Arrow Energy

Surat Gas Expansion Project – CSG WMMP

Section 13(b)

CDM Smith

Arrow Energy

Surat Gas Expansion Project – CSG WMMP Section 13(b)

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Executive Summary

Arrow Energy ("Arrow") received approval for the Surat Gas Expansion Project (the "Approval") in December 2013. Under the terms of the Approval, Arrow needs to prepare and gain approval for a Stage 1 CSG Water Monitoring and Management Plan ("CSG WMMP" or "CWMMP") before it can start producing coal seam gas ("CSG") as part of the Surat Gas Expansion Project.

Section 13(b) of the Approval requires Arrow to prepare "a *fit for purpose numerical simulation* to assess *potential impacts on water resources arising from the action in the project area*, *subsequent surface water-groundwater interactions* in *the Condamine Alluvium* and *impacts to (sic.) dependent ecosystems*".

This report provides a brief introduction to the CSG project (the "Project") which is "*the action*" under consideration, and a summary of water resources, surface water – groundwater interaction and dependent ecosystems, in the area known as the Condamine Alluvium.

In preparing a "*fit for purpose numerical simulation*", this report relies on models developed and/or managed by the Office of Groundwater Impact Assessment (OGIA), the Department of Natural Resources and Mines (DNRM) and the Department of Science, Information Technology and Innovation (DSITI) in Queensland. These models are based on the most comprehensive collations of data available at the time they were developed. Rather than developing a new model or suite of models, CDM Smith has used the Surat Cumulative Management Area (CMA) Groundwater Model (often referred to as the "OGIA model"), the Central Condamine Alluvium Model (CCAM) and Integrated Quantity and Quality Modelling (IQQM) software, knowing that all three have been used in various combinations in environmental impact assessment of large-scale resources projects.

Potential impacts have been evaluated rigorously in the past, by the developers of existing models, and again during this study, using existing models. This report explains the connections and relationships between models in more detail than in earlier reports. The OGIA model predicts the amount of water that will be produced (co-produced) during production of CSG over a period of 65 years. The zone of depressurisation caused by CSG production will draw groundwater towards that zone to replace the produced water, but complete recovery will take in the order of 3,000 years. The maximum reduction in flux from underlying hydrostratigraphic units to the Condamine Alluvium, caused by Arrow's water production, is predicted to occur around 45 years from now, and to be slightly less than 3 ML/d within the area of the Condamine Alluvium, an area of about 8,000 km^2.

The maximum reduction of flux to the Condamine Alluvium of 3 ML/d is equivalent to 1 GL/y and can be compared with current licensed groundwater abstraction of 87 GL/y in the four sub-management areas of the Central Condamine Alluvium (DNRM 2014). The predicted reduction in flux across the base of the Condamine Alluvium caused by Arrow will increase from zero to 1 GL/y over a period of approximately 45 years, with the time of maximum in around year 2050, and then fall again to zero over almost 3,000 years, with 30 to 50% recovery in flux rate approximately 65 to 135 years after the maximum change in flux.

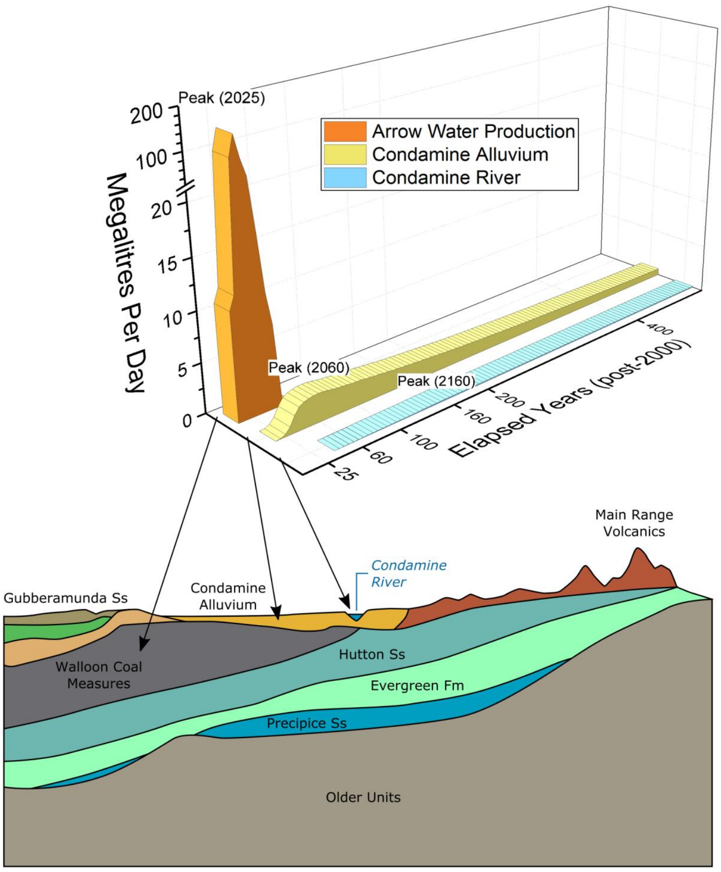
The predicted maximum change in flux across the base of the Condamine Alluvium caused by Arrow is 2.97 ML/d, which when distributed over 5,321 km^2 of alluvium is equivalent to an average change in flux of 0.21 mm/y in the year when the maximum occurs. At the water table, the predicted rate of change in elevation is of the order of 1 to 2 mm/y and is imperceptible compared to background rates of change, which can be greater than 1 m/y (three orders of magnitude larger) and with fluctuations up to tens of metres during irrigation seasons (MDBA, 2012). The very low rates of change in water table elevation caused by Arrow water production, compared to other influences indicates negligible impacts to stygofauna from CSG development.

The Condamine River is disconnected from the underlying water table and losing water along much of its length (CSIRO 2008). This is confirmed by independent analysis of water table elevations relative to bed levels of rivers and streams.

Slight lowering of piezometric head in groundwater in the Condamine Alluvium will tend to increase the leakage of surface water from rivers and streams to groundwater in the alluvium. The maximum increase in flux of surface water from the Condamine River to groundwater, as a result of Arrow's water production, is predicted to be less than 0.13 ML/d (0.05 GL/y) with the time of maximum occurring in around year 2160, approximately 145 years from now.

CSIRO (2008) reported that average surface water availability in the Condamine-Balonne was 1,363 GL/y, of which 53% was diverted for use. The potential impact of Arrow's CSG production has been simulated using the IQQM software. The IQQM software suggests that any additional diversion will have almost no influence on performance indicators with respect to Environmental Flow Objectives (EFOs) and Water Allocation Security Objectives (WASOs). The IQQM software does not explicitly include CSG, but the impact of additional demands (such as leakage) can be assessed by modifying the setup of the IQQM software. The predicted maximum change in flux from the Condamine River to groundwater of 0.05 GL/y caused by Arrow's water production is less than 0.004% of the surface water availability in the Condamine-Balonne reported by CSIRO (2008).

Potential impacts on dependent ecosystems (DEs) depend on the amount of change in water table elevation and the rate of change. Assuming constant climate and absence of major flood events, the maximum drawdown in the Condamine Alluvium as a result of CSG production is predicted to be of the order of 1 m, and it will take hundreds of years to reach that maximum drawdown, before a long slow recovery. The maximum drawdown is small enough and the rate of change in water table elevation is slow enough for dependent ecosystems to adapt and survive.



Predicted groundwater fluxes induced by Arrow for the high-case model realisation

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Section 1 Introduction

1.1 Preamble

Arrow Energy ("Arrow") received approval for the Surat Gas Expansion Project (the "Approval") in December 2013. Under the terms of the Approval, Arrow needs to prepare and gain approval for a Stage 1 CSG Water Monitoring and Management Plan ("CSG WMMP" or "CWMMP") before it can start producing coal seam gas ("CSG") as part of the Surat Gas Expansion Project (the "Project").

> **The Approval**
>
> Section 13(b) of the Approval requires Arrow to prepare "a *fit for purpose numerical simulation* to assess *potential impacts on water resources arising from the action in the project area, subsequent surface water-groundwater interactions* in *the Condamine Alluvium* and *impacts to (sic.) dependent ecosystems*".

CDM Smith was engaged by Arrow in June 2014 to scope a number of activities aimed at meeting the requirements of Section 13(b). Those activities commenced late in 2014 and are reported here.

The work reported here has been undertaken in the knowledge that Arrow prepared and submitted a formal Environmental Impact Statement (EIS) (Coffey Environments 2012), and later prepared and submitted a Supplementary Report to the Environmental Impact Statement (SREIS) (Coffey Environments 2013). The EIS and SREIS reports covered all aspects required by State and Federal Governments, and led to the Approval referred to above.

Approval for the Project relies on models developed for the Queensland Water Commission (QWC), now known as the Office of Groundwater Impact Assessment (OGIA), and others. Because of the lead-time required to address Section 13(b), Arrow commissioned CDM Smith in 2014 to prepare this response to Section 13(b) based on models known by that time as the OGIA model(s). These models had been developed for QWC to support the preparation of an Underground Water Impact Report (UWIR) for the Surat Cumulative Management Area (CMA) (QWC 2012a).

A "consultation draft" of a revised UWIR was released in March 2016 (OGIA 2016). No information has yet been published about new OGIA models

1.2 Objective

The objective of this report is to present the results of studies undertaken to meet the requirements of Section 13(b), as quoted in italics above. This report has been prepared by CDM Smith as a standalone document with the expectation that the report will be provided to reviewers and regulators in its entirety, while at the same time being summarised in the CWMMP.

1.3 Approach

The approach taken by CDM Smith has been to analyse the wording of Section 13(b), in the context of other parts of the Approval, and to propose and prepare a "*fit for purpose numerical simulation*" as required.

Interpretation of Section 13(b) relies on the fact that Section 13 has 17 other clauses.

Furthermore, the work has been undertaken in the context of Section 14 of the Approval, which requires that the "*CSG WMMP must be peer reviewed by a suitable qualified water resources expert/s approved by the Minister in writing*", with the "*peer review submitted to the Minister together with the Stage 1 CSG WMMP and a statement from the suitably qualified water resource/s expert/s stating that they carried out the peer review and endorse the findings of the Stage 1 CSG WMMP*".

1.3.1 Reliance on the Most Recent OGIA Model and Other Recent Models

Section 13(**a**) of the Approval requires Arrow to provide "*an analysis of the results of the most recent OGIA model (built or endorsed by OGIA), relevant to all of the project's tenement areas*".

Section 13(**p**) requires "*a cumulative impact assessment based on the outputs of the OGIA model which integrates groundwater model outputs with known and potential groundwater dependent ecosystems and presents the outputs in map form*".

