Assessment of impacts of the proposed coal seam gas operations on surface and groundwater systems in the Murray-Darling Basin.

Prepared by:  Professor Chris Moran, Dr Sue Vink  
Centre for Water in the Minerals Industry  
Sustainable Minerals Institute  
The University of Queensland  

Commenced: 14 October 2010  
Final report: 29 November 2010
Disclaimer:
The views and opinions expressed in this publication are those of the authors and do not necessarily reflect those of the Australian Government or the Minister for Sustainability, Environment, Water, Population and Communities.

While reasonable efforts have been made to ensure that the contents of this publication are factually correct, the Commonwealth does not accept responsibility for the accuracy or completeness of the contents, and shall not be liable for any loss or damage that may be occasioned directly or indirectly through the use of, or reliance on, the contents of this publication.
Contents

List of Tables ........................................................................................................ iv
List of Figures ......................................................................................................... iv
1 Executive Summary ............................................................................................. 1
2 Purpose .................................................................................................................. 6
   2.1 Scope of work .................................................................................................... 6
   2.2 This report ........................................................................................................ 6
3 Background and Context ..................................................................................... 7
   3.1 Coal Seam Gas Development ......................................................................... 11
4 Murray Darling Basin ........................................................................................... 13
   4.1 Setting ............................................................................................................. 13
5 Conceptual model of flows and processes ........................................................... 15
   5.1 MDB Surface waters ....................................................................................... 18
      5.1.1 Imports ..................................................................................................... 19
      5.1.2 Exports ..................................................................................................... 19
      5.1.3 Hydraulic Interactions with Groundwater ................................................ 19
      5.1.4 Water quality ............................................................................................ 21
   5.2 MDB Alluvial Aquifers .................................................................................... 22
      5.2.1 Imports ..................................................................................................... 23
      5.2.2 Exports ..................................................................................................... 23
      5.2.3 Hydraulic interactions ............................................................................... 23
      5.2.4 Water Quality ........................................................................................... 27
6 Assessment of Impacts on Surface and Groundwater in the MDB ..................... 29
   6.1 System Interactions: processes and significance ............................................ 29
      6.1.1 Significant Changes and/or local impact .................................................. 31
      6.1.2 Intermediate Changes ............................................................................. 32
      6.1.3 Minor Changes ........................................................................................ 34
      6.1.4 No changes ............................................................................................... 35
   6.2 Groundwater Impacts ..................................................................................... 36
      6.2.1 Groundwater Quantity .......................................................................... 37
      6.2.2 Groundwater water quality ................................................................... 44
   6.3 Surface water changes ................................................................................... 44
      6.3.1 Surface water quantity .......................................................................... 44
      6.3.2 Surface water quality ............................................................................. 45
   6.4 Mitigation activities ......................................................................................... 47
7 Discussion ............................................................................................................ 48
   7.1 Regional Impact .............................................................................................. 49
   7.2 Local impacts .................................................................................................. 50
   7.3 Gaps ................................................................................................................ 52
8 References .......................................................................................................... 54
9 Appendix 1: Terms of Reference ...................................................................... 55
10 Appendix 2: CSG Proponent Groundwater Modelling for assessing impacts on groundwater ........................................................................................................... 57
List of Tables

Table 1. Summary of CSG tenements within the boundary of the MBD.................................11
Table 2. Processes of water recharge, discharge and redistribution under pre- and post-CSG. .........................................................................................................................17
Table 3. Summary of water quality parameters ..........................................................................................................................22
Table 4. Water balance for the Central Condamine Alluvium.........................................................24
Table 5. Comparison of water quality of Central Condamine Alluvium, Walloon Coal Measures and Marburg Sandstone ............................................................................28
Table 6. Processes of water recharge, discharge and redistribution post-CSG..................30
Table 7. Summary of predicted drawdown for aquifers .............................................................43

List of Figures

Figure 1. Alluvial extent and CSG tenements. .............................................................................9
Figure 2. Location of CSG wells in the study area........................................................................10
Figure 3. Simplified stratigraphic sequence and corresponding aquifers and confining units in the study area .................................................................................................14
Figure 4. Conceptual diagram of the water balance for surface and groundwaters in the study...............................................................................................................................16
Figure 5. Location of the Murray Darling Basin, major catchments and coal seam gas tenements.........................................................................................................................18
Figure 6. Gaining and losing stream reaches of the MDB..........................................................20
Figure 7. Location of thalweg and hydraulic basement highs in the Condamine Alluvium. ....26
Figure 8. Area of drawdown of the water table predicted by APLNG........................................40
Figure 9. Predicted drawdown area in the Gubberamunda Aquifer for APLNG project........41
Figure 10. Predicted drawdown area in the Springbok Sandstone for APLNG Project ..........42
1 Executive Summary

Context and Scope
This report was commissioned by Department of Sustainability, Environment, Water, Population and Communities on advice in a report by Geoscience Australia and Habermehl (2010) that the location and nature of current and proposed CSG activities in Queensland may trigger Section 255AA - Mitigation of unintended diversions - of the Commonwealth Water Act 2007. The scope of this study was to undertake a desktop study to determine the impacts of the proposed CSG operations on the connectivity of groundwater systems, surface water and groundwater flows and water quality in the Murray-Darling Basin.

Underlying the MDB, the primary target of CSG development are the seams of the Walloon Coal Measures located in the Surat/ Clarence Morton Basins. In order to extract gas, the hydrostatic pressure must be reduced by pumping water from cleats in the coal seams so that gas is desorbed from the coal pores. This dewatering has been predicted to result in drawdown of water levels in overlying and underlying aquifers in the region during CSG production.

The scope of this study included rivers, streams and associated alluvial aquifers in the MDB. The spatial coverage defined as alluvium was supplied by the government and covers an area of 172,898 km$^2$. Assessment was restricted to CSG activities on this area. Although the Great Artesian Basin aquifers are not part of the MDB surface water management area, the impacts of dewatering of the Walloon Coal Measures on these aquifers may also impact alluvial aquifers, in particular the Condamine Alluvium. Given the spatial extent of CSG activities the primary focus of the report was the Condamine-Balonne River system and Central Condamine Alluvium. The Condamine River and the alluvium have been extensively used as water resource for agriculture. No data have been made available to examine the possible implications of hydrocarbons, eg, BTEX, in associated water. Engineering solutions for surface water storage, water treatment facilities and consequential brine management were not examined.
As of November 2010, there were 105 tenements in the MDB with a total area of 18,903 km$^2$. The area of alluvial extent within these tenements is 4,130 km$^2$. Arrow Energy and QGC have the highest proportion of alluvium in their tenements.

**Assessment of impacts on MDB surface and groundwater systems**

A conceptual diagram of flows and processes driving flows in the system was constructed. Imports, exports and hydraulic interactions between the system components were reviewed. Changes to the processes controlling water flows and interactions as a result of CSG activity were categorised according to the relative significance of change and/or local risk. Four interactions are identified as creating significant changes and/or local impacts. Three interactions are categorised as intermediate, six as minor and eight with no changes.

<table>
<thead>
<tr>
<th>From</th>
<th>Surface water</th>
<th>Groundwater</th>
<th>Mixed S/G</th>
<th>Other uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers</td>
<td>14. recharge from losing streams</td>
<td>15. recharge from losing streams into outcrop intake beds</td>
<td>16. recharge from losing streams into outcrop intake bed</td>
<td>12. crops, forestry, municipal</td>
</tr>
<tr>
<td>Alluvium</td>
<td>17. discharge (gaining streams)</td>
<td>3. redistribution potentially with water quality change</td>
<td>7. redistribution potentially with water quality change</td>
<td>10. redistribution potentially with water quality change</td>
</tr>
<tr>
<td>WCM</td>
<td>1. discharge of associated water (with treatment if required)</td>
<td>2. reinjection of co-produced water via surface bores</td>
<td>8. reinjection of co-produced water via surface bores</td>
<td>6. reinjection of co-produced water via surface bores</td>
</tr>
<tr>
<td>GAB</td>
<td>11. discharge (gaining streams)</td>
<td>9. redistribution potentially with water quality change</td>
<td>4. redistribution potentially with water quality change</td>
<td>redistribution potentially with water quality change</td>
</tr>
<tr>
<td>Other Uses</td>
<td>Discharge (Municipal effluent)</td>
<td>recharge (Drainage below root zone)</td>
<td>recharge (Drainage below root zone)</td>
<td></td>
</tr>
</tbody>
</table>

Blue = significant and/or local risk; Green = intermediate changes; Yellow = minor changes; White = no change.
**MDB Surface waters**

The Upper Condamine River is a losing stream (water moves from the stream to recharge aquifers) under which groundwater is already significantly depleted and currently not connected to the stream. Flow is therefore unlikely to be changed by further drawdown of water level in the alluvium as a result of CSG extraction. Below the Chinchilla Weir, flow in the Condamine River may be increased by discharge of treated associated water (permeate). Modelling of stream flow by one proponent (APLNG, 2010) suggested that permeate discharge could be managed to meet environmental flow requirements and not significantly affect water quality. Permeate discharge proposed by APLNG could return on the order of 2-17% of pre-development flows to the River. QGC and Santos have investigated disposal of treated associated water to streams as an option, currently this is not the preferred option for Santos (QGC, 2010, Vol 3 Ch. 11; Santos, 2010, Appendix Q). If more than one proponent discharges to the Condamine River, an assessment will required to determine the cumulative impact of discharges from multiple proponents. This assessment will need to consider the physical and ecological implications of changes to water quantity and quality and account for the timing of discharge.

Mitigation strategies proposed by the proponents should minimise the risk of water quality compromise to surface waters due principally to potential sediment production from construction activities (APLNG, 2010, Vol 5 Att. 22; QGC, 2010, Vol. 3 Ch.9; Santos, 2010, Section 6.5).

**Alluvial Aquifer**

Hydraulic connectivity between the Central Condamine Alluvium and both the Walloon Coal Measures and some GAB aquifers has been demonstrated by analysis of bore water levels and water quality data (KCB, draft in review; Hillier, 2010). Current hydraulic relationships between the alluvium and the underlying units may be altered by dewatering of the coal measures. Loss of water availability from the Central Condamine Alluvium due to direct or indirect induced leakage caused by dewatering of the coal seams could not be separately assessed due to lack of sufficiently detailed numerical model outputs and measurements from current operations. Drawdown of the water table was predicted to be ~2 m on average by one of the proponents (APLNG, 2010, Vol. 5 Att. 21). The predicted drawdown area was
not expected to extend appreciably beyond the current tenement boundaries. Thus only a small area of the Central Condamine Alluvium was predicted by proponents to be affected by CSG activities.

The area of maximum drawdown of the water table (5-7m) is restricted to a small area around Miles and immediately downstream of the Chinchilla Weir (APLNG, 2010, Vol. 5 Att. 21). One water bore user was identified as likely to be affected by water table drawdown in these areas (APLNG, 2010, Vol. 5 Att. 21).

Water quality in the Central Condamine Alluvium is most likely to be affected by redistribution of water within the alluvium in response to aquifer drawdown because net movement of water is into the coal measures as a result of dewatering. Water quality in the alluvium is heterogeneous and in some areas varies considerably between bores. While the movement of water within the alluvium will not likely change water quality over a wide spatial extent it may impact individual bore holders.

