of the induced rates of storage release (net induced take of groundwater) due to coal seam water production from groundwater sources defined in NSW water sharing plans. Note split scale of ordinate axis. |
| | Time variation of flow rates between WSPRAs | Time variation of the rate of groundwater flux across the base of each WSPRA to the underlying WSPRAs. The **flow rate** curve indicates the absolute value of flux. The **change in flow rate** curve represents the change in flux due to coal seam water production. |
| Sankey diagram | Total volumetric contributions to coal seam water production | Volumetric contributions to total coal seam water production from each of the six WSP groundwater sources at the end of the simulation period; representing the additional recharge and/or reduced discharge from each groundwater source in response to coal seam water production. Summed inputs equal summed outputs if full recovery to steady state has occurred before the end of the simulation. |
| Maps | Maximum predicted drawdown | Contours of maximum drawdown of hydraulic head; representing the maximum values of drawdown at any time during the model simulation. The time at which the maximum drawdown occurs at each location (model cell) is symbolised by colour. The combination of contour lines and colours display the largest value of drawdown at all locations and the time (to the nearest model time step) when this happens. |

## 6.9 Potential Groundwater Impacts

This section presents the results of the predictive simulations listed in Table 6-16, which all uses the adopted estimates of hydrogeological properties in Table 6-7.

The first simulation considers the potential impacts of the Base Case (BC) simulated water production in isolation from other existing and proposed developments in the Gunnedah Basin.

The second and third simulations consider the potential impacts of the Low Case (LC) and High Case (HC) simulated water production.

The fourth and fifth simulations considers the potential cumulative impacts of the Narrabri Coal Mine Stage 2 Longwall Project and the Base Case simulation of water production (denoted NCM-BC) as well as the potential impacts of isolated development of the Stage 2 Longwall Project (denoted NCM).

**Table 6-16 Model simulations**

| Short Name | Groundwater Stresses | Period of Simulation |
|---|---|---|
| BC | The water production profile that is being used as the base case for the project construction and design concept | 1997 to 3517 (1520 y) |
| LC | A forecast of water production that is based on a lower than expected value of porosity in the target coal seams, resulting in a lower than expected estimate of water production | |
| HC | A forecast of water production that is based on a higher than expected value of porosity in the target coal seams, resulting in a higher than expected estimate of water production | |
| NCM-BC | Narrabri Mine Stage 2 Longwall Project and Base Case simulated water production profile | |
| NCM | Narrabri Mine Stage 2 Longwall Project | |

### 6.9.1 Base Case Simulated Water Production

This simulation considers the potential impacts of the Base Case (BC) simulated water production profile described in Section 6.8.2 and uses the adopted hydrogeological properties in Table 6-7. The simulated water production profile is shown in Figure 6-31 and includes the following stresses to groundwater:

- Historical water production from the existing twelve gas pilots within the Gunnedah Basin, commencing in 1998 (approximately 1 GL);
- Base Case simulated future water production from the Early Permian coal seam targets, commencing in in July 2017 and ceasing after June 2042 (35.6 GL); and
- Base Case simulated future water production from the Late Permian coal seam gas targets, commencing in July 2027 and ceasing after June 2042 (1.89 GL).

Total water production for this simulation consists of 1 GL historical extraction and 37.5 GL future extraction. There are no stresses to groundwater in year one of the simulation. The period of historical water production is approximately 18 years. The simulated FDP spans a period of 25 years and the recovery period spans 1475 years after the FDP ceases. The total simulation period is 1520.5 years.

Results for this simulation are summarised in Table 6-17 to Table 6-19 and Figure 6-32 to Figure 6-38. Explanation of these tables and figure is provided in Table 6-15 of Section 6.8.9.

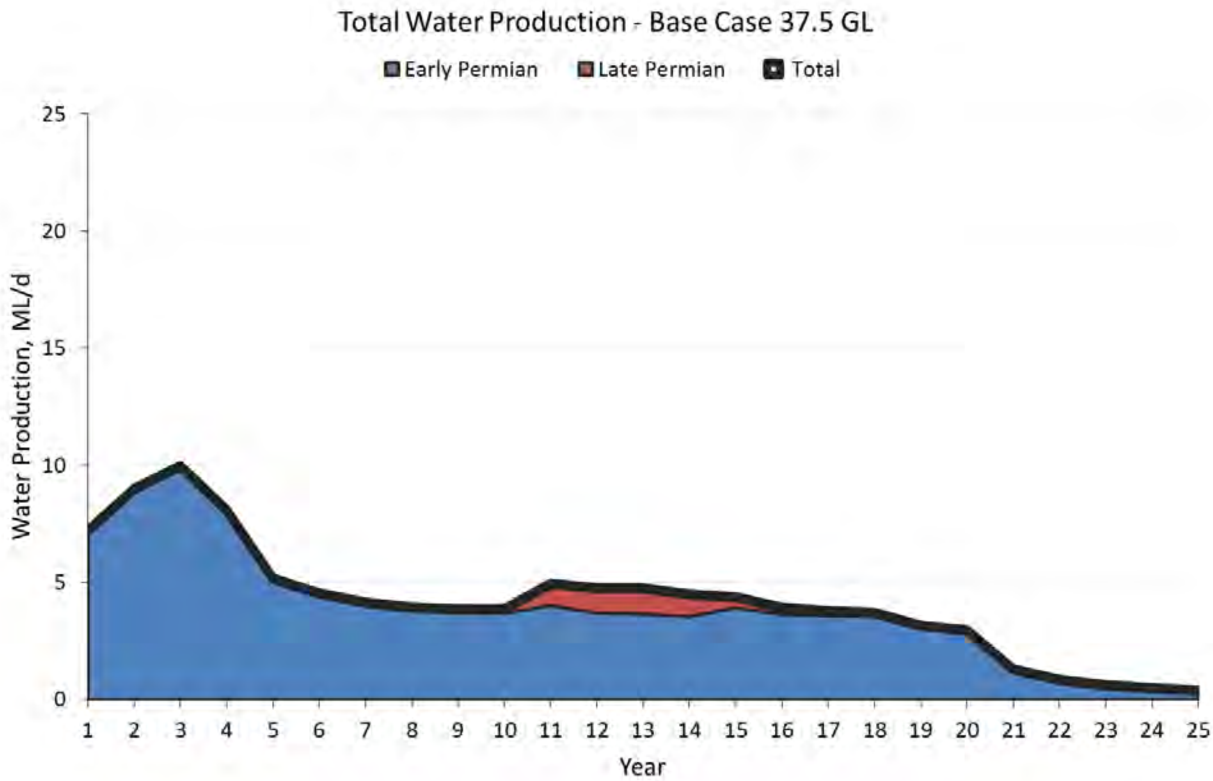


**Figure 6-31 Base Case (BC) simulated future water production over the 25-y field development plan**

#### 6.9.1.1 Predicted Impacts

- In the Early Permian targets the largest value of maximum predicted drawdown within a model cell (i.e. the predicted averaged drawdown over a 1 km × 1 km area surrounding the gas well) is 153 m., which is approximately one-sixth the amount of depressurisation required locally at the well to produce gas (Figure 6-35); noting that the quantity of water removed in the scenario is consistent with the simulated water production profile. Within the Late Permian targets the largest value of maximum predicted drawdown in a model cell is approximately 16.4 m (Figure 6-36); noting again that the quantity of water removed is consistent with the water production profile. It is recognised that the model predicts in the order of 150 m of drawdown, whilst the depressurisation required to yield coal seam gas is likely to be significantly greater. This is considered to be due to the leaky characteristics of the groundwater flow model in contrast to the less leaky dual phase reservoir models used in the derivation of the water production profiles. Leakage of groundwater into the target coal seams is considered to be a conservative feature of the groundwater flow modelling because the leakage is associated with faster migration of depressurisation into bounding formations, both laterally and vertically.
- Centrally within the project area, the maximum predicted drawdown in Early Permian coal seam targets is contemporary with the 25 year FDP; however, it can be seen that maximum drawdowns occur much later around the extremities of the zone of drawdown. The predicted time difference between maximum drawdown at the centre and margins of the zone of drawdown is up to 300 years (to the nearest model time step difference of ten years) (Section 6.8.4). This effect is due to ongoing lateral flow of groundwater toward the central area of drawdown within the targets coal seams long after the FDP ceases. The hydraulic gradient toward the depressurised zone is maintained after coal seam gas production ceases and until full recovery of drawdown occurs.
- Within Late Permian coal seam targets the maximum drawdown due to simulated water production in WEAs 11 and 13, as well as vertical propagation of drawdown from the Early Permian targets, is predicted to occur less than 25 years after commencement of the FDP. Elsewhere, delayed vertical propagation of drawdown from the Early Permian targets results in predicted maximum drawdown occurring at 25 to 300 years after commencement of the FDP.
- In the GAB , the maximum predicted drawdown in the Pilliga Sandstone is less than 0.5 m (Figure 6-37).
- At the water table the largest value of maximum predicted drawdown in a model cell is less than 0.5 m, including the area of the Namoi alluvium (Figure 6-38). The predicted downward flow of groundwater from the alluvium into underlying depressurised units is small and occurs very gradually; this small extra demand is easily met by lateral groundwater flow within the alluvium.
- The maximum predicted change in groundwater flow rate between WSPRAs is 1.52 GL/y (48 L/s) from the Gunnedah Basin to the Early Permian coal seam targets (WSPRA 19) (Figure 6-32). This maximum occurs at approximately 3 years after the start of the FDP. The maximum predicted change in flow rate between the Gunnedah Basin and Late Permian targets (WSPRA 18) is 0.17 GL/y (5.4 L/s) occurring approximately 13 years after the start of the FDP. Predicted impacts on the GAB are minor with maximum predicted change in flow rate between the GAB Southern Recharge Area and Gunnedah Basin (WSPRA 20) of 0.06 GL/y (1.8 L/s) at approximately 190 years after the start of the FDP. Changes in the rates of groundwater flow between other WSPRAs are predicted to be less than or equal to 0.01 GL/y (0.3 L/s). Thus, the induced groundwater flow at the base of the Namoi alluvium is predicted to be negligible

compared to the existing estimates of total recharge and extraction in the alluvium, which are order-of-magnitude 100 GL/y.

- The majority of the produced water is predicted to come from induced storage release in the Gunnedah-Oxley Basin and GAB, and a small contribution from the Lower Namoi Alluvium (Figure 6-33). Predicted maximum rate of storage release of 2.9 GL/y from the Gunnedah-Oxley Basin occurs at around 3 years after the start of the FDP, and the predicted maximum rate of storage release of 0.1 GL/y from the GAB occurs at approximately 190 years after the start of the FDP. Predicted maximum storage release from the Lower Namoi Alluvium is approximately 0.05 GL/y. From around 40 years the predicted flow from the Gunnedah-Oxley Basin to the coal seam gas targets is approximately matched by flow from the GAB and Lower Namoi Alluvium to the Gunnedah-Oxley Basin. Very small predicted storage changes of less than 0.002 GL/y (0.06 L/s) at the end of the simulation indicate that full recovery to pre-development conditions is not quite achieved 1500 years after the start of the FDP.

- In general the simulated groundwater fluxes from the shallow groundwater sources are very small because the water transfers take place over a long period of time. For example, the total simulated water production of 37.5 GL is equivalent to a groundwater recharge rate of 0.026 mm/y over the 950 km$^2$ project area for the duration of the FDP and 1475-year recovery period (equivalent to 2.6 mm every 100 years).

- At the end of the recovery period (1500 years after the start of the FDP) the predicted contributions to the total simulated water production of 38.5 GL are approximately: 28.6 GL (74.4%) from the GAB; 5.9 GL (15.4%) from the Gunnedah-Oxley Basin; 3.3 GL (8.6%) from the Lower Namoi Alluvium and 0.6 GL (less than 2%) from the Upper Namoi Alluvium (Figure 6-34). These amounts are counter balanced by matching additional inflow and reduced outflow in each of the groundwater source areas over the period of the simulation. Since net recharge fluxes to the Lower Namoi Alluvium are fixed and the river is disconnected in this region, the contribution to total simulated water production from the Lower Namoi Alluvium (WSPRA 2) is counter balanced by increased lateral inflow to the alluvium. In the Upper Namoi Alluvium (WSPRAs 4 and 7) the river is connected and the contribution to total simulated water production is counter balanced by increased leakage from the river and increased lateral inflow. Outside of the alluvium, the contributions to total simulated water production from the GAB and Gunnedah-Oxley Basin are counter balanced by reduced evapotranspiration at the water table.

**Table 6-17 Simulation BC: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | < 0.5 | - |
| Pilliga Sandstone | < 0.5 | - |
| Late Permian Targets | 16.4 | Pre-FDP to 300 |
| Early Permian Targets | 153 | 1 to 300 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-18 Simulation BC: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | 0.00 | N |
| 2 | -1.26 | 0.01 | - | 3.30 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.15 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 0.48 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.00 | N |
| 18 | -0.14 | 0.17 | 13 | 31.71 | Y |
| 19 | 0.00 | 1.52 | 3 | 35.31 | Y |
| 20 | 0.89 | 0.06 | 190 | 31.84 | Y |
| 21 | -0.08 | 0.00 | - | 0.10 | N |

[1]Years since start of FDP

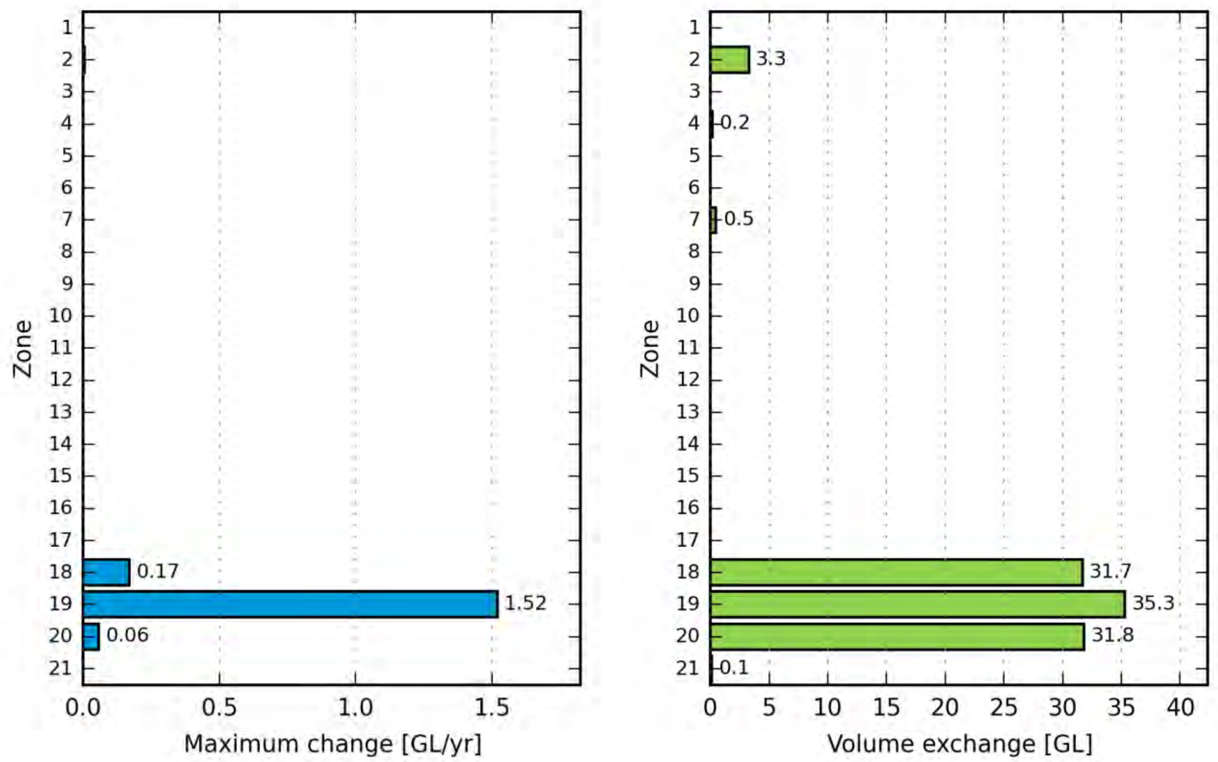


**Figure 6-32 Simulation BC: (a) maximum predicted change in WSPRA flow rates and (b) total predicted volumetric exchange between WSPRAs (from Table 6-18)**

**Table 6-19 Simulation BC: predicted rates of induced storage release (net induced take) from WSP groundwater sources**

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 1 | 1932 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2457 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 2909 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2605 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1889 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1643 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1472 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1291 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 1240 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 1252 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 1506 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 1467 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1352 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 1305 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 1391 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 1236 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 1179 | 1 | 0 | 0 | 0 | 0 | 0 |
| 18 | 1166 | 1 | 0 | 0 | 0 | 0 | 0 |
| 19 | 1053 | 1 | 0 | 0 | 0 | 0 | 0 |
| 20 | 981 | 1 | 0 | 0 | 0 | 0 | 0 |
| 21 | 519 | 2 | 0 | 0 | 0 | 0 | 0 |
| 22 | 350 | 2 | 0 | 0 | 0 | 0 | 0 |
| 23 | 257 | 2 | 0 | 0 | 0 | 0 | 0 |
| 24 | 198 | 2 | 0 | 0 | 0 | 0 | 0 |
| 25 | 157 | 3 | 0 | 0 | 0 | 0 | 0 |
| 25 | 89 | 3 | 0 | 0 | 0 | 0 | 0 |
| 26 | 65 | 3 | 0 | 0 | 0 | 0 | 0 |
| 26 | 52 | 3 | 0 | 0 | 0 | 0 | 0 |
| 27 | 42 | 3 | 0 | 0 | 0 | 0 | 0 |
| 27 | 35 | 3 | 0 | 0 | 0 | 0 | 0 |
| 28 | 28 | 4 | 0 | 0 | 0 | 0 | 0 |
| 29 | 22 | 4 | 0 | 0 | 0 | 0 | 0 |
| 30 | 17 | 4 | 0 | 0 | 0 | 0 | 0 |
| 31 | 12 | 5 | 0 | 0 | 0 | 0 | 0 |
| 32 | 7 | 5 | 0 | 0 | 0 | 0 | 0 |
| 34 | 4 | 6 | 0 | 0 | 0 | 0 | 0 |
| 35 | 0 | 6 | 0 | 0 | 0 | 0 | 0 |
| 37 | -2 | 7 | 0 | 0 | 0 | 0 | 0 |
| 39 | -5 | 8 | 0 | 0 | 0 | 0 | 0 |
| 42 | -7 | 9 | 0 | 1 | 0 | 0 | 0 |
| 45 | -8 | 11 | 0 | 1 | 0 | 0 | 0 |
| 48 | -10 | 12 | 0 | 1 | 0 | 0 | 0 |
| 52 | -11 | 15 | 0 | 1 | 0 | 0 | 0 |
| 56 | -13 | 17 | 0 | 1 | 0 | 0 | 0 |
| 61 | -15 | 20 | 0 | 1 | 0 | 0 | 0 |
| 67 | -18 | 23 | 0 | 1 | 0 | 0 | 0 |
| 74 | -21 | 27 | 0 | 2 | 0 | 0 | 0 |
| 81 | -24 | 31 | 0 | 2 | 0 | 0 | 0 |
| 90 | -28 | 35 | 0 | 2 | 0 | 0 | 0 |
| 100 | -32 | 39 | 0 | 3 | 0 | 0 | 0 |

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 110 | -36 | 42 | 0 | 3 | 1 | 0 | 0 |
| 120 | -39 | 45 | 0 | 3 | 1 | 0 | 0 |
| 130 | -42 | 47 | 0 | 4 | 1 | 0 | 0 |
| 140 | -44 | 49 | 0 | 4 | 1 | 0 | 0 |
| 150 | -46 | 50 | 0 | 4 | 1 | 0 | 0 |
| 160 | -47 | 51 | 0 | 4 | 1 | 0 | 0 |
| 170 | -48 | 52 | 0 | 5 | 1 | 0 | 0 |
| 180 | -49 | 52 | 0 | 5 | 1 | 0 | 0 |
| 190 | -49 | 52 | 0 | 5 | 1 | 0 | 0 |
| 200 | -50 | 52 | 0 | 5 | 1 | 0 | 0 |
| 250 | -48 | 50 | 0 | 5 | 1 | 0 | 0 |
| 300 | -45 | 45 | 0 | 5 | 1 | 0 | 0 |
| 350 | -41 | 41 | 0 | 5 | 1 | 0 | 0 |
| 400 | -37 | 36 | 0 | 5 | 1 | 0 | 0 |
| 450 | -33 | 32 | 0 | 4 | 1 | 0 | 0 |
| 500 | -29 | 28 | 0 | 4 | 1 | 0 | 0 |
| 550 | -26 | 25 | 0 | 3 | 1 | 0 | 0 |
| 600 | -23 | 22 | 0 | 3 | 1 | 0 | 0 |
| 650 | -20 | 19 | 0 | 3 | 1 | 0 | 0 |
| 700 | -18 | 17 | 0 | 2 | 0 | 0 | 0 |
| 751 | -16 | 15 | 0 | 2 | 0 | 0 | 0 |
| 801 | -14 | 13 | 0 | 2 | 0 | 0 | 0 |
| 851 | -12 | 11 | 0 | 2 | 0 | 0 | 0 |
| 901 | -11 | 10 | 0 | 1 | 0 | 0 | 0 |
| 951 | -9 | 9 | 0 | 1 | 0 | 0 | 0 |
| 1001 | -8 | 8 | 0 | 1 | 0 | 0 | 0 |
| 1051 | -7 | 7 | 0 | 1 | 0 | 0 | 0 |
| 1101 | -6 | 6 | 0 | 1 | 0 | 0 | 0 |
| 1151 | -6 | 5 | 0 | 1 | 0 | 0 | 0 |
| 1201 | -5 | 5 | 0 | 1 | 0 | 0 | 0 |
| 1251 | -4 | 4 | 0 | 0 | 0 | 0 | 0 |
| 1301 | -4 | 4 | 0 | 0 | 0 | 0 | 0 |
| 1351 | -3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 1401 | -3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 1451 | -3 | 2 | 0 | 0 | 0 | 0 | 0 |

GOB - Gunnedah-Oxley Basin, GABSR - GAB Southern Recharge, GABS - GAB Surat, LNA - Lower Namoi Alluvium, UNA - Upper Namoi Alluvium, LRB - Liverpool Ranges Basalt, WRB - Warrumbungle Basalt,

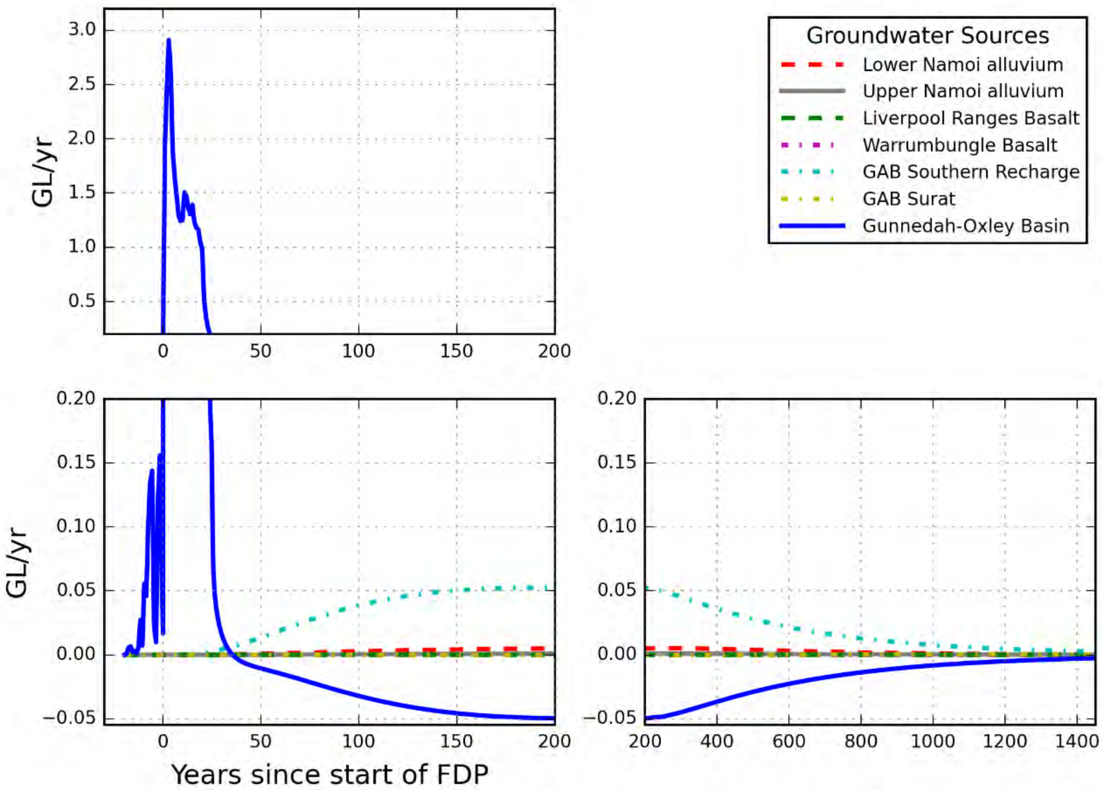


**Figure 6-33 Simulation BC: predicted rates of induced storage releases (net induced take) from WSP groundwater sources**

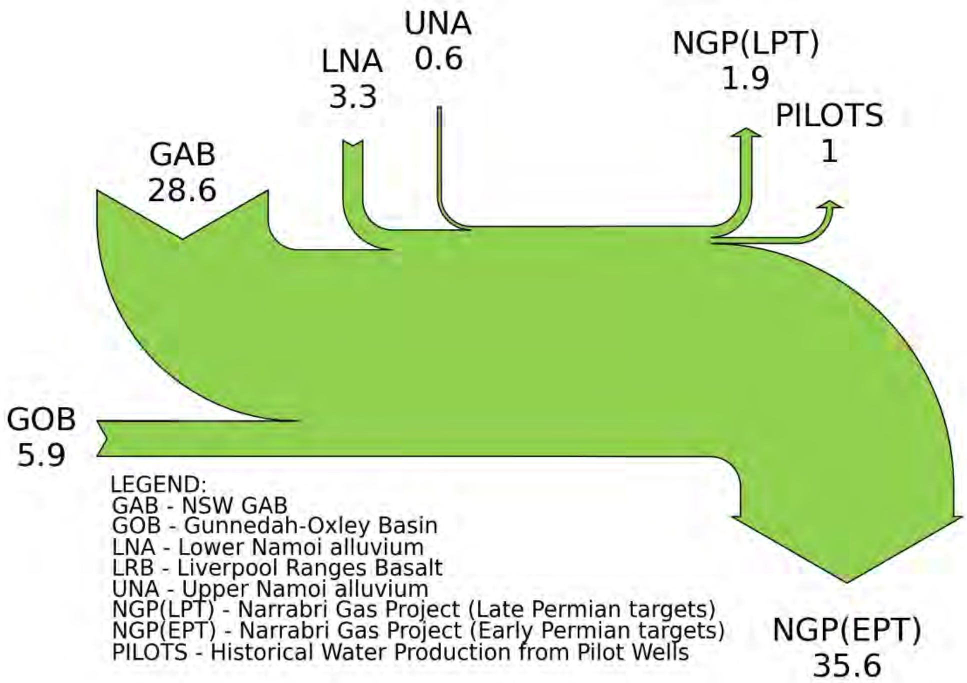


**Figure 6-34 Simulation BC: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

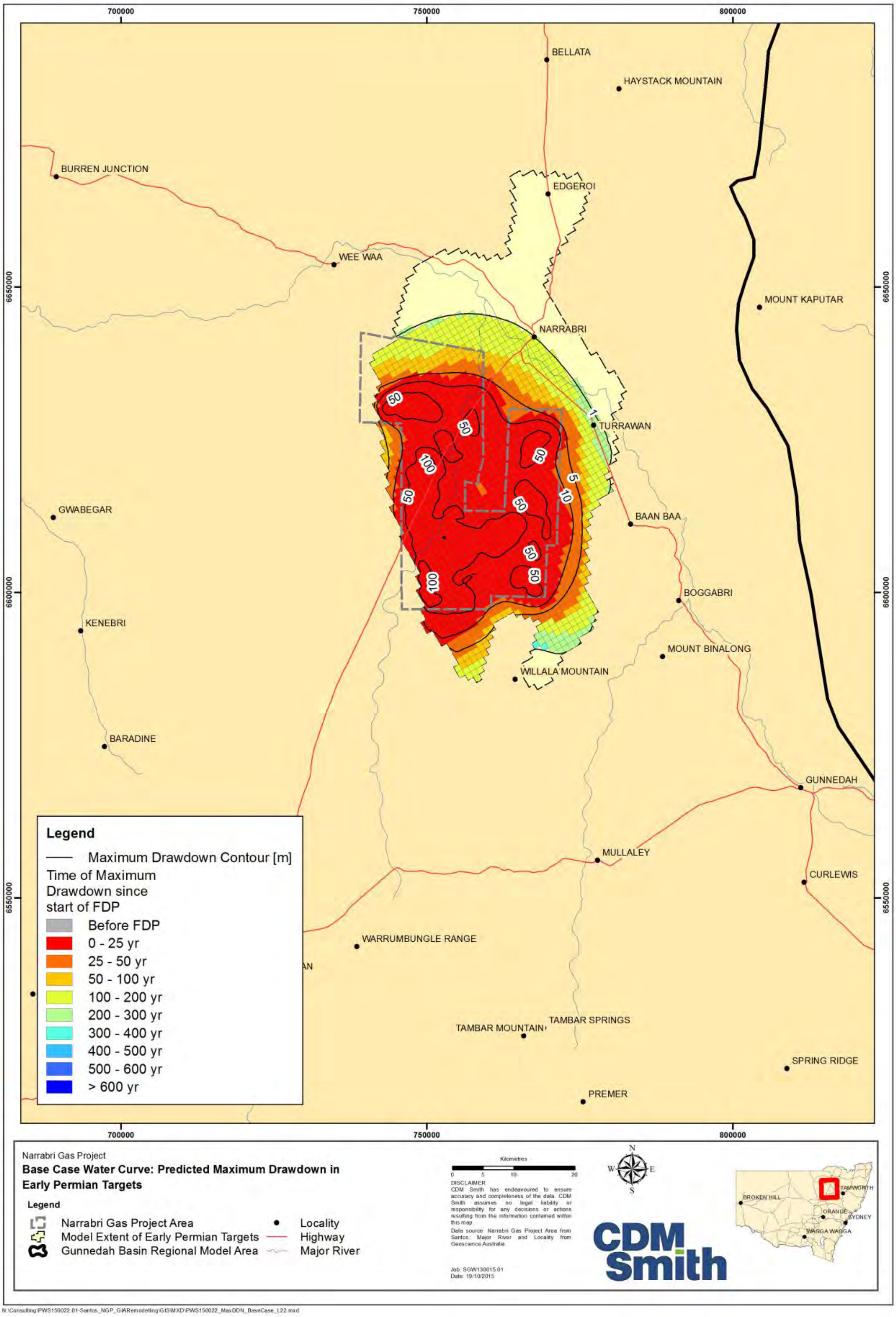


**Figure 6-35 Simulation BC: predicted maximum drawdown in Early Permian targets**

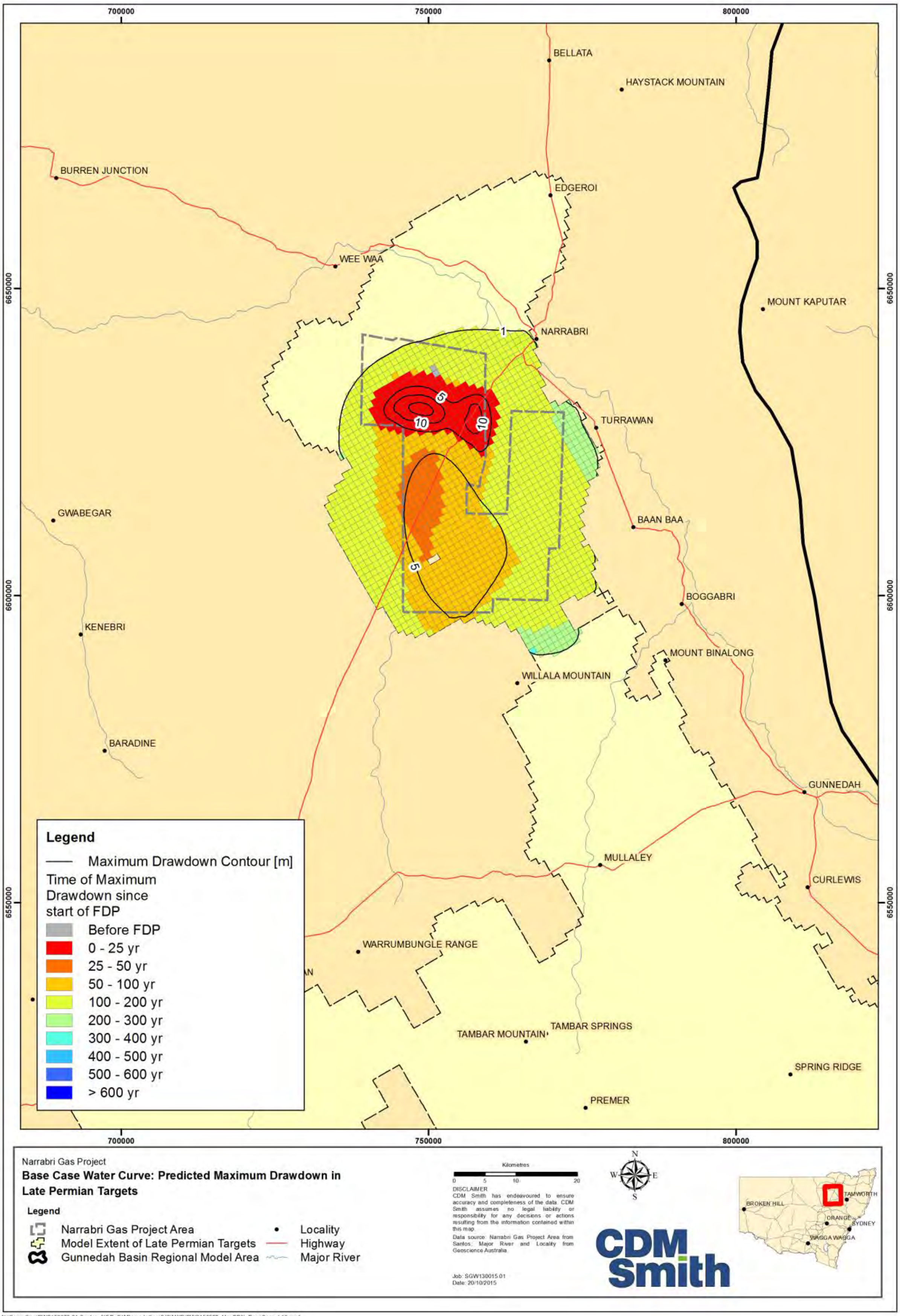


**Figure 6-36 Simulation BC: predicted maximum drawdown in Late Permian targets**

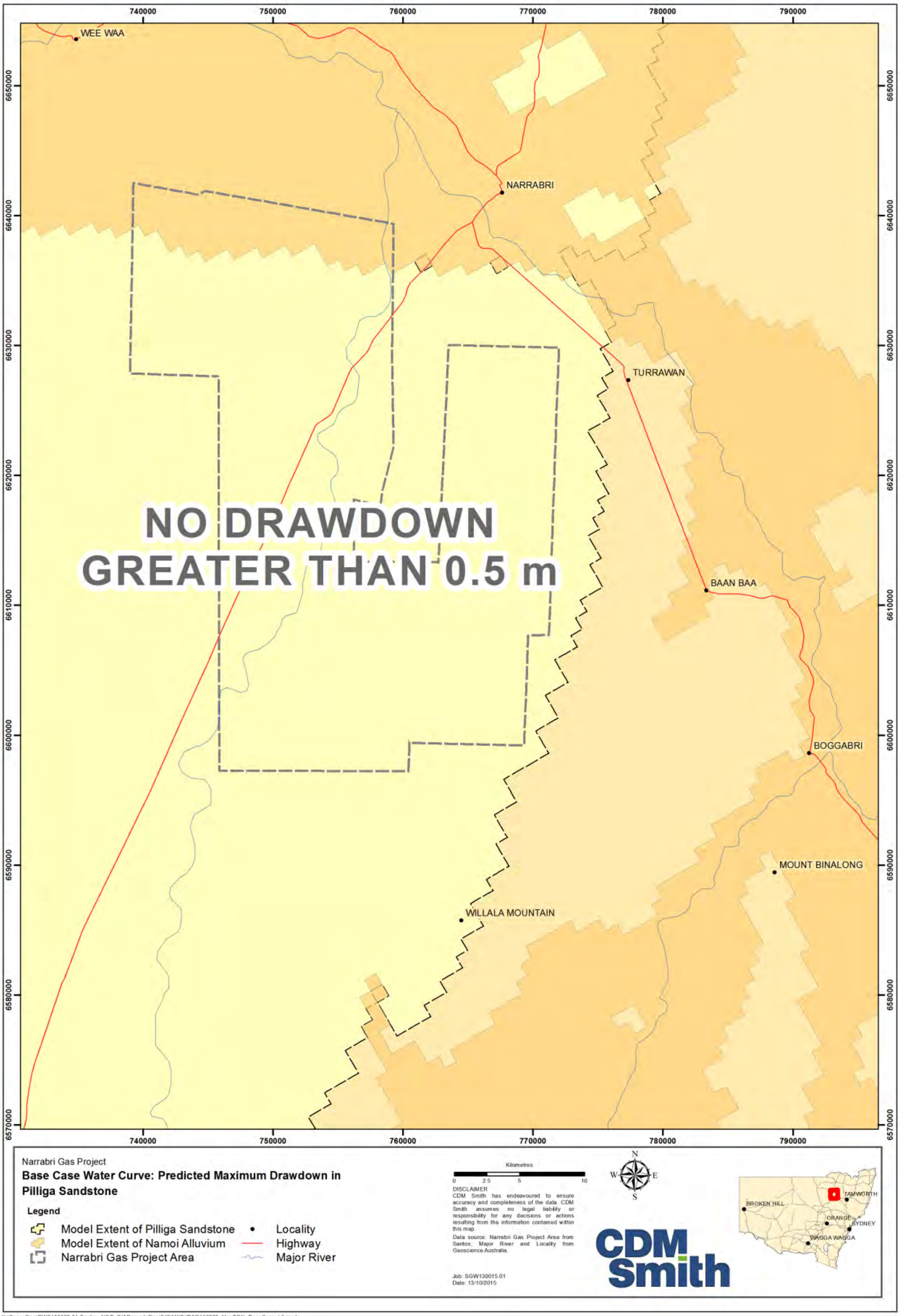


**Figure 6-37 Simulation BC: predicted maximum drawdown in Pilliga Sandstone**

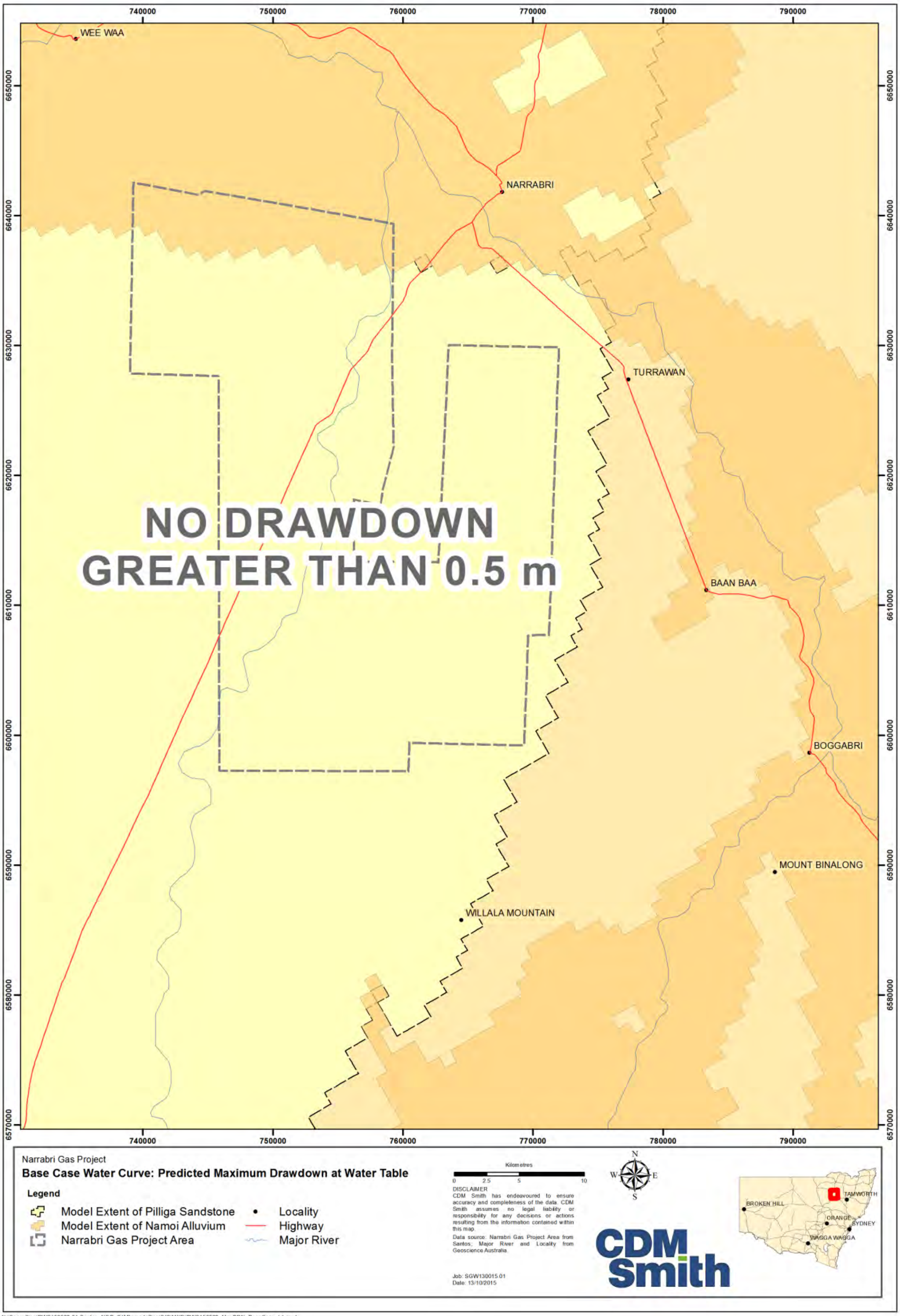


**Figure 6-38 Simulation BC: predicted maximum drawdown at the water table**

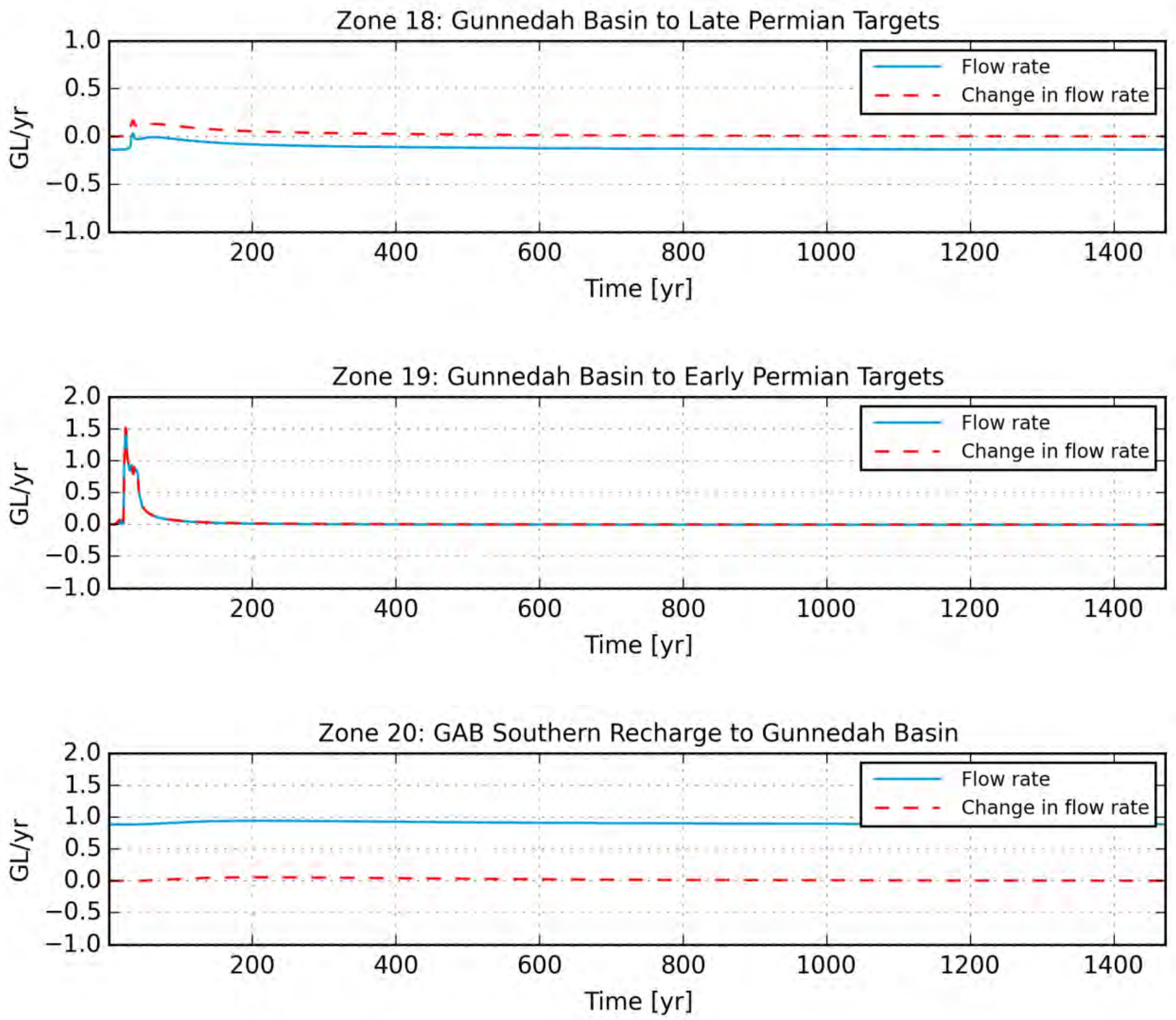


**Figure 6-39 Simulation BC: time variation of flow rates between selected WSPRAs**

### 6.9.2 Low Case Simulated Water Production

This simulation considers the potential impacts of the Low Case (LC) simulated water production profile described in Section 6.8.2 and uses the adopted hydrogeological properties in Table 6-7. The simulated water production profile is shown in Figure 6-40 and includes the following stresses to groundwater:

- Historical water production from the existing twelve gas pilots within the Gunnedah Basin, commencing in 1998 (approximately 1 GL);
- Low Case simulated future water production from the Early Permian coal seam gas targets, commencing in in July 2017 and ceasing after June 2042 (33.3 GL); and
- Low Case simulated water production from the Late Permian coal seam gas targets, commencing in July 2027 and ceasing after 2042 (1.75 GL).

Total water production for this simulation consists of 1 GL historical extraction and 35.0 GL future extraction. There are no stresses to groundwater in year one of the simulation. The period of historical water production is approximately 18 years. The simulated FDP spans a period of 25 years and the recovery period spans 1475 years after the FDP ceases. The total simulation period is 1520.5 years.

Results for this simulation are summarised in Table 6-20, Table 6-21 and Figure 6-41 to Figure 6-48. Explanation of these tables and figure is provided in Table 6-15 of Section 6.8.9.

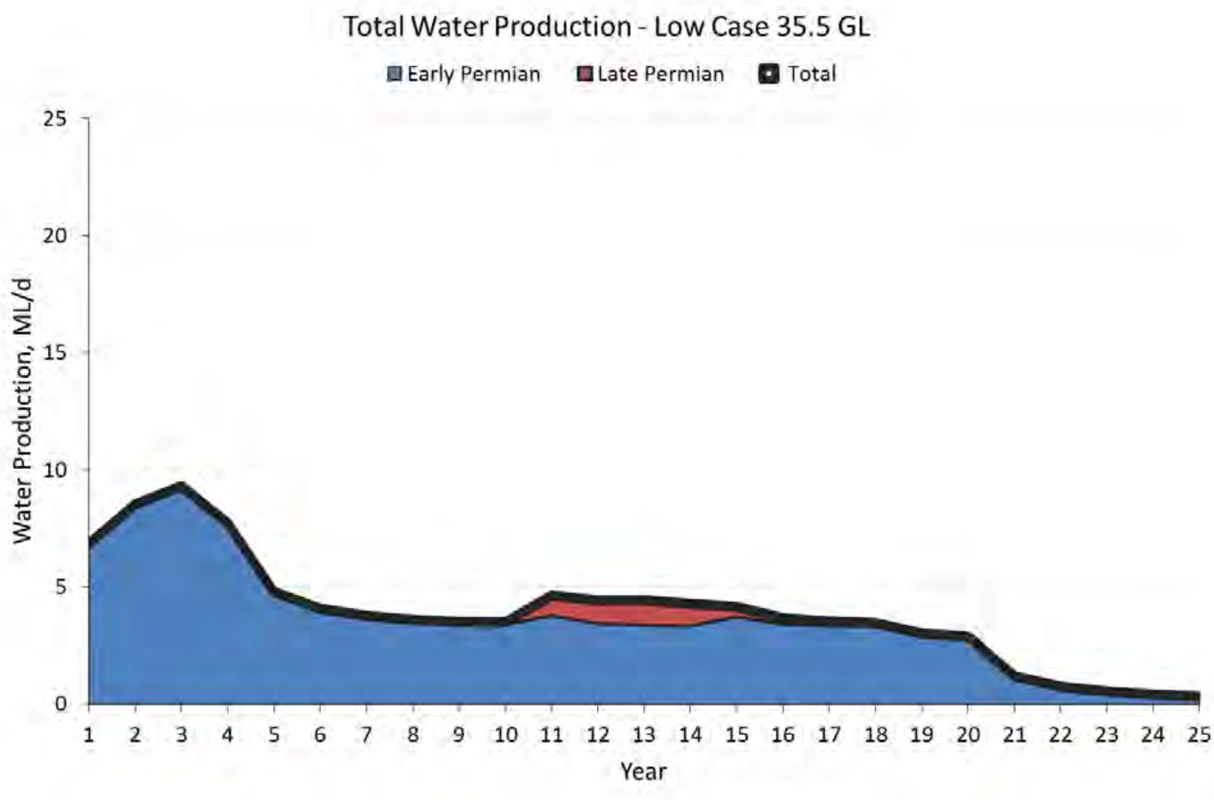


**Figure 6-40 Low Case (LC) Simulated future water production over the 25-y field development plan**

#### 6.9.2.1 Predicted Impacts

The predicted impacts of the Low Case simulated water production profile are similar to the Base Case predictions but with smaller drawdown and less induced flow.

- The largest predicted drawdown in the Early Permian targets is 150 m with maximum drawdown occurring between 1 and 300 years after the start of gas production dependent on location (Figure 6-44). The largest predicted drawdown in the Late Permian targets is 16 m with maximum drawdown occurring up to 300 years after the start of the FDP (Figure 6-45).

- No drawdown greater than 0.5 m is predicted in Pilliga Sandstone (Figure 6-46).

- No drawdown greater than 0.5 m is predicted at the water table, including the area of the Namoi alluvium (Figure 6-47).

- The maximum predicted change in groundwater flow rate between WSPRAs is 1.44 GL/y (46 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19) (Figure 6-41). This occurs at approximately 3 years after the start of the simulated FDP. The maximum predicted change in flow rate between the Gunnedah Basin and Late Permian targets (WSPRA 18) is 0.16 GL/y (5.1 L/s) at approximately 14 years after the start of the FDP. Predicted impacts on the GAB are minor with maximum predicted change in flow rate between the GAB Southern Recharge Area and Gunnedah Basin (WSPRA 20) of 0.05 GL/y (1.7 L/s) at approximately 190 years after the start of the FDP. Maximum induced groundwater flows between other WSPRAs are predicted to be negligible.

- The majority of the produced water is predicted to come from induced storage release in the Gunnedah-Oxley Basin and GAB, with a small contribution from the Lower Namoi Alluvium (Figure 6-42). Predicted maximum rate of storage release of 2.8 GL/y from the Gunnedah-Oxley Basin occurs at around 3 years after the start of the simulated FDP, and the predicted maximum rate of storage release of 0.05 GL/y (50 ML/y) from the GAB occurs at approximately 190 years after the start of the FDP. Predicted maximum storage release from the Lower Namoi Alluvium is approximately 0.005 GL/y (5 ML/y). Almost a full recovery of hydraulic head can be seen 1500 years after the start of the FDP when there is negligible change in storage.

- At the end of the recovery period (1500 years after the start of the FDP) the predicted contributions to the total simulated water production of 36.0 GL are approximately: 26.8 GL (74.4%) from the GAB; 5.5 GL (15.4%) from the Gunnedah-Oxley Basin; 3.1 GL (8.6%) from the Lower Namoi Alluvium and 0.6 GL (1.7%) from the Upper Namoi Alluvium (Figure 6-43). Since net recharge fluxes to the Lower Namoi Alluvium are fixed and the river is disconnected in this region, the contribution to total simulated water production from the Lower Namoi Alluvium (WSPRA 2) is counter balanced by increased lateral inflow to the alluvium. In the Upper Namoi Alluvium (WSPRAs 4 and 7) the river is connected and the contribution to total simulated water production is counter balanced by increased leakage from the river and increased lateral inflow. Outside of the alluvium, the contributions to total simulated water production from the GAB and Gunnedah-Oxley Basin are counter balanced by reduced evapotranspiration at the water table.

**Table 6-20 Simulation LC: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | < 0.5 | - |
| Pilliga Sandstone | < 0.5 | - |
| Late Permian Targets | 16 | Pre-FDP to 300 |
| Early Permian Targets | 150 | 1 to 300 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-21 Simulation LC: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | 0.00 | N |
| 2 | -1.26 | 0.00 | - | 3.09 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.14 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 0.45 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.00 | N |
| 18 | -0.14 | 0.16 | 14 | 29.70 | Y |
| 19 | 0.00 | 1.44 | 3 | 33.09 | Y |
| 20 | 0.89 | 0.05 | 190 | 29.81 | Y |
| 21 | -0.08 | 0.00 | - | 0.09 | N |

[1]Years since start of FDP

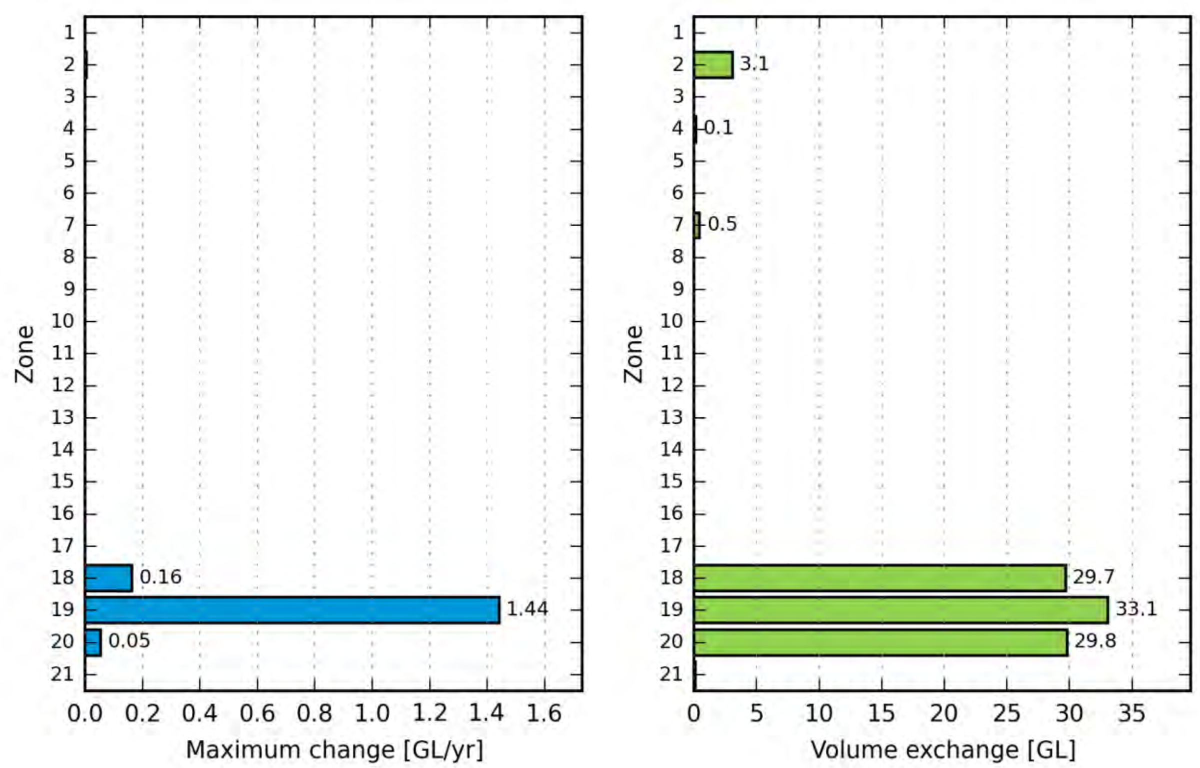


**Figure 6-41 Simulation LC: (a) maximum predicted change in WSPRA flow rates and (b) total predicted volumetric exchange between WSPRAs (from Table 6-21)**

**Table 6-22 Simulation LC: predicted rates of induced storage release (net induced take) from WSP groundwater sources**

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 1 | 1843 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 2323 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 2761 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 2481 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1761 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1493 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1348 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1182 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 1130 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 1139 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 1408 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 1374 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1251 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 1227 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 1322 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16 | 1159 | 0 | 0 | 0 | 0 | 0 | 0 |
| 17 | 1097 | 1 | 0 | 0 | 0 | 0 | 0 |
| 18 | 1085 | 1 | 0 | 0 | 0 | 0 | 0 |
| 19 | 1003 | 1 | 0 | 0 | 0 | 0 | 0 |
| 20 | 954 | 1 | 0 | 0 | 0 | 0 | 0 |
| 21 | 485 | 1 | 0 | 0 | 0 | 0 | 0 |
| 22 | 318 | 2 | 0 | 0 | 0 | 0 | 0 |
| 23 | 228 | 2 | 0 | 0 | 0 | 0 | 0 |
| 24 | 172 | 2 | 0 | 0 | 0 | 0 | 0 |
| 25 | 134 | 3 | 0 | 0 | 0 | 0 | 0 |
| 25 | 79 | 3 | 0 | 0 | 0 | 0 | 0 |
| 26 | 59 | 3 | 0 | 0 | 0 | 0 | 0 |
| 26 | 47 | 3 | 0 | 0 | 0 | 0 | 0 |
| 27 | 39 | 3 | 0 | 0 | 0 | 0 | 0 |
| 27 | 32 | 3 | 0 | 0 | 0 | 0 | 0 |
| 28 | 26 | 3 | 0 | 0 | 0 | 0 | 0 |
| 29 | 21 | 4 | 0 | 0 | 0 | 0 | 0 |
| 30 | 16 | 4 | 0 | 0 | 0 | 0 | 0 |
| 31 | 11 | 4 | 0 | 0 | 0 | 0 | 0 |
| 32 | 7 | 5 | 0 | 0 | 0 | 0 | 0 |
| 34 | 4 | 5 | 0 | 0 | 0 | 0 | 0 |
| 35 | 1 | 6 | 0 | 0 | 0 | 0 | 0 |
| 37 | -2 | 7 | 0 | 0 | 0 | 0 | 0 |
| 39 | -4 | 8 | 0 | 0 | 0 | 0 | 0 |
| 42 | -6 | 9 | 0 | 0 | 0 | 0 | 0 |
| 45 | -8 | 10 | 0 | 1 | 0 | 0 | 0 |
| 48 | -9 | 12 | 0 | 1 | 0 | 0 | 0 |
| 52 | -11 | 14 | 0 | 1 | 0 | 0 | 0 |
| 56 | -12 | 16 | 0 | 1 | 0 | 0 | 0 |
| 61 | -14 | 18 | 0 | 1 | 0 | 0 | 0 |
| 67 | -17 | 22 | 0 | 1 | 0 | 0 | 0 |
| 74 | -19 | 25 | 0 | 2 | 0 | 0 | 0 |
| 81 | -23 | 29 | 0 | 2 | 0 | 0 | 0 |
| 90 | -26 | 32 | 0 | 2 | 0 | 0 | 0 |
| 100 | -30 | 36 | 0 | 3 | 0 | 0 | 0 |

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 110 | -34 | 39 | 0 | 3 | 0 | 0 | 0 |
| 120 | -37 | 42 | 0 | 3 | 1 | 0 | 0 |
| 130 | -39 | 44 | 0 | 3 | 1 | 0 | 0 |
| 140 | -41 | 46 | 0 | 4 | 1 | 0 | 0 |
| 150 | -43 | 47 | 0 | 4 | 1 | 0 | 0 |
| 160 | -44 | 48 | 0 | 4 | 1 | 0 | 0 |
| 170 | -45 | 49 | 0 | 4 | 1 | 0 | 0 |
| 180 | -46 | 49 | 0 | 4 | 1 | 0 | 0 |
| 190 | -46 | 49 | 0 | 5 | 1 | 0 | 0 |
| 200 | -46 | 49 | 0 | 5 | 1 | 0 | 0 |
| 250 | -45 | 47 | 0 | 5 | 1 | 0 | 0 |
| 300 | -42 | 42 | 0 | 5 | 1 | 0 | 0 |
| 350 | -38 | 38 | 0 | 5 | 1 | 0 | 0 |
| 400 | -34 | 34 | 0 | 4 | 1 | 0 | 0 |
| 450 | -31 | 30 | 0 | 4 | 1 | 0 | 0 |
| 500 | -27 | 26 | 0 | 4 | 1 | 0 | 0 |
| 550 | -24 | 23 | 0 | 3 | 1 | 0 | 0 |
| 600 | -21 | 20 | 0 | 3 | 1 | 0 | 0 |
| 650 | -19 | 18 | 0 | 3 | 0 | 0 | 0 |
| 700 | -17 | 16 | 0 | 2 | 0 | 0 | 0 |
| 751 | -15 | 14 | 0 | 2 | 0 | 0 | 0 |
| 801 | -13 | 12 | 0 | 2 | 0 | 0 | 0 |
| 851 | -11 | 11 | 0 | 2 | 0 | 0 | 0 |
| 901 | -10 | 9 | 0 | 1 | 0 | 0 | 0 |
| 951 | -9 | 8 | 0 | 1 | 0 | 0 | 0 |
| 1001 | -8 | 7 | 0 | 1 | 0 | 0 | 0 |
| 1051 | -7 | 6 | 0 | 1 | 0 | 0 | 0 |
| 1101 | -6 | 6 | 0 | 1 | 0 | 0 | 0 |
| 1151 | -5 | 5 | 0 | 1 | 0 | 0 | 0 |
| 1201 | -5 | 4 | 0 | 1 | 0 | 0 | 0 |
| 1251 | -4 | 4 | 0 | 0 | 0 | 0 | 0 |
| 1301 | -4 | 3 | 0 | 0 | 0 | 0 | 0 |
| 1351 | -3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 1401 | -3 | 3 | 0 | 0 | 0 | 0 | 0 |
| 1451 | -2 | 2 | 0 | 0 | 0 | 0 | 0 |

GOB - Gunnedah-Oxley Basin, GABSR - GAB Southern Recharge, GABS - GAB Surat, LNA - Lower Namoi Alluvium, UNA - Upper Namoi Alluvium, LRB - Liverpool Ranges Basalt, WRB - Warrumbungle Basalt,

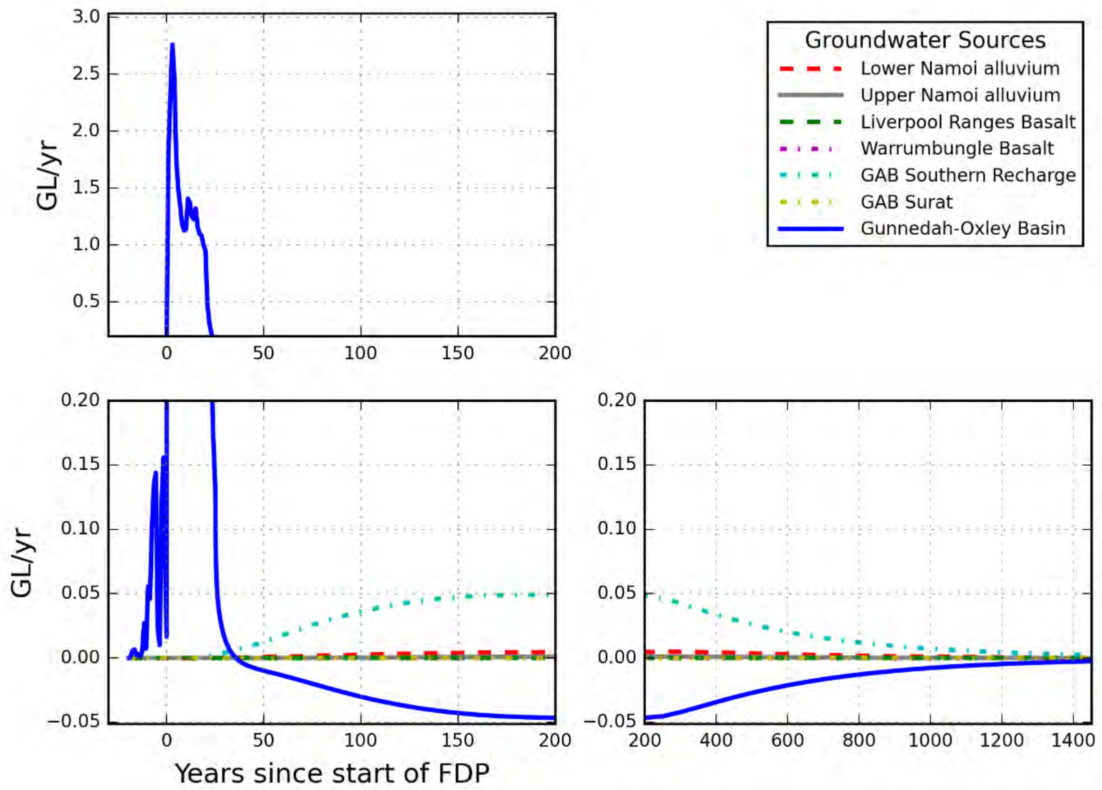


**Figure 6-42 Simulation LC: predicted rates of induced storage releases (net induced take) from WSP groundwater sources**