Regulators have accepted the OGIA model as the best possible representation of groundwater flow processes based on the most comprehensive collation of data available at the time of its preparation (in 2012). CDM Smith and Arrow have therefore chosen during preparation of this response to Section 13 (**b**) to rely on:

- the most recent available (regional scale) OGIA model (QWC 2012a, 2012b, 2012c; GHD 2012);
- the most recent available (local scale) Central Condamine Alluvium Model (CCAM) run by OGIA in parallel with and effectively as part of the OGIA model (QWC 2012a, KCB 2011b); and
- the most recent available Integrated Quantity and Quality Modelling (IQQM) models developed by the Department of Natural Resources and Mines (DNRM) for management of surface water resources in the Condamine River and its tributaries (Simons et al. 1996; Paul Harding pers.comm.).

In other words, given the significant investment by Government agencies in the development of models of groundwater and surface water processes, CDM Smith and Arrow have chosen to utilise models that have been reviewed and used by others, rather than to build new models that might be similar but slightly different, based on smaller amounts of data, and requiring additional review.

A "*fit for purpose numerical simulation*" does not mean development and execution of a single numerical model. Given the range of spatial and temporal scales that need to be taken into account, a number of models of different types can be run in combination and iteratively to gain a more complete and useful understanding of processes than would be possible with a single model. The focus of this report is on "modelling", rather than on a single model.

1.3.2 Peer Review and Site Visit

Knowing from the outset that the whole of the CWMMP would be peer reviewed by a water resources expert approved by the Minister in writing, and knowing that this project addressing Section 13(b) has been considered to be a long lead-time component of the CWMMP, an important part of this project was engagement with the peer reviewer, starting in advance of work on other parts of the CWMMP.

In July 2015, Arrow confirmed that the Minister had approved the appointment of Dr Glenn Harrington (Innovative Groundwater Solutions) as a suitably qualified water expert. It was decided that it would be beneficial for the project team to meet the peer reviewer well before completion of the project, in order to discuss progress to date, and the methodology proposed and adopted to meet the requirements of Section 13(b).

A meeting took place at Arrow's office in Brisbane on the morning of Tuesday 11 August 2015, to discuss progress, methodology and a site visit over the coming days. The meeting was attended by:

- Simon Gossmann (Arrow Energy);
- St.John Herbert (Arrow Energy);
- Dr Glenn Harrington (Innovative Groundwater Solutions);
- Dr Lloyd Townley (CDM Smith);
- Dr Tony Smith (CDM Smith); and
- Dr Dougal Currie (CDM Smith).

On the afternoon of Tuesday 11 August, another meeting was held at the offices of the National Centre for Engineering in Agriculture (NCEA) at the University of Southern Queensland (USQ) in Toowoomba. The purpose of the meeting was to discuss the project with hydrologists based in the region and with expertise in the area known as the Condamine Alluvium. The meeting was attended by:

- five representatives of Arrow (all of those listed above, except Simon Gossmann);
- Dr Mark Silburn (Queensland Department of Natural Resources and Mines, DNRM);
- Dr Andrew Biggs (Queensland Department of Natural Resources and Mines, DNRM); and
- Dr Elad Dafny (University of Southern Queensland).

While at USQ, the five representatives of Arrow also met with Ken Klaasen, senior hydrographer for DNRM.

During the next 48 hours, the five representatives of Arrow explored:

- the full length of the Condamine Alluvium from west of Chinchilla to Yarramalong Weir;
- the catchments of Wambo Creek, Charleys Creek, Couranga Creek and Jimbour Creek;
- the area known as Long Swamp;
- the area surrounding Lake Broadwater (to the south of the Condamine Alluvium); and
- the region upstream of Cecil Plains where the Condamine River has a northern anabranch.

The team visited nearly all weirs along the length of the Condamine River where it lies above the Condamine Alluvium, and most publicly accessible stream gauging stations and groundwater observation bores. The overarching purpose of the site visit was to allow open discussion and to develop a shared understanding of the nature of water resources, surface water – groundwater interaction and dependent ecosystems in the area of the Condamine Alluvium.

Additional meetings took place in Melbourne in June 2016, to review a draft of this report.

1.4 Magnitude of Potential Impacts

At the start of this assessment of potential impacts, it is useful to consider the nature and magnitude of the impacts being assessed. Conceptualising the processes that are expected to take place may help stakeholders to imagine the nature of the impacts that will ultimately be predicted. Conceptualisation is the essential first step taken by professionals in the process of developing and running simulation models to predict potential impacts.

In many respects, Section 13(b) seeks an assessment of potential impacts that is similar to the assessment that was undertaken during preparation of the EIS (Coffey Environments 2012) and SREIS (Coffey Environments 2013). Potential impacts were assessed almost concurrently by QWC during preparation of a UWIR for the Surat CMA to assess the impacts of CSG production by all CSG producers (QWC 2012a).

QWC's focus was on predicting the impacts of production by all producers, not only by Arrow. Section 6.3.2 of QWC (2012a) explains that "the maximum predicted" drawdown in the Condamine Alluvium "is about 1.2 m on the western edge of the alluvium, with an average of about 0.5 m for most of the area". According to QWC (2012a), "declining water levels" (pressures and heads) "in the Walloon Coal Measures are likely to start affecting the Condamine Alluvium around 2017". "Induced leakage" (a reduction of discharge from surrounding units to the Condamine Alluvium) "will continue long after the cessation of CSG water extraction". "The average estimated net loss from the Condamine Alluvium to the Walloon Coal Measures is expected to be about 1,100 ML/y (1.1 GL/y) over the next 100 years." "Maximum impacts in any aquifer will occur at different times at different geographic locations". "Maximum impacts in the … Condamine Alluvium are expected to occur between 2060 and 2075".

Arrow's SREIS (Coffey Environments 2013) included the results of revised numerical modelling undertaken using the model prepared by QWC and used to support the UWIR (QWC 2012a). In order to predict the potential impacts of Arrow's CSG production (the "Arrow-only Case"), impacts were calculated (see Section 8.3.2 in Coffey Environments 2013) as the difference between predicted levels and flows for the "Cumulative Case" (including CSG production by GLNG[1], QCLNG, APLNG and Arrow's proposed Surat Gas Expansion Project) and the "Base Case" (including CSG production by GLNG, QCLNG and APLNG). The results for the Arrow-only Case (see Section 8.4.3 and Table 8.7 in Coffey Environments 2013) include predictions of: average drawdown of 0.18 m in the Condamine Alluvium; maximum drawdown of 0.5 m near Dalby in 2100, 105 years after the start of model runs in 1995; and 65 GL of impact on fluxes between deeper units and the Condamine Alluvium over 100 years, being an average of 650 ML/y (0.65 GL/y).

These predictions are summarised here to provide context, prior to much more detailed analysis in this report. Several characteristics of predictions are important to keep in mind:

- all potential impacts vary in space and time;
- there are important distinctions to be made between the volumes of water pumped (produced) from deep coal seams in order for CSG to be released and produced, the changes in fluxes between hydrostratigraphic units (HSUs) beneath and beyond the Condamine Alluvium and the Condamine Alluvium itself, and possible changes in surface water – groundwater interaction between the Condamine River and its tributaries and the water table in the Condamine Alluvium;

[1] GLNG: Gladstone Liquefied Natural Gas; QCLNG: Queensland Curtis Liquefied Natural Gas; APLNG: Australia Pacific Liquefied Natural Gas.

- there are important distinctions between the depressurisation that must occur at depth in coal seams in order for CSG to be released and produced, the depressurisation that may occur in hydrostratigraphic units (HSUs) beneath and beyond the Condamine Alluvium as the hydrogeological system recovers after the end of CSG production, and drawdown at the water table in the Condamine Alluvium;
- the focus of predictions in the UWIR is on the next 100 years, even though some potential impacts will peak much later; and
- there is an important distinction to be made between the potential impacts of Arrow's production and the potential cumulative impacts of Arrow's production including the potential impacts of production by other CSG producers.

All of these matters will be discussed in detail in this report.

1.5 Structure of this Report

The structure of this report reflects the requirements of Section 13(b).

The structure has similarities with the structure of a complete EIS, in the sense that one section describes the proposed Project, three sections describe parts of the environment and natural processes prior to the Project, one section describes the methodology used for assessing potential impacts of the Project on the environment, and a final section summarises potential impacts of the Project on the environment. The naming of sections is based directly on Section 13(b).

- Section 2 describes conceptualisation, because this is fundamental to understanding and simulation. A brief introduction is provided to the physical setting (including topography, geology and hydrogeology), the extent of "*the Condamine Alluvium*" (because this is explicitly referred to in Section 13(b)), and aquifer connectivity.
- Section 3 describes the Surat Gas Expansion Project, being "*the action in the project area*" whose potential impacts Arrow is required to assess.
- Section 4 describes surface water and groundwater resources, in order to explore what is known about "*water resources*" in and near the Project area, especially those that might be considered to be affected by the Project. Most water resources are accessed within the area of the Condamine Alluvium. This Section includes reference to sources of information, as well as legislation and policies that influence the management of water resources.
- Section 5 describes the nature of "*surface water – groundwater interactions*" in the area of the Condamine Alluvium. The Section starts with a discussion of stream-aquifer interaction, with gaining, losing and flow-through reaches, and then explores the distinction between losing connected and losing disconnected streams. The geometry of the Condamine River and its tributaries is explored, considering the relationship between streambed elevation and measurements of water table elevation nearby. The Condamine River is neither permanently wet nor permanently flowing, so temporal variability of flows and depths of surface water is likely to have a significant effect on surface water – groundwater interaction. Methods for simulating surface water – groundwater (stream – aquifer) interaction in the Condamine River and its tributaries are discussed.
- Section 6 describes "*dependent ecosystems*" (DEs), including ecosystems that may depend on surface water, groundwater or both. The initial focus is on the Condamine River and its tributaries, but dependencies on flood plains are also mentioned. The primary focus is on Aquatic Flora and Fauna Type DEs and Terrestrial Ecosystem Type DEs.

- Section 7 describes the modelling that has been undertaken, and explains how the modelling satisfies the requirement for a "*fit for purpose numerical simulation*". This Section has many parts. At least four main types of modelling have been undertaken, including regional scale groundwater modelling, near field simulation of surface water – groundwater interaction, simulation of groundwater in the Condamine Alluvium, and surface water allocation modelling using IQQM.
- Section 8 addresses "*potential impacts*" of the Surat Gas Expansion Project. The impacts are considered under three headings: water resources, surface water – groundwater interaction and dependent ecosystems. The primary focus is on the impacts of Arrow's production, rather than on cumulative impacts.
- Section 9 provides a summary of the report and its key conclusions.