Reinjection of treated associated water into aquifers may lessen the impact of drawdown created by dewatering of the coal seams. A significant amount of further technical work is required to determine appropriate reinjection targets, timing and water quality/treatment needs.

Subsidence effects due to aquifer compaction were predicted by all proponents to be minor (APLNG, 2010, Vol. 5 Att. 21; QGC, 2010, Vol 3 Ch. 10; Santos, 2010, Appendix P1). However, even small changes to the land surface due to subsidence may alter overland flow paths initiating new erosion features in susceptible areas. Additionally, subsidence may also change or cause fracturing in aquifers which may alter the hydraulic connectivity.

Current predicted drawdown of the Condamine Alluvium by CSG proponents suggest that the drawdown of the alluvial aquifer due to CSG activity is likely to be considerably smaller than the drawdown that has occurred over recent decades due to water extraction for agricultural purposes. None-the-less there are significant gaps in knowledge of the system and the numerical models currently being used to assess likely impacts.
**Gaps**

Localised drawdown effects are likely to be significantly different to the predicted regional average drawdown owing to the spatial variability in hydraulic connectivity between the coal measures and aquifers, rates of water movement, depth of the coal seam and the thickness confining layers. No proponents have considered the effect of faulting or fractures in their models. These preferential flow features can alter local drawdown. Data on hydraulic properties is scarce. More spatially explicit hydraulic data should be collected and incorporated into models on an on-going basis.

Targeted areas for monitoring and additional data on hydraulic properties should be prioritised. Ongoing validation of model predictions of drawdown and water production will provide insights into areas requiring better characterisation and/or additional monitoring. Water production data should also include water produced during exploration because this extraction will contribute to the water deficit of the system. It is not clear whether this is currently included in water production estimates and, if so, how.

Water quality analyses, including isotope tracers and dating of waters may aid in identification of changes to local hydraulic conditions. Changes in water types and salinity in the Central Condamine Alluvium in combination with analysis of water levels have been interpreted to be indicative of hydraulic exchange between the alluvium and underlying Walloon Coal Measures and sandstone aquifers. Incorporation of geochemical analysis into a monitoring program with water level monitoring may improve understanding of changes to aquifer interactions.

An adaptive management regime, supported by significant monitoring at the individual well level, with specific management actions stated upfront to cope with predictable localised effects should provide an acceptable mechanism for ongoing system control. Transparency of information and impact reporting provides a strong adjunct to adaptive management to assist community, government and industry to maximally benefit from the full range of resource uses available in the region.
2 Purpose

Professor C. J. Moran, on behalf of the Centre for Water in the Minerals Industry, was contracted by the Department of Sustainability, Environment, Water, Population and Communities (DSEWPAC) to conduct an independent expert study in relation to development of coal seam gas (CSG) industry in Queensland and potential for impacts on the Murray Darling Basin water flows. The need for this study was based on advice in a report by Geoscience Australia and Habermehl (2010) that the location and nature of current and proposed CSG activities in Queensland may trigger Section 255AA - Mitigation of unintended diversions - of the Commonwealth Water Act 2007.

Section 255AA of the Water Act 2007 states that:

“Prior to licences being granted for subsidence mining operations on floodplains that have underlying groundwater systems forming part of the Murray-Darling system inflows, an independent expert study must be undertaken to determine the impacts of the proposed mining operations on the connectivity of groundwater systems, surface water and groundwater flows and water quality”.

2.1 Scope of work

The scope of this study was to determine the impacts of the proposed CSG operations on the connectivity of groundwater systems, surface water and groundwater flows and water quality in the Murray-Darling Basin. Terms of References for the study are given in Appendix 1.

The study scope did not include analysis of engineering structures or solutions such as storage pond design, well completion techniques or brine management strategies.

2.2 This report

This report is the final deliverable for the project. The information assessed in this report was predominantly obtained from the Environmental Impact Statement (EIS) documents of three CSG proponents (APLNG, Santos and QGC), as well as a report prepared by Geoscience Australia (GA) (GA and Habermehl, 2010). Published literature and reports obtained from Queensland Department of Environment and Resource Management (DERM) were also reviewed. Technical data and information was requested from the CSG proponents and
science and data agencies within the Queensland and Commonwealth governments. To date, only data downloaded from the Queensland Government website (QPED) has been obtained. No information has been obtained from Arrow Energy Ltd.

Discussion of water quality is largely restricted in this report to consider salinity and major anion/cation composition. While there is a small amount of dissolved heavy metal and nutrient data reported in the proponent EIS documents it was not considered sufficiently spatially or temporally detailed to form an assessment. Analytical results for dissolved organic compounds (including BTEX) were not available for this report.

3 Background and Context
The preconditions for triggering the provisions of Section 255AA of the Commonwealth Water Act (2007) are that the activity must be:

- a subsidence mining operation;
- occur on a floodplain; and
- have potential to impact on Murray-Darling Basin (MDB) system inflows.

Based on advice in a report by Geoscience Australia (GA and Habermehl 2010), the location and nature of current proposed coal seam gas (CSG) developments in Queensland mean that the above preconditions may potentially be met and it is therefore prudent to commission an independent expert study in accordance with s255AA of the Water Act 2007 in order to inform government decision makers prior to approvals being granted. The independent expert sought advice from the Joint Liaison Committee for definition of the floodplain. A map of the extent of alluvial sediment in the Queensland Murray Darling Basin was supplied for this purpose.

Under the Commonwealth Water ACT 2007 this study is restricted to analysis and evaluation of CSG activities that are physically occurring on the floodplain and therefore does not consider activities in CSG tenements that are not overlying alluvium. Figure 1 shows the extent of alluvium in the Murray Darling Basin and location of CSG tenements. The total area of alluvium shown in Figure 1 is 172,898 km². Production schedules, proposed well locations during development of the fields, estimates of water production for individual
wells and detailed hydrological modelling were not available for this report. Consequently the smallest spatial unit available for the assessment presented in this report is the tenement. Thus if a tenement intersected the alluvial extent shown in Figure 1, it was considered to be part of this assessment.

Within the study region, there are 13 companies undertaking CSG activities (including exploration, extraction and processing activities). The majority of tenements are to be developed by four proponents: Santos, BG/QGC, APLNG and Arrow Energy. Both Santos and QGC have had their developments approved with a significant number of conditions imposed by both State and Commonwealth Governments. The APLNG Environmental Impact Statement is currently under review by the Queensland State Government. The number and area of tenements intersecting alluvium are summarised in Table 1. As of November 2010, there were 105 tenements in the MDB with a total area of 18,903 km\(^2\). The area of alluvial extent within these tenements is 4,130 km\(^2\). Arrow Energy and QGC have the highest proportion of alluvium in their tenements. There is 1,646 km\(^2\) of the Condamine Alluvium under CSG tenement.

Within the study region, there are currently 1,272 CSG wells. Figure 2 shows the current distribution of CSG production wells in the study area (QPED, October 2010). It can be clearly seen that current production is concentrated in well defined areas. Each proponent is proposing that ~10,000 wells will be staged in operations over the lifetime of their projects (~ 40 years). Most CSG activity is occurring on the Northwestern – Western margin of the Condamine Alluvium (Figure 2).

The primary areas under consideration are: Santos tenements in the vicinity of Roma, the central and south-east development areas under development by QGC, all APLNG tenements and all Arrow Energy tenements. It should be noted that no information was available regarding Arrow Energy CSG developments.

In addition, only considering activities that occur on alluvium may represent a significant gap in this analysis. CSG activities located outside of the alluvium may indirectly impact on MDB alluvium and surface water flows by changing hydraulic conditions in surrounding aquifers which may change aquifer connectivity.
Figure 1. Alluvial extent and CSG tenements.
Figure 2. Location of CSG wells in the study area.
Table 1. Summary of CSG tenements within the boundary of the MBD and area of alluvium in the tenements.

<table>
<thead>
<tr>
<th>Company</th>
<th>Number of Tenements</th>
<th>Area of Tenements (km²)</th>
<th>Alluvium area in tenements (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANGARI PTY LIMITED</td>
<td>2</td>
<td>153</td>
<td>16</td>
</tr>
<tr>
<td>ARROW ENERGY</td>
<td>8</td>
<td>1240</td>
<td>819</td>
</tr>
<tr>
<td>AUSTRALIA PACIFIC LNG PTY LTD</td>
<td>17</td>
<td>5802</td>
<td>863</td>
</tr>
<tr>
<td>AUSTRALIAN CBM PTY LTD</td>
<td>3</td>
<td>667</td>
<td>425</td>
</tr>
<tr>
<td>BNG (SURAT) PTY LTD</td>
<td>2</td>
<td>312</td>
<td>4</td>
</tr>
<tr>
<td>BRISBANE PETROLEUM LTD</td>
<td>3</td>
<td>357</td>
<td>0</td>
</tr>
<tr>
<td>BRONCO ENERGY PTY LIMITED</td>
<td>2</td>
<td>465</td>
<td>46</td>
</tr>
<tr>
<td>MOSAIC OIL NL</td>
<td>3</td>
<td>102</td>
<td>24</td>
</tr>
<tr>
<td>MOSAIC OIL QLD PTY LIMITED</td>
<td>8</td>
<td>874</td>
<td>30</td>
</tr>
<tr>
<td>OIL INVESTMENTS PTY LIMITED</td>
<td>9</td>
<td>1266</td>
<td>415</td>
</tr>
<tr>
<td>QGC PTY LIMITED</td>
<td>21</td>
<td>2786</td>
<td>651</td>
</tr>
<tr>
<td>SANTOS QNT PTY LTD</td>
<td>26</td>
<td>4771</td>
<td>752</td>
</tr>
<tr>
<td>SOUTHERN CROSS PETROLEUM &amp; EXPLORATION PTY LTD</td>
<td>1</td>
<td>108</td>
<td>85</td>
</tr>
<tr>
<td>Total</td>
<td>105</td>
<td>18,903</td>
<td>4,130</td>
</tr>
</tbody>
</table>

3.1 Coal Seam Gas Development

Current approval of significant expansion of CSG development within the MBD has been given for two companies located in the Surat Basin. Further expansion is projected in order to supply gas to Liquefied Natural Gas (LNG) plants to be located in Gladstone. The primary target of CSG development are the seams of the Walloon Coal Measures located in the Surat/Clarence Morton Basins. The Walloon Coal Measures extend from surface outcrops to as deep as 1600 m below ground level, with the area being targeted for CSG primarily being where the coal is between 250 m and 600 m below ground level. The Walloon Coal Measures is composed of at least three coal seams (composed of 9 coal intervals) of variable thickness. In contrast to the relatively contiguous coal seams of the Bowen Basin, the seams of the Walloon Coal measures typically present as discontinuous relatively thin seams (Draper and Boreham, 2006). The coal seams are embedded in mudstone, siltstone and sandstones.
In order to extract gas, the hydrostatic pressure must be reduced by pumping water from cleats in the coal seams so that gas is desorbed from the coal pores. In the Surat Basin, CGS proponents typically reduce the hydraulic head to within 35 m of the upper coal seam. This groundwater drawdown has been predicted to result in drawdown from overlying and underlying aquifers in the region during CSG production. The spatial extent of the drawdown is expected to extend beyond the boundary of the gas field production area and recovery of the groundwater systems is expected to extend significantly beyond cessation of CSG operations.