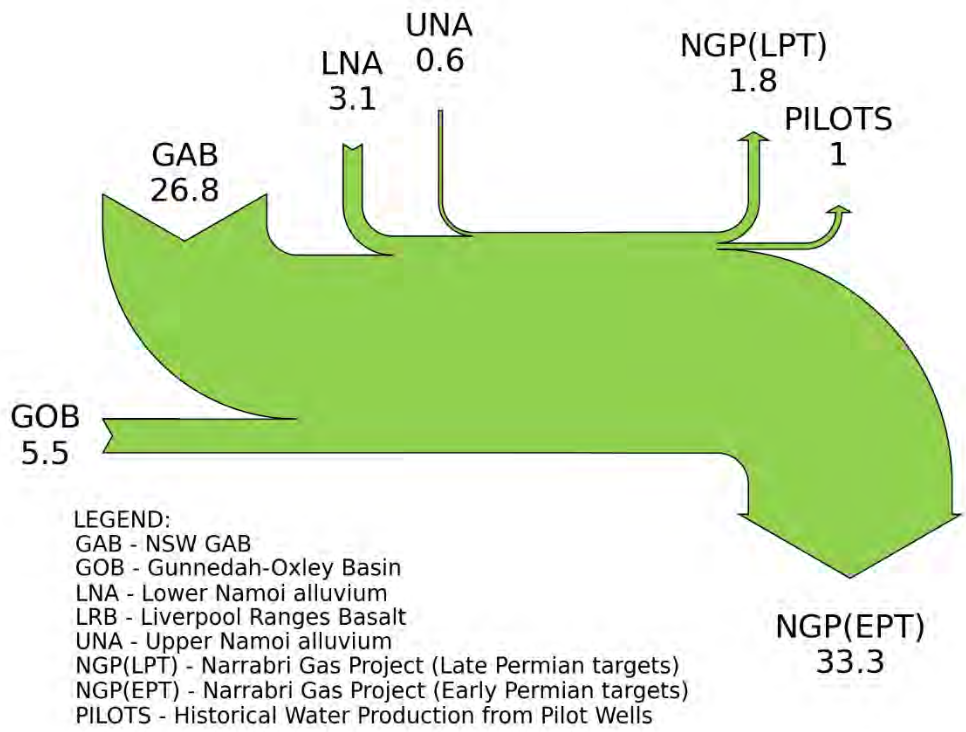


**Figure 6-43 Simulation LC: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

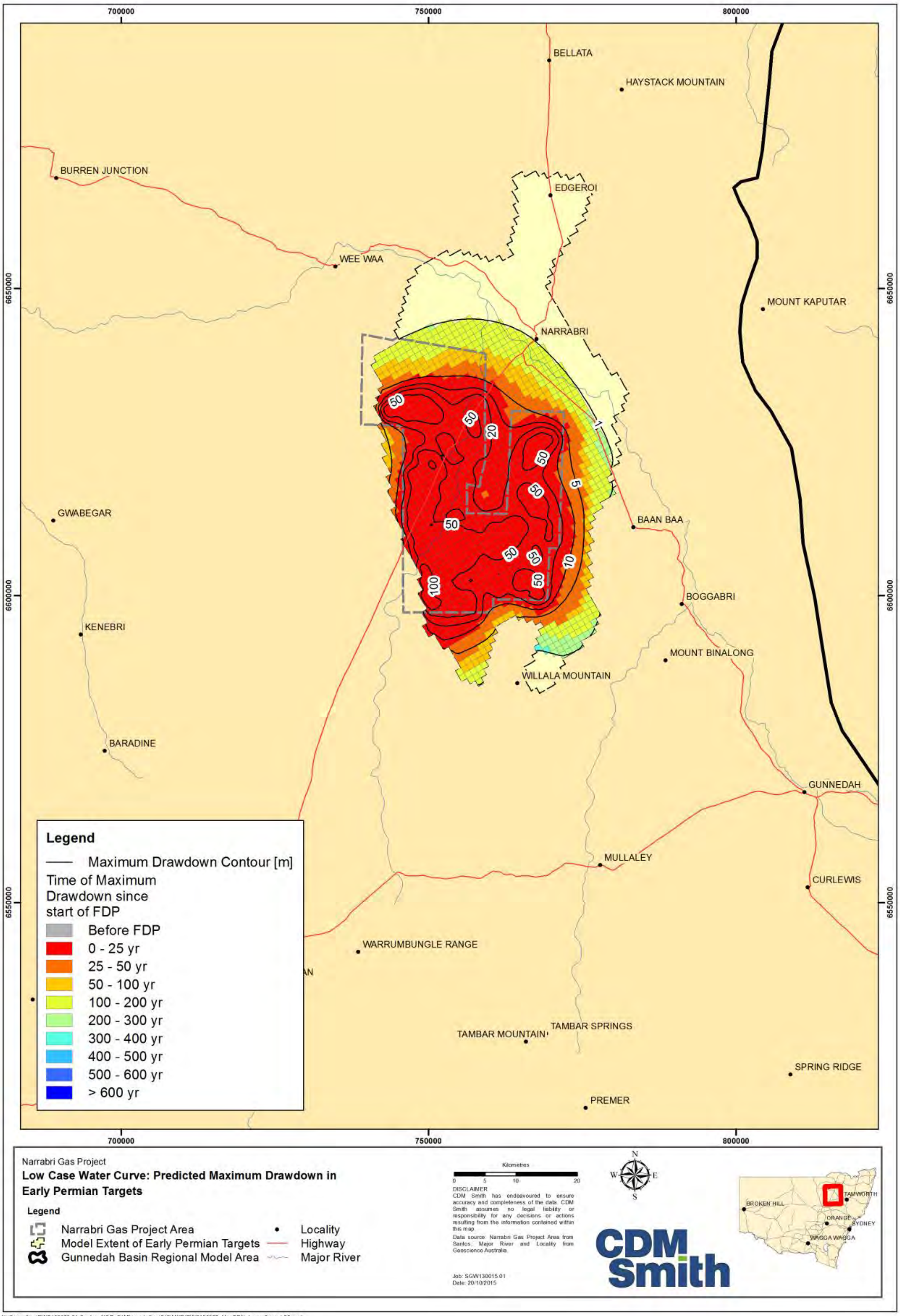


**Figure 6-44 Simulation LC: predicted maximum drawdown in Early Permian targets**

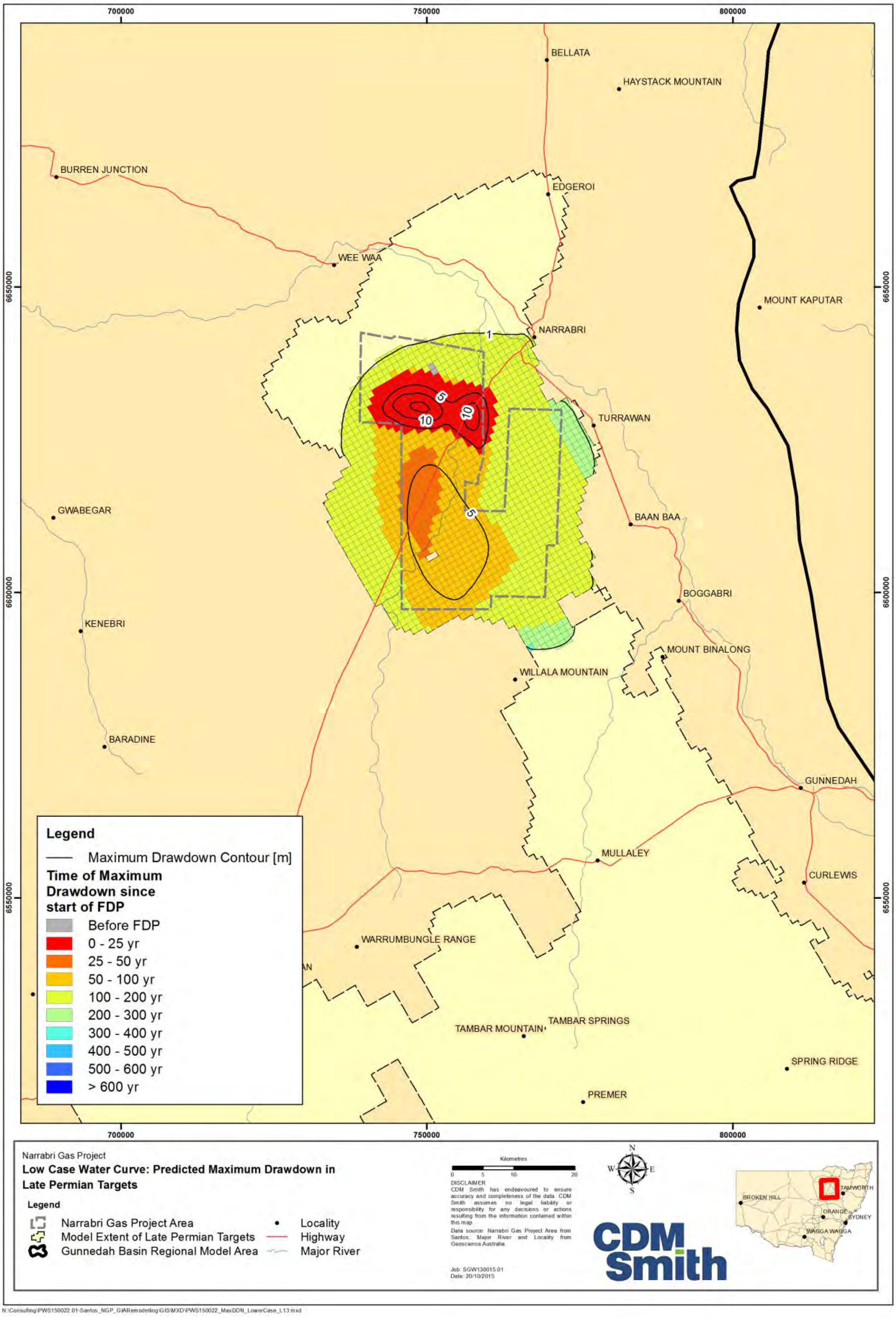


**Figure 6-45 Simulation LC: predicted maximum drawdown in Late Permian targets**

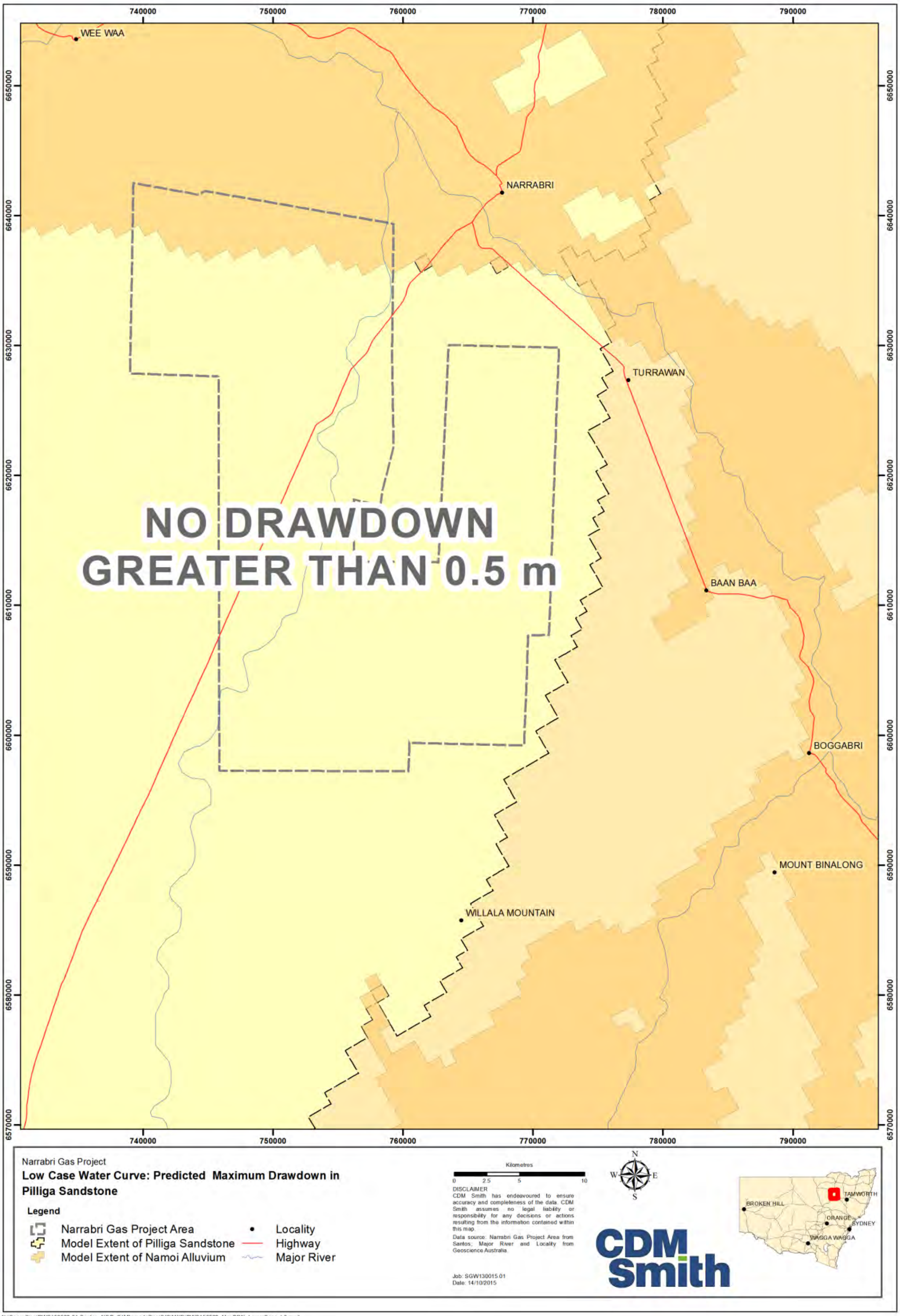


**Figure 6-46 Simulation LC: predicted maximum drawdown in Pilliga Sandstone**

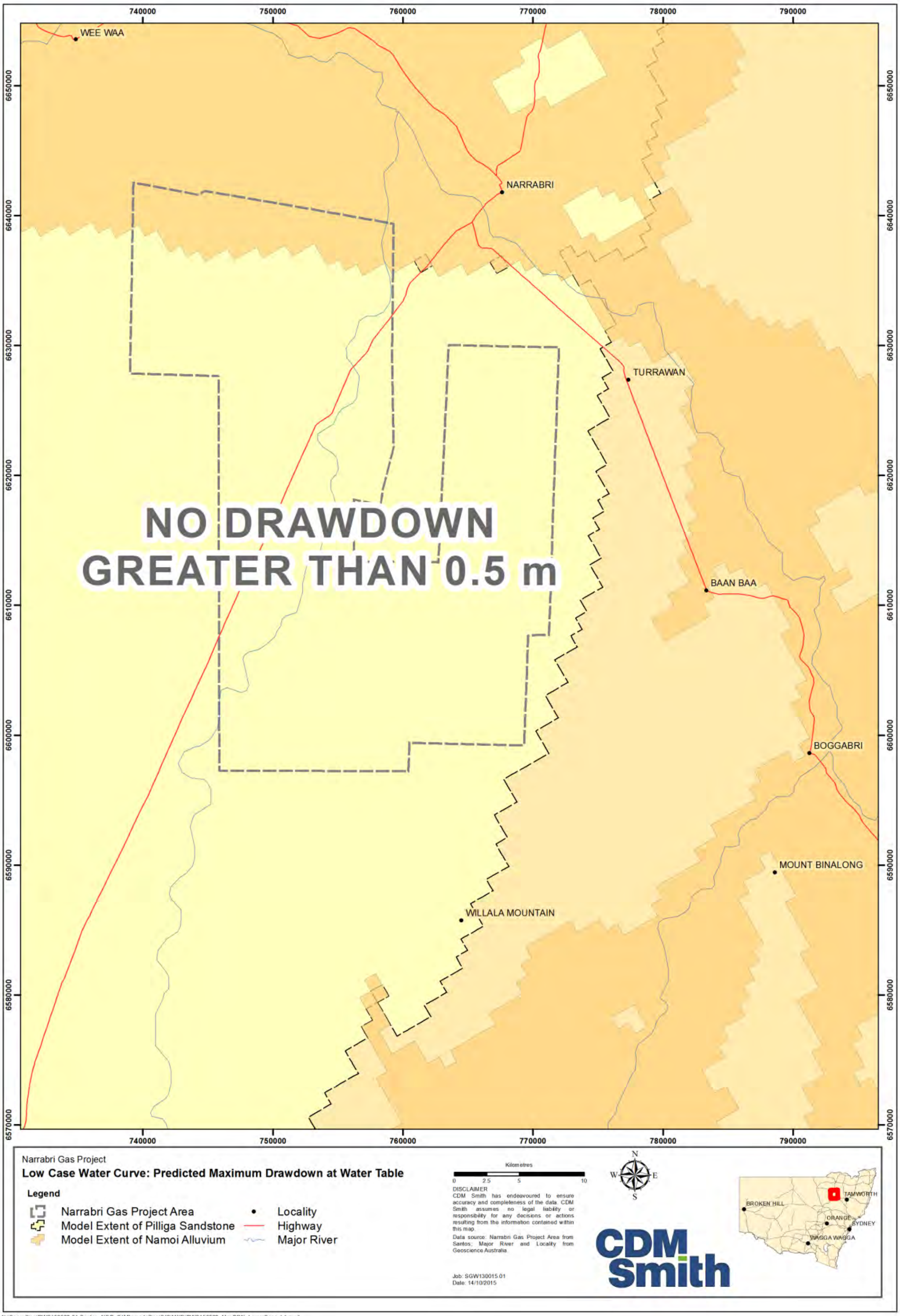


**Figure 6-47 Simulation LC: predicted maximum drawdown at the water table**

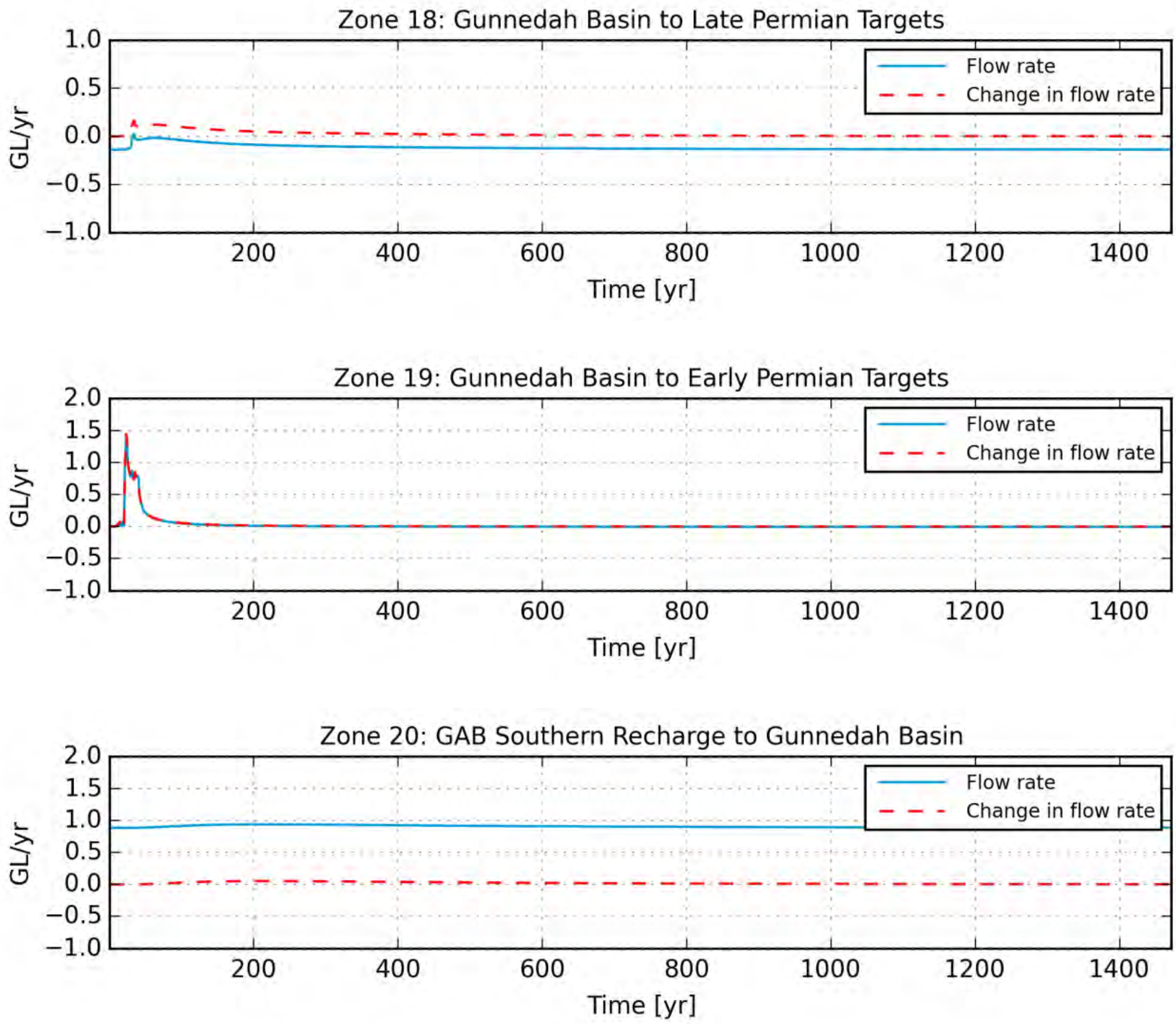


**Figure 6-48 Simulation LC: time variation of flow rates between selected WSPRAs**

### 6.9.3 High Case Simulated Water Production

This simulation considers the potential impacts of the High Case (HC) simulated water production profile described in Section 6.8.2 and uses the adopted hydrogeological properties in Table 6-7. The simulated water production profile is shown in Figure 6-49 and includes the following groundwater stresses:

- Historical water production from the existing twelve gas pilots within the Gunnedah Basin, commencing in 1998 (approximately 1 GL);
- High Case simulated water production from the Early Permian coal seam gas targets, commencing in in July 2017 and ceasing after June 2042 (82.5 GL); and
- High Case simulated water production from the Late Permian coal seam gas targets, commencing in July 2027 and ceasing after 2042 (4.63 GL).

Total water production for this simulation consists of 1 GL historical extraction and 87.1 GL future extraction. There are no stresses to groundwater in year one of the simulation. The period of historical water production is approximately 18 years. The simulated FDP spans a period of 25 years and the recovery period spans 1475 years after the FDP ceases. The total simulation period of 1520.5 years.

Results for this simulations are summarised in Table 6-23, Table 6-24 and Figure 6-50 to Figure 6-57. Explanation of these tables and figure is provided in Table 6-15 of Section 6.8.9.

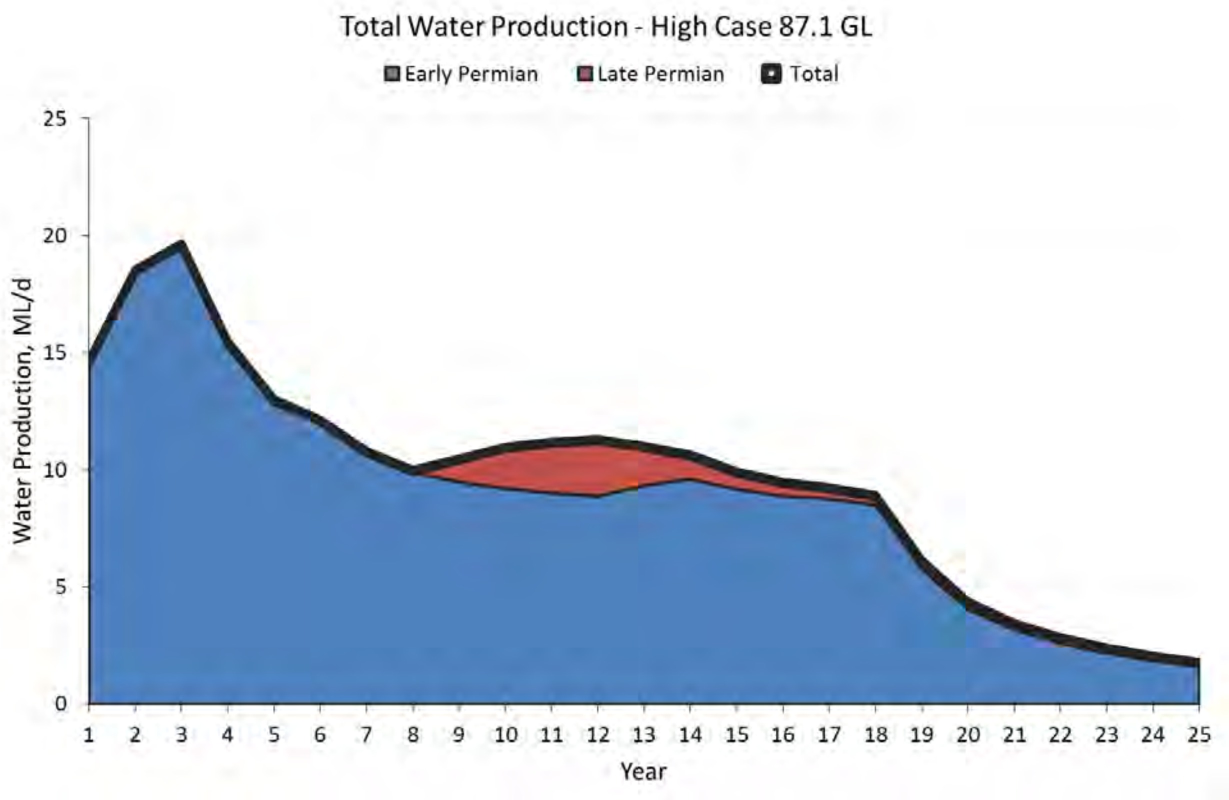


**Figure 6-49 High Case (HC) simulated future water production over the 25-y field development plan**

#### 6.9.3.1 Predicted Impacts

The predicted impacts of the High Case simulated water production profile are similar to the Base Case predictions but with larger drawdown and greater induced flow. The most significant difference is predicted maximum drawdown greater than 0.5 m, though less than 0.7 m, in the Pilliga Sandstone.

- The largest predicted drawdown in the Early Permian targets is 224 m with maximum drawdown occurring between 2 and 500 years after the start of the simulated FDP (Figure 6-53).
- The largest predicted drawdown in the Late Permian targets is 32.3 m with maximum drawdown occurring up to 350 years after the start of the FDP (Figure 6-54). The pattern and timing of maximum drawdown reflects a combination of indirect impacts due to simulated water production in the Early Permian targets and direct impacts due to simulated water production in the Late Permian targets. Over most of the affected area, the maximum drawdowns occur at between 25 and 400 years after the start of the FDP due to vertical propagation of depressurisation emanating in the Early Permian targets. Thus, in these areas the predicted maximum drawdowns in the Late Permian targets due to water extraction in the Early Permian targets are larger than the drawdowns predicted due to simulated water production directly within the Late Permian targets (and they occur later in time). In contrast, the smaller area of red coloured cells in WEAs 11 and 13 shows the area where the direct impacts of simulated water production in the Late Permian targets are larger (and occur earlier).
- The predicted largest drawdown in the Pilliga Sandstone is 0.6 m with maximum drawdown occurring between 190 and 200 years after the start of the FDP (Figure 6-55). The predicted area of drawdown is located near the western edge the project area and does not underlie the Namoi alluvium.
- At the water table the largest value of predicted drawdown is approximately 1.1 m with predicted time to reach maximum drawdown greater than 0.5 m varying from 350 to 550 years after the start of the FDP dependent on location (Figure 6-56). Predicted drawdown of the water table in the Namoi alluvium is less than the minimum value of 0.5 m considered in this assessment.
- The maximum predicted change in groundwater flow rate between WSPRAs is 3.11 GL/y (99 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19) (Figure 6-50). This occurs at approximately 3 years after the start of simulated FDP. The maximum predicted change in flow rate between the Gunnedah Basin and Late Permian targets (WSPRA 18) is 0.35 GL/y (11 L/s) at approximately 12 years after the start of the FDP. Predicted impacts on the GAB are minor with maximum predicted change in flow rate between the GAB Southern Recharge Area and Gunnedah Basin (WSPRA 20) of 0.13 GL/y (4.2 L/s) at approximately 190 years after the start of the FDP. Maximum induced groundwater flows between other WSPRAs are predicted to be negligible.
- The majority of the produced water is predicted to come from induced storage release in the Gunnedah-Oxley Basin and GAB, with a small contribution from the Lower Namoi Alluvium (Figure 6-51). The predicted maximum rate of storage release of 5.9 GL/y from the Gunnedah-Oxley Basin occurs at around 3 years after the start of the simulated FDP, and predicted maximum rate of storage release of 0.12 GL/y from the GAB occurs at approximately 190 years after the start of the FDP. Predicted maximum storage release from the Lower Namoi Alluvium

is approximately 0.01 GL/y. Almost a full recovery of hydraulic head occurs 1500 years after the start of the FDP.

- At the end of the recovery period (1500 years after the start of the FDP) the predicted contributions to the total simulated water production of 88.1 GL are approximately: 65.5 GL (74.3%) from the GAB; 13.6 GL (15.4%) from the Gunnedah-Oxley Basin; 7.6 GL (8.6%) from the Lower Namoi Alluvium and 1.4 GL (1.6%) from the Upper Namoi Alluvium (Figure 6-52). Since net recharge fluxes to the Lower Namoi Alluvium are fixed and the river is disconnected in this region, the contribution to total simulated water production from the Lower Namoi Alluvium (WSPRA 2) is counter balanced by increased lateral inflow to the alluvium. In the Upper Namoi Alluvium (WSPRAs 4 and 7) the river is connected and the contribution to total simulated water production is counter balanced by increased leakage from the river and increased lateral inflow. Outside of the alluvium, the contributions to total simulated water production from the GAB and Gunnedah-Oxley Basin are counter balanced by reduced evapotranspiration at the water table.

**Table 6-23 Simulation HC: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 1.1 | 350 to 550 |
| Pilliga Sandstone | 0.6 | 190 to 200 |
| Late Permian Targets | 32.3 | Pre-FDP to 350 |
| Early Permian Targets | 224 | 2 to 500 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-24 Simulation HC: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | 0.01 | N |
| 2 | -1.26 | 0.01 | - | 7.60 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.35 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 1.10 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.01 | N |
| 18 | -0.14 | 0.35 | 12 | 72.54 | Y |
| 19 | 0.00 | 3.11 | 3 | 80.51 | Y |
| 20 | 0.89 | 0.13 | 190 | 72.86 | Y |
| 21 | -0.08 | 0.00 | - | 0.24 | N |

[1]Years since start of FDP

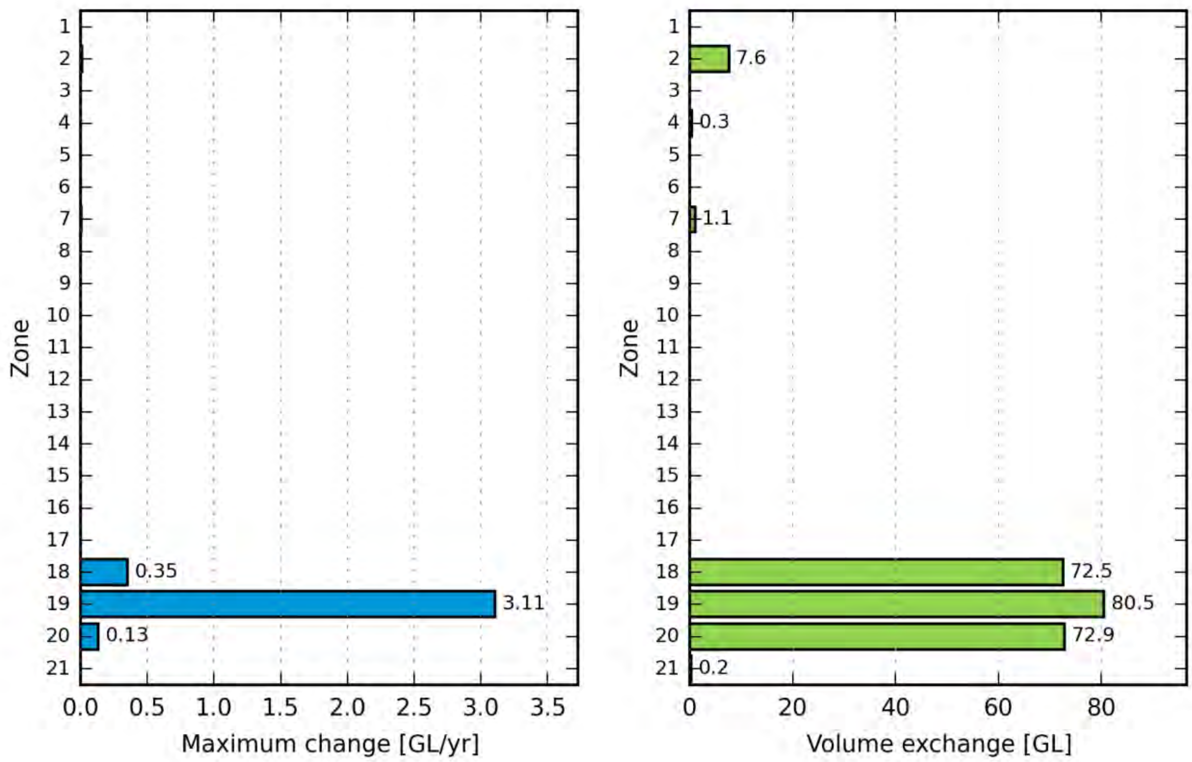


**Figure 6-50 Simulation HC: (a) maximum predicted change in WSPRA flow rates and (b) total predicted volumetric exchange between WSPRAs (from Table 6-24)**

**Table 6-25 Simulation HC: predicted rates of induced storage release (net induced take) from WSP groundwater sources**

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 1 | 3752 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 5191 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 5922 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 5125 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 4503 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 4125 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 3604 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 3313 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 3360 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 3459 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 3448 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 3314 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 3367 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 3360 | 1 | 0 | 0 | 0 | 0 | 0 |
| 15 | 3130 | 1 | 0 | 0 | 0 | 0 | 0 |
| 16 | 2992 | 1 | 0 | 0 | 0 | 0 | 0 |
| 17 | 2963 | 2 | 0 | 0 | 0 | 0 | 0 |
| 18 | 2892 | 2 | 0 | 0 | 0 | 0 | 0 |
| 19 | 2133 | 3 | 0 | 0 | 0 | 0 | 0 |
| 20 | 1580 | 3 | 0 | 0 | 0 | 0 | 0 |
| 21 | 1260 | 4 | 0 | 0 | 0 | 0 | 0 |
| 22 | 1039 | 4 | 0 | 0 | 0 | 0 | 0 |
| 23 | 874 | 5 | 0 | 0 | 0 | 0 | 0 |
| 24 | 745 | 6 | 0 | 0 | 0 | 0 | 0 |
| 25 | 640 | 6 | 0 | 0 | 0 | 0 | 0 |
| 25 | 310 | 7 | 0 | 0 | 0 | 0 | 0 |
| 26 | 204 | 7 | 0 | 0 | 0 | 0 | 0 |
| 26 | 153 | 7 | 0 | 0 | 0 | 0 | 0 |
| 27 | 120 | 8 | 0 | 0 | 0 | 0 | 0 |
| 27 | 95 | 8 | 0 | 0 | 0 | 0 | 0 |
| 28 | 74 | 9 | 0 | 0 | 0 | 0 | 0 |
| 29 | 57 | 9 | 0 | 0 | 0 | 0 | 0 |
| 30 | 43 | 10 | 0 | 0 | 0 | 0 | 0 |
| 31 | 30 | 11 | 0 | 1 | 0 | 0 | 0 |
| 32 | 19 | 12 | 0 | 1 | 0 | 0 | 0 |
| 34 | 9 | 13 | 0 | 1 | 0 | 0 | 0 |
| 35 | 1 | 15 | 0 | 1 | 0 | 0 | 0 |
| 37 | -6 | 17 | 0 | 1 | 0 | 0 | 0 |
| 39 | -11 | 19 | 0 | 1 | 0 | 0 | 0 |
| 42 | -16 | 21 | 0 | 1 | 0 | 0 | 0 |
| 45 | -19 | 25 | 0 | 1 | 0 | 0 | 0 |
| 48 | -23 | 28 | 0 | 2 | 0 | 0 | 0 |
| 52 | -26 | 33 | 0 | 2 | 0 | 0 | 0 |
| 56 | -30 | 38 | 0 | 2 | 0 | 0 | 0 |
| 61 | -35 | 45 | 0 | 3 | 0 | 0 | 0 |
| 67 | -40 | 52 | 0 | 3 | 0 | 0 | 0 |
| 74 | -47 | 61 | 0 | 4 | 1 | 0 | 0 |
| 81 | -55 | 69 | 0 | 5 | 1 | 0 | 0 |
| 90 | -64 | 79 | 0 | 5 | 1 | 0 | 0 |
| 100 | -74 | 88 | 0 | 6 | 1 | 0 | 0 |

| Years from start of FDP | GOB [ML/yr] | GABSR [ML/yr] | GABS [ML/yr] | LNA [ML/yr] | UNA [ML/yr] | LRB [ML/yr] | WRB [ML/yr] |
|---|---|---|---|---|---|---|---|
| 110 | -82 | 96 | 0 | 7 | 1 | 0 | 0 |
| 120 | -89 | 103 | 0 | 8 | 1 | 0 | 0 |
| 130 | -95 | 108 | 0 | 9 | 1 | 0 | 0 |
| 140 | -100 | 112 | 0 | 9 | 2 | 0 | 0 |
| 150 | -105 | 115 | 0 | 10 | 2 | 0 | 0 |
| 160 | -108 | 117 | 0 | 10 | 2 | 0 | 0 |
| 170 | -110 | 119 | 0 | 11 | 2 | 0 | 0 |
| 180 | -112 | 120 | 0 | 11 | 2 | 0 | 0 |
| 190 | -113 | 120 | 0 | 11 | 2 | 0 | 0 |
| 200 | -114 | 120 | 0 | 11 | 2 | 0 | 0 |
| 250 | -111 | 114 | 0 | 12 | 2 | 0 | 0 |
| 300 | -103 | 104 | 0 | 12 | 2 | 0 | 0 |
| 350 | -94 | 93 | 0 | 11 | 2 | 0 | 0 |
| 400 | -84 | 82 | 0 | 11 | 2 | 0 | 0 |
| 450 | -75 | 73 | 0 | 10 | 2 | 0 | 0 |
| 500 | -66 | 64 | 0 | 9 | 2 | 0 | 0 |
| 550 | -59 | 56 | 0 | 8 | 2 | 0 | 0 |
| 600 | -52 | 49 | 0 | 7 | 1 | 0 | 0 |
| 650 | -46 | 43 | 0 | 6 | 1 | 0 | 0 |
| 700 | -40 | 38 | 0 | 6 | 1 | 0 | 0 |
| 751 | -36 | 33 | 0 | 5 | 1 | 0 | 0 |
| 801 | -31 | 29 | 0 | 4 | 1 | 0 | 0 |
| 851 | -28 | 26 | 0 | 4 | 1 | 0 | 0 |
| 901 | -24 | 23 | 0 | 3 | 1 | 0 | 0 |
| 951 | -21 | 20 | 0 | 3 | 1 | 0 | 0 |
| 1001 | -19 | 18 | 0 | 2 | 0 | 0 | 0 |
| 1051 | -17 | 15 | 0 | 2 | 0 | 0 | 0 |
| 1101 | -15 | 14 | 0 | 2 | 0 | 0 | 0 |
| 1151 | -13 | 12 | 0 | 2 | 0 | 0 | 0 |
| 1201 | -11 | 11 | 0 | 1 | 0 | 0 | 0 |
| 1251 | -10 | 9 | 0 | 1 | 0 | 0 | 0 |
| 1301 | -9 | 8 | 0 | 1 | 0 | 0 | 0 |
| 1351 | -8 | 7 | 0 | 1 | 0 | 0 | 0 |
| 1401 | -7 | 6 | 0 | 1 | 0 | 0 | 0 |
| 1451 | -6 | 6 | 0 | 0 | 0 | 0 | 0 |

GOB - Gunnedah-Oxley Basin, GABSR - GAB Southern Recharge, GABS - GAB Surat, LNA - Lower Namoi Alluvium, UNA - Upper Namoi Alluvium, LRB - Liverpool Ranges Basalt, WRB - Warrumbungle Basalt,

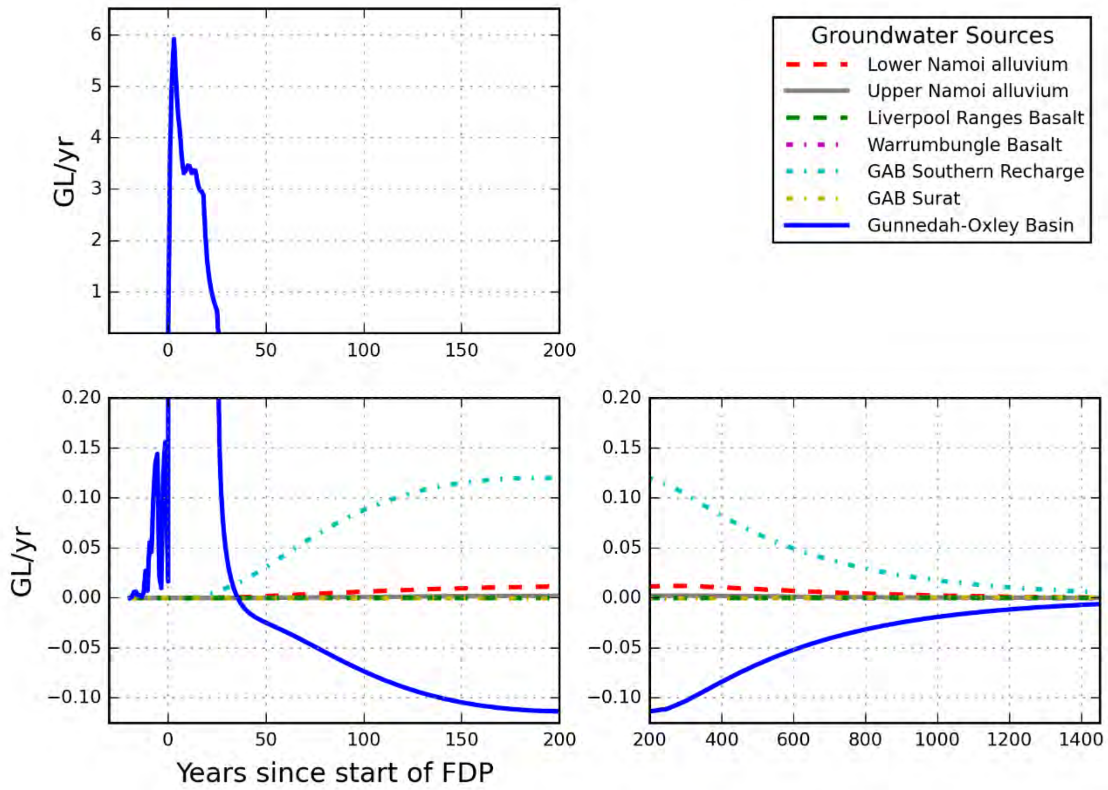


**Figure 6-51 Simulation HC: predicted rates of induced storage releases (net induced take) from WSP groundwater sources**

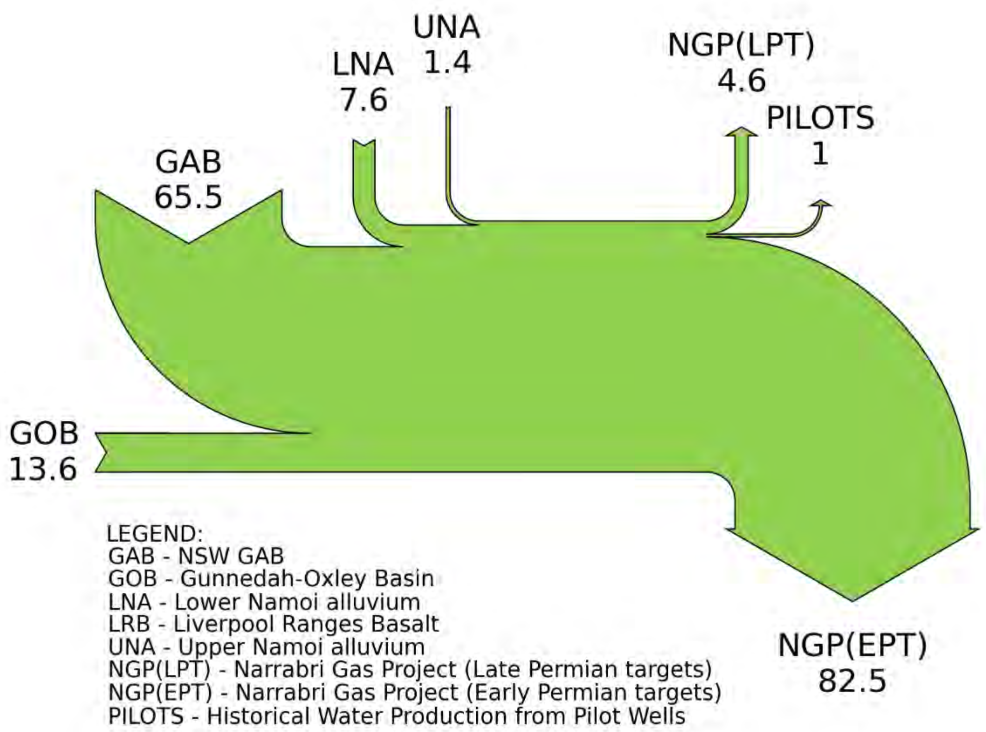


**Figure 6-52 Simulation HC: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

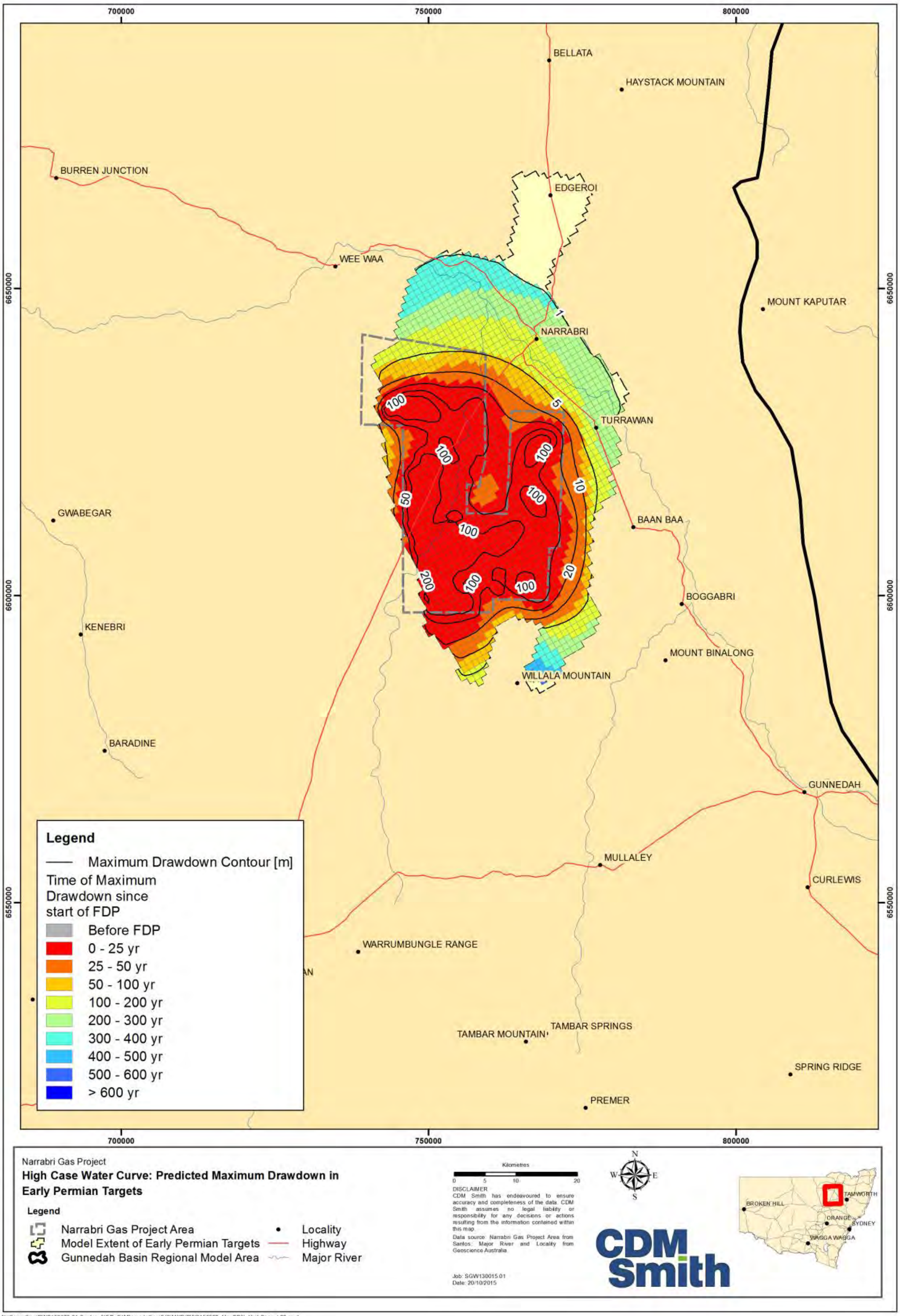


**Figure 6-53 Simulation HC: predicted maximum drawdown in Early Permian targets**

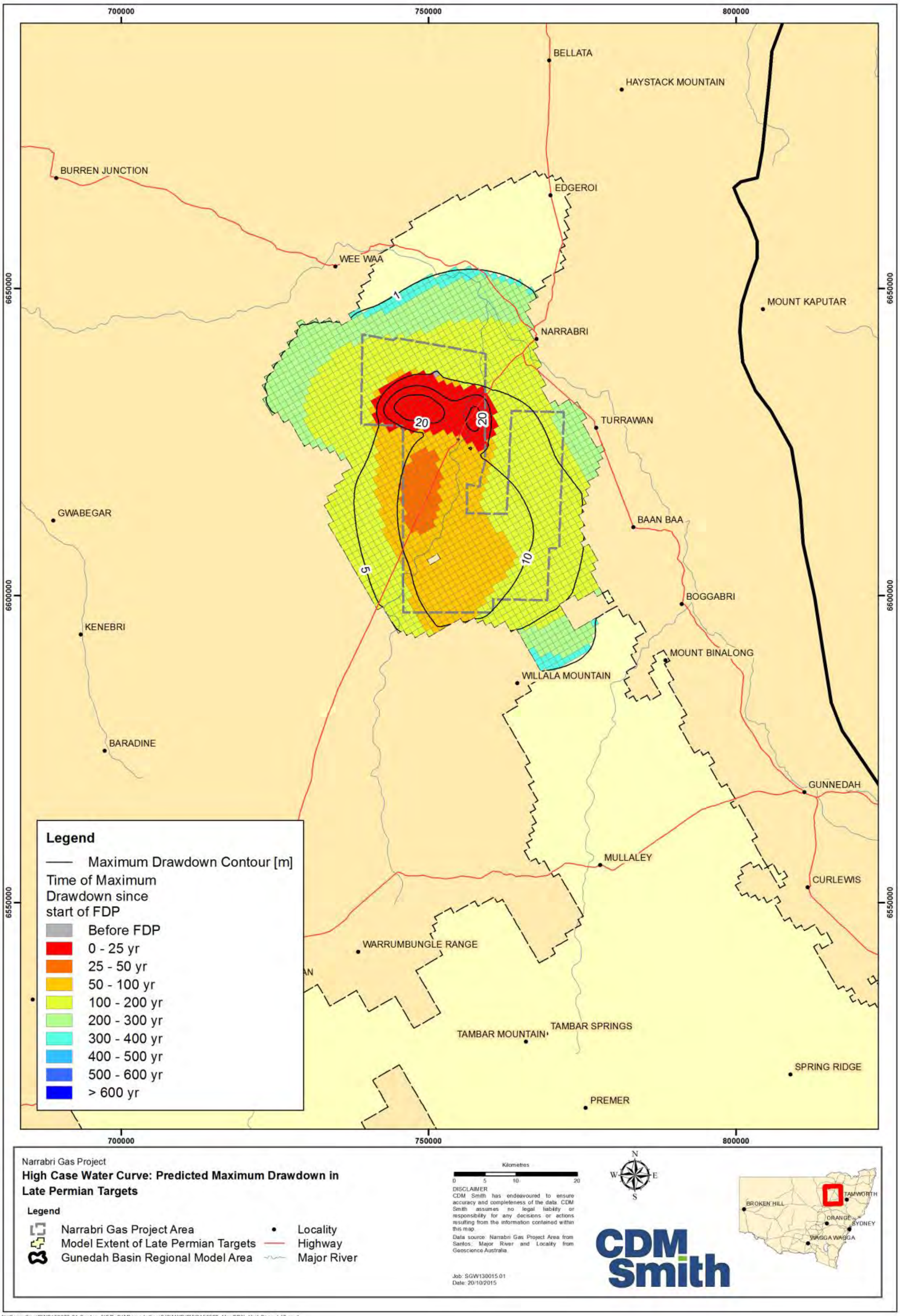


**Figure 6-54 Simulation HC: predicted maximum drawdown in Late Permian targets**

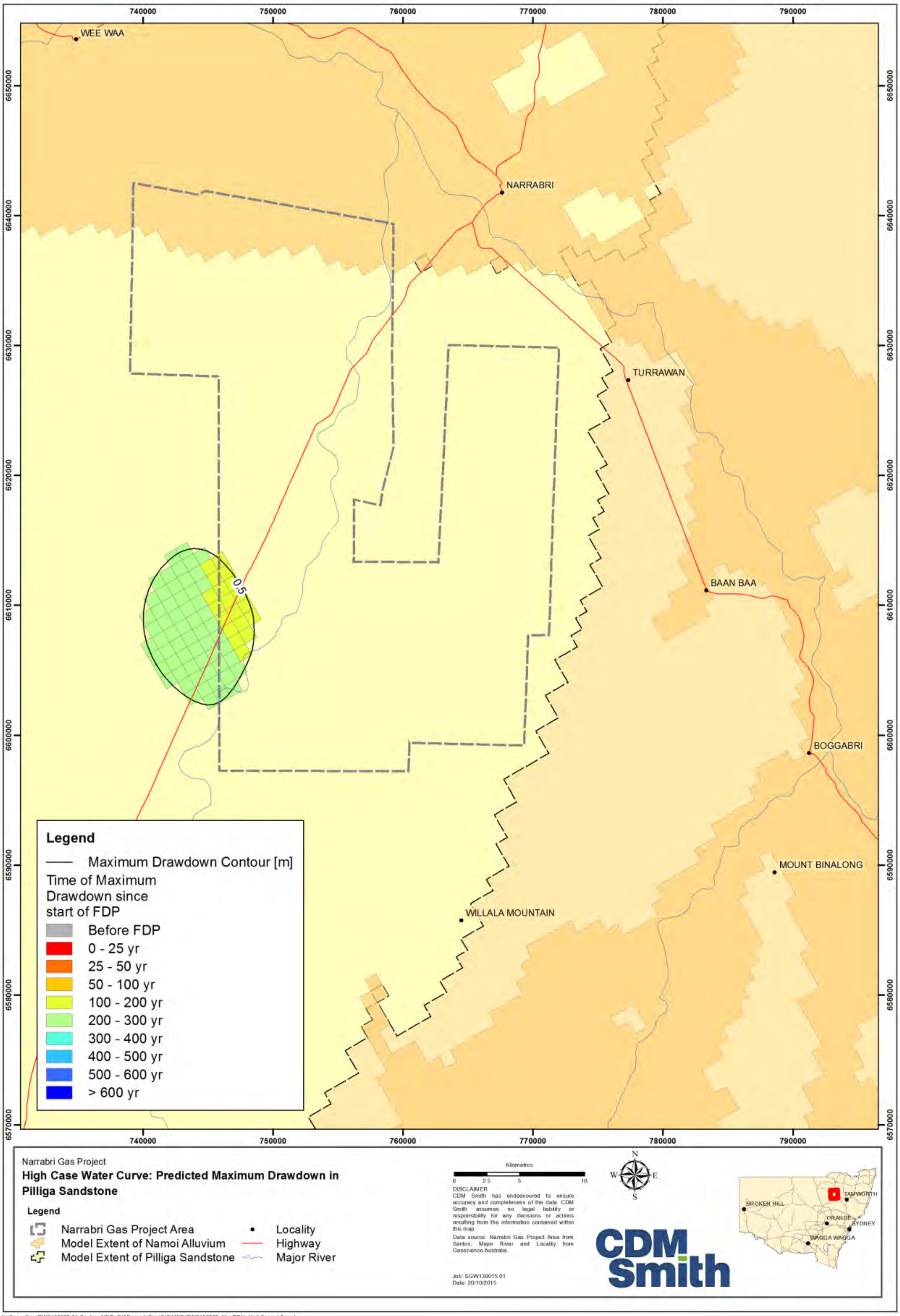


**Figure 6-55 Simulation HC: predicted maximum drawdown in Pilliga Sandstone**

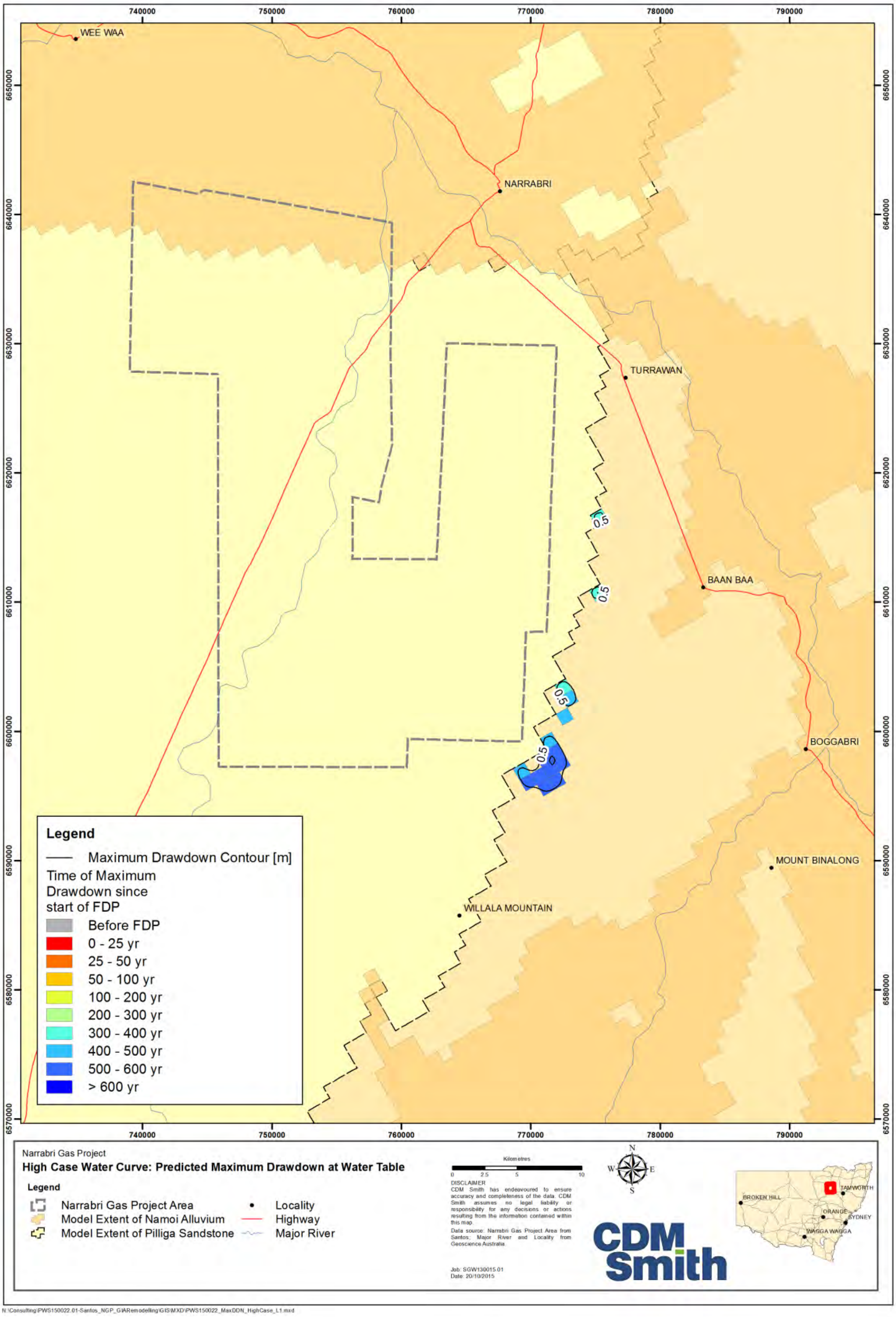


Figure 6-56 Simulation HC: predicted maximum drawdown at the water table

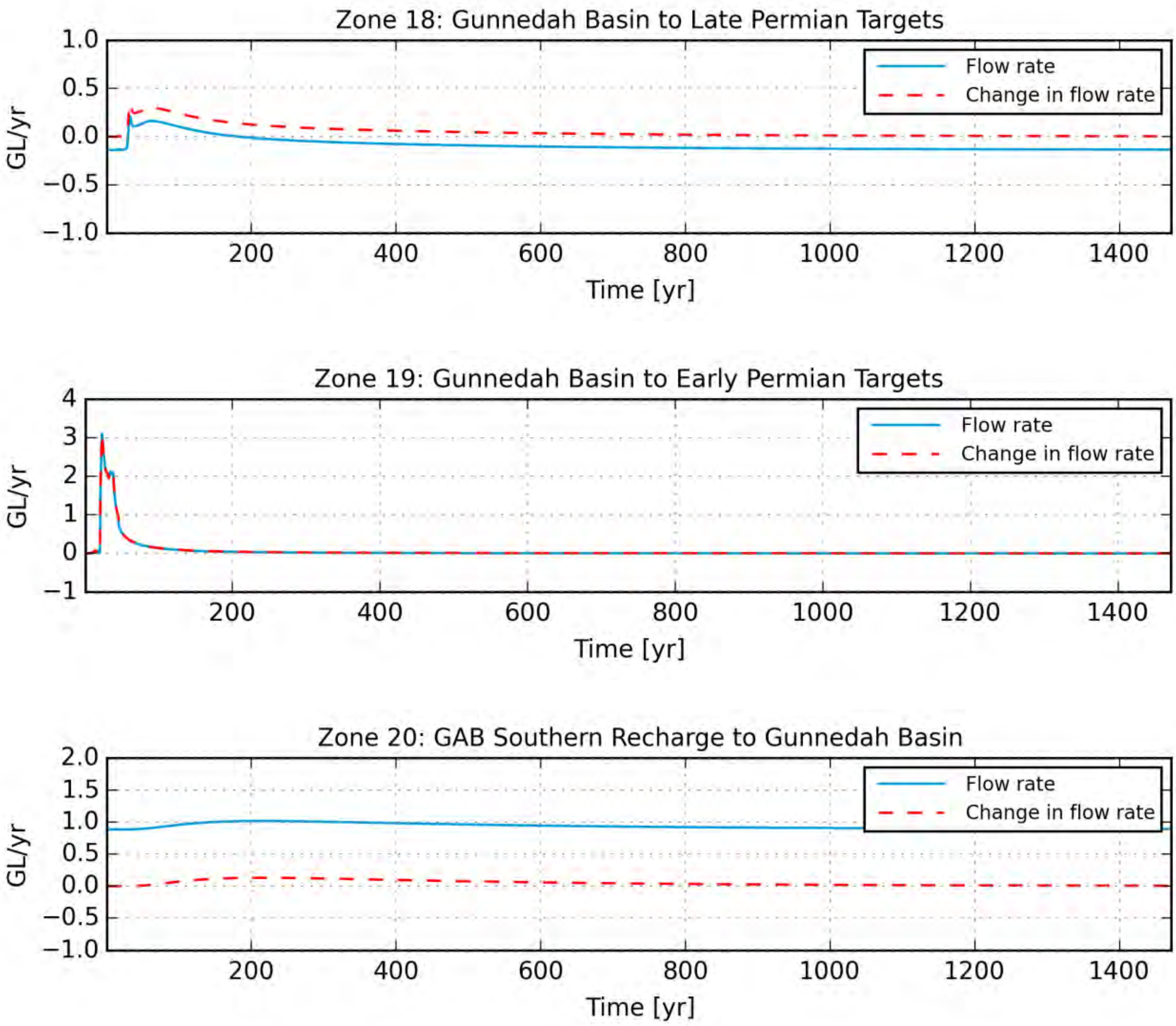


**Figure 6-57 Simulation HC: time variation of flow rates between selected WSPRAs**

### 6.9.4 Narrabri Coal Mine and Base Case Simulated Water Production

These simulations considers the potential impacts of sole development of the Narrabri Coal Mine Stage 2 Longwall Project without coal seam gas development (NCM) and the potential cumulative impacts of the Narrabri Coal Mine Stage 2 Longwall Project and the Base Case water production profile (NCM-BC). The review of predicted drawdown at the existing and approved coal mines within the GIA study in Section 5.5.6 concludes that cumulative impacts from the other mines are unlikely. As such they have not been considered further in this assessment.

Potential impacts of the Narrabri Coal Mine Stage 2 Longwall Project are based on existing predictions of mine inflow rates over the proposed 29-year life of mine (Aquaterra 2009). Table 6-26 lists the predicted average annual inflow rates for this period. Full commercial production of coal from the longwall was achieved in October 2012 and therefore mine year 1 in Table 6-26 is taken to be 2012 in this assessment.

Figure 6-58 shows the cumulative water extraction profile including the predicted mine inflow in Table 6-26 and the simulated Early and Late Permian water production for the Base Case, assuming first water production from the project commences in 2017. Year 1 in Figure 6-58 corresponds to year 2012. Mine inflow represents the predicted rate of groundwater drainage from the Hoskissons Coal (Late Permian) into the underground mine workings during the course of mining.

The locations of model cells used for simulating water extraction associated with mine inflow are shown in Figure 6-59.

It is understood that post mining there will be a need to dispose of approximately 2018 ML of saline water, which is proposed to be reinjected into the Hoskissons Coal (Aquaterra 2009). This has been represented in existing modelling simulations by Aquaterra as reinjection over 2 years (2.76 ML/d) using 20 reinjection bores (0.14 ML/d/bore) and with the goaf and fracture zone parameter values retained during this period. The proposed spacing of bores is unknown.

Within the above context, two predictive simulations are considered in this section.

#### 6.9.4.1 Narrabri Coal Mine (NCM)

The first simulation considers the potential impacts of the Narrabri Coal Mine Stage 2 Longwall in isolation from other activities, and includes following stresses to groundwater:

- Historical water production from the existing twelve gas pilots within the Gunnedah Basin, commencing in 1998 (approximately 1 GL);
- Inflow from Hoskissons Coal to the Narrabri Mine underground workings, commencing in 2012 and ceasing after 2040 (22.6 GL); and
- Reinjection into Hoskissons Coal commencing in 2041 and ceasing after 2042 (2 GL);

Total groundwater extraction for this simulation consists of 1 GL of historical water production from existing pilots, 22.6 GL of mine inflow and 2 GL of reinjection, giving net groundwater extraction of 21.6 GL. The simulated period for development of the Narrabri Coal Mine Stage 2 Longwall Project is 31 years. The total simulation period is 1520.5 years, commencing in 1997.

#### 6.9.4.2 Narrabri Coal Mine and Base Case Scenario (NCM-BC)

The second simulation considers the potential cumulative impacts of the Narrabri Coal Mine Stage 2 Longwall Project and the Base Case simulated water production for the Narrabri Gas Project, and includes following stresses to groundwater:

- Historical water production from the existing twelve gas pilots within the Gunnedah Basin, commencing in 1998 (approximately 1 GL);
- Inflow from Hoskissons Coal to Narrabri Mine underground workings commencing in 2012 and ceasing after 2040 (22.6 GL);
- Reinjection into Hoskissons Coal commencing in 2041 and ceasing after 2042 (2 GL);
- Base Case simulated future water production from the Early Permian coal seam targets, commencing in in July 2017 and ceasing after June 2042 (35.6 GL); and
- Base Case simulated future water production from the Late Permian coal seam gas targets, commencing in July 2027 and ceasing after June 2042 (1.89 GL).

Total water production and extraction for this simulation consists of 1 GL of historical extraction from pilots, 20.6 GL net extraction from the Narrabri Coal Mine and 37.5 GL future extraction from the project, giving net total groundwater extraction of 59.1 GL. The simulated period for development of the Narrabri Coal Mine Stage 2 Longwall Project is 31 years. The total simulation period is 1520.5 years, commencing in 1997.

**Table 6-26 Narrabri Coal Mine predicted groundwater inflow (after Aquaterra 2009)**

| Mine Year | Weighted Average Inflow | | |
|---|---|---|---|
| | kL/d | ML/d | ML/y |
| 1 | 213 | 0.21 | 78 |
| 2 | 226 | 0.23 | 82 |
| 3 | 337 | 0.34 | 123 |
| 4 | 923 | 0.92 | 337 |
| 5 | 914 | 0.91 | 334 |
| 6 | 1393 | 1.39 | 508 |
| 7 | 1386 | 1.39 | 506 |
| 8 | 1746 | 1.75 | 637 |
| 9 | 1771 | 1.77 | 646 |
| 10 | 2099 | 2.10 | 766 |
| 11 | 1999 | 2.00 | 730 |
| 12 | 2508 | 2.51 | 915 |
| 13 | 2381 | 2.38 | 869 |
| 14 | 3118 | 3.12 | 1138 |
| 15 | 2901 | 2.90 | 1059 |
| 16 | 3554 | 3.55 | 1297 |
| 17 | 3328 | 3.33 | 1215 |
| 18 | 3889 | 3.89 | 1419 |
| 19 | 3773 | 3.77 | 1377 |
| 20 | 3837 | 3.84 | 1401 |
| 21 | 3807 | 3.81 | 1390 |
| 22 | 2623 | 2.62 | 957 |
| 23 | 3019 | 3.02 | 1102 |
| 24 | 1956 | 1.96 | 714 |
| 25 | 2281 | 2.28 | 833 |
| 26 | 1559 | 1.56 | 569 |

| Mine Year | Weighted Average Inflow | | |
|---|---|---|---|
| | kL/d | ML/d | ML/y |
| 27 | 1709 | 1.71 | 624 |
| 28 | 1174 | 1.17 | 429 |
| 29 | 1454 | 1.45 | 531 |

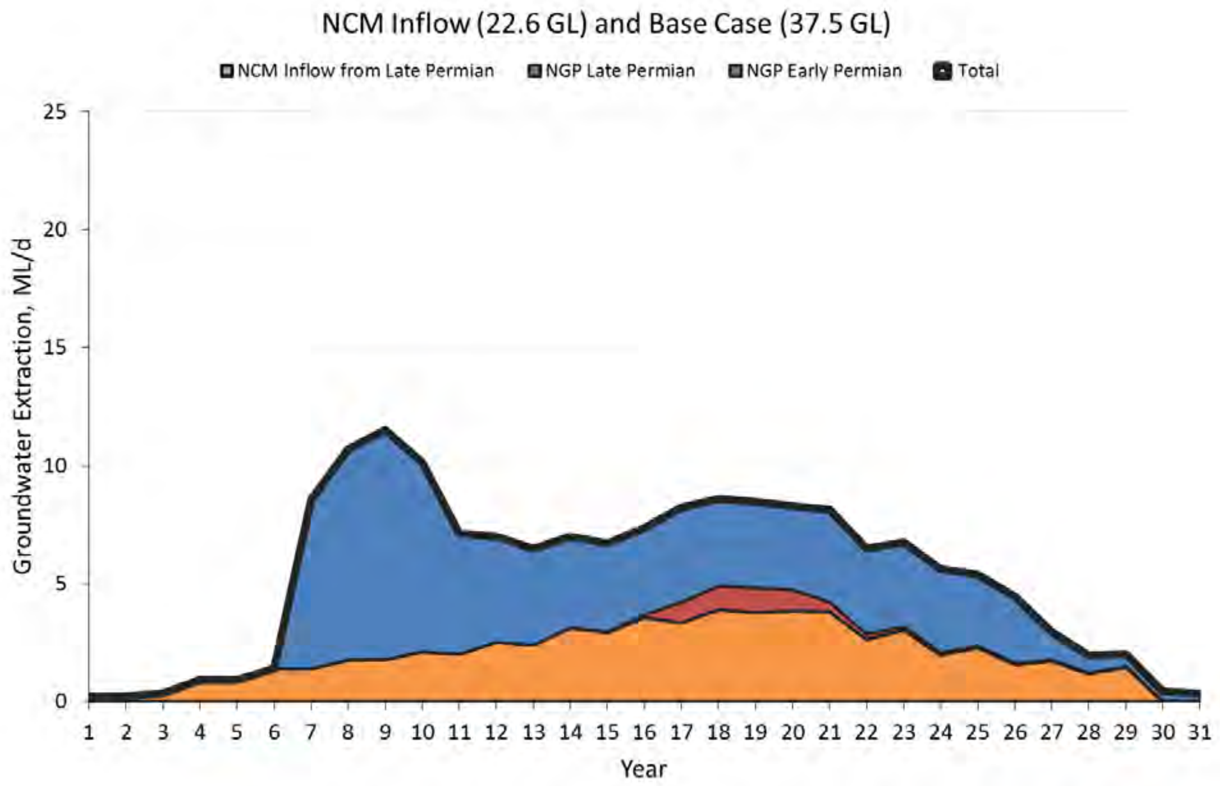


**Figure 6-58 Cumulative water profile for Narrabri Coal Mine inflow and Base Case water profile**

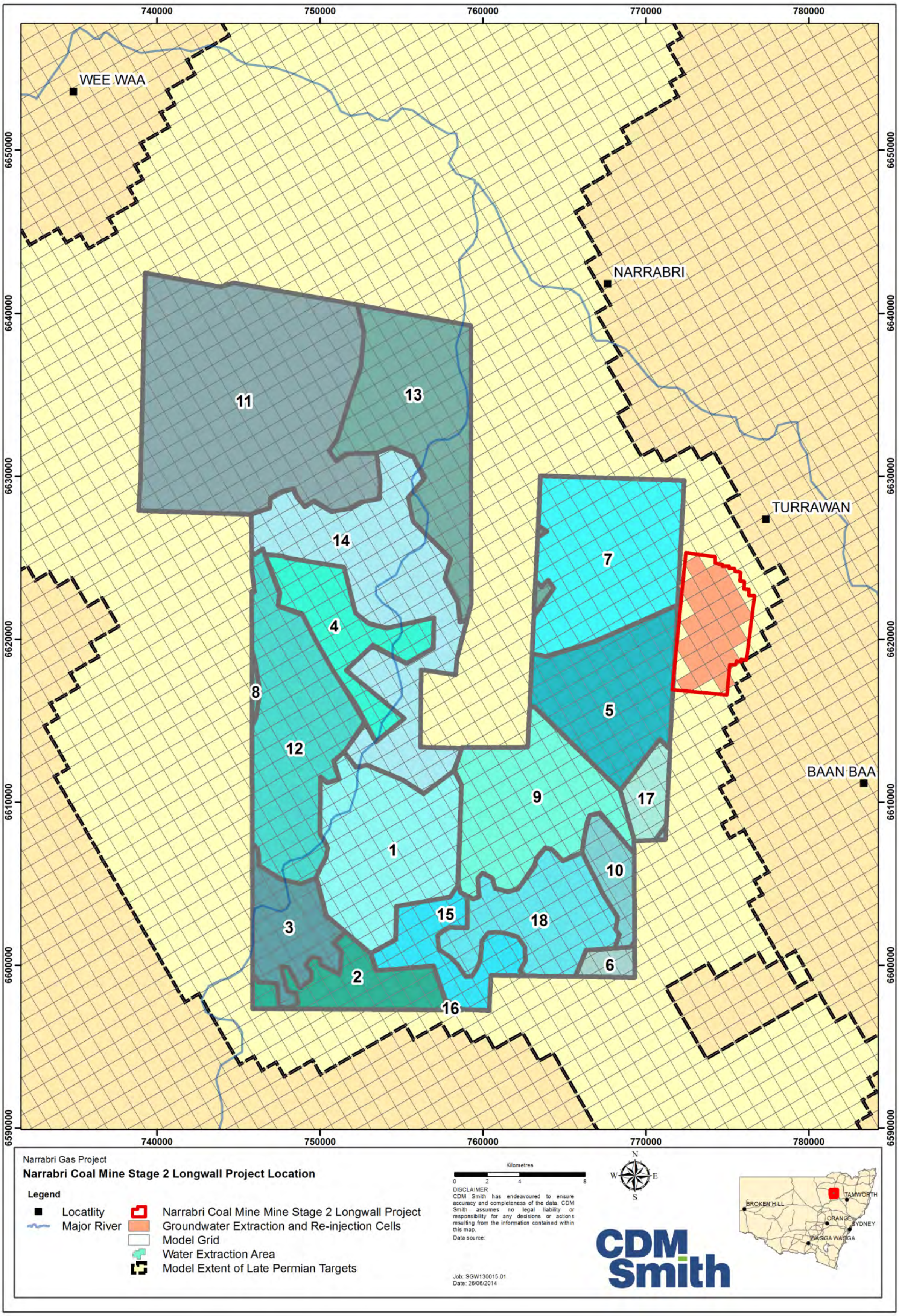


**Figure 6-59 Narrabri Coal Mine Stage 2 Longwall Project location**

#### 6.9.4.3 Predicted Impacts

The predicted impacts in these simulations differ significantly from the Base Case water production profile due to the influence of mine inflow at the Narrabri Coal Mine. The most significant differences are predicted maximum drawdown of up to 276 m in the Late Permian coal seam targets, 1.8 m in the Pilliga Sandstone and 5.2 m at the water table outside of the Namoi alluvium. These larger impacts are dominated by the effects from mine inflow. Predicted maximum drawdown of the water table within the Namoi alluvium is less than 0.5 m.