Section 2 Conceptualisation

2.1 Preamble

The purpose of this section is to prepare the reader for the detailed discussions that follow, focused on the requirements of Section 13(b). The section includes descriptions of the physical setting; the extent of the "*Condamine Alluvium*"; hydrogeology and aquifer connectivity; and groundwater flow processes.

Conceptualisation

The Condamine Alluvium is a surficial hydrostratigraphic unit (HSU) in an area near the eastern margin of the Surat Basin, west of the Great Dividing Range. The Walloon Coal Measures subcrop much of the area of the Condamine Alluvium, and dip gently to the west.

The topography in the area of the Condamine Alluvium has little relief, especially compared to the hills to the east.

Under natural conditions, prior to pumping for agricultural and other demands and prior to CSG production, groundwater flowed towards the Condamine Alluvium from east and west, ultimately discharging to the Condamine River. Significant withdrawals have led to lowering of the water table in the Condamine Alluvium, and less discharge to the Condamine River and its tributaries.

Production of CSG by Arrow will require pumping of water from the Walloon Coal Measures. Depressurisation will lead to a tendency for lower discharge from the Walloon Coal Measures to the Condamine Alluvium. In time this will lead to a slight reduction in water table elevation in the Condamine Alluvium, but this may not cause greater leakage from the Condamine River to groundwater, because the river and the water table are already "disconnected", with leakage already at occurring at the maximum possible rate along most of the length of surface drainage lines.

2.2 Physical Setting

Topography is fundamental to consideration of surface flows, flooding and surface water – groundwater interaction (see Figure 2-1).

- LiDAR (Light Detection and Ranging) data were obtained over Arrow's Surat tenements between 16 June and 29 July 2012. The LiDAR dataset has a horizontal resolution of 1 m, with accuracy of 0.29 m horizontally and 0.12 m vertically (Fugro Spatial Solutions Pty Ltd). Figure 2-1 shows the LiDAR survey footprint. Only part of the Condamine Alluvium and part of the length of the Condamine River are covered by LiDAR data. Since LiDAR data are the most accurate measurements available, they have been used in this study to infer depth to groundwater wherever possible.

- Geoscience Australia (GA) offers a suite of SRTM-derived products (Shuttle Radar Topography Mission) for the whole of Australia. The horizontal resolution of GA's digital elevation map (DEM) is 1 second (approximately 30 m). The vertical accuracy of the dataset varies but is said to be 7.592 m at the 95th percentile on flat terrain. This accuracy is only true in "not densely vegetated" or "high relief" areas (Gallant et al. 2011). The data are important to this study because they provide estimates of depth to water table in areas where LiDAR data are not available.

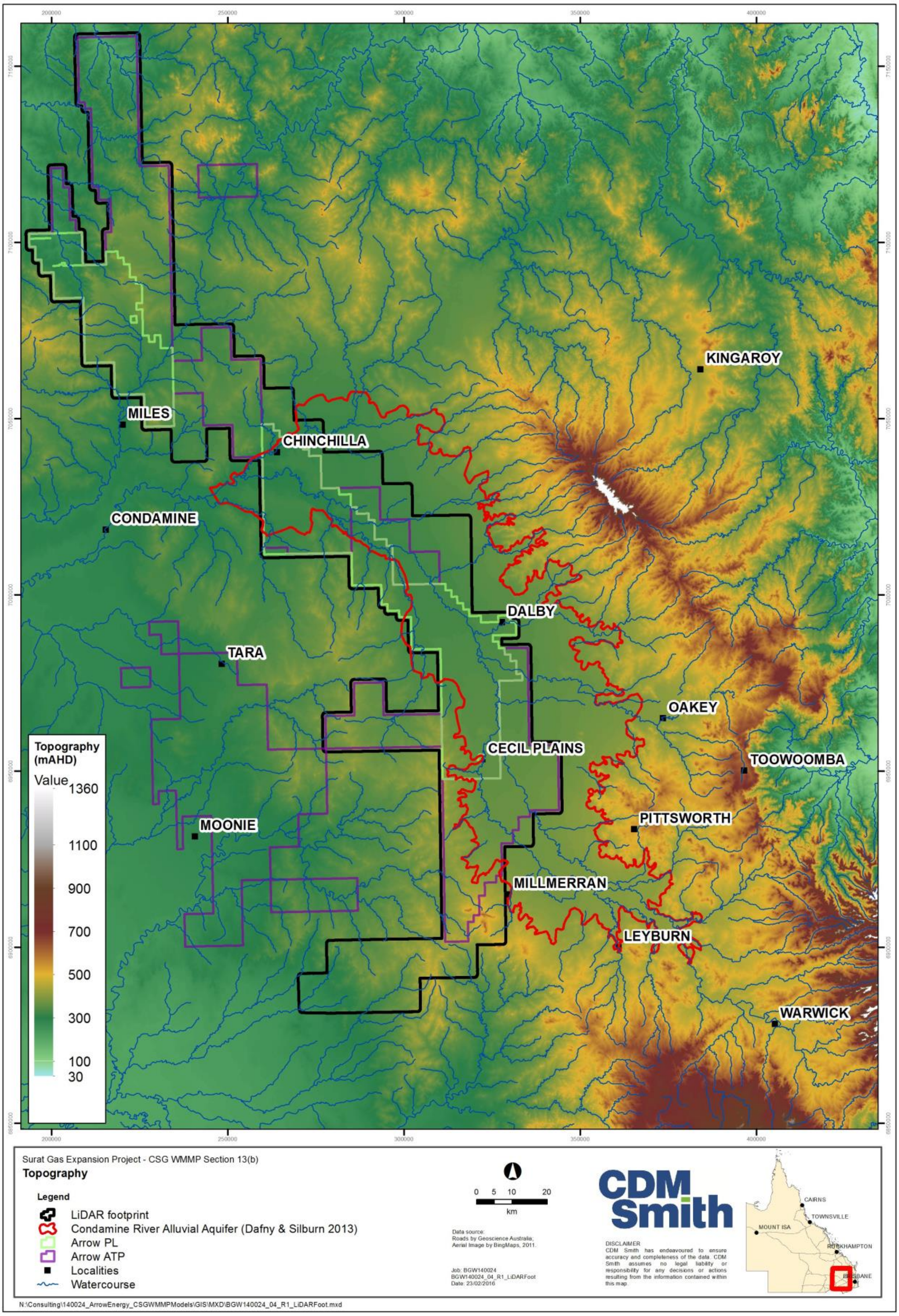

Figure 2-1 Topography

- Each of the groundwater flow models used in this study (the most recent available OGIA regional scale model, and the most recent available local scale Condamine Alluvium model run by OGIA in parallel with and effectively as part of the OGIA model) includes a representation of surface topography, at the resolution of finite difference cells. All modelling relies on these levels embedded in the models.

2.3 Condamine Alluvium

Section 13(b) of the Approval requires an assessment of "*surface water-groundwater interactions in the Condamine Alluvium*". This suggests that it is important to have or develop a shared understanding of what is meant by the "Condamine Alluvium", in particular its spatial extent.

Section 13(b) refers to the Condamine Alluvium because the Condamine River is a major river in the area, especially when it flows and floods, and because it is an important part of the hydrological system. The Condamine Alluvium is important as a groundwater resource, and the soil is fertile and used for farming. Surface water – groundwater interactions are most likely to occur along the length of the Condamine River and its major tributaries, all of which flow episodically, in response to significant rainfall events.

Environmental impact assessments by proponents of CSG projects near the Condamine Alluvium include representations of the alluvium, as well as regional hydrogeological systems that cover a much larger area. The regional groundwater flow model developed by QWC, now known as the OGIA model, covers an area of 360,000 km^2 (550 km x 660 km), of which the active area is about 280,000 km^2. The footprint of the Condamine Alluvium in the Surat CMA groundwater model covers an area of 5,904 km^2. The Condamine Alluvium covers about 2% of the area of the OGIA model.

There is no universally accepted definition of the extent to the Condamine Alluvium. Figure 2-2 shows four different boundaries of the Condamine Alluvium, chosen by different authors for different purposes:

- Dafny and Silburn (2013) collated available data from different water disciplines to assess the hydrogeology of the Condamine River Alluvial Aquifer (CRAA). They concluded that the lack of historical measurements combined with the lack of defined "closed" boundaries complicates the conceptualisation of the aquifer, especially its water balance and hydrogeological processes. During that study, they developed a boundary for the CRAA.
- A boundary of the Condamine Alluvium groundwater management area was developed by DNRM in 2013 and later revised (DNRM 2015a). This boundary is smaller and seems to include only the Central Condamine Alluvium (CCA).
- The Bureau of Meteorology (BOM) Geofabric Groundwater Cartography is a set of groundwater boundaries obtained from the best available digital groundwater data sourced from Commonwealth, State and Territory jurisdictions as part of the Australian Water Information Dictionary Interim Groundwater Data (IGWD) project.
- The domain of the Central Condamine Alluvium Model (CCAM) (KCB 2011b) follows a boundary chosen to include the Central Condamine Alluvium (CCA) and the Lower Condamine Alluvium (LCA).

Section 13(b) refers to "*surface water – groundwater interactions in the Condamine Alluvium*", which suggests that the alignment of the Condamine River and major tributaries, where they overlie the alluvium, is more important than the boundary of alluvium itself. The length of rivers and river beds overlying the alluvium is important hydrologically.

The CRAA boundary (shown in red in Figure 2-2) has been adopted for many purposes in this study (see also Figure 2-1). The decision to choose this boundary was based on discussions with Elad Dafny, Mark Silburn and Andrew Biggs in Toowoomba on 11 August 2015, largely because their work is based on extensive field work in the Condamine Alluvium (local knowledge) and they are confident that the boundary proposed by Dafny and Silburn (2013) is the best possible boundary at this time. The authors believe that the BOM boundary (shown in black in Figure 2-2) includes soils that should not be classified as Condamine Alluvium.

The CCAM boundary (shown in green in Figure 2-2) is also used in this study, for practical reasons, i.e. since the report relies extensively on the CCAM, it is possible to extract fluxes for cells inside the boundary of the CCAM but not outside that area.

The real question is whether the choice of boundary makes a significant difference, in practice or to the findings of this study. The bed of the Condamine River and its tributaries lies above the regional water table along nearly all of the length of these drainage lines where they overlie the Condamine Alluvium. Leakage of surface water to the water table is already occurring, and is not expected to increase significantly if the water table elevation declines. For this reason, the choice of boundary is not of critical importance.