Water quality in the Walloon Coal Measures is variable, reflecting the depositional environment, depth of burial and coal type. In general, waters are slightly brackish to brackish, although some bores in the Walloon Coal measures yield freshwater (i.e. Total Dissolved Solids (TDS) < 1000 mg/L). Salinity (measured as TDS) ranges between 950 -12,894 mg/L, with an average values across the Surat Basin of 4,494 mg/L. Average composition is compared to the only information available from the alluvium, specifically from the Central Condamine Alluvium, in Table 5.

Coal seam water from the Walloon Coal Measures is typically Na-Cl or Na-HCO3-Cl. Water type varies spatially. QGC state that saltier Na-Cl coal seam waters dominate in the northwest area of their tenements, while fresher Na-HCO3 waters occur in the Southeast area (QGC, 2010). Water samples from the Walloon Coal Measures in the area underlying the Central Condamine Alluvium also show spatial variation. KCB (draft in review) showed that Na-Cl type waters predominantly occur in the Walloon Coal Measures underlying the western margin of the alluvium, whereas Na-HCO3-Cl and to a lesser extent Na-Cl-HCO3 dominate to the east.
4 Murray Darling Basin

4.1 Setting

The MDB is the catchment for the Murray and Darling rivers and tributaries. The region has an approximate area of 1,060,000 km$^2$, occupying approximately 14% of Australia’s total area, and spanning across the States of Queensland, New South Wales, Victoria, South Australia, and the Australian Capital Territory (Figure 5).

The region provides important economic, social and ecological values for the country. It is Australia’s most important agricultural area, supporting 65% of Australia’s irrigated agricultural land, it produces over one-third of Australia’s food supply and generates 39% of the national income derived from agricultural production. The region is home to more than 2 million people and supports an additional 1.5 million people reliant on the MDB water resources. Important environmental assets of the region include wetlands of national significance (as listed under the Ramsar Convention) and other groundwater dependent ecosystems.

This scope of this study included rivers, streams and associated alluvial aquifers in the MDB. Although the Great Artesian Basin aquifers are not part of the MDB surface water management area, the impacts of dewatering of the Walloon Coal Measures on these aquifers may also impact surface waters and alluvial aquifers, in particular the Condamine River and Alluvium. The hydrogeology of the area, and particularly the Great Artesian Basin, has been described extensively and a simplified stratigraphic sequence is presented in Figure 3. In general the sandstone sequences are confined aquifers. The confining units (aquitards) are generally siltstone and mudstones and include the Walloon Coal Measures. The units considered at greatest risk from CSG development are the Hutton (the Hutton sandstone grades into the Marburg sandstone in the Clarence Moreton Basin) and Precipice Aquifers located below the Walloon Coal Measures and the Springbok and Gubberamunda Aquifers located above the coal measures. There is also considerable concern regarding possible impacts on the Condamine Alluvium.
Figure 3. Simplified stratigraphic sequence and corresponding aquifers (blue) and confining units (grey) in the study area (after Radke et al., 2000; Draper and Boreham, 2006).
5 Conceptual model of flows and processes

Figure 4 is a conceptual model of the flows in the system. Exchanges between aquifers and surface waters are presented. At the top of the figure the pre-CSG flows are represented. Below, CSG direct drivers are shown. Water is extracted from the Walloons to reduce pressure to release gas from the coal. The water is drawn to the surface and then may be:

- Discharged to streams after treatment;
- Used in forestry, cropping, municipal and other beneficial purposes (with consequential redistribution of deep drainage and discharge of effluent); and
- Recharged into aquifers via reinjection bores.

Water can move between aquifers when a gradient of total potential (osmotic, pressure and capillary) exists. Pressure gradients exist where connected aquifers have different heads of water. This occurs because the water flows are more-or-less separate with respect to water sources into them. These pressures, and the hydraulic conductivity and juxtaposition of layers determines the actual water flows in space and time between strata. Water flows represented by the arrows may not be the same during dewatering and re-wetting. The term hysteresis\(^1\) is used to describe this. Hysteresis is important in the design and optimisation of the relationship between water extraction and reinjection.

Water extracted outside the area of CSG extraction overlying the alluvium could be introduced to the alluvium by reinjection via bores and by regulated discharge to local waterways.

Figure 4 also indicates that each of the water system components has imports and exports. Exports from the Walloon coal measures resulting in additional beneficial use of water at the surface (with brine management) and potentially abstractions for licensed use are the only import/export fluxes affected by CSG. Table 2 is a tabulation of the conceptual model. Four categories of water movement process are used: Recharge, Discharge, Re-distribution and Other beneficial uses.

\(^1\) Hysteresis is the term used to describe the well known phenomenon that porous materials do not wet and dry in the same way. There is evidence that dewatering can alter the pore structure of aquifers and coal potentially increasing the magnitude of hysteresis. Surface subsidence is one expression of loss of void space in the system.
Figure 4. Conceptual diagram of the water balance for surface and groundwaters in the study. Arrows represent water fluxes. Dotted arrows represent input of treated coal seam water discharged to surface waters or re-injected into aquifers.
Table 2. Processes of water recharge, discharge and redistribution under pre- and post-CSG.

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Surface water</th>
<th>MDB Alluvium</th>
<th>WCM</th>
<th>GAB</th>
<th>Mixed S/G</th>
<th>Other Beneficial Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers</td>
<td>Rivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDB Alluvium</td>
<td>discharge (gaining</td>
<td>recharge from losing streams</td>
<td>recharge from losing streams into outcrop intake beds</td>
<td>recharge from losing streams into outcrop intake beds</td>
<td>crops, forestry, municipal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WBAC</td>
<td>discharge of associated water (with treatment if required)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WCM</td>
<td>discharge of associated water (with treatment if required)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAB</td>
<td>discharge (gaining</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Beneficial Uses</td>
<td>Discharge (Municipal effluent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rivers rehabilitation is potentially with water quality change.
5.1 MDB Surface waters

The major surface water systems of the Queensland MDB are the Condamine - Balonne River system and the Border Rivers (Figure 5). As can be seen in Figure 5, development of coal seam gas industry is predominantly occurring in the Condamine-Balonne Catchment with tenements distributed across the catchment. Six tenements intersect the headwaters of streams in the Border Rivers catchment.

Figure 5. Location of the Murray Darling Basin (inset), major catchments and coal seam gas tenements.
All proponents have rivers or streams flowing through some tenements. APLNG, QGC and Arrow Energy all have tenements that intersect the Condamine River. Bungil Creek, Wallumbilla Creek and Yuleba Creek, within the Condamine-Balonne Catchment, flow across Santos tenements located near Roma.

5.1.1 Imports
Streams in the Condamine-Balonne catchment are ephemeral, with flow generally occurring during summer between December – February. Streamflow is rainfall/runoff dependent. Average annual rainfall is 514 mm (CSIRO, 2008) for the region with average annual rainfall of 635 mm and 634 mm at Miles and Dalby respectively. Annual stream flow is highly variable due to long term variations in rainfall.

5.1.2 Exports
Average annual evaporation is 2.5 - 3 times greater than average rainfall. Average annual evaporation at Miles is 1740 mm and Dalby is 1992 mm.

Total water entitlements for the Condamine – Balonne system is 729,000 ML/y. Water entitlements from the Condamine River, primarily for agriculture, are on the order of 240,000 ML/y or ~ 54% of the pre-development flow measured at the Chinchilla Weir (DERM, pers comm.).

5.1.3 Hydraulic Interactions with Groundwater
Surface water-groundwater interactions are often complex and difficult to quantify, particularly in areas where stream flow is ephemeral or intermittent. Where stream baseflow is derived from groundwater the stream is classified as a gaining stream and conversely where stream flow is lost to the groundwater the stream is classified as a losing stream. Connectivity between streams of the Condamine-Balonne and the alluvial aquifers is spatially and temporally variable.

5.1.3.1 Interactions with Alluvial Aquifer
CSIRO (2008) classified the Condamine River to be a high to medium losing stream upstream of Chinchilla Weir and as low - medium gaining stream downstream of the weir. KCB (draft in review) recently reviewed the conceptualisation of the Central Condamine Alluvium and also concluded that the Condamine River upstream of the Chinchilla Weir was a losing stream. These authors suggested that “the zone of hydraulic disconnection between
surface water and groundwater (maximum rate of conceptual stream loss) is considered to extend further downstream than indicated by CSIRO (2008), with possible connectivity being apparent only downstream of the Tipton (bore) Line” (KCB, draft in review p 33). The Tipton bore line is in the vicinity of current CSG leases operated by Arrow Energy. In this upstream reach, stream loss during flow periods will be governed by the hydraulic conductivity of the stream bed and unsaturated zone of the aquifer rather than the difference in hydraulic head between the stream and groundwater. However, KCB (draft in review) stress that the mechanisms governing stream loss to the alluvium are complex and at least five processes may be occurring depending on river flow conditions. Preliminary modelling by QGC estimated that at most 17 % of flow in the Condamine River downstream of Dalby may be baseflow contributed by groundwater. This baseflow was only apparent during periods of heavy rainfall (QGC, 2010, Vol. 3 Ch. 10) and may be reflecting short-term storage in stream banks during high flows returning to the river during flow recession (KCB, draft in review).

The Condamine River, immediately downstream of the Chinchilla Weir was classified as a low gaining stream by CSIRO (2008) (Figure 6). Advice from the Queensland Government provided for this report is that there is unlikely to be any measureable baseflow contributed from groundwater in this reach due to the limited extent of the alluvium and evidence from IQQM stream flow modelling.

5.1.3.2 Connectivity to GAB Aquifers

AGE (2005) using depth to water table mapping for GAB aquifers and results from Kellett et al. (2003) determined that some river reaches in the area under CSG development could potentially receive baseflow from GAB aquifers. Of particular interest are reaches of the Condamine River (near Condamine), Dogwood Creek, Wambo Creek, Moonie River which were identified by Kellett et al., (2003) as being fed from the Hooray Sandstone equivalents (Gubberamunda and Mooga sandstone in the Surat Basin). Also, a reach of both the Weir River and Western Creek could be fed from the Kumbarilla Beds (AGE, 2005). No estimates of the baseflow contribution to these streams from GAB aquifers has been made.

Advice from the Queensland Government provided for this study is that there is no evidence of connectivity between surface waters and GAB aquifers in the study area.
5.1.4 Water quality
Surface waters of the Condamine-Balonne system typically have low salinity, slightly alkaline pH and high turbidity. Statistics for stations on the upper Condamine River and four creeks in the Roma area are summarised in Table 3. The two Condamine River stations are located near Cecil Plains (station 422316A) and Dalby (Station 422333A) (ANRA, 2009; Santos, 2010; QGC, 2010; APLNG, 2010). Surface waters of the upper Condamine River have salinity between 200 – 1800 μS/cm. Median salinity is higher at the downstream station. Turbidity is highly variable. Surface waters downstream of Chinchilla are considered to be poor quality with high turbidity.