- The largest predicted drawdown in the Early Permian targets due to the cumulative impacts of mine inflow and the simulated Base Case water production is predicted to be 153 m with maximum drawdowns occurring at between 1 and 450 years after the start of the FDP (Figure 6-67). In relation to the magnitude of this cumulative impact, there is no discernible difference between this results and the predicted maximum drawdown for the Base Case alone (compare Figure 6-67 and Figure 6-35); however, the period of time over which maximum drawdowns occur in the cumulative case (1 to 450 years) is larger than the Base Case alone (1 to 300 years).
- The largest drawdown in the Late Permian targets is predicted to be approximately 275 m both for sole development of the Narrabri Coal Mine and for concurrent development with the Narrabri Gas Project, with maximum drawdowns occurring up to 300 years after the start of the FDP for the cumulative case, and up to 250 years after the start of the FDP for the Base Case alone (Figure 6-68 and Figure 6-69). The predicted cumulative impacts of mine inflow and simulated coal seam water production occur within a radial distance of around 15 km from the centre of the Narrabri Coal Mine Stage 2 Longwall Project area, wherein the drawdown is dominated by the impacts of mine inflow. In comparison, the largest predicted drawdown in the Late Permian targets for the Base Case is 16.4 m. No cumulative impacts are predicted in the Late Permian targets outside of this area.
- The largest predicted drawdown in the Pilliga Sandstone is 1.8 m both for sole development of the Narrabri Coal Mine and with concurrent development of the Narrabri Gas Project, with maximum drawdowns occurring at between 48 and 90 years after the start of the FDP (Figure 6-70 and Figure 6-71). Based on the patterns and timing of predicted maximum drawdown, there are no predicted cumulative impacts from the projects in the Pilliga Sandstone.
- The largest value of drawdown at the water table is predicted to be 5.2 m both for sole development of the Narrabri Coal Mine and with concurrent development of the Narrabri Gas Project (Figure 6-72 and Figure 6-73). In the cumulative case, the extent of maximum drawdown is slightly larger and the time to reach maximum drawdown is also longer in some areas. In comparison, the largest predicted drawdown at the water table for the Base Case alone is less than 0.5 m. The predicted cumulative drawdown at the water table is dominated by the effects of mine inflow from Late Permian strata.
- The maximum predicted change in groundwater flow rate between WSPRAs is compared in Figure 6-61. A small cumulative impact of concurrent development of the Narrabri Coal Mine and Narrabri Gas Project can be seen as an increase in the maximum change in flow rate between the Gunnedah Basin and Late Permian targets (WSPRA 18) which increases from 0.17 GL/y (5.4 L/s) to 0.83 GL/y (26 L/s) (compare Figure 6-61a and c). Other predicted cumulative impacts on groundwater exchanges between WSPRP are negligible.
- The majority of the produced water is predicted to come from induced storage release in the Gunnedah-Oxley Basin and GAB, with a small contribution from the Lower Namoi Alluvium (Figure 6-63 and Figure 6-62). For sole development of the Narrabri Coal Mine the predicted maximum storage release from the Gunnedah-Oxley Basin is approximately 1.2 GL/y at around

15 years after the start of the simulated FDP. In comparison, for concurrent development with the Narrabri Gas Project, the predicted maximum storage release from the Gunnedah-Oxley Basin is approximately 3.5 GL/y at around 3 years after the start of the FDP. The predicted maximum rate of storage release from the Gunnedah-Oxley Basin for the Base Case is approximately 2.9 GL/y. For concurrent development of the Narrabri Coal Mine and Narrabri Gas Project the predicted maximum rate of storage release from the GAB is approximately 0.17 GL/y at around 150 years after the start of the FDP compared to 0.1 GL/y at around 190 years for the Base Case.

- At the end of the recovery period (1500 years after the start of the FDP) and with concurrent development of the Narrabri Coal Mine and Narrabri Gas Project the predicted contributions to the total simulated water extraction of 61.1 GL are approximately: 40.3 GL (66%) from the GAB; 13.5 GL (22.1%) from the Gunnedah-Oxley Basin; 3.9 GL (6.4%) from the Lower Namoi Alluvium and 1.3 GL (2.2%) from the Upper Namoi Alluvium and 2 GL (3.3%) from reinjection (Figure 6-65). These amounts are counter balanced by matching additional inflow and reduced outflow in each of the groundwater source area over the period of the simulation.

**Table 6-27 Simulation NCM: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 5.2 | 48 to 120 |
| Pilliga Sandstone | 1.8 | 48 to 81 |
| Late Permian Targets | 275 | Pre-FDP to 250 |
| Early Permian Targets | 57 | Pre-FDP to 250 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-28 Simulation NCM-BC: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 5.2 | 48 to 550 |
| Pilliga Sandstone | 1.8 | 48 to 90 |
| Late Permian Targets | 276 | Pre-FDP to 300 |
| Early Permian Targets | 153 | 1 to 450 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-29 Simulation NCM: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | -0.01 | N |
| 2 | -1.26 | 0.00 | - | 0.69 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.03 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 0.67 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.00 | N |
| 18 | -0.14 | 0.67 | 25 | 17.3 | Y |
| 19 | 0.00 | 0.08 | -1 | 0.66 | Y |
| 20 | 0.89 | 0.05 | - | 13.2 | N |
| 21 | -0.08 | 0.00 | - | 0.02 | N |

[1]Years since start of FDP

**Table 6-30 Simulation NCM-BC: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | 0.00 | N |
| 2 | -1.26 | 0.01 | - | 3.93 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.18 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 1.14 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.01 | N |
| 18 | -0.14 | 0.83 | 14 | 48.14 | Y |
| 19 | 0.00 | 1.52 | 3 | 35.02 | Y |
| 20 | 0.89 | 0.08 | 160 | 44.14 | Y |
| 21 | -0.08 | 0.00 | - | 0.13 | N |

[1]Years since start of FDP

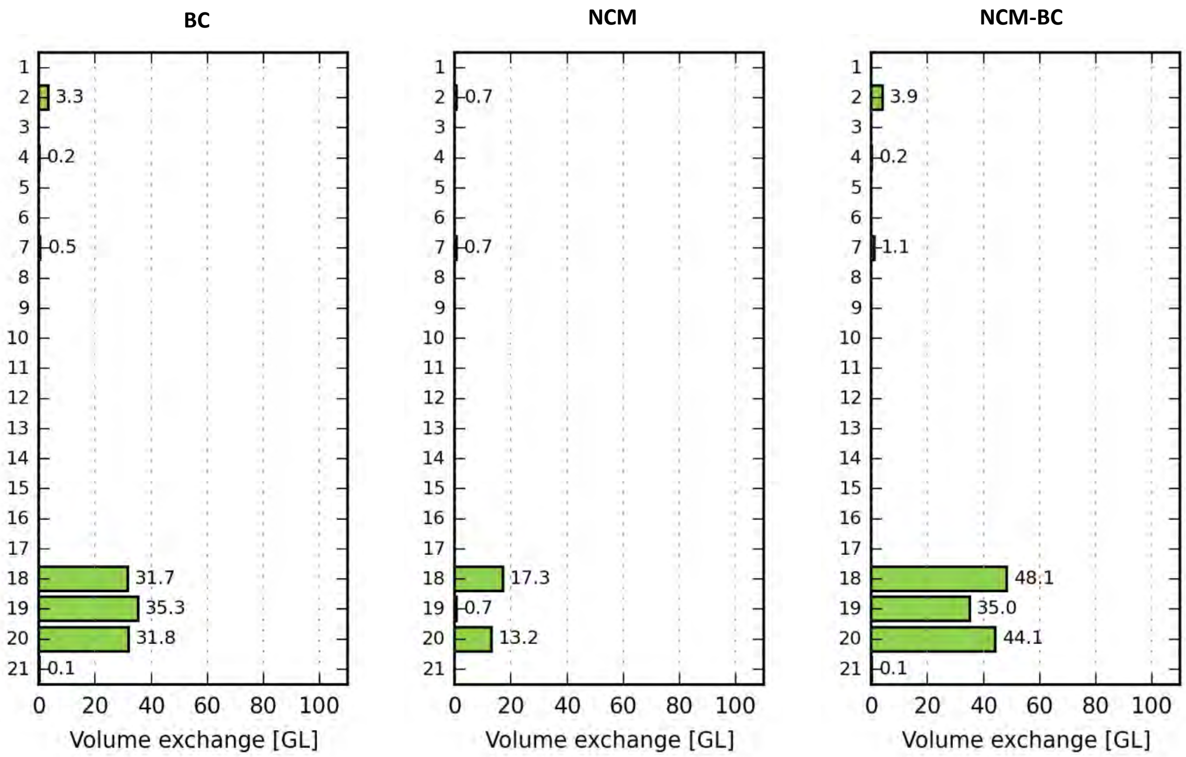


**Figure 6-60 Comparison of total predicted volumetric exchange between WSPRAs (a) simulation BC, (b) simulation NCM and (c) simulation NCM-BC**

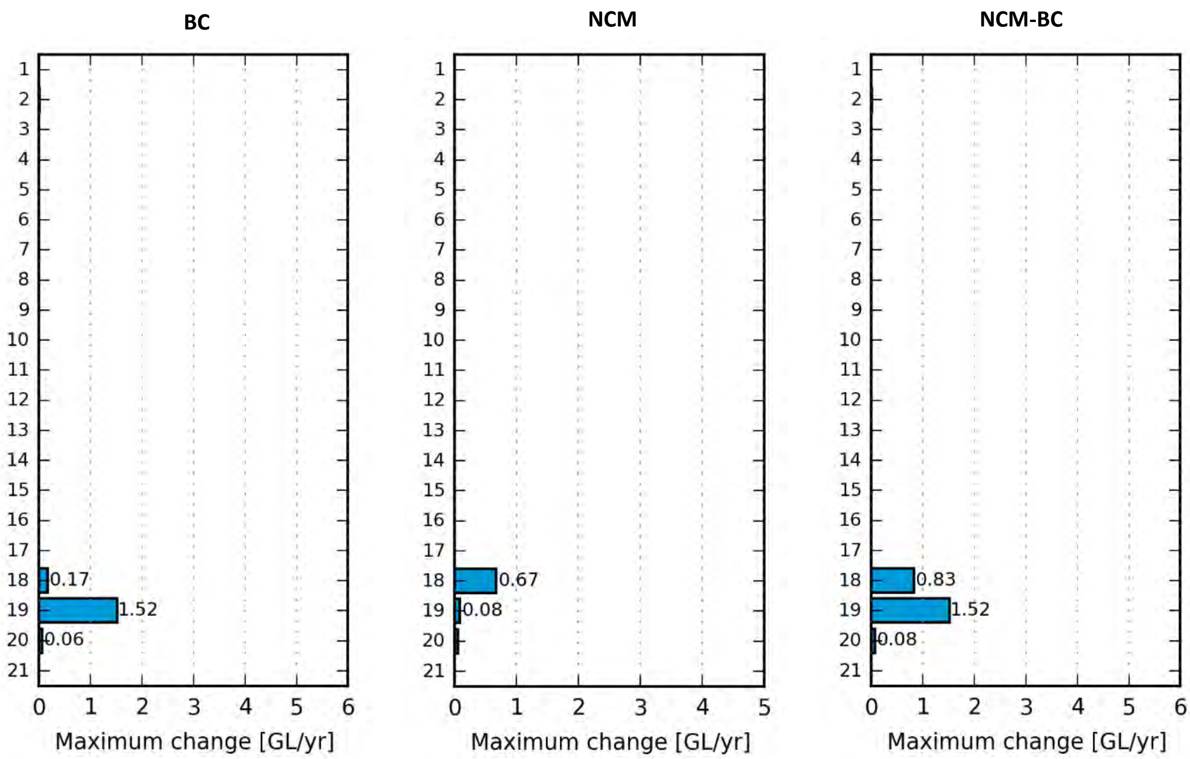


**Figure 6-61 Comparison of maximum predicted change in WSPRA Flow Rates (a) simulation BC, (b) simulation NCM and (c) simulation NCM-BC**

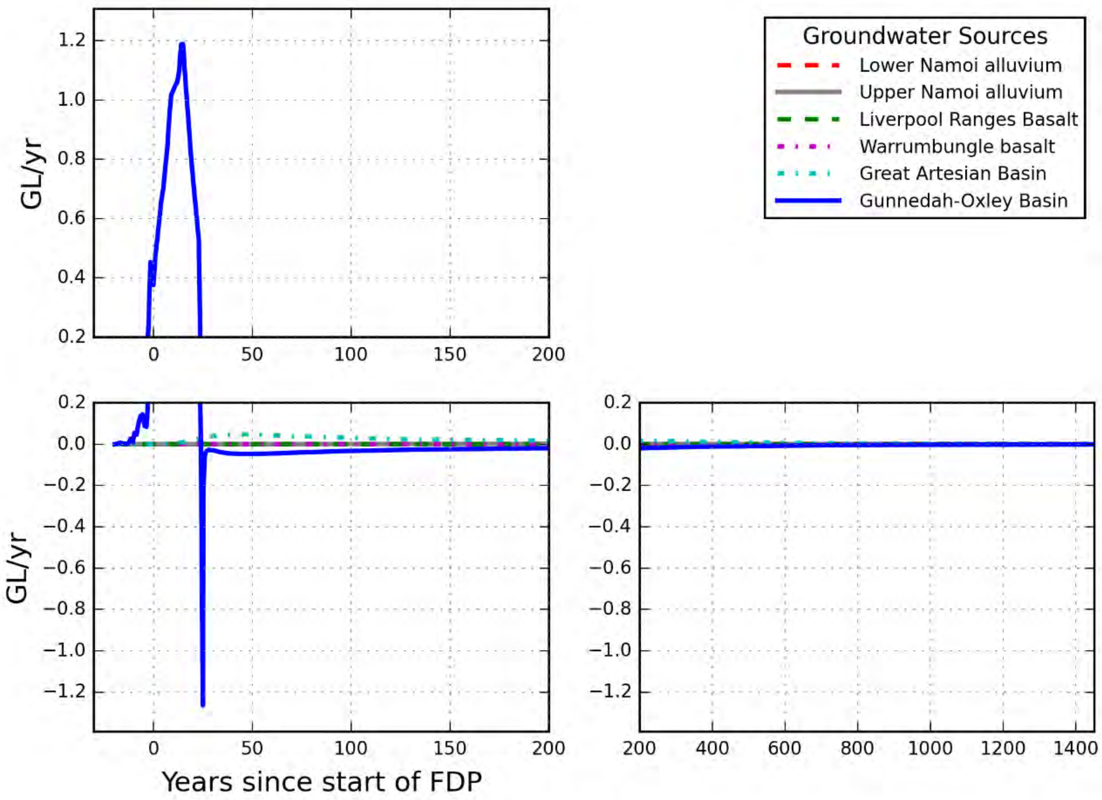


**Figure 6-62 Simulation NCM: predicted rates of induced storage releases**

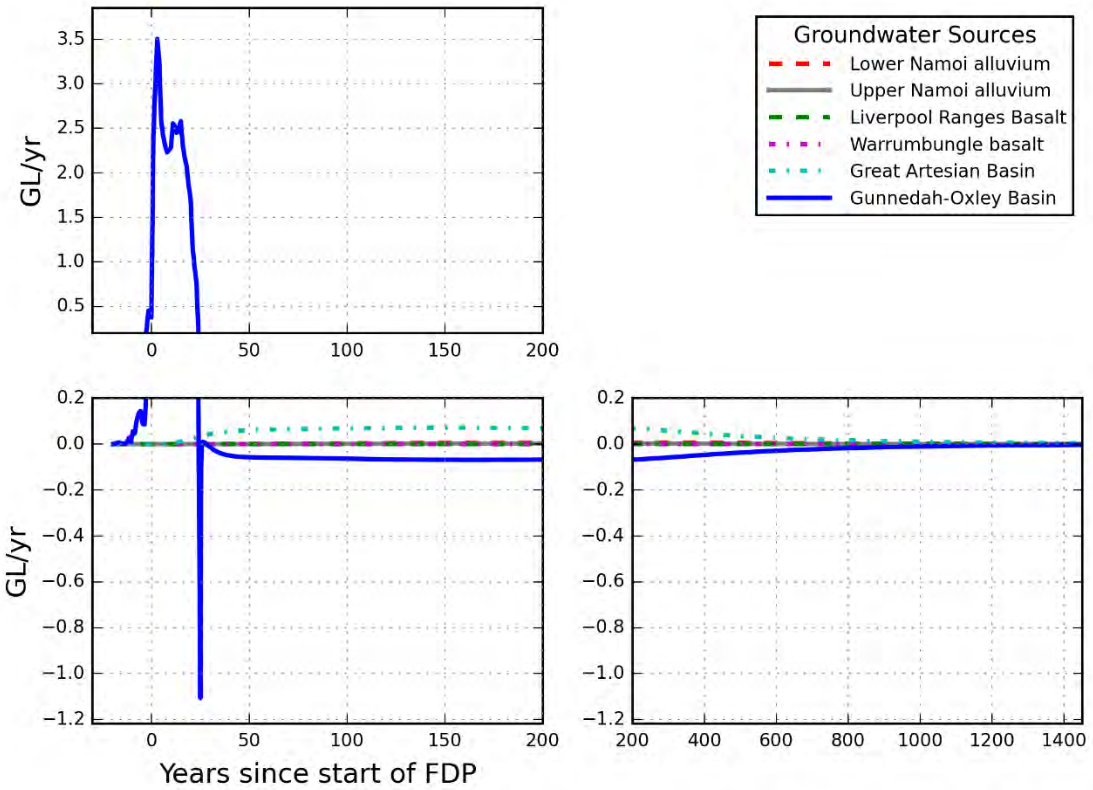


**Figure 6-63 Simulation NCM-BC: predicted rates of induced storage releases**

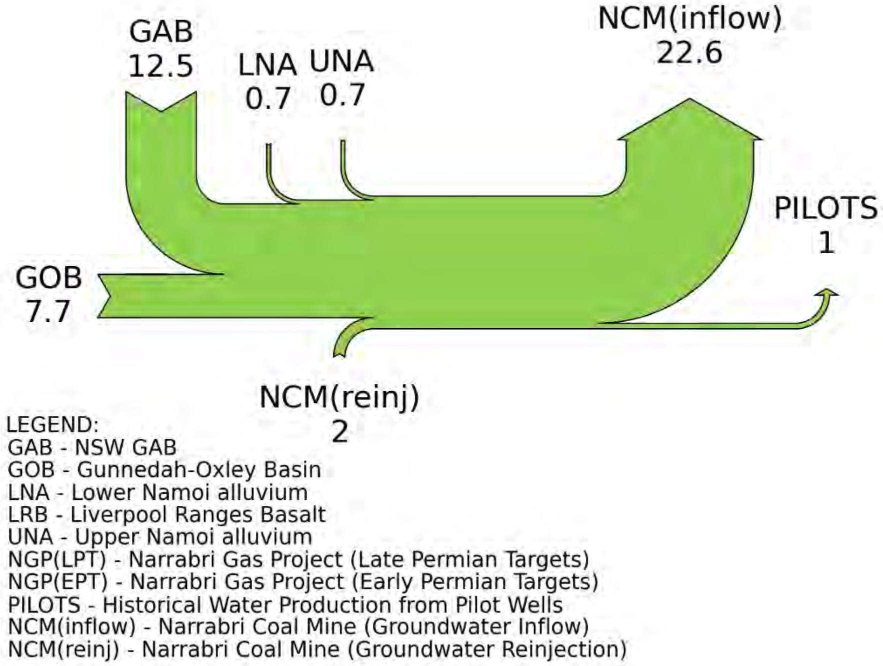


**Figure 6-64 Simulation NCM: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

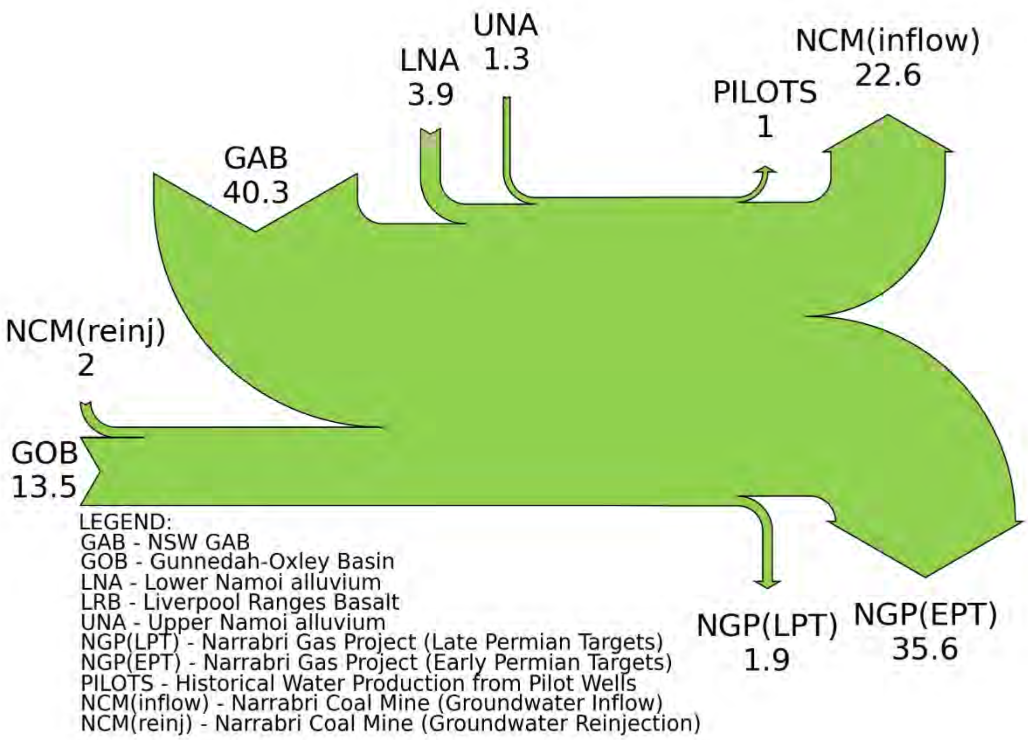


**Figure 6-65 Simulation NCM-BC: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

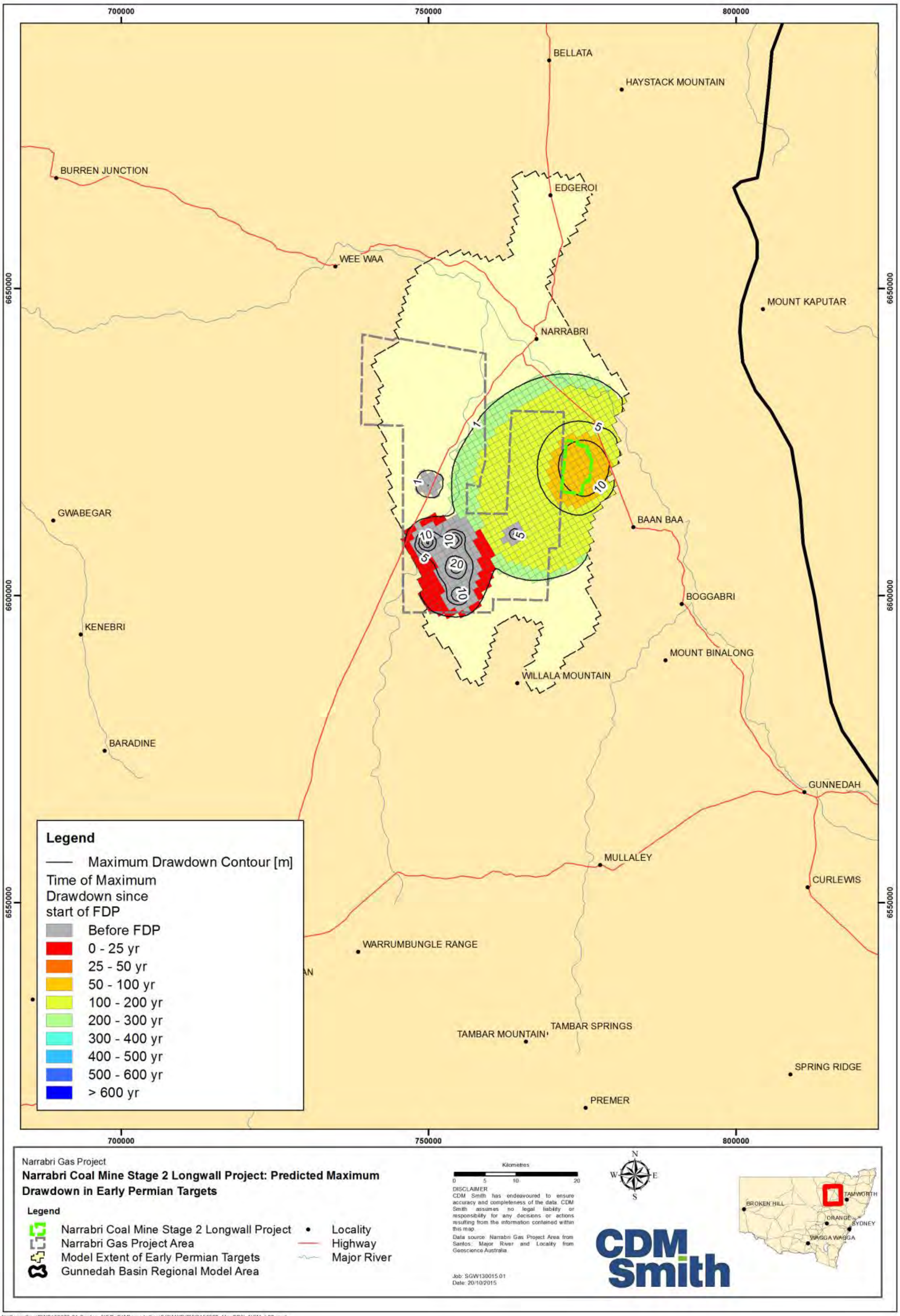


**Figure 6-66 Simulation NCM: predicted maximum drawdown in Early Permian targets**

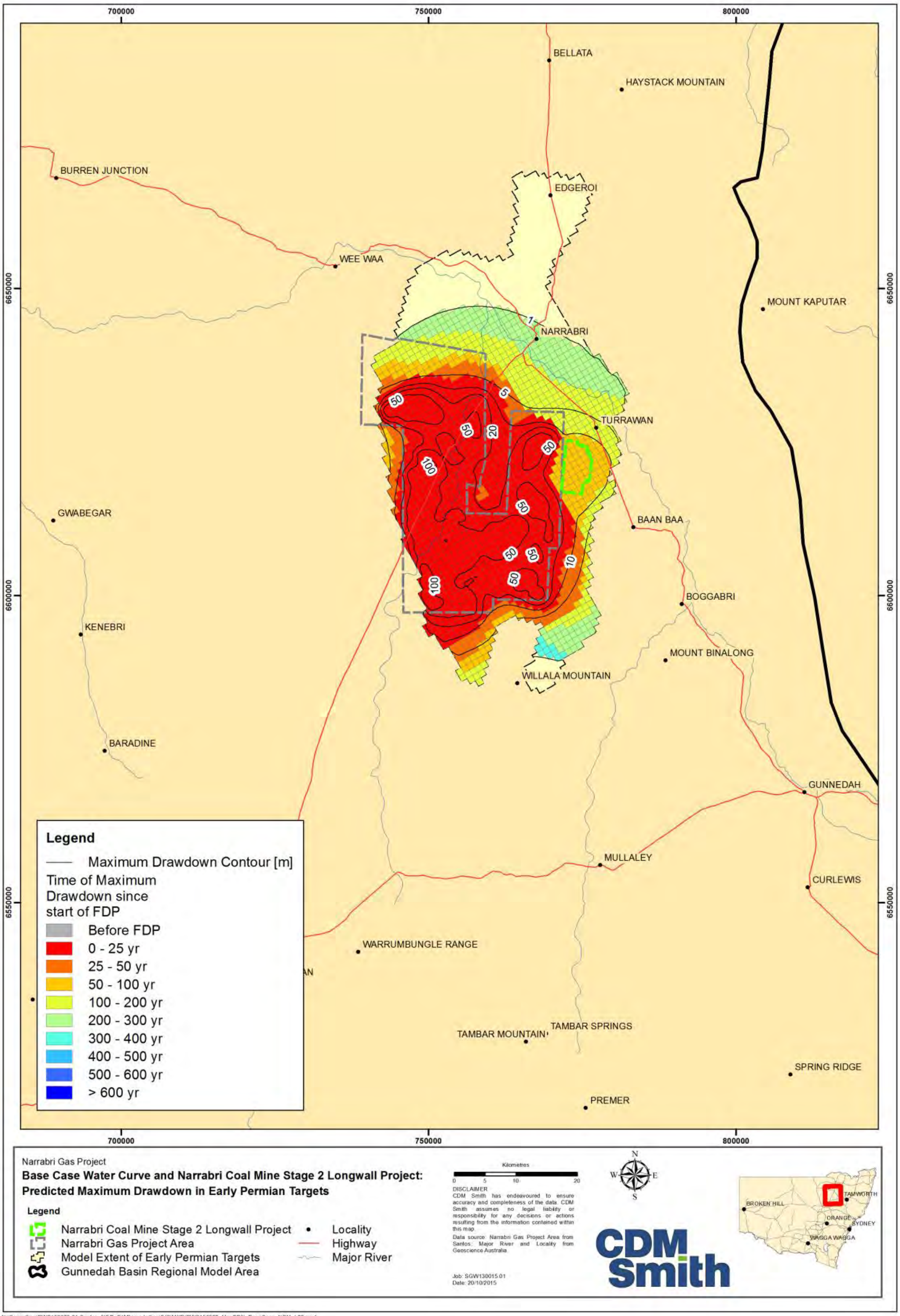


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**Figure 6-67 Simulation NCM-BC: predicted maximum drawdown in Early Permian targets**

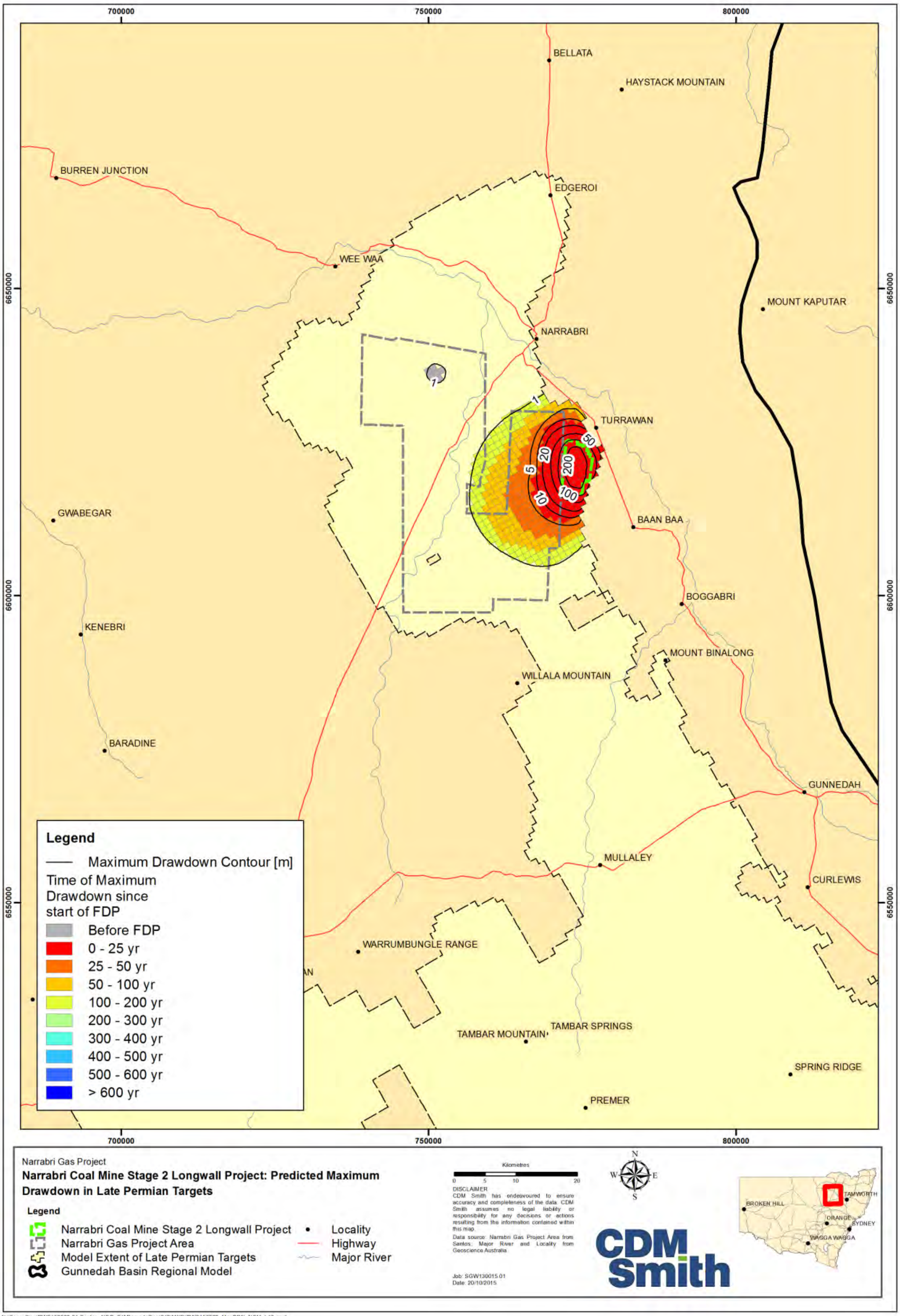


**Figure 6-68 Simulation NCM: predicted maximum drawdown in Late Permian targets**

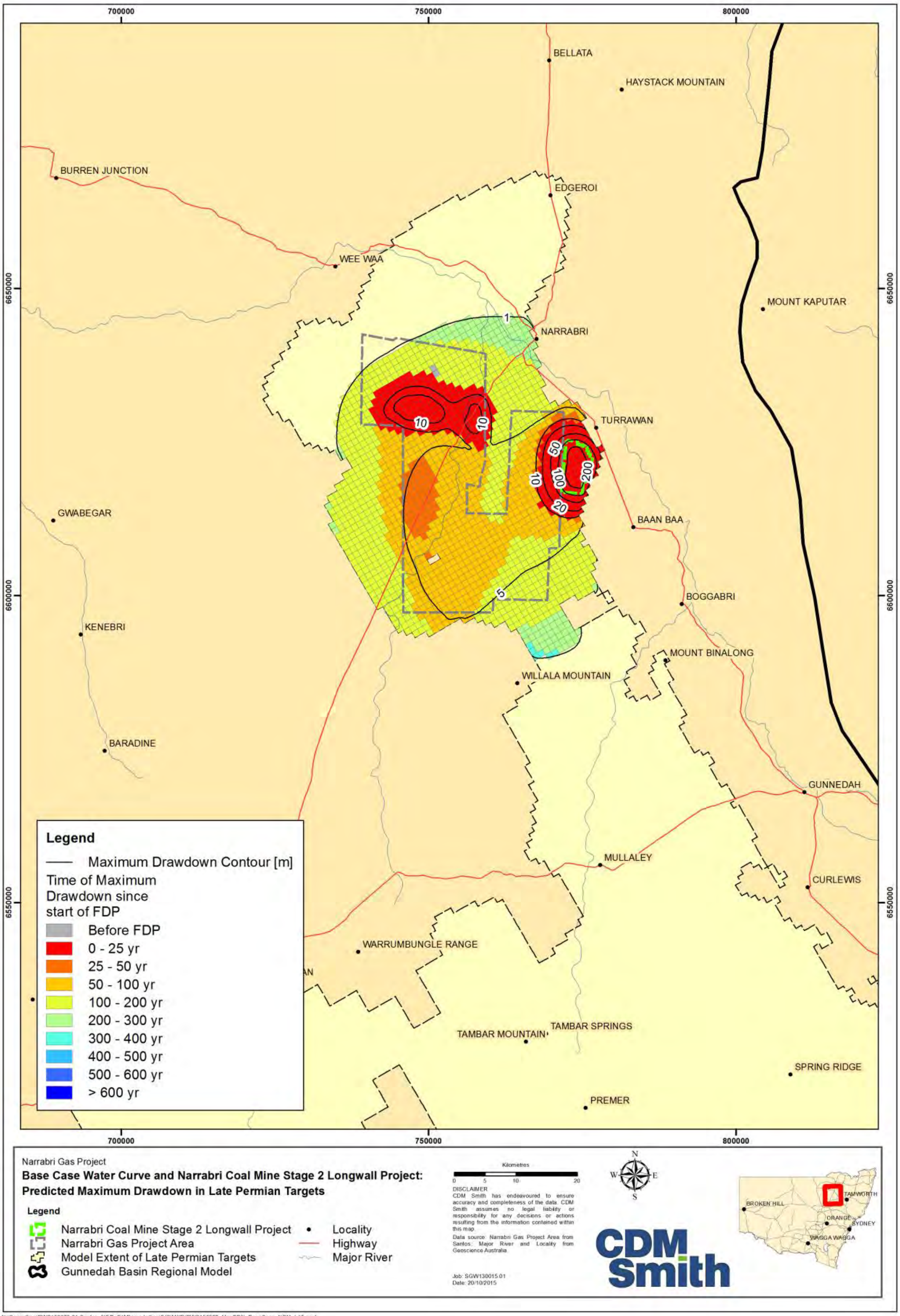


**Figure 6-69 Simulation NCM-BC: predicted maximum drawdown in Late Permian targets**

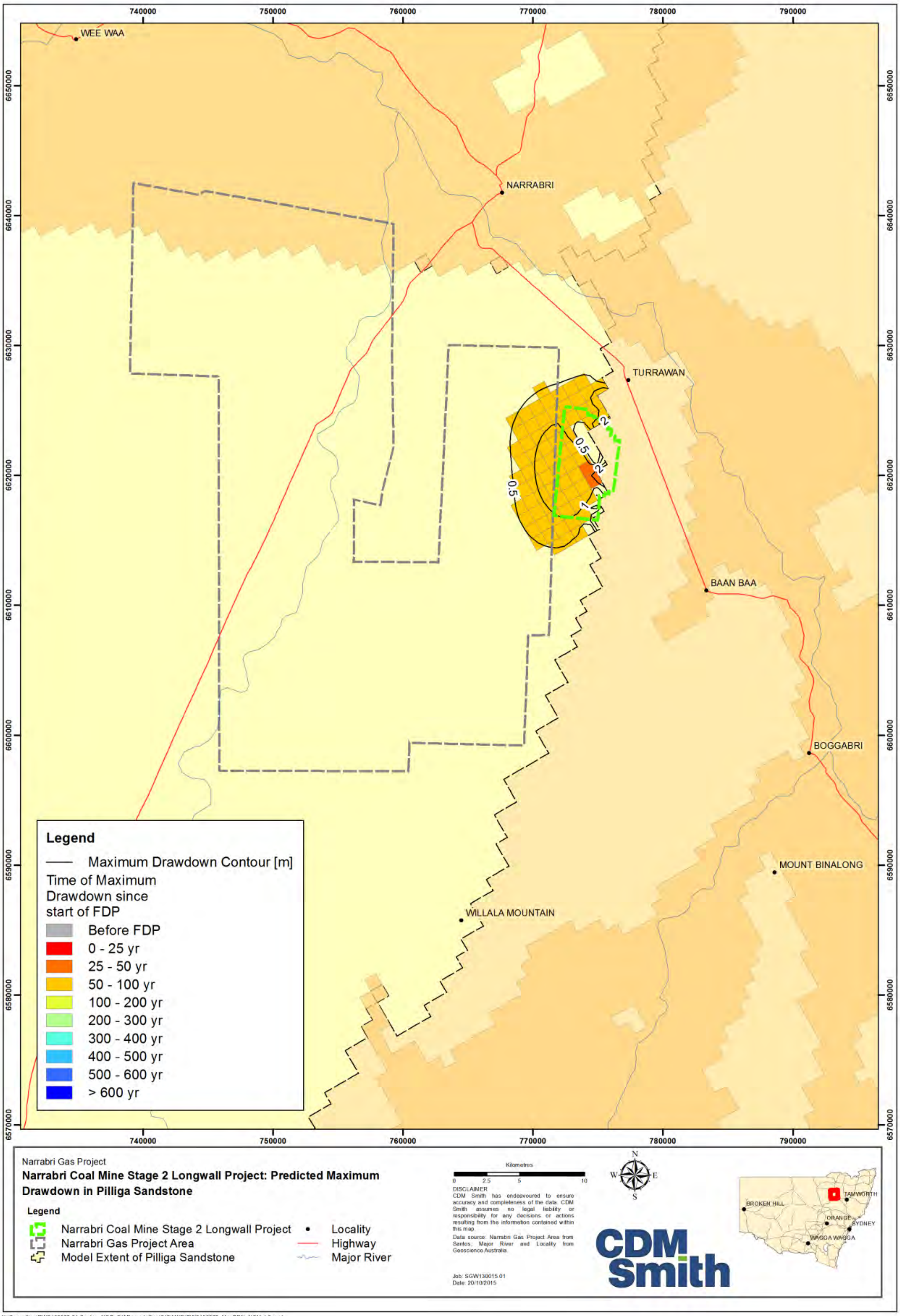


Figure 6-70 Simulation NCM: predicted maximum drawdown in Pilliga Sandstone

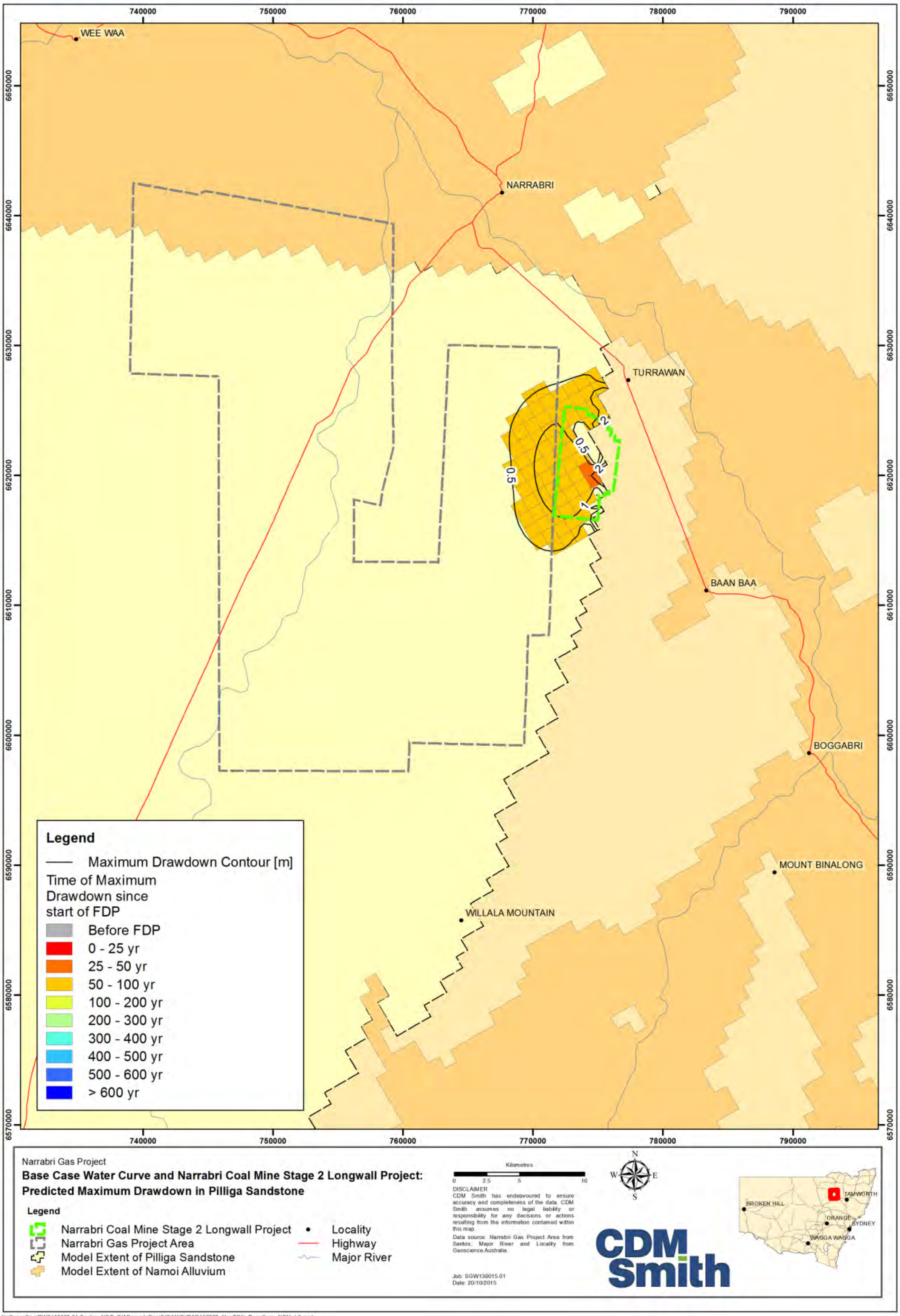


**Figure 6-71 Simulation NCM-BC: predicted maximum drawdown in Pilliga Sandstone**

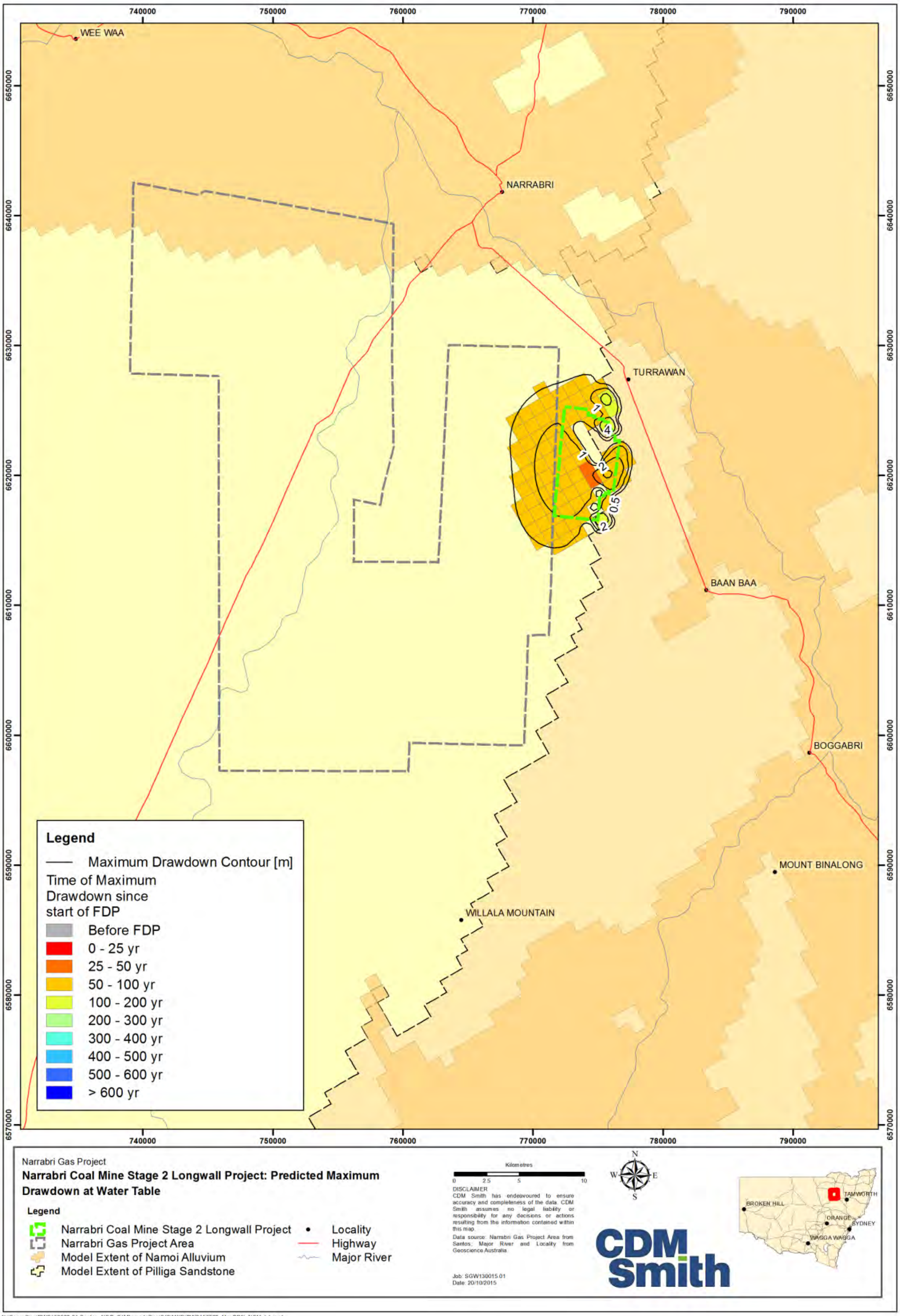


**Figure 6-72 Simulation NCM: predicted maximum drawdown at the water table**

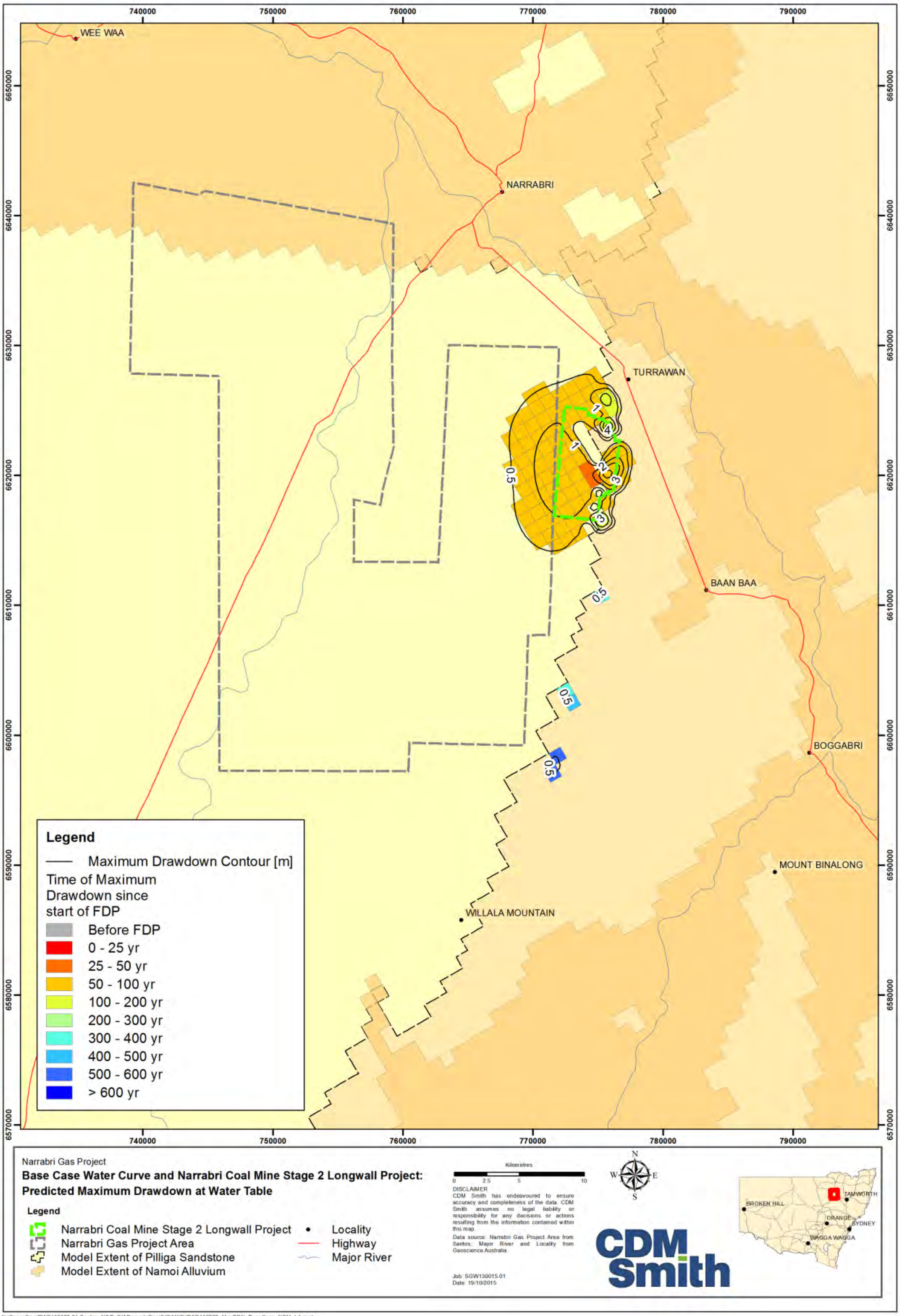


**Figure 6-73 Simulation NCM-BC: predicted maximum drawdown at the water table**

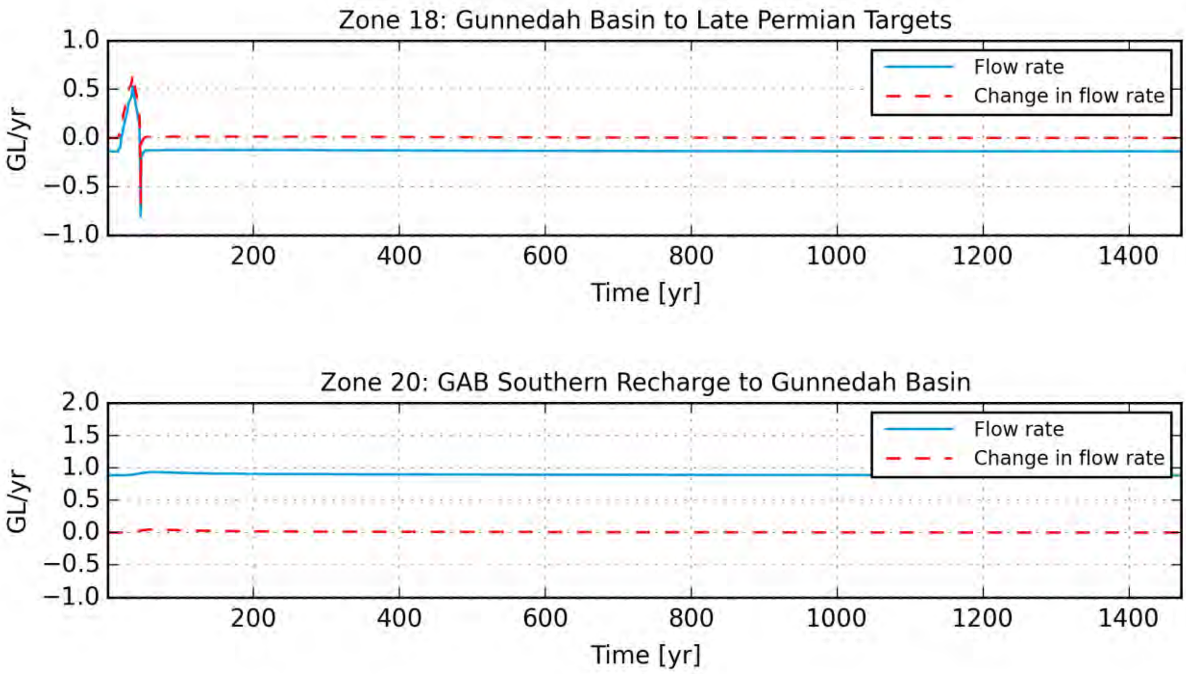


**Figure 6-74 Simulation NCM: time variation of flow rates between selected WSPRAs**

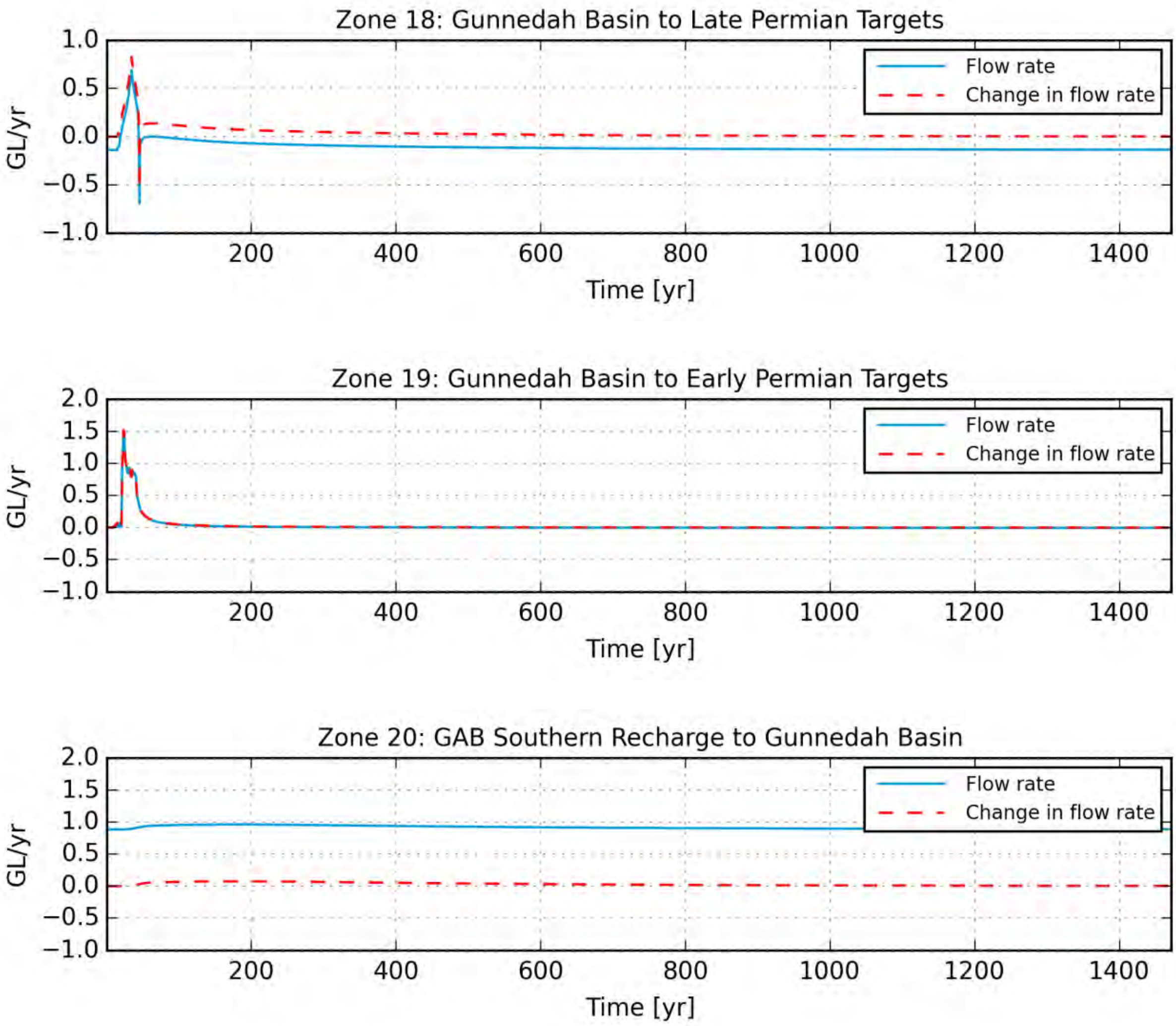


**Figure 6-75 Simulation NCM-BC: time variation of flow rates between selected WSPRAs**

# 6.10 Model Uncertainty and Sensitivity

## 6.10.1 Uncertainty in Simulated Water Production Volumes

In this assessment the rates and total volumes of simulated water production in each WEA in the Early Permian targets are inputs to the groundwater modelling that are provided by Santos based on the results of reservoir modelling. A degree of uncertainty in the predictions of the groundwater modelling is incorporated into the assessment by simulating three water production profiles that represent the Base Case and a Low Case and a High Case, as described in Section 6.8.2.

## 6.10.2 Sensitivity to Variation of Recharge

Groundwater simulations are normally expected to be sensitive to the rates of groundwater recharge that are imposed in the modelling; however, there are several reasons why a sensitivity analysis of recharge has not been assessed quantitatively in this study. The reasons are different for the areas inside and outside of the Namoi Alluvium.

Within the Namoi alluvium the sensitivity of predicted drawdown to variation of recharge must be considered within the context of the method used to match steady state heads (Section 6.5.2). It would be incorrect to simply vary the net recharge fluxes and re-run the predictive simulations as a sensitivity analysis because the new fluxes would be inconsistent with the hydrogeological properties and the initial heads. If done this way, the water table in the alluvium would change over time in response to the new net recharge fluxes but this change would be unrelated to simulated water production in the target coal seams. Done properly; each time the hydraulic conductivity is changed somewhere in the model, the net recharge fluxes in the alluvium must also be re-calculated to ensure that the initial condition is in steady state. It follows that a sensitivity analysis on the net recharge fluxes in the alluvium is effectively a sensitivity analysis on hydraulic conductivity in the alluvium. Within this context, simulated drawdown in the alluvium (less than 0.5 m for all predictive simulations) is not expected to be overly sensitive to hydraulic conductivity within the range of values that is consistent with existing investigations (Merrick 2001, McNeilage 2006, CSIRO 2007a).

Outside of the Namoi Alluvium, groundwater recharge is specified as a fixed percentage of annual average rainfall that is dependent on the subcrop geology (Section 6.4.5). Variations of these values for a sensitivity analysis would require new distributions of initial head for the predictive simulations. Larger recharge rates would tend to produce higher initial head outside of the alluvium and thereby raise the head throughout the system; and vice versa. In this situation the amount that recharge can be increased is limited because the water table may become unrealistically high, or the additional recharge may simply be 'rejected' as additional evapotranspiration. More generally, it is expected that predictions of drawdown of the water table outside of the alluvium will not be overly sensitive to variation of recharge because the principal mechanism for recovery of drawdown is reduced evapotranspiration. At locations where drawdown at the water table is predicted there will be a corresponding increase in the depth to water table toward the evapotranspiration extinction depth, thereby causing a decrease in the rate of evapotranspiration. Thus, recovery of the water table in areas outside of the alluvium occurs predominantly by reduced discharge rather than increased recharge.

## 6.10.3 Sensitivity to Variation of Hydrogeological Properties

Formal uncertainty analysis based on the identification of plausible combinations of the model parameters that satisfy acceptable calibration criteria has not been attempted due to the lack of suitable calibration data.

The following observations are made in relation to sensitivity analysis:

- Variation of the hydrogeological properties of hydrostratigraphic units will not affect the rates and volumes of simulated water production, which are inputs to the groundwater modelling. Sensitivity analysis can therefore be conducted without consideration of potential effects on simulated water production.
- The lateral extent of depressurisation within the Bohena Trough is controlled mainly by the lateral extent of the model layers representing the Early and Late Permian targets. The Early Permian targets pinch out at depth and are fully contained within the Bohena Trough. Similarly, depressurisation within the Late Permian targets is mostly restricted to the Bohena Trough. Thus, it is expected that the lateral extent of drawdown predicted in the groundwater modelling is not overly sensitive to variation of horizontal hydraulic conductivity in these units, and instead is mainly controlled by their lateral extents, which are fixed in the modelling.
- It is expected that the main hydrogeological properties affecting drawdown and vertical propagation to the water table are vertical hydraulic conductivity, specific storativity and specific yield at the water table. In particular, the vertical hydraulic conductivities of the three aquitard sequences control the rate of upward vertical propagation (noting that downward propagation is prevented by the no flow condition at the base of the model). Specific storativity controls the magnitude of drawdown per unit volume of water production in confined formations, and specific yield influences the magnitude of drawdown at the water table.

Within the above context, this section considers the seven sensitivity simulations listed in Table 6-31, which are based on the Base Case simulated water production profile. They consist of selected variations of vertical hydraulic conductivity (*Kv*), specific storativity (*Ss*) and specific yield (*Sy*) as follows; noting that the sensitivity simulations are not equally likely and are considered to represent extreme conditions:

- **BC-S1** – *Kv* of aquitards is decreased by a factor of 10, thereby increasing the resistance to, and slowing the vertical propagation of drawdown. The decreased value of *Kv* is within the middle range of values expected for an aquitard compared to the adopted value of *Kv* which is within the upper range of these values (refer to Figure 5-4). Thus, in this sensitivity simulation the aquitards are more effective barriers to vertical flow compared to the predictive simulations.
- **BC-S2** – *Kv* of aquitards is increased by a factor of 10, thereby decreasing the resistance to, and speeding the vertical propagation of drawdown. The increased value of *Kv* is at the upper range of values expected for an aquitard and at the lower range of values expected for a poor aquifer (Figure 5-4). Thus, in this sensitivity simulation the aquitards are less effective barriers to vertical flow compared to the predictive simulations.
- **BC-S3** – *Ss* of aquitards and transmissive units is decreased by a factor of 10, thereby increasing the magnitude of drawdown per unit volume of simulated water production and speeding the propagation of drawdown. The decreased value of *Ss* is at the lower range of values expected for sedimentary rock compared to the adopted value of *Ss* which is within the middle range of these values (refer to Table 6-8). Thus, in this sensitivity simulation the transmissive strata have smaller storage capacities and experience larger drawdown compared to the predictive simulations.
- **BC-S4** – *Ss* of aquitards and transmissive units is increased by a factor of 10, thereby decreasing the magnitude of drawdown per unit volume of simulated water production and speeding the propagation of drawdown. The increased value of *Ss* is at the upper range of values expected for

sedimentary rocks (Table 6-8) and therefore the transmissive strata have larger storage capacities and experience smaller drawdown compared to the predictive simulations.

- **BC-S5 -** *Kv* of aquitards is increased by a factor of 10 and *Ss* of aquitards and transmissive units decreased by a factor of 10, representing a combination of BC-S2 and BC-S3. The increased value of *Kv* is at the upper range of values expected for an aquitard and at the lower range of values for a poor aquifer (Figure 5-4) and the decreased value of *Ss* is at the lower range of values expected for sedimentary rocks. Thus, in this sensitivity simulation the aquitards are less effective barriers to vertical flow and the transmissive strata have smaller storage capacities and experience larger drawdown compared to the predictive simulations.
- **BC-S6** – *Sy* of the Namoi alluvium is increased by a factor of 2 and *Sy* of all other outcropping formations are increased by a factor of 5, thereby decreasing the magnitude of drawdown at the water table.
- **BC-S7** – *Sy* of the Namoi alluvium is decreased by a factor of 2 and *Sy* of all other outcropping formations are decreased by a factor of 2, thereby increasing the magnitude of drawdown at the water table.

Because a head matching technique is used to derive net recharge fluxes within the Namoi alluvium (see Sections 6.4.4 and 6.5.2) a new distribution these fluxes and a new distribution of the initial heads is created each time the value of hydraulic conductivity is varied. As the initial conditions are generated from steady state simulations they are independent of variation of specific storativity and specific yield.

Results for the sensitivity simulations are presented and discussed in the following sections.