2.4 Hydrogeology and Aquifer Connectivity

The focus of Section 13(b) is on potential impacts in the area of the Condamine Alluvium, partly because this is an area where impacts may occur, and also because stakeholders are particularly interested in potential impacts in this area. It is important at the outset to have a shared understanding of why this is the case. The answer depends on conceptualisation of hydrogeological and hydrological processes that has evolved over a number of years, prior to and during the preparation of a number of environmental impact assessments by proponents of CSG projects in the Surat Basin.

Table 2-1 lists a number of studies that have been undertaken in recent years, with reports totalling nearly 4,000 pages in length. The purpose of this list is to emphasise the fact that conclusions reached in this study rely on a significant body of earlier work.

Table 2-1 Key studies of groundwater in the Surat Basin and the Condamine Alluvium

Purpose	Reference	No. of pages
Studies of groundwater in the Condamine Alluvium	Central Condamine Alluvium Data Availability Review (KCB 2010a)	98
	Condamine Alluvium Stage II – Conceptual Hydrogeological Summary (KCB 2010b)	192
	Central Condamine Alluvium Stage III – Detailed Water Balance (KCB 2011a)	78
	Central Condamine Alluvium Stage IV – Numerical Modelling (KCB 2011b)	139
UWIR for the Surat Cumulative Management Area	Surat CMA Underground Water Impact Report (QWC 2012a)	224
	Hydrogeology of the Surat Cumulative Management Area (QWC 2012b)	144
	Surat Cumulative Management Area (CMA) groundwater model (GHD 2012)	290
	Predictive Uncertainty of the Regional-Scale Groundwater Flow Model for the Surat Cumulative Management Area (QWC 2012c)	311
Arrow's EIS	Surat Gas Project Environmental Impact Statement (EIS) (Coffey Environments 2012)	823
	(Appendix G – Groundwater Impact Assessment Report)	361
Arrow's SREIS	Surat Gas Project Supplementary Report to the Environmental Impact Statement (SREIS) (Coffey Environments 2013)	434
	(Appendix 04 – Supplementary Groundwater Assessment Arrow Energy Gas Project)	811

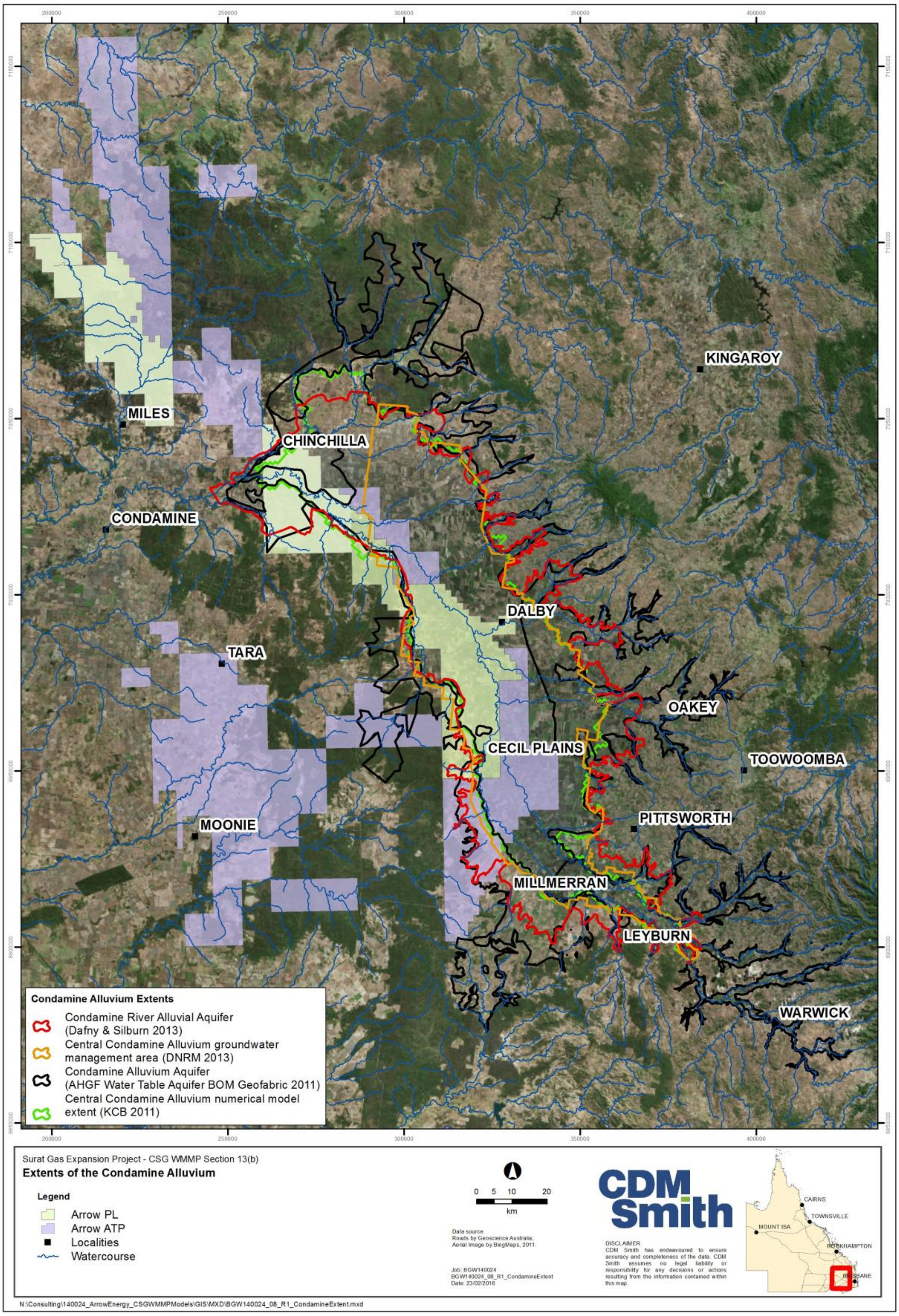

Figure 2-2 Extents of the Condamine Alluvium

Hydrogeological conceptualisation starts with geology, and is modified to take into account hydraulic conductivity and storage properties, which are together known as hydrogeological properties. Figure 2-3, from QWC's (2012) UWIR, shows a three-dimensional representation of the Surat Basin, with alternating aquifers and aquitards; the Condamine Alluvium can be seen in the top right; it is partly underlain by the Walloon Coal Measures, which behave as an aquitard relative to overlying and underlying sandstone aquifers, the Springbok Sandstone and Hutton Sandstone, respectively. Figure 2-4, from OGIA's (2016b) draft UWIR, is described as a geological model, rather than a hydrogeological model; it is based on actual geometry and is less idealised. Figure 2-5 is focused more on structure near the Condamine Alluvium; this Figure appears in OGIA’s (2016b) draft UWIR, based on an earlier but slightly different version, appearing as both Figure 2-3 and Figure 8-1 in a draft report on the Condamine Interconnectivity Research Project (CIRP) (OGIA 2016a).

These three similar but different representations are shown here to illustrate the evolution of ideas, and varying degrees of realism. All of the Figures are useful, as they set the scene for fit-for-purpose numerical modelling that represents geometry as accurately as possible, especially at interfaces between units with different hydrogeological properties. Schematic diagrams tend to be vertically exaggerated, making the dip of HSUs appear steeper than they really are. Arrows showing flow directions are indicative, but numerical models calculate rates and directions that satisfy principles of conservation of mass.

Figure 2-5 is significant in that it allows internal structure within the Condamine Alluvium to be seen, with sheetwash in the east overlying true alluvium, and a clayey transition zone at the base of the Condamine Alluvium. These variations in materials and properties are important to flow processes at some scales.

The Figures show that the Walloon Coal Measures subcrop the Condamine Alluvium. They meet the base of the alluvium at a low angle of dip. The Coal Measures themselves are anisotropic, with very low vertical hydraulic conductivity. The anisotropy is caused by the large numbers of very thin layers within the measures. Each layer is internally anisotropic, but the existence of many layers enhances the effective anisotropy of the HSU.

The hydrogeological properties of the Walloon Coal Measures play an important role in influencing the potential impacts of CSG production in Arrow’s tenements. The CIRP (OGA 2016a) is one of many studies being undertaken to inform predictions. Vertical hydraulic conductivities in the Walloon Coal Measures and in the transition zone are inferred to be in the range 10^{-9} to 10^{-4} m/d, perhaps with an overall effective average of 10^{-6} m/d, lower than had been expected.

Figure 2-6 (Figure 4-1 from OGIA 2016a) shows that the Walloon Coal Measures subcrop beneath half of the area of the Condamine Alluvium. The extent of the Condamine Alluvium shown in this Figure is the BOM boundary (see Figure 2-2) believed by Dafny et al. to be too large.

Figure 2-6 in OGIA (2016a), not shown here, shows trends in piezometric heads in the Condamine Alluvium since about 1965. Heads near Dalby have dropped about 10 m in the past 50 years, and heads near Tipton have dropped as much as 20 m. Long-term lowering of heads in the Condamine Alluvium is a result of abstraction of groundwater for irrigated agriculture, and potential impacts of CSG production should be considered in the context of these earlier impacts.

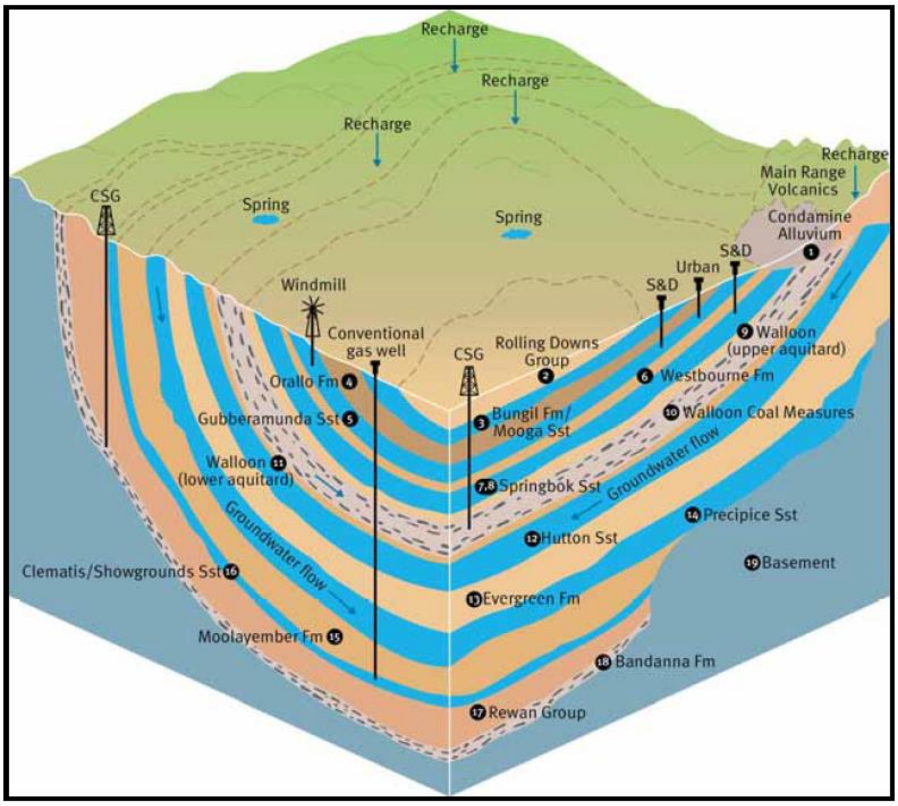

Figure 2-3 Hydrostratigraphy (Figure 6-3 from QWC 2012a)