Figure 6. Gaining and losing stream reaches of the MDB. Taken from CSIRO (2008).
Water quality of surface water in the creeks near Roma are similarly variable although appear to have lower median salinities. Turbidity is also high and varies with rainfall and stream flow. Turbidity generally increases downstream (QMDC, 2010; Santos, 2010).

Table 3. Summary of water quality parameters for two stations located on the Condamine River and three stations in streams located in the Santos development near Roma (ANRA, 2010; QMDC, 2010; Santos, 2010; APLNG, 2010; QGC, 2010)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condamine River</th>
<th>Bungle Creek @Tabers</th>
<th>Yuleba Creek @Forestry</th>
<th>Balonne River@ Surat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (μS/cm)</td>
<td>422316A</td>
<td>422333A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>median</td>
<td>310</td>
<td>586</td>
<td>160</td>
<td>164</td>
</tr>
<tr>
<td>min</td>
<td>188</td>
<td>226</td>
<td>66</td>
<td>72</td>
</tr>
<tr>
<td>max</td>
<td>654</td>
<td>1350</td>
<td>1890</td>
<td>455</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>median</td>
<td>7.72</td>
<td>7.78</td>
<td>7.5</td>
<td>7.4</td>
</tr>
<tr>
<td>min</td>
<td>7.1</td>
<td>7.28</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>max</td>
<td>8.6</td>
<td>9.2</td>
<td>8.5</td>
<td>7.9</td>
</tr>
<tr>
<td>Turbidity (mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>median</td>
<td>82.2</td>
<td>133</td>
<td>96.5</td>
<td>107</td>
</tr>
<tr>
<td>min</td>
<td>0.9</td>
<td>0.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>max</td>
<td>898</td>
<td>1390</td>
<td>1500</td>
<td>360</td>
</tr>
</tbody>
</table>

5.2 MDB Alluvial Aquifers

The primary alluvial aquifer in the study area is the Central Condamine Alluvium and alluvium associated with tributaries of the Condamine-Balonne River system. The Central Condamine Alluvium extends across an area between Chinchilla, Dalby and Millmerran and is shown in Figure 1. The alluvium is heavily utilised as a water resource for agriculture and water abstraction has significantly impacted water levels in the alluvium. The conceptualisation and water balance of the Condamine alluvium was recently reviewed by KCB (draft in review). The alluvium is up to 100m thick in the thalweg located slightly to the east of the current river channel (KCB, draft in review). On average the alluvium is 20 - 30 m thick. Thick alluvial sediments are also associated with the Balonne River system. These alluvial sediments are Tertiary age and contain poor quality groundwater except in the area of the Maranoa and Balonne River junction.
The Central Condamine Alluvial basement sequences vary depending on how deeply the river channel eroded into the underlying sequences shown in Figure 3. In some areas the river cut through to the underlying Walloon Coal Measures providing opportunity for direct hydraulic connectivity between these units.

The water balance for the Central Condamine Alluvium presented in KCB (draft in review) is shown in Table 4.

5.2.1 Imports
Recharge of the alluvial aquifer is predominantly through rainfall and stream flow with smaller inflows to the Central Condamine Alluvium from bedrock and tributaries in the east (Table 4).

5.2.2 Exports
The largest outflow from the Alluvium is via groundwater abstraction. The current water deficit in the alluvium is estimated to be between 30,351 – 41,954 ML/y (KCB, draft in review). Groundwater flow in the alluvium is generally in the downstream direction (i.e. North-Westward). There has been significant drawdown of the watertable for agriculture in some areas (KCB draft in review). The area most affected by agricultural groundwater extraction is the area between Dalby and Macalister and to the east of Cecil Plains. Local internal groundwater flow developed in this area between 1990 – 2000 in response to groundwater abstraction resulting in drawdown of the aquifer water level by around 5-30 m (KCB, draft in review, p 40). This area lies adjacent to the current extent of CSG tenements located on the Western margin of the Central Condamine Alluvium.

5.2.3 Hydraulic interactions
5.2.3.1 Surface waters
Connectivity with surface waters was discussed above in Section 5.1.3.1. The alluvium is generally hydraulically disconnected from surface waters upstream of the Chinchilla Weir. Downstream of the weir there is not likely to be a measurable contribution of groundwater to Condamine River baseflow.
## Table 4. Water balance for the Central Condamine Alluvium (from KCB, draft in review).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Imports:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Streambed Recharge</td>
<td>12170 - 20810</td>
<td>19085-32634</td>
<td>15500 - 20239</td>
<td>11539</td>
<td>11158 - 22761</td>
</tr>
<tr>
<td>Bedrock contributions from the East</td>
<td>3610 - 3760</td>
<td>1130</td>
<td>1140</td>
<td>1604</td>
<td>1500</td>
</tr>
<tr>
<td>Bedrock contributions from the West</td>
<td>520</td>
<td>267</td>
<td>249</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Tributary Alluvium Contributions from the East</td>
<td>280 - 410</td>
<td>1470</td>
<td>250</td>
<td>250</td>
<td>705</td>
</tr>
<tr>
<td>Flux into Alluvium from Upstream</td>
<td>760</td>
<td>-</td>
<td>-</td>
<td>316</td>
<td></td>
</tr>
<tr>
<td>Rainfall Recharge</td>
<td>-</td>
<td>-</td>
<td>1%¹</td>
<td>0.10%¹</td>
<td>10265</td>
</tr>
<tr>
<td>Irrigation Deep Drainage</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>446.3</td>
</tr>
<tr>
<td>Flood Recharge</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Meander Channels Seepage</td>
<td>-</td>
<td>2000</td>
<td>2100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Exports:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater abstraction (unmetered)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>20200</td>
</tr>
<tr>
<td>Groundwater Abstraction</td>
<td>58903</td>
<td>61403</td>
<td>50000</td>
<td>50000</td>
<td>46400</td>
</tr>
<tr>
<td>Basement (bedrock) Leakage</td>
<td>8050</td>
<td>-</td>
<td>1649</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flux Out of Alluvium at Downstream</td>
<td>645</td>
<td>-</td>
<td>16467</td>
<td>12568</td>
<td>244.5</td>
</tr>
<tr>
<td>Evapo-transpiration</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹ presented as % rainfall.
5.2.3.2 Walloon Coal Measures and GAB Aquifers

The basement of the alluvium includes Marburg (Hutton) Sandstone, Walloon Coal Measures and the Springbok Sandstone. Historically, the Condamine River has incised valleys into the Springbok Sandstone (Kumbarilla Beds) and the Walloon Coal Measures (Hillier, 2010; KCB, draft in review). These valleys have subsequently been in-filled with what is today termed the Condamine Alluvium. Therefore water can move into and out of the alluvium depending on the hydraulic gradient. The details of the hydraulic conductivity and bedding of the alluvium also determines the rates and quantities of water movement. Given that these historical processes are highly spatially variable and the beds being incised were not homogeneous a great deal of local variation exists in both the connectivity and the potential for water exchange between strata across the alluvium. This explains why different studies in different parts of the Central Condamine Alluvium have reached what appear to be conflicting conclusions regarding water exchange. A brief summary follows.

Generally, water levels in the alluvium reflect basement topography. Discrete areas of basement highs have been mapped by KCB (draft in review) and were also noted by Huxley (1982) (Figure 7). Huxley (1982) interpreted the areas of basement highs to be intersection with the Walloon Coal Measures.

Hydraulic connection of the alluvium with the Walloon Coal Measures and other aquifers has been inferred from analysis of groundwater level records by Hillier (2010) and more recently by KCB (draft in review). KCB (draft in review) concluded that there was a general slight gradient driving water from the alluvium to Walloon Coal Measures. The strength of the gradient was variable, in the upstream section of the alluvium (the Southern area) there is a negligible or only slightly pressure gradient driving water from the alluvium in to the Walloons. Further north, around Dalby, water levels in the Walloon Coal Measures were similar to water levels in the alluvium implying little net water movement. There is evidence of variation around this general picture. KCB (draft in review) provided an example where water levels in the Walloon Coal Measures were up to 25 m lower than the alluvium. CSG dewatering of the Walloon Coal Measures will increase this gradient. Implications for water movement will depend on the hydraulic properties at the interface between the alluvium and Walloon Coal Measures. On the other hand, Hillier (2010) found alluvium water levels
to be on the order of 10-15 m below the water level of bores in the Walloon Coal Measures in the area just south of Dalby and east to Oakey. Dewatering of the Walloon Coal Measures may neutralise or reverse this gradient. This is a possible driver for local re-distribution of water within the alluvium. For example water quality may be observed to change in bores from local re-distribution within the alluvium (see section 6.2.2).

Connectivity of the Condamine Alluvium with the Marburg sequence is similarly variable but generally there appears to be neutral to moderately upward hydraulic gradient (KCB, draft in review).

A detailed assessment of the sequences underlying the alluvium is currently being undertaken for DERM (Healthy Headwaters Program), results were not available for this report. Adaptive management will require this information to respond to local effects. For example, with this information it will be easier to target priority areas for reinjection into the Walloon Coal Measures to minimise the impact of dewatering on flows from the alluvium. This may be particularly important if action is taken to reduce abstraction to restore water levels in the alluvium.

Figure 7. Location of thalweg and hydraulic basement highs in the Condamine Alluvium (from KCB, draft in review).
5.2.4 Water Quality
Water quality of the Condamine alluvium is spatially variable reflecting proximity to basin margins, tributary inflows and the Condamine River as well as variations in basement geology/water chemistry. Time-series of individual bore water quality data were not available for this report, consequently temporal changes in water type or water quality could not be determined. KCB (draft in review) reviewed groundwater chemistry and presented spatially contoured salinity maps. Their analysis suggested “that the spatial salinity distribution shows only minor variations over time, with changes in the continuity of individual sampling influencing these patterns. While minor changes occur, the overall trends in the dataset remain relatively constant” (KCB, draft in review, p 61). A summary of the findings of KCB (draft in review) water quality analysis is given below. It should be noted that the trends observed by KCB represent modal (most commonly occurring) or average changes in water chemistry throughout the alluvium. KCB (draft in review, p 64) note that for bores in proximity of Tipton, Westend, Oakey, Dalby, Yarrala and Pirrinuan “While broad trends associated with water chemistry and geology are inferred, the trend is not obvious, with different hydrochemical values often observed to occur in adjacent boreholes”.

Salinity (as total dissolved solids) ranges between 103 – 24,473 mg/L. In general, salinity increases northward (i.e. downstream). Lower salinities are typically observed in the alluvium where bores are located close to the Condamine River and tributary inflows. Higher salinities are found in the northern area of the alluvium. Bores in this area tend to be drawing from deeper in the alluvium close to the basement contact. It is not clear whether these higher salinities are due to longer residence time (due to lower transmissivity), inflow from basement rocks or interaction with different parent material (KCB, draft in review). It is likely that all three processes may be influencing water quality.