**Table 6-31 Selected simulations for sensitivity analysis**

| Short Name | Groundwater Stresses | Period of Simulation |
|---|---|---|
| BC-S1 | Base Case water production profile with vertical hydraulic conductivity of aquitards decreased by factor 10; aquitards include model layers 2-5, 7-12, 14-21 and 23-24 | 1997 to 3517 (1520.5 y) |
| BC-S2 | Base Case water production profile with vertical hydraulic conductivity of aquitards increased by factor 10; aquitards include model layers 2-5, 7-12, 14-21 and 23-24 | |
| BC-S3 | Base Case water production profile with storativity of aquitards and transmissive units decreased by factor 10; aquitards include model layers 2-5, 7-12, 14-21 and 23-24, and transmissive units include model layers 1, 6, 13 and 22 | |
| BC-S4 | Base Case water production profile with storativity of aquitards and transmissive units increased by factor 10; aquitards include model layers 2-5, 7-12, 14-21 and 23-24, and transmissive units include model layers 1, 6, 13 and 22 | |
| BC-S5 | Base Case water production profile with vertical hydraulic conductivity of aquitards increased by factor 10 and storativity of aquitards and transmissive units decreased by factor 10; aquitards include model layers 2-5, 7-12, 14-21 and 23-24, and transmissive units include model layers 1, 6, 13 and 22 | |
| BC-S6 | Base Case water production profile with specific yield of the Namoi alluvium increased by factor 2 and specific yield of all other outcropping units increased by factor 5 | |
| BC-S7 | Base Case water production profile with specific yield of the Namoi alluvium decreased by factor 2 and specific yield of all other outcropping units decreased by factor 2 | |

### 6.10.4 Variation of Vertical Hydraulic Conductivity

Results for simulations BC-S1 and BC-S2 are presented in Table 6-33 to Table 6-36 and Figure 6-76 to Figure 6-90. Variation of vertical hydraulic conductivity (*Kv*) of the three main aquitard sequences influences the vertical propagation of drawdown by affecting the rate of vertical groundwater flow through the aquitards. Decreasing *Kv* has the effect of increasing local drawdown at extraction locations by slowing the rate of inflow from overlying and underlying formations. Increasing *Kv* has the opposite effect, decreasing local drawdown but increasing the speed at which effects are propagated into adjacent formations. The applied values of *Kv* for each simulation are indicated in Table 6-32.

**Table 6-32 Variation of vertical hydraulic conductivity**

| Simulation | Kv [m/d] | Applicable Model Layers |
|---|---|---|
| BC | 1E-5 | 2-5, 7-12, 14-21, 23, 24 |
| BC-S1 | 1E-6 | |
| BC-S2 | 1E-4 | |

### 6.10.4.1 Key Results BC-S1

- Within 1500 years after the start of the FDP nearly all of the impact of depressurisation is retained within Permian and Triassic strata of the Gunnedah Basin due to very slow propagation of drawdown through the aquitards.
- Compared to simulation BC the predicted result for decreased *Kv* of the aquitard sequences is larger maximum drawdown in the Early and Late Permian targets and much longer times for recovery of hydraulic head (Table 6-33). At the end of the simulation (approximately 1500 years) the zones of depressurisation in the Early and late Permian targets is still expanding and therefore the maximum drawdown values have not been reached at all locations. No drawdown greater than 0.5 m has propagated to the Pilliga Sandstone or water table by the end of the simulation.
- The maximum predicted change in groundwater flow rates between WSPRAs is compared in Figure 6-76. Relative to simulation BC, the maximum change in flow rates are smaller, including 1.08 GL/y (34 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19), 0.06 GL/y (2.0 L/s) from the Gunnedah Basin to the Late Permian targets (WSPRA 18) and less than 0.01 GL/y (<0.3 L/s) from the GAB Southern Recharge Area to the Gunnedah Basin. These reduced fluxes are the consequence of reduced *Kv* and increased resistance to vertical flow through the aquitards.
- Within the period of the simulation, almost all of the simulated water production is derived from induced storage release from the Gunnedah-Oxley Basin, with a predicted maximum rate of storage release of 2.1 GL/y at around 4 years after the start of the FDP. The predicted maximum rate of storage release from the GAB is less than 0.005 GL/y (5 ML/y) and occurs at the end of the simulation (Figure 6-78).
- Assessment of the final contributions from each groundwater source to total simulated water production is not possible in this instance because only partial recovery of hydraulic head occurs within 1500 years after the start of the FDP. Thus, small inter-formational flows induced by the simulated water production are predicted to be still active after 1500 years.

### 6.10.4.2 Key Results BC-S2

- Compared to simulation BC the predicted result for increased *Kv* of the aquitard sequences is decreased maximum drawdown in the Early Permian targets, and larger and more rapid maximum drawdown in the Late Permian targets, Pilliga Sandstone and at the water table due to upward vertical propagation of drawdown from the Early Permian targets.

- The largest value of drawdown in the Pilliga Sandstone is predicted to increase from less than 0.5 m in simulation BC to approximately 1 m in simulation BC-S2 with maximum drawdowns occurring between 27 and 90 years after the start of the FDP (Table 6-34). The largest value of drawdown at the water table outside of the Namoi alluvium is predicted to increase from less than 0.5 m to 0.9 m with maximum drawdowns occurring between 35 and 120 years after the start of the FDP. The patterns of predicted maximum drawdowns show predominantly vertical propagation of depressurisation to the water table (Figure 6-86 and Figure 6-88). No drawdown greater than 0.5 m is predicted in the Namoi alluvium.
- Relative to simulation BC, the maximum induced flows between WSPRAs are all larger, including 2.31 GL/y (73 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19), 0.8 GL/y (25 L/s) from the Gunnedah Basin to the Late Permian targets (WSPRA 18) and 0.47 GL/y (15 L/s) from the GAB Southern Recharge Area to the Gunnedah Basin (Figure 6-76).
- Almost all of the simulated water production comes from induced storage release from the Gunnedah-Oxley Basin and GAB. The predicted maximum rate of storage release of 3.1 GL/y from the Gunnedah-Oxley Basin occurs at around 3 years after the start of the FDP, and the predicted maximum rate of storage release of 0.46 GL/y from the GAB occurs at around 31 years after the start of the FDP (Figure 6-79). Complete recovery of hydraulic head occurs after around 400 years.
- At the end of simulation BC-S2, the predicted contributions to the total simulated water production of 38.5 GL are predominantly from the GAB (38.2 GL). Enhanced vertical propagation of drawdown results in a larger contribution to simulated water production from the GAB and a much smaller contribution from the Gunnedah-Oxley Basin (less than 1 GL).

**Table 6-33 Simulation BC-S1: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | < 0.5 | - |
| Pilliga Sandstone | < 0.5 | - |
| Late Permian Targets | 22 | Pre-FDP to >1500 |
| Early Permian Targets | 323 | 1 to >1500 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-34 Simulation BC-S2: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 0.9 | 35 to 120 |
| Pilliga Sandstone | 1.0 | 27 to 90 |
| Late Permian Targets | 12 | Pre-FDP to 61 |
| Early Permian Targets | 68 | Pre-FDP to 61 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-35 Simulation BC-S1: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -0.24 | 0.00 | - | 0.00 | N |
| 2 | -1.58 | 0.00 | - | 1.11 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.13 | 0.00 | - | 0.43 | N |
| 5 | -0.04 | 0.00 | - | 0.00 | N |
| 6 | -0.03 | 0.00 | - | 0.01 | N |
| 7 | -0.21 | 0.00 | - | 0.87 | N |
| 8 | -1.32 | 0.00 | - | 0.00 | N |
| 9 | -0.10 | 0.00 | - | 0.00 | N |
| 10 | -0.04 | 0.00 | - | 0.00 | N |
| 11 | -1.44 | 0.00 | - | 0.00 | N |
| 12 | 0.00 | 0.00 | - | 0.00 | N |
| 13 | -0.02 | 0.00 | - | 0.00 | N |
| 14 | 1.51 | 0.00 | - | 0.00 | N |
| 15 | 0.49 | 0.00 | - | 0.00 | N |
| 16 | 0.87 | 0.00 | - | 0.00 | N |
| 17 | 0.13 | 0.00 | - | 0.02 | N |
| 18 | -0.16 | 0.06 | 14 | 13.73 | Y |
| 19 | 0.00 | 1.08 | 4 | 29.91 | Y |
| 20 | 0.21 | 0.01 | - | 5.30 | N |
| 21 | -0.06 | 0.00 | - | 0.11 | N |

[1]Years since start of FDP

**Table 6-36 Simulation BC-S2: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -2.31 | 0.00 | - | -0.35 | N |
| 2 | -1.08 | 0.01 | - | 0.88 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.38 | 0.00 | - | 0.00 | N |
| 5 | -0.08 | 0.00 | - | 0.00 | N |
| 6 | -0.07 | 0.00 | - | 0.00 | N |
| 7 | -0.24 | 0.00 | - | -0.06 | N |
| 8 | -1.51 | 0.00 | - | 0.00 | N |
| 9 | -0.20 | 0.00 | - | 0.00 | N |
| 10 | -0.11 | 0.00 | - | 0.00 | N |
| 11 | -1.67 | 0.00 | - | 0.00 | N |
| 12 | -0.04 | 0.00 | - | 0.00 | N |
| 13 | -0.04 | 0.00 | - | 0.00 | N |
| 14 | 1.54 | 0.00 | - | 0.00 | N |
| 15 | 0.52 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | -0.19 | 0.00 | - | 0.00 | N |
| 18 | 0.15 | 0.80 | 12 | 37.15 | Y |
| 19 | 0.00 | 2.31 | 3 | 36.46 | Y |
| 20 | 1.80 | 0.47 | 31 | 38.82 | Y |
| 21 | -0.10 | 0.00 | - | -0.08 | N |

[1]Years since start of FDP

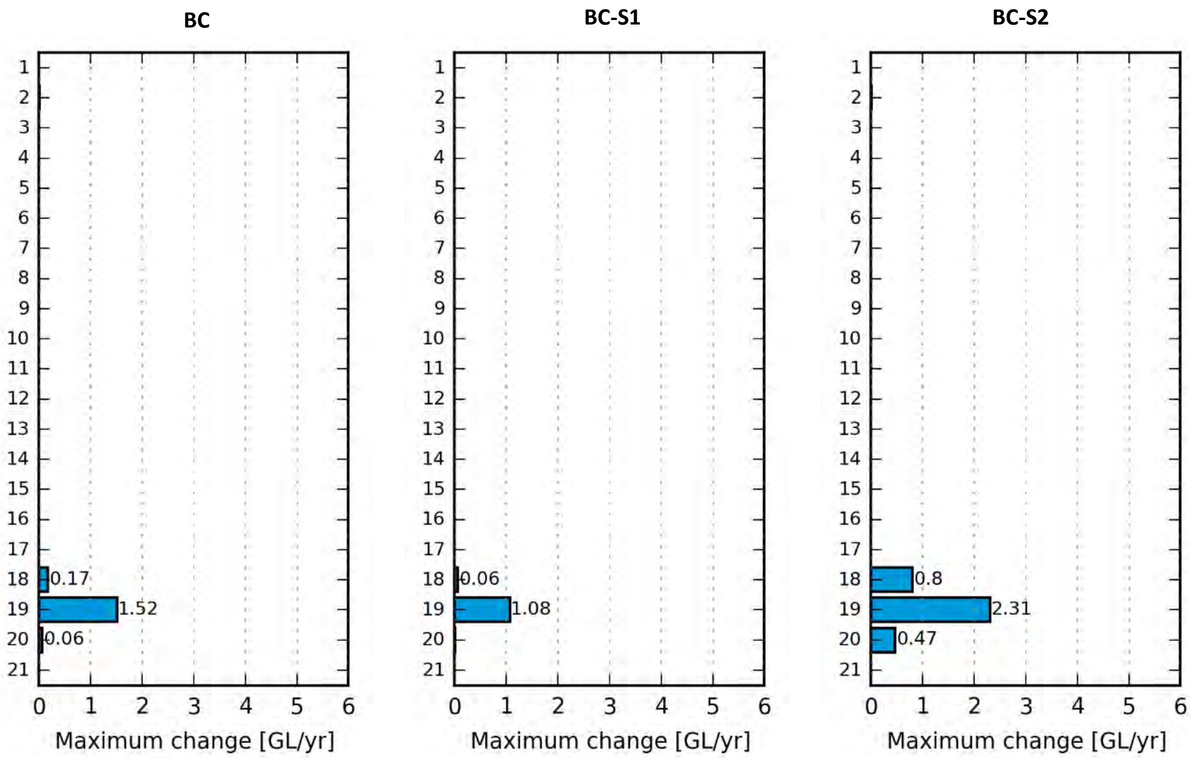


**Figure 6-76 Comparison of maximum predicted change in WSPRA Flow Rates (a) simulation BC, (b) simulation BC-S1 and (c) simulation BC-S2**

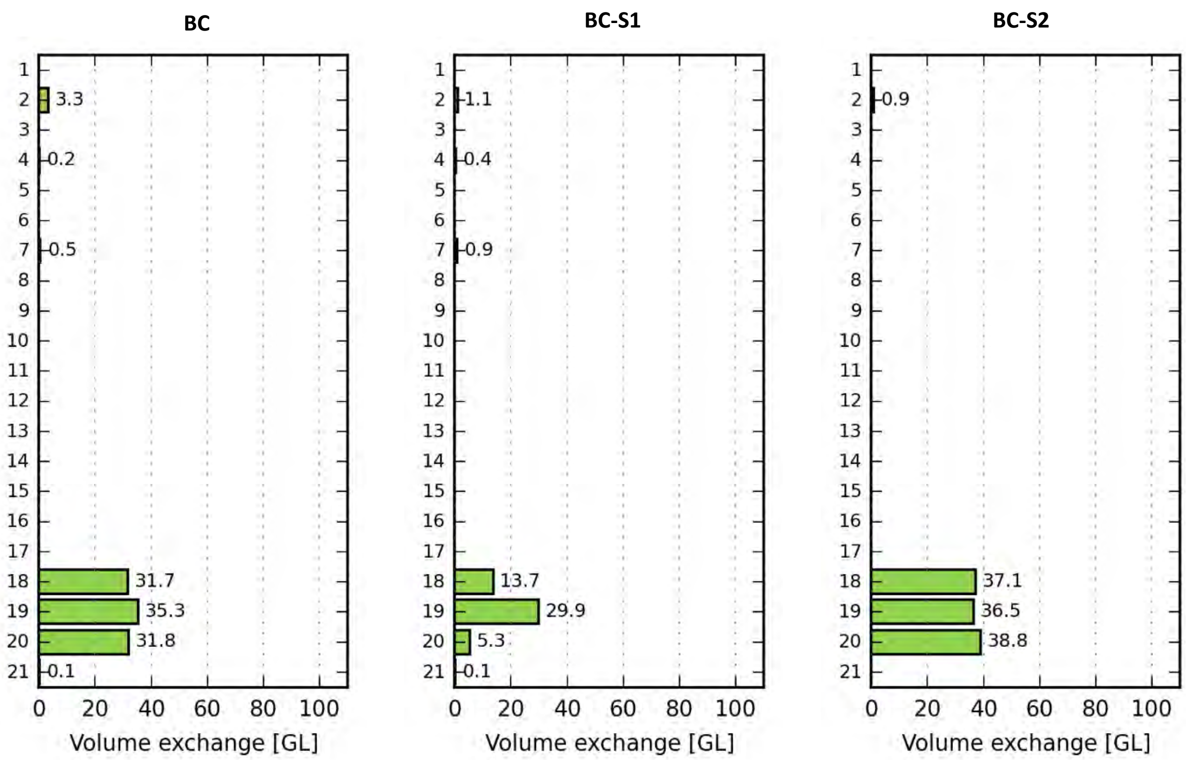


**Figure 6-77 Comparison of total predicted volumetric exchange between WSPRAs (a) simulation BC, (b) simulation BC-S1 and (c) simulation BC-S2**

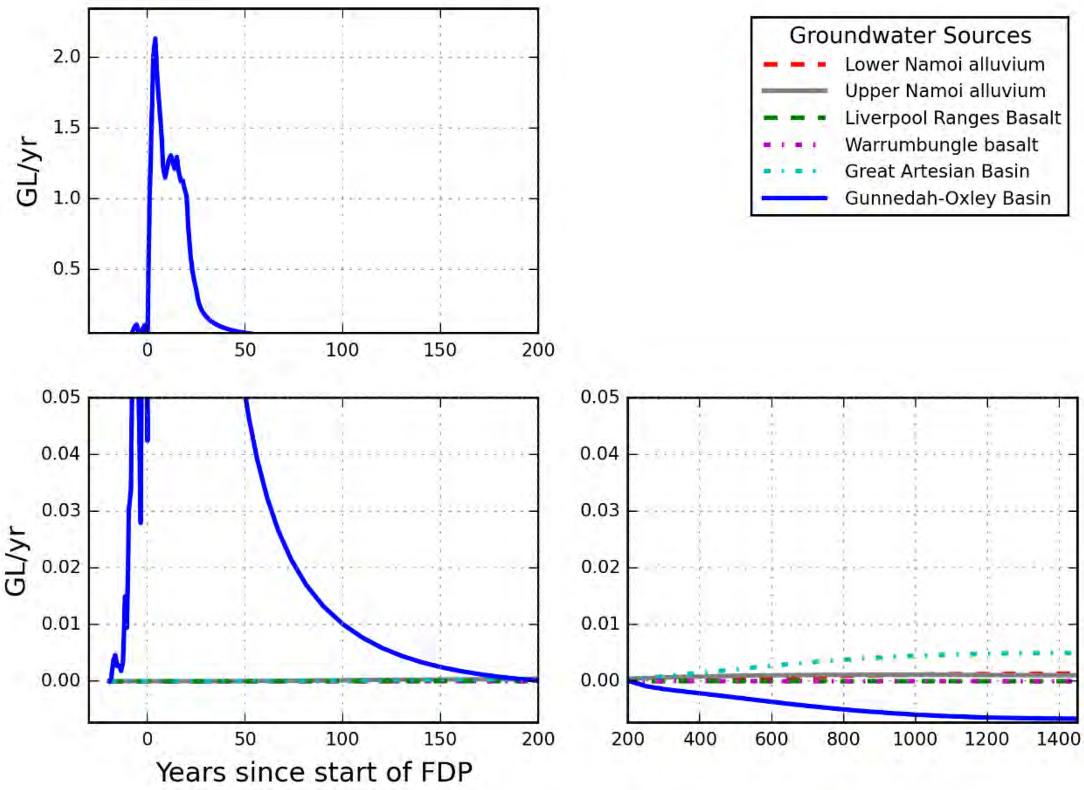


**Figure 6-78 Simulation BC-S1: predicted rates of induced storage releases**

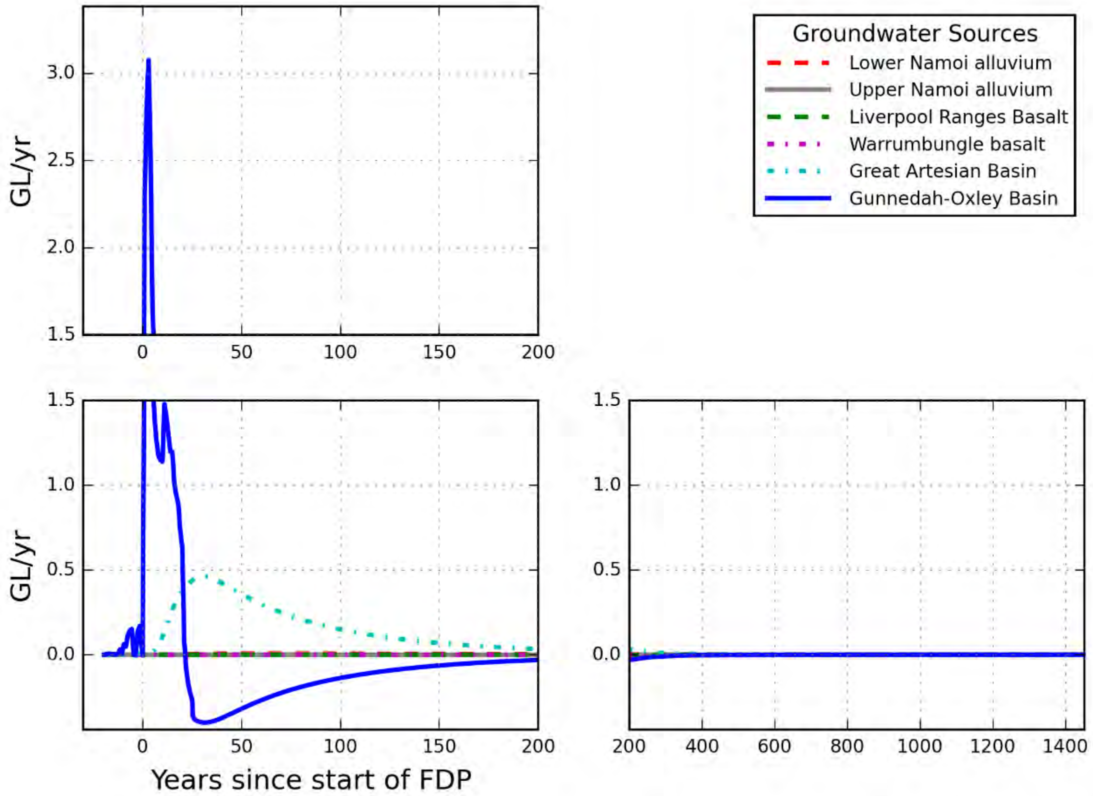


**Figure 6-79 Simulation BC-S2: predicted rates of induced storage releases**

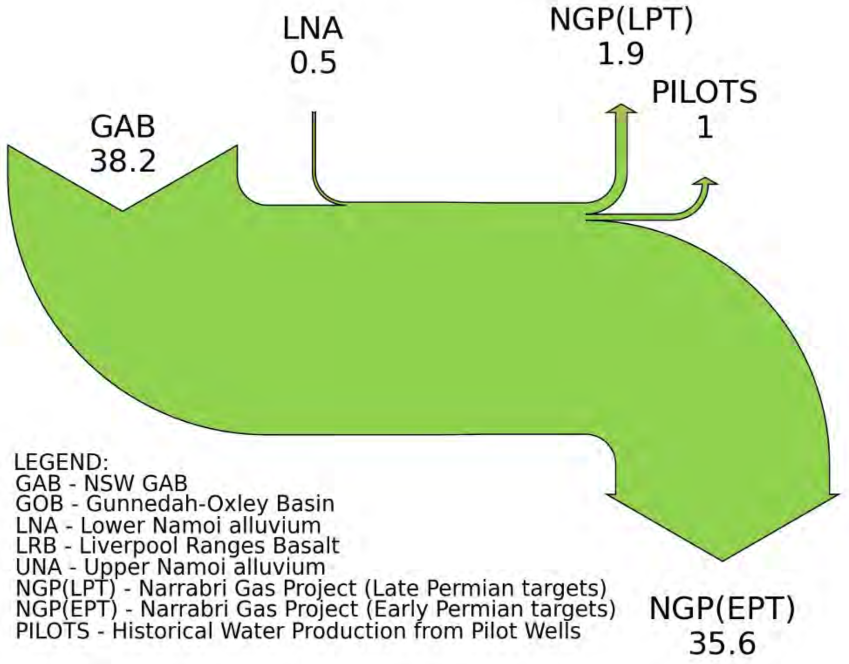


**Figure 6-80 Simulation BC-S2: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

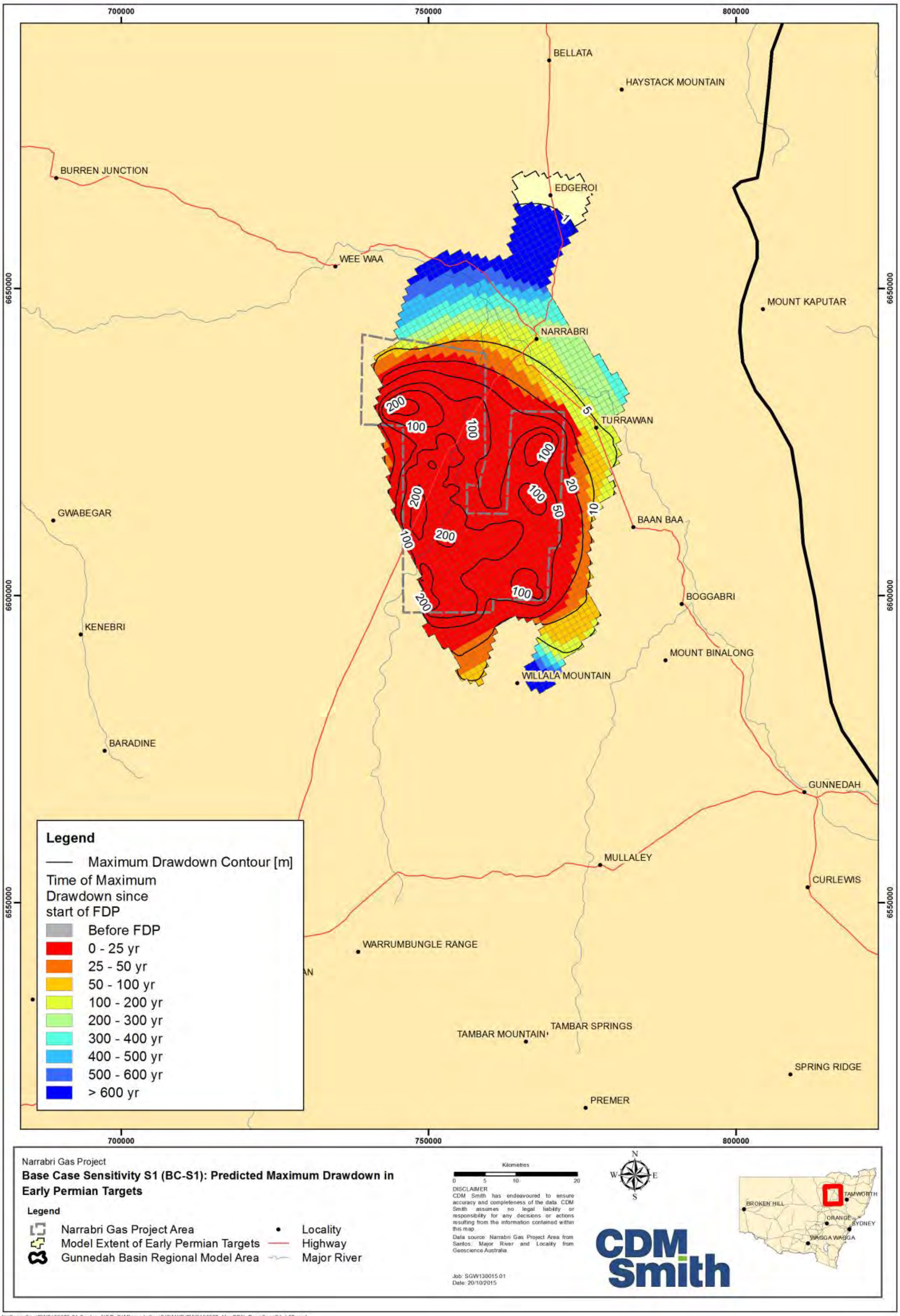


**Figure 6-81 Simulation BC-S1: predicted maximum drawdown in Early Permian targets**

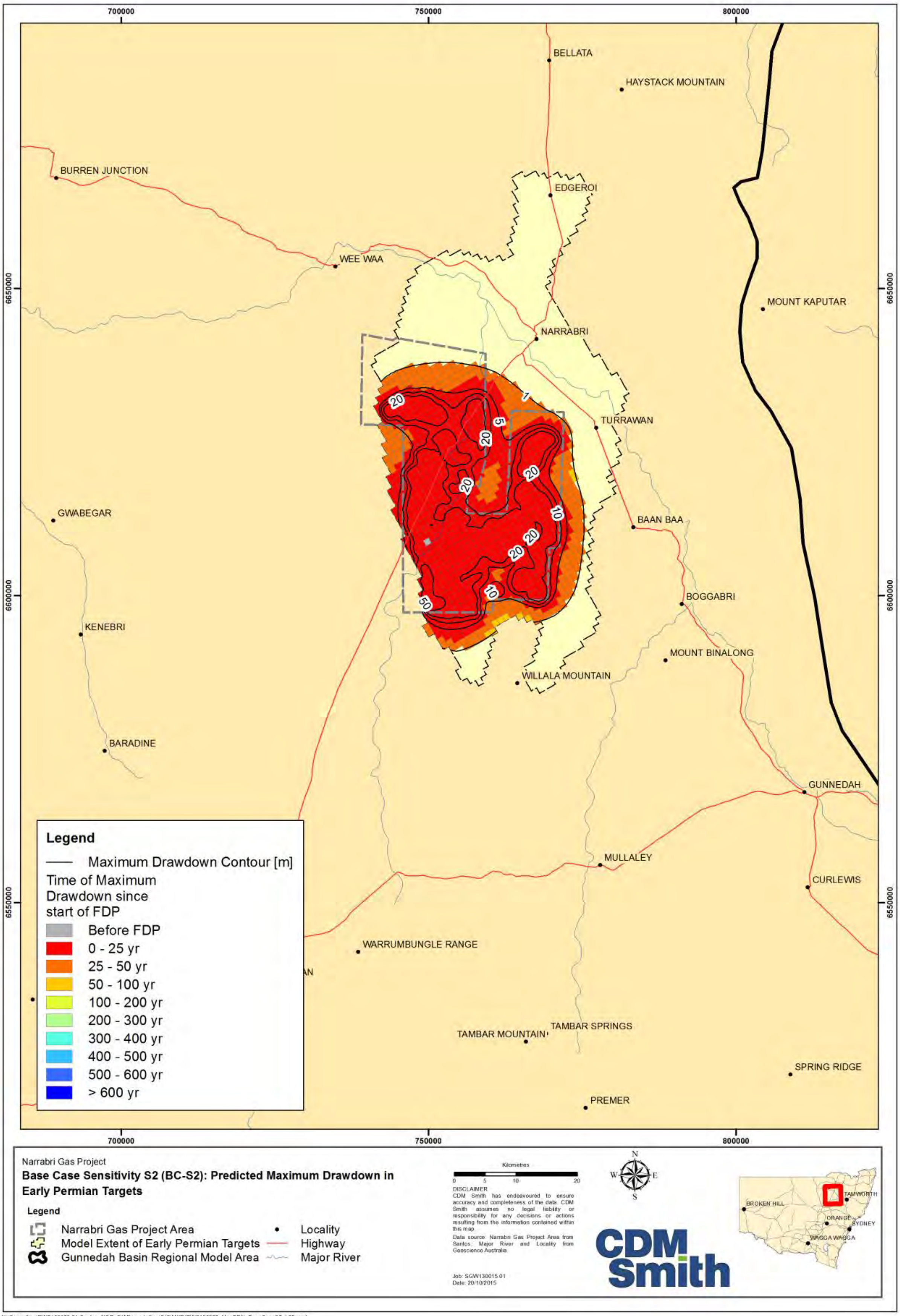


Figure 6-82 Simulation BC-S2: predicted maximum drawdown in Early Permian targets

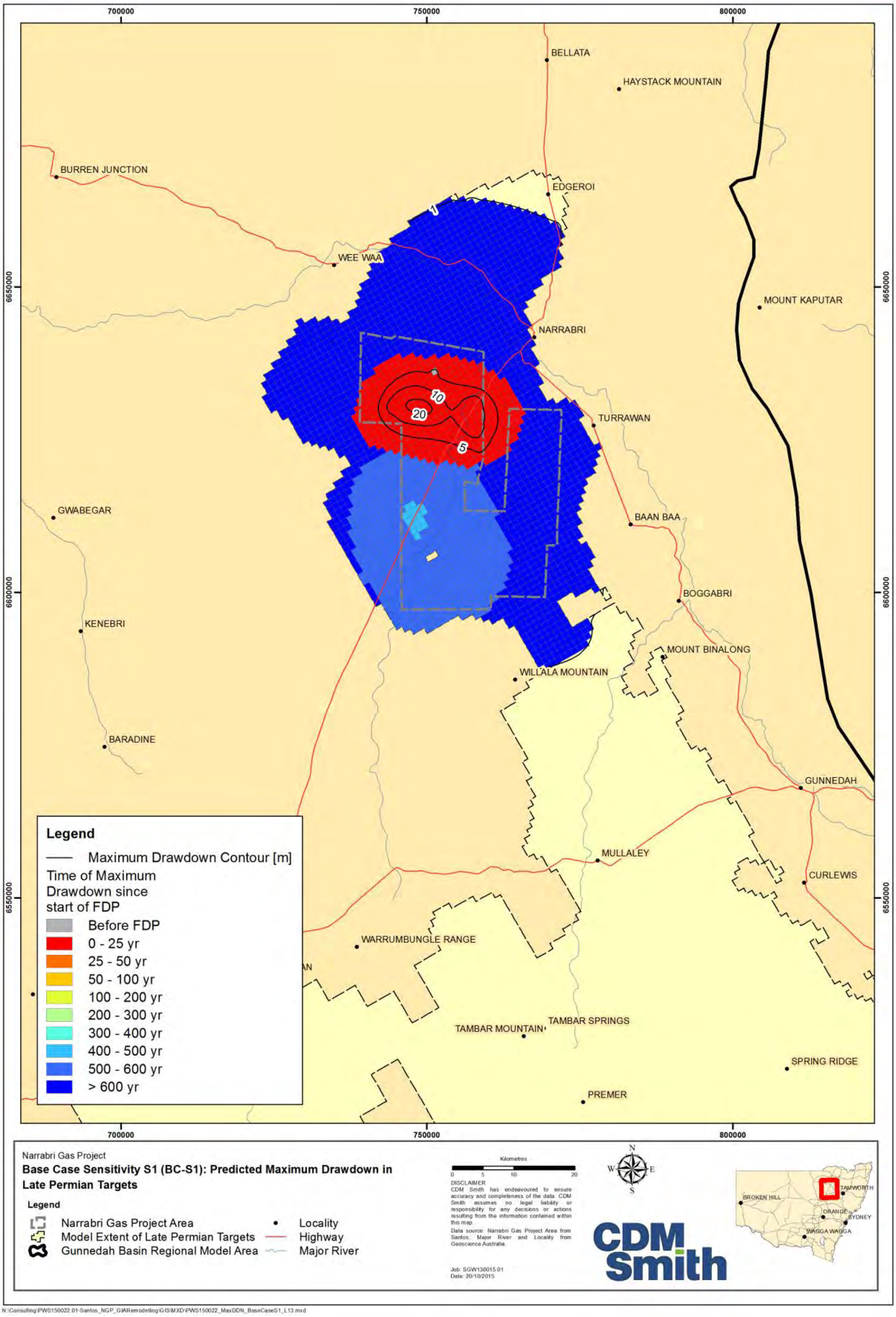


**Figure 6-83 Simulation BC-S1: predicted maximum drawdown in Late Permian targets**

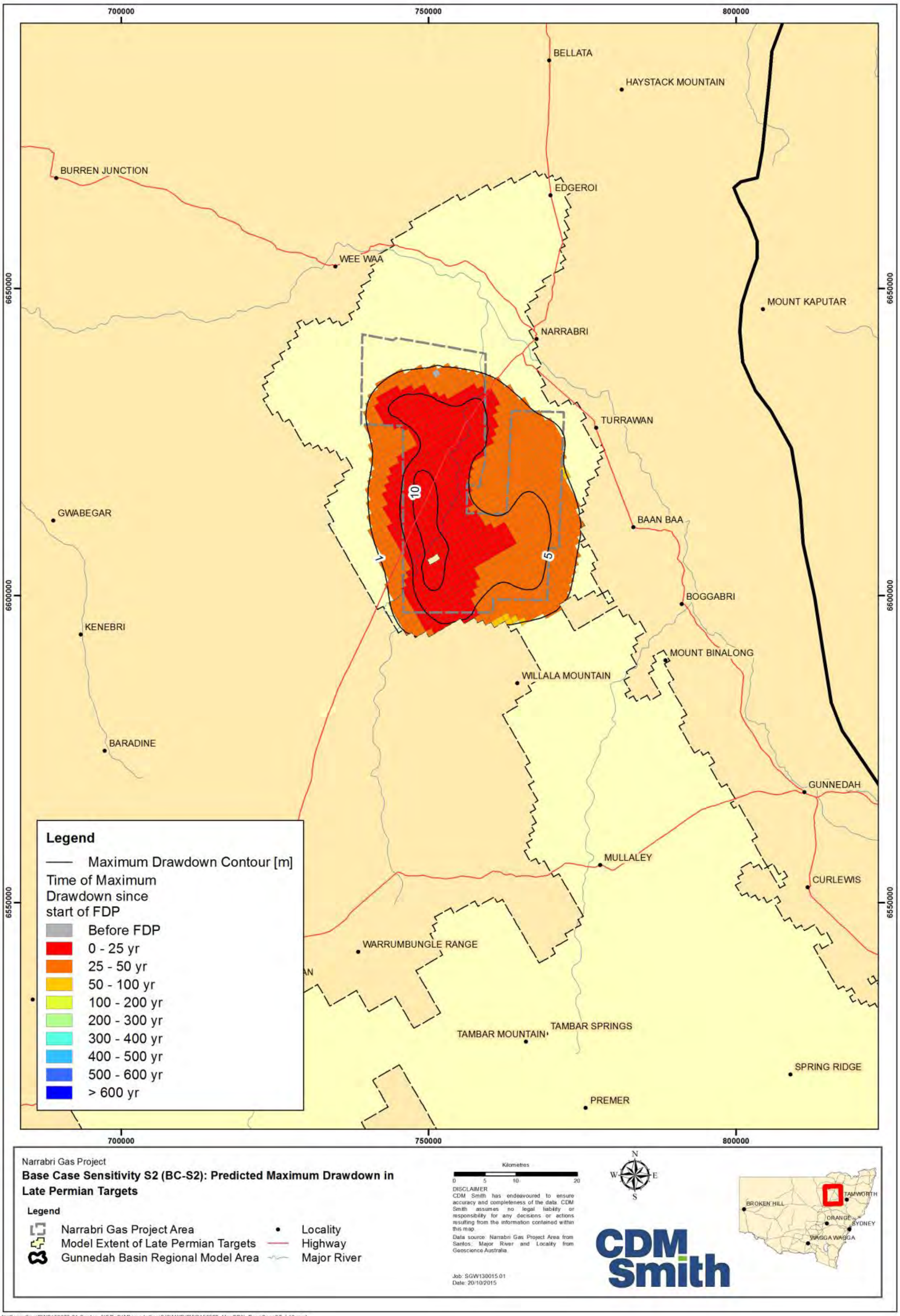


**Figure 6-84 Simulation BC-S2: predicted maximum drawdown in Late Permian targets**

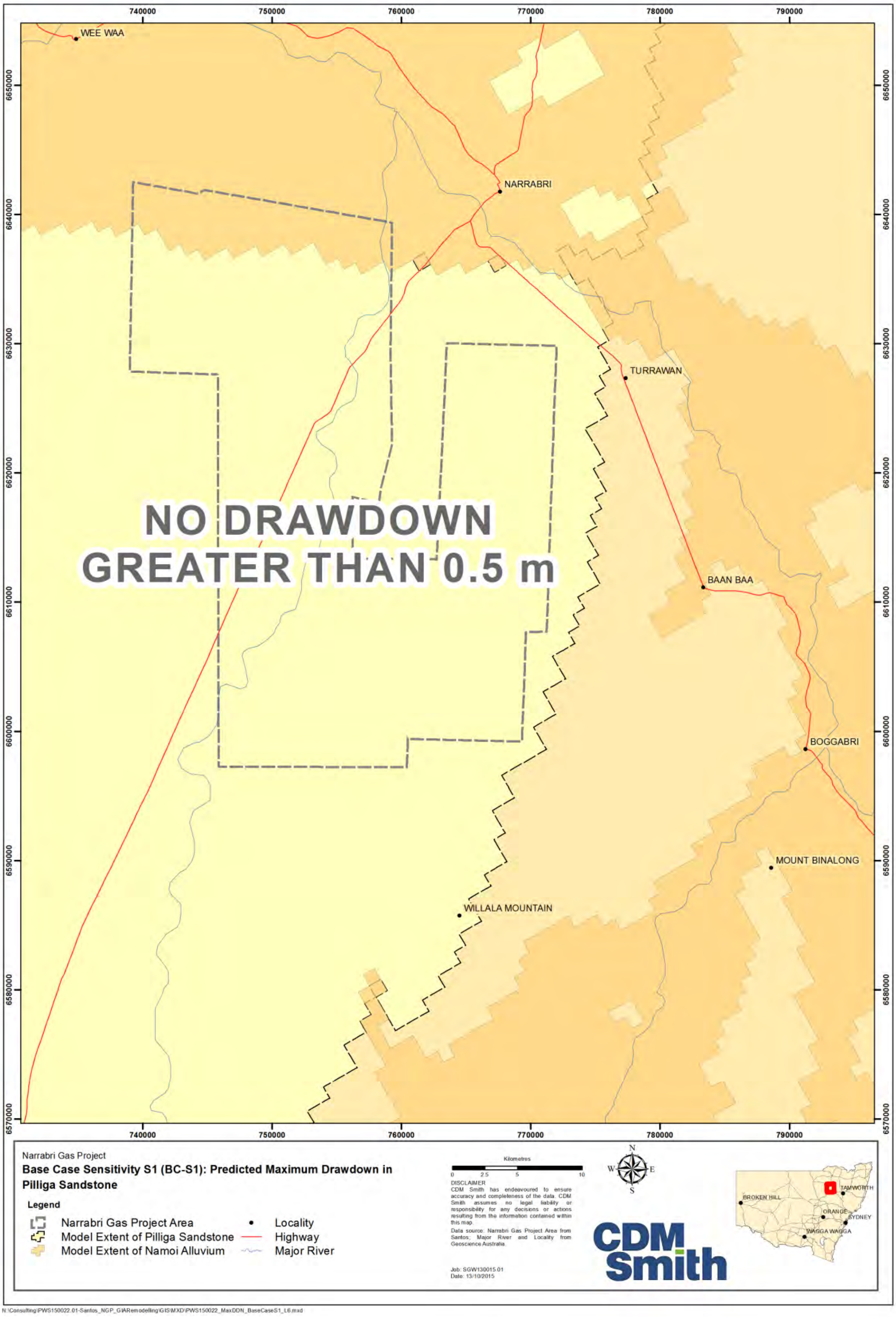


**Figure 6-85 Simulation BC-S1: predicted maximum drawdown in Pilliga Sandstone**

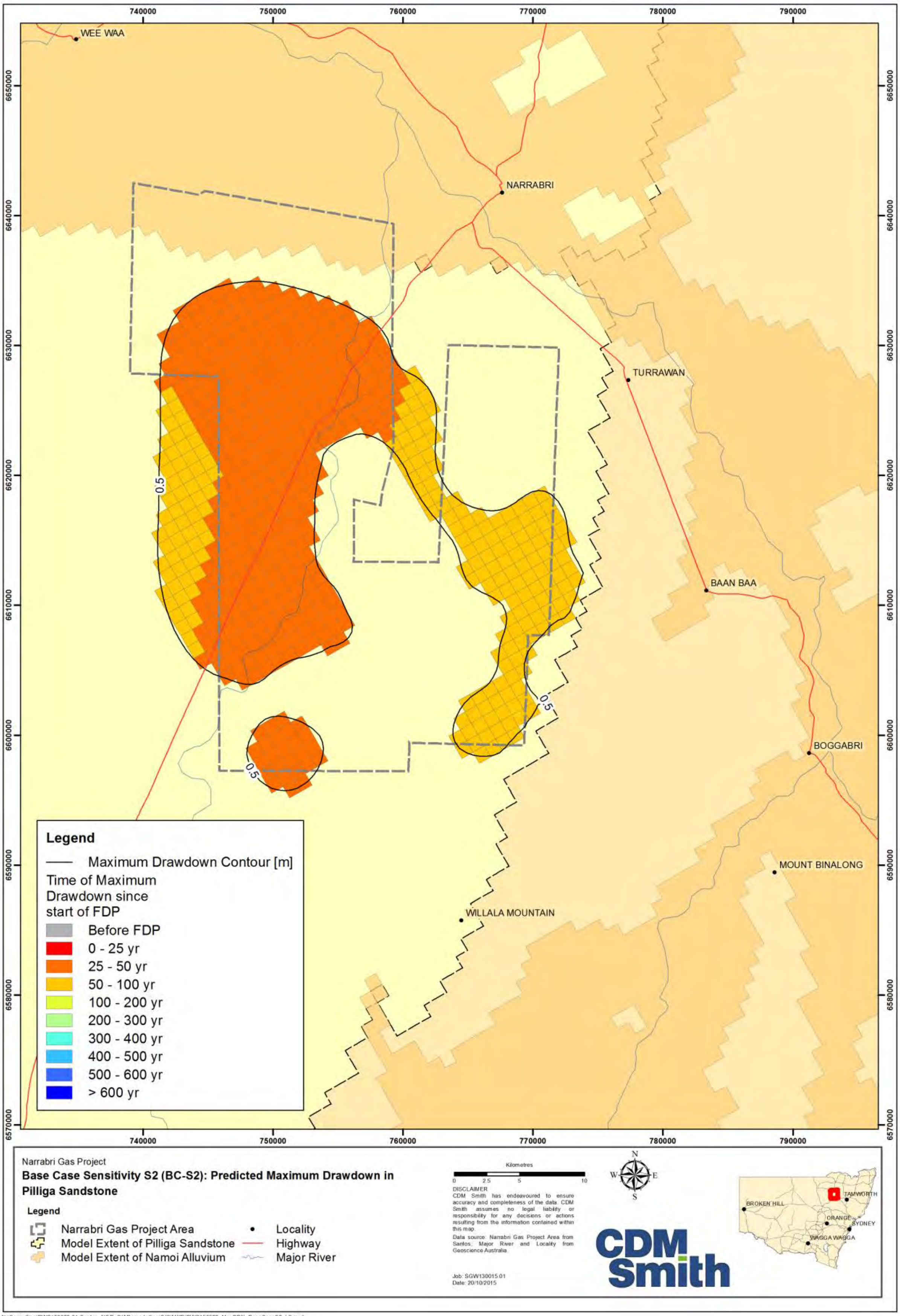


**Figure 6-86 Simulation BC-S2: predicted maximum drawdown in Pilliga Sandstone**

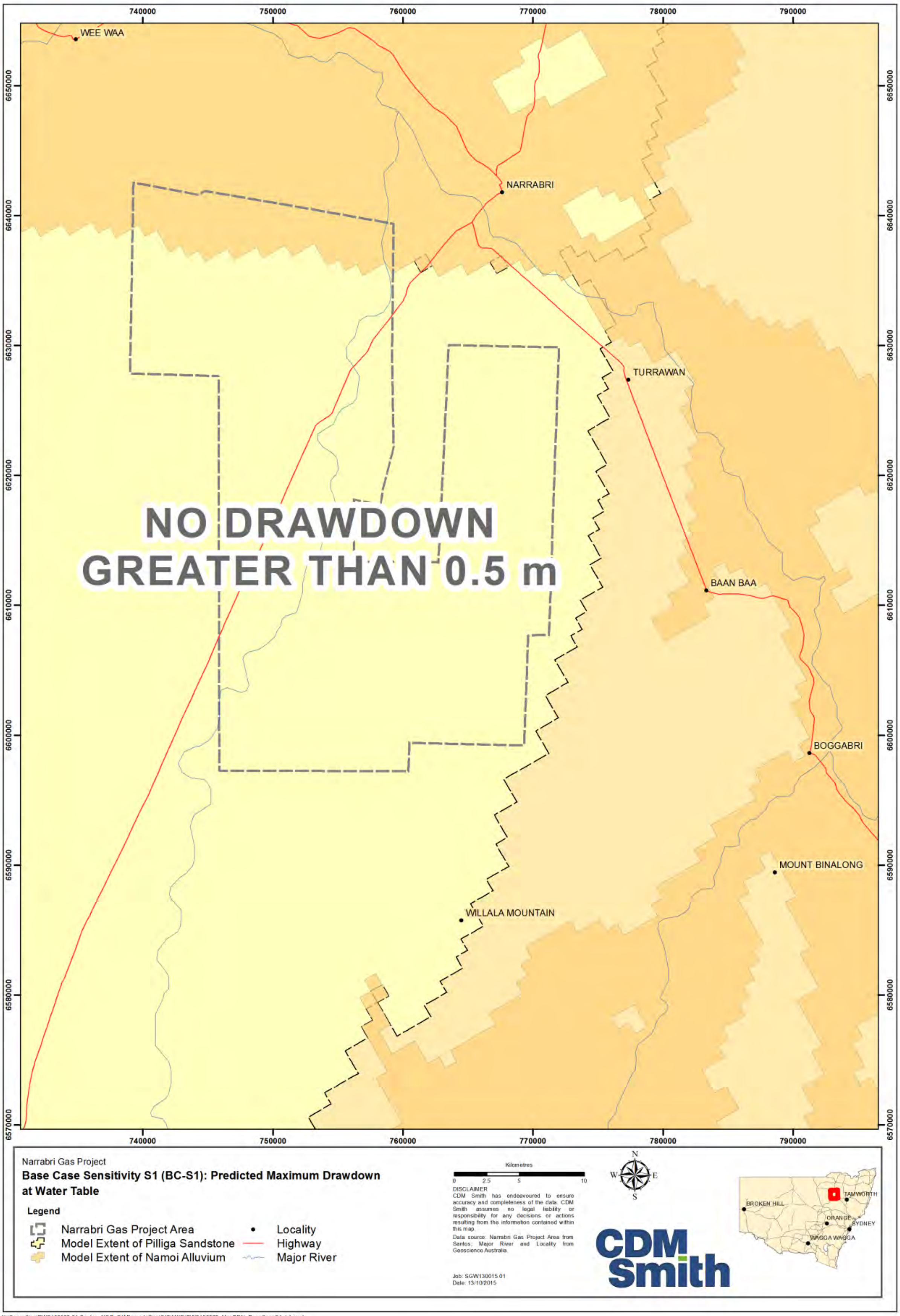


**Figure 6-87 Simulation BC-S1: predicted maximum drawdown at the water table**

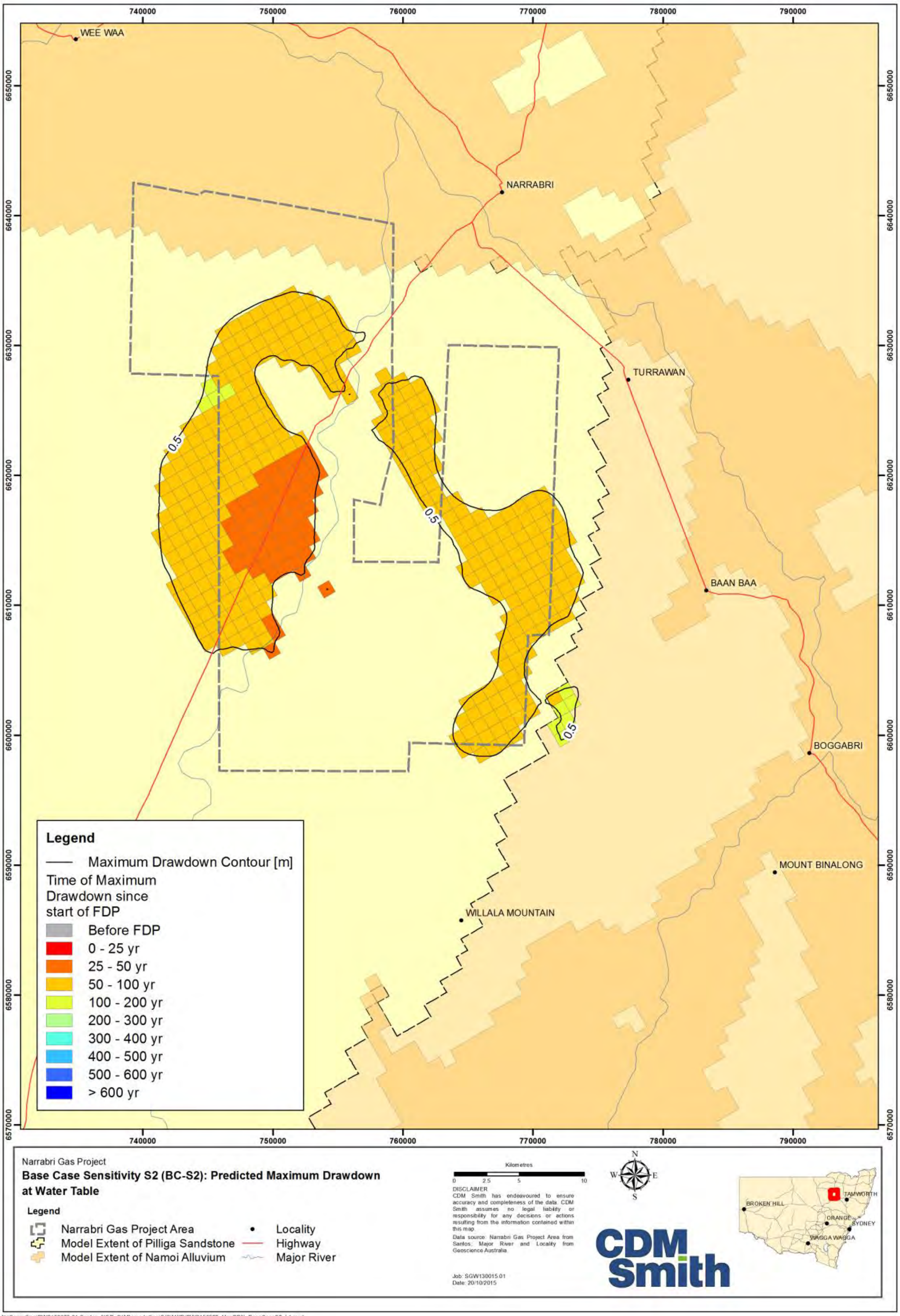


**Figure 6-88 Simulation BC-S2: predicted maximum drawdown at the water table**

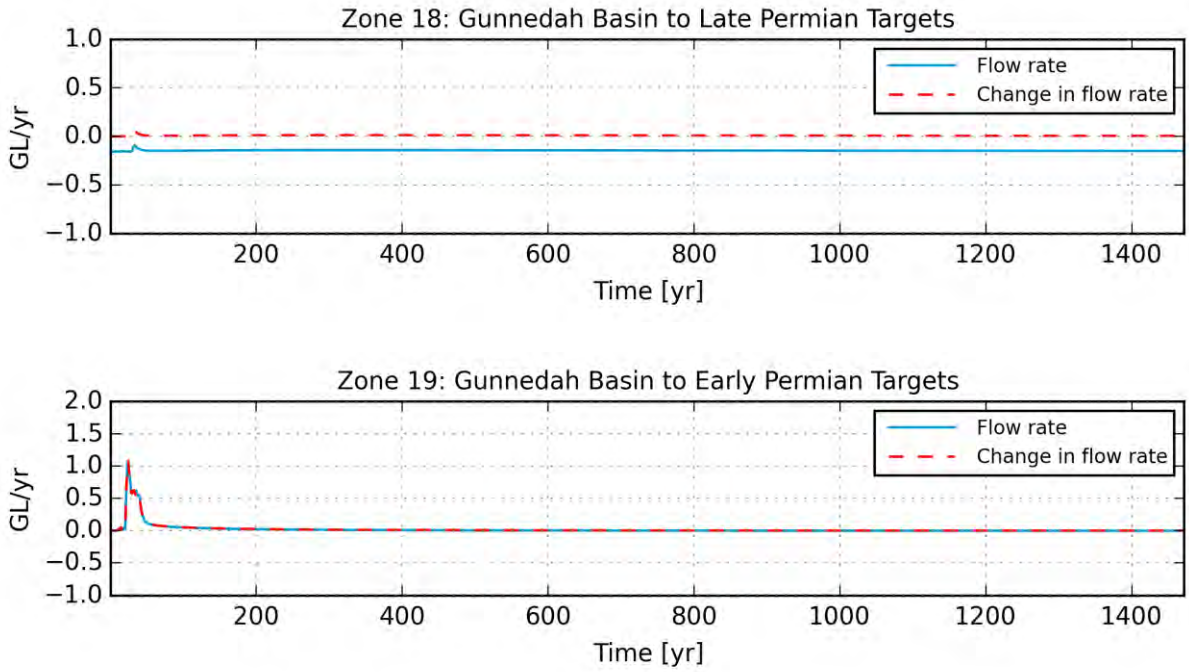


**Figure 6-89 Simulation BC-S1: time variation of flow rates between selected WSPRAs**

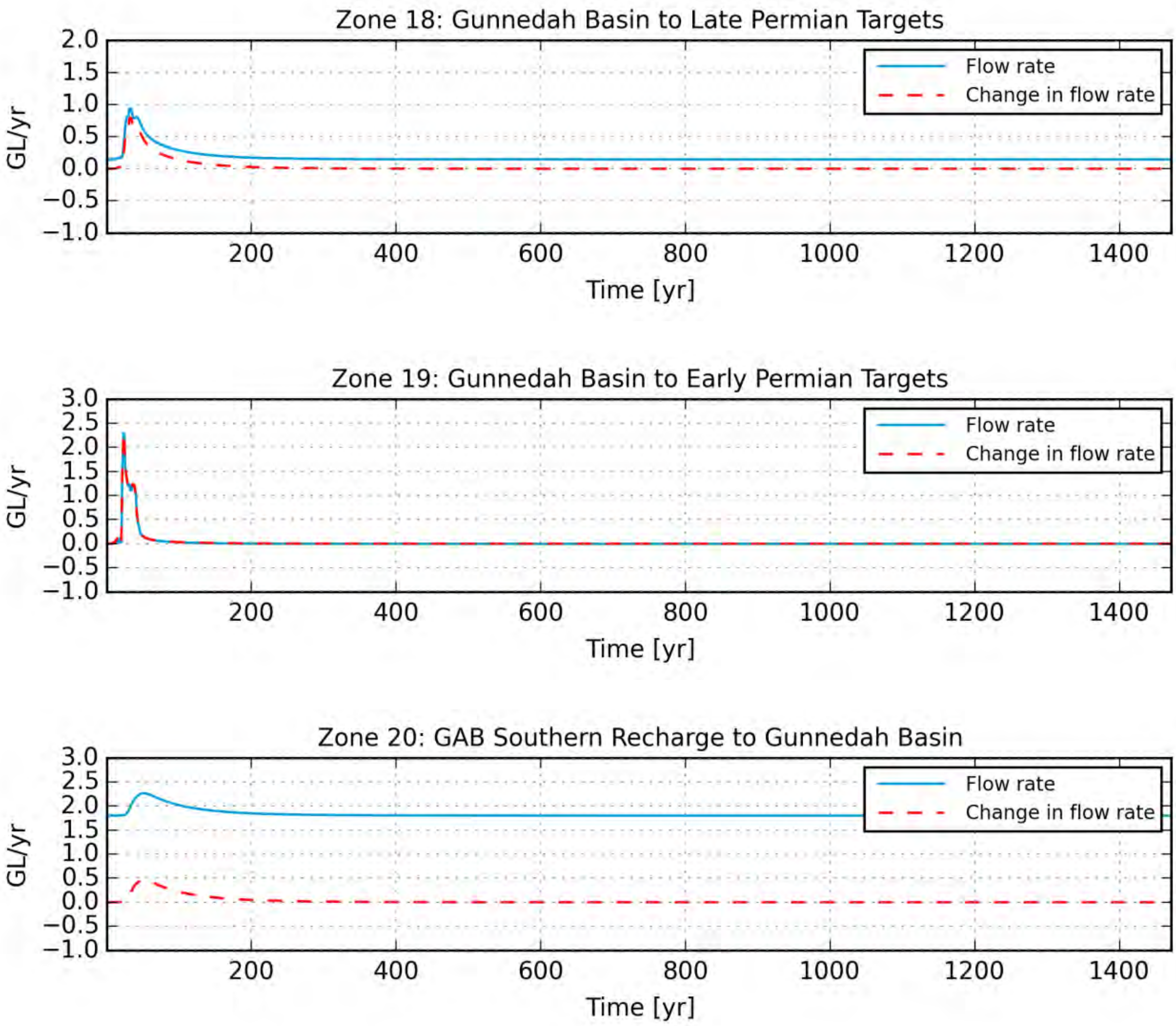


**Figure 6-90 Simulation BC-S2: time variation of flow rates between selected WSPRAs**

### 6.10.5 Variation of Specific Storativity

Results for simulations BC-S3 and BC-S4 are presented in Table 6-38 to Table 6-41 and Figure 6-91 to Figure 6-105. Variation of specific storativity (*Ss*) affects the magnitude of drawdown per unit volume of water removed from formation storage. Decreasing *Ss* causes larger drawdown per unit volume of water extracted and faster propagation of drawdown, while increasing *Ss* has the opposite effect. The applied values of *Ss* for each simulation are listed in Table 6-37.

**Table 6-37 Variation of specific storativity**

| Simulation | Ss [1/m] | Applicable Model Layers |
|---|---|---|
| BC | 1E-5 | 2-24 |
| BC-S3 | 1E-6 | |
| BC-S4 | 1E-4 | |

#### 6.10.5.1 Key Results for BC-S3

- Compared to simulation BC the predicted result for decreased *Ss* of the aquitard sequences and transmissive units is larger and more rapid drawdown in all formations, including the Early and Late Permian targets, Pilliga Sandstone and at the water table.
- The largest value of drawdown in the Pilliga Sandstone is predicted to increase from less than 0.5 m in simulation BC to 2.0 m in simulation BC-S3 with maximum drawdowns occurring between 25 and 56 years after the start of the FDP (Table 6-38). The area of drawdown is predicted to extend 10 to 15 km east of the project area (Figure 6-100).
- The largest value of drawdown at the water table outside of the Namoi alluvium is predicted to increase from less than 0.5 m in simulation BC to 1.5 m in simulation BC-S3, with maximum drawdowns occurring between 29 and 130 years after the start of the FDP. The area of drawdown corresponds generally to the area of drawdown in the Pilliga Sandstone but the distribution of drawdown at the water table is less continuous with large areas of drawdown less than 0.5 m (Figure 6-102). No drawdown greater than 0.5 m is predicted in the Namoi alluvium.
- Relative to simulation BC the maximum induced flows between WSPRAs are all larger, including 2.34 GL/y (74 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19), 0.8 GL/y (25 L/s) from the Gunnedah Basin to the Late Permian targets (WSPRA 18) and 0.54 GL/y (17 L/s) from the GAB Southern Recharge Area to the Gunnedah Basin.
- Most simulated water production for simulation BC-S3 comes from induced storage release from the Gunnedah-Oxley Basin and GAB with a smaller contribution from the Lower Namoi Alluvium. The predicted maximum rate of storage release of 3.1 GL/y from the Gunnedah-Oxley Basin occurs at around 3 years after the start of the FDP. The predicted maximum rate of storage release from the GAB is 0.48 GL/y at around 28 years after the start of the FDP, and from the Lower Namoi Alluvium is 0.06 GL/y at approximately 35 years (Figure 6-93). Complete recovery of hydraulic head occurs approximately 200 years after the start of the FDP.
- At the end of the simulation, the predicted contributions to the total simulated water production of 38.5 GL are approximately: 31.0 GL (80.6%) from the GAB; 3.8 GL (9.8%) from the Lower Namoi Alluvium; 3.0 GL (7.8%) from the Gunnedah-Oxley Basin; and 0.7 GL (1.8%) from the Upper Namoi Alluvium (Figure 6-95).

### 6.10.5.2 Key Results for BC-S4

- Compared to simulation BC the overall effect of increased *Ss* in the aquitard sequences and transmissive units is smaller and slower drawdown in all formations, including the Early and Late Permian targets, Pilliga Sandstone and at the water table.
- For simulation BC-S4 no drawdown greater than 0.5 m is predicted in the Pilliga Sandstone or at the water table (Table 6-39).
- Relative to simulation BC the maximum induced flows between WSPRAs are all smaller, including 1.06 GL/y (34 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19) and 0.06 GL/y (2.0 L/s) from the Gunnedah Basin to the Late Permian targets (WSPRA 18). Other induced flows are negligible.
- Within 1500 year of the start of the FDP simulation period most simulated water production comes from induced storage release in the Gunnedah-Oxley Basin with a small contribution from the GAB; noting that only partial recovery of drawdown occurs within the 1500 years after the start of the FDP. The predicted maximum rate of storage release of 2.1 GL/y from the Gunnedah-Oxley Basin occurs at around 4 years after the start of the FDP, and the predicted maximum rate of storage release of 0.005 GL/y from the GAB occurs at the end of the simulation (Figure 6-94).
- Assessment of the final contributions from each groundwater source to total simulated water production is not possible in this instance because only partial recovery of hydraulic head occurs within 1500 years after the start of the FDP. Thus, small inter-formational flows induced by the simulated water production are predicted to be still active after 1500 years.