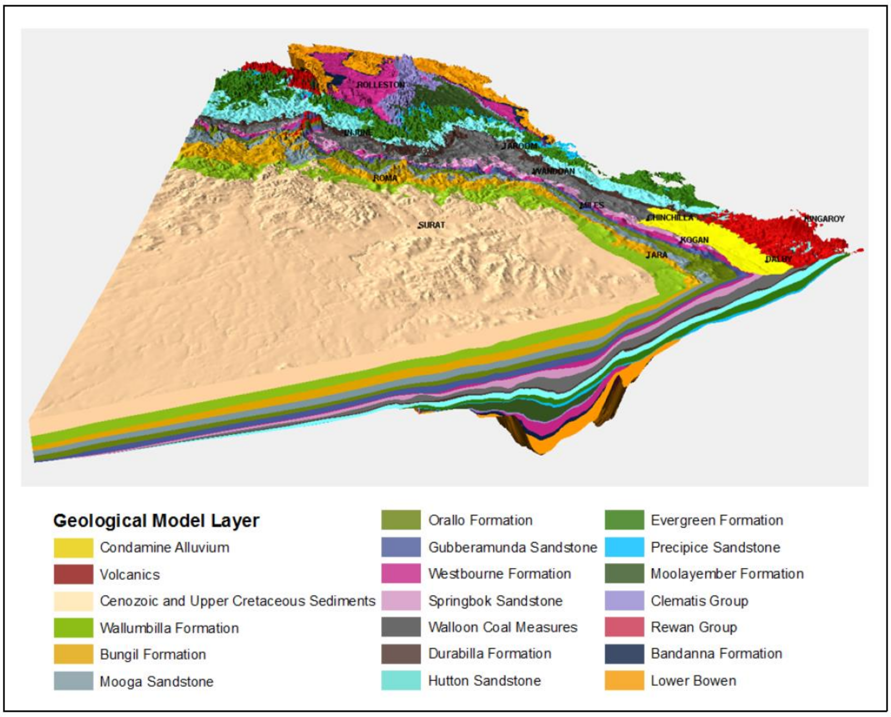

Figure 2-4 Regional geology (Figure 3-6 from OGIA 2016b)

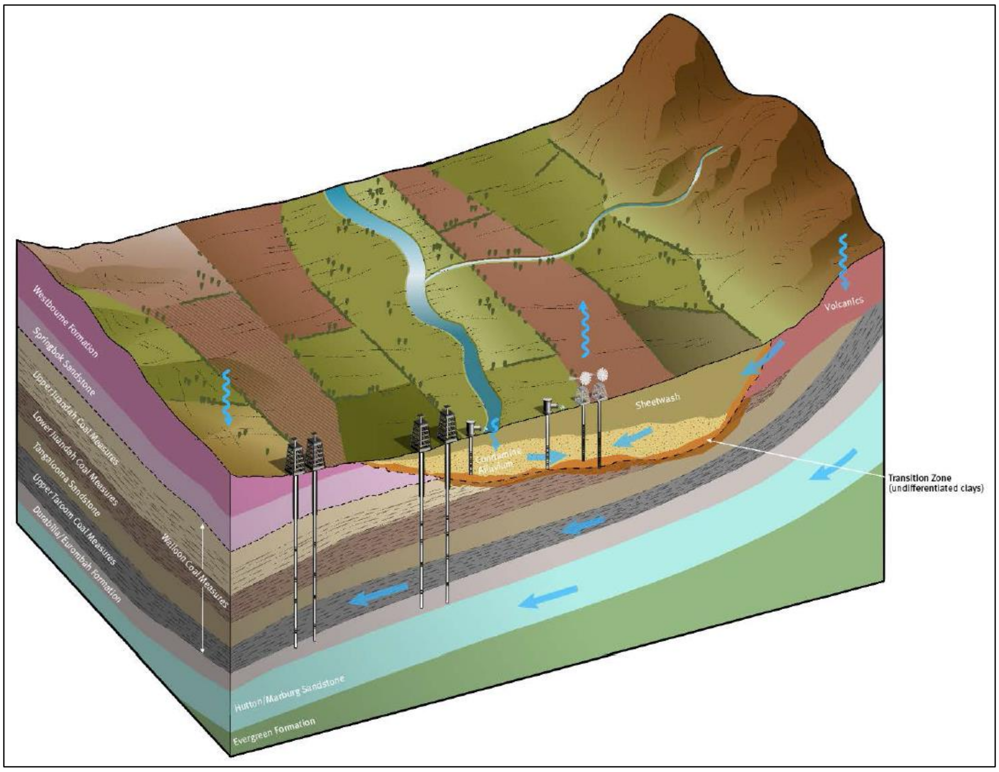

Figure 2-5 Hydrogeological setting near the Condamine Alluvium (Figure 4-5 from OGIA 2016b)

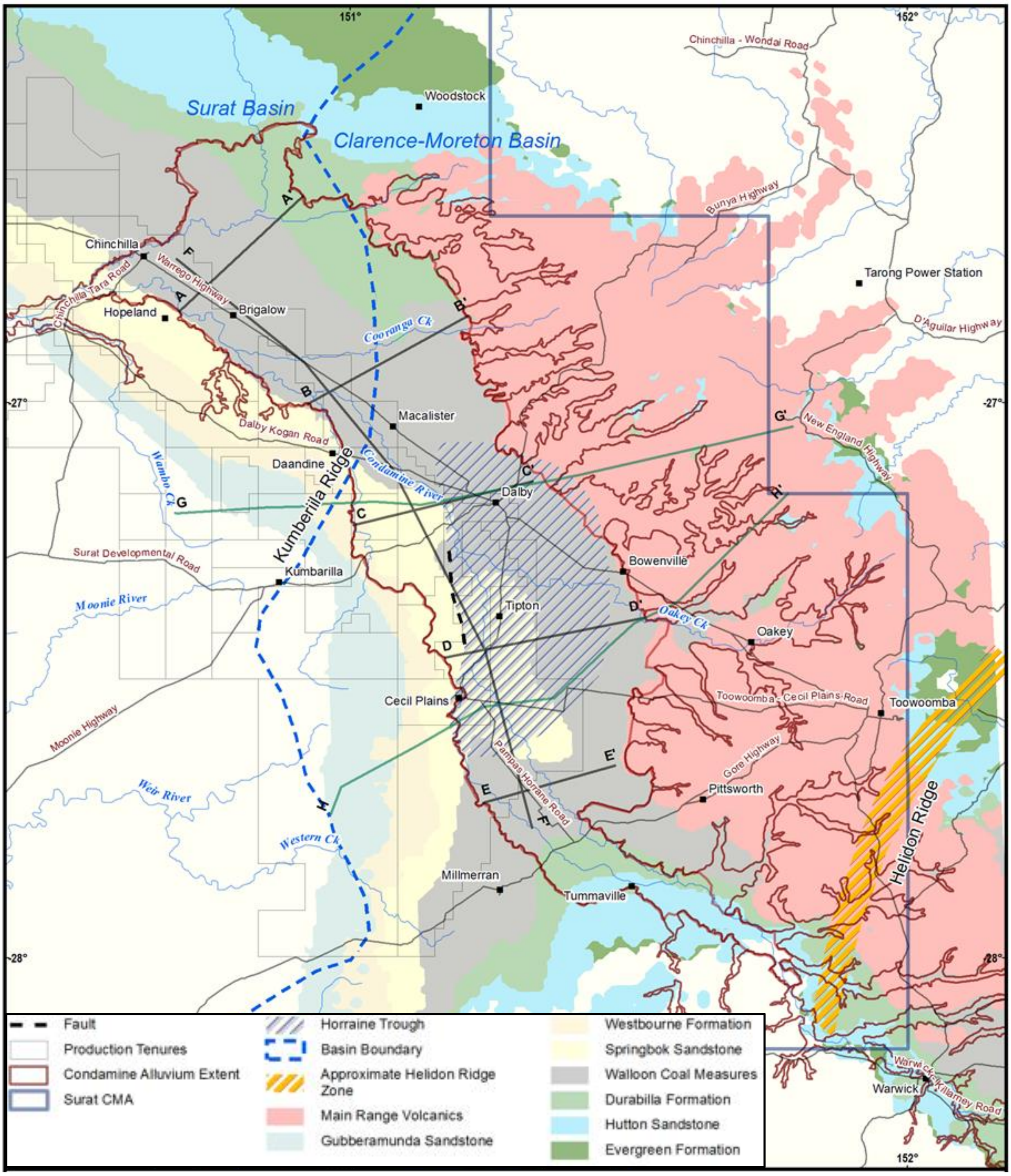

Figure 2-6 Subcrop geology near the Condamine Alluvium (Figure 4-1 from OGIA 2016a)

2.5 Groundwater Flow Processes

In some respects, the most important part of conceptualisation is the consideration of processes that control groundwater flow, in the past, present and future. This step is essential before development of numerical models because it guides the choice of processes that need to be included in a model, the resolution of a model in space and time, and the choice of software and modelling methods.

The hydrostratigraphy near the Condamine Alluvium is represented in various ways in Figure 2-3, Figure 2-4, Figure 2-5 and Figure 2-6. The following processes are expected to occur:

- Coal seam gas will be produced from the Walloon Coal Measures, to the west of and beneath the Condamine Alluvium. The process of producing gas requires the removal of water by pumping, during the period of production, in order to lower pressures in the coal seams to levels low enough to cause gas to be released (desorbed). Within the coal seams themselves, or more specifically within the cleats (joints) within the plies (thin layers) within the seams with 10 m or so of production wells, gas will flow together with water towards production wells, as two-phase flow. The amount of water that needs to be pumped in order to produce gas is estimated by reservoir engineers, and is known in the industry as the "water curve". Arrow water production is predicted to reach a maximum rate about 10 years from now with no more production of water for CSG production within approximately 40 years.