Water type generally changes down the inferred groundwater gradient. The upper alluvial area waters are dominated by Na-Cl-HCO₃ as are waters from bores located close to the Condamine River. Deeper bores located in the upper Condamine located east of the river are Na-Mg-Ca-HCO₃. Margins of the alluvium are Na-Mg-Cl dominated which is thought to reflect the influence of Walloon Coal Measures and Main Range Volcanics, although there
may also be some influence of lower recharge (KCB, draft in review). Downstream of Oakey Creek alluvium water chemistry is Na-Cl-HCO₃ and Na-Cl. This change was consistent with change in water type of the underlying strata.

Table 5. Comparison of water quality of Central Condamine Alluvium, Walloon Coal Measures and Marburg Sandstone

<table>
<thead>
<tr>
<th></th>
<th>Central Condamine Alluvium</th>
<th>Walloon Coal Measures</th>
<th>Marburg Aquifer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductivity (µS/cm)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>2385</td>
<td>4305</td>
<td>1319</td>
</tr>
<tr>
<td>minimum</td>
<td>187</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>maximum</td>
<td>30000</td>
<td>31000</td>
<td>39000</td>
</tr>
<tr>
<td><strong>TDS (mg/L)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>1437</td>
<td>2667</td>
<td>763</td>
</tr>
<tr>
<td>minimum</td>
<td>103</td>
<td>30</td>
<td>12</td>
</tr>
<tr>
<td>maximum</td>
<td>24473</td>
<td>21794</td>
<td>39819</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>3.6</td>
<td>7.8</td>
<td>7.9</td>
</tr>
<tr>
<td>minimum</td>
<td>7.9</td>
<td>3.8</td>
<td>2.3</td>
</tr>
<tr>
<td>maximum</td>
<td>11</td>
<td>11.6</td>
<td>11</td>
</tr>
</tbody>
</table>
6 Assessment of Impacts on Surface and Groundwater in the MDB

Review of the fluxes presented in Figure 4 and Table 2 shows that CSG operations are not likely to affect a number of the fluxes. These fluxes are summarised in Table 7.

6.1 System Interactions: processes and significance

The water fluxes in the conceptual model (Section 5) will be influenced by CSG development to varying degrees. In this section, the flows between system components and the processes via which they occur are categorised in terms of significance. The category of main interest is where significant changes in flows are created by the introduction of CSG extraction. These changes include consideration of the management and technical challenges not just the magnitude of the changes to flows. For example, reinjection of water has significant engineering and sequencing challenges as well as difficult water quality issues including changes in mineral saturation status.

Flows were separately categorised into significant, intermediate and minor changes. Also, flows where no changes are expected are identified. Minor or no changes could be because of limited footprint of development and/or being dependent on factors not affected by CSG development (e.g. diffuse recharge dependent on flood frequency and hydraulic conductivity of alluvium).

Finally, flows that are part of realisation of other beneficial uses that may be enabled by the availability of associated water are identified. For example, water availability for agriculture and town supplies as well as surface water flows may be increased by availability of associated water.

The processes, interactions and their relative significance are summarised in Table 6. Four interactions are identified as creating significant changes and/or local impacts. Three interactions are categorised as intermediate, six as minor and eight with no changes.
Table 6. Processes of water recharge, discharge and redistribution post-CSG. White = no significant changes; yellow = minor changes; green = intermediate changes; blue = significant changes and/or local risk

<table>
<thead>
<tr>
<th>From</th>
<th>Surface water</th>
<th>Groundwater</th>
<th>Mixed S/G</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rivers</td>
<td>Alluvium</td>
<td>WCM</td>
</tr>
<tr>
<td>Rivers</td>
<td></td>
<td>14. recharge from losing streams</td>
<td>15. recharge from losing streams into outcrop intake beds</td>
</tr>
<tr>
<td>Alluvium</td>
<td>17. discharge (gaining streams)</td>
<td>3. redistribution potentially with water quality change</td>
<td>7. redistribution potentially with water quality change</td>
</tr>
<tr>
<td>WCM</td>
<td>1. discharge of associated water (with treatment if required)</td>
<td>2. reinjection of co-produced water via surface bores</td>
<td>8. reinjection of co-produced water via surface bores</td>
</tr>
<tr>
<td>GAB</td>
<td>11. discharge (gaining streams)</td>
<td>9. redistribution potentially with water quality change</td>
<td>4. redistribution potentially with water quality change</td>
</tr>
<tr>
<td>Other Uses</td>
<td>Discharge (Municipal effluent)</td>
<td>recharge (Drainage below root zone)</td>
<td>recharge (Drainage below root zone)</td>
</tr>
</tbody>
</table>
6.1.1 Significant Changes and/or local impact

1. Discharge of associated water from Walloon Coal Measures to Rivers
   - Proponents have identified discharge of treated associated water to MDB streams as a water management option. Discharge of treated associated water could supplement streamflow.
   - APLNG have modelled potential permeate discharge between 20 - 100 ML/d (APLNG, 2010 Vol 5 att 23). This discharge volume represents 3 - 15 % of the volume currently being extracted from the Condamine River, upstream of Chinchilla Weir, under water entitlements (240, 000 ML/y, DERM).
   - QGC estimate total peak water production to be 190 ML/d and average production to be ~165 ML/d between 2015 – 2025 (QGC Vol 3, Chapt 11). If all associated water was treated and discharged this would represent ~25 % of the volume currently being extracted from the Condamine River, upstream of Chinchilla Weir, under water entitlements.
   - Santos stated that stream discharge is not a preferred option for the Roma development (Santos, 2010; Appendix Q).
   - Timing of discharge will be critical to ensure natural flow regimes are maintained and environmental flow objectives are met.
   - Where more than one operator is discharging associated water to streams, stream flow modelling will need to be conducted to determine the cumulative impact of multiple discharges.
   - Brine management will need to be carefully considered where associated water is treated.

2. Reinjection (of associated water via surface bores) from Walloon Coal Measures to Alluvium
   - Options for direct re-injection of associated water to the Central Condamine Alluvium is currently being investigated in Healthy Headwaters Program.

3. Redistribution (potentially with water quality change) within the Alluvium
   - Local redistribution of water in the alluvium in response to water table drawdown may result in water quality compromise of some water bores (Section 6.2.1,
6.2.2. Significant differences in bore water chemistry have been noted in some areas of the Central Condamine Alluvium (Section 5.2.4).

- During water table drawdown, water in the alluvium may be redistributed so that in some cases low quality water may flow to areas where water quality was previously high. This local (individual water bores) change to water quality may be significant, but the number of bores likely to be affected and the locations cannot currently be predicted or the magnitude of change estimated.

4. **Redistribution (potentially with water quality change) from GAB to Walloon Coal Measures**

- Even though this process is from one non-MDB water component to another, it represents a change to system flows.

- It is possible that water that has redistributed from other aquifers to the Walloon Coal Measures is subsequently extracted as associated water. Therefore, if this is licensed for other beneficial uses, it may actually be a re-allocation of entitlement from the source aquifer. Therefore, overall, entitlements may be increased if this is not monitored and appropriate corrections made. It is likely that this water will have been the subject of make good provisions if it was previously allocated to an entitlement holder.

- GA and Habermehl (2010) presented an order of magnitude comparison between estimated aquifer recharge and estimated leakage from various GAB aquifers induced by dewatering of the Walloon Coal Measures. This analysis was only possible for QGC and Santos development areas. Depending on associated water production scenarios, development area and affected aquifer, these induced leakage was estimated to range between 0.07 – 111 % of recharge.

- Reinjection of associated water to GAB aquifers may mitigate the induced leakage from GAB.

6.1.2 **Intermediate Changes**

5. **Redistribution (potentially with water quality change) from Walloon Coal Measures to Alluvium**
For areas where Walloon Coal Measures is currently hydraulically connected to the alluvium and flow is from Walloons to the Alluvium (Section 5.2.3.2) this exchange may decrease as the Walloon Coal Measures are dewatered. The magnitude of this exchange is currently not quantified.

6. Reinjection (of associated water following treatment via surface bores) from Walloon Coal Measures to GAB aquifers

- Even though this process is from one non-MDB water component to another, it is a driver of potential changes to MDB water flows and has management and/or technical challenges. All proponents are investigating re-injection (APLNG, 2010, Vol. 5, Ch. 24; Santos, 2010, Appendix Q). QGC suggesting reinjection to GAB aquifers only. 2 - 4ML/well/d expect to need 70 wells targeting Hutton/Precipice Sandstone (QGC 2010, Vol. 3, Ch. 11).

7. Redistribution (potentially with water quality change) from Alluvium to Walloon Coal Measures

- It is possible that water that has redistributed from other aquifers to the Walloon Coal Measures is subsequently extracted as associated water. Therefore, if this is licensed for other beneficial uses, it may actually be a re-allocation of entitlement from the source aquifer. Therefore, overall, entitlements may be increased if this is not monitored and appropriate corrections made. It is likely that this water will have been the subject of make good provisions if it was previously allocated to an entitlement holder.

- The only proponent to predict water table drawdown (APLNG, 2010, Vol 5 att 21) has not estimated leakage rate from the alluvium to underlying strata. The predicted drawdown was on average 2 m and was not predicted to extend beyond the current boundaries of CSG tenements. Thus drawdown of the alluvium water table may be restricted to a small area of the Central Condamine Alluvium.

- A conceptualisation of the basement of the Central Condamine Alluvium is currently being undertaken in the Healthy Headwaters Program. Water level analysis and bore water chemistry suggest that direct connectivity between the alluvium and Walloon Coal Measures may exist, although mostly outside of the
CSG development area (Sections 5.2.3.1, 5.2.3.2). Exchange between these units has not been quantified and will be dependent on the hydraulic conductivity.

6.1.3 Minor Changes

8. Reinjection (of associated water via surface bores) from Walloon Coal Measures to Walloon Coal Measures
   - Even though this process is from one non-MDB water component to another, it is a driver of potential significant changes to MDB water flows and has significant management and/or technical challenges. All proponents are investigating re-injection. However, reinjecting water back into the Walloon Coal Measures is not likely to be feasible during CSG operations without storing water for significant periods of time.
   - Reinjection into other aquifers affected by dewatering of the Walloon Coal Measures is the preferred option of the Queensland Government (see point 6 above).

9. Redistribution (potentially with water quality change) from GAB aquifers to Alluvium
   - GAB aquifers underlie the Condamine Alluvium in some areas. Water levels in the Marburg aquifer are typically higher than in the alluvium (Section 5.2.3.2) and water quality data suggest there may be some exchange from the Marburg aquifer to the alluvium. This exchange has not been quantified. It should also be noted that the area of the alluvium where water level analysis has suggested that Marburg aquifer waters may exchange with the alluvium is not located within the area of CSG development or the area of predicted drawdown of this aquifer. Hydraulic relationship between the Springbok or Gubberamunda aquifer and the Condamine Alluvium has not been quantified.

10. Redistribution (potentially with water quality change) from Alluvium to GAB aquifers
    - Water level analysis suggests that Marburg aquifer water levels are neutral or higher than water levels in the Alluvium (Section 5.2.3.2). Drawdown of the Marburg aquifer could reverse the gradient. The area where this water level
analysis has been conducted is outside of the area where drawdown of the Hutton/Marburg aquifer is predicted.