**Table 6-38 Simulation BC-S3: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 1.5 | 29 to 130 |
| Pilliga Sandstone | 2.0 | 25 to 56 |
| Late Permian Targets | 50 | 9 to 74 |
| Early Permian Targets | 442 | 2 to 67 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-39 Simulation BC-S4: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | <0.5 | - |
| Pilliga Sandstone | <0.5 | - |
| Late Permian Targets | 4.2 | Pre-FDP to 21 |
| Early Permian Targets | 46 | Pre-FDP to 300 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-40 Simulation BC-S3: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [1y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | 0.12 | N |
| 2 | -1.26 | 0.06 | 56 | 3.66 | Y |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.19 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.01 | - | 0.50 | N |
| 8 | -1.36 | 0.00 | - | 0.00 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.01 | N |
| 18 | -0.14 | 0.80 | 13 | 33.34 | Y |
| 19 | 0.00 | 2.34 | 3 | 35.66 | Y |
| 20 | 0.89 | 0.54 | 29 | 34.53 | Y |
| 21 | -0.08 | 0.00 | - | 0.27 | N |

[1]Years since start of FDP

**Table 6-41 Simulation BC-S4: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [1y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -1.05 | 0.00 | - | -0.04 | N |
| 2 | -1.26 | 0.00 | - | 0.22 | N |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.26 | 0.00 | - | 0.00 | N |
| 5 | -0.07 | 0.00 | - | 0.00 | N |
| 6 | -0.05 | 0.00 | - | 0.00 | N |
| 7 | -0.23 | 0.00 | - | 0.03 | N |
| 8 | -1.36 | 0.00 | - | 0.01 | N |
| 9 | -0.14 | 0.00 | - | 0.00 | N |
| 10 | -0.08 | 0.00 | - | 0.00 | N |
| 11 | -1.52 | 0.00 | - | 0.00 | N |
| 12 | -0.02 | 0.00 | - | 0.00 | N |
| 13 | -0.03 | 0.00 | - | 0.00 | N |
| 14 | 1.52 | 0.00 | - | 0.00 | N |
| 15 | 0.50 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | 0.08 | 0.00 | - | 0.00 | N |
| 18 | -0.14 | 0.06 | 13 | 14.30 | Y |
| 19 | 0.00 | 1.06 | 4 | 30.76 | Y |
| 20 | 0.89 | 0.01 | - | 4.29 | N |
| 21 | -0.08 | 0.00 | - | -0.01 | N |

[1]Years since start of FDP

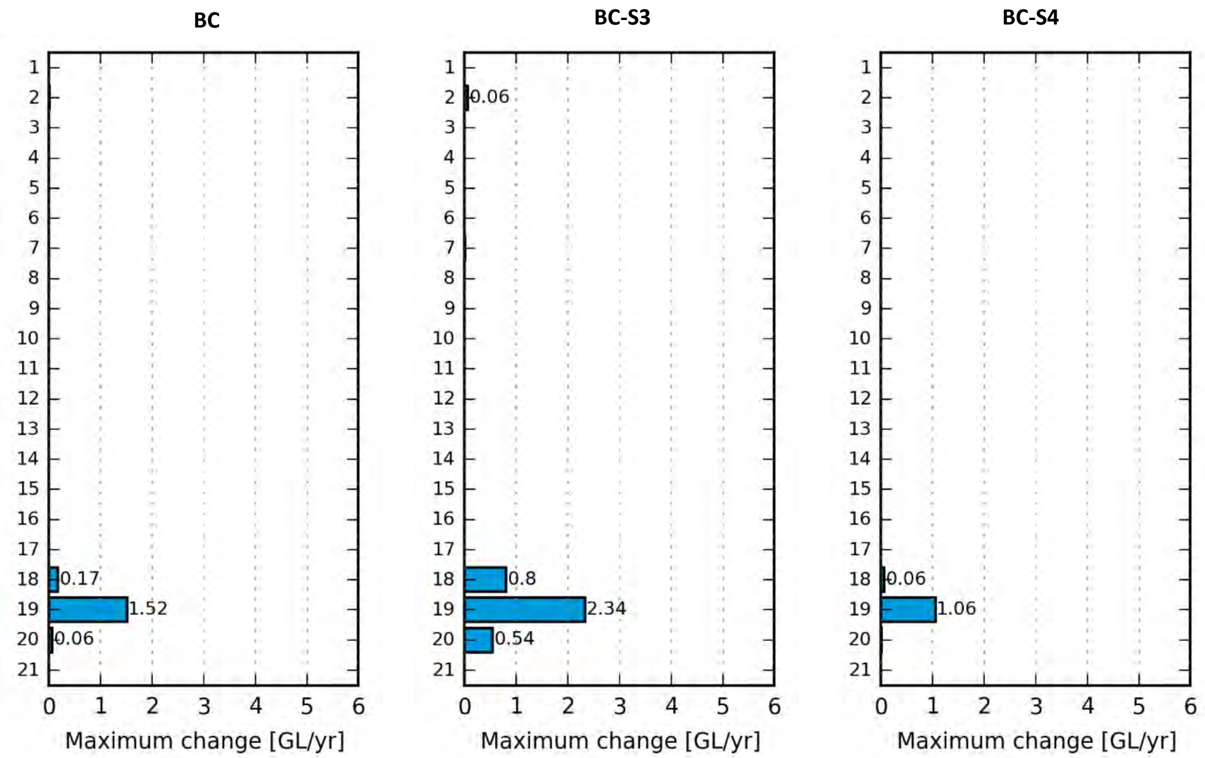


**Figure 6-91 Comparison of maximum predicted change in WSPRA Flow Rates (a) simulation BC, (b) simulation BC-S3 and (c) simulation BC-S4**

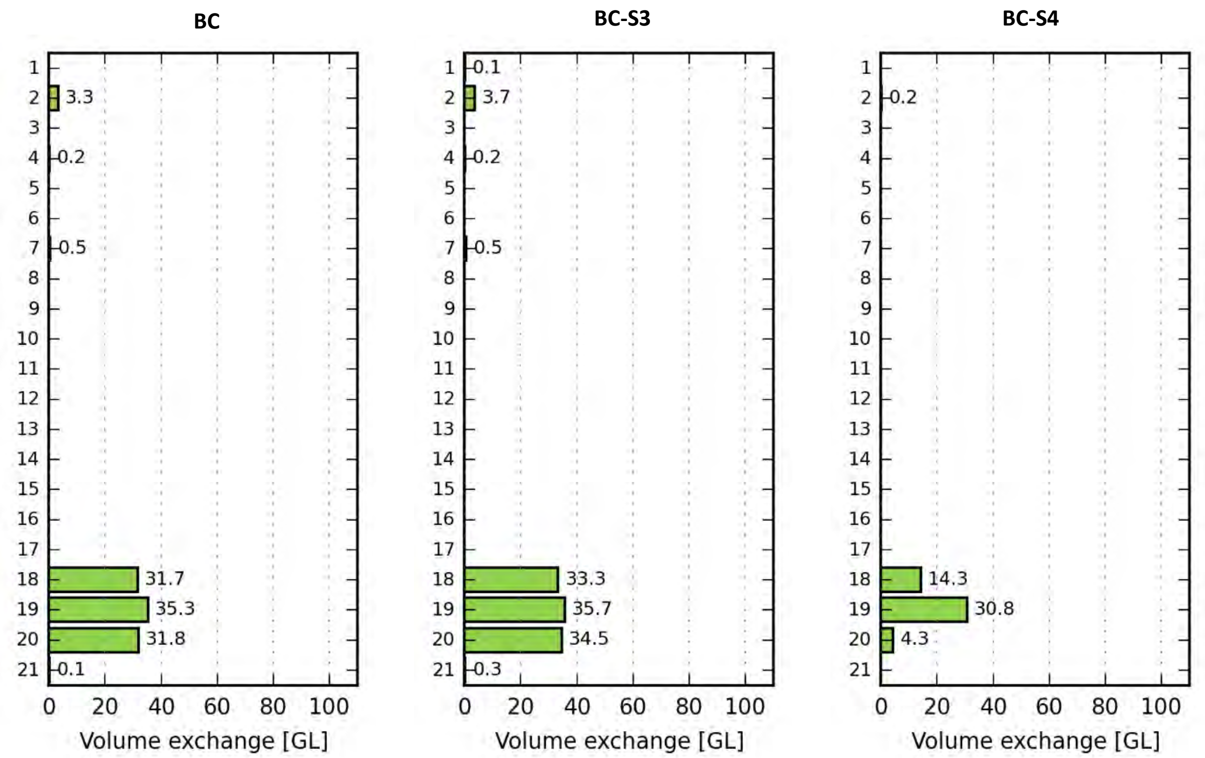


**Figure 6-92 Comparison of total predicted volumetric exchange between WSPRAs (a) simulation BC, (b) simulation BC-S3 and (c) simulation BC-S4**

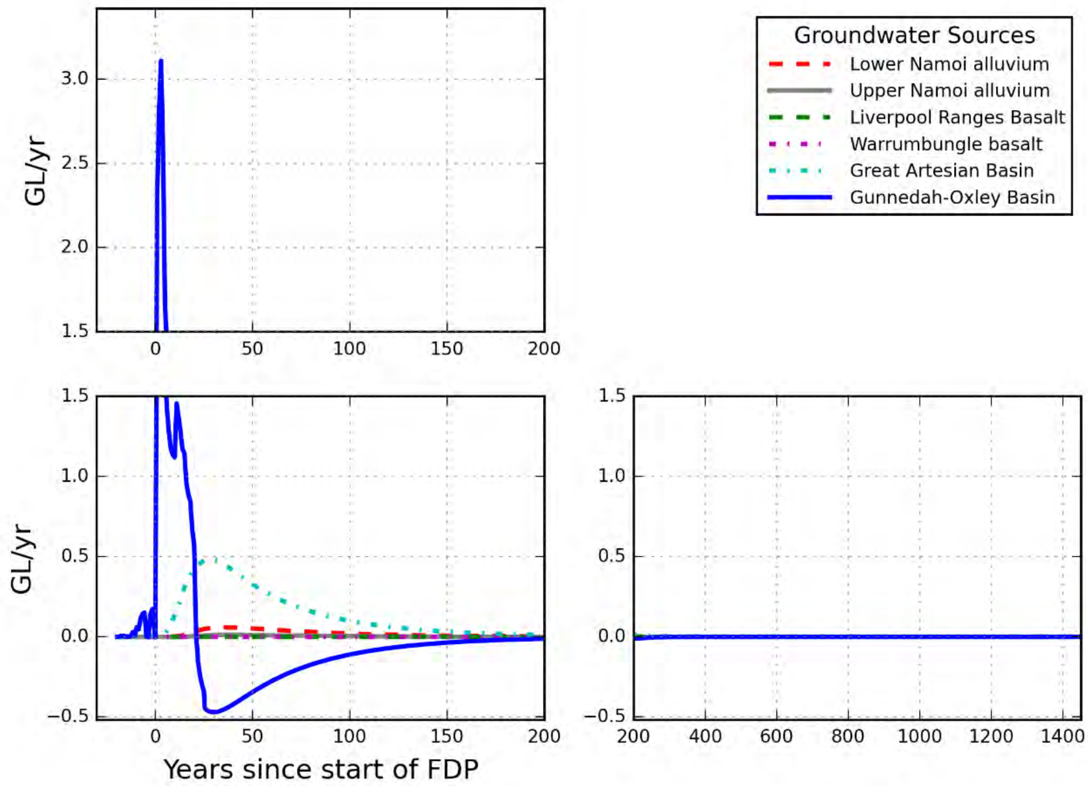


**Figure 6-93 Simulation BC-S3: predicted rates of induced storage releases**

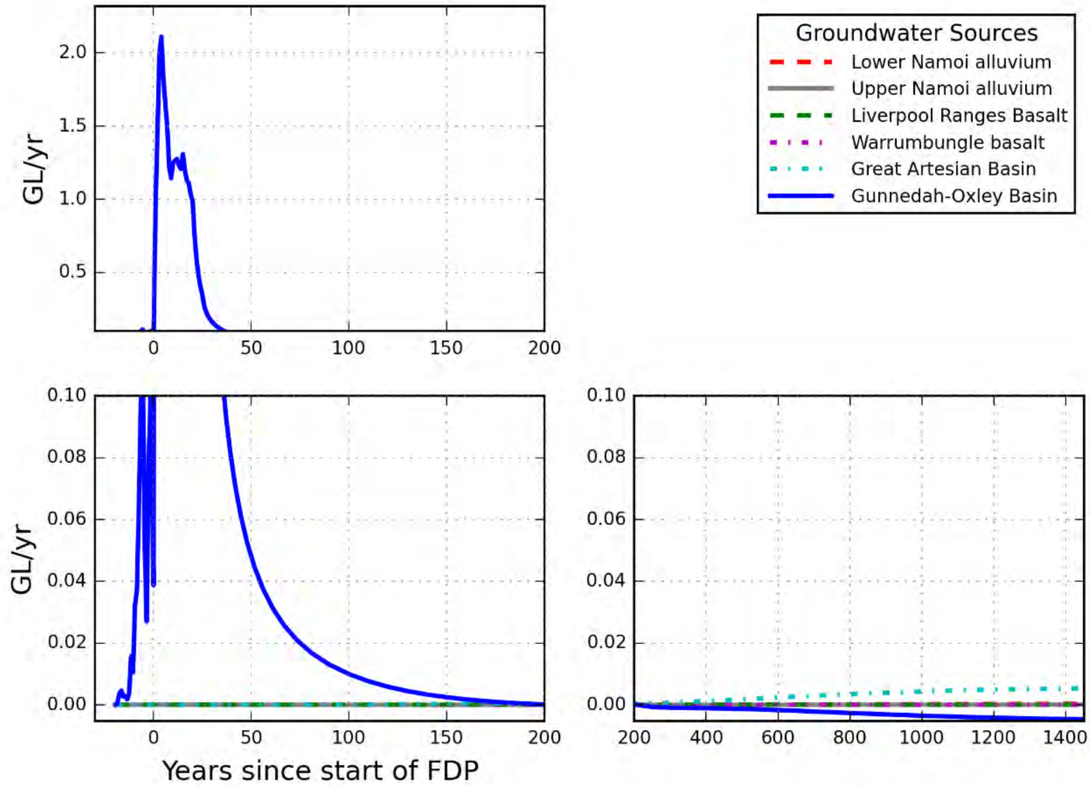


**Figure 6-94 Simulation BC-S4: predicted rates of induced storage releases**

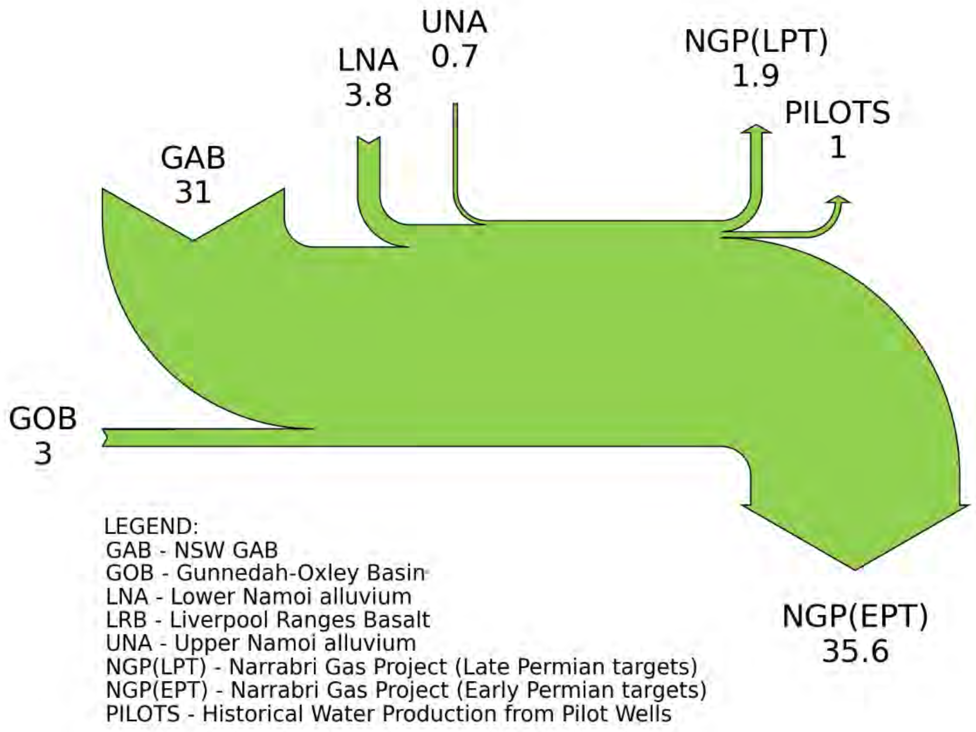


**Figure 6-95 Simulation BC-S3: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

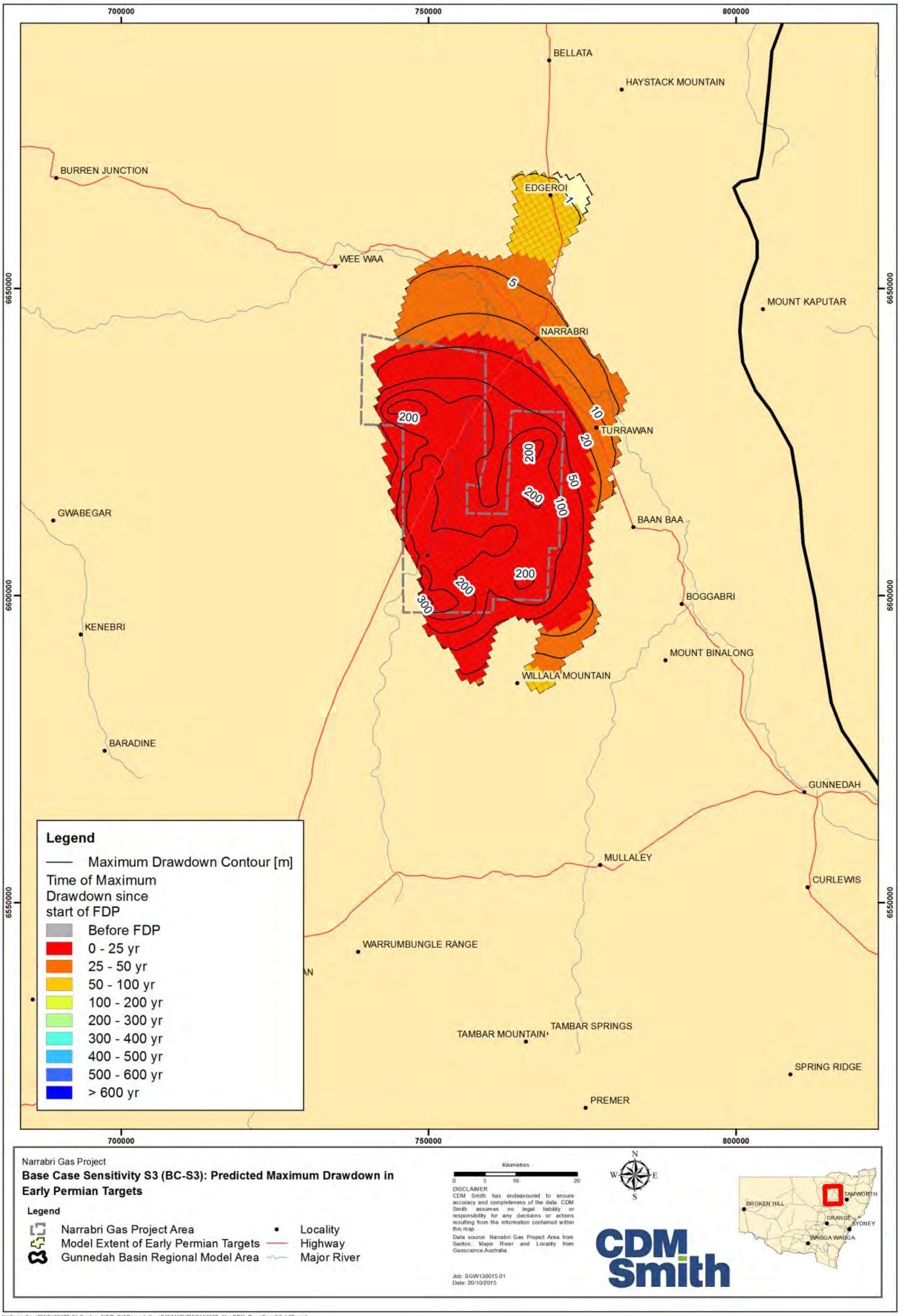


**Figure 6-96 Simulation BC-S3: predicted maximum drawdown in Early Permian targets**

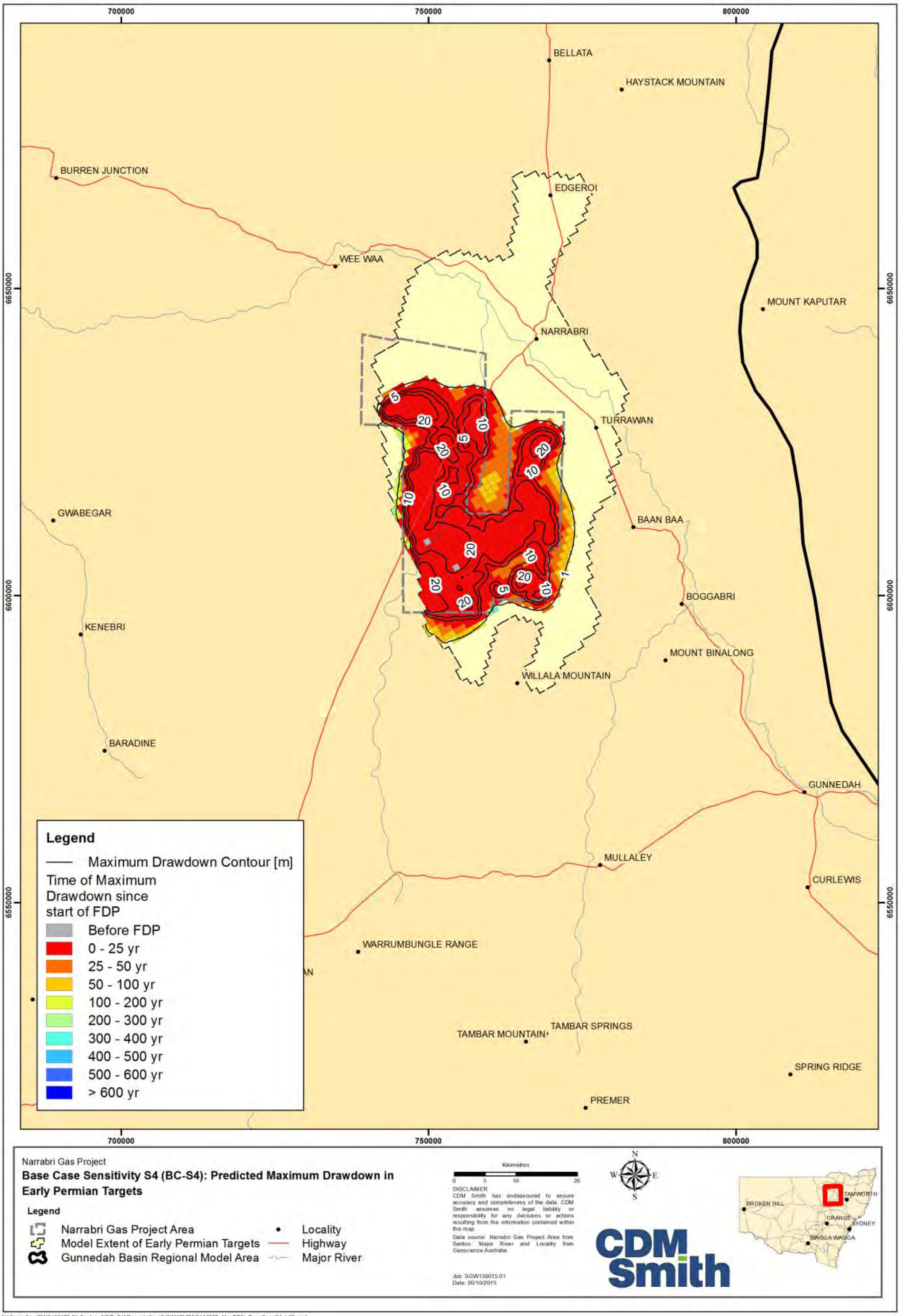


**Figure 6-97 Simulation BC-S4: predicted maximum drawdown in Early Permian targets**

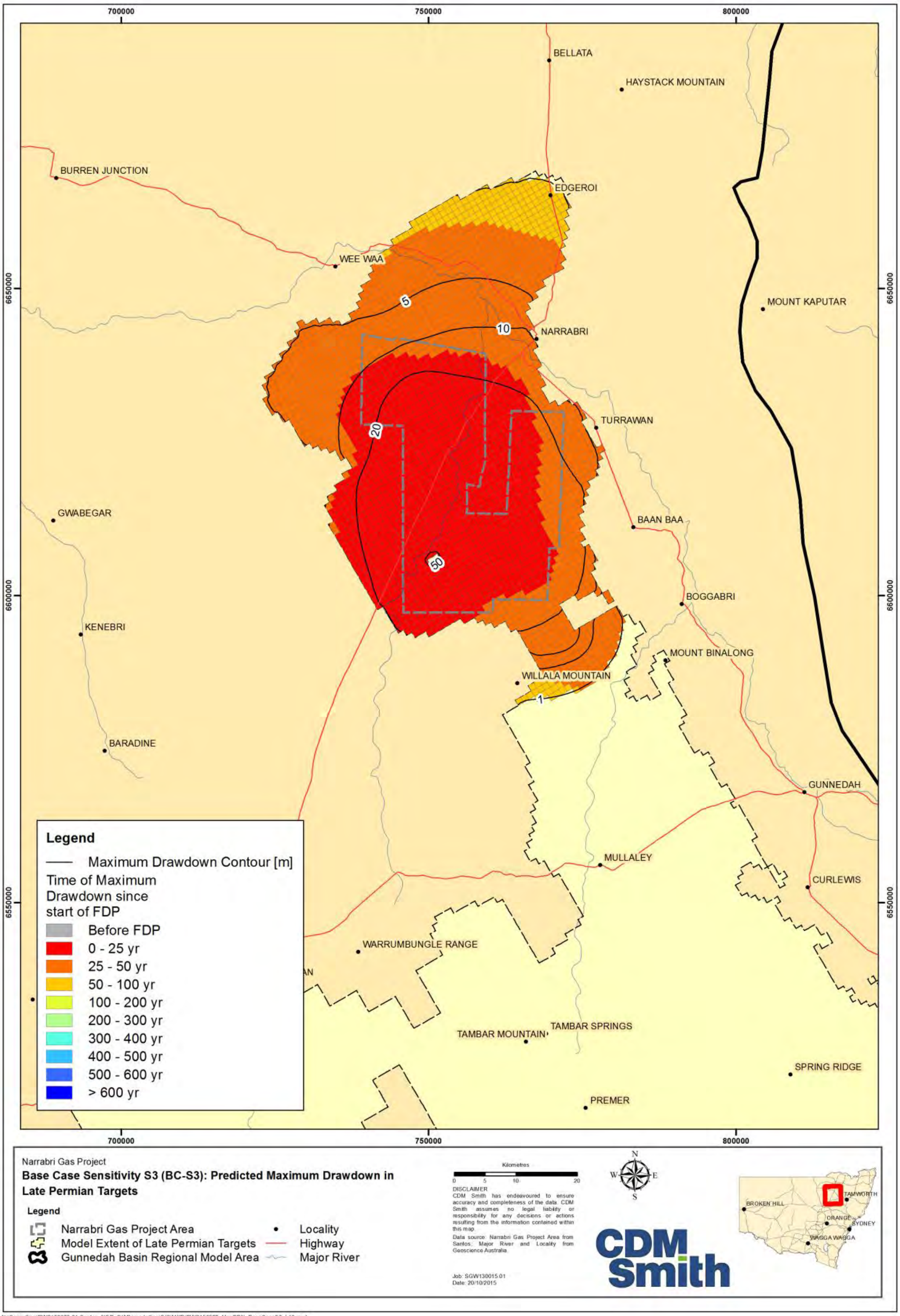


**Figure 6-98 Simulation BC-S3: predicted maximum drawdown in Late Permian targets**

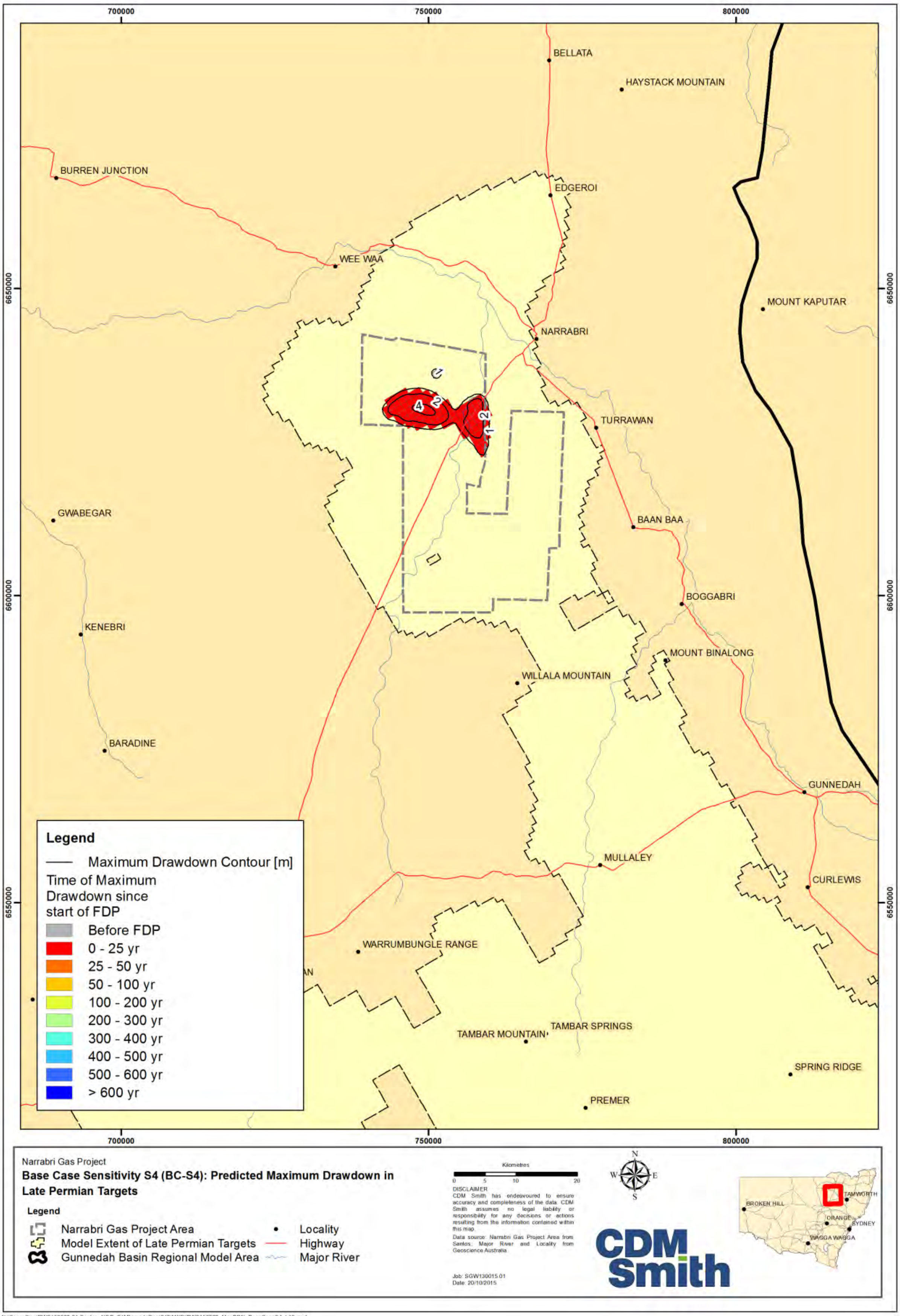


**Figure 6-99 Simulation BC-S4: predicted maximum drawdown in Late Permian targets**

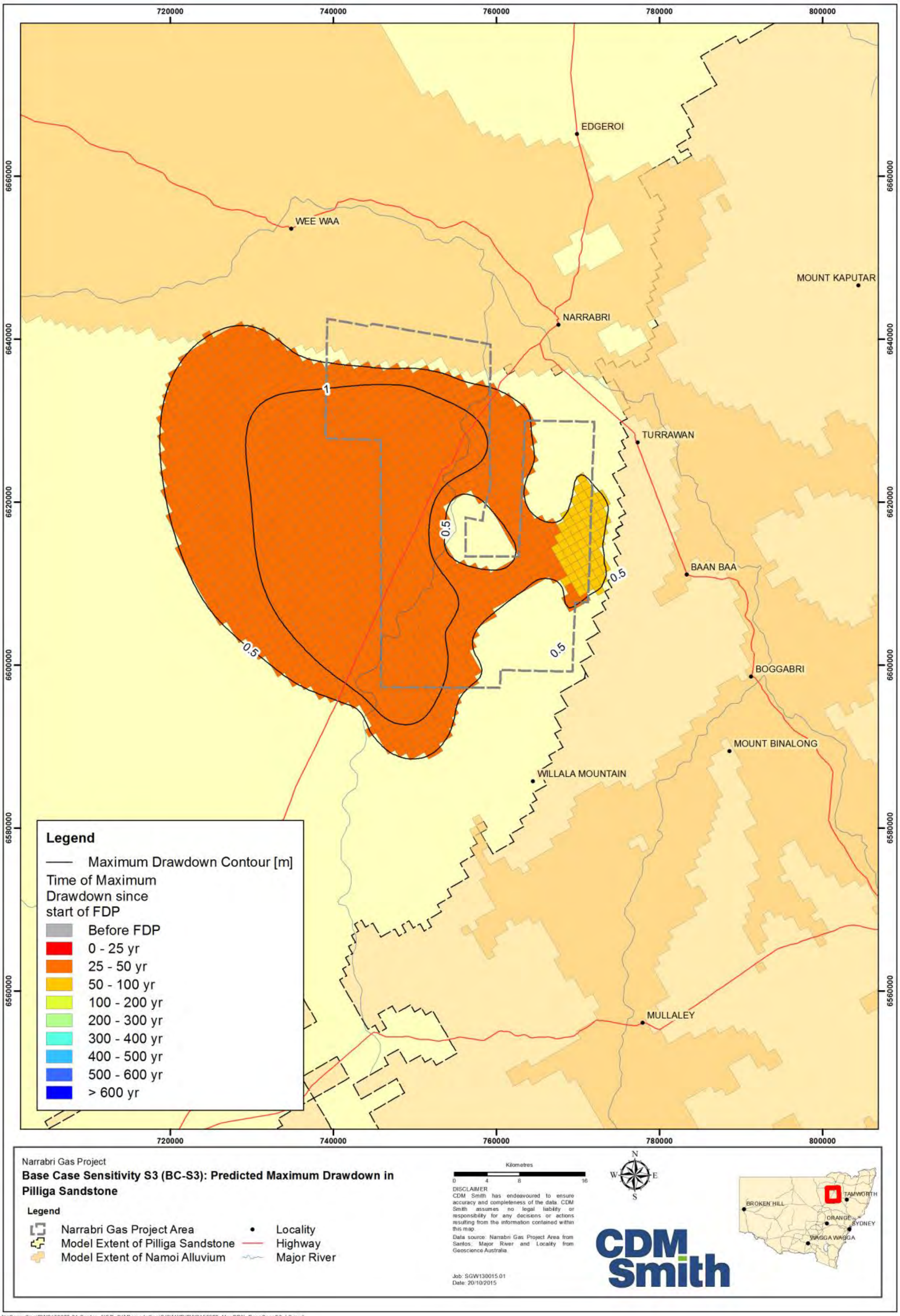


**Figure 6-100 Simulation BC-S3: predicted maximum drawdown in Pilliga Sandstone**

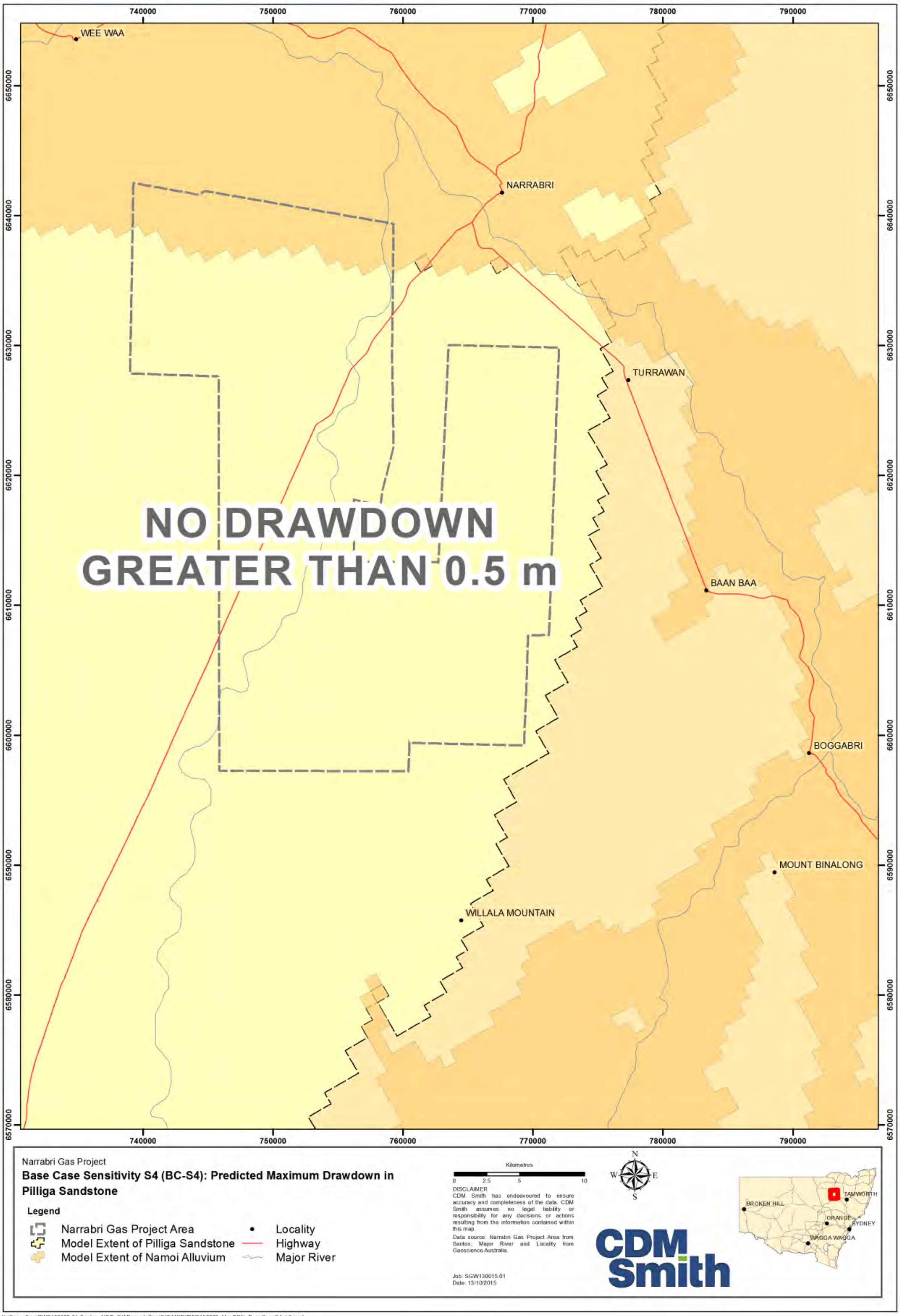


**Figure 6-101 Simulation BC-S4: predicted maximum drawdown in Pilliga Sandstone**

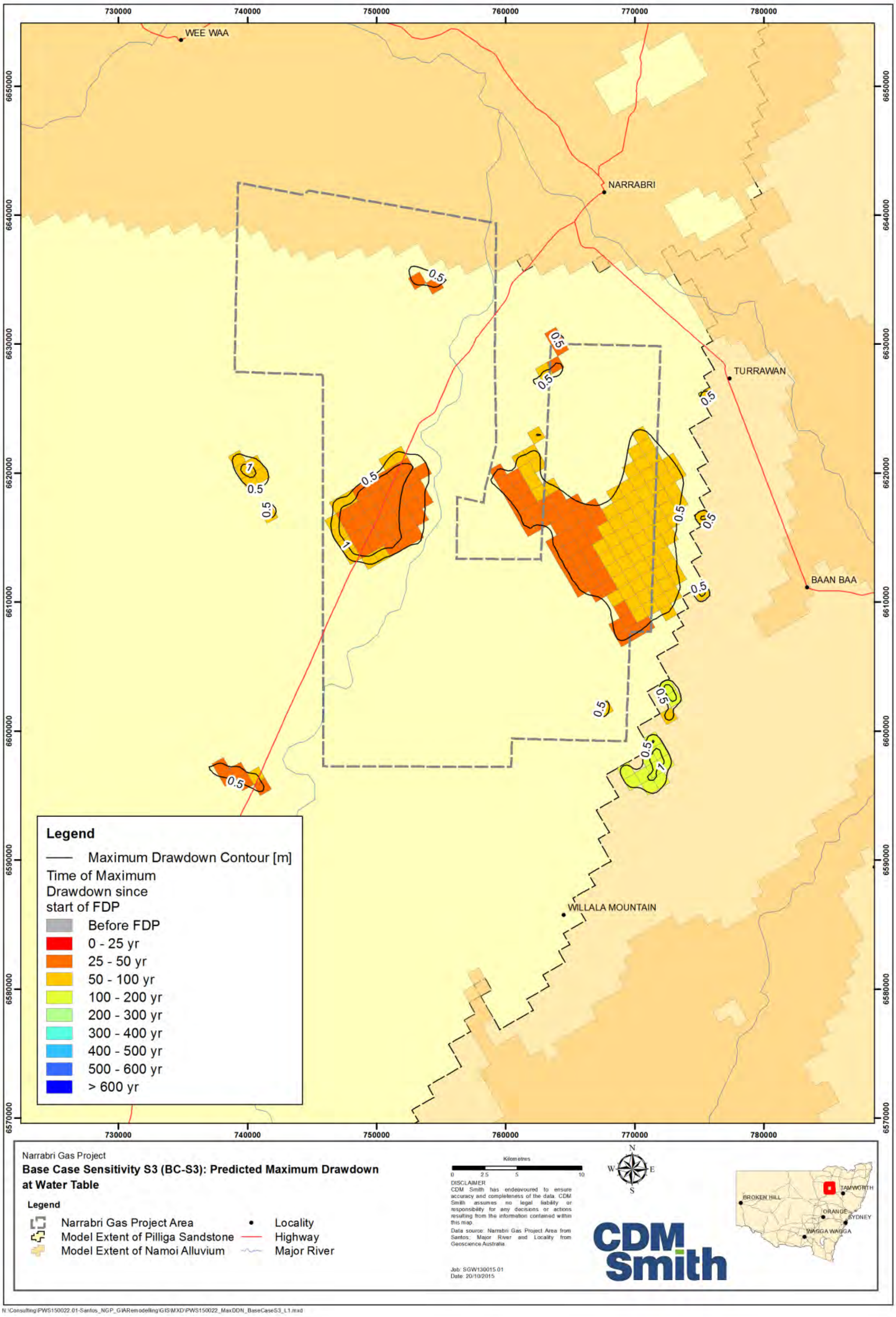


**Figure 6-102 Simulation BC-S3: predicted maximum drawdown at the water table**

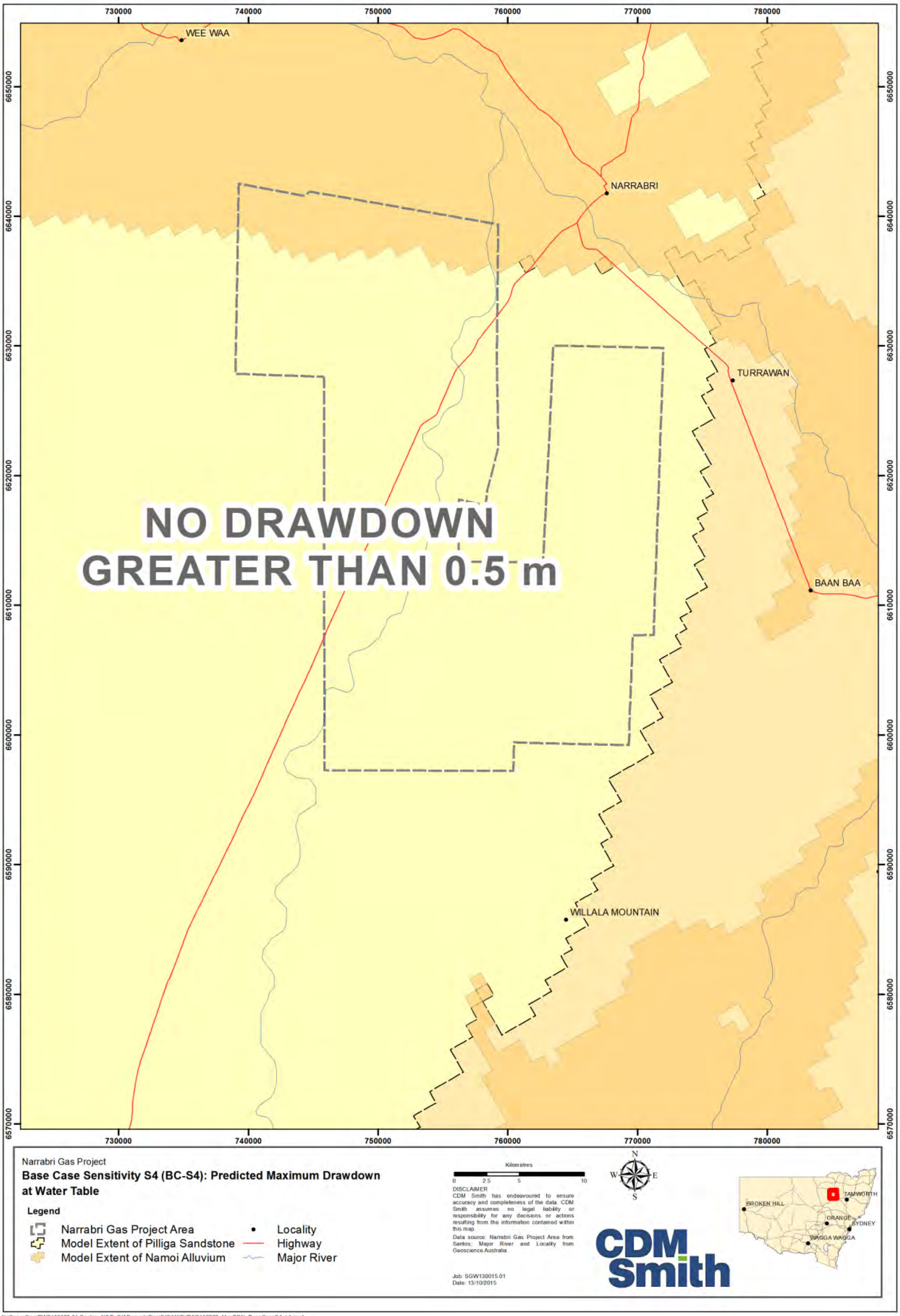


**Figure 6-103 Simulation BC-S4: predicted maximum drawdown at the water table**

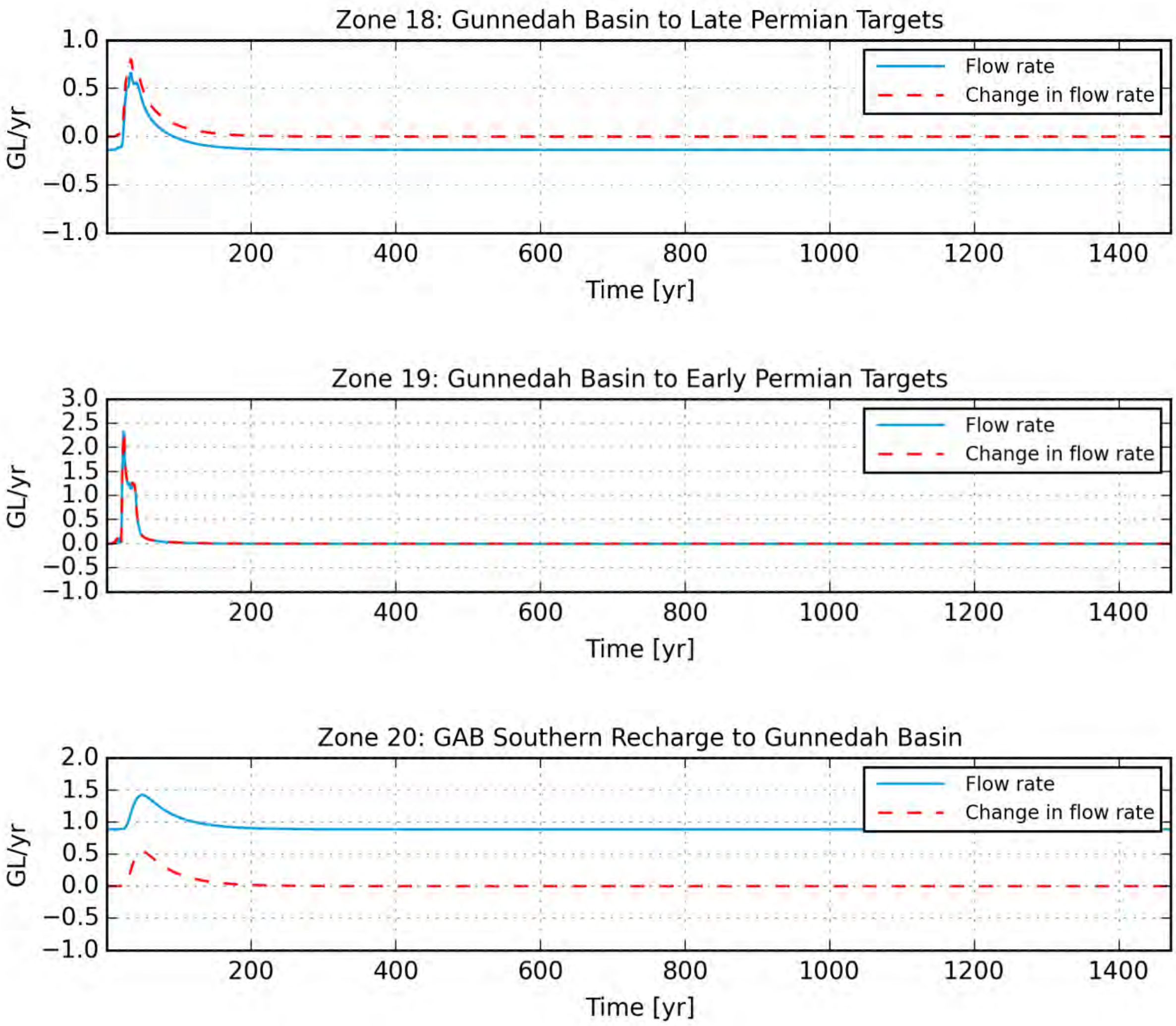


**Figure 6-104 Simulation BC-S3: time variation of flow rates between selected WSPRAs**

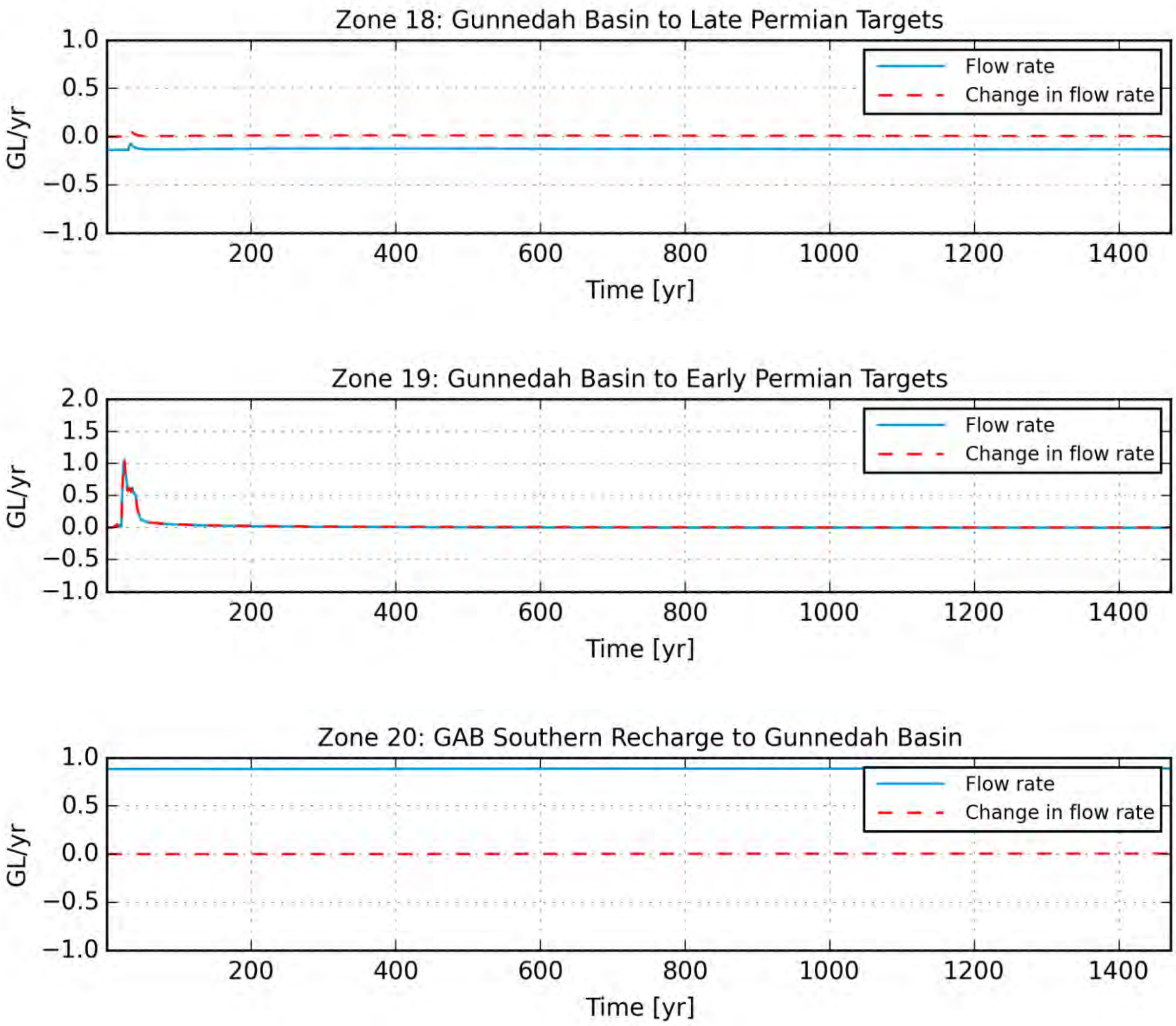


**Figure 6-105 Simulation BC-S4: time variation of flow rates between selected WSPRAs**

## 6.10.6 Variation of Vertical Hydraulic Conductivity and Storativity

The results for simulation BC-S5 are presented in Table 6-42, Table 6-43 and Figure 6-106 to Figure 6-114. This simulation represents a combination of simulations BC-S2 and BC-S3 in which *Kv* of the aquitard sequences is increased, promoting faster vertical propagation of drawdown, and *Ss* of aquitard sequences and transmissive units is decreased, promoting larger drawdown per unit volume of simulated water production. It therefore represents the largest potential impact on the Pilliga Sandstone and water table for the range of parameter variations considered in this analysis.

### 6.10.6.1 Key Results for BC-S5

- Compared to simulation BC the overall effect of increasing *Kv* in the aquitard sequences and decreased *Ss* in the aquitard sequences and transmissive units is considerably larger and faster drawdown in all formations, including the Early and Late Permian targets, Pilliga Sandstone and at the water table.
- In simulation BC-S5 the maximum drawdowns in the Early and Late Permian targets are predicted to occur rapidly and are contemporary with the 25-year period of the FDP
- The largest value of drawdown in the Pilliga Sandstone is predicted to increase from less than 0.5 m in simulation BC to 5.7 m in simulation BC-S5 with maximum drawdowns occurring between 5 and 39 years after the start of the FDP (Table 6-42). The area of drawdown is predicted to extend from north to south across the project area and from the eastern boundary of the Pilliga Sandstone to around 10 km west of the project area (Figure 6-112).
- The largest value of drawdown at the water table outside of the Namoi alluvium is predicted to increase from less than 0.5 m in simulation BC to 3.0 m in simulation BC-S5, with maximum drawdowns occurring between 7 and 56 years after the start of the FDP. The area of drawdown corresponds generally with the predicted area of drawdown in the Pilliga Sandstone (Figure 6-113).
- Relative to simulation BC the maximum induced flows between WSPRAs are all larger, including 3.15 GL/y (100 L/s) from the Gunnedah Basin to the Early Permian targets (WSPRA 19), 1.96 GL/y (62 L/s) from the Gunnedah Basin to the Late Permian targets (WSPRA 18), 1.73 GL/y (55 L/s) from the GAB Southern Recharge Area to the Gunnedah Basin (WSPRA 20) and 0.06 GL/y (2.0 L/s) from the Lower Namoi Alluvium to the GAB Southern Recharge source (WSPRA 2).
- Most of the simulated water production in simulation BC-S5 is derived from induced storage release in the Gunnedah-Oxley Basin and GAB with a small contribution from the Lower Namoi Alluvium. The predicted maximum rate of storage release of 2.4 GL/y from the Gunnedah-Oxley Basin occurs at around 2 years after the start of the FDP, and the predicted maximum rate of storage release of 1.7 GL/y from the GAB occurs around 7 years after the start of the FDP (Figure 6-108). Almost complete recovery of hydraulic head can be seen around 50 years after the start of the FDP.
- The characteristics of Figure 6-108 are different in this simulation because of enhanced connection between the Early Permian targets and overlying strata. For example, approximately 6 years after the start of the FDP the rate of inflow from the GAB to the Gunnedah Basin temporarily exceeds the rate of water extraction from the coal seams and the Gunnedah Basin begins to recover groundwater storage (i.e. the rate of storage release becomes negative); thus, there is recovery of storage in the basin despite ongoing extraction. As the system recovers

further, the vertical hydraulic gradient between the GAB and Gunnedah Basin declines and the rate of storage recovery also slows.

- At the end of the simulation, the predicted contributions to the total simulated water production of 38.5 GL are approximately: 36.9 GL (95.9%) from the GAB; 1.0 GL (2.7%) from the Gunnedah-Oxley Basin; and 0.6 GL (1.6%) from the Lower Namoi Alluvium (Figure 6-109).

**Table 6-42 Simulation BC-S5: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 3.0 | 7 to 56 |
| Pilliga Sandstone | 5.7 | 5 to 39 |
| Late Permian Targets | 52 | 2 to 25 |
| Early Permian Targets | 182 | 1 to 25 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-43 Simulation BC-S5: summary of predicted WSPRA groundwater fluxes**

| Zone # | Initial Flow Rate [GL/y] | Maximum Change in Flow Rate [GL/y] | Time of Maximum Change [[1]y] | Induced Volume Exchange [GL] | Time Series Graph |
|---|---|---|---|---|---|
| 1 | -2.31 | 0.00 | - | -0.27 | N |
| 2 | -1.08 | 0.06 | 38 | 0.89 | Y |
| 3 | 0.00 | 0.00 | - | 0.00 | N |
| 4 | -0.38 | 0.00 | - | 0.00 | N |
| 5 | -0.08 | 0.00 | - | 0.00 | N |
| 6 | -0.07 | 0.00 | - | 0.00 | N |
| 7 | -0.24 | 0.00 | - | -0.07 | N |
| 8 | -1.51 | 0.00 | - | 0.00 | N |
| 9 | -0.20 | 0.00 | - | 0.00 | N |
| 10 | -0.11 | 0.00 | - | 0.00 | N |
| 11 | -1.67 | 0.00 | - | 0.00 | N |
| 12 | -0.04 | 0.00 | - | 0.00 | N |
| 13 | -0.04 | 0.00 | - | 0.00 | N |
| 14 | 1.54 | 0.00 | - | 0.00 | N |
| 15 | 0.52 | 0.00 | - | 0.00 | N |
| 16 | 0.88 | 0.00 | - | 0.00 | N |
| 17 | -0.19 | 0.00 | - | 0.00 | N |
| 18 | 0.15 | 1.96 | 4 | 37.45 | Y |
| 19 | 0.00 | 3.15 | 3 | 36.49 | Y |
| 20 | 1.80 | 1.73 | 7 | 37.53 | Y |
| 21 | -0.10 | 0.00 | - | 0.00 | N |

[1]Years since start of FDP

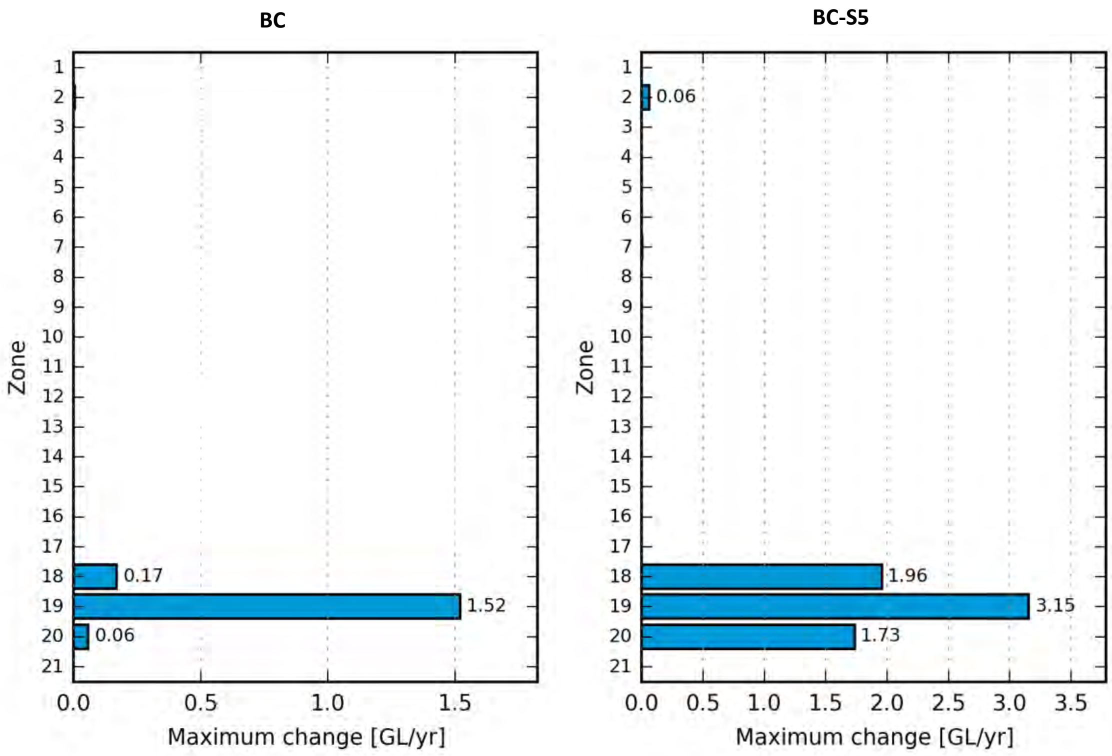


**Figure 6-106 Comparison of maximum predicted change in WSPRA Flow Rates (a) simulation BC and (b) simulation BC-S5**

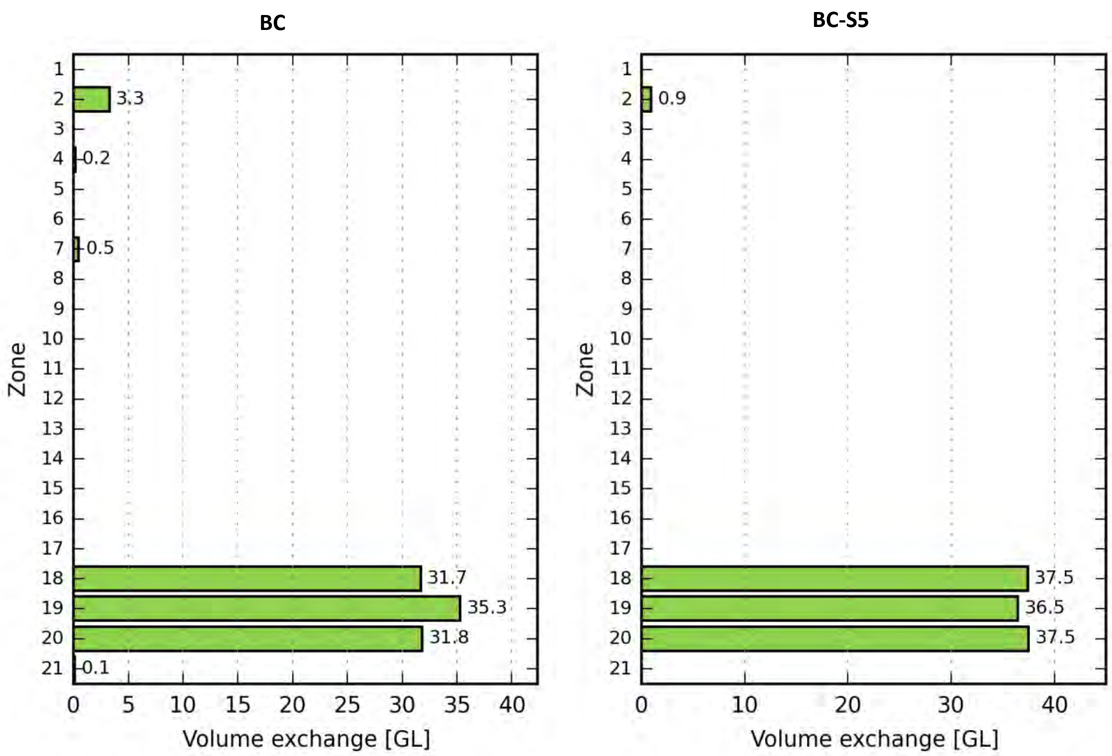


**Figure 6-107 Comparison of total predicted volumetric exchange between WSPRAs (a) simulation BC and (b) simulation BC-S5**

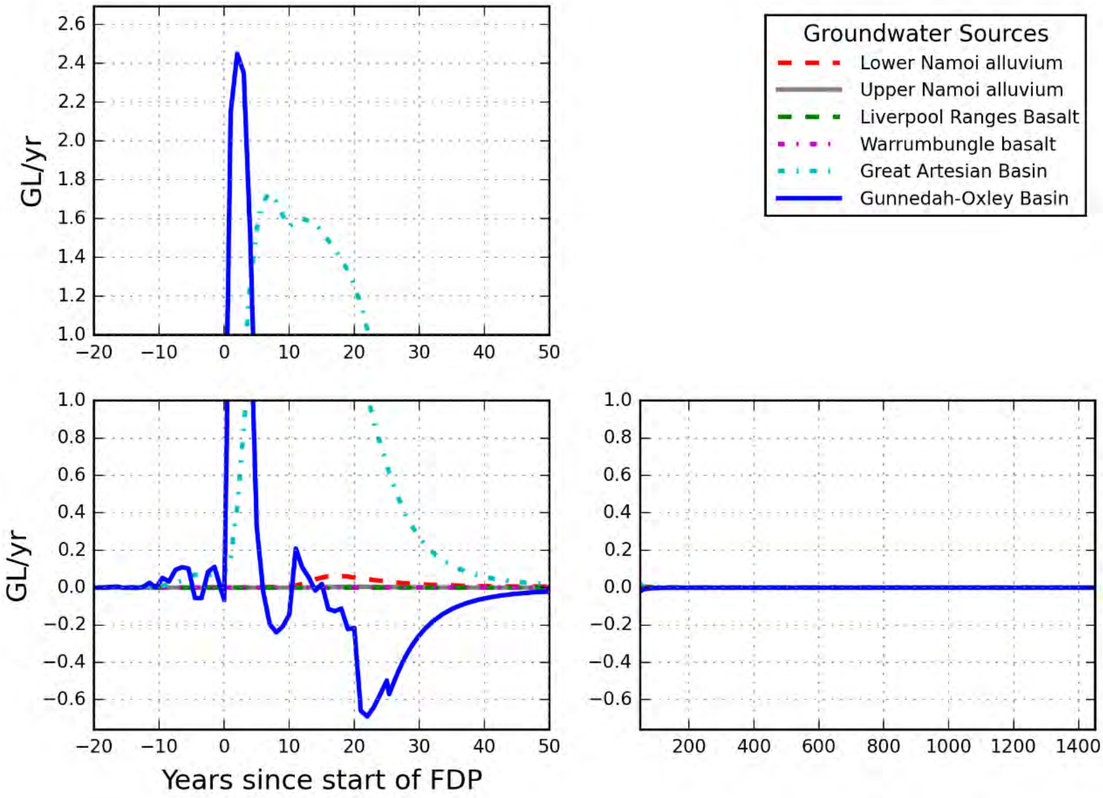


**Figure 6-108 Simulation BC-S5: predicted rates of induced storage releases**

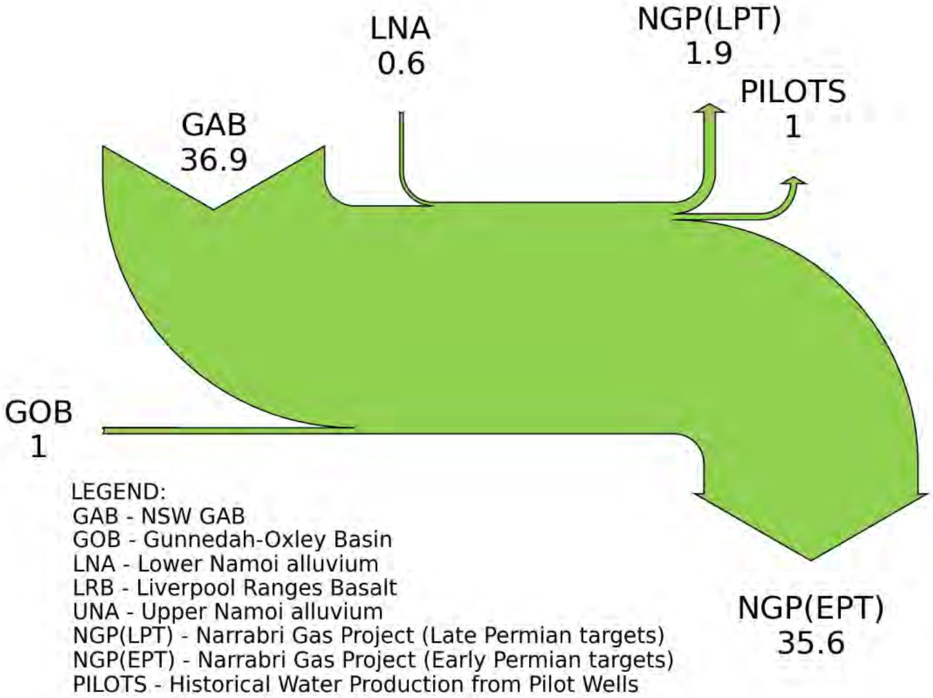


**Figure 6-109 Simulation BC-S5: predicted volumetric contributions to simulated water production [GL] 1500 years after the start of the FDP**