- Lower pressures in the Walloon Coal Measures will affect regional scale groundwater flows. Historically, groundwater flowed from the coal measures towards the Condamine Alluvium. The Condamine River was the "drain" for the region; recharge to regional aquifers flowed towards the alluvium and the river. The Condamine River no longer receives groundwater over most of its length because of the impact of groundwater abstraction for irrigated agriculture. Lowering pressures in the Walloon Coal Measures will either reduce the rate of groundwater flow towards the alluvium, or in some places reverse the direction of flow so that groundwater flows from the alluvium to the coal measures. The rate at which these changes occur will be slow. The maximum change in flux between the Walloon Coal Measures and the Condamine Alluvium will be a few ML/d, over the area of the whole of the Condamine Alluvium, peaking in about 80 years, with a long slow decline in impact thereafter.

- QWC (2012a) predicted the extent of Long-term Affected Areas (LAAs), defined as areas in plan within which HSUs may experience drawdown (lowering of piezometric heads) of 5 m or more in consolidated aquifers (such as sandstone). Figure 2-7 (being Figure 6-5 from QWC 2012a) shows the LAAs in hard rock aquifers. The black contour shows that drawdown in the Walloon Coal Measures will have the greatest areal extent. Red and blue contours show that the extent of LAAs in the overlying Springbok Sandstone and underlying Hutton Marburg Sandstone, respectively, will be less. LAAs in the overlying Gubberamunda Sandstone (dark green) and underlying Precipice Sandstone (orange) and Clematis Showgrounds Sandstone (light green) will be even smaller. Section 6.3.2 of QWC (2012a) explains that the maximum predicted impact in the Condamine Alluvium is about 1.2 m along the western edge; this is less than the 2 m threshold for an LAA in unconsolidated aquifers, so this is not shown in the Figure.

- Since less groundwater will be supplied to the Condamine Alluvium, groundwater in the alluvium will move towards a new equilibrium. There are many users of groundwater in the Condamine Alluvium, and under current conditions, the water table in the Condamine Alluvium is generally below the bed of the Condamine River. This means that the river loses water to the water table along most of its length, i.e. surface water provides recharge to the aquifer along the river and its tributaries. There will be a slight tendency for the water table to be lowered further, but because the water table is already below the bed of the river, leakage from the river to groundwater will increase very little. This is a phenomenon associated with "losing disconnected" streams, where the water table is so low that there is an unsaturated zone between the river and the water table below. The maximum increase in losses from the

Condamine River to groundwater is expected to be less than 1 ML/d, peaking in more than 200 years, with a long slow decline in impact lasting up to thousands of years. This is an expected result, based on conceptualisation of processes; a purpose of this report is to confirm this expectation.

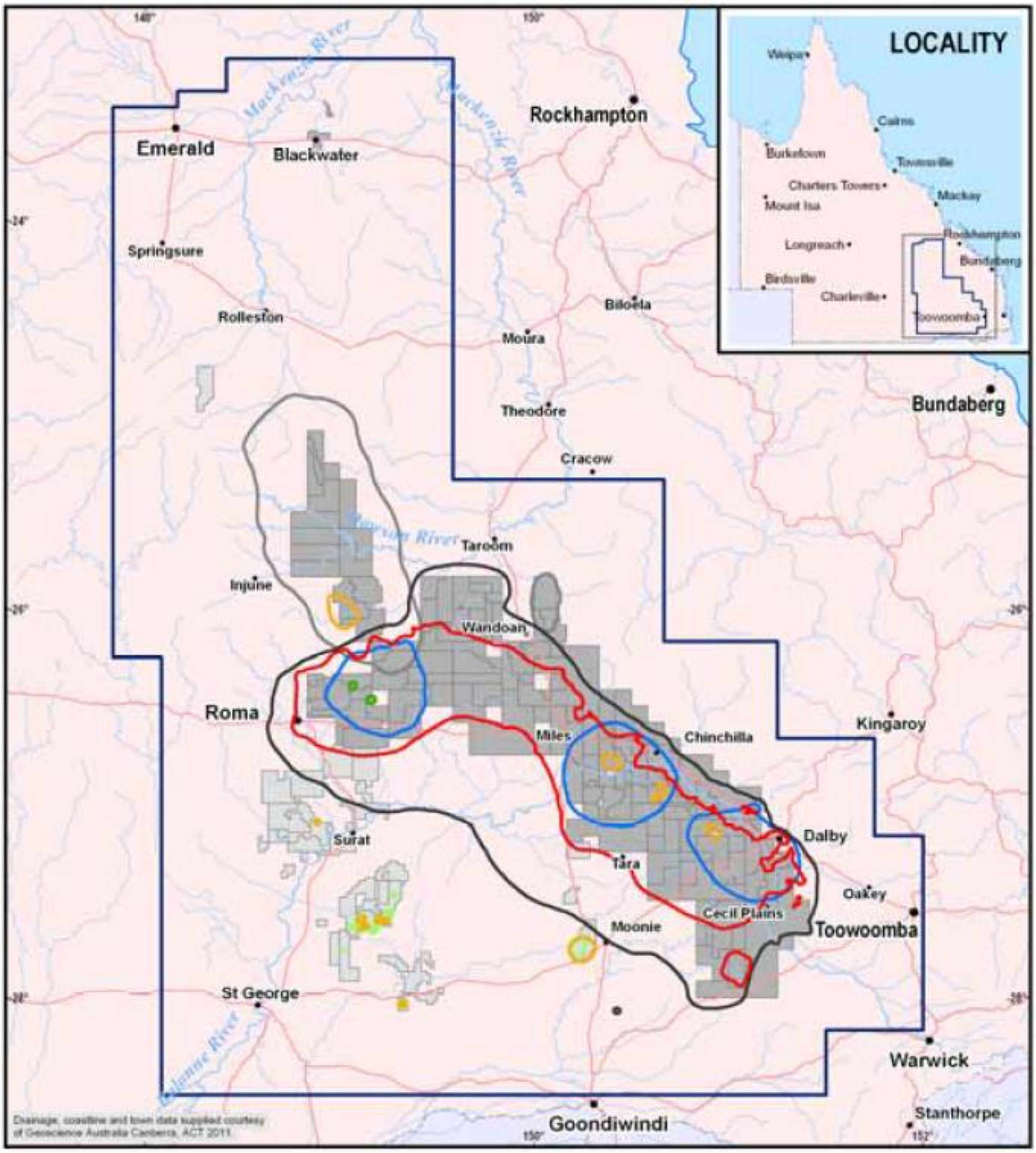

Figure 2-7 Predicted extent of Long-term Affected Areas (Figure 6-5 from OGIA 2012a)

Section 3 The Action

3.1 Preamble

The purpose of this section is to define (by reference to the EIS and SREIS) the proposed "*action*".

The action
The "*action*" is the Surat Gas Expansion Project.

3.2 Surat Gas Expansion Project

Section 3 of the SREIS (Coffey Environments 2013) indicates that Arrow's Project Development Area (PDA) covers an area of approximately 6,100 km^2 (Figure 3-1). The PDA will ultimately be smaller.

At the time of preparation of the EIS, the PDA comprised Petroleum Leases (PLs) 194, 198, 230, 238, 252, 258, 260; Petroleum Lease Applications (PL(A)s) 185, 253, 304, 305, 306, 307, 308; Authorities to Prospect (ATPs) 676, 683, 689, 810; part of ATP 747; and parts of Authority to Prospect Application (ATP(A)) 746. Some areas were relinquished prior to submission of the SREIS.

The PDA is divided into 11 "drainage areas" (DAs) that correspond with known gas resources. These are numbered DA1, DA2 and DA4 to DA12 (Figure 3.1 in the SREIS). The DAs are not shown in this report, but it is important for stakeholders to understand that development is planned in stages, not simultaneously in all areas.

The Approval, under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), approves the "*proposed action*" "*to expand coal seam gas operations in the Surat Basin, Queensland, as described in the referral received under the EPBC Act on 2 February 2010; and as described in the Surat Gas Project Environmental Impact Statement (March 2012) and Supplementary Report to the Environmental Impact Statement (June 2013)*".

In essence, the proposed "*action*" is as described in Section 5 of the EIS (Coffey Environments 2012) and Section 3 of the SREIS (Coffey Environments 2013).

The Approval approves the proposed action for each of the following controlling provisions under the EPBC Act:

- listed threatened species and communities (sections 18 and 18A);
- listed migratory species (sections 20 and 20A); and
- a water resource, in relation to coal seam gas development and large coal mining development (sections 24O and 24E).

There is a clear link between the requirements of Section 13(b) of the Approval and these controlling provisions in the Act. The wording of Section 13(b), with its focus on potential impacts on water resources and dependent ecosystems, echoes the wording of the EPBC Act.