11. **Discharge (gaining stream reaches) from GAB aquifers to Rivers**
   - Only a limited number of river reaches possibly receive baseflow from GAB aquifers, this baseflow contribution is likely to occur only sporadically (Section 5.1.3.2). Regional impact on flow in MDB streams is likely to be minimal. Local effect is also likely to be limited.

12. **Licensing of associated water (potentially following treatment) extracted from any system component other than the Walloon Coal Measures to other beneficial uses**
   - It is possible that water that has redistributed from other aquifers to the Walloon Coal Measures is subsequently extracted as associated water. Therefore, if this is licensed for other beneficial uses, it may actually be a re-allocation of entitlement from the source aquifer. Therefore, overall, entitlements may be increased if this is not monitored and appropriate corrections made. It is likely that this water will have been the subject of make good provisions if it was previously allocated to an entitlement holder.

13. **Licensing of associated water (potentially following treatment) extracted directly from the Walloon Coal Measures to other beneficial uses**
   - It is possible that water that has redistributed from other aquifers to the Walloon Coal Measures is subsequently extracted as associated water. Therefore, if this is licensed for other beneficial uses, it may actually be a re-allocation of entitlement from the source aquifer. Therefore, overall, entitlements may be increased if this is not monitored and appropriate corrections made. It is likely that this water will have been the subject of make good provisions if it was previously allocated to an entitlement holder.
   - Use of treated associated water to supplement town water supply, crops and forestry plantations has been proposed.

**6.1.4 No changes**

14. **Recharge (from losing stream reaches) from Rivers to Alluvium**
• This “no change” categorisation assumes that cumulative water entry under conditions including associated water regulated discharge is the same as under current conditions because historical water extraction has disconnected the alluvial aquifer from the streams.

• Alluvium water table drawdown for streams not at maximum losing capacity may reduce stream flow for short periods of time (Section 5.1.3.1).

15. Recharge from losing streams into intake beds (Walloon Coal Measures)

• Recharge mechanisms of Walloon Coal Measures have not been quantified. However, dewatering is unlikely to affect recharge because it will be dependent on rainfall and stream input in exposed outcrops. The recharge rate will be dependent on the hydraulic conductivity of intake beds.

16. Recharge from losing streams into intake beds (GAB aquifers)

• It is expected that recharge of GAB aquifers via intake beds will not be affected by CSG activities and therefore will not impact streamflow.

17. Discharge (gaining stream reaches) from Alluvium to Rivers

• Central Condamine alluvial aquifer may be connected to Condamine River for only brief periods (days) after large rainfall events (Section 5.1.3.1). Contribution of alluvial aquifer to stream flow is negligible (Table 4).

• Balonne River alluvium water levels are not likely to be impacted by CSG activities.

6.2 Groundwater Impacts

Based on the analysis presented above CSG development is likely to principally impact the alluvial aquifer in the following ways:

1. Alluvial aquifer water availability due to:
   a. drawdown of the water table by induced leakage into the Walloon Coal Measures.
   b. drawdown of the water table by induced leakage into GAB aquifers. This is a secondary effect of induced leakage of GAB aquifers created by dewatering of the Walloon Coal Measures.

2. Alluvial aquifer bore water quality may be affected by local re-distribution of water responding to drawdown.
6.2.1 Groundwater Quantity

From the information available in the EIS documents it is not possible to separately assess drawdown of the alluvium water table resulting from direct connectivity with the Walloon Coal Measures and drawdown as a result of connectivity of the alluvial aquifer with other aquifers, in particular GAB aquifers.

Drawdown of aquifers predicted by all proponents is summarised in Table 7. It can be clearly seen that the predicted drawdown varies considerably between aquifers and between proponent estimates. Interestingly, although QGC state that the conservative assumptions in their model would provide estimates of drawdown that are likely to represent maximum values, APLNG estimates for drawdown in the Springbok aquifer (for example) in a similar area are on the order of 3 times greater. Possible explanation of the differences between proponent estimates include:

- Differences in sophistication of models: number of layers and size of spatial elements.
- Values used for hydraulic properties.
- Assumptions used as boundary conditions - QGC assumed constant head conditions beyond the model boundary
- Reported drawdown on different spatial basis. For example, QGC estimated drawdown is for a point 1.8 km from the edge of the depressurised zone. Neither the extent of the depressurisation zone or maximum drawdown was specified.

In general the largest predicted drawdown occurs in areas where the coals are located at deeper depths and the confining units are thin.

The predicted drawdown by APLNG for the cumulative case (i.e. considering all proponents) was “essentially the same as predicted for their project case, with an extension in the predicted area of drawdown” (APLNG, 2010, Vol 5 att 21). No figures or data were available to assess the increased extent. Higher than average drawdown might be expected to occur in tenements of each of the proponents with a higher concentration of producing wells (Figure 2).

APLNG was the only proponent to estimate drawdown of the water table (APLNG, 2010, Vol 5 att 21). Numerical groundwater modelling showed that for the APLNG tenement area
only, maximum average drawdown occurred in 2049 with average watertable drawdown estimated to be less than 2 m with localised areas of higher drawdown (APLNG, 2010, Vol 5 att 21). Drawdown between 5 – 7 m was predicted to occur in two small areas. These areas are located immediately downstream of the Chinchilla Weir and in an area on the margin of the alluvium just south of Miles (Figure 8). Higher drawdown was coincident with the area of greater predicted drawdown of the underlying Gubberamunda and Springbok aquifers (Figure 9, Figure 10) and where the confining layer was thin or absent (APLNG, 2010, Vol 5 att 21). APLNG (2010) suggest that operation of the weir may compensate for the expected decrease in baseflow in the Condamine River due to drawdown of the water table in the area downstream of the Chinchilla Weir. It should be noted that groundwater use downstream of the Chinchilla Weir is low.

APLNG modelling results for all proponents (cumulative case) suggested that on average drawdown was < 2 m, although again with localised higher drawdown predicted in the same areas as above and also to the north and northwest of their Gilbert Gully development area. Although the area of increased drawdown for this southern area was not shown in the APLNG EIS the location is likely to correspond to the southern extent of Arrow and QGC development areas (APLNG, 2010, Vol 5 att 21).

The timing of maximum drawdown for the cumulative case was not specified in the APLNG EIS (APLNG, 2010, Vol 5 att 21). During CSG production the areal extent of watertable drawdown was projected to be close to the tenement boundaries and projected to increase during the recovery phase. No maximum areal extent was given in the APLNG EIS (APLNG, 2010, Vol 5 att 21).

Water level drawdown in some areas of the Condamine Alluvium due to groundwater abstraction has been on the order of 5 – 30m (Macalister – Dalby – Cecil Plains) in the decade between 1990 -2000. By comparison the projected drawdown of the alluvial water table predicted by APLNG, on average 2 m by 2049, is comparatively small. Even the greater drawdown predicted in localised areas of 5 - 7m is comparatively small. Thus on average, CSG activities are not likely to dramatically impact water availability in the Condamine Alluvium. However, local impacts may be more significant. Data and model outputs were not available for this report to determine the likely local drawdown. APLNG and other
proponents used average hydraulic properties in the models. Hydraulic connectivity between the alluvium and underlying sequences, including the Walloon Coal Measures, has been indicated by both water level analysis and water quality data (Hillier, 2010; KCB draft in review). Currently there are no estimates of the magnitude of this exchange. This connectivity is likely to be heterogeneous and will therefore result in drawdown that deviates from the average in some areas.

It should be noted that only one water bore was identified in the area where drawdown of the water table was predicted to be greater than 5 m by APLNG (2010). However, a significantly greater number of bores are located along the western margin of the Condamine Alluvium (the Eastern extent of CSG development, Figure 1). Further work is required to predict magnitude and spatial and temporal extent of drawdown along the western margin of the Central Condamine Alluvium.
Figure 8. Area of > 5m drawdown of the water table predicted by APLNG (APLNG, 2010, Vol 5 att 21).
Figure 9. Predicted drawdown area of > 5m in the Gubberamunda Aquifer for APLNG project (APLNG, 2010, Vol 5 att 21).

Moran, Vink

MDBinflows.doc
Figure 10. Predicted drawdown area of > 5 m in the Springbok Sandstone for APLNG Project (APLNG, 2010, Vol 5 att 21).

Moran, Vink
MDBinflows.doc
Table 7. Summary of predicted drawdown for aquifers potentially affected by CSG activities (from APLNG 2010; QGC 2010; Santos2010).

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>APLNG - Project</th>
<th>QGC</th>
<th>Santos (Roma field)</th>
<th>APLNG - Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Table</td>
<td>2</td>
<td></td>
<td>max (m) 5-7</td>
<td>East of Condabri Central and South; East of Condabri Central and South; north and Northwest of Gilbert Gully</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>East of Condabri Central and South; East of Condabri Central and South; north and Northwest of Gilbert Gully</td>
<td></td>
</tr>
<tr>
<td>BMO and Gilbert</td>
<td>3</td>
<td></td>
<td>max (m) 8</td>
<td>Carinya</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Carinya</td>
<td></td>
</tr>
<tr>
<td>Gubberamunda</td>
<td>average (m) 10</td>
<td>minimal</td>
<td>max (m) 10</td>
<td>100km SW Pine Hills</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time 2029 - 2199</td>
<td>Southwestern Miles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Southwestern Miles</td>
<td></td>
</tr>
<tr>
<td>Springbok</td>
<td>average (m) 15</td>
<td></td>
<td>max (m) 300</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range (m) 10 - 85</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time 2019-2039</td>
<td>South Miles CDA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>South Miles CDA</td>
<td></td>
</tr>
<tr>
<td>Hutton</td>
<td>average (m) 2</td>
<td></td>
<td>max (m) 10</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range (m) 0 - 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time 2029 - 2149</td>
<td>West Miles SEDA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>West Miles SEDA</td>
<td>Tenement boundary</td>
</tr>
<tr>
<td>Precipice</td>
<td>average (m) 0</td>
<td></td>
<td>max (m) 0</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Range (m) 0 - 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Area of maximum drawdown</td>
<td>SEDA</td>
</tr>
</tbody>
</table>
6.2.2 Groundwater water quality
Determining the impact of CSG activities on water quality in the alluvial aquifer, and more specifically the impact on individual bore water quality is difficult to quantify with the data that is currently available.

Given the wide range of salinity and water types determined in the alluvial aquifer, CSG activities are perhaps not likely to significantly impact general water quality in the aquifer. Dewatering of the Walloon Coal Measures in areas where the alluvium is hydraulically connected will likely alter the hydraulic gradient between the two units so that water will tend to flow from the alluvium to the coal measures. On average, therefore, water with lower salinity would be expected to move from the alluvium to the Walloon Coal Measures. Similarly, where GAB aquifers are hydraulically connected to the alluvium, drawdown of the GAB aquifers will tend to weaken or reverse the hydraulic gradient between the alluvium and GAB aquifers. However, given the heterogeneity of water quality in the alluvium and particularly the variation in hydrochemistry between boreholes in some areas (Section 5.2.4), local redistribution of groundwater within the alluvium in response to the changes in hydraulic gradient may result in movement of poorer quality water to areas where water quality was previously good. This local redistribution may therefore compromise water quality of individual bores.