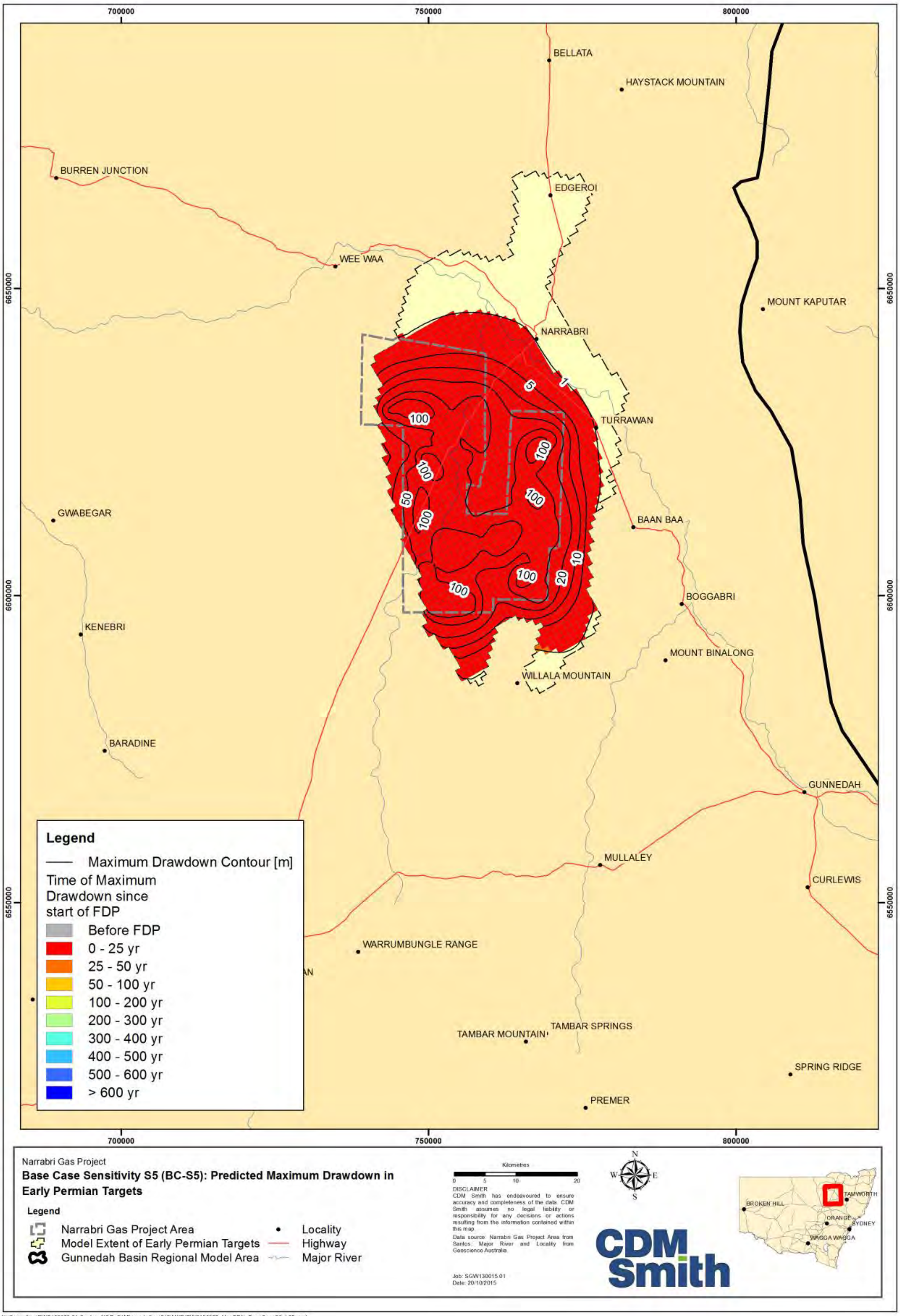


**Figure 6-110 Simulation BC-S5: predicted maximum drawdown in Early Permian targets**

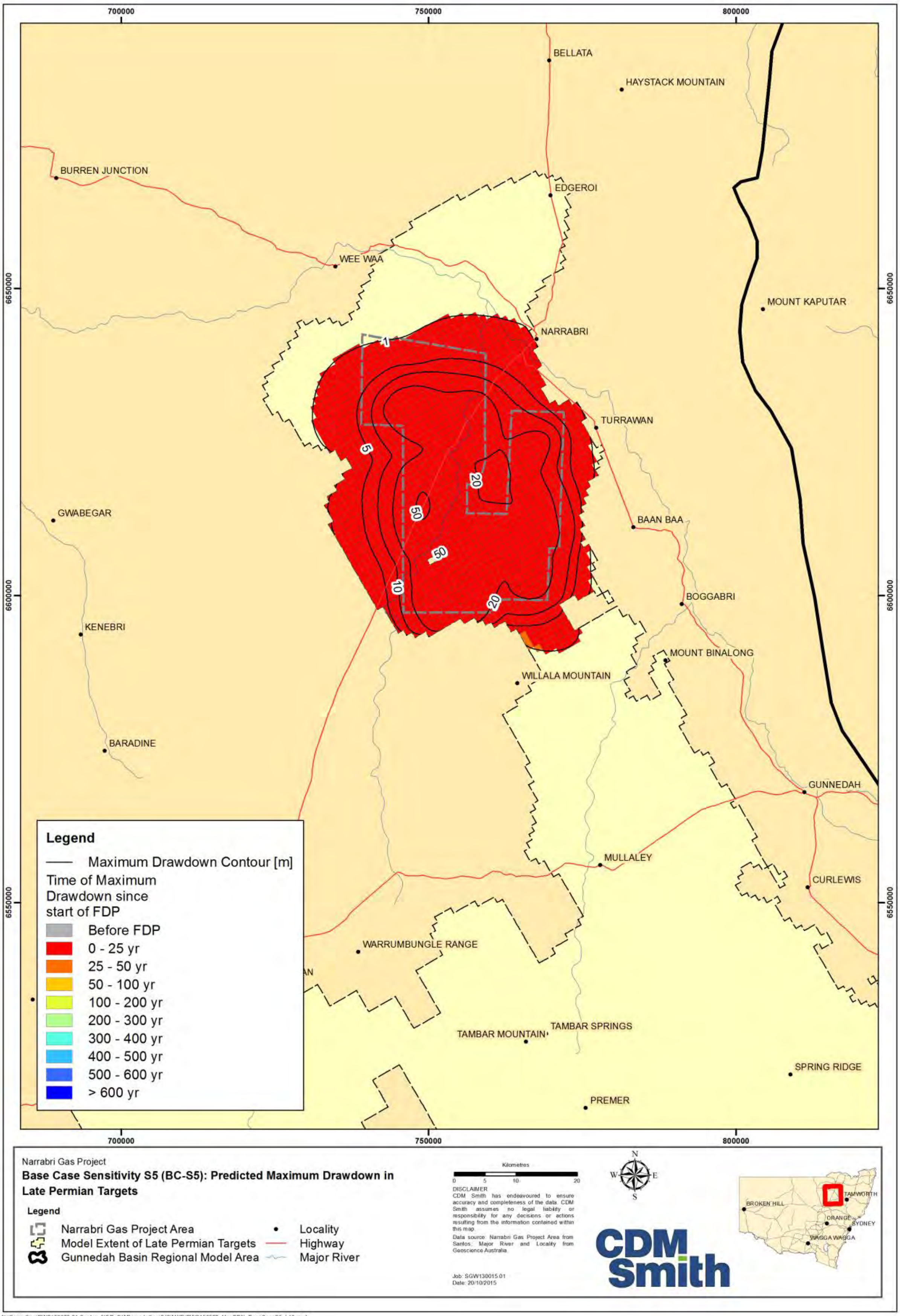


**Figure 6-111 Simulation BC-S5: predicted maximum drawdown in Late Permian targets**

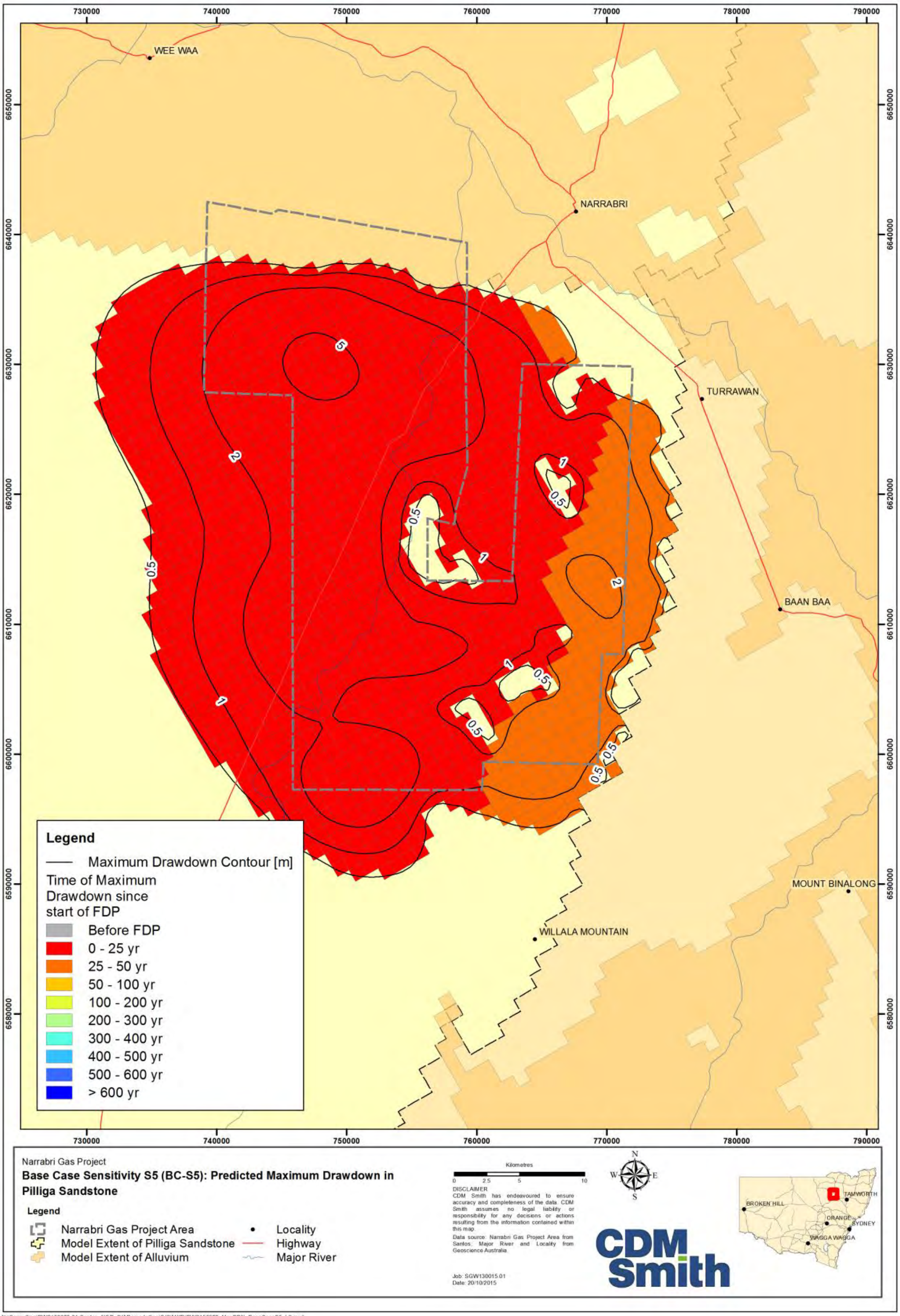


**Figure 6-112 Simulation BC-S5: predicted maximum drawdown in Pilliga Sandstone**

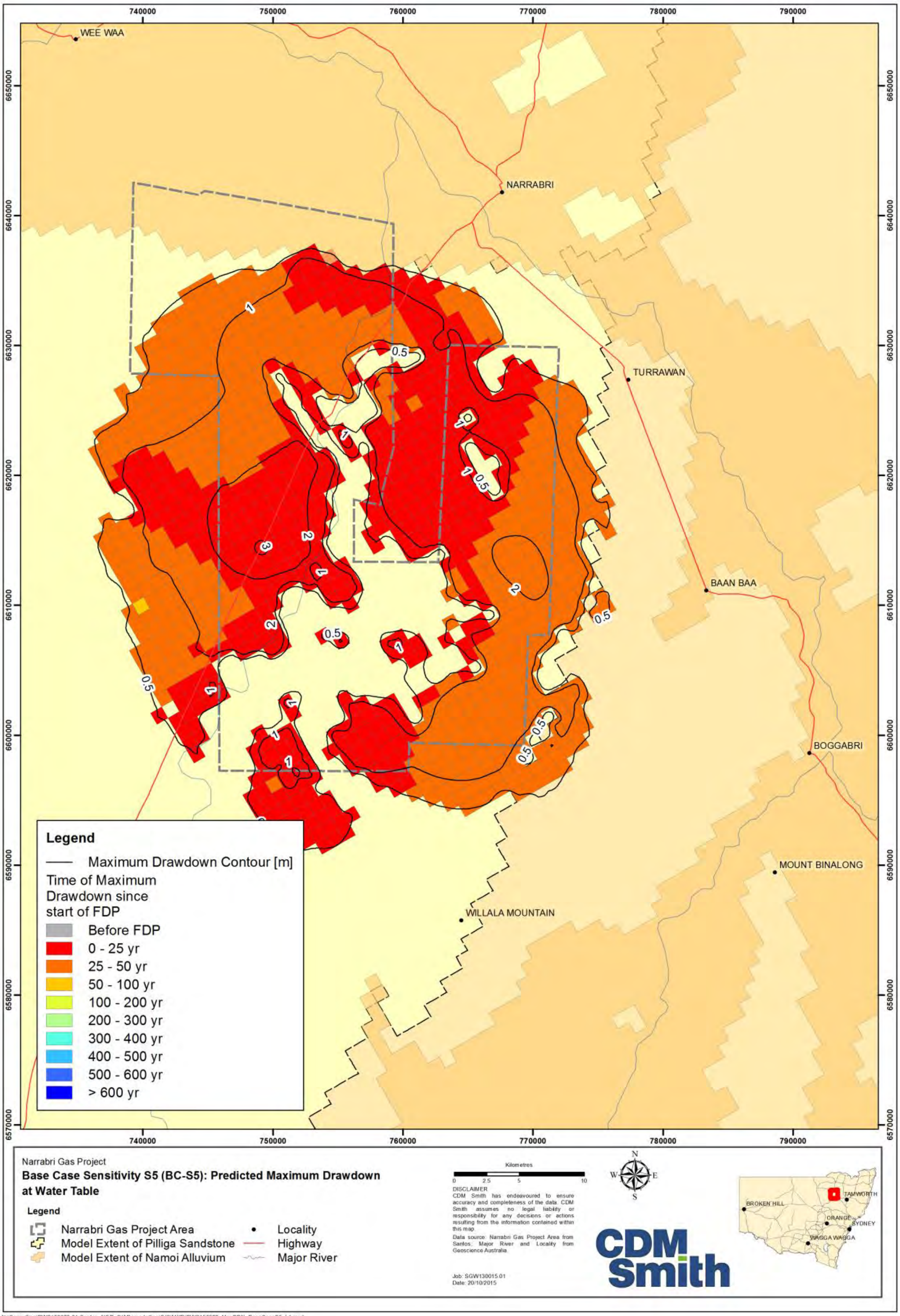


**Figure 6-113 Simulation BC-S5: predicted maximum drawdown at the water table**

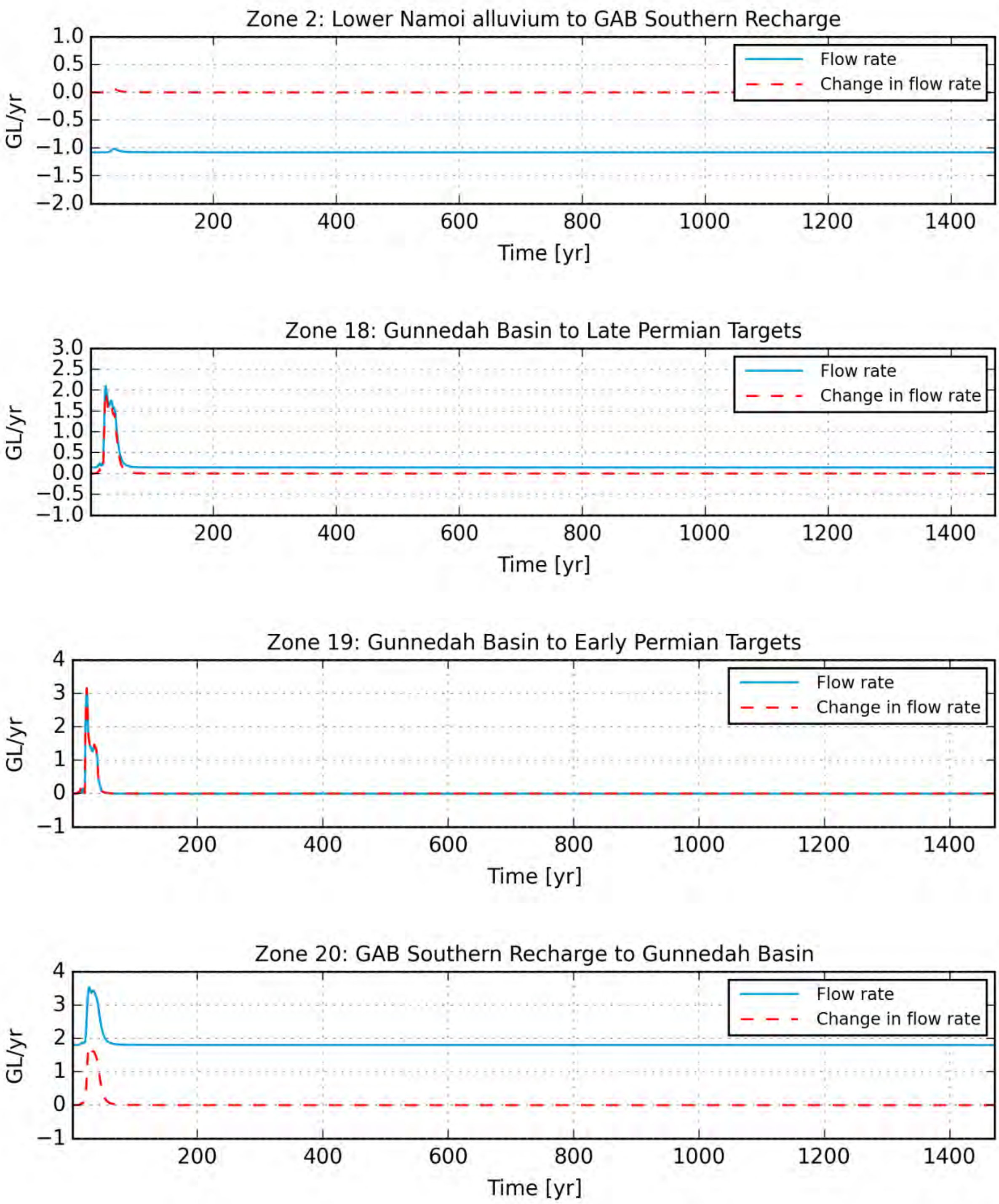


**Figure 6-114 Simulation BC-S5: time variation of flow rates between selected WSPRAs**

### 6.10.7 Variation of Specific Yield

Results for simulations BC-S6 and BC-S7 are presented in Table 6-45, Table 6-46, Figure 6-115 and Figure 6-116. Relative small changes to the model prediction are observed. The applied values of specific yield for each simulation are indicated in Table 6-44.

**Table 6-44 Variation of specific yield**

| Simulation | *Sy* Namoi Alluvium [-] | *Sy* Other Outcropping Units [-] |
|---|---|---|
| BC | 0.1 | 0.01 |
| BC-S6 | 0.2 | 0.05 |
| BC-S7 | 0.05 | 0.005 |

#### 6.10.7.1 Key Results for BC-S6 and BC-S7

- Predicted impacts for simulations BC-S6 and BC-S7 are almost identical to the Base Case with the exception of relatively small changes in drawdown at the water table.
- For simulation BC-S7, with smaller specific yield, the largest drawdown at the water table increases slightly from less than 0.5 m in the Base Case to approximately 0.57 m. There is no predicted drawdown greater than 0.5 m in the Namoi alluvium.

**Table 6-45 Simulation BC-S6: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | < 0.5 | - |
| Pilliga Sandstone | < 0.5 | - |
| Late Permian Targets | 16.4 | Pre-FDP to 350 |
| Early Permian Targets | 152 | 1 to 400 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-46 Simulation BC-S7: summary of predicted maximum drawdown**

| Hydrostratigraphic Unit (HSU) | Largest Drawdown in any Model Cell [m] | Time to Reach Maximum Drawdown within HSU [y*] |
|---|---|---|
| Water Table** | 0.57 | 250 to 400 |
| Pilliga Sandstone | 0.57 | 250 to 400 |
| Late Permian Targets | 16.4 | Pre-FDP to 350 |
| Early Permian Targets | 153 | 1 to 400 |

*Years since start of FDP

**Across the full area of the model domain, inclusive of all HSU containing the water table

### 6.10.8 Sensitivity to Variation of Boundary Conditions

Since predicted drawdowns due to simulated water production do not extend to the model boundaries for either the predictive simulations or the sensitivity simulations, it can be concluded that the predicted impacts on groundwater are not sensitive to the choice of the regional boundary conditions (Section 6.4.3.7). On this basis, no additional sensitivity simulations on the model boundary conditions were conducted.

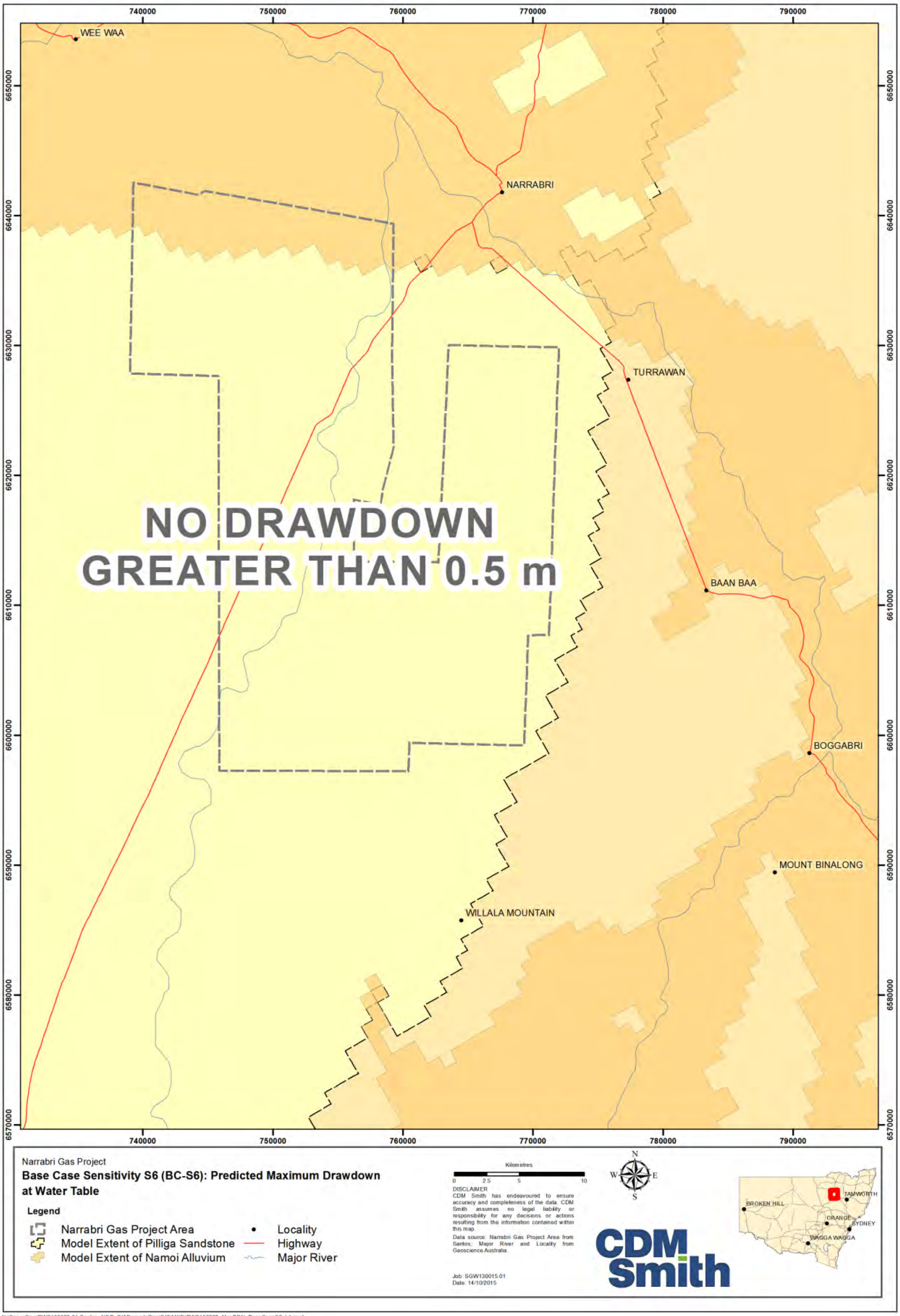


Figure 6-115 Simulation BC-S6: predicted maximum drawdown at the water table

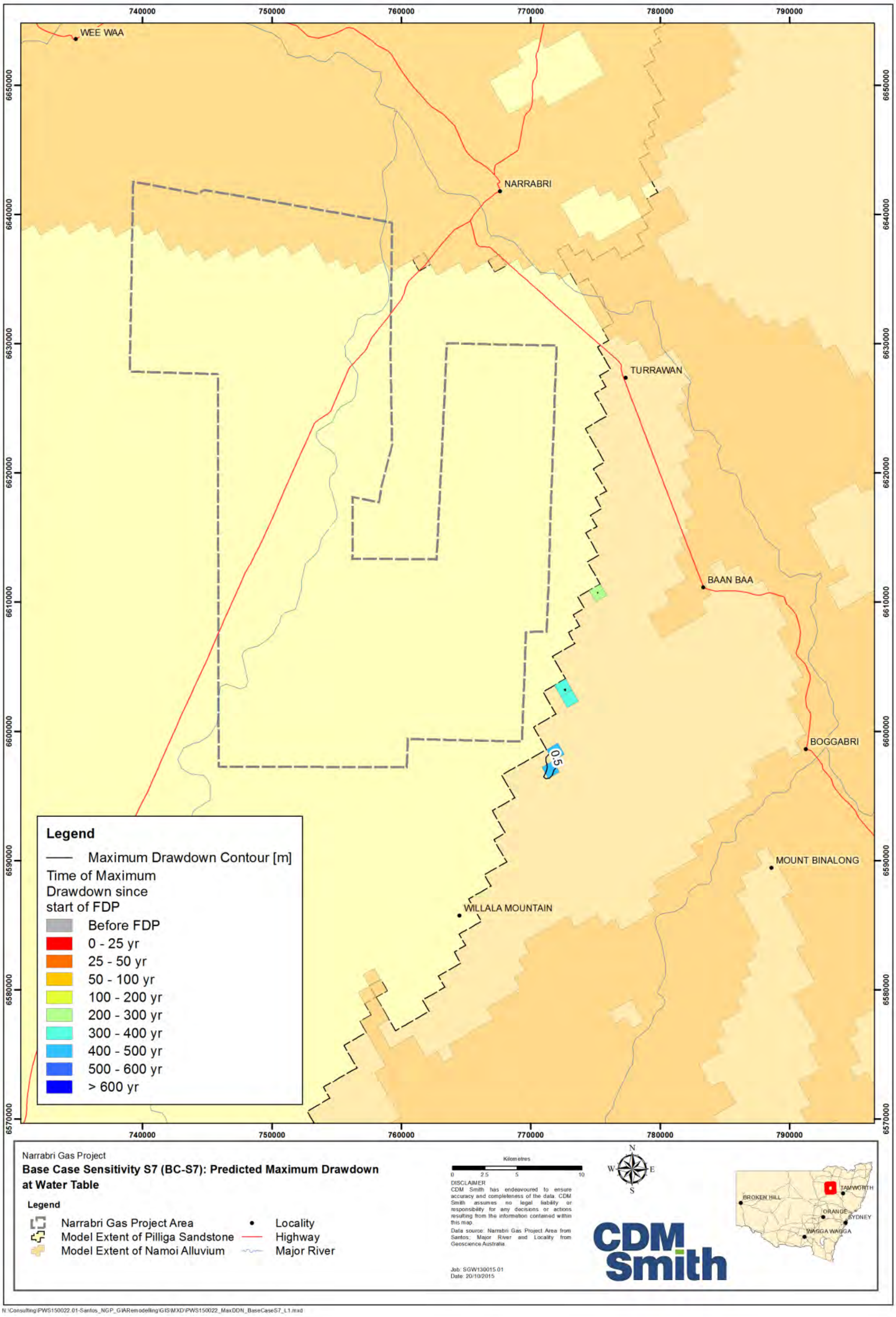


**Figure 6-116 Simulation BC-S7: predicted maximum drawdown at the water table**

# 6.11 Summary of the Modelling Results

Tabulated summaries of the groundwater modelling results are presented in the following tables and general and specific conclusions are discussed in the sections below:

- **Table 6-47** – a list of all simulations considered in this assessment;
- **Table 6-48 –** a summary of the largest value of drawdown in the Early and Late Permian targets, Pilliga Sandstone and at the water table for all simulations in this assessment;
- **Table 6-49** – a summary of the range of times to reach maximum drawdown in the Early and Late Permian targets, Pilliga Sandstone and at the water table for all simulations in this assessment;
- **Table 6-50** – a summary of the maximum induced flows between the 21 water sharing plan reporting areas for all simulations in this assessment;
- **Table 6-51** – a summary of the maximum rates of induced storage release in the Upper Namoi Alluvium, Lower Namoi Alluvium, GAB and Gunnedah-Oxley Basin groundwater sources for all simulations in this assessment; and
- **Table 6-52** – volumetric and percentage summaries of the predicted contributions to total simulated water production from the Upper Namoi Alluvium, Lower Namoi Alluvium, GAB and Gunnedah-Oxley Basin groundwater sources for all simulations in this assessment.

## 6.11.1 General Conclusions

- Water production from deep coal seams in the Bohena Trough of the Gunnedah Basin will result in drawdown of hydraulic head and reduction of groundwater storage in the target coal seams and overlying and underlying formations. The principal mechanism for recovery of hydraulic head in the basin following cessation of simulated water production is increased recharge and decreased discharge at the water table.
- Large predicted time lags between the start of simulated gas and water production and eventual recovery of hydraulic head following cessation of the 25-year field development plan reflect the long periods of time required for predicted drawdown in the coal seams to be transmitted to the water table by means of vertical flow in overlying aquitards.
- The magnitude and timing of predicted impacts in the Pilliga Sandstone and at the water table are influenced by the model geometry and layering, which define the pathways for groundwater flow, and by the choice of values for hydrogeological properties, which affect the rates of flow within these pathways.
- The values of hydrogeological properties used in existing modelling studies do not consistently reflect the existing hydrogeological classification of strata in the Gunnedah Basin and the expected hydrogeological properties for those strata types. The values of hydrogeological properties adopted in this assessment are based partly on the existing modelling studies but are modified to reflect the range of values for these strata that are consistent with the accepted ranges of values within the hydrogeological literature.
- Predicted impacts on drawdown in the Pilliga Sandstone and at the water table are smaller when resistance to vertical flow through aquitards is larger. Slower recovery of storage in the basin implies smaller inter-formational flows over longer periods of time, and ultimately less

drawdown in the formations supplying this water. Less resistance to vertical flow through aquitards has an opposite influence.

- For the simulations considered in this assessment, predicted drawdown does not extend to the sections of the model boundary where prescribed head conditions are assigned. The locations of these boundaries are therefore considered to be sufficiently distant from the project area that they do not significantly influence the predictions of drawdown.

### 6.11.2 Predictive Simulations

The predictive simulations consider potential impacts of the Base Case simulated water production profile for the project; the Low Case simulated water production profile; the High Case simulated water production profile; and concurrent mine inflows to the Narrabri Coal Mine Stage 2 Longwall and the Base Case simulated water production profile.

- For the Base Case water production profile (simulation BC) the largest predicted drawdown at the water table is less than 0.5 m including the area of the Namoi alluvium. The predicted times to reach maximum drawdown at the water table are up to 300 years after the start of the FDP. Induced groundwater flow at the base of the Namoi alluvium is predicted to be negligible (less than order-of-magnitude 0.01 GL/y) compared to the existing estimates of total recharge and extraction in the alluvium (order-of-magnitude 100 GL/y). No drawdown greater than 0.5 m is predicted in the Pilliga Sandstone. Almost full recovery of hydraulic head in the basin is predicted after approximately 1500 years. The majority of the simulated water production of 38.5 GL is counter balanced by additional net recharge in the GAB (74.4%), Gunnedah-Oxley Basin (15.4%), Lower Namoi Alluvium (8.6%) and Upper Namoi alluvium (less than 2%) with negligible predicted contributions from other groundwater sources.

- The predicted impacts for the Low Case water production profile (simulation LC) are slightly smaller compared to the Base Case. No drawdown greater 0.5 m is predicted at the water table, including the area of the Namoi alluvium, or within Pilliga Sandstone. Almost full recovery of hydraulic head in the basin is predicted after approximately 1500 years. The majority of the simulated water production of 36.0 GL is counter balanced by additional net recharge in the GAB (74.4%), Gunnedah-Oxley Basin (15.4%), Lower Namoi Alluvium (8.6%) and Upper Namoi alluvium (less than 2%).

- The predicted impacts for the High Case water production profile (simulation HC) are larger compared to the Base Case. The largest predicted drawdown at the water table is 1.1 m with times to reach maximum drawdown of between 350 and 550 years after the start of the FDP. No drawdown greater than 0.5 m is predicted in the Namoi alluvium. The largest value of drawdown in the Pilliga Sandstone is predicted to be 0.6 m with times to reach maximum drawdown of 190 to 200 years after the start of the FDP. Almost full recovery of hydraulic head is predicted after approximately 1500 years. The majority of the simulated water production of 88.1 GL is counter balanced by additional net recharge in the GAB (74.3%), Gunnedah-Oxley Basin (15.4%), Lower Namoi Alluvium (8.6%) and Upper Namoi alluvium (less than 2%).

- Indiscernible cumulative impacts of the Narrabri Coal Mine and Narrabri Gas Project are predicted in the Pilliga Sandstone and small cumulative impacts are predicted at the water table outside of the area of the Namoi alluvium. Predicted maximum drawdown in the Pilliga Sandstone and at the water table is dominated by the impacts of the mine inflow in the underlying Hoskissons Coal, with relatively smaller contributions to drawdown from the Base Case simulated water production. For isolated development of the Narrabri Coal Mine Stage 2 Longwall Project the majority of simulated groundwater extraction of 21.6 GL (20.6 GL from mine inflow) is ultimately supplied from the GAB (57.9%), Gunnedah-Oxley Basin (35.6%), Upper Namoi Alluvium (3.2%) and Lower Namoi alluvium (3.2%).

### 6.11.3 Sensitivity Simulations

The sensitivity simulations consider the influences of selected variations of formation hydrogeological properties on the model predictions of drawdown and induced flows, including variation of the vertical hydraulic conductivity (*Kv*) of aquitards; variation of the specific storativity (*Ss*) of aquitards and transmissive units; and variation of specific yield (*Sy*) at the water table. The model predictions are found to be most sensitive to variation in the vertical hydraulic conductivity of aquitards and variation in the specific storativity of confined hydrostratigraphic units. There is less sensitivity to variation of specific yield at the water table because the largest and most rapid changes in storage take place at depth within the basin and are predicted to propagate slowly to the surface over long periods of time. The sensitivity simulations are not all equally likely but instead are considered to represent extreme conditions.

- Decreasing *Kv* of aquitards relative to the Base Case (simulation BC-S1) results in larger drawdown in the target coal seams, slower recovery of hydraulic head following depressurisation, and smaller impacts in the Pilliga Sandstone and at the water table. In contrast, increasing *Kv* of aquitards (simulation BC-S2) causes smaller drawdown in the target coal seams, faster recovery of hydraulic head following depressurisation, and larger and more rapid impacts in the Pilliga Sandstone and at the water table. Increasing *Kv* by an order of magnitude results in predicted maximum drawdown of up to 1.0 m in the Pilliga Sandstone compared to less than 0.5 m in the Base Case, and predicted maximum drawdown up to 0.9 m at the water table compared to less than 0.5 m in the Base Case. In the Namoi alluvium no drawdown of the water table greater than 0.5 m is predicted.

- Decreasing *Ss* of confined hydrostratigraphic units relative to the Base Case results in larger drawdown per unit volume of simulated water production and faster propagation of drawdown from the target coal seams to the Pilliga Sandstone and water table. Decreasing *Ss* by an order of magnitude (simulation BC-S3) causes predicted maximum drawdown of up to 2.0 m in the Pilliga Sandstone compared to less than 0.5 m in the Base Case, and predicted maximum drawdown up to 1.5 m at the water table compared to less than 0.5 m in the Base Case. In the Namoi alluvium, no drawdown greater 0.5 m at the water table is predicted. Increasing *Ss* of the confined hydrostratigraphic units (simulation BC-S4) results in smaller drawdown in the target coal seams, slower propagation of drawdown and smaller impacts in the Pilliga Sandstone and at the water table.

- Simultaneous increase of *Kv* and decrease of *Ss* both contribute to larger drawdown in the Pilliga Sandstone and at the water table. Increasing *Kv* of aquitards by an order of magnitude relative to the Base Case and decreasing *Ss* of confined hydrostratigraphic units by an order of magnitude (simulation BC-S5) causes predicted maximum drawdown of up to 5.7 m in the Pilliga Sandstone compared to less than 0.5 m in the Base Case, and predicted maximum drawdown up to 3.0 m at the water table compared to less than 0.5 m in the Base Case. In the Namoi alluvium, no drawdown greater 0.5 m at the water table is predicted.

- Changing the values of specific yield in outcropping units influences the predicted drawdown of the water table. Increasing the specific yield by a factor of 5 (from 1% to 5%) in the outcropping hydrostratigraphic units where drawdown at the water table is predicted (simulation BC-S6) results in an approximate halving of the predicted maximum drawdown. Reducing the specific yield by a factor of 2 (from 1% to 0.5%) in the outcropping hydrostratigraphic units (simulation BC-S7) results in a relatively small increase in the predicted maximum drawdowns at the water table. No significant drawdown of the water table in the Namoi alluvium is predicted for the sensitivity simulations.

**Table 6-47 Model Simulations**

| Short Name | Groundwater Stresses |
|---|---|
| BC | Base Case water production profile |
| LC | Low Case water production profile |
| HC | High Case water production profile |
| NCM-BC | Narrabri Mine Stage 2 Longwall Project and Base Case water production profile |
| NCM | Narrabri Mine Stage 2 Longwall Project |
| BC-S1 | Base Case water production profile with vertical hydraulic conductivity of aquitards decreased by factor 10 |
| BC-S2 | Base Case water production profile with vertical hydraulic conductivity of aquitards increased by factor 10 |
| BC-S3 | Base Case water production profile with storativity of aquitards and aquifers decreased by factor 10 |
| BC-S4 | Base Case water production profile with storativity of aquitards and aquifers increased by factor 10 |
| BC-S5 | Base Case water production profile with vertical hydraulic conductivity of aquitards increased by factor 10 and storativity of aquitards and aquifers decreased by factor 10 (BC-S2 and BC-S3) |
| BC-S6 | Base Case water production profile with specific yield at the water table increased |
| BC-S7 | Base Case water production profile with specific yield at the water table decreased |

All simulations are run for a period of 1520.5 year (1997 to 3517)

**Table 6-48 Largest drawdowns for all model simulations**

| HSU | Largest Drawdown [m] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| Water table | <0.5 | <0.5 | 1.1 | 5.2 | 5.2 | <0.5 | 0.9 | 1.5 | <0.5 | 3.0 | <0.5 | 0.57 |
| Pilliga Sandstone | <0.5 | <0.5 | 0.6 | 1.8 | 1.8 | <0.5 | 1.0 | 2.0 | <0.5 | 5.7 | <0.5 | 0.57 |
| Late Permian targets | 16.4 | 16.0 | 32.3 | 276 | 275 | 22.0 | 12.0 | 50.0 | 4.2 | 52.0 | 16.4 | 16.4 |
| Early Permian targets | 153 | 150 | 224 | 153 | 57 | 323 | 68.0 | 442 | 46.0 | 182 | 152 | 153 |

**Table 6-49 Times to reach maximum drawdown for all simulations**

| HSU | Time Range to Reach Maximum Drawdown [years after start of FDP] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| Water table** | - | - | 350 to 550 | 48 to 550 | 48 to 120 | - | 35 to 120 | 29 to 130 | - | 7 to 56 | - | 250 to 450 |
| Pilliga Sandstone | - | - | 190 to 200 | 48 to 90 | 48 to 81 | - | 27 to 90 | 25 to 56 | - | 5 to 39 | - | 250 to 450 |
| Late Permian targets | Up to 300 | Up to 300 | Up to 350 | Up to 300 | Up to 250 | Up to >1500 | Up to 61 | 9 to 74 | Up to 21 | 2 to 25 | Up to 350 | Up to 350 |
| Early Permian targets | 1 to 300 | 1 to 300 | 2 to 500 | 1 to 450 | Up to 250 | 1 to >1500 | Up to 61 | 2 to 67 | Up to 300 | 1 to 25 | 1 to 400 | 1 to 400 |

**Across the full area of the model domain, inclusive of all HSU containing the water table

**Table 6-50 Maximum induced flows between WSPRAs for all simulations**

| WSPRA | Maximum Change in Flow Rate between WSPRAs [GL/y] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| 1 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 2 | 0.01 | 0.01 | 0.01 | 0.01 | <0.01 | <0.01 | 0.01 | 0.06 | <0.01 | 0.06 | 0.01 | <0.01 |
| 3 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 4 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 5 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 6 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 7 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.03 | <0.01 | 0.01 | <0.01 | <0.01 |
| 8 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 9 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 10 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 11 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 12 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 13 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 14 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 15 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 16 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 17 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 18 | 0.17 | 0.16 | 0.35 | 0.83 | 0.67 | 0.06 | 0.08 | 0.80 | 0.06 | 1.96 | 0.17 | 0.17 |
| 19 | 1.52 | 1.44 | 3.11 | 1.52 | 0.08 | 1.08 | 2.31 | 2.34 | 1.06 | 3.15 | 1.52 | 1.52 |
| 20 | 0.06 | 0.05 | 0.13 | 0.08 | 0.05 | 0.01 | 0.47 | 0.54 | 0.01 | 1.73 | 0.06 | 0.06 |
| 21 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |

**Table 6-51 Maximum rates of induced storage releases for all simulations**

| Groundwater Source | Maximum Rate of Take from Storage [GL/y] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| Upper Namoi Alluvium | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Lower Namoi Alluvium | <0.01 | <0.01 | 0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.06 | <0.01 | 0.06 | <0.01 | <0.01 |
| GAB | 0.05 | 0.05 | 0.12 | 0.07 | 0.05 | <0.01 | 0.46 | 0.48 | <0.01 | 1.7 | 0.05 | 0.05 |
| Gunnedah-Oxley Basin | 2.9 | 2.8 | 5.9 | 3.5 | 1.2 | 2.1 | 3.1 | 3.1 | 2.1 | 2.5 | 2.9 | 2.9 |

**Table 6-52 Volumetric contributions to total simulated water production for all simulations**

| Groundwater Source | Contribution to Total Simulated Coal Seam Water Production [GL] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| Upper Namoi Alluvium | 0.6 | 0.6 | 1.4 | 1.3 | 0.7 | IR | 0.0 | 3.8 | IR | 0.0 | 0.7 | 0.6 |
| Lower Namoi Alluvium | 3.3 | 3.1 | 7.6 | 3.9 | 0.7 | IR | 0.5 | 0.7 | IR | 0.6 | 3.6 | 3.0 |
| GAB | 28.6 | 26.8 | 65.5 | 40.3 | 12.5 | IR | 38.0 | 31.0 | IR | 36.9 | 28.3 | 28.9 |
| Gunnedah-Oxley Basin | 5.9 | 5.5 | 13.6 | 13.5 | 7.7 | IR | 0.0 | 3.0 | IR | 1.0 | 5.9 | 6.0 |
| **TOTAL** | **38.5** | **36.0** | **88.1** | **59.1** | **21.6** | **-** | **38.5** | **38.5** | **-** | **38.5** | **38.5** | **38.5** |

IR – Incomplete recovery of storage at end of model simulation (total contributions cannot be determined)

**Table 6-53 Percentage contributions to total simulated water production for all simulations**

| Groundwater Source | Contribution to Total Simulated Coal seam water Production [%] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BC | LC | HC | NCM-BC | NCM | BC-S1 | BC-S2 | BC-S3 | BC-S4 | BC-S5 | BC-S6 | BC-S7 |
| Upper Namoi Alluvium | 1.6 | 1.7 | 1.6 | 2.2 | 3.2 | IR | 0.0 | 1.8 | IR | 1.6 | 1.7 | 1.6 |
| Lower Namoi Alluvium | 8.6 | 8.6 | 8.6 | 6.6 | 3.2 | IR | 1.4 | 9.8 | IR | 0.0 | 9.3 | 7.8 |
| GAB | 74.4 | 74.4 | 74.3 | 68.2 | 57.9 | IR | 98.7 | 80.6 | IR | 95.9 | 73.6 | 75.1 |
| Gunnedah-Oxley Basin | 15.4 | 15.4 | 15.4 | 22.8 | 35.6 | IR | 0.0 | 7.8 | IR | 2.7 | 15.4 | 15.6 |
| **TOTAL** | **100** | **100** | **100** | **100** | **100** | **-** | **100** | **100** | **-** | **100** | **100** | **100** |

IR – Incomplete recovery of storage at end of model simulation (total contributions cannot be determined)

# 6.12 Implications in Relation to the NSW Aquifer Interference Policy

This section considers the significance of the modelling predictions of potential impacts in relation to the "minimal impact considerations" established in the NSW Aquifer Interference Policy (AIP) (NSW DPI 2012), which are described in Section 2.2.5.1 (Table 2-3). The framework for making an assessment of potential aquifer interference is prescribed in NSW DPI (2013) and Santos' response is provided in Appendix D

The following observations are made in relation to the AIP:

- The **Upper and Lower Namoi Groundwater Sources** (*Upper and Lower Namoi Groundwater Sources Water Sharing Plan*) are recognised as "Highly Productive Groundwater Sources" and "Alluvial Water Sources" under the AIP classification of water sources. In this assessment, no impacts on the water table elevation in the alluvium exceeding 0.5 m drawdown are predicted as a consequence of the Base Case, Low Case and High Case simulated water production profiles;
- The **Southern Recharge Groundwater Source** (*NSW Great Artesian Basin Groundwater Sources Water Sharing Plan 2008*) falls within the "Highly Productive Groundwater Sources" and "Porous Rock Water Sources" under the AIP classification. These strata are represented in the groundwater model by model layer 6 (Pilliga Sandstone). No impacts on hydraulic head in the Pilliga Sandstone exceeding 0.5 m drawdown are predicted for the Base Case and Low Case simulated water production profiles. The largest drawdown predicted for the High Case water production profile is 0.56 m approximately 200 years after the start of the 25-year FDP;
- The **Gunnedah-Oxley Basin Groundwater Source** (*NSW Murray Darling Basin Porous Rock Groundwater Sources Water Sharing Plan*) falls within the "Less Productive Groundwater Sources" and "Porous Rock Water Sources" under the AIP classification. These strata are represented by model layers 7 to 24 (Jurassic-to-Late Permian aquitards sequence, Late Permian coal seam targets, Mid-to-Late Permian aquitards sequence and Early Permian coal seam targets);
    - Significant potential drawdowns are predicted for the Base Case, Low Case and High Case simulated water production profiles in the following strata, and would constitute an aquifer interference under the AIP that would require licensing;
        - Late Permian coal seam targets;
        - strata immediately overlying and underlying the Late Permian coal seam targets;
        - Early Permian coal seam targets;
        - strata immediately overlying and underlying the Early Permian coal seam targets;
- Groundwater dependent ecosystems (GDEs) in the project area are identified in Section 4.6.1 and in the GDE impact assessment (Appendix B). No stygofauna communities (Type 1 GDEs) with potential to be impacted by the project are identified in the GDE study area. In relation to potential impacts to GDEs that may be reliant on surface expression of groundwater (potential Type 2 GDEs) eight of the nine potential Type 2 GDEs are understood to be fed by groundwater from the Pilliga Sandstone within the GAB Southern Recharge Beds. No impacts on hydraulic head in the Pilliga Sandstone exceeding 0.5 m drawdown are predicted for the Base Case and

Low Case water production profiles. The largest drawdown predicted for the High Case water production profile is 0.56 m, occurring approximately 200 years after the start of the 25-year field development plan, with this impact predicted near the western boundary of the project area. The ninth GDE (Teds Hole) is understood to be perched on a shale bed of the Orallo Formation, well above the Pilliga Sandstone, where impacts from depressurisation are expected to be negligible;

- In relation to potential impacts to GDEs that may be reliant on sub-surface expression of groundwater (potential Type 3 GDEs) the predicted maximum declines in water table elevation and hydraulic head in the alluvial aquifers and Pilliga Sandstone are less than 0.5 m, with the predicted declines and recoveries occurring gradually over hundreds of years. Changes in groundwater pressure of this magnitude are not expected to be discernible relative to the existing effects from variability in climate and extractive use patterns.
- Predicted impacts on water supply works within the Upper and Lower Namoi Groundwater Sources and the Southern Recharge Groundwater Source are less than the minimum impact consideration of 2 m;
- The potential impacts on water supply works within the Gunnedah-Oxley Basin Groundwater Source are more difficult to assess due to the lack of information about groundwater supply bores in the Gunnedah Basin and within the area of predicted potential drawdown. The Clare Sandstone is the only recognised hydrostratigraphic unit within the Black Jack Group with potentially significant transmissivity. It is not generally utilised as a groundwater source due to a combination of its large depth below ground surface, unreliable water quality and the availability of other shallower and better quality groundwater sources.

## 6.13 Implications in Relation to the Water Trigger of the EPBC Act

The EPBC Act establishes a process for environmental assessment and approval of proposed actions that have, or are likely to have, a significant impact on MNES. This section considers the significance of the modelling predictions of potential impacts in relation to the "significant impact guidelines" of the EPBC Act, which are described in Section 2.1.1 (Table 2-1). Appendix E incorporates the IESC's Information Requirements Checklist (IESC 2015) which has been modified to indicate where the IESC's information requirements have been addressed in this groundwater impact assessment.

The following observations are made in relation to the EPBC water trigger:

- The predicted impacts to the **Gunnedah Oxley Basin Groundwater Source** may be considered as significant due to the following model outputs; however, this groundwater source has a relatively low value given the high saline content of groundwater within the strata hosting the target coal seams and the subsequent lack of usage by existing or reasonably foreseeable third party users;
    - the very long-term duration of the predicted impacts (e.g. an approximate 1500 year recovery time for the Base Case);
    - the regional-scale extent of depressurisation and drawdown within the Gunnedah Basin (e.g. greater than 50 km for the Base Case);

- The predicted changes to the hydrological characteristics of the **Southern Recharge Groundwater Source** and **Surat Groundwater Source** of the GAB are unlikely to be considered as significant due to;
  - no predicted drawdown greater than 0.56m in the Pilliga Sandstone for the Base Case, Low Case and High Case water production profiles;
  - minor induced change in groundwater storage in the GAB (e.g. approximately 0.1 GL/y maximum rate of storage change for the Base Case);
  - minor induced groundwater flow within the GAB;
- The predicted changes to the hydrological characteristics of the **Upper and Lower Namoi Groundwater Sources** are unlikely to be considered as significant due to;
  - no predicted water table drawdown greater than 0.5 m in the Namoi alluvium for the Base Case, Low Case and High Case water production profiles;
  - negligible induced change in groundwater storage in the Namoi alluvium (e.g. less than 0.01 GL/y maximum rate of storage change for the Base Case);
  - insignificant induced change to groundwater flow in the Namoi alluvium;

Although changes to groundwater quality are not directly simulated in the groundwater flow modelling, the implied changes to water quality in the Gunnedah-Oxley Basin Groundwater Source, and specifically within the Early and Late Permian coal seam targets are unlikely to be considered as significant due to the relatively low values of the water source. Induced groundwater flows from overlying formations, which will eventually replace the water extracted during coal seam gas production, generally have lower salinity relative to the extracted water and may result in slight freshening of groundwater in the coal seams over the very long period of pressure recovery.

Thus, the groundwater flow induced by depressurisation will act to improve water quality because the induced gradients will tend to draw fresher water from shallow aquifers into more saline, deeper formations. The amount of induced inter-formational flow is predicted to be very small relatively to the total volume of water in the receiving formations, such that the likelihood of observable changes in groundwater quality due to CSG depressurisation is considered also to be very small small.

## 6.14 Model Limitations

The numerical groundwater model has been developed for the purpose of assessing potential hydrological impacts of coal seam gas activities in the Gunnedah Basin at regional scale. The design of the model and the approaches adopted in the modelling reflect this purpose, and it follows that the model is not suitable for all applications. While the assumptions and the restrictions of the modelling in this assessment are discussed throughout the report, the central limitations of the model are noted below.

- The model has been designed to understand and predict the potential impacts of regional-scale extraction of groundwater from deep coal seams on induced flows within the Gunnedah-Oxley Basin and from the overlying shallow aquifers, including the GAB and Namoi alluvial groundwater sources. It is considered fit for purpose for simulating the potential groundwater impacts of the project; however, the model has not been designed to simulate the potential impacts of direct activities and actions within the Namoi alluvium (e.g. pumping, irrigation, river flooding and changed land use within the alluvium) and in general should not be used for these purposes. Other groundwater models for the Upper Namoi (McNeilage 2006) and Lower Namoi (Merrick 1999, 2000, 2001) have been developed for these groundwater sources.

- The model is designed to understand regional-scale depressurisation in the target coal seams, and predicts drawdown of hydraulic head in each model cell. The predicted values of drawdown at coal seam gas wells represent the average drawdowns over the areas of the model cells containing the wells. Within this context, it is recognised that the predicted drawdown in model cells is less than the the amount of depressurisation required to yield coal seam gas within the target coal seams at the well extraction points, which exist at sub-grid scale. In part, this difference between depressurisation in reservoir models and groundwater flow models that use equal extraction volumes is due to the more ‘leaky’ characteristics of the groundwater flow model, which allow inflow to the depressurised coal seam from the bounding HSUs. This leakiness of the groundwater flow model is likely to represent a conservative feature in the modelling in so far as simulated depressurisation effects may migrate faster both laterally and vertically in the groundwater modelling compared to expectations from reservoir modelling. It follows that the results from the groundwater model should not be compared or audited directly against local measurements of depressurisation in coals seam gas wells, particularly over short time scales when the wells are actively producing.
- The hydrogeological properties for the regional aquitard sequences (Cretaceous, Jurassic-to-Late Permian and Mid-to-Late Permian) are vertically averaged and are not necessarily directly transferable to the individual hydrostratigraphic units that they comprise.
- Simulated values of hydraulic head within the regional aquitard sequences are also vertical averages and should not be directly compared with measurements in the aquitards and minor aquifers they comprise.

# 7 Risk Assessment

A risk is defined by the Australian and New Zealand Standard for Risk Management (AS/NZS ISO 31000:2009) as *the chance of something happening that will have an impact on objectives*. It is measured in terms of a combination of the likelihood of an event occurring and the potential consequence of the event.

The risks to groundwater and environmental values associated with the project have been identified and assigned a risk rating based on the likelihood and consequence criteria discussed below.

Definitions that are applicable to the risk assessment process are outlined in Table 7-1.

**Table 7-1 Definitions for assessment of hazard and risk**

| Term | Definition |
|---|---|
| Hazard | Something with the potential to cause harm; in this assessment, a predicted impact on the groundwater resources of the GIA study area is a *hazard* with the potential to cause harm to existing groundwater uses. |
| Likelihood | The chance or probability of an impact occurring. |
| Consequence | How much harm the impact can cause. |
| Unmitigated Risk | The initial level of risk without mitigation measures. |
| Residual Risk | The reduced level of risk after consideration of mitigation measures. |

## 7.1 Risks Assessed in this Report

Not all groundwater risks associated with the project are assessed in this report. The GIA risk assessment considers risks associated with the following activities:

- Change in water quality of aquifers by induced flows of groundwater and hydrocarbons via pathways within geological faulting and via compromised well integrity; these risks are assessed based on the conclusions from supporting studies commissioned by Santos for the project EIS.
- Depressurisation and drawdown of hydraulic head in the Gunnedah Basin due to the proposed extraction of water for coal seam gas production; these risks are assessed directly through the numerical modelling in this report.
- Compaction and subsidence at depth due to depressurisation and reduction in the matrix volume of target coal seams, and potential subsidence at ground surface due to settlement of the compacted strata and overburden.

Actions that are excluded from the risk assessment include surface activities associated with the project construction (e.g. creek crossings and storage ponds); surface activities associated with the installation of coal seam gas wells (e.g. well pads and pipelines); and managed releases of surface water during the project construction and operation (e.g. dust suppression and irrigation). Proposed managed releases of treated water to Bohena Creek are assessed in the Managed Release technical appendix to the EIS.

## 7.2 Risk Assessment Process

The overarching purpose of this GIA is to predict the potential impacts on groundwater resources due to the proposed actions of the project; and to assess the risks posed to existing groundwater uses (including the environment) due to those impacts.

In the language of risk assessment, the potential impacts of the project represent *hazards* that have the potential to cause harm. The assessment of *risk* is based on the combination of the likelihood of these impacts occurring and the consequence of the impacts should they occur.

The risk assessment process considers both unmitigated risks and residual (mitigated) risks through:

- Identification of potential impacts on groundwater resources due to the proposed actions of the project;
- Rating of the likelihood of impacts occurring;
- Rating of the probable consequence of impacts, if realised;
- Consideration of measures to mitigate or reduce the risks; and
- Assessment of contributions to cumulative risks within the GIA study area.

## 7.3 Risk Matrix

The likelihood and consequence criteria adopted for the project, and the resulting risk matrix developed by Santos are shown in Table 7-2. The ratings for likelihood and consequence are self-explanatory within the tables. The colour shading of the risk matrix shows qualitative bands of risk level, with blue bands representing the lowest risk ratings and red bands representing the highest risk rating:

- blue – very low
- green – low
- yellow – medium
- orange – high
- red – very high

**Table 7-2 Santos risk matrix**

| Consequence Type | | | CONSEQUENCE | | | | |
|---|---|---|---|---|---|---|---|
| | | | Negligible | Minor | Moderate | Major | Critical |
| **Health and Safety** | | | Minor injury - first aid treatment | Injury requiring medical treatment with no lost time | Injury requiring medical treatment, time off work and rehabilitation | Permanent disabling injury, long term off work | Fatality |
| **Natural Environment** | | | Negligible impact on fauna/flora, habitat, aquatic ecosystem or water resources. Incident reporting according to routine protocols | Impact on fauna, flora, habitat but no negative effects on ecosystem. Requires immediate regulator notification | Short term impact on sensitive environmental features (e.g. gibber plain). Triggers regulatory investigation. | Long term impact of regional significance on sensitive environmental features. Likely to result in regulatory intervention/action | Destruction of sensitive environmental features. Severe impact on ecosystem. Regulatory & high level Government intervention/action. |
| **Reputation** | | | Minimal impact to reputation | Some impact on business reputation | Moderate to small impact on business reputation. Regional media exposure. | Significant impact on business reputation and/or national media exposure. | Critical impact on business reputation /or international media exposure |
| **Financial** | | | Financial loss from $0 to $500,000 | Financial loss from $500,000 to $5 Million. | Financial loss from $5 Million to $50 Million | Financial loss from $50 Million to $100 Million | Financial loss in excess of $100 Million |
| | | | **I** | **II** | **III** | **IV** | **V** |
| **LIKLIHOOD** | **Almost Certain** Is expected to occur in most circumstances | **A** | **2** | **3** | **4** | **5** | **5** |
| | **Likely** Could occur in most circumstances | **B** | **1** | **3** | **3** | **4** | **5** |
| | **Possible** Has occurred here or elsewhere | **C** | **1** | **2** | **3** | **3** | **4** |
| | **Unlikely** Hasn't occurred yet but could | **D** | **1** | **1** | **2** | **2** | **3** |
| | **Remote** May occur in exceptional circumstances | **E** | **1** | **1** | **1** | **1** | **2** |

# 7.4 Potential Impacts and Mitigation Measures

## 7.4.1 Subsidence

The potential impacts of subsidence at depth within the target coal seams and hosting strata and at ground surface have been assessed in a technical memorandum prepared by Eco Logicall (Appendix G) for this GIA. Two mechanisms for subsidence were assessed: (i) subsidence at depth due to compaction of the target coal seams and hydraulically connected strata caused by depressurisation, and (ii) potential subsidence at ground surface due to settlement of these compacted layers and their overburden.

The processes of compaction at depth and associated settlement of overburden are expected to take many years to become measurable at ground surface if this occurs.

Subsidence has potential to cause impacts to surface and sub-surface infrastructure and water resources. The IESC (Commonwealth of Australia 2014c) have stated that predicted impacts of subsidence from coal seam gas development are relatively small compared to those from long wall coal mining, due to the broad spatial extent of the predicted subsidence from coal seam gas activities and the relatively small magnitude. At present, there is no confirmed subsidence resulting from coal seam gas development in Australia (Commonwealth of Australia 2014c). Potential impacts of subsidence include damage to infrastructure caused by differential settlement; localised fracturing and faulting of aquifers and aquitards; alteration of hydraulic connections between aquifers and aquitards; and alteration of flow paths in rivers and wetlands.

For this GIA, potential compaction at depth due to extraction of water and depressurisation of the target coal seams has been assessed using two methods known as *Linear Elastic Theory* and *Compaction at a Specific Location* (Commonwealth of Australia 2014b) with the following results:

- Extraction of water and coal seam gas has the potential to cause compaction at depth and subsidence at ground surface due to settlement of compacted strata;
- The probable worst case range of subsidence at depth due to depressurisation of coal seams and their hosting strata is estimated to be 137 mm to 205 mm of vertical compaction;
- The estimated maximum potential compaction at depth of 205 mm is likely to cause negligible subsidence at ground surface due to the large depth below ground surface of the target coal seams and the presence and thickness of structurally competent rock formations within the overburden; and
- The predicted maximum tilt at ground surface induced by subsidence is less than 0.08 mm/m (<0.01%).

The predicted maximum subsidence from the project is only slightly larger that subsidence predicted from agricultural activities, and orders of magnitude smaller than subsidence predicted for the nearby Narrabri Coal Mine.

Based on the above assessment, the risk of impacts to sub-infrastructure and groundwater resources due to potential subsidence at depth arising from the project is assessed to be low to very low (residual risk score 1) due to unlikely occurrence and minor or negligible consequence. The risk of impacts on surface infrastructure and surface water resources due to differential settlement and subsidence at ground surface is similarly assessed to be very low (residual risk score 1) due to remote likelihood and negligible consequence.

Santos has adopted interferometric synthetic aperture radar (InSAR) surveys to monitor and detect subsidence at ground surface across the project area. Application of this method over 16,000 $km^2$ of the Gunnedah Basin utilising data from January 2007 to March 2011 has shown that the InSAR data are suitable to monitor the motion of the ground surface with suitable accuracy and precision to identify potential subsidence arising from the project.

## 7.4.2 Aquifer Connectivity via Wells

Development of coal seam gas in the Gunnedah Basin involves drilling and installation of deep wells for exploration, production and monitoring purposes. The wells can intersect multiple stacked formations, including water-bearing hydrostratigraphic units of varying yield and water quality. Penetration of multiple formations by wells creates a potential for inter-formational flows between the formations, with the drill holes and wells providing a conduit for preferential vertical flow.

The potential risks associated with instigation of fluid flows in proposed and existing wells within the GIA study area have been assessed by Santos. The potential for induced inter-aquifer flows within the coal seam gas wells proposed as part of the project, as well as within existing plugged or converted conventional gas wells, coal mine core holes and groundwater bores within the Gunnedah Basin has been investigated.

Regardless of the type of well or bore, there remains a potential for inter-aquifer flow of groundwater and gas, driven by differences in pressure, if the drill hole is un-cased or only partially cased to isolate the intersected hydrostratigraphic units, or if the casing integrity is compromised.

Santos' hazard assessment focused on identifying the potential hazards from conventional gas wells within the project area. The related risk assessment was broader in scope and considered the potential risks associated with historical coal exploration core holes and conventional gas wells; existing water supply bores; and existing and proposed coal seam gas wells. The risk matrix in section 7.3 was applied to the assessment and the results are considered to be semi-quantitative.

### 7.4.2.1 Coal Seam Gas Wells

Whilst the development of each coal seam gas well carries risk, the likelihood and potential consequences will be mitigated to the extent possible through the following actions:

- Development of Well Integrity Plans for each coal seam gas well; designed to reduce risk to the environment and beneficial groundwater uses
- Using industry best practices for drilling and well completion works.

The risk of local failure of well casings due to earth movements within fault zones or the presence of swelling clays is mitigated through the well design, including geological mapping and seismic investigation prior to selecting well locations, and adherence to petroleum industry standards and guidelines for drilling and well completion and the selection of appropriate casings and completion materials.

Risks of inter-formational flows following the abandonment of coal seam gas wells are mitigated by cement plugging of the wells at strategic depths and conducting tests to check the integrity of the cement bond.

The risk assessment concluded that properly constructed coal seam gas wells are likely to pose a very low risk (residual risk score 1) for gas or water migration between formations due to unlikely occurrence of leakage and minor consequence.

#### 7.4.2.2 Conventional Gas Wells

The hazard of inter-formational flows via conventional gas wells acting as connecting conduits between vertically stacked formations was assessed. A review of approximately 71 wells with suitable records, indicated that the majority of wells were adequately plugged or cemented to obviate potential migration of gas and water to other formations. The assessment of hazards is considered to be qualitative and conservative.

A small number of former conventional gas wells were identified where the potential risk of inter-formational flow was likely to be greater than negligible risk. The need for further investigation and rehabilitation will be assessed through the groundwater monitoring program, which will detect in advance if significant impacts from the project activities are expected at these locations in the future.

If found to be posing a risk of risk of inter-formation gas or fluid migration, conventional gas wells may be entered, cement plugged and abandoned to industry standards. On the basis of unlikely occurrence after mitigation and minor consequence this risk is assessed to be very low (residual risk score 1).

#### 7.4.2.3 Coal Mine Core Holes

The assessment found that historical core samples for coal mining exploration were collected mainly from near-surface stratigraphic units and generally did not penetrate multiple aquifers. The assessment identified that many core holes were drilled as open holes in single geological formations. Santos is in the process of locating historical coal mine core holes to manage potential risks at these locations.

Present-day core holes must be backfilled and sealed in accordance with the requirements of Part 5 of the *Coal Mines Regulation Act 1982*, and therefore they are considered to pose a negligible risk.

The risk of induced flows within coal mine core holes that materially affects the quantity or quality of groundwater sources in the GIA study area is assessed to be very low (residual risk score 1) based on unlikely occurrence and negligible consequence.

#### 7.4.2.4 Groundwater Bores

The assessment found that completion guidelines for groundwater bores did not exist prior to 1997, with some groundwater bores drilled as open holes and others completed with cast iron or mild steel casings. All bores were found to be completed in aquifers that are considerably shallower than the target coal seams for coal seam gas production, with bores commonly intersecting multiple water-bearing zones to increase the bore yield. Significant degradation of bore casings may have occurred in bores more than 70-years old. Santos is conducting a survey of landholder groundwater bores to monitor water levels and manage potential impacts on groundwater head in these bores should they occur.

For groundwater bores greater than 150 m deep, there is generally insufficient information available to identify which groundwater sources they tap, although they are most likely to be screened within locally permeable layers within the upper part of the Permo-Triassic strata sequence. Section 4.8.1 identifies approximately 15 bores of depth 150 m to 270 m within the Gunnedah Basin GMA to the east and southeast of the project area. By comparison, the coal seams to be targeted for gas production are considerably deeper, with the primary Early-Permian target seams being located approximately 850 m to 1000 m deep within the Maules Creek Formation, and the secondary Late-Permian target seams being located 600 m to 700 m deep within the Black Jack Group. Within this context, the potential impacts of the project on deeper groundwater bores will be managed through the Water Monitoring Plan (CDM Smith 2016c) and the make good provisions outlined in Section 7.6.

Gas migration into groundwater bores is considered to be a low risk because the bores are not completed in the target coal seams or the immediately overlying formations. Estimation of leakage rates by Santos indicates that greater than 5 bores per $km^2$ intersecting the Late Permian coal seam targets, or greater than 30 bores per $km^2$ intersecting the Early Permian coal seam targets would need to fully fail before flow in the bores accounted for greater than 10% of the pre-existing vertical flux.

Installation of groundwater monitoring bores by Santos for the project will be undertaken in accordance with the Minimum Construction Requirements for Water Bores in Australia (NUDLC 2012) including the mandatory requirements, and adoption of the recommendations for good industry practice.

Overall, the risk of induced aquifer connectivity via groundwater bores is assessed to be very low (residual risk score 1) due to unlikely occurrence and negligible consequence.

### 7.4.3 Enhanced Aquifer Connectivity via Geological Faulting

Fault zones (a volume of geological material altered by faulting) can influence groundwater flow through strata by either obstructing or channelling groundwater flow. Geological faulting in the Gunnedah Basin would have potential to enhance the vertical connectivity between rock layers if there are major fault zones that extend through multiple formations and which channel groundwater flow.

The recent faulting study by Santos examined the available seismic lines to identify the major faulting within the project area, including identification of fault types and their extents and probable ages (Section 4.5.11). Information provided by Santos concludes that the majority of faults in the project area are Permian to Triassic in age and mainly displace Permian and, to a lesser extent, Triassic strata. The typical amount of displacement is estimated to be significantly less than 100 m in the Triassic strata. From the seismic data, there is no evidence of large post-Jurassic age faults that displace Jurassic strata and extend into underlying Triassic and Permian strata. Where it is present, surface faulting and displacement in the Jurassic strata was found to be minor.

On the basis of the faulting investigation and associated interpretation, the individual fault zones within the project area are considered to be unlikely to act as conduits for preferential groundwater flow or gas migration between hydrostratigraphic units in the Gunnedah-Oxley Basin (Triassic to Permian age) or between groundwater sources in the GAB (Cretaceous to Jurassic age) or shallow alluvial systems (Cenozoic age). Overall, the risk of changes in the vertical connectivity between groundwater sources due to activation of vertical groundwater flow in faults that is induced by depressurisation of coal seams is assessed to be very low (residual risk score 1) due to moderate consequence but remote likelihood.

### 7.4.4 Depressurisation of Coal Seams

Coal seam depressurisation is an essential part of the process of coal seam gas production and is achieved by pumping water from the confined coal seams. Modelling simulations in this study predict that depressurisation within the target coal seams will propagate vertically into the overlying and underlying formations; however, the magnitude of depressurisation is predicted to reduce significantly with increasing vertical distance from the coal seam targets due to a decreased capacity for water to flow through the hosting strata.

The primary risk associated with coal seam depressurisation is induced leakage of groundwater from adjacent water bearing formations into the producing coal seams and the associated drawdown of hydraulic head within the leaking formations. This potential for inter-formational transfer of groundwater is due to the large vertical hydraulic gradients that develop above and below the depressurised coal seams.

In the subsurface formations, the primary risks associated with coal seam depressurisation and the associated drawdown of hydraulic head include:

- A reduction in available drawdown in existing supply bores and reduction or loss of artesian pressure;
- Unacceptable induced flow of between groundwater sources that would materially impact NSW Water Sharing Plans;
- Impacts to water quality as a result of the induced groundwater flows;
- A reduction or loss of groundwater baseflow to surface water features and ecosystems including adverse impacts on GAB springs;
- Induced gas flows into bores that materially impacts the ability of a bore to produce water;
- Community values and visual amenity of rivers and stream.

#### 7.4.4.1 Drawdown in Existing Groundwater Bores

Potential impacts to available water in existing groundwater bores due to depressurisation of the coal seam targets depend on a number of factors:

- Location of the bore relative to the project area;
- Hydrostratigraphic unit in which the bore is screened;
- Groundwater intake (bore screen) depth;
- Extractive capacity of the bore; and
- Potential decline of hydraulic head caused by coal seam gas production.

The groundwater model simulation for the Base Case water production profile predicts no drawdown greater than 0.5 m in the shallow groundwater source of the Pilliga Sandstone, with the largest predicted drawdown occurring approximately 325 years after coal seam gas production ceases. Smaller drawdown is predicted in the Namoi alluvium. The majority of bores in the region are installed within these water sources. The modelling results for the High Case water production profile predicts no drawdown greater than 0.6 m in the Pilliga Sandstone and no drawdown greater than 0.5 m within the Namoi alluvium.

Simulation of potential cumulative impacts of the Narrabri Coal Mine Stage 2 Longwall Project and the Base Case water production profile predicts a maximum drawdown of approximately 1.8 m in the Pilliga Sandstone approximately 47 years after the start of the Stage 2 Longwall Project, and a maximum drawdown at the water table of approximately 5.2 m outside of the Namoi alluvium around 95 years after the start of the Stage 2 Longwall Project. No drawdown greater than 0.5 m is predicted within the Namoi alluvium.

For simulation of the Stage 2 Longwall Project in isolation from coal seam gas development, the modelling predicts very similar values of maximum drawdown in the Pilliga Sandstone and at the water table. Thus, only minor cumulative impacts on maximum drawdown from the project are predicted because the drawdown is smaller and occurs later.

The groundwater modelling predicts large drawdown of hydraulic head within deeper hydrostratigraphic units of the Gunnedah Basin, including the intentional drawdown of head in the target coal seams and immediately underlying and overlying strata. Although review of the PINNEENA (v4.1) database did not identify bores installed into these deeper formations for water supply (Section 4.8.1), in general there is insufficient information about the registered bores in this area to identify which, if any, groundwater sources they tap. For example, Section 4.8.1 identifies approximately 15 bores of depth 150 to 270 m within the Gunnedah Basin GMA to the east and southeast of the project area, and additional bores less than 150 m deep in the same area. It is likely that the bores in this area are screened within locally permeable layers within the upper part of the Permo-Triassic strata sequence, which regionally is considered to isolate groundwater in Permian coal seams from shallower groundwater sources in the GAB and Namoi alluvium.

In comparison, the target coal seams for gas production are considerably deeper than the deepest groundwater bores registederd in the PINNEENA database, with the primary Early-Permian targets being located approximately 850 m to 1000 m deep within the Maules Creek Formation, and the secondary Late-Permian targets being located 600 m to 700 m deep within the Black Jack Group. Thus, the deepest known groundwater bores are less than half the depth of the shallowest coal seam targets).

It is possible that some bores within the Gunnedah Basin GMA to the east and southeast of the project area could experience drawdown of standing water level in the bore due to simulated water production from coal seam gas wells. Given the low yields and poor water quality generally associated with the deeper formations of the Permo-Triassic sequence, it is unlikely that these deeper units have been targeted for groundwater supply. Potential impacts of the project on the deeper groundwater bores will be managed through the Water Monitoring Plan (CDM Smith 2016c) and the make good provisions outlined in Section 7.6.

Overall, the risk that depressurisation of coal seams will materially impact the quantity of water supplied from existing deep groundwater bores (i.e., those bores with most potential to be affected by depressurisation) is assessed to be low (residual risk score 2) based on possible occurrence and minor consequence.

#### 7.4.4.2 Drawdown at High Priority GDEs

Groundwater dependent ecosystems potentially impacted by the project are identified in Section 4.6.1 and in the GDE impact assessment (Appendix B). Eight of the nine GDEs that may be reliant on surface expression of groundwater (potential Type 2 GDEs) are understood to be fed by groundwater from the Pilliga Sandstone located within the Southern Recharge Bed of the GAB. For the Base Case water production profile, the groundwater modelling predicts drawdown less than 0.5 m in the Pilliga Sandstone at the locations of all GDEs. identified as being fed by groundwater in the Pilliga Sandstone. The ninth potential Type 2 GDE (Teds Hole) is understood to be perched on a shale bed of the Orallo Formation, well above the Pilliga Sandstone where drawdown impacts from the project are not expected.

None of the potential Type 2 GDEs identified in the GDE impact assessment meet the definition of a high-priority GDE in NSW, and therefore they fall outside of the minimal impact considerations of the NSW Aquifer Interference Policy, and none of the identified GDEs support Matters of National Environmental Significance (MNES) defined under the EPBC Act.

In relation to potential impacts to GDEs that may be reliant on sub-surface expression of groundwater (potential Type 3 GDEs) the predicted maximum declines in water table elevation and hydraulic head in the alluvial aquifers and Pilliga Sandstone are less than 0.5 m, with the predicted declines and recoveries occurring gradually over hundreds of years. Changes in groundwater pressure of this magnitude are not expected to be discernible relative to the existing effects from variability in climate and extractive use patterns.

Within this context, the risk of damaged to GDEs from depressurisation of deep coal seams is assessed to be low (residual risk score 2) based on major consequence but unlikely occurrence.