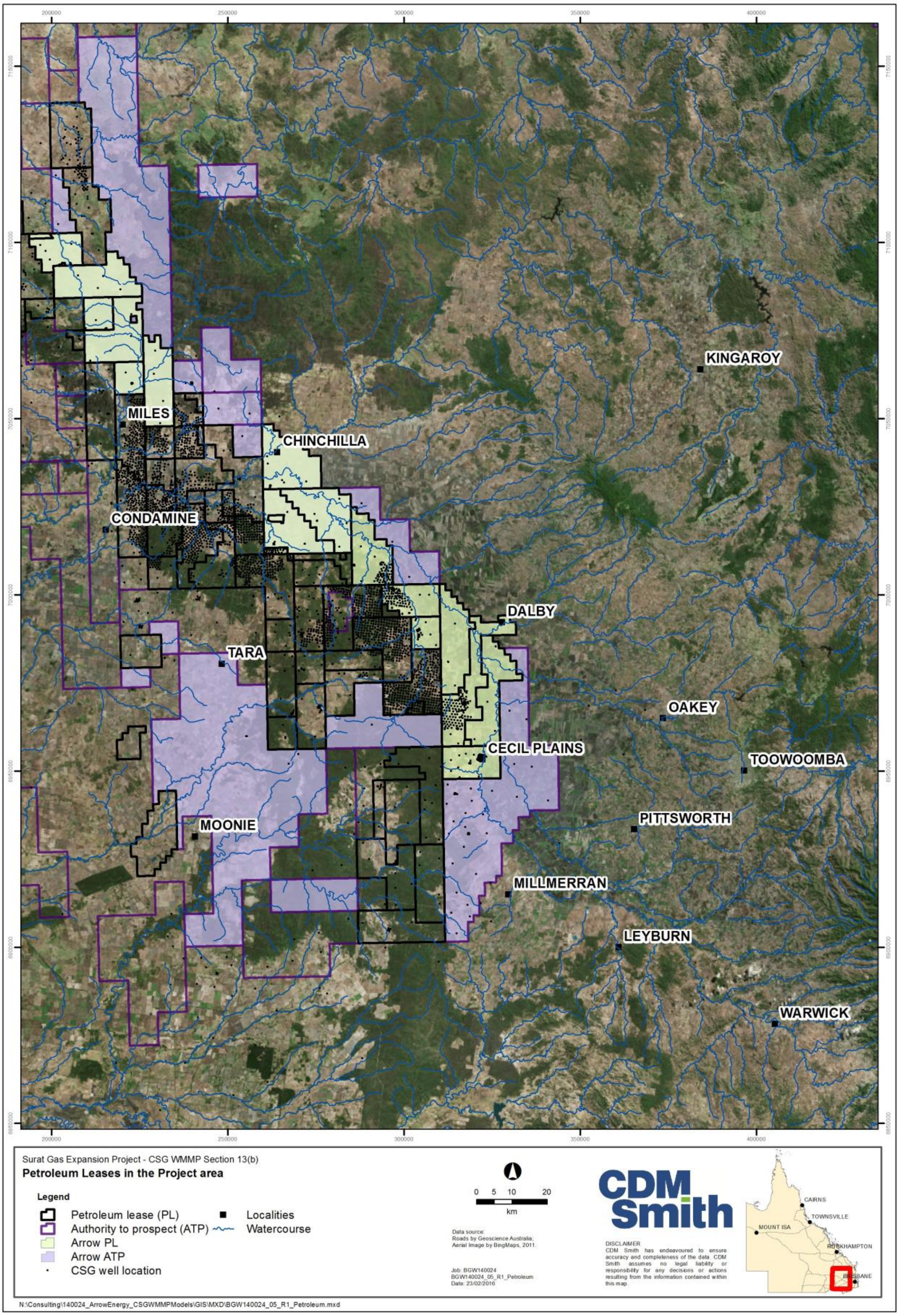

Figure 3-1 Petroleum Leases in the Project area

Section 4 Water Resources

4.1 Preamble

The purpose of Section 4 is to provide an introduction to the "*water resources*" of the area, in order to facilitate later discussion of the potential impacts of the "*action in the project area*" on "*water resources*".

Water resources
"Water resources" are considered to be surface water and groundwater resources, as managed by the Queensland Government. Surface water resources are drawn mainly from the Condamine River and its tributaries. In this study, the focus of attention is on the possibility that water drawn from the Walloon Coal Measures for CSG production could ultimately affect groundwater in the Condamine Alluvium and hence water levels and flows in the Condamine River and its tributaries, where they overlie the Condamine Alluvium. Surface water is drawn from the Condamine River both upstream and downstream of the Condamine Alluvium; there is no suggestion that CSG production could affect these surface water resources, directly or indirectly. Surface water resources in the area of the Condamine Alluvium, an area straddling two IQQM models, is of the order of hundreds of GL per year. Groundwater is drawn mainly from the Condamine Alluvium, so consideration of groundwater resources in this study is focused on the alluvium. Groundwater is also drawn from aquifers beyond the area of the Condamine Alluvium; potential impacts on bores in these areas has been assessed by QWC and Arrow in previous studies. Throughout the Central Condamine Alluvium Groundwater Management Area, there are 320 active groundwater abstraction licences with a total entitlement of 87 GL/y.

Section 13(b) does not explicitly refer to the Australian Government's Bioregional Assessment Programme (Bioregional Assessment Programme 2016) which is currently being trialled in a number of regions. However, there are links between the questions being addressed in that Programme and the phrasing of Section 13(b).

Bioregional Assessments (BAs) are designed to help the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) to provide advice to the Federal Minister for the Environment on potential water-related impacts of coal seam gas (CSG) and large coal mining developments. "*A BA is a scientific analysis, providing a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of CSG and coal mining development on water resources.*"

The BA methodology (BRAM) defines "water-dependent assets" and distinguishes between water assets and water resources. A water-dependent asset is "*an entity contained within a bioregion where the characteristics can be ascribed a defined value and which can be clearly linked, either directly or indirectly, to a dependency on groundwater or surface water quantity or quality*". Water resources are not explicitly defined.

In this report, "water resources" are considered to be surface water and groundwater resources, as managed by the Queensland Government, which issues licenses to users to allow them to draw on such resources. Water resources are different from "dependent ecosystems", which are discussed separately in Section 6. This distinction may be different from that used in Bioregional Assessments, but is based on the wording of Section 13(b).

Historically, long before significant use of water resources, the Condamine Alluvium was part of a hydrological drainage system in which rainfall-recharge flowed via regional aquifers towards the alluvium (from the Great Dividing Range in the east and slightly elevated land in the west), then to tributaries of the Condamine River, to the Condamine River itself (via surface water or groundwater flows) and ultimately westwards to the northern end of the Murray-Darling Basin (Dafny and Silburn 2013).

According to current modelling, the Condamine Alluvium still receives groundwater from underlying hydrostratigraphic units, over most of the base of the alluvium. In other words, the alluvium is still acting as part of a regional drainage system, even though surface water flows are less than they used to be (QWC 2012a).

As explained in Section 2.5, production of water during the Project will cause a reduction of discharge from the Walloon Coal Measures to the Condamine Alluvium, and possibly a reversal in flow direction in some places such that groundwater may flow from the Condamine Alluvium towards the Walloon Coal Measures and other deeper aquifers. A reduction in groundwater inflow to the Condamine Alluvium will cause the water table to drop.

Section 4.2 and Section 4.3 provide an introduction to the surface water and groundwater resources in the region, to facilitate consideration of potential impacts.

4.2 Surface Water Resources

The Condamine River is part of the Murray-Darling Basin and drains the northern portion of the Darling Downs. The river becomes the Balonne River downstream of the town of Roma.

The surface water resources of primary interest in this report are those that overlie the Condamine Alluvium. Figure 4-1 shows the alignment of the Condamine River and the names of major tributaries.

The Condamine Alluvium is significant, because groundwater flows towards this zone with higher hydraulic conductivity than the surrounding rocks. Groundwater modelling shows that the greatest impacts of CSG production are on this area (QWC 2013).

This Section starts with a general description of the stream network, largely to emphasise that surface drainage occurs via more drainage lines than the Condamine River. The sources of hydrological data (surface water monitoring stations) are discussed. This is followed by a brief description of flooding. The *Water Resource (Condamine and Balonne) Plan 2004* (Queensland Government 2004) is introduced, with additional sections on Commonwealth Environmental Water and surface water use.

Of primary interest is the magnitude of surface water use. This is important so that possible impacts of CSG production on surface water availability can be considered relative to existing entitlements.

4.2.1 Stream Network

The Condamine River flows in a northwesterly direction through the project area before its confluence with the Balonne River.

Different GIS datasets of watercourses and drainage lines are available within the project area:

- Surface network from Geofabric version 2 (BOM 2011).
- Queensland 25k drainage network from DNRM. These data have been derived from digital photogrammetry or scanning of existing maps. The dataset includes watercourses, channels, and outlines of lakes and dams. Feature attributes include name, perenniality (whether or not a watercourse flows all year) and length.
- Queensland 100k ordered drainage network from DNRM. This dataset is based on the Geoscience Australia 1:100,000 drainage network of Queensland and includes ordered reaches.
- Queensland Watercourse lines from DNRM. This dataset displays watercourses and includes a linear network for hydrological modelling. Feature attributes include name, perenniality and hierarchy. The dataset was derived from multiple data sources including orthophotography, satellite imagery and topographic data.

Only the Geofabric dataset and the Queensland Watercourse lines contain information about perenniality and stream names. The Geofabric dataset has a coarser resolution and does not always follow the local river meanders when compared to Bing Maps Aerial (Microsoft Corporation 2015). The Queensland Watercourse lines provide the best available representation of the Condamine River and its tributaries.

The length of a watercourse along its centreline depends on the resolution with which it is drawn: the higher the resolution, the longer the length.

Table 4-1 shows watercourse lengths derived from the Queensland Watercourse lines dataset within the area of the Condamine River Alluvial Aquifer (Dafny and Silburn 2013). It is significant, from a surface water – groundwater interaction point of view, that the length of watercourses in the area of the Condamine Alluvium is nearly six times the length of the Condamine River itself.

Further analysis of watercourse lengths is presented in Table 4-2. In this case the length of water courses is based on the footprint of the CCAM, the model used in this study. Lengths are provided for the Condamine River and 12 named tributaries which together are about 80% as long as the Condamine River itself.

Table 4-1 Watercourse lengths within area of CRAA

Watercourse(s)	Length (km)
Condamine River (including North Branch)	500
Named Streams	1,512
Unnamed streams	1,372
“Major” streams	378
“Minor” streams	1,906
Total length	**2,884**

Table 4-2 Watercourse lengths within area of CCAM

Watercourse(s)	Length (km)
Condamine River	351
Condamine River North Branch	119
Charleys Creek	45
Dead Man Gully	37
Cooranga Creek	62
Wilkie Creek	39
Jimbour Creek	39
Myall Creek	37
Oakey Creek	60
Grasstree Creek	40
Canal Creek	16
Hodgson Creek	3
Kings Creek	1
Dalrymple Creek	6
Total: Condamine River (including North Branch)	**470**
Total: Other tributaries	**385**
Total	**855**

4.2.2 Surface Hydrological Data

Daily flow and water level data have been extracted from DNRM's Water Monitoring Portal and the Bureau of Meteorology (BOM) website. Of those near the Condamine region, 27 monitoring stations are currently active and 13 of those are located within the extent of the Condamine River Alluvial Aquifer (Dafny and Silburn 2013). Historical data from 47 closed stations are also available, with 15 sites located within the area of the Condamine River Alluvial Aquifer (Dafny and Silburn 2013). The majority of the discontinued stations have short periods of record. Attention has therefore been focused on those stations that are currently active.

The locations of surface water gauging stations and weirs are shown in Figure 4-2. Table 4-3 summarises available surface water data around the project area. Figure 4-3 shows a schematic diagram of the hydrological system showing the Condamine River and its tributaries, the active monitoring stations and weirs.

The percentage of time when flow (>0 ML/day) has been recorded within the period of the streamflow record has been calculated based on daily flow data and is shown in Figure 4-2. This percentage provides an indication of the extent to which a stream is perennial, intermittent or ephemeral. Of the 13 gauging stations inside the area of the Condamine Alluvium (as defined by Dafny and Silburn 2013), only two flow less than half the time, while six flow more than three-quarters of the time.