Changes to alluvium water quality during re-pressurisation of the Walloon Coal Measures and GAB after CSG extraction has ceased cannot currently be predicted.

In addition, alluvial aquifer water quality may changed in cases where CSG wells are compromised, e.g. due to lack of maintenance, faults or accidents.

6.3 Surface water changes

6.3.1 Surface water quantity
All proponents have identified discharge of treated associated water (permeate) to rivers as a management option. Santos have indicated that it is not their preferred option for the Roma development. All proponents have conducted modelling to estimate the impact of associated water discharge on stream flow.
APLNG have proposed to discharge permeate into the Condamine River downstream of the Chinchilla Weir at Talinga and Condabri. APLNG (2010) undertook IQQM modelling to establish the expected changes to flow regime in the Condamine River under a range of release scenarios. This modelling showed that while continuous discharge would significantly alter low/no flow periods, releases could be managed to conform to the Environmental Flow Objectives in the Water Resource (Condamine and Balonne) Plan (2004). Permeate discharge by APLNG only was estimated to be in the range of 20-100 ML/d (APLNG, 2010, Vol. 5 Att. 23) would represent 3 - 17 % of the volumes currently being extracted upstream of the Chinchilla Weir in the Condamine River.

The modelling conducted by APLNG (2010) showed that the timing and volume of permeate discharge to the Condamine River could be managed so that the flow regime was not significantly altered.

If either of the other proponents discharge associated water to the Condamine River in addition to APLNG, an assessment will required to determine the cumulative impact of discharges from multiple proponents. Timing and volumes of discharge from different proponents will most likely need to be managed in a coordinated fashion in order to avoid significant changes to river flow regimes.

6.3.2 Surface water quality
The Queensland regulatory framework under the Environmental Protection Act (EP ACT) requires that any CSG water discharged to surface water needs to be of an appropriate quality to ensure the receiving waters environmental values are protected. Discharges will be conditioned through an environmental authority issued under the EP Act. In addition, town water quality requirements to protect public health are addressed under the proposed amendment to the Water Supply Act currently under consideration by the Queensland Parliament.

Some proponents have identified some dissolved constituents in permeate may be present in concentrations that exceed ANZECC/ARMCANZ (2000) water quality guidelines. The constituents of primary concern are Boron and Fluoride (APLNG, 2010, Vol. 5 Att. 22; Santos, 2010, Section 6.5). Conversely, permeate discharge may reduce the concentration of key constituents such as calcium. These impacts can be managed through setting
appropriate discharge criteria for aquatic ecosystem protection and in some cases selected ion addition prior to discharge.

Increased erosion and delivery of sediment the streams could result from three activities. These are construction activities, including road construction; changes to stream hydraulics during permeate discharge; and, changes to overland flow paths as a result of subsidence.

All proponents identified increased erosion during construction activities as a risk to stream water quality. Activities include road construction and in some areas waterway crossings. The mitigation activities such as undertaking activities during the dry season and containment of runoff in sedimentation dams should minimise the water quality risk to streams.

Each of the proponents conducted hydraulic modelling to determine possible changes to stream hydraulics during permeate discharge that may result in increased erosion of stream banks or stream meander migration. Mitigation activities including managing discharge volume and conditions at the point of discharge (e.g. rock armouring of streambed etc.) should minimise impacts of these activities.

Each of the proponents estimated compaction of the coal seams and consequent subsidence. The predicted compaction from these studies is similar to predictions from CSG field in the Western United States (Case, 2000). A subsidence bore was established in the Condamine in the early seventies and indicates that there may have been minor subsidence due to water extraction. DERM has recently established a bore line for monitoring subsidence along a transect across the alluvium that will be monitored on an ongoing basis.

Based on current knowledge, subsidence due to dewatering of the coal seams is likely to be significant in spatial extent but minor, by comparison with long wall mining for example, in magnitude vertically. However, consequences of subsidence and small changes to land surface topography in the study region could be important in terms of changing overland flow patterns, which may increase erosion and gully formation.

In addition, proponents did not consider whether compaction of coal seams in the Walloon Coal Measures after dewatering might result in deformation of overlying or underlying aquifers or confining units. This deformation may result in opening of new or existing
fractures in these units which would change the hydraulic relationships and may change groundwater flows between aquifers.

6.4 Mitigation activities

The CSG industry water management and environmental performance in Queensland is regulated under the EP Act (EIS/EA and adaptive environmental regulatory regime) and the Water Act 2000.

The proposed WOLA Bill amends the Water Act 2000 to ensure any impacts on landholder’s water supply bores are properly managed in order to maintain a reasonable or alternative water supply. WOLA includes an obligation on CSG companies to enter into an agreement to “make good” any impairment on landholder’s bores prior to these impacts actually occurring. Importantly, the WOLA Bill requires the production of underground water impact reports at least every three years. These reports will provide an assessment of monitoring results, a projection of predicted water level impacts using progressively updated groundwater flow models, a spring impact management strategy, and an updated water monitoring strategy. This adaptive management regime will apply to allow progressive improvement in the understanding of impacts and also to support timely implementation of “make good” arrangements.

Make good obligations will continue beyond the life of the tenure – this is due to the fact that the impacts on underground water resources may possibly continue beyond the life of the tenure. As such, there will be no cap on the period for which tenure holders’ underground water obligations continue.

It should be noted that ‘make good’ provisions only apply to the impact resulting from water extracted under CSG activities not general water extraction for other purposes or natural change.

Two issues are raised by these provisions. Firstly the length of time that the water supply might be affected and secondly the spatial heterogeneity in water quality and quantity must be considered. Predicting the time when re-pressurisation is likely to be achieved is difficult and although associated water could be treated during CSG production phase and used to supplement existing bore owners this option will become increasingly difficult as gas
production ramps up and water production declines. Sourcing water after gas production has ceased and until aquifer re-pressurisation has occurred may be required for a considerable length of time.

The Queensland State Government’s preferred option for management of associated water from CSG development is aquifer reinjection and proponents have included reinjection as part of their water management strategy. The timing of re-injection and targeted aquifers will be critical to mitigate some of the potential impacts on surrounding aquifers. A substantial amount of additional work will be required to better quantify changes to hydraulic interactions between aquifers and the dewatered coal seams.

7 Discussion

The spatial scope of this study has been restricted to activities directly upon alluvium as opposed to impacts of activity anywhere on alluvium and related surface and ground water flows. Only 22% of the total area of CSG tenements in the MDB is classed as alluvial in this study. Consequently, the volumes of water are relatively small by comparison to the volumes for agriculture and urban uses that are extracted from the alluvium.

There are significant challenges to separate changes from CSG from activities on the alluvium with CSG activities more generally and other activities that impact the water balances of the alluvium. For example, Great Artesian Basin Strategic Management Plan aims to save 211,000 ML/y across the basin over a 15 year period. The total water savings during the Phase 1 of the GABSI for Queensland has been 53,771 ML/y (Surat only = 10,782 ML/y) and for the whole of the GAB has been 98,004 ML/y (SKM, 2008). Total average water production reported in GA and Habermehl (2010) for APLNG and QGC was 36,656 ML/y (APLNG: 15,931 ML/y; QGC: 20,725 ML/y based on 829 GL produced over 40 years). Using the estimates of water production for these two proponents provided to GA and Habermehl (2010) and assuming the same average water production both on and off the alluvium, the total water production for activity of these two proponents on the alluvium would be expected to be on the order of 7,223 ML/y.
The proponents however acknowledge uncertainty in the estimates of water production and the values noted above are lower than previously predicted in the EIS documents:

- **QGC** estimated total peak water production to be 190 ML/d (in 2012/2013) and average production to be ~165 ML/d between 2015 – 2025 yielding 1,200 GL over the life of the project (QGC Vol 3, Ch. 11).
- **Santos** estimated water production from the Roma field to peak at around 20 ML/d in 2014, declining to 10 ML/d for the following 5 years, with a maximum total estimated production of 91,336 ML over the life of the field (Santos, 2010, Att. Q).
- **APLNG** anticipate their water production to peak 170 ML/day (62,050 ML/year) in sometime in the first twenty years (APLNG, 2010, Vol. 5, Att. 24).

### 7.1 Regional Impact

As noted earlier, the scope of this report is restricted to activities undertaken on the alluvial plains of the MDB. Therefore, it is important that the water volumes and changes in aquifer interaction are interpreted in terms of this area and not confused with the entire extent of proposed CSG activities. The analysis above, and the analysis conducted by GA and Habermehl (2010) suggests that although large volumes of water will be extracted from the Walloon Coal Measures during extraction of CSG across the entire spatial extent of CSG, the changes to regional groundwater fluxes and balances of MDB aquifers due solely to CSG activities on the floodplain may be relatively minor. Depending on the water production scenario, estimated leakage between GAB aquifers induced by dewatering of the Walloon Coal Measures in any given development area varies between 0.07 – 111 % of recharge for individual GAB aquifers (GA and Habermehl, 2010). Reinjection into GAB aquifers could alleviate some of the predicted drawdown of these aquifers.

No estimates of induced leakage from the alluvial aquifer have been made, although drawdown of this aquifer has been predicted by one proponent (APLNG, 2010) to be on average 2m. This average drawdown predicted to occur over the next ~ 40 years is smaller than the drawdown that has occurred due to abstraction from some areas of the alluvium for agricultural production and smaller than drawdown predicted for GAB aquifers.
Induced leakage from the alluvial aquifer is likely to be variable depending on whether the Walloon Coal Measures have direct hydraulic connectivity to the alluvium or whether drawdown is induced indirectly via a GAB aquifer. CSG activity is likely to have little impact on processes of diffuse recharge to the alluvial aquifers. Riverine recharge may be impacted but, again, the volumes are not large, particularly in comparison to the abstractions associated with irrigation from aquifers and downstream surface waters.

Several aspects of the regional water balance remain unestimated or have only been estimated using analogue (by area equivalent) approaches rather than the preferred method of direct measurement. Recharge rates were computed using an area estimate by GA and Habermehl (2010) to provide an order of magnitude estimate for comparing with induced leakage rates for GAB aquifers. Current numerical modelling by proponents either does not include recharge or uses average rates. In reality, this process for both GAB and Alluvial aquifers is likely to be a stochastic process and only occur during high rainfall events. Sensitivity analyses for hydraulic properties and for stratigraphical conceptualisation could be conducted to improve understanding of likelihood of regional effects.

At a regional level better understanding of recharge processes and subsurface redistribution of water recharged to the GAB aquifers is required to better predict changes during repressurisation of the both GAB and alluvial aquifers and the coal measures. This is also important for determining reinjection strategy. Better constraining these hydraulic relationships will also help better understand potential consequent water quality changes in some parts of the system.