#### 7.4.4.3 Induced Groundwater Flows

Extraction of water from the coal seam targets and associated depressurisation of the coal seams has the potential to induce groundwater flows between water sources identified in NSW Water Sharing Plans. Taking of water from one groundwater source, and thereby inducing inflow to that water source from another groundwater source constitutes “aquifer interference” in both water sources under the definition established in the NSW Aquifer Interference Policy (AIP).

The potential for induced flows between groundwater sources in the GIA study area include exchanges between:

- Shallow groundwater within the Pilliga Sandstone (Southern Recharge Groundwater Source) and groundwater within the underlying strata of the Gunnedah-Oxley Basin (Gunnedah-Oxley Basin Groundwater Source);
- Shallow groundwater within the Namoi alluvium (Upper and Lower Namoi Groundwater Sources) and
    - the underlying portion of the Pilliga Sandstone (Southern Recharge Groundwater Source); and
    - the underlying portion of the Gunnedah-Oxley Basin (Gunnedah-Oxley Basin Groundwater Source).

In general, the induced flow rates between these water sources are expected to be very small because the recovery of depressurisation is predicted to occur over a very long period of time (i.e. average flow rate = extracted volume ÷ recovery time).

For the Base Case water production profile, the groundwater modelling predicts a small induced flow rate from the Southern Recharge Groundwater Source to the Gunnedah-Oxley Basin Groundwater Source that would persist for over a thousand years. The maximum predicted rate of induced flow from the Southern Recharge to Gunnedah-Oxley Basin Groundwater Source is approximately 0.06 GL/y (equivalent to 1.8 L/s) at around 175 years after the field development plan ceases. Distributed over the project area of 950 km$^2$ this maximum flow rate is equivalent to a very small distributed flux of 0.06 mm/y (6.3 mm per 100 years). The predicted maximum rate of induced flow from the Namoi alluvium (Upper and Lower Namoi Groundwater Sources) to the underlying strata is approximately 0.01 GL/y (equivalent to 0.16 L/s). At all other times, the predicted rates of induced flow are smaller than these maximum values.

Overall, the risk of induced groundwater flows caused by depressurisation of coal seams, which would result in material change in the quantity or quality of groundwater sources in the project area is assessed to be low (residual risk score 2) based on almost certain likelihood but negligible consequence (i.e., very small magnitude).

#### 7.4.4.4 Induced Changes in Groundwater Quality

The development of a depressurised zone within a hydrostratigraphic unit can induce vertical leakage of groundwater from the underlying and overlying strata. The magnitude and timing of vertical leakage from stacked strata is dependent on the magnitude of the depressurisation; the hydrogeological properties of the overlying and underlying stratigraphic units; the presence or absence of structural features that may provide preferential pathways for groundwater flow, such as a fault; and the distance above or below the depressurised zone. This process of vertical leakage through hydrostratigraphic units in response to an induced gradient in hydraulic head can cause changes in groundwater quality over time. Water quality can deteriorate if poorer quality water leaks into a formation, or the water quality may improve if the leaking water has better quality than the strata it is entering.

Coal seam gas operations are likely to extract relatively poor quality groundwater from the target coal seams. A large negative hydraulic gradient toward the depressurised coal seams will cause groundwater leakage into the coal seams. As the strata hosting the coals seams also begin to depressurise they may in turn receive leakage from their bounding formations, and so on.

With respect to the highly productive groundwater sources within the Pilliga Sandstone and Namoi alluvium, there is potential for minor induced leakage from the Pilliga Sandstone into the underlying depressurised strata within the Gunnedah Basin, and minor leakage from the Namoi alluvium to the Pilliga Sandstone and Gunnedah Basin. Because the induced flow will be downward toward the deeper depressurised coals seams, the potential for change in water quality of shallow groundwater sources by poorer quality water in the deeper strata is not considered to be a possibility (i.e. there is no pathway for this impact). There may be minor improvement of water quality in some parts of the Gunnedah Basin due to leakage of groundwater from the Pilliga Sandstone and Namoi alluvium.

Within this context, the risk of adverse changes in the quality of water supply to existing groundwater users due to depressurisation of coal seams in assessed to be very low (residual risk score 1) based on likely improvement in water quality in shallow groundwater sources and negligible consequence.

#### 7.4.4.5 Reduction of Base Flow and Ecosystem Change

A reduction or loss of groundwater contributions to surface water systems from lowering of the water table could potentially affect surface water ecosystems. The Project area has the potential to support four Threatened Ecological Communities (TECs) listed under the EPBC Act and eighteen broad-scale vegetation communities identified in NSW vegetation mapping (Section 4.7). Nine GDEs that may be reliant on surface expression of groundwater (potential Type 2 GDEs) are identified within the study (Section 4.6.1) although none of these GDEs meet the definition of a high-priority GDE in NSW, and none support Matters of National Environmental Significance (MNES) defined under the EPBC Act. Detailed vegetation mapping within the project area has shown that the distribution of GDEs that may be reliant on sub-surface expression of groundwater (potential Type 3 GDEs) is much smaller than the areas mapped using the methodology of the GDE Atlas. These areas of potential Type 3 GDEs are confined mainly to riparian areas where vegetation can access the water table.

For significant impacts to occur to aquatic and terrestrial ecosystems, induced inter-formational recharge due to coal seam depressurisation must first propagate through thick aquitard sequences. Groundwater modelling results from the Base case, Low Case and High Case water production profiles predict no drawdown greater than 0.56 m in the Pilliga Sandstone (occurring only in the High Case) with the maximum drawdown taking place around 175 years after the proposed 25-year field development plan has ended. Smaller drawdowns of less than 0.5 m are predicted at the water table within the alluvial groundwater sources. On the preceding basis, the potential impacts to surface water systems are assessed to be very low (residual risk score 1) based on remote likelihood and minor consequences compared to the amount of variation in groundwater pressure and water table elevations that are expected from natural climate variability and other extractive use patterns.

#### 7.4.4.6 Induced Gas Flows

Coal seam depressurisation has the potential to cause incidental occurrence of coal seam gas in private bores that are screened within the coal seam targets or immediately overlying strata. Within the project area, the depth and water quality of groundwater in the Early and Late Permian coal seams and their hosting formations generally preclude alternative uses. No private bores are known to be completed within the Early or Late Permian coals within the project area.

Depressurisation of coal seams for gas production is only likely to cause 'incidental' migration of gas within the coal seams themselves (i.e., lateral migration through the seams). Because there are no known groundwater bores at the depth of the target seams (i.e., the deepest groundwater bores in the PINNEENA database are less than half the depth of the shallowest coal seam targets), and there is no vertical connectivity other than natural connectivity, it follows that the risk of gas migration into groundwater bores is very small.The groundwater quality and depth of the target coal seams, along with the presence of relatively good quality water at shallower depth means that gas flows into private bores are unlikely to be an issue in the project area.

Overall, the risk of induced gas flows in existing groundwater bores is assessed to be very low (residual risk score 1) based on remote likelihood and minor consequence.

#### 7.4.4.7 Community Values and Visual Amenity of Rivers and Streams

Potential groundwater impacts of the project related to the Namoi Catchment River Flow Objectives (RFO) and Water Quality Objectives (WQO) are summarised below.

- *Protect Pools in Dry Times (RFO)* – protection of natural water levels in pools of creeks and rivers and wetlands during periods of no flow. Although the persistence of natural pools within the downstream reach of the Bohena and Jacks Creeks is unknown, the Base Case simulation predicts a minor impact on the water table, which is likely to have a negligible impact on the natural pools within surface water systems within the GIA study area.

- *Protect Natural Low Flow (RFO)* – very low natural flows should be fully protected for the environment. There are currently no reliable low flow records in Bohena Creek or Jacks Creek; however, the minor predicted drawdown of the water table in the shallow alluvium for the Base Case simulation is unlikely to have a discernible impact on low surface flows.

- *Mimic Natural Drying in Temporary Waterways (RFO)* – mimic the natural frequency, duration and seasonal nature of drying periods in natural temporary waterways. Due to the negligible predicted drawdown of the water table in the Namoi alluvium, there should be no impact on the frequency and duration of natural drying of temporary waterways.

- *Maintain Groundwater for Ecosystems (RFO)* – maintain groundwater within natural levels and variability, critical to surface flows and ecosystems. It is likely that shallow groundwater in the alluvium of Bohena Creek and Jacks Creek provides base flow during dry periods and is most likely a source of water to riparian vegetation and aquatic flora and fauna associated with pools in the creeks. As drawdown in the shallow alluvium is predicted to be less than 0.5 m for the Base Case, Low Case and High Case simulated water production profiles, the project is unlikely to impact groundwater levels adjacent to ephemeral creeks.

- *Visual Amenity (WQO)* – aesthetic qualities of waters. The relevance of the key indicators and numerical criteria used to assess and monitor the aesthetic qualities of waters are limited in this particular case. The visual amenity WQO relates to the visual clarity and colour, presence of surface films and debris and nuisance organisms. The predicted drawdown in the shallow alluvium is likely to have a negligible impact on flows and pools and visual amenity of the surface waters.

In summary, depressurisation of the Early and Late Permian coal seam targets at depth within the Gunnedah Basin, and the predicted negligible impacts on the elevation of the water table in the shallow alluvial groundwater sources is not expected to adversely impact the RFO and WQO of the Namoi Catchment area.

## 7.5 Risk Assessment Outcomes

The risk assessment in this GIA has been undertaken by applying the EIS risk matrix in Section 7.3 to the potential impacts and mitigations identified and discussed in Section 7.4. The resulting risk ratings are summarised in Table 7-3 below.

The ratings of un-mitigated and residual risks to groundwater in Table 7-3 vary from a risk score of medium risk (risk score 3) to very low risk (risk score 1). No high or very high risks (risk scores greater than 3) were identified; noting that this would require an almost certain impact (A) with moderate consequence (III), a likely impact (B) with major consequence (IV), or a possible impact (C) with critical consequence (V).

Thirteen of the sixteen risks identified in the risk assessment are assessed to have the lowest possible residual risk score of 1 (very low risk) and the remaining three risks are assessed to have residual risk scores of 2 (low risk). Justifications for these scores are provided in the preceding report section (Section 7.4).

The three potential impacts with low residual risks (i.e., the highest-ranked risks identified in the assessment) are assessed as follows:

- Drawdown in existing groundwater bores - decline of water levels in existing deep groundwater bores screened below the Pilliga Sandstone aquifer that would materially affect the water supply from the bores is assessed to be possible but the potential consequences are considered to be minor and manageable. Mitigation would be achieved through the Water Monitoring Plan, which is designed to detect if adverse impacts on the pressure in existing bores is going to occur before those impacts are realised, and implementation of make good options if water supply from an existing bore is materially affected by depressurisation from the project.

- Drawdown of hydraulic head at GDEs - potential damage to GDEs caused by long-term decline of hydraulic head at the location of GDEs is classified as a major consequence under the criteria of the risk matrix; however, these potential impacts are assessed to be unlikely, resulting in a medium risk score. Maximum drawdowns in the source aquifers for GDEs are predicted to be less than 0.5 m and are small compared to existing and expected future variation of water pressure in the source aquifers due to natural variation in climate patterns and variation in other extractive use patterns. None of the GDEs identified in the GDE impact assessment (Appendix B) meet the definition of a high-priority GDE in NSW, and none support MNES defined under the EPBC Act.

- Induced groundwater flows between groundwater sources - depressurisation of deep coal seams for coal seam gas production is almost certain to induce very small rates of groundwater flow from overlying groundwater sources as the water extracted from the coal seams is replaced by downward flow through the overlying thick aquitard sequences. This replacement of the extracted water will take place naturally and very slowly over hundreds of years. The consequence of such small induced changes in the inter-formational flows in hydrostratigraphic units above the coal seam targets are assessed to be negligible.

**Table 7-3 Risk assessment outcomes**

| Risk / Issue | Cause | Potential Impact | Without Mitigation Measures | | | Possible Mitigation Measures | With Mitigation Measures | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Consequence | Likelihood | Unmitigated Risk Rating | | Consequence | Likelihood | Residual Risk Rating |
| Subsidence at depth due to compaction within target coal seams and their hosting strata | Depressurisation of coal seams and gas desorption from the matrix | Damage to sub-surface infrastructure caused by differential settlement | II. Minor | D. Unlikely | 1 | ▪ Implement make good protocols | II. Minor | D. Unlikely | 1 |
| | | Fracturing and alteration of hydraulic connections between aquifers and aquitards | I. Negligible | D. Unlikely | 1 | ▪ No direct action | I. Negligible | D. Unlikely | 1 |
| Subsidence at ground surface due to settlement of compacted strata at depth and overburden | Depressurisation of coal seams and gas desorption from the matrix | Damage to surface infrastructure due to differential settlement | I. Negligible | E. Remote | 1 | ▪ Implement make good protocols | I. Negligible | E. Remote | 1 |
| | | Alteration of flow paths in rivers and wetlands | I. Negligible | E. Remote | 1 | ▪ Implement surface control structures if appropriate | I. Negligible | E. Remote | 1 |
| Induced aquifer connectivity via vertical groundwater leakage in coal seam gas wells | Drilling and well installation | Inter-formational groundwater flow and resultant change in water quality of groundwater | III. Moderate | C. Possible | 3 | ▪ Drilling, completion and rehabilitation of CSG wells in compliance with the NSW Code of Practice for Coal Seam Gas Well Integrity<br>▪ Implementation of the Narrabri Gas Project Water Monitoring Plan which includes groundwater pressure and quality monitoring<br>▪ Adoption of petroleum industry standards and guidelines for drilling and well completion. | II. Minor | D. Unlikely | 1 |

| Risk / Issue | Cause | Potential Impact | Without Mitigation Measures: Consequence | Without Mitigation Measures: Likelihood | Without Mitigation Measures: Unmitigated Risk Rating | Possible Mitigation Measures | With Mitigation Measures: Consequence | With Mitigation Measures: Likelihood | With Mitigation Measures: Residual Risk Rating |
|---|---|---|---|---|---|---|---|---|---|
| Induced aquifer connectivity via activation of vertical groundwater leakage in conventional gas wells | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | II. Minor | C. Possible | 2 | ▪ Rehabilitation of Santos' conventional gas wells in compliance with the NSW Code of Practice for Coal Seam Gas Well Integrity | II. Minor | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical groundwater leakage in coal mine core holes | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | II. Minor | D. Unlikely | 1 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan which includes groundwater pressure and quality monitoring | I. Negligible | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical flow in groundwater bores | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | II. Minor | D. Unlikely | 1 | ▪ Groundwater bores do not intersect the coal seam targets or immediately overlying strata.<br>▪ Significant impact on vertical groundwater flux would require an improbable number of leaking bores.<br>▪ Santos' groundwater monitoring bores will be completed in accordance with the Minimum Construction Requirements for Water Bores in Australia. | I. Negligible | D. Unlikely | 1 |
| Induced aquifer connectivity via activation of vertical groundwater in fault zones | Water extraction from coal seams | Inter-formational groundwater flow and resultant change in water quality of groundwater | III. Moderate | E. Remote | 1 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head | III. Moderate | E. Remote | 1 |

| Risk / Issue | Cause | Potential Impact | Without Mitigation Measures | | | Possible Mitigation Measures | With Mitigation Measures | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Consequence | Likelihood | Unmitigated Risk Rating | | Consequence | Likelihood | Residual Risk Rating |
| Drawdown in existing groundwater bores | Water extraction from coal seams | Reduced access and availability of groundwater for existing uses | III. Moderate | D. Possible | 3 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan, which includes an early detection system to detect un-anticipated drawdown of hydraulic head<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water supply to the owners of impacted bores. | II. Minor | C. Possible | 2 |
| Drawdown of hydraulic head at GDEs | Water extraction from coal seams | Damage or destruction of GDEs | IV. Major | D. Unlikely | 2 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head | IV. Major | D. Unlikely | 2 |
| Induced groundwater flows between groundwater sources | Water extraction from coal seams | Reduced availability of groundwater sources for existing uses | I. Negligible | A. Almost Certain | 2 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan which includes an early detection system to detect un-anticipated or premature drawdown of hydraulic head<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water supply to the owners of impacted bores. | I. Negligible | A. Almost certain | 2 |

| Risk / Issue | Cause | Potential Impact | Without Mitigation Measures: Consequence | Without Mitigation Measures: Likelihood | Unmitigated Risk Rating | Possible Mitigation Measures | With Mitigation Measures: Consequence | With Mitigation Measures: Likelihood | Residual Risk Rating |
|---|---|---|---|---|---|---|---|---|---|
| Induced changes in groundwater quality | Water extraction from coal seams and associated induced groundwater flows | Change in water quality for existing uses | I. Negligible | B. Likely | 1 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy<br>▪ Induced downward flows have potential to cause freshening but not deterioration of deep groundwater sources, which currently have low value due to high salinity<br>▪ Induced downward flows means there is no pathway for deterioration of shallow groundwater sources | I. Negligible | B. Likely | 1 |
| Reduction of base flow to rivers | Water extraction from coal seams and associated induced groundwater flows | Reduction of low rivers flows and decline or loss of riparian GDEs | IV. Minor | E. Remote | 1 | ▪ Minor to negligible impacts on water table elevation in river alluvium are predicted hundreds of years after coal seam gas production has ceased<br>▪ Implementation of the Narrabri Gas Project Water Monitoring Plan, which includes an early detection system to detect un-anticipated drawdown<br>▪ | IV. Minor | E. Remote | 1 |
| Induced gas flow in existing groundwater bores | Water extraction from coal seams and associated depressurisation | Deterioration of existing groundwater uses and potential exposure to fugitive gas emissions | III. Moderate | D. Unlikely | 2 | ▪ Implementation of the Narrabri Gas Project Water Monitoring Plan<br>▪ Implement make good protocols in accordance with the Aquifer Interference Policy to maintain the water quality and supply to the owners of impacted bores. | II. Minor | E. Remote | 1 |

| Risk / Issue | Cause | Potential Impact | Without Mitigation Measures | | | Possible Mitigation Measures | With Mitigation Measures | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Consequence | Likelihood | Unmitigated Risk Rating | | Consequence | Likelihood | Residual Risk Rating |
| Visual amenity of rivers and streams | Water extraction from coal seams and associated induced drawdown of water table | Degradation of community values | IV. Major | E. Remote | 1 | ▪ Minor to negligible impacts on water table elevation in river alluvium are predicted hundreds of years after coal seam gas production has ceased<br>▪ Implementation of the Narrabri Gas Project Water Monitoring Plan, which includes an early detection system to detect un-anticipated drawdown | IV. Minor | E. Remote | 1 |

## 7.6 Make Good Provisions

Mitigation measures identified in the risk assessment include make good provisions that may be followed in the event of unanticipated impacts from the project. The make good provisions relate mainly to unanticipated drawdown or depressurisation of groundwater effecting the existing users.

In the event that an impact greater than the approved level of impact for the project is thought to have occurred at an existing water supply bore, Santos may undertake an assessment of the bore to determine the extent to which the bore is impaired and the likelihood that the impairment has been caused by the activities of the project. If impairment of the bore is shown to be an impact of the project, Santos may enter into a make good agreement with the bore owner for the purpose of ensuring access to reasonable quantity and quality of water supply (groundwater or otherwise) that would be consistent with the authorised purpose of the bore prior to the impact occurring.

The types of make good provisions that will be considered in the make good agreement will include:

- Lowering the pump setting in the bore;
- Increasing the water column above the pump;
- Improving the pressure at the bore head, if the bore is artesian (e.g. new headworks and piping);
- Changing the type of pump to suit the lower water level in the bore;
- Deepening the bore to allow it to draw groundwater from a deeper part of the aquifer;
- Bore reconditioning to improve hydraulic efficiency;
- Drilling a new bore;
- Other modification to the bore that will mitigate the impairment;
- Providing an alternate water supply; and

- Providing compensation, which could be monetary, for impairment of the water supply.

Make good agreements will include a plan to monitor and undertake periodic assessments of the affected bore.

# 7.7 Monitoring and Management Measures

Santos is undertaking a comprehensive program of monitoring across a range of environmental values and has already committed significant investment to the development of monitoring networks and the collection of preliminary baseline data. Monitoring sites that have been utilised for the collection of baseline water data, including those associated with exploration and appraisal activities have provided data to the project Water Baseline Report (CDM Smith 2016b) and have been developed for use as part of the project Water Monitoring Plan (CDM Smith 2016c).

## 7.7.1 Groundwater Monitoring

The potential impacts to the groundwater sources that are used for stock, agricultural and domestic purposes within the GIA study area are predicted to be minor in this GIA. Thirteen of the sixteen risks identified in the groundwater risk assessment are assessed to have the lowest possible residual risk score of 1 (very low risk) and the remaining three risks are assessed to have residual risk scores of 2 (low risk).

Within this context, the Water Monitoring Plan (WMP) is designed to validate the predictions of potential impacts of the project on water resources, and to address uncertainty in those predictions. In this way, implementation of the WMP would enable Santos to take appropriate action to monitor the project performance against water-related risks and to compare and validate observed changes in groundwater conditions against those predicted in the GIA. Should the monitoring indicate a trend towards a potential unexpected impact, this early identification would allow Santos to take appropriately-scaled management actions to either avoid the impacts or to 'make good' on potential adverse impacts that are unavoidable.

Further information about the triggers and thresholds for water monitoring, and the associated response actions is provided in the WMP.

## 7.7.2 Subsidence Monitoring

Santos has adopted interferometric synthetic aperture radar (InSAR) surveys to monitor and detect subsidence at ground surface across the project area. Application of this method over 16,000 $km^2$ of the Gunnedah Basin utilising data from January 2007 to March 2011 has shown that the InSAR data are suitable to monitor the motion of the ground surface with the accuracy and precision required to identify potential subsidence arising from the project.

## 7.7.3 Future Groundwater Modelling

Advice of DPI Water within the Secretary's Environmental Assessment Requirements (SEARS) for the project (see Section 1.4, Table 1-2) recommends that the project EIS should describe a plan for ongoing validation, calibration and development of the groundwater model.

Santos proposes the following ordered approach for reviewing and updating the groundwater modelling in this GIA, subsequent to finalisation of the EIS, and subject to the project proceeding:

1. Review of relevant groundwater information and data from ongoing field operations, initially following project approval and subsequently after three years from project approval, including new data obtained from the following sources;
    a. evolution of the field development plan;
    b. groundwater monitoring program, including hydraulic head and water quality data;
    c. drilling and installation of groundwater monitoring bores in formations that are stratigraphically close to the depressurised coal seams, where effects from depressurisation will occur first;
    d. coal seam gas appraisal activities, such as hydrogeological interpretations drawn from pilot testing activities;
2. Assessment of whether these new data support the hydrogeological conceptualisation, the current modelling assumptions, and the choices of hydrogeological properties, or indicate inconsistencies of a magnitude that could significantly change the modelled predictions of potential impacts, and which would predicate a need to update or re-run the model;
3. Updating of the numerical model if warranted by the review of new data;
4. Re-running of the predictive scenario based on the realised field development plan to date and the updated future field development plan, if relevant; and
5. Comparison of the updated model results against the observed data from the groundwater monitoring program and re-calibration of the model if necessary.

Steps 1 to 3 would be required to assess whether or not there is a basis for updating the model design or the model predictions, or both. Steps 4 to 6 are iterative and would seek to establish consistency between model design and calibration to observed data.

# 8 Summary and Conclusions

The potential impacts to groundwater resources resulting from the Narrabri Gas Project (Project) have been evaluated in this Groundwater Impact Assessment (GIA) through:

- A review of the regulations applicable to coal seam gas fields and specifically to groundwater and related environmental factors;
- A description of the existing environmental values and hydrological setting of the project;
- Review and analysis of the DPI Water's (formerly NSW Office of Water's) bore database, published reports and coal seam gas exploration and appraisal data to develop a conceptual hydrogeological model and define the GIA study area;
- Identification of the environmental values potentially affected by the project and specifically affected by the depressurisation of the target coal seams;
- Prediction of potential subsidence arising from the project due to depressurisation of coal seams and associated compaction;
- Prediction of the potential impacts of the project on groundwater resources through the development and application of a numerical groundwater flow model;
- Evaluation of the predicted impacts on groundwater with specific reference to the "minimal impact considerations" established in the NSW Aquifer Interference Policy (AIP) and the "significant impact guidelines" of the EPBC Act; and
- Semi-quantitative risk assessment using likelihood and consequences criteria, to identify and rate the un-mitigated and residual risks to groundwater posed by the project.

## 8.1 General Conclusions

1. Whilst the shallow water resources in the region are heavily utilised and regulated, there is relatively sparse data to describe and interpret the deep hydrogeology of the Gunnedah Basin, including the regional-scale processes governing groundwater flow beyond the immediate zone of utilisation.
2. Groundwater in the region is drawn for private use and town supply predominantly from the shallow groundwater sources of the Upper and Lower Namoi alluvium and to a lesser extent from the Pilliga Sandstone aquifer of the GAB. Extraction of water to depressurise coal seams for the recovery of coal seam gas will be conducted at greater depth and within hydrostratigraphic units that are hydraulically remote from the shallow groundwater sources.
3. Extraction of water from deep coal seams in the Gunnedah-Oxley Basin is likely to result in depressurisation and drawdown of hydraulic head that will span hundreds to several thousands of years. The anticipated slow rate of recovery in deep strata is due to very small downward induced flows from the overlying shallow groundwater sources that are restricted by intervening strata with low permeability. The downward flows are a very small component of the water balances of the shallow groundwater sources and occur over a long period of time, resulting in minor to negligible predicted impacts on head and flow in the shallow groundwater sources.

4. Multiple lines of evidence, including laboratory measurements, drill stem tests in coal seams, inferences based on water quality and estimates based on borehole lithology logs indicate that the host strata of the coal seams in the Gunnedah Basin exhibit very low hydraulic conductivity and storativity.

5. Numerical groundwater modelling shows that considerable depressurisation can be achieved through the extraction of relatively small volumes of water relative to the total extractions currently made from the alluvial groundwater sources.

6. The numerical simulations indicate that drawdown of hydraulic head due to depressurisation of the target coal seams will initially be localised to the area of water extraction with the propagation of drawdown away from these areas being impeded by the low hydraulic conductivity of the host strata.

7. The characteristically small hydraulic conductivity of the deep basin strata also impedes groundwater replenishment from overlying groundwater sources, prolonging the localised impact in the coal seams and host strata, and prolonging but thereby attenuating the impacts in the overlying groundwater sources.

## 8.2 Subsidence

Potential compaction at depth due to extraction of water and depressurisation of the target coal seams has been assessed using two methods known as *Linear Elastic Theory* and *Compaction at a Specific Location* (Commonwealth of Australia 2014b). Based on these results it is concluded that:

8. The probable worst case range of subsidence at depth due to depressurisation of coal seams and their hosting strata is estimated to be 137 mm to 205 mm of vertical compaction.

9. The maximum potential compaction at depth of 205 mm is likely to cause negligible subsidence at ground surface due to the large depth below ground surface of the target coal seams and the presence and thickness of structurally competent rock formations within the overburden.

10. The predicted maximum tilt at ground surface induced by subsidence is less than 0.02 mm/m (<0.002%).

11. The risk of impacts to sub-infrastructure and groundwater resources due to potential subsidence at depth arising from the project is assessed to be low to very low, and the associated risk of impacts on surface infrastructure and surface water from subsidence at ground surface and differential settlement is assessed to be very low.

The Water Monitoring Plan (CDM Smith 2016c) for the project includes Interferometric Synthetic Aperture Radar (InSAR) surveys every 10 years.

## 8.3 Predictive Simulations of Water Production

The simulated rates of water production associated with the project have been estimated by Santos using a reservoir model and based on data from coal seam gas pilot wells and appraisal activities. The Base Case estimate of simulated water production is 37.5 GL over a period of 25 years, representing the volume water production that is being used as the basis for the project construction and design concept.

Approximately 95 percent of the Base Case estimate is simulated water production from coal seam targets within the Early Permian Maules Creek Formation; the remaining 5 percent is simulated water production from coal seam targets within the Late Permian Upper Black Jack Group.

The Low Case and High Case estimates of total simulated water production are 35.5 GL and 87.1 GL over 25 years, respectively, representing estimates of total simulated water production that are based on lower-than expected and higher than expected porosity in the target coal seams.

The main conclusions from the numerical modelling indicate:

12. There is likely to be no discernible impact to groundwater in the Upper and Lower Namoi Alluvium. The results for the Base Case, Low Case and High Case simulations show that the maximum drawdown of the water table in the alluvium is predicted to be less than 0.5 m. On this basis, negligible impact on the exchange of groundwater between the Namoi alluvium and Namoi River is predicted.

13. There is likely to be a minor to negligible impact to groundwater in the Pilliga Sandstone of the GAB. The Base Case and Low Case simulations predict no drawdown in the Pilliga Sandstone greater than 0.5 m, while the High Case simulation predicts a maximum drawdown of approximately 0.56 m near the western boundary of the project area, approximately 175 years after the 25-year field development plan ceases.

14. Almost full recovery of the drawdown is predicted after approximately 1500 years due to additional net recharge in the basin. In the Base Case simulation the majority of the water removed during the simulated field development plan (37.5 GL) is eventually replenished by additional net recharge in the GAB (74% after 1500 years), the Gunnedah-Oxley Basin (15% after 1500 years) and the Namoi alluvium (10% after 1500 years). It follows that slow recovery of head at depth in the basin results in small predicted impacts to overlying shallow water sources.

## 8.4 Cumulative Impacts Including the Narrabri Coal Mine

Based on existing groundwater modelling, approximately 22.6 GL of groundwater inflow from the Hoskissons Coal into the underground workings of the Narrabri Coal Mine Stage 2 Longwall Project is predicted over the proposed 31 years of mining operations. Approximately 2 GL of reinjection into the Hoskissons Coal is also planned at the completion of the longwall, resulting in predicted net extraction of 20.6 GL.

Potential cumulative impacts of the six other existing or approved coal mines within the GIA study area are expected to not occur or be negligible and are not simulated in this assessment.

The main conclusions from the numerical modelling indicate:

15. The cumulative impacts of the Narrabri Coal Mine Stage 2 Longwall Project and Narrabri Gas Project are likely to be dominated by the effects of groundwater inflow to the Narrabri Mine, with relatively minor cumulative contributions to maximum drawdowns from the Narrabri Gas Project in the areas impacted by both activities.

## 8.5 Minimal Impact Considerations of the NSW Aquifer Interference Policy

The NSW Aquifer Interference Policy (AIP) sets out the water licensing and approval processes and requirements for aquifer interference activities under the *Water Management Act 2000*. Water Sharing Plans are statutory documents currently used to manage water resources under the *Water Management Act 2000*. The framework for making an assessment of potential aquifer interference was prescribed by [9]NOW (2013) and Santos' response is provided in Appendix D.

I think the minimal impact to interference is most neatly expressed by the maximum modelled rate of leakage from the various WSP units – 0.01GL/yr (0.16 L/s) from the Namoi Groundwater sources WSP (insert under bullet 16), and 0.06 GL/yr (1.8 L/s) from the GAB groundwater WSP (insert under bullet 17).

The GIA study area includes three groundwater sources identified in NSW Water Sharing Plans that are subject to the minimal impact considerations of the AIP:

16. The Upper and Lower Namoi Groundwater Sources (*Upper and Lower Namoi Groundwater Sources Water Sharing Plan*) are "Highly Productive Groundwater Sources" and "Alluvial Water Sources" under the AIP. No impacts on the water table elevation in the alluvium exceeding 0.5 m drawdown are predicted as a consequence of the Base Case, Low Case and High Case simulated water production profiles. The predicted maximum induced flow rates from all WSPRPs of the Upper and Lower Namoi Groundwater Sources are less than 0.01 GL/y (0.3 L/s).
17. The Southern Recharge Groundwater Source (*NSW Great Artesian Basin Groundwater Sources Water Sharing Plan 2008*) is a "Highly Productive Groundwater Source" and "Porous Rock Water Source" under the AIP. No impacts on hydraulic head in the Pilliga Sandstone exceeding 0.5 m drawdown are predicted for the Base Case and Low Case water production profiles. The largest drawdown predicted for the High Case water production profile is 0.56 m at approximately 175 years after the proposed 25-year field development plan ceases. The predicted maximum induced flow rate from the Southern Recharge Groundwater Source is 0.06 GL/y (1.8 L/s).
18. The Gunnedah-Oxley Basin Groundwater Source (*NSW Murray Darling Basin Porous Rock Groundwater Sources Water Sharing Plan*) is a "Less Productive Groundwater Source" and "Porous Rock Water Source" under the AIP. Significant potential drawdown is predicted on this groundwater source, which would constitute "aquifer interference" under the AIP. It should be noted that in the project area, the Gunnedah-Oxley Basin Groundwater Source has a relatively low value due to high salinity, with no known groundwater users abstracting water from the coal seams or surrounding source rock in the project area. In addition, the volume of water abstracted under a Water Access Licence (WAL) is well within the sustainable diversion limits (maximum usage cap) of the targeted water source. Therefore, any depressurisation effects would be considered negligible on existing water users targeting this water source, and hence should not be considered to constitute an aquifer interference.

## 8.6 Significant Impact Guidelines of the EPBC Act

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) provides a legal framework to protect and manage Matters of National Environmental Significance, which include "a water resource in relation to coal seam gas development and large coal mining development"—

[9] NSW Office of Water (NOW) is now DPI Water

known as the "water trigger". The significance of an impact determines whether it should be assessed under the EPBC Act, with guidance given in the *Significant Impact Guidelines 1.3: Coal Seam Gas and Large Coal Mining Developments-Impacts on Water Resources*. Appendix E incorporates the IESC's Information Requirements Checklist (IESC 2015) which has been modified to indicate where the IESC's information requirements have been addressed in this groundwater impact assessment.

The predicted impacts in this GIA have been assessed against the significant impacts guidelines:

19. The drawdown predicted from groundwater modelling to the Gunnedah-Oxley Basin Groundwater Source may be considered as significant due to the very long-term duration of the predicted drawdown (greater than 1000 y recovery time for the Base Case) and the regional-scale extent of depressurisation and drawdown within the Gunnedah Basin (greater than 50 km for the Base Case). Notwithstanding these criteria, the Gunnedah-Oxley Basin Groundwater Source within the project area has a relatively low value due to high salinity, with no known groundwater users abstracting water from the coal seams or surrounding host rock in the project area. In addition, the total volume of water that would be abstracted under a Water Access Licence (WAL) is well within the sustainable diversion limits (maximum usage cap) of the targeted water source, and would have negligible impact on existing water users targeting this water source. On balance of these considerations, the predicted depressurisation effects in the Gunnedah-Oxley Basin from the project are unlikely to be considered a significant impact.

20. The predicted impacts on the Southern Recharge Groundwater Source and Surat Groundwater Source of the GAB are unlikely to be considered as significant due to: no predicted drawdown in the Pilliga Sandstone greater than 0.6 m for the Base Case, Low Case and High Case water production profiles; minor predicted changes in groundwater storage in the GAB (approximately 0.1 GL/y maximum rate of storage change for the Base Case); and minor induced groundwater flow within the GAB.

21. The predicted changes on the Upper and Lower Namoi Groundwater Sources are unlikely to be considered as significant due to: no predicted water table drawdown greater than 0.5 m in the Namoi alluvium; negligible induced change in groundwater storage in the Namoi alluvium (less than 0.01 GL/y maximum rate of storage change for the Base Case); and insignificant induced change to groundwater flow in the Namoi alluvium.

22. The groundwater modelling results imply that changes to water quality in the Gunnedah-Oxley Basin Groundwater Source, and specifically within the Early and Late Permian coal seam targets are unlikely to be considered as significant due to their relatively low values. Potential changes to water quality in the GAB and Namoi alluvium are unlikely to be considered as significant due to minor to negligible predicted changes in inter-aquifer flow rates and volumes.

## 8.7 Sensitivity Simulations

Numerical simulations have been undertaken to assess the sensitivity of the groundwater model to variations of the adopted values of the hydrogeological properties. Before considering the results of the sensitivity simulations, it is important to stress that they do not represent equally likely alternatives to the predictive simulations for the project. Instead, they are considered to represent improbable conditions. The sensitivity simulations are designed to understand and demonstrate the behaviour of the model to depressurisation of the target coals seams under a range of extreme conditions and should not be interpreted as predictions of possible outcomes.

The main conclusions from the sensitivity simulations include:

23. The rate at which depressurisation in the target coal seams is transmitted to the overlying formations, and eventually to the water table, is influenced by the choice of hydrogeological properties in the modelling, specifically the vertical hydraulic conductivity (*Kv*) and specific storativity (*Ss*). The simulation results were found to be less sensitive to specific yield at the water table.

24. An increase in *Kv* of the hydrostratigraphic units overlying the target coal seams reduces the resistance to vertical flow and results in larger and faster propagation of drawdown from the coal seams into the overlying strata. At the same time, an increase in *Kv* also implies that more water will leak into the target coal seams from the bounding strata, and that larger water production volumes would be required to achieve coal seam gas production. On this basis, high values of *Kv* are considered to be inconsistent with the known potential to depressurise and produce gas from the target coal seams.

25. A decrease in *Ss* of the target coal seams and overlying strata results in larger drawdown per unit volume of produced water and faster propagation of the drawdown.

26. The sensitivity analysis conducted on *Kv* and *Ss* shows that drawdown of the water table greater than 0.5 m within the Namoi alluvium is very unlikely to occur. The results show that significant drawdown in the Pilliga Sandstone and at the water table outside of the Namoi alluvium can be simulated—with potential impacts on the environmental values of the project—however, this result requires variations of the hydrogeological properties in the modelling that are currently considered to be highly improbable due to the implications for water and gas production.

## 8.8 Risk Assessment

A risk assessment has been undertaken by rating the potential groundwater impacts of the project using ratings of consequence and likelihood, which classify each risk into one of five categories varying from very low to very high. Thirteen of the sixteen risks identified in the risk assessment are assessed to have the lowest possible residual risk score of 1 (very low risk) while the remaining three risks are assessed to have residual risk scores of 2 (low risk). Justifications for these scores are provided in Section 7.4). The three potential impacts with low residual risks (i.e., the highest-ranked risks identified in the assessment) are:

27. Drawdown in existing groundwater bores - decline of water levels in existing deep groundwater bores screened below the Pilliga Sandstone aquifer that would materially affect the water supply from the bores is assessed to be possible but the potential consequences are considered to be minor and manageable. Mitigation would be achieved through the Water Monitoring Plan, which is designed to detect if adverse impacts on the pressure in existing bores is going to occur before those impacts are realised, and implementation of make good options if water supply from an existing bore is materially affected by depressurisation from the project.

28. Drawdown of hydraulic head at GDEs - potential damage to GDEs caused by long-term decline of hydraulic head at the location of GDEs is classified as a major consequence under the criteria of the risk matrix; however, these potential impacts are assessed to be unlikely, resulting in a medium risk score. Maximum drawdowns in the source aquifers for GDEs are predicted to be less than 0.5 m and are small compared to existing and expected future variation of water pressure in the source aquifers due to natural variation in climate patterns and variation in other extractive use patterns. None of the GDEs identified in the GDE impact assessment (Appendix B) meet the definition of a high-priority GDE in NSW, and none support MNES defined under the EPBC Act.

29. Induced groundwater flows between groundwater sources - depressurisation of deep coal seams for coal seam gas production is almost certain to induce very small rates of groundwater flow from overlying groundwater sources as the water extracted from the coal seams is replaced by downward flow through the overlying thick aquitard sequences. This replacement of the extracted water will take place naturally and very slowly over hundreds of years. The consequence of such small induced changes in the inter-formational flows in hydrostratigraphic units above the coal seam targets are assessed to be negligible.

Based on the results of the modelling, the environmental values of the GIA study area are not expected to be adversely affected due to the small and gradual predicted impacts on drawdown in the Pilliga Sandstone, and negligible predicted impacts at the water table in the Namoi alluvium.

## 8.9 Monitoring and Management Measures

Santos has undertaken a comprehensive program of monitoring across a range of environmental values and has committed significant investment into the development of water monitoring networks and the collection of preliminary baseline data, including monitoring of potential subsidence.

Although the predicted impacts to the shallow aquifer systems are low, ongoing monitoring will enable Santos to take appropriate action to monitor project performance against the predictions. Should monitoring indicate a trend towards an impact, monitoring will enable early identification and allow Santos to take appropriately scaled management actions to avoid the impacts and 'make good' on potential adverse impacts.

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# Appendix A - Disclaimer and Limitations

This report has been prepared by CDM Smith Australia Pty Ltd (CDM Smith) for the sole benefit of Santos Limited for the sole purpose of assessment of potential environmental impacts of the proposed Narrabri Gas Project.

This report should not be used or relied upon for any other purpose without CDM Smith's prior written consent. Neither CDM Smith, nor any officer or employee of CDM Smith, accepts responsibility or liability in any way whatsoever for the use or reliance of this report for any purpose other than that for which it has been prepared.

Except with CDM Smith's prior written consent, this report may not be:

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The information on which this report is based has been provided by Santos Limited and third parties. CDM Smith (including its officer and employee):

(a) has relied upon and presumed the accuracy of this information;

(b) has not verified the accuracy or reliability of this information (other than as expressly stated in this report);

(c) has not made any independent investigations or enquiries in respect of those matters of which it has no actual knowledge at the time of giving this report to Santos Limited; and

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In recognition of the limited use to be made by Santos Limited of this report, Santos Limited agrees that, to the maximum extent permitted by law, CDM Smith (including its officer and employee) shall not be liable for any losses, claims, costs, expenses, damages (whether in statute, in contract or tort for negligence or otherwise) suffered or incurred by Santos Limited or any third party as a result of or in connection with the information, findings, opinions, estimates, recommendations and conclusions provided in the course of this report.

If further information becomes available, or additional assumptions need to be made, CDM Smith reserves its right to amend this report.

# Appendix B - GDE Impact Assessment Report

Santos NSW (Eastern) Pty Ltd

**Narrabri Gas Project**

**GDE Impact Assessment**

Santos NSW (Eastern) Pty Ltd

# Narrabri Gas Project
# GDE Impact Assessment

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# Appendices

# Executive Summary

The proponent is proposing to develop Coal Seam Gas within the Gunnedah Basin in New South Wales (NSW). Under the NSW Director General's Environmental Assessment Requirements, the proponent is required to consider whether the Narrabri Gas Project (NGP) would have a significant impact on the environment, including potential impacts on groundwater dependent ecosystems (GDEs) through depressurisation of deep coal seams.

The assessment of GDEs in this study adopts the methods described within the GDE toolbox (Richardson et al. 2011) and DPI Water's *Risk assessment guidelines for groundwater dependent ecosystems, Volume 1 – The conceptual framework* (Serov et al. 2012). The assessment also draws on the recommendations of the Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Projects (Commonwealth of Australia 2015) in relation to the expected requirements for assessing water-related ecological responses to coal seam gas extraction.

The key objectives of the report are to:

- Identify known and potential GDEs within the study area
- Describe the hydrogeological processes and nature of groundwater connections at the identified sites
- Describe the sensitivity of each site to disturbance using a Driver/Stressor diagram
- Assess the risks posed to the identified sites using the methodology and risk matrix developed for the GDE risk assessment guidelines (Serov et al. 2012).

The study area for the assessment is defined by the extent of maximum predicted depressurisation (CDM Smith 2016a) exceeding 0.5 metres drawdown of hydraulic head, projected vertically to the land surface and extended in size by a buffer zone of 5 kilometres. The resulting study area covers approximately 3,946 $km^2$.

The potential for GDEs to be present within the study area is assessed under two categories; Type 2 GDEs that may be reliant on the surface expression of groundwater (springs and baseflow) and Type 3 GDEs that may be reliant on the sub-surface expression of groundwater (terrestrial vegetation). There are no potential Type 1 GDEs (aquifers and stygofauna) identified in the study area.

Potential Type 2 GDEs are identified and assessed by Eco Logical (2016c) in Appendix B of this report. Potential Type 3 GDEs are identified and assessed in the body of this report. Assessment of stygofauna communities in the study area is made in the Aquatic Ecology and Stygofauna Assessment (Eco Logical 2016b) which forms Appendix C of the Managed Release Study for the NGP (Eco Logical 2016d). All of these assessments are synthesised into the risk assessment in this report using the risk assessment framework from DPI Water's GDE risk assessment guidelines (Serov et al. 2012).

In relation to the nine potential Type 2 GDEs identified in the study area:

- There are no known groundwater-dependent protected species or habitats in the study area.
- There are nine potential Type 2 GDEs considered likely to be dependent on groundwater.

- All potential Type 2 GDEs are assessed to have low ecological values, mainly due to the absence of protected or important wetland species, and due to the heavily or moderately modified nature of the sites.
- None of the potential Type 2 GDEs meet the definition of a high-priority GDE in NSW, and therefore they fall outside of the minimal impact considerations of the NSW Aquifer Interference Policy.
- None of the potential Type 2 GDEs support Matters of National Environmental Significance (MNES) defined under the EPBC Act.
- All nine potential Type 2 GDEs have water sources derived from either the Pilliga Sandstone aquifer or alluvial aquifers. At least two of the potential GDEs derive their water sources from pre-existing bores flowing freely to the land surface under artesian pressure.
- Maximum drawdown of the water table elevation and hydraulic head in the source aquifers for potential Type 2 GDEs is predicted to be less than 0.5 m, with very slow change over hundreds of years (CDM Smith 2016a). These potential impacts are expected to be indiscernible relative to the existing variations in groundwater pressure due to climate patterns and extractive uses.
- The overall risk assessment score for all nine potential Type 2 GDEs is low.
- No mitigation or specific management measures are required for potential Type 2 GDEs based on the outcomes of the risk assessment. Adopting the principle of adaptive management, the proponent would review the conceptual hydrogeology at each GDE if additional relevant data became available through monitoring or field investigation.
- For GDEs with low ecological values and low risk, the GDE risk assessment guidelines (Serov et al. 2012) recommend continued long-term monitoring. The proponent is committed to monitoring groundwater level and pressure within its groundwater monitoring network through the NGP Water Monitoring Plan (CDM Smith 2016b).

In relation to potential Type 3 GDEs identified in the study area:

- The Type 3 GDEs identified in this assessment are categorised as potential GDEs based on absence of field data to verify if the vegetation uses groundwater. Potential dependence on groundwater is identified based on local-scale (1:10,000) vegetation mapping inside the project area, and based on the GDE atlas outside of the project area.
- Two vegetation communities listed as endangered under the TSC Act are identified as potential Type 3 GDEs within the project area; these being located predominantly in riparian areas of Bohena Creek and its tributaries.
- Potential Type 3 GDEs source groundwater predominantly from the water table; however, they are also able to source soil water from rainfall recharge and surface flow events within alluvial settings.
- Predicted drawdowns in the source aquifers due to the project are less than 0.5 m and occur very slowly over hundreds of years, resulting in negligible predicted impacts on GDEs.
- The overall risk assessment score for potential Type 3 GDEs is low, based on high ecological values but low likelihoods of potential impacts.
- No mitigation or specific management measures are required for potential Type 3 GDEs identified in the study area based on the outcomes of the risk assessment. Adopting the principle

of adaptive management, the proponent would review the conceptual hydrogeology at each GDE if additional relevant data became available through monitoring, drilling, or other field investigation.

- For potential Type 3 GDEs with low risk and low ecological values, the GDE risk assessment guidelines (Serov et al. 2012) recommend continued long-term monitoring. The proponent is committed to monitoring groundwater level and pressure within their groundwater monitoring network through the Water Monitoring Plan for the NGP (CDM Smith 2016b).

# Glossary

| Term | Definition |
|---|---|
| Aquifer | A saturated permeable geologic unit that transmits significant quantities of water under ordinary hydraulic gradients. |
| Aquitard | A saturated but poorly permeable bed, formation or group of formations that can store water but only yields it slowly to a well or spring. Aquitards can sometimes transmit appreciable groundwater to or from adjacent aquifers. |
| Groundwater (GW) | Water occurring naturally below ground level (whether in an aquifer or otherwise); or<br><br>Water occurring at a place below ground that has been pumped, diverted or released to that place for the purpose of being stored there; but does not include water held in underground tanks, pipes or other works.<br><br>Source: Water Act 2007.<br><br>Note: This definition includes the capillary zone, which is an important source of water for many GDEs. It also includes recently infiltrated rainwater in the unsaturated zone however, which should be excluded as it is a component of rainfall rather than groundwater, and pumping of groundwater would have little impact on soil water stores. |
| Confined aquifer | An aquifer that lies below low permeability material (aquitard) and where the piezometric surface lies above the base of the confining material. |
| Ecosystem | The community of a plant, animal and other organisms existing within a defined area, and their interactions within the community and their non-living environment. |
| Groundwater Dependent Ecosystem (GDE) | Ecosystems which have their species composition and their natural ecological processes determined to some extent by groundwater. Natural ecosystems that require access to groundwater to meet all or some of their water requirements on a permanent or intermittent basis, so as to maintain their communities of plants and animals, ecosystem processes and ecosystem services.<br><br>Source: GDE toolbox (Richardson et al. 2011). |
| Type 1 GDE - aquifers and stygofauna | Ecosystem that reside within the spaces of caves and aquifers. |
| Type 2 GDE - dependent on the surface expression of groundwater | Ecosystems that are connected to groundwater that comes to the earth's surface, within wetlands, lakes, seeps, springs and river baseflow. |
| Type 3 GDE - dependent on the sub-surface expression of groundwater | Ecosystems associated with terrestrial vegetation that utilises the water table or capillary zone. |

# Section 1 Introduction

## 1.1 Project Scope

The proponent is proposing to develop natural gas from coal seams in the Gunnedah Basin in New South Wales (NSW) southwest of Narrabri. Under the NSW Director General's Environmental Assessment Requirements, the proponent is required to consider whether the Narrabri Gas Project (NGP) would have a significant impact on the environment, including potential impacts on groundwater dependent ecosystems (GDEs) through depressurisation of deep coal seams.

This report:

- Considers the assessment of potential Type 1 GDEs (e.g. aquifers and stygofauna) by Eco Logical (2016b) which forms Appendix C of the Managed Release Study for the NGP (Eco Logical 2016d)
- Considers the assessment of potential Type 2 GDEs that may be reliant on surface expression of groundwater (e.g., springs and baseflow) by Eco Logical (2016c) which forms Appendix B of this report)
- Provides an assessment of potential Type 3 GDEs in the project area that may be reliant on sub-surface expression of groundwater (water table) within the root zone
- Integrates the findings from the above studies into a single risk assessment.

The assessment of potential Type 2 GDEs (Eco Logical 2016c) was undertaken based on DPI Water's *Risk assessment guidelines for groundwater dependent ecosystems, Volume 1 – The conceptual framework*, which is referred to in this report as the GDE risk assessment guidelines (Serov et al. 2012). Similarly, the assessment of potential Type 3GDEs in this report follows the GDE risk assessment guidelines, and also gives consideration to the definitions and assessment approaches defined in the GDE Tool Box (Richardson et al. 2011).

## 1.2 Objectives

Under the New South Wales Government Director General's Environmental Assessment Requirements, the proponent is required to consider whether depressurisation and associated impacts from coal seam gas abstraction would have a significant impact on the environment. The proponent is required to identify, characterise and assess the risk to GDEs. The project will also be assessed against Commonwealth Government information requirements published by the Independent Scientific Committee on Coal Seam Gas (IESC).

This report aims to fulfil these requirements by adopting assessment processes described within the GDE risk assessment guidelines (Serov et al. 2012) and the GDE toolbox (Richardson et al. 2011).

The aims of this GDE impact assessment are achieved by:

- Identifying potential GDEs within the GDE study area
- Describing the potential hydrogeological processes and nature of groundwater connections between these sites and identified water sources
- Conceptualising the sensitivity of each site using a Driver/Stressor diagram

- Assessing the risks of the project at these sites using the methodology and risk matrix developed for the GDE risk assessment guidelines (Serov et al. 2012).

## 1.3 GDE Study Area

The potential impact of water level drawdown as a result of coal seam gas activities, and its predicted maximum extent in individual hydrostratigraphic units is identified from groundwater flow modelling undertaken for the project Groundwater Impact Assessment (GIA) (CDM Smith 2016a). The GDE study area in this impact assessment is defined by the predicted maximum extent of drawdown exceeding 0.5 m from the modelling of the proponent's' proposed development activities in the project area, extrapolated vertically to the ground surface.

Specifically, the GDE study area is defined in two steps:

1. A polygon is constructed that encapsulates the areal extent of all predicted sub-surface depressurisation that exceeds 0.5 m head change at any depth within the basin sediments over the 1500-year period of the model simulation.

2. A 5-km wide buffer area is added to the polygon to form the GDE study area boundary, which provides additional conservatism to the estimate of potential impacts to groundwater levels; noting that the numerical groundwater model is already considered to be conservative.

The resulting boundary of the GDE study area, shown in Figure 1-1, has an area of 3,946 km$^2$. The GDE study area is conservative in size in the sense that it exceeds the area in which there is considered to be potential for impacts to GDEs. While its size is based on the predicted extent of drawdown exceeding 0.5 m at depth within the Gunnedah-Oxley Basin, the GIA predicts that there will be no drawdown exceeding 0.5 m anywhere within the shallow high-valued aquifers that are identified as the water sources supporting potential GDEs. The pressure changes expected in these high-valued aquifers are predicted to be indiscernible relative to the existing much larger fluctuations caused by variations in climate and existing extractive use patterns.

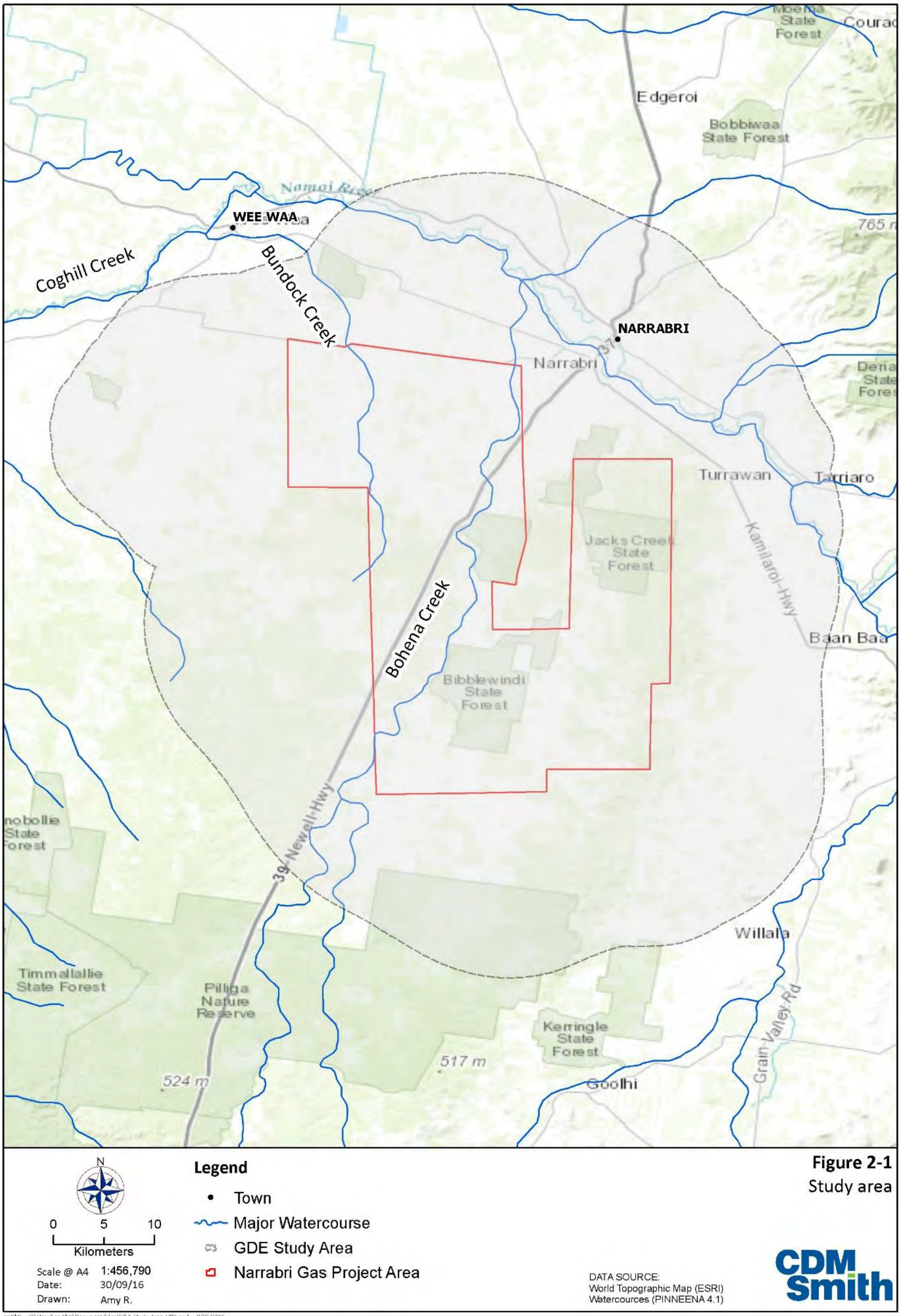


**Figure 1-1 GDE study area**

# Section 2 Project Context

This section briefly outlines the types of GDEs that are recognised under State and Commonwealth legislation and the associated policies and guidance.

## 2.1 Definition of GDE Types

The terminology used in this report is adopted from two current national approaches for defining and managing GDEs; the National Atlas of Groundwater Dependent Ecosystems[1] (GDE atlas) and the GDE toolbox (Richardson et al. 2011). Both of these approaches were informed by definitions within the Australian National Aquatic Ecosystem Framework (Aquatic Ecosystems Task Group 2012) and definitions developed by Eamus and Froend (2006). They are preferred to older definitions because they describe the nature of the groundwater connection to ecosystems.

Three classifications of GDEs exist:

- Type 1 GDE - aquifers and stygofauna ecosystems referring to ecosystems that reside within the spaces of caves and aquifers
- Type 2 GDE - ecosystems dependent on the surface expression of groundwater referring to ecosystems that are connected to groundwater that comes to the earth's surface, within wetlands, lakes, seeps, springs and river baseflow
- Type 3 GDE - ecosystems dependent on the sub surface presence of groundwater referring to ecosystems associated with terrestrial vegetation utilising the water table below the natural surface.

The Namoi subregion bioregional assessment (Welsh et al. 2014; see Section 2.4) recognises six broad types of GDEs that can be further simplified into the three GDE types of Eamus and Froend (2006) described above.

GDEs are defined by the Department of Land and Water Conservation (2008) as '*ecosystems which have their species composition and natural ecological processes wholly or partially determined by groundwater*'.

A High Priority GDE is defined as having high ecological value and is therefore considered a high priority for management action. High ecological value might be recognised, for example, where species or habitats protected under the EPBC Act are present.

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[1] http://www.bom.gov.au/water/groundwater/gde/index.shtml

## 2.2 Legislative Context

### 2.2.1 Federal

A consideration of this study is to identify if the project might have impacts that could be assessed as significant to Matters of National Environmental Significance (MNES) as defined in the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). If present in the GDE study area, MNES relevant to GDEs could reasonably be expected to include:

- Wetlands of international importance (listed under the RAMSAR Convention)
- Listed threatened species and ecological communities
- Migratory species, listed under international agreements
- A water resource, in relation to coal seam gas development.

The presence or absence of MNES is an important influence on the sensitivity that is ascribed to GDEs in the GDE study area. The potential impact of the project will be assessed by the Federal Department of the Environment, including predicted impacts to GDEs.

### 2.2.2 State

The *Water Management Act 2000* is the key piece of legislation for the management of water in NSW, and ensures the protection and enhancement of water sources and their associated ecosystems.

Principles within the act that are relevant to the management of GDEs include the following:

- Water sources, floodplains and dependent ecosystems should be protected and restored, and, where possible, land should not be degraded
- Habitats, animals and plants that benefit from water or are potentially affected by managed activities should be protected and restored
- The quality of all water sources should be protected and, where possible, enhanced
- The cumulative impacts of water management licenses and approvals and other activities on water sources and their dependent ecosystems, should be considered and minimised
- The principles of adaptive management should be applied.

The *NSW Aquifer Interference Policy 2012* and Water Sharing Plans are the main tools for managing water resources under the *Water Management Act 2000*. Water Sharing Plans list high priority GDEs within the sharing plan zone and provide conditions on works undertaken in the vicinity of GDEs. The *NSW Aquifer Interference Policy 2012* specifies thresholds of minimal impact considerations to high priority GDEs within highly productive and less productive groundwater sources.

The *NSW State Groundwater Dependent Ecosystems Policy (2002)* implements the *Water Management Act 2000* by providing guidance to protect and manage GDEs. The Policy sets out management objectives and principles to ensure that:

- Vulnerable and valuable GDEs are protected
- Groundwater extraction is managed within defined limits, thereby providing flow sufficient to sustain ecological processes and maintain biodiversity

- Sufficient groundwater of suitable quality is made available to ecosystems where needed
- The precautionary principle is applied to protect GDEs, particularly the dynamics of flow and availability and the species reliant of these attributes
- Land use activities aim to minimize adverse impacts on GDEs.

## 2.3 Environmental Assessment Requirements

The NSW Office of the Director General has released Environmental Assessment Requirements. A summary of the requirements considering the assessment of impact to GDEs is shown in Table 2-1. This report follows the assessment method recommended in DPI Water's GDE risk assessment guidelines (Serov et al. 2012) and, in doing so, is targeted to meet State requirements.

**Table 2-1 NSW Office of the Director General Environmental Assessment Requirements**

| Office of the Director General Environmental Assessment Requirements | |
|---|---|
| General Requirements | The EIS must include a water management strategy, including:<br>▪ Sufficient baseline monitoring for groundwater quantity and quality for all aquifers and GDEs to establish a baseline incorporating typical temporal and spatial variations<br>▪ Consideration of potential impacts on groundwater, including GDEs in the vicinity of the site<br>▪ Identification of potential impacts on GDEs as a result of the proposal, including the effect on the function of GDEs (habitat, groundwater levels, connectivity)<br>▪ Protective measures and safeguard measures for GDEs |
| | The EIS must address the requirements of the Commonwealth Department of the Environment and Energy issued in accordance with the Bilateral Agreement under the *Environment Protection and Biodiversity Conservation Act 1999*, including:<br>▪ Baseline condition of the proposed development area, including baseline water quality for all relevant surface and groundwater resources, including chemistry and ecology, at the local and regional scale<br>▪ Assessment of all relevant impacts upon water resources and their dependent assets, which must be consistent with the requirements of the most recent version of the IESC's *Information Guidelines for Independent Expert Scientific Committee Advice on Coal Seam Gas and Large Coal Mining*, and including -<br>- aquatic and terrestrial ecosystems that are dependent on the water resource, including those dependent upon the particular geomorphology of a water resource<br>- ecosystems that are dependent on springs and groundwater, including identification of the relevant source hydrogeological unit<br>▪ Information on proposed avoidance and mitigation measures to manage impacts<br>▪ Requirements for ongoing management and monitoring of potential impacts to water resources |
| Key Issues | The EIS must address water as a specific issue, and in reference to GDEs should:<br>▪ Assess the likely impacts of the development on GDEs, including an assessment of these impacts against the NSW Aquifer Interference Policy |

## 2.4 Namoi Subregion Bioregional Assessment

Bioregional assessments (BAs) are one of the key mechanisms to assist the IESC in developing advice to the federal Minister for the Environment on potential water-related impacts of coal seam gas and large coal mining developments. The Namoi subregion BA is one of four subregion BAs that constitute the Northern Inland Catchments bioregion.

The project area of the NGP lies entirely within the area of the Namoi subregion BA.

The Namoi subregion BA will provide new scientific information about the potential impacts of coal and coal seam gas development in the Namoi subregion, including potential impacts on water within the central and eastern parts of the subregion. The assessment will also examine the cumulative impacts for surface water and groundwater across the Namoi river basin.

Products of the Namoi subregion BA available at the time of preparing this GDE impact assessment include:

- Context statement for the Namoi subregion (Product 1.1) (Welsh et al 2014)
- Coal and coal seam gas resource assessment for the Namoi subregion (Product 1.2) (Northey et al. 2014)
- Description of the water-dependent asset register for the Namoi subregion (Product 1.3) (O'Grady et al 2015a) –
    - Water-dependent asset register and asset list for the Namoi subregion on 15 January 2015 (O'Grady et al 2015b)
- Current water accounts and water quality for the Namoi subregion (Product 1.5) (Pena-Arancibia et al 2016)
- Data register for the Namoi subregion (Product 1.6); including among many –
    - Directory of Important Wetlands in Australia (DIWA) Spatial Database (Public) – the GDE study area does not contain any wetlands listed in the directory; the closest listed wetland is Lake Goran located approximately 50 km beyond the boundary of the GDE study area to the southeast
    - Ramsar Wetlands of Australia – the GDE study area does not contain any Ramsar listed wetlands; the closest Ramsar listed wetland is the Macquarie Marshes located more than 150 km beyond the boundary of the GDE study area to the east
    - National Groundwater Dependent Ecosystems (GDE) Atlas – the GDE atlas covers all of the GDE study but is superseded within the project area by local scale mapping of vegetation communities and potential groundwater dependence (Eco Logical 2016a)

The context statement for the Namoi subregion (Welsh et al 2014) identified that the key sources of information about GDEs in the subregion are maps from the 2010 NSW state of the catchment report for groundwater in the Namoi region, which focused on Type 2 GDEs and the GDE atlas. Mapping of potential GDEs in the 'Asset database for the Namoi subregion on 18 February 2016 Public' is based primarily on the mapping of GDEs in the GDE atlas.

The GDE atlas is recognised as a national-scale assessment that may not be accurate at regional-to-local scales appropriate to the project, and is not supported by detailed field investigations within the GDE study area. Within the project area the GDE atlas is superseded by detailed local scale mapping of vegetation communities and potential groundwater dependence conducted for the project (Eco Logical 2016a).

Other aspects of the Namoi subregion BA that are relevant to GDEs are incorporated into the GDE assessment in Section 5 of this report.

# Section 3 Study Methodology

## 3.1 Literature and database review

Information sources accessed in the existing GDE studies and this assessment include:

- State of the Catchment (SoC) Report (DECCW 2010a, b)
- Namoi Wetland Assessment and Prioritisation Project (Eco Logical 2008)
- Water Sharing Plans (NSW Office of Water (now DPI Water), 2003, 2008 and 2011) for groundwater sources relevant to the GDE study area, including –
  - NSW Great Artesian Basin Groundwater Sources 2008
  - Upper and Lower Namoi Groundwater Sources 2003
  - NSW Murray Darling Basin Porous Rock Groundwater Sources 2011
- Narrabri Gas Project Groundwater Impact Assessment (CDM Smith 2016a)
- Narrabri Gas Project Ecological Impact Assessment (Eco Logical 2016a)
- Publically available spatial mapping and data, including -
  - geological maps- surface and solid geology
  - topographic data- SRTM
- NSW Government's PINEENA database of registered groundwater works
- Water Asset Information Tool (WAIT) Database (Namoi and Border Rivers-Gwydir CMA 2012)
- National Atlas of Groundwater Dependent Ecosystems (Bureau of Meteorology 2013)
- Namoi subregional Bioregional Assessment products –
  - Product 1.1.- Context statement for the Namoi subregion (Welsh et al. 2014)
  - Product 1.2 - Coal and coal seam gas resource assessment for the Namoi subregion (Northey et al. 2014)
  - Product 1.3 - Description of the water-dependent asset register for the Namoi subregion (O'Grady et al 2015a)
  - Product 1.5 - Current water accounts and water quality for the Namoi subregion (Pena-Arancibia et al 2016)
  - Product 1.6 - Data register for the Namoi subregion[2]

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[2] http://www.bioregionalassessments.gov.au/assessments/16-data-register-namoi-subregion

## 3.2 Assessment Procedure

The assessment of potential impact on GDEs is undertaken in line with the current national framework for assessing the environmental water requirements of GDEs and utilises the GDE toolbox (Richardson et al. 2011). The GDE toolbox provides a starting point for investigating potential impacts on the GDEs and is used as a framework to ensure that critical questions regarding risks to GDEs are addressed in the assessment. The assessment also follows DPI Water's GDE risk assessment guidelines (Serov et al. 2012) for all of the GDE types present.

The GDE toolbox approach considers three stages of assessment that are related to the ecological values of GDEs, level of threat, required level of certainty and availability of data. The complexity of the assessment and associated data requirements increase through the assessment levels as follows:

- Stage 1 assessments are least detailed and focus on gaining a base understanding of where the GDEs exist, classification of processes, and basic conceptualisation of the bio-physical setting.
- Stage 2 assessments verify the susceptibility of the GDE to altered groundwater regime(s), supported by a conceptual understanding of seasonal hydrology and groundwater interaction with the ecology, including the identification of ecological end points and specific components of the terrestrial vegetation that are directly related to the nature of groundwater connection requirements.
- Stage 3 assessments involve understanding the threats posed to the GDEs and how a change in groundwater regime might affect GDE condition. This stage requires the development of hypotheses that are tested through expert knowledge, modelling and additional field data.

Figure 3-1 presents the application of the framework to potential GDEs identified within the GDE study area. Potential impacts of coal seam gas activities (Stage 3 assessment) and the drivers and stressors that influence the dynamics and health of GDEs prior to and during coal seam gas development are considered through an eco-hydrogeological conceptualisation based on the control and stressor model of Gross (2003). The eco-hydrogeological conceptual model provides a schematic representation of critical processes that link GDE water requirements to the landscape, surface water and groundwater systems, and provides context for hypothesising the causal pathways and likely GDE responses to effect caused by coal seam gas development.

The components of the eco-hydrogeological conceptual model are as follows:

- Baseline (pre-development) natural and anthropogenic drivers that influence the landscape, and groundwater and surface water systems that support GDEs
- Hydrogeological processes that control the existence of GDEs
- Stresses to the ecological processes and, ultimately to GDEs, imposed by coal seam gas development.

The GDE risk assessment guidelines (Serov et al. 2012) are based on various ecological and risk factors that are important to decisions on the implementation and management of a proposed activity or development. They provide a conceptual framework by which a methodology can be devised to identify, characterise and assess potential risks to GDEs. The guidelines also identify typical management and mitigation measures that may be adopted based on the risk category assigned to each type of GDE.

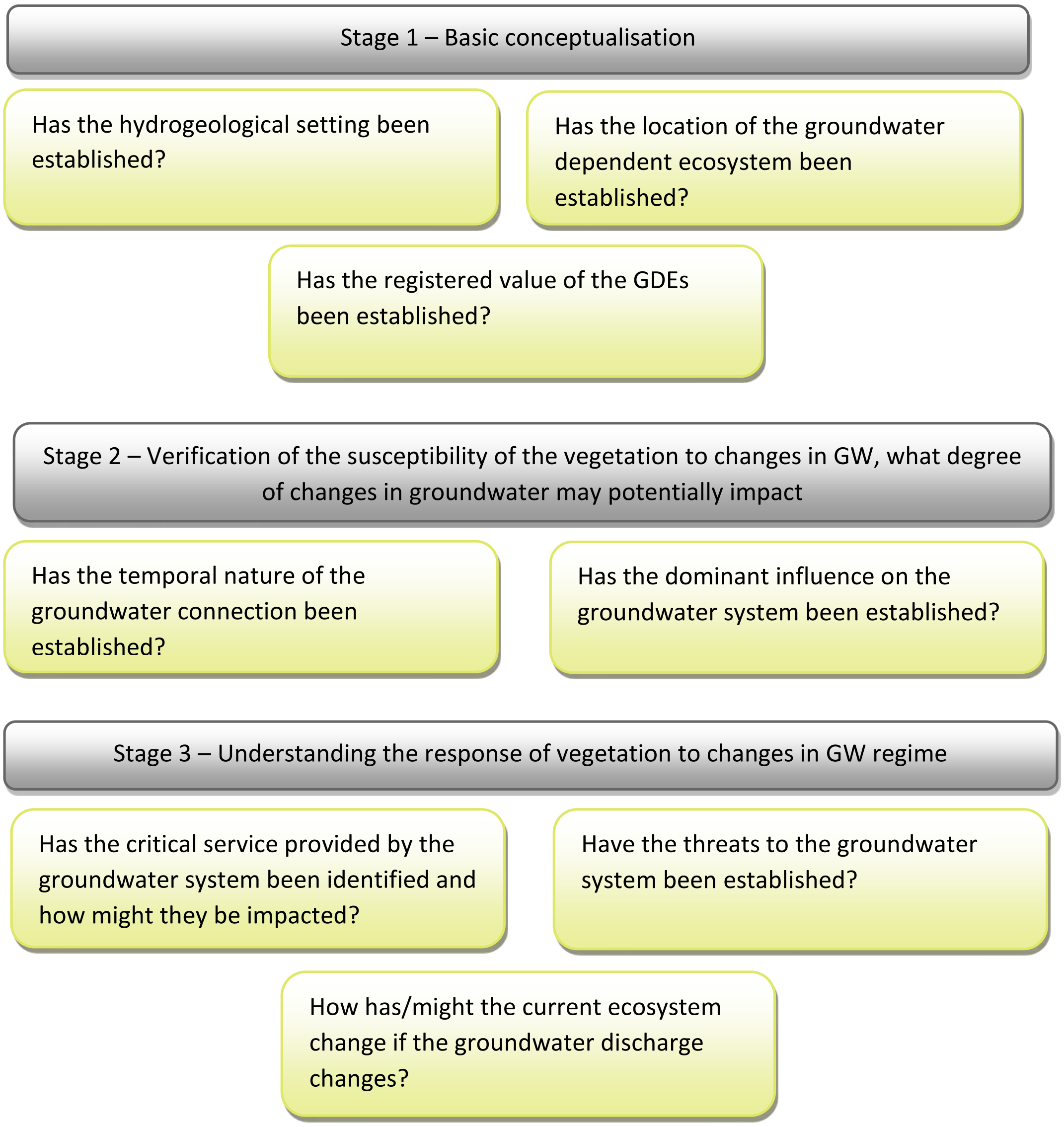


**Figure 3-1 Framework for GDE impact assessment** (after Richardson et al. 2011)

# Section 4 Physical Setting

Information about the climate, hydrology, geology and hydrogeology of the project area is contained in the GIA for the project (CDM Smith 2016a). The GIA also provides broad-level information about the terrestrial environment of the project area but without specific focus on terrestrial environments that may have potential to support Type 3 GDEs that are reliant on sub-surface expression of groundwater.

This section of the report provides additional contextual information that is relevant to the identification and assessment of potential Type 3 GDEs for this GDE impact assessment. The reader is referred to the GIA (CDM Smith 2016a) for other relevant information about the physical setting of the project area.

## 4.1 Terrestrial Environment

A requirement of this report is to assess the risk to Type 3 GDEs that are reliant on the sub-surface expression of groundwater (also referred to as terrestrial GDEs). A first step in achieving this requirement is to identify where high-valued terrestrial vegetation exist and may be accessing groundwater.

The assessment of potential impacts to GDEs is concentrated in the area where the predicted impact of coal seam gas activities is largest, and where mapping of the value of terrestrial communities has been completed (Eco Logical 2016a).

Vegetation communities in the project area are diverse and vary with slope, aspect and soil type. The vegetation mapping for the project area by Eco Logical Australia, conducted at a scale of 1:10,000, identified five plant community types with potential dependence on groundwater that cover a total area of 7,599 ha (Figure 4-1) representing around 8 percent of the project area. The potential for vegetation to be dependent on subsurface expression of groundwater was based on the water-use characteristics of the community plant species, their characteristic rooting depths and the local depth to the water table (i.e., the ability of vegetation to uptake groundwater from the water table and local access to the water table). The approach adopted for mapping the distributions of these communities is considered to be 'inclusive' in the sense that it includes communities that may from time to time access groundwater but otherwise, for most of the time, probably do not access groundwater.

Plant community types within the project area that are listed as endangered or vulnerable ecological communities include:

- Weeping Myall Woodlands (endangered under the EPBC Act) and Myall Woodland; endangered under the *NSW Threatened Species Conservation Act 1995* (TSC Act)
  - no areas of Weeping Myall Woodlands with potential groundwater dependence are identified in the project area
- Brigalow (Acacia harpophylla dominant and co-dominant); endangered under the EPBC Act
  - no areas of Brigalow with potential groundwater dependence are identified in the project area
- Fuzzy Box Woodland; endangered under the TSC Act

  - identified on alluvial soils on the floodplain of Bohena Creek and tributaries

- Carbeen Open Forest community; endangered under the TSC Act
  - a small patch is identified in the north of the GDE study area on Bohena Creek.

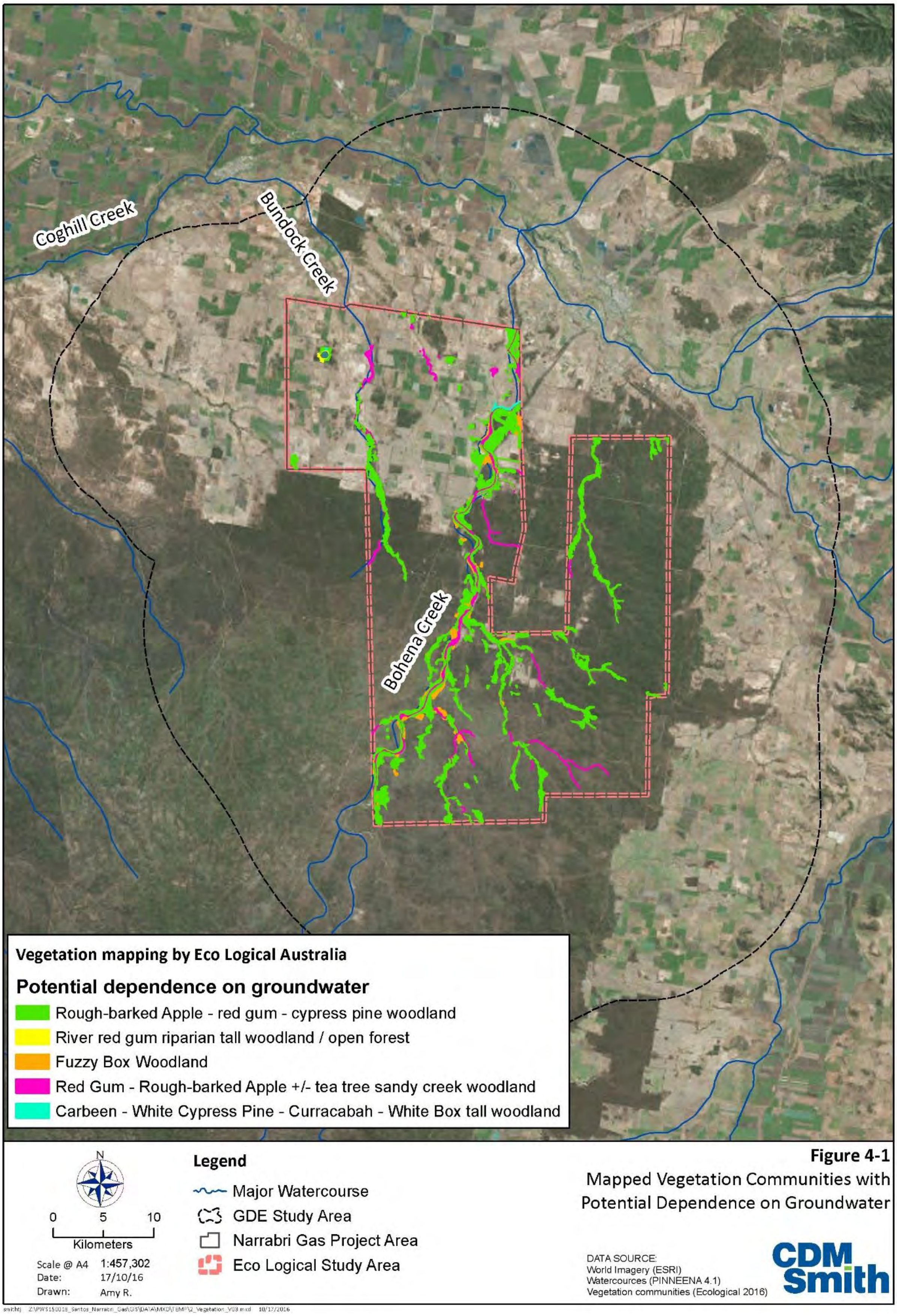


**Figure 4-1 Mapped vegetation communities with potential dependence on groundwater**

# Section 5 GDE Assessment

## 5.1 Identification of Potential GDEs

### 5.1.1 Potential Type 1 GDEs - aquifers and stygofauna

An assessment of stygofauna was undertaken by Eco Logical (2016b) to identify stygofauna communities in the aquifers beneath the NGP area. The study included sampling of bores and pits in the Bohena Creek Alluvium and several deep production bores in the Black Jack Group. No stygofauna were found to be present in the bore samples after two rounds of sampling.

The assessment found that it is extremely unlikely that there are stygofauna living in the coal seams that would be used for gas extraction due to the high salinity, large depth and lack of surface connectivity. Stygofauna are considered unlikely to occur in the Bohena Creek Alluvium because of its shallow depth and ephemeral flow regime. If Stygofauna were to exist within the water table of the NGP area, they would have evolved to cope with seasonal and long term water table fluctuations. On this basis, and considering the minimal predicted impact on the water table, the assessment found that the project would have an extremely low risk of impacting stygofauna communities if they were in fact present.

### 5.1.2 Potential Type 2 GDEs – springs and baseflow

The Groundwater Dependent Ecosystems (Springs) Risk Assessment (Eco Logical 2016c; Appendix B of this report) focused on identifying and characterising the potential Type 2 GDEs within the GDE study area; the potential risks at those sites from the project; and possible mitigation measures for managing the potential risk. The methodology of the assessment report followed the conceptual framework recommended by DPI Water's GDE impact assessment guidelines (Serov et al. 2012).

- Phase 1 of the assessment involved the identification of fifty-four potential Type 2 GDEs that may be reliant on the surface expression of groundwater, using a two-step procedure
  - literature review that identified twenty-one potential GDEs
  - remote sensing analysis, utilising characteristics of the potential GDEs from the literature review as a reference for identifying thirty-four other potential GDEs from satellite and aerial imagery.

  The resulting fifty-four potential GDEs were then subject to an initial screening exercise using indirect evidence to assess the potential for groundwater dependency, including the location, type of feature, topography, proximity to natural drainage features and geology. If the potential for groundwater dependency was low (e.g. the source of water was probably not groundwater) or the site had low ecological value, then it was removed from further assessment. As a result of this process, twenty-one potential GDEs were taken through to Phase 2 of the assessment, based on a medium to high confidence that GDEs were likely to exist at those locations.

- Phase 2 of the assessment involved further investigation and characterisation based on hydrogeological conceptualisation of the sites, and supplemented where possible by site inspections. This process reduced the number of potential GDEs to nine sites at which the water sources were concluded to be primarily from the alluvial or Pilliga Sandstone aquifers, included two potential artesian sites. The nine sites identified in phase 2 of the assessment are listed and described in Table 5-1 and their locations are shown on the map in Figure 5-1.

- The risk assessment conducted in phase 3 assigned a risk score to each of the nine potential GDEs based on the ecological value at the sites and likelihoods of impacts from the project at those locations. The overall risk score for all nine potential GDEs was found to be very low and therefore no management or mitigation measures were prescribed other than continued regional monitoring and adaptive management if required.

Eco Logical (2016c) identified that water at Teds Hole is sourced from the Bohena Creek Alluvium, within or immediately adjacent to Bohena Creek. This identification is consistent with the GDE atlas, which shows Bohena Creek as an area of moderate potential for interaction with surface expression of groundwater. Coghill Creek, located towards the western boundary of the GDE study area, is also mapped as an area of moderate potential for surface interaction with groundwater.

Other potential Type 2 GDEs identified by Eco Logical (2016c) are primarily associated with shallow water tables in the Pilliga Sandstone or alluvium, which provide a 'window into the water table', or contact geology, whereby the water table expresses along the contact of geologies of different permeability (e.g. Pilliga Sandstone and Purlawaugh Formation). These GDEs were all assessed as having low ecological values based on their species populations. Notwithstanding, Hardys Spring and Eather Spring (identified as farm dams) have been recognised by DPI Water as high priority GDEs due to the value of the groundwater source from which they originate (Appendix B).

There are also several groundwater dependent wetlands identified as being associated with former gas wells that are assumed to be free flowing to ground surface. These wetlands have water sources most likely from the Pilliga Sandstone with high-value water quality, but dependent ecosystems that are considered to have low value. A summary of the potential Type 2 GDE sites identified by Eco Logical (2016c) (Appendix B) is provided in Table 5-1.

The GDE atlas shows that Namoi River is classified as a GDE with high potential for groundwater interaction on the basis of previous desktop studies.

**Table 5-1 Summary of potential Type 2 GDEs (Eco Logical 2016c)**

| Site | Rationale for groundwater dependency | GDE type | Ecological evaluation | Valuation score (Eco Logical 2016c) |
|---|---|---|---|---|
| 12 | Located on the Pilliga Sandstone, small ecological community with no signs of surface water inputs, therefore assumed to be groundwater dependent. | Window into the water table | Likely sourced from the Pilliga sandstone. Generally considered to be of low value. Considered to be of high value due to water quality and limited contamination. Absence of rare, threatened or endangered species. | Low |
| 65 | Located at a former gas well (Bohena 1) which sources water from the Pilliga Sandstone, it is assumed that the wetland is directly dependent on the water flowing from the bore located at the base of the pool. | Flowing former gas well | Likely sourced from a bore in the Pilliga Sandstone issuing freely at surface. Generally considered to be of low value. Considered to be of high value due to water quality and limited contamination. Absence of rare, threatened or endangered species. | Low |

| Site | Rationale for groundwater dependency | GDE type | Ecological evaluation | Valuation score (Eco Logical 2016c) |
|---|---|---|---|---|
| 980 | Aerial photography suggests that this site may be groundwater dependent because the site appears to contain fresh (not turbid) water, there is potentially a water table spring located to the south-east of the site, and the naming of 'Spring Creek' located in proximity to the site suggests springs occur in the area. | Window into the water table | Unclear as to whether source aquifer is alluvial aquifer or Pilliga sandstone. Existing pressures on groundwater unknown. Greater number of unknowns but majority of ecological valuation indicates low value. | Low |
| Eather Spring | This site has been recognised by DPI Water as a high priority GDE. Given proximity to the interface between the Pilliga Sandstone and the Purlawaugh Formation this is considered to be a water table spring (contact spring). This is a farm dam and is highly modified through excavation and damming of drainage lines, and through stock access. | Contact geology | Likely sourced from Pilliga Sandstone at interface with Purlawaugh Formation on eastern flank. Minor modifications to GDE have occurred. May be impacts on groundwater quantity from local uses. Groundwater quality generally high. Low ecological value based on species population but reasonable size feature within the landscape. Identified by NCA as having high ecological value. | Low |
| Hardys Spring | This site has been recognised by DPI WATER as a high priority GDE. Given proximity to the interface between the Pilliga Sandstone and the Purlawaugh Formation this is considered to be a water table spring (contact spring). This is a farm dam and is highly modified through excavation and damming of drainage lines, and through stock access. | Contact geology | Likely sourced from Pilliga Sandstone at interface with Purlawaugh Formation on eastern flank. Minor modifications to GDE have occurred. May be impacts on groundwater quantity from local uses. Groundwater quality generally high. Low ecological value based on species population but reasonable size feature within the landscape. Identified by NCA as having high ecological value. | Low |
| Mayfield Spring | Identified as a spring in other studies. Given proximity to the interface between the Pilliga Sandstone and the Purlawaugh Formation this is considered to be a water table spring. Identified as a farm dam. | Contact geology | Likely sourced from Pilliga Sandstone at interface with Purlawaugh Formation on eastern flank. Modifications to GDE have occurred. May be impacts on groundwater quantity from local uses. Groundwater quality generally high. Low ecological value based on species population but reasonable size feature within the landscape. | Low |
| Teds Hole | This site is a permanent waterhole which is relatively fresh with no obvious surface water input. The GDE is likely to represent a perched feature, occupying a depression in an Orallo Sandstone member, perched on an Orallo shale bed, well above the Pilliga Sandstone. The evidence suggest that the site is at least partially dependent on groundwater. | Window into the water table | Likely sourced from Bohena Creek Alluvium (Quaternary alluvium) within or immediately adjacent to Bohena Creek. Minor modifications to GDE have occurred. May be impacts on groundwater quantity from local uses. Groundwater quality generally high. Low ecological value based on species population. | Low |

| Site | Rationale for groundwater dependency | GDE type | Ecological evaluation | Valuation score (Eco Logical 2016c) |
|---|---|---|---|---|
| Well Ford | Considered to be located at a former gas well (Galloway 1) which is currently assumed to supply water to the feature from the Pilliga Sandstone. High resolution aerial photography of the site does not clearly show a wetland feature, the area surrounding the location is in part densely forested. | Flowing former gas well | Likely sourced form Pilliga Sandstone. Generally low ecological value with small number of unknowns. Water quality considered to be high value. | Low |
| Drysdale | Located immediately adjacent to the Wee Waa 1 bore which the borehole log indicates sources water from the Pilliga Sandstone. Artificial wetland with a dependence on groundwater upwelling from an open bore. | Flowing former gas well | Bore fed wetland sourcing water from Pilliga Sandstone under artesian conditions. Generally considered to be of low ecological value with few unknowns. Water quality considered to be high value however dependent species have low value. | Low |

### 5.1.3 Potential Type 3 GDEs – terrestrial vegetation

Eco Logical (2016a) identified terrestrial vegetation listed under the TSC Act or EPBC Act and conducted detailed local-scale mapping of terrestrial vegetation and potential groundwater dependence within the project area. The extent of potential Type 3 GDEs mapped by Eco Logical is shown in Figure 5-2; noting that the vegetation communities that comprise these areas can be seen in Figure 4-1. The potential for groundwater dependence outside of the project area in Figure 5-2 is reproduced from the GDE atlas, which is recognised as a national-scale assessment that may not be reliable at the regional-to-local scale of the project. This difference in level of detail and accuracy between the GDE atlas and the local-scale vegetation mapping is evident from visual comparison of the maps inside and outside of the project area in Figure 5-2. For example, the large areas of low potential for groundwater interaction in the GDE atlas are shown to have no potential for groundwater dependence in the local detailed vegetation mapping.

Within the project area, the local-scale vegetation mapping shows a smaller distribution of potential Type 3 GDEs compared to the GDE atlas that is mainly confined to riparian areas. The areas of potential Type 3 GDEs mapped by Eco Logical generally lie within the region in the GDE atlas classified as having moderate potential for Type 3 GDEs. These areas contain vegetation communities of Rough-barked Apple – red gum – cypress pine woodland, Red gum – Rough-barked Apple with and without tea tree sandy creek woodland, Fuzzy Box Woodland (listed as endangered under the TSC Act), River Red Gum riparian tall woodland / open forest wetland around Yarrie Lake and a small area of Carbeen - White Cypress Pine – Curracabah – White Box tall woodland (listed as endangered under the TSC Act). The areas of Carbeen - White Cypress Pine – Curracabah – White Box tall woodland mapped in the north of the GDE study area corresponds to an area with moderate to high potential for Type 3 GDEs in the GDE atlas.

A search of the GDE atlas for information on the extent of potential Type 3 GDEs shows large areas of potential sub-surface dependent GDEs that broadly correspond to the extent of the Pilliga Forest (Figure 5-2). Within the GDE study area, these GDEs are classified predominantly as having moderate potential for sub-surface groundwater interaction, and include ecosystems of *Eucalyptus fibrosa* (Red Ironbark), *Callitris* (Cypress Pine), *Allocasuarina luehmannii* (Bulloak), *Eucalyptus crebra* (Narrow leaved Ironbark), *Eucalyptus blakelyi* (Red Gum) and *Angophora floribunda* (Rough barked apple tree).

The GDE atlas shows patches of vegetation having high potential for sub-surface groundwater interaction in the northern portion of the GDE study area. These areas are classified as *Callitris* (Cypress Pine) and *Eucalyptus largiflorens* (Black Box). A larger band of vegetation having high GDE potential is mapped to the west of the GDE study area, including ecosystems of Ironbark, *Callitris* (Cypress Pine) and Eucalyptus.

The water-dependent assets register of the Namoi subregion BA (O'Grady et al 2015b) listed 382 GDEs with potential dependence on subsurface expression of groundwater. The rationale for groundwater dependence in the assets register is derived from the GDE atlas for all of these sites. Of the 382 GDEs with potential dependence on subsurface expression of groundwater, 318 are classified as having moderate potential for groundwater interaction, and 57 are classified as having high potential for groundwater interaction.

### 5.1.4 Summary

The potential for occurrence of GDEs in the GDE study area is summarised as follows:

- No Type 1 GDEs with potential to be impacted by the project are considered to be present in the GDE study area
- Potential Type 2 GDEs -
  - The nine site in Figure 5-1 are identified as potential Type 2 GDEs that may be reliant on surface expression of groundwater
  - Namoi River, Bohena Creek and Coghill Creek have all been identified in the GDE atlas as streams potentially receiving surface expression of groundwater
  - Within the GDE study area, Bohena Creek and Coghill Creek have perennial flow regimes and are more likely to recharge groundwater than receive groundwater.
- Potential Type 3 GDEs -
  - Local-scale mapping of vegetation communities within the project area by Eco Logical (2105a) supersedes the GDE atlas
  - The local-scale vegetation mapping shows that potential Type 3 GDEs are located mainly within riparian areas, consisting of Rough-barked Apple – red gum – cypress pine woodland, Red gum – Rough-barked Apple with and without tea tree sandy creek woodland, Fuzzy Box Woodland (listed as endangered under the TSC Act), River Red Gum riparian tall woodland / open forest wetland and a small area of Carbeen - White Cypress Pine – Curracabah – White Box tall woodland (listed as endangered under the TSC Act)
  - Vegetation communities in the GDE atlas outside of the project area that are potentially Type 3 GDEs include *Eucalyptus fibrosa* (Red Ironbark), *Callitris* (Cypress Pine), *Casuarina luehmannii* (Bulloak), *Eucalyptus crebra* (Narrow leaved Ironbark), *Eucalyptus blakelyi* (Red Gum) and *Angophora floribunda* (Rough barked apple tree)

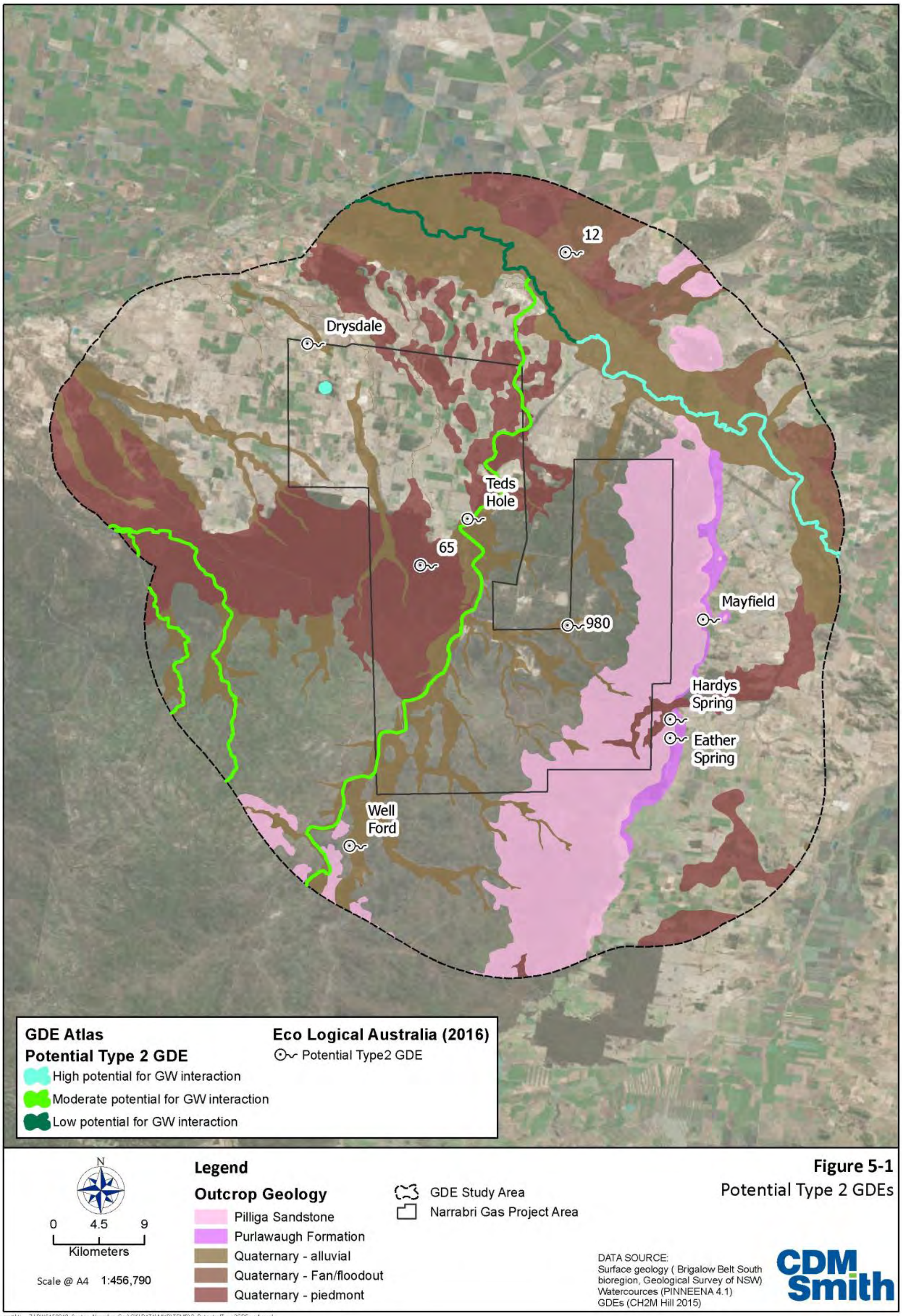


**Figure 5-1 Potential Type 2 GDEs**

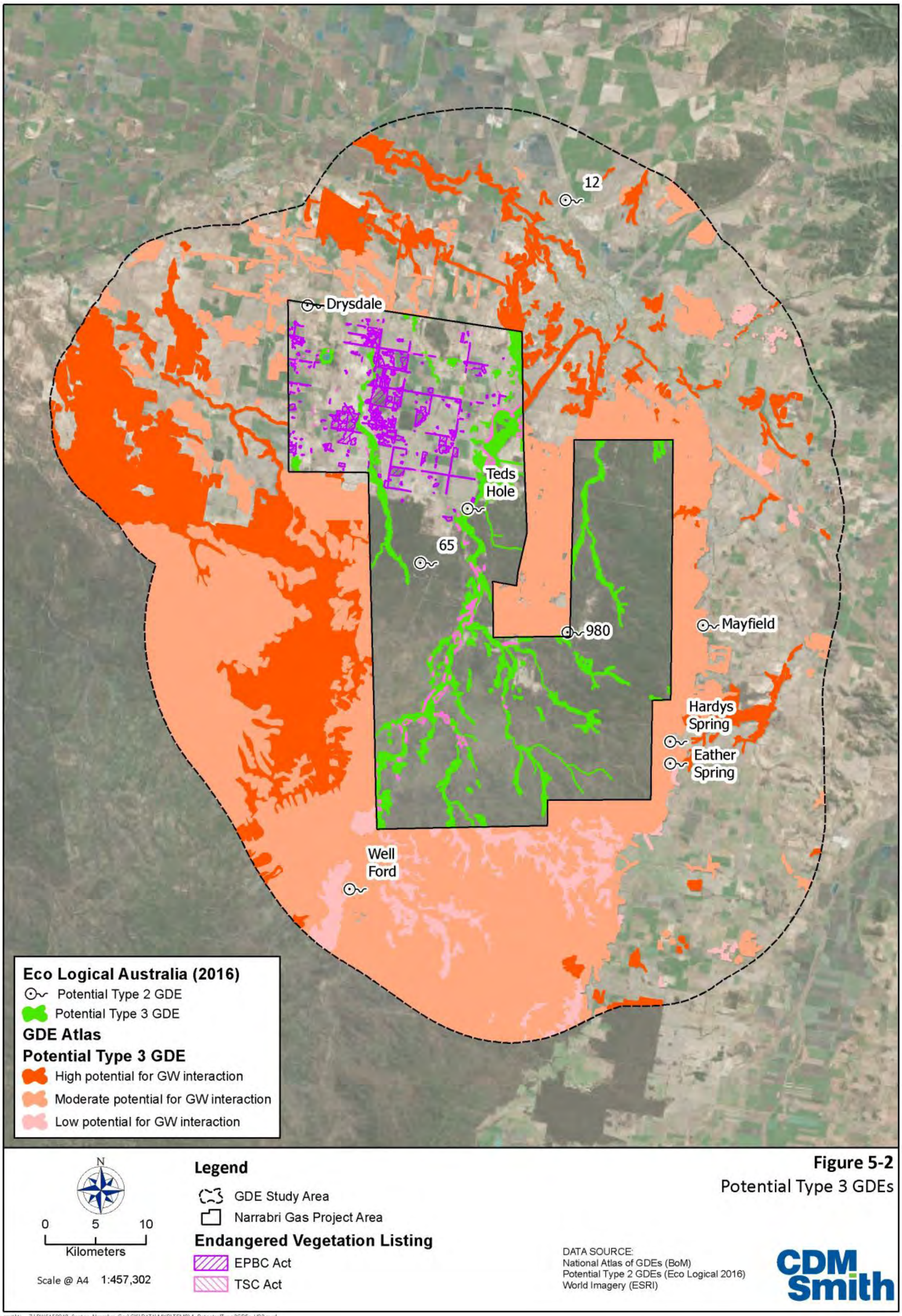


**Figure 5-2 Potential Type 3 GDEs**

## 5.2 Conceptualisation of Potential GDEs

Eco Logical (2016c) conceptualised three ways in which potential Type 2 GDEs in the GDE study area may be reliant on the surface expression of groundwater:

- Within low-lying areas where the water table has come in contact with the land surface (window to the water table). In this situation, the GDE is associated with the water table of outcropping geological units. Eco Logical (2016c) identified three sites, “12”, “980” and Teds Hole that fit this model.
- Where a change in the geology causes groundwater to flow to the land surface (most likely a change in hydraulic properties). Eco Logical (2016c) identified Eather, Hardys and Mayfield Springs (identified as farm dams) as fitting this model.
- Groundwater from flowing wells sourced from the Pilliga Sandstone. Eco Logical (2016c) identified three sites, “65”, Well Ford and Drysdale that fit this model.

In the GDE atlas, classification of the potential for terrestrial vegetation to be a GDE was based upon regional modelling using the following rules:

- Vegetation that demonstrates evapotranspiration (ET) is higher than rainfall is more likely to be using groundwater (as identified from remote sensing)
- Vegetation is more likely to be using groundwater where water tables are shallow (<10 m)
- Vegetation growing in areas of low soil water holding capacity is more likely to use groundwater
- Vegetation surrounding potential GDEs (identified in previous studies) is likely to also be using groundwater
- Vegetation surrounding springs or other known GDEs is likely to be using groundwater
- Particular vegetation communities and plant species have higher potential for using groundwater based upon existing literature and landscape position
- Particular landscapes and topographies are more indicative of shallow groundwater, and are therefore more likely to support GDEs.

In the absence of field-based evaluation of the water use patterns of the terrestrial vegetation, a validation of the classification is complicated by the multiple sources of water available. It is likely that terrestrial vegetation might rely on groundwater where the water table comes close to the land surface (within low lying areas and alluvial settings) and during dry periods when soil water stores would become depleted. Notwithstanding, the vegetation communities within these settings are likely to have developed less reliance on groundwater as a result of existing large fluctuations of water table elevation that are caused by variability in climate and associated consumptive use patterns (e.g., wet and dry climate cycles).

Figure 5-3 presents the components of the Drivers and Stressors conceptual model for the NGP and potential GDEs, including:

- Baseline (pre-development) natural and anthropogenic drivers that influence the landscape and the groundwater and surface water systems that support GDEs
- Hydrogeological processes that control the existence of GDEs

- Potential stresses to ecological processes, and ultimately to GDEs, which are imposed by coal seam gas development.

The key driver that controls the presence of potential GDEs (Table 5-3) in the GDE study area is periodic fluctuation in the water table elevation, which can result in groundwater rising to the rooting depth of vegetation communities (Type 2 GDE) or to the land surface as surface expression of groundwater (Type 3 GDE). Groundwater levels across the GDE study area fluctuate seasonally in response to seasonal patterns in rainfall and groundwater extraction. For example, in the Namoi alluvium there is an observed longer-term decline in water table elevation, caused by over extraction from alluvial groundwater sources that is superimposed on the seasonal dynamics. The locations of potential Type 3 GDEs are largely a function of the topography, while the locations of potential Type 2 GDEs depend on both the topography and underlying geology. With the exception of springs at flowing wells, there appear to be no GDEs that are reliant on artesian pressure from deep groundwater sources

The review of existing information and conceptualisation of GDEs types and supporting hydrological process in the GDE study area facilitates an assessment of the groundwater environmental water requirements for the GDEs, which is presented in Table 5-2.

Potential stressors from the project on Type 2 and Type 3 GDEs would depend on the likelihood of alteration to future water table fluctuations; noting that groundwater extraction and climate trends are already affecting the water source of GDEs through seasonal and long-term effects on water table elevation and hydraulic head in the GDE study area.

**Table 5-2 GDE groundwater requirements**

<table>
<tr><th colspan="2">GDE type</th><th>Groundwater requirements</th></tr>
<tr><td rowspan="2">Type 2 GDEs reliant on the surface expression of groundwater (springs and baseflow)</td><td>GDEs reliant on the surface expression of groundwater (springs) from the Pilliga Sandstone aquifer</td><td>▪ A permanent supply of groundwater sourced from the Pilliga Sandstone that maintains permanent inundation within the spring zone</td></tr>
<tr><td>GDEs reliant on the surface expression of groundwater (springs) from the alluvial aquifer.</td><td>▪ A permanent supply of groundwater from the alluvial and Pilliga Sandstone that maintains permanent inundation within the spring zone<br>▪ Due to their landform setting it is likely that overland flow during flood events may act as a water source.</td></tr>
<tr><td rowspan="2">Type 3 GDEs reliant on the sub-surface expression of groundwater (terrestrial vegetation)</td><td>GDEs reliant on the sub-surface expression of groundwater located on alluvial settings.</td><td>▪ Periodical access to shallow groundwater sourced from the alluvial aquifer and Pilliga Sandstone that provides a dry period source of water for transpiration.<br>▪ Rainfall induced soil water stores are most likely the dominate source of water for terrestrial vegetation as well as overland flow during flood events may act as a water source.</td></tr>
<tr><td>GDEs reliant on the sub-surface expression of groundwater located on Pilliga Sandstone.</td><td>▪ Periodical access to shallow groundwater sourced from the Pilliga Sandstone that provides a dry period source of water for transpiration.<br>▪ Rainfall induced soil water stores are most likely the dominate source of water for terrestrial vegetation.</td></tr>
</table>

**Table 5-3 Driver and Stressor conceptual model components relevant to the existence of GDEs**

| Type | Driver | Stressor | Hypothesised effects |
|---|---|---|---|
| Natural | Climate | Evapotranspiration | Groundwater discharge, lowering of water table and evaporative salt concentration. |
| | | Rainfall | Trends and seasonal fluctuations of groundwater recharge |
| | Hydrology | Groundwater recharge | Trends and seasonal fluctuation of water table elevation. |
| | | Seasonal water table fluctuations | Large seasonal fluctuations of between 3-10m observed in alluvium. Smaller seasonal fluctuations of around 2-4m observed in the Pilliga Sandstone. Water table may locally reach rooting depth and discharge to form intermittent wetlands. |
| | | Surface expression of groundwater | Seasonal discharge along Bohena Creek, Coghill Creek and Namoi River Creek. |
| | | Water source for transpiration | Potential terrestrial vegetation dependence on seasonal or longer-term water table fluctuations in response to climatic variations. |
| | | Erosion | Sedimentation and water quality changes |
| | Landform | Slope-drainage lines | Steep slopes lead to run-off, flatter area encourages ponding and recharge. |
| | | Overland flow | Contribute to recharge down gradient, can mobilise sediments and contaminants. |
| | | Contact geology | Preferential flow and discharge along geological contacts (e.g. springs). |
| | | Proximity to shallow groundwater | Depth to water table is shallower in low lying areas with local seasonal discharge, may enhance likelihood of terrestrial vegetation accessing groundwater. |
| Anthropogenic | Agriculture | Groundwater extraction | Impacts seasonal fluctuations in groundwater levels and pressures. Appears to be contributing to a long term decline in groundwater levels. |
| | | Land use disturbance | Increased susceptibility to erosion/sedimentation |
| | Coal seam gas | Change in groundwater pressure | Predicted <0.5 metre change in groundwater pressure over an 800-year period within the Pilliga Sandstone and deeper HSUs. Minimal drawdown in water table. |

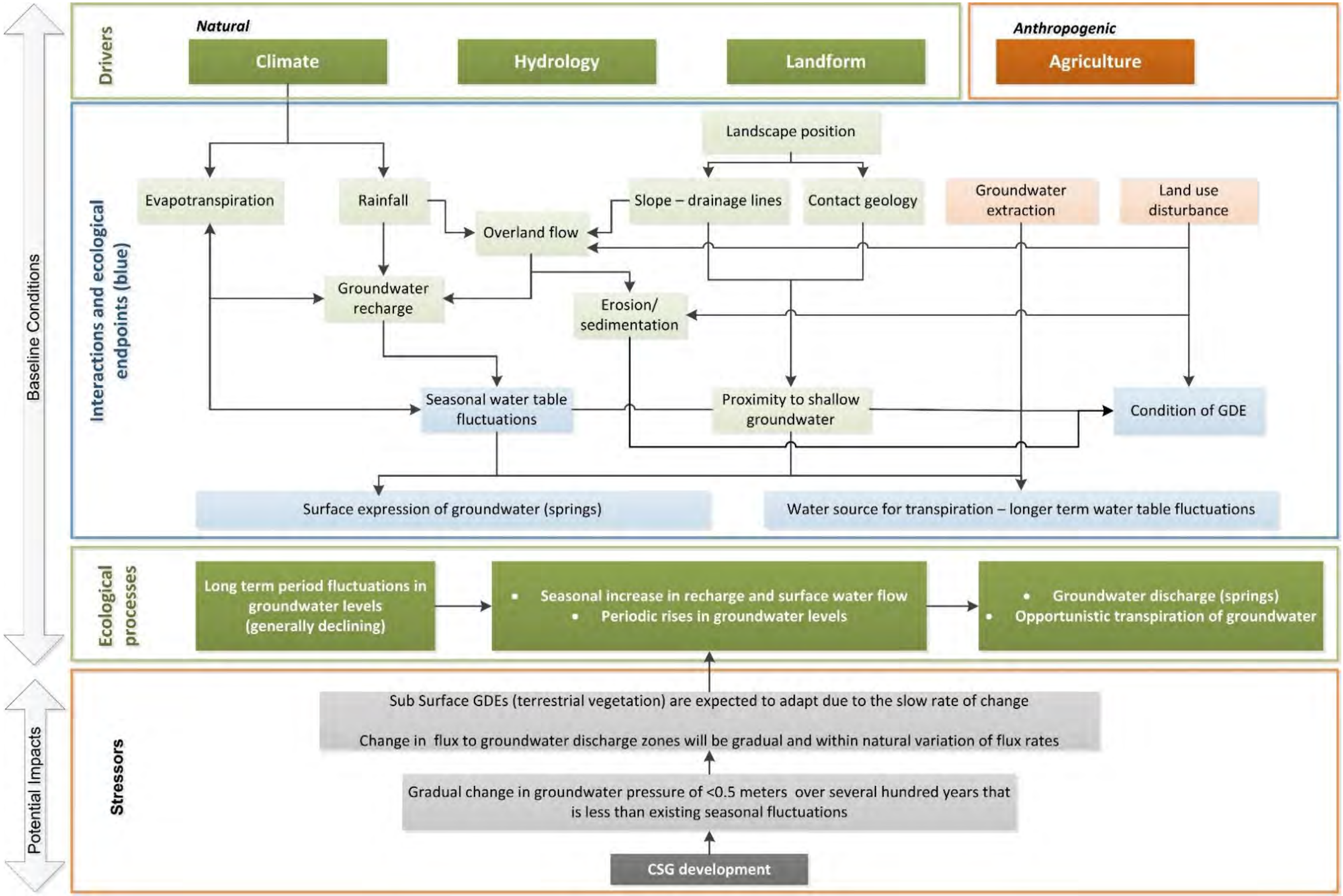


**Figure 5-3 Driver and Stressor conceptual model for Type 3 GDEs**

### 5.2.1 Summary of GDE assessment framework

The approach adopted for the GDE assessment (Section 3) is based upon recommendations made within the GDE toolbox (Richardson et al. 2011). Information collated and described for this report and by Eco Logical (2016c) has enabled each stage of the GDE framework (Figure 5-4) to be addressed.

The current groundwater regime is characterised by seasonal fluctuations and longer-term variation in the depth to the water table. A longer-term decline in groundwater levels is also evident due to a combination of drier climate and existing groundwater extraction.

Potential drawdown at the water table from the project is predicted to be less than 0.5 m in the alluvial groundwater sources and Pilliga Sandstone, and would occur gradually over hundreds of years (CDM Smith 2016a). Within this context, it is anticipated that the potential impacts on GDEs due to potential drawdown of the water table and hydraulic head would be minimal and within the existing (natural and anthropogenic influenced) range of variation; this includes GDEs reliant on groundwater sourced from the water table in the alluvium or Pilliga Sandstone, from artesian water in the Pilliga Sandstone, and from water perched at the contact of the Pilliga Sandstone and Pulawaugh Formation.

In relation to Type 3 GDEs, the potential impacts of the project are assessed to be well within the natural variation of water table elevation and hydraulic head. Terrestrial vegetation communities have evolved to cope with larger fluctuations of water table than predicted from the project and have additional water sources from rainfall recharge and overland flow.

Overall, it is anticipated that a small and gradual decline (and recovery) in groundwater pressure over an 800-year period, as predicted by the groundwater modelling, would have no measureable or meaningful impacts on the water requirements of the GDEs identified in the GDE study area.

| Question | | Outcome |
|---|---|---|
| **Level 1 – Basic conceptualisation** | | |
| Has the hydrogeological setting been established? | Yes | Conceptualisation of the interaction between the GW and surface systems is established.<br>Numerical groundwater model describing the hydrogeological processes exists. |
| Has the location of the groundwater dependent ecosystem been established? | Yes | GDEs reliant on the surface expression are mapped and field evaluated<br>GDEs reliant on the subsurface expression are mapped, with no field evaluation.<br>No Cave and Aquifer GDEs were identified through field evaluation. |
| Has the registered value of the GDEs been established? | Yes | All registered values have been assigned to mapped GDEs. |
| **Level 2 – Verification of the susceptibility of the vegetation to changes in GW, what degree of changes in groundwater may potentially impact** | | |
| Has the temporal nature of the groundwater connection been established. | Yes | The temporal nature of groundwater in the water table aquifer is established through groundwater monitoring.<br>*Less certain is the understanding in the variability in the rooting depth of the vegetation and its capacity to draw upon the water table as a water source.* |
| Has the dominant influence on the groundwater system been established? | Yes | The overall water budget (recharge to discharge) of the groundwater system and impact of CSG established through modelling.<br>The nature of recharge and fluctuations in the water table are observed within existing groundwater monitoring. |
| **Level 3 – Understanding the response of vegetation to changes in GW regime** | | |
| Has the critical service provided by the groundwater system been identified and how might they be impacted? | Partially | Assumption have been made regarding the likely interaction between groundwater and terrestrial vegetation, therefore the likely impact is made upon assumptions. |
| Have the threats to the groundwater system been established? | Yes | The impacts to the GW system are established through a Stressor and Driver diagram.<br>The impact of CSG activities on the groundwater system has been modelled, with the impact of non-CSG extraction and climate change observed through existing GW monitoring. |
| How has/might the current ecosystem change if the groundwater discharge changes? | Yes | Maximum drawdown of the water table elevation and hydraulic head in the source aquifers for surface and subsurface GDEs is predicted to be less than 0.5 m, with very slow change over hundreds of years.<br>These potential impacts are expected to be indiscernible relative to the existing variations in groundwater pressure due to climate patterns and extractive uses. |

**Figure 5-4 Summary of GDE assessment framework (Richardson et al. 2011)**

# Section 6 Risk Assessment

## 6.1 Methods

The risk assessment is undertaken in accordance with the GDE risk assessment guidelines (Serov et al. 2012) and includes the following tasks:

- Identification of proposed activities associated with the development of the Narrabri Gas Project and locations of the proposed activities with respect GDEs (CDM Smith 2016a)
- Assessment of the potential impacts of the proposed activities on groundwater and associated GDEs (Section 6.2), including the work completed by Eco Logical (2016c)
- Assessment of the magnitude of risk from the proposed activities on the ecological values of aquifers and associated GDEs (Section 6.3).

### 6.1.1 Determining the potential impacts to GDEs

The proposed project activities are assessed with respect to their potential impacts on five main aquifer assets (Serov et al. 2012) as follows:

- Water quantity impacts -
  - Will there be alterations to the water table elevation, aquifer flow paths, aquifer discharge volumes, or frequency or timing of water table fluctuations?
  - Will there be an alteration of groundwater base flow to rivers?
  - Will there be reductions in artesian water pressure or spring flows?
- Water quality impacts -
  - Will there be alterations to the existing groundwater chemistry or chemical gradients?
  - Will there be alterations in nutrient loads, sediment loads, salinity levels, groundwater temperatures or heavy metals?
- Aquifer integrity impacts -
  - Will substrate alteration occur through compaction?
  - Will cracking or fracturing of bedrock occur?
- Biological integrity impacts -
  - Will there be alterations to the number or composition of native species within the groundwater dependent communities?
- Exotic flora or fauna impacts -
  - Will there be removal or alteration of a GDE type or subtype habitat?

### 6.1.2 Determining the level of risk to GDEs

The magnitude of potential risk to each aquifer and GDE is assessed using a risk management matrix that considers the characteristics of the GDE and the potential impact to the GDE as a result of the proposed activity. The likelihood and degree of threat to each aquifer and GDE are assessed and potential impacts are ranked as high, medium or low (Eco Logical 2016c).

The GDE risk assessment guidelines (Serov et al. 2012) specify that if the risk rating is unable to be quantified for greater than half (50%) of the potential impacts, then the risk is to be considered as high until proven otherwise. This requirement has been adopted within this assessment.

#### 6.1.2.1 Risk management matrix

The GDE risk assessment guidelines (Serov et al. 2012) developed a risk management matrix that identifies the level of management required to mitigate a risk, and the timeframe in which management needs to be implemented. The matrix is shown in Figure 6-1 and requires that the ecological value of a GDE and the level of risk posed to the GDE from a project activity are already established.

The risk management matrix consists of two axes; the vertical axis represents the level of ecological value of the GDE and the horizontal axis represents the level of potential risk to the GDE. For example, a moderate risk to a GDE with high ecological value would receive a risk rating "B".

The risk rating determined from the matrix is then translated into the management actions and timeframes listed in Table 6-1; these include short-term, mid-term and long-term actions.

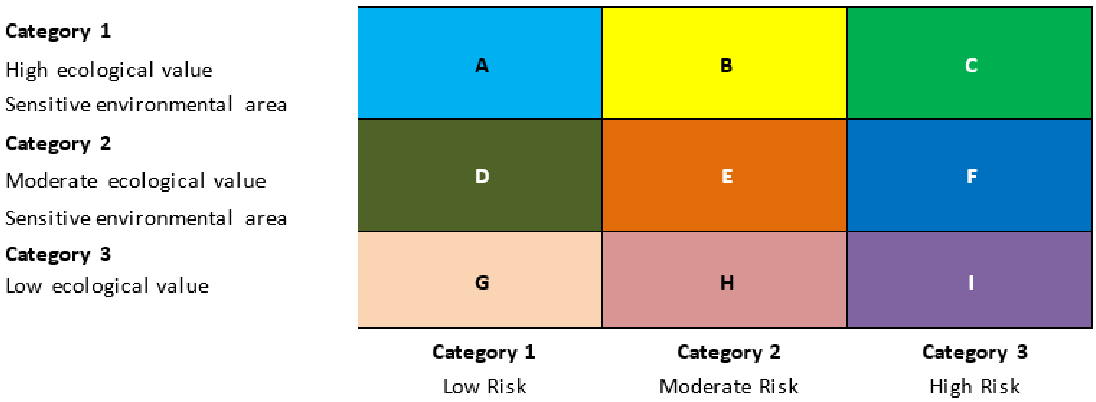


**Figure 6-1 Risk Matrix** (after Serov et al. 2012)

**Table 6-1 Recommended management actions and timeframes**

| Risk matrix score | Management action short term | Management action mid term | Management action long term |
|---|---|---|---|
| **A** high value low risk | Protection measures for aquifer and GDEs. Baseline risk monitoring. | Continue protection measures for aquifers and GDEs. Periodic monitoring and assessment. | Adaptive management. Continue monitoring. |
| **B** high value moderate risk | Protection measures for aquifer and GDEs. Baseline risk monitoring. Mitigation action. | Protection measures for aquifer and GDEs. Monitoring and periodic assessment of mitigation. | Adaptive management. Continue monitoring. |
| **C** high value high risk | Protection measures for aquifer and GDEs. Baseline risk monitoring. Mitigation. | Protection measures for aquifer and GDEs. Monitoring and annual assessment of mitigation. | Adaptive management. Continue monitoring. |
| **D** moderate value low risk | Protection of hotspots Baseline risk monitoring. | Protection of hotspots Baseline risk monitoring | Adaptive management. Continue monitoring. |
| **E** moderate value moderate risk | Protection of hotspots Baseline risk monitoring Mitigation action | Protection of hotspots. Monitoring and periodic assessment of mitigation. | Adaptive management. Continue monitoring. |
| **F** moderate value high risk | Protect hotspots Baseline risk monitoring. Mitigation action | Protect hotspots. Monitoring and annual assessment of mitigation. | Adaptive management. Continue monitoring. |
| **G** low value low risk | Protect hotspots (if any) Baseline risk monitoring | Protect hotspots (if any) Baseline risk monitoring | Adaptive management. Continue monitoring. |
| **H** low value moderate risk | Protect hotspots (if any) Baseline risk monitoring Mitigation action. | Protect hotspots (if any). Monitoring and periodic assessment of mitigation | Adaptive management. Continue monitoring. |
| **I** low value high risk | Protect hotspots (if any) | Protect hotspots (if any). | Adaptive management. Continue monitoring. |

## 6.2 Potential Impacts to GDEs

Groundwater modelling in the GIA (CDM Smith 2016a) predicts minor potential declines in groundwater pressure in the hydrostratigraphic units overlying the Purlawaugh Formation, including the Pilliga Sandstone that may provide the water sources for the potential GDEs identified in the GDE study area.

The predicted maximum declines in water table elevation and hydraulic head in the Namoi Alluvium and Pilliga Sandstone are less than 0.5 m, with the predicted decline and recovery of pressures occurring gradually over hundreds of years. Changes in groundwater pressure of this magnitude are not expected to be discernible relative to the existing effects from variability in climate and extractive use patterns.

Within this context, the potential impacts on water levels and pressures at GDE sites within the GDE study area are expected to be negligible to very small in magnitude and would occur very gradually.

## 6.3 Risk Assessment of Potential GDEs

This section brings together several existing risk assessments that are described in more detail in the reports referenced below:

- Risk assessment by Eco Logical (2016c) for nine potential Type 2 GDEs within the GDE study area that may be reliant on the surface expression of groundwater
- Risk assessment in this report of potential Type 3 GDEs that may be reliant on sub-surface expression of groundwater, including –
    - within the project area, detailed local-scale mapping of terrestrial vegetation communities and potential groundwater dependence by Eco Logical (2016a)
    - outside of the project area, national-scale assessment of potential groundwater dependence in the GDE atlas.

The following sections provide summaries of the outcomes of these GDE risk assessments.

### 6.3.1 Likelihood of Impacts to Potential GDEs

The prediction of the likelihood of impact to each potential GDE is determined via a series of questions with a choice of answers; likely, unlikely or insufficient data.

The detailed likelihood assessments for potential Type 2 and Type 3 GDEs are provided in Appendix B (Eco Logical 2016c) and Appendix C, respectively.

A summary of the likelihood of impacts to potential Type 2 GDEs can be seen in Table 6-2. The assessment indicates that impacts to potential GDEs are unlikely as a result of maximum predicted pressure decline in the source aquifers of less than 0.5 m head change, occurring over hundreds of years.

The summary of the likelihood of impacts to potential Type 3 GDEs is provided in Table 6-3. As above, the assessment indicates that impacts to potential GDEs are unlikely in response to maximum predicted pressure decline in the source aquifers of less than 0.5 m head change that would occur over hundreds of years.

### 6.3.2 Risk to Potential GDEs

The risk matrix from the GDE risk assessment guidelines (Serov et al. 2012) is presented with the prediction of the probability of impact to each potential GDE. Changes to a GDE are predicted based on a series of questions with answer choices of likely, unlikely or insufficient data.

A summary of the risk of impacts at sites of Potential Type 2 GDEs, which may be reliant on the surface expression of groundwater is provided in Table 6-4. The assessment indicates that the overall risk to the GDEs by predicted change in water table elevation of less than 0.5 drawdown over an 800-year period is low. The detailed risk assessments for potential Type 2 is included as Appendix B (Eco Logical 2016c)

The summary of the risk of impacts for potential Type 2 GDEs, which may be reliant on the sub surface expression of groundwater can be seen in Table 6-5. The assessment indicates that the overall risk to the GDEs by the impact of predicted change in water table elevation of less than 0.5 drawdown over an 800-year period is low. The detailed risk assessments for potential Type 3 GDEs is included as Appendix C.

**Table 6-2 Likelihood of impacts on potential Type 2 GDEs**

| Site | Summary of likelihood of impact | Valuation score |
|---|---|---|
| 12 | It is considered likely, based on the results of the GIA (CDM Smith 2016a) that there would be some alteration to water levels in the Pilliga Sandstone, although this is predicted to be less than 0.5m drawdown and would be felt gradually over hundreds of years. This magnitude of change is considered to be negligible compared to the natural variation in water level and pressure. All other risks are considered to be unlikely. | Unlikely |
| 65 | Small reduction in artesian pressure within the Pilliga Sandstone is possible based on a predicted maximum impact of less than 0.5m drawdown, which would be felt gradually over hundreds of years. This level of change is considered to be negligible compared to the natural variation in water level and pressure. All other impacts are considered to be unlikely. | Unlikely |
| 980 | Predicted impacts to the alluvial groundwater source are considered to be negligible and would not impact GDEs. | Unlikely |
| Eather Spring | It is considered likely that there would be some alteration to water levels in the Pilliga Sandstone, although this is predicted to be less than 0.5m drawdown with very gradual change over hundreds of years. All other risks are considered to be unlikely. | Unlikely |
| Hardys Spring | It is considered likely that there would be some alteration to water levels in the Pilliga Sandstone, although this is predicted to be less than 0.5 m drawdown with very gradual change over hundreds of years. All other risks are considered to be unlikely. | Unlikely |
| Mayfield Spring | It is considered likely that there would be some alteration to water levels in the Pilliga Sandstone, although this is predicted to be less than 0.5 m drawdown with very gradual change over hundreds of years. All other risks are considered to be unlikely. | Unlikely |
| Teds Hole | The GDE might be impacted by potential changes to natural groundwater chemistry and/or chemical gradients due to proximity to the proposed Bohena Creek managed release scheme; however, the discharges would be managed to minimise potential impacts through releasing to a creek flowing at greater than 100 ML/day (Eco Logical 2016d). This might affect groundwater salinity levels in the Bohena Creek Alluvium. All other risks are considered to be unlikely. | Unlikely |
| Well Ford | It is considered likely that there would be some alteration to water levels in the Pilliga Sandstone, or to groundwater pressure if the aquifer is confined or artesian; however, this potential impact is predicted to be less than 0.5 m and would occur gradually over hundreds of years. All other risks are considered to be unlikely. | Unlikely |
| Drysdale | It is considered likely that there would be some alteration to water levels in the Pilliga Sandstone, or to groundwater pressure if the aquifer is confined or artesian; however, this potential impact is predicted to be less than 0.5 m and would occur gradually over hundreds of years. All other risks are considered to be unlikely. | Unlikely |

**Table 6-3 Likelihood of impacts on potential Type 3 GDEs**

| Potential Type 3 GDE | Summary of predicted likelihood of impact | Valuation score |
|---|---|---|
| Within the project area, based on 1:10,000 vegetation mapping[1] (Eco Logical 2016a) | It is considered likely, based on the results of the GIA (CDM Smith 2016a) that there would be some alteration to the water table, although this is predicted to be less than 0.5 m drawdown with very gradual change over hundreds of years. This potential change is considered to be negligible compared to the natural variation in water level and pressure. All other risks are considered to be unlikely. | Unlikely |
| Outside of the project area, based on GDE atlas[2] | It is considered likely, based on the results of the GIA (CDM Smith 2016a) that there would be some alteration to the water table, although this is predicted to be less than 0.5 m drawdown with very gradual change over hundreds of years. This potential change is considered to be negligible compared to the natural variation in water level and pressure. All other risks are considered to be unlikely. | Unlikely |

[1]Rough-barked Apple – red gum – cypress pine woodland, Red gum – Rough-barked Apple +/- tea tree sandy creek woodland, Fuzzy Box Woodland), River Red Gum riparian tall woodland / open forest wetland and Carbeen - White Cypress Pine – Curracabah – White Box tall woodland; [2]*Eucalyptus fibrosa* (Red Ironbark), *Callitris* (Cypress Pine), *Casuarina luehmannii* (Bulloak), *Eucalyptus crebra* (Narrow leaved Ironbark), *Eucalyptus blakelyi* (Red Gum) and *Angophora floribunda* (Rough barked apple tree)

**Table 6-4 Summary of predicted risk at sites of potential Type 2 GDEs**

| Site | Risk assessment comments | Overall risk score |
|---|---|---|
| 12 | Potential impacts to the Pilliga Sandstone aquifer that are predicted in the GIA are less than seasonal variations. All criteria are scored as low risk. | Low |
| 65 | Predicted impacts to groundwater pressure in Pilliga Sandstone aquifer are considered to be less than seasonal variations. All criteria are scored as low risk. | Low |
| 980 | Predicted impacts to the Quaternary alluvium are considered to be significantly less than seasonal variation. | Low |
| Eather Spring | Predicted impacts to the Pilliga Sandstone aquifer are demonstrated in the GIA to be less than seasonal variations. Identified as a farm dam. All criteria are scored as low risk. | Low |
| Hardys Spring | Predicted impacts to the Pilliga Sandstone aquifer are demonstrated in the GIA to be less than seasonal variations. Identified as a farm dam. All criteria are scored as low risk. | Low |
| Mayfield Spring | Predicted impacts to the Pilliga Sandstone aquifer are demonstrated in the GIA to be less than seasonal variations. Identified as a farm dam). All criteria are scored as low risk. | Low |
| Teds Hole | There may be negligible changes to the groundwater quality at Teds Hole downstream of the proposed Bohena Creek managed release site. The Managed Bohena Creek Release Study (Eco Logical 2016d) provides a detailed assessment of risk associated with the managed release scheme indicating impacts are considered to be negligible. | Low |
| Well Ford | Predicted impacts to the Pilliga Sandstone aquifer are considered to be less than seasonal variations. All criteria are scored as low risk. | Low |
| Drysdale | Predicted impacts to groundwater pressure in Pilliga Sandstone aquifer are considered to be less than seasonal variations. All criteria are scored as low risk. | Low |

**Table 6-5 Summary of predicted risk for potential Type 3 GDEs**

| Type 3 GDE | Summary of predicted risk of impact | Valuation score |
|---|---|---|
| Within the project area, based on 1:10,000 vegetation mapping[1] (Eco Logical 2016a) | It is considered likely, based on the results of the GIA (CDM Smith 2016a) that there will be some alteration to the water table, although this is predicted to be less than 0.5m drawdown that will occur gradually over an 800-year period. This change is considered to be negligible compared to the natural variation in water level and pressure. | Low |
| Outside of the project area, based on GDE atlas[2] | It is considered likely, based on the results of the GIA (CDM Smith 2016a) that there will be some alteration to the water table, although this is predicted to be less than 0.5m drawdown occurring gradually over an 800-year period. This change is considered to be negligible compared to the natural variation in water level and pressure. | Low |

[1]Rough-barked Apple – red gum – cypress pine woodland, Red gum – Rough-barked Apple +/- tea tree sandy creek woodland, Fuzzy Box Woodland, River Red Gum riparian tall woodland / open forest wetland and Carbeen - White Cypress Pine – Curracabah – White Box tall woodland; [2]*Eucalyptus fibrosa* (Red Ironbark), *Callitris* (Cypress Pine), *Allocasuarina luehmannii* (Bulloak), *Eucalyptus crebra* (Narrow leaved Ironbark), *Eucalyptus blakelyi* (Red Gum) and *Angophora floribunda* (Rough barked apple tree)

# Section 7 Management and Mitigation

The GDE risk assessment guidelines (Serov et al. 2012) specify that management strategies are required to maintain or improve the ecological value of a GDE and reduce the level of risk to the aquifer and associated GDE.

The management measures recommended for each GDE can be identified through assessments of the ecological value of the GDE and the potential risk to the source aquifer and GDE as a result of the proposed development activities. This approach to assessing the potential management requirements for GDEs is described in Section 6.1.2.

The GDE risk assessment guidelines (Serov et al. 2012) recommend adaptive management for all GDEs regardless of their ecological value or risk rating. Changes to the monitoring, management and mitigation actions for each GDE might be required as a result of observed responses of the GDEs to development activities once implemented.

Mitigation measures are defined as being different to management actions, in that they are additional measures for managing short-term or localised impacts (Serov et al. 2012). Mitigation measures might be required dependent on the risk category of a GDE or when an activity has had a measurable impact and requires immediate action.

Where a GDE is defined as a High Priority GDE within a Water Sharing Plan, the Water Sharing Plan rules for protecting the High Priority GDE must be adhered to.

## 7.1 Risk Categorisation

Using the methods and risk management matrix recommended in the GDE risk assessment guidelines (Serov et al. 2012) and applied within the GDE study area:

- All nine potential Type 2 GDEs that may be reliant on the surface expression of groundwater are assessed to have -
    - Low Ecological Value (Category 3) – they are highly modified from natural state, and have no rare, threatened or unique species or unique abiotic features
    - Low Risk (Category 1) - minor to no discernible impact is predicted, resulting in no change or minor change to the aquifer or associated GDEs
    - Overall risk category G – they have low value and the assessed risk is low.
- The two potential Type 3 GDE that may be reliant on the sub-surface expression of groundwater are assessed to have –
    - High Ecological Value (Category 1) – they are sensitive environmental areas with high conservation value
    - Low Risk (Category 1) - minor to no discernible impact is predicted, resulting in no change or minor change to the aquifer or associated GDEs
    - Overall. risk category A - they have high value but the assessed risk is low.

## 7.2 Recommended Management Strategy

For potential Type 2 GDEs that are assessed as having overall risk category G (low value/low risk) the management actions recommended in the GDE risk assessment guidelines (Serov et al. 2012) are to (Table 6-1):

- short term and mid-term, protect hotspots (if any) and conduct baseline risk monitoring if required
- long-term, adaptive management and continued monitoring if required.

On the basis of these recommendation, no need for mitigation actions for potential Type 2 GDEs is identified at this time.

For potential Type 3 GDEs that are assessed as having overall risk category A (high value/low risk) the short-term management actions recommended in the GDE risk assessment guidelines (Serov et al. 2012) are to:

- provide protective measures for the source aquifers and GDEs
- undertake baseline risk monitoring.

Within this context, it is necessary to consider the magnitude of the potential impact on groundwater pressure, which is predicted to be less than 0.5 m decline in water table elevation, with subsequent recovery over hundreds of years. A shift of such small magnitude over such a long period of time is less than the expected 'background' variations in groundwater pressure due to climate patterns and extractive uses of groundwater, and would be difficult (if not impossible) to measure or monitor. On this basis, no need for protective measures for Type 3 GDEs is identified at this time.

## 7.3 Adaptive Management

The proponent is currently collecting baseline environmental and water data that would be used as reference data for assessing potential impacts of the project should it proceed. In the course of conducting the baseline monitoring, it is possible that additional hydrogeological data will become available, which might change the current conceptualisation of GDEs and their ecological values. Furthermore, a number of GDEs have not been visited. Further evidence that may become available after future site investigations might also change the current conceptualisation of GDEs and their ecological values.

The location and construction of future surface assets, such as well pads, pipelines, water treatment facilities and access roads should avoid, where possible, impacting on the locations of potential GDEs.

## 7.4 Water Monitoring Plan

The proponent has designed an integrated groundwater monitoring network that includes monitoring of the GDE source aquifers as a key feature. Given the low risk to potential Type 2 and Type 3 GDEs identified in this study, monitoring at specific GDE locations is not required.

Monitoring of groundwater level would be undertaken at a number of locations targeting the alluvial and Pilliga Sandstone aquifers, which are identified as the source aquifers for all potential GDEs identified within the GDE study area.

Further information is available in the Water Monitoring Plan for the NGP (CDM Smith 2016b) including details of the early detection system, trigger and threshold values for groundwater monitoring, and associated management actions in the advent that trigger and threshold values are exceeded.

# Section 8 Conclusions

This report aims to fulfil the New South Wales Government Director General's Environmental Assessment Requirements to consider whether depressurisation for coal seam gas production would have a significant impact on the environment, with specific reference to potential impacts on groundwater dependent ecosystems (GDEs).

The assessment approach adopts the methods described within the GDE toolbox (Richardson et al. 2011) and DPI Water's GDE risk assessment guidelines (Serov et al. 2012). The assessment also draws on the recommendations of the Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Projects (IESC 2015) in relation to the expected requirements for assessing water-related ecological responses to coal seam gas extraction.

Potential Type 2 and Type 3 GDEs that may rely on surface and sub-surface expressions of groundwater are identified in the study, whereas no Type 1 GDEs (stygofauna and aquifers) with potential to be impacted by the project are identified in the GDE study area.

In relation to potential Type 2 GDEs that may be reliant on surface expression of groundwater the following conclusions are made in this assessment:

- There are no known groundwater-dependent protected species or habitats in the GDE study area.
- There are nine potential Type 2 GDEs considered likely to be dependent on groundwater.
- All potential Type 2 GDEs are assessed to have low ecological values, mainly due to the absence of protected or important wetland species, and due to the heavily or moderately modified nature of the sites.
- None of the potential Type 2 GDEs meet the definition of a high-priority GDE in NSW, and therefore they fall outside of the minimal impact considerations of the NSW Aquifer Interference Policy.
- None of the potential Type 2 GDEs support Matters of National Environmental Significance (MNES) defined under the EPBC Act.
- All nine potential Type 2 GDEs have water sources derived from either the Pilliga Sandstone aquifer or alluvial aquifers. At least two of the potential GDEs derive their water sources from pre-existing bores flowing freely to the land surface under artesian pressure.
- Maximum drawdown of the water table elevation and hydraulic head in the source aquifers for potential Type 2 GDEs is predicted to be less than 0.5 m, with very slow change over hundreds of years (CDM Smith 2016a). These potential impacts are expected to be indiscernible relative to the existing variations in groundwater pressure due to climate patterns and extractive uses.
- The overall risk assessment score for all nine potential Type 2 GDEs is low.
- No mitigation or specific management measures are required for potential Type 2 GDEs based on the outcomes of the risk assessment. Adopting the principle of adaptive management, the proponent would review the conceptual hydrogeology at each GDE if additional relevant data became available through monitoring or field investigation.

- For GDEs with low ecological values and low risk, the GDE risk assessment guidelines (Serov et al. 2012) recommend continued long-term monitoring. The proponent is committed to monitoring groundwater level and pressure within its groundwater monitoring network through the NGP Water Monitoring Plan (CDM Smith 2016b).

In relation to potential Type 3 GDEs that may be reliant of the sub-surface expression of groundwater the following conclusions are made in this assessment:

- The Type 3 GDEs identified in this assessment are categorised as potential GDEs based on absence of field data to verify if the vegetation uses groundwater.
- Potential dependence on groundwater is identified based on detailed local-scale (1:10,000) vegetation mapping by Eco Logical (2016a) within the project area, and the GDE atlas outside of the project area.
- Two vegetation communities listed as endangered under the TSC Act are identified as potential Type 3 GDEs within the project area; these being located predominantly in riparian areas of Bohena Creek and its tributaries.
- Potential Type 3 GDEs source groundwater predominantly from the water table; however, they are also able to source soil water from rainfall recharge and surface flow events within alluvial settings.
- Predicted drawdowns in the source aquifers due to the project are less than 0.5 m and occur very slowly over hundreds of years, resulting in negligible predicted impacts on GDEs.
- The overall risk assessment score for potential Type 3 GDEs is low, based on high ecological values but low likelihoods of potential impacts.
- No mitigation or specific management measures are required for potential Type 3 GDEs identified in the GDE study area based on the outcomes of the risk assessment. Adopting the principle of adaptive management, the proponent would review the conceptual hydrogeology at each GDE if additional relevant data became available through monitoring, drilling, or other field investigation.
- For potential Type 3 GDEs with low risk and low ecological values, the GDE risk assessment guidelines (Serov et al. 2012) recommend continued long-term monitoring. The proponent is committed to monitoring groundwater level and pressure within their groundwater monitoring network through the Water Monitoring Plan for the NGP (CDM Smith 2016b).

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