7.2 Local impacts

Although the proponents did not provide detailed estimates or contour maps of the predicted drawdown, the APLNG EIS modelling and subsequent information provided to GA suggests that in some areas large local decreases in potentiometric head could occur (APLNG, 2010, Vol 5 att 21; QGC, 2010; Santos, 2010). In particular, the area south of Miles and North East of Chinchilla and the area north of APLNG’s Gilbert Gully tenement were identified in the APLNG EIS cumulative case as areas of great drawdown of both the water table and underlying GAB aquifers (APLNG, 2010, Vol 5 att 21). It is important to note that the areas of greater drawdown were predicted from numerical models using regional
average hydraulic parameters. Local drawdown will be determined by local hydraulic conditions, including thickness of confining layers, and the presence of fractures or faults. There is currently insufficient information to determine the extent to which local drawdown will deviate from the average.

Data on hydraulic properties is scarce, there is evidence of considerable spatial heterogeneity in the hydraulic properties of some aquifers (Hodgkinson et al., 2010; KCB, draft in review), confining units (Hodgkinson et al. 2010) and Walloon Coal Measures (Hodgkinson et al., 2010; APLNG, 2010, Vol 5 att 21). Isopach thickness of the confining units is similarly variable. This variability could result in local drawdown that is dramatically different from the average predicted by current models.

In addition, the location of fractures and faults have not been included in the models or considered by the proponents. These features may alter local drawdown and connectivity of aquifers.

Numerical groundwater models will be required to be updated to include local data as it becomes available, this will likely necessitate improved parameterisation and process/stratigraphic representation in the models. Targeted areas for monitoring and additional data on hydraulic properties should be prioritised. Ongoing validation of model predictions of drawdown and water production could provide insights into areas that may require better characterisation and/or additional monitoring. Water production data must also include water produced during exploration as this extraction will contribute to the water deficit of the system. It is not clear that this is currently included in water production estimates.

Water quality analyses, including isotope tracers and dating of waters may aid in identification of changes to local hydraulic conditions. Changes in water types and salinity in the Central Condamine Alluvium in combination with analysis of water levels have been interpreted to be indicative of hydraulic exchange between the alluvium and underlying Walloon Coal Measures and sandstone aquifers. Colloquial reports of changes to water quality in some Condamine Alluvium water bores have been reported. However, good quality water quality time series from individual bores were not available for this study. Given the heterogeneity of water quality in the alluvium (KCB, draft in review) changes to
bore water quality may occur due to lateral migration of poor quality water rather than changes to vertical connectivity with the underlying Walloon Coal measures or GAB aquifers.

In summary, given the certainty of variability/spatial heterogeneity in stratigraphy, hydraulic properties, recharge rate variations and hydraulic connectivity of aquifers and intervening regolith, it is certain that local effects will occur. The nature of these effects can be described. However, where and when they will manifest will remain unpredictable until more data is available. It is important that communities are made aware of the types of effects that may occur and that the governing authorities have adaptive management processes in place to deal with them when they arise.

7.3 Gaps

Many of the gaps identified in this work are similar to those identified by GA and Habermahl (2010). In particular, there appears to be little data that quantifies spatial variation in fundamental aquifer hydraulic properties. For impacts to be predicted and adequate management to be put in place then these data would need to be collected and be made available to the government, and the Queensland Water Commission.

To allow improvements in the assessment of aquifer drawdown and impact on other water users, the proponents would need to provide spatially explicit contour maps of the drawdown areas. The cumulative effect of all proponent activities is currently not able to be assessed.

All the proponents have postulated an adaptive management regime to development, with monitoring networks of water levels and water quality. The adaptive management loop will also need to include ongoing updating of the groundwater models used to predict drawdown with data on the hydraulic properties as well as ongoing review of the predicted with measured drawdown. Data required for this would need to include storativity, horizontal and vertical permeability for both aquifers and confining units. It will be critical to establish in advance what corrective measures will be enacted (risk mitigation strategies) when local effects occur.
The proponents acknowledge uncertainty in their estimates of water production. The average annual production estimates of QGC for example are ± 50% (GA and Habermehl, 2010). There are significant differences between different methods for estimating the amount of associated water depending on modelling approach, information available and assumptions regarding gas production quantities over time. Individual well water production should be monitored and data made available to the government along with water:gas profiles. These would be required to monitor predicted and actual water production allowing better forecasting predicted drawdown and aquifer impacts. Further, to improve modelling and forecasting assumptions and methods for estimating associated water would need to be explicitly stated with error estimates to ensure comparability of different estimation techniques and the volumes predicted.

A great deal of relevant data is currently held by the proponents. To enable this data to be included in models and assessments of cumulative impacts, data provided by proponents could be held as confidential for a period of time before becoming publically available. This would ensure the competitive and commercial interests of the companies while allowing the government to review model predictions and monitoring results thereby increasing the certainty of impact prediction and a timely and appropriate management response.

Vertical permeability and connectivity between aquifers has not been well quantified. Full sensitivity analyses should be done using project and cumulative scenarios for the likely range of hydraulic variables. Results need to be spatially explicit and presented as contour plots.

The impact of such large scale dewatering and changes to capillary pull of the coal seams is completely unknown.

Existing faults and fractures must be accounted in the models, or at least signalled as areas of concern. To enable models to be kept up to date, ongoing monitoring of water levels and water production (including during exploration) in areas with known faults or fractures should be compared with modelled predictions and the models updated. In some areas analysis of the water:gas profile of different wells in relation to known locations of faults or fractures may be a useful first assessment of the importance of these fast flow paths.
8 References


Condamine Catchment Management Association (CCMA) (1999) Condamine Catchment
Strategic Plan.

Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO,
Australia.

Basin. Report to the Great Artesian Basin Coordinating Committee under the auspices of a
Consultancy Agreement: Commonwealth Dept of Environment and Water Resources,
Canberra

Hillier, J.R. (2010) Groundwater connections between the Walloon Coal Measures and the

Huxley, W. J. (1982). Condamine River Groundwater Investigation, The hydrogeology,
hydrology and hydrochemistry of the Condamine River valley Alluvium, Queensland Water
Resources Commission.

KCB, (draft in review). Central Condamine Alluvium. Stage II Conceptual Hydrogeological
Summary. Final Report. DERM

and J. R. Hillier (2003). Groundwater Recharge in the Great Artesian Basin Intake beds,
Queensland. Final Report for NHT Project 982713 Sustainable Groundwater use in the GAB
Intake Beds, Queensland.

Lane, W. B. (1979). Progress Report on Condamine Underground investigation to December


prepared for Department of the Environment and Water Resources, Australian Government,
Canberra.
9 Appendix 1: Terms of Reference

Terms of Reference for an independent expert study under s255AA of the Commonwealth Water Act 2007

Background

1. Section 255AA – Mitigation of unintended diversions – of the Commonwealth Water Act 2007 states that:

   “Prior to licences being granted for subsidence mining operations on floodplains that have underlying groundwater systems forming part of the Murray-Darling system inflows, an independent expert study must be undertaken to determine the impacts of the proposed mining operations on the connectivity of groundwater systems, surface water and groundwater flows and water quality”.

2. The preconditions for triggering this provision and necessitating an independent expert study (referred to hereafter as “the study”) are:

   • It needs to be a subsidence mining operation;
   • It needs to be on a floodplain; and
   • It needs to have potential to impact on Murray-Darling Basin (MDB) system inflows.

3. Based on advice in a report by Geoscience Australia (Geoscience Australia and Habermehl 2010), the location and nature of current proposed coal seam gas (CSG) developments in Queensland mean that the above preconditions may potentially be met and it is therefore prudent to commission an independent expert study.

Scope of work

4. The study will seek to determine the impacts of the proposed mining operations on the connectivity of groundwater systems, surface water and groundwater flows and water quality in the Murray-Darling Basin.

5. The study will be conducted by an independent expert with relevant science qualifications and experience and be assisted by Geoscience Australia.
6. The study will involve a review of all available information on the proposed developments, including reports by the Queensland Coordinator General, Geoscience Australia, and other relevant information. The independent expert will be able to request further information from the CSG proponents and other experts as they see fit. In particular, the independent expert will engage with holders of relevant technical data, information and knowledge, including:

- the proponent companies: Santos, British Gas, AP LNG, Arrow, and Shell;
- science and data agencies within the Commonwealth and Queensland governments; and
- the Murray-Darling Basin Authority.

**Governance**

7. The Commonwealth Department of Sustainability, Environment, Water, Population and Communities (DSEWPAC) and the Queensland Department of Environment and Resource Management (DERM) will jointly facilitate technical and logistical support as requested by the independent expert. Senior officials of both agencies will form a joint liaison committee for this purpose.

8. The final report will be provided to the Commonwealth and Queensland governments, who may make the report publicly available.

**Timeframe**

9. The review will be completed no later than 22 November 2010. A draft report will be provided to the joint liaison committee by no later than 8 November 2010.

Three CSG operators have used groundwater models to estimate drawdown in surrounding aquifers due to CSG activity. APLNG used FEFLOW a finite element groundwater simulation model with 22 layers and variable sized elements. The model had a finer (3km) mesh close to APLNG tenements that increased to 12km at distances greater than 70km from the tenements. QGC and Santos used MODFLOW, a finite difference model approach, in their EIS. All models were assessed by GA and Habermehl (2010) as providing reasonable preliminary estimates of likely impacts of dewatering for CSG extraction. The model used by APLNG was clearly superior in its extent, conceptualisation, discretisation (i.e. greater number of layers represented, particularly in the Walloons and smaller spatial elements) and calibration.

No information was available from Arrow to provide an assessment. However, the cumulative case presented by APLNG includes projected water production from the development of all tenements in the area under study.

The conceptualisations of the groundwater systems used by the proponents were consistent with previous work. The models also represented structural geological features based on stratigraphic interpretation derived from company records, DERM and GSQ.

All the proponent models contained significant assumptions that introduce uncertainty into the predicted drawdowns and changes to water balance of surface water, alluvial and GAB groundwater systems.

These assumptions include:

- Average hydraulic parameter values for each layer based on literature values for all layers - except perhaps Walloons in APLNG
- Vertical hydraulic conductivity data is lacking; APLNG used assumed anistrophy values
- APLNG assumed uniform storativity value 4 x 10^-6 (derived from pump test in precipice near Kogan Ck) and specific yield 0.03 in upper layers. GA and Habermehl (2010) suggested that these values may be low estimates.
- The APLNG model included recharge estimates for the upper alluvial layers based on Kellett et al., (2003), Lane (1979) and Huxley (1982). The QGC model did not include recharge.
- The QGC model assumed constant head boundary at the model domain
- All models assumed the Precipice sandstone to be a no flow boundary (ie no connectivity with the underlying Bowen Basin)

There was a general consensus that there is a paucity of data against which to calibrate the models. The methods by which the models were calibrated varied between proponents. QGC calibrated the model by matching predicted water production. Estimates of water production were reported to have an uncertainty of + 50% and four water:gas typologies were identified. The method by which these typologies were used to estimate water production is not clear. APLNG and Santos calibrated the models against measured water levels. The models relied heavily on calibration to set the values used in model runs in particular hydraulic conductivity values. None of the proponents specified hydraulic properties after calibration used to produce drawdown estimates.

There was no representation of fractures and faults- this could represent a significant source of underestimation of drawdown and may be exacerbated where well completion includes fraccing.