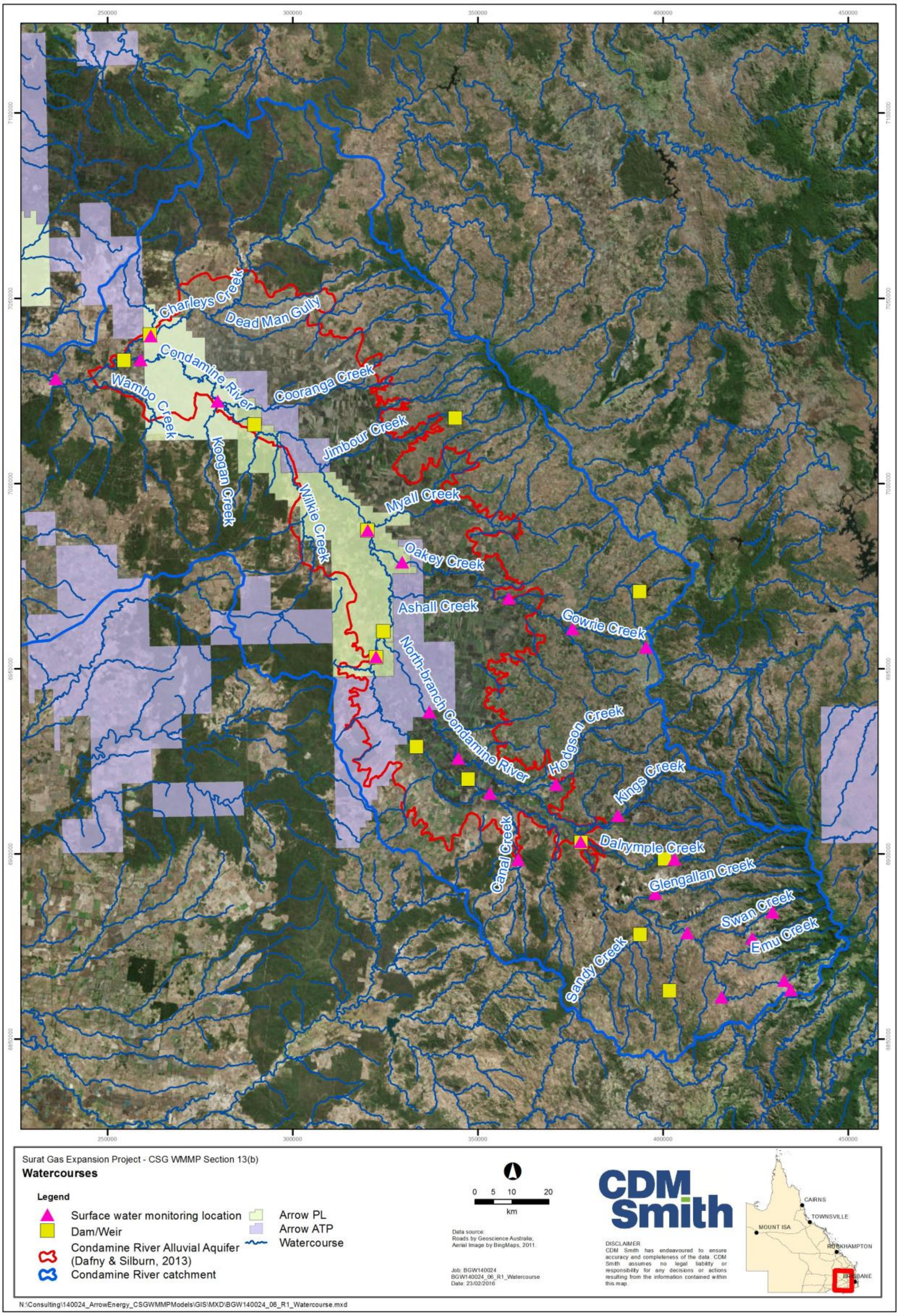

Figure 4-1 Stream network

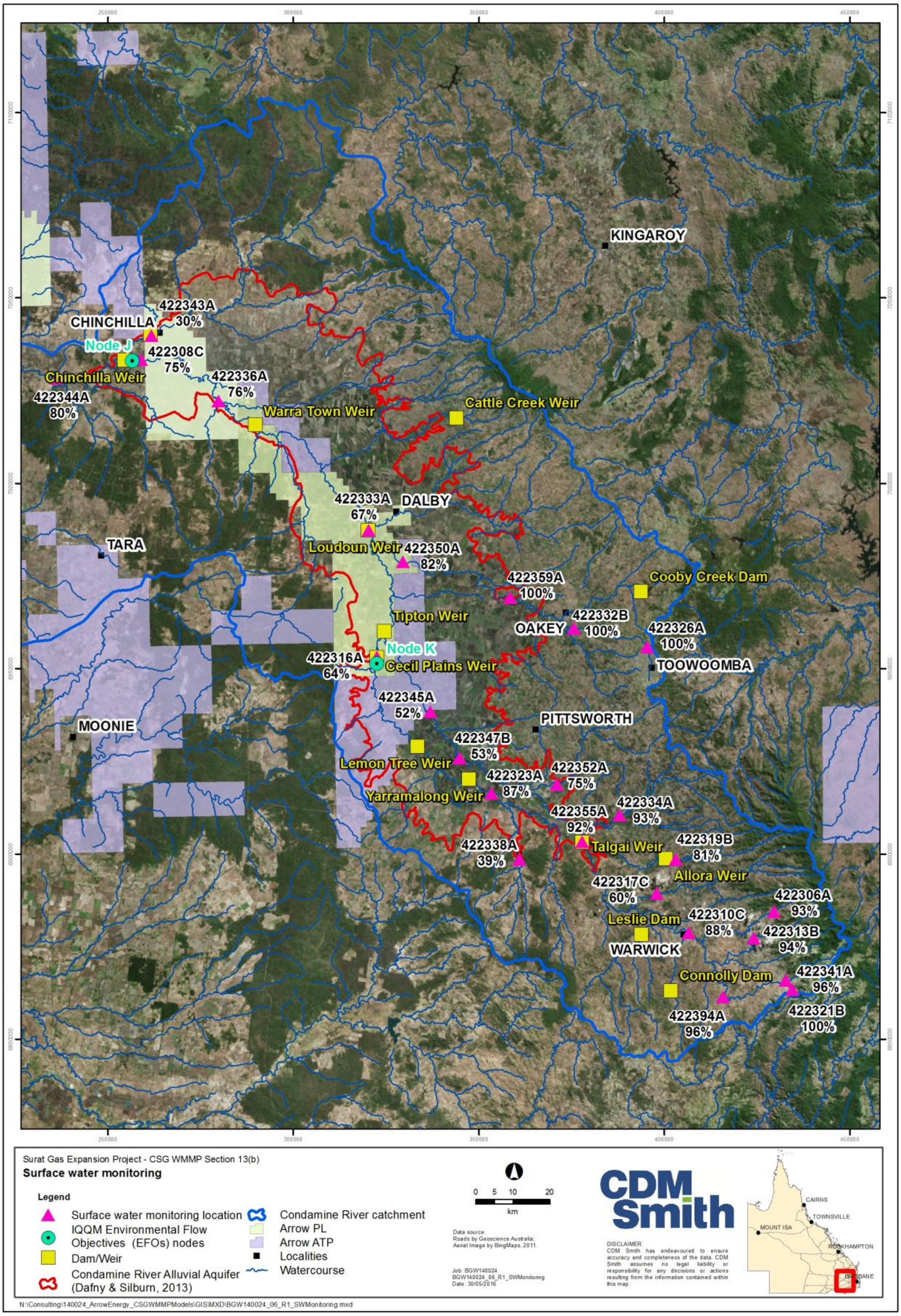

Figure 4-2 Surface water monitoring locations

Table 4-3 Current stream gauging station network

Station No	Station Name	Watercourse	Catchment Area (km²)	Zero Gauge (mAHD)	Recording Period	Data type
422202B	Dogwood Creek at Gilweir	Dogwood Creek	3010	283.257	16/10/1949 - NOW	Water Level
					16/10/1949 - NOW	Discharge
422306A	Swan Creek at Swanfels	Swan Creek	83	535.895	01/06/1919 - NOW	Water Level
					3/09/1920 - NOW	Discharge
422308C	Condamine River at Chinchilla	Condamine River	19190	286.007	02/10/1955 - NOW	Water Level
					09/01/1974- NOW	Discharge
422310C	Condamine River at Warwick	Condamine River	1360	446.573	02/10/1960 - NOW	Water Level
					02/10/1960 - NOW	Discharge
					03/11/1993 - NOW	Rainfall
422313B	Emu Creek at Emu Vale	Emu Creek	25.5	490.916	24/01/1973 - NOW	Water Level
					24/01/1973 - NOW	Discharge
					11/04/1990 - NOW	Rainfall
422316A	Condamine River at Cecil Plains Weir	Condamine River	7795	347.507	25/10/1947 - NOW	Water Level
					31/10/1972 - NOW	Discharge
422317C	Glengallan Creek at Rocky Ridge	Glengallan Creek	474	441.504	17/06/2011 - NOW	Water Level
					17/06/2011 - NOW	Discharge
422319B	Dalrymple Creek at Allora	Dalrymple Creek	246	471.253	28/03/1969 - NOW	Water Level
					28/03/1969 - NOW	Discharge
					05/09/2007 - NOW	Rainfall
422321B	Spring Creek at Killarney	Spring Creek	35	552.003	24/01/1973 - NOW	Water Level
					24/01/1973 - NOW	Discharge
					16/08/1991 - NOW	Rainfall
422323A	Condamine River at Tummaville	Condamine River	6475	380.926	30/08/1961 - NOW	Water Level
					30/09/1961 - NOW	Discharge
422325A	Condamine River at Cotswold	Condamine River	28930	249.064	02/06/1966 - NOW	Water Level
					02/06/1966 - NOW	Discharge
422326A	Gowrie Creek at Cranley	Gowrie Creek	47	539.377	20/11/1969 - NOW	Water Level
					20/11/1969 - NOW	Discharge
422332B	Gowrie Creek at Oakey	Gowrie Creek	142	405.920	01/07/1992 - NOW	Water Level
					01/07/1992 - NOW	Discharge
					03/02/1993 - NOW	Rainfall
422333A	Condamine River at Loudouns Bridge	Condamine River	12380	327.804	24/03/1969 - NOW	Water Level
					24/03/1969 - NOW	Discharge

Station No	Station Name	Watercourse	Catchment Area (km²)	Zero Gauge (mAHD)	Recording Period	Data type
422334A	Kings Creek at Aides Bridge	Kings Creek	516	421.787	17/04/1969 - NOW	Water Level
					17/04/1969 - NOW	Discharge
422336A	Condamine River at Brigalow	Condamine River	18000	296.995	26/10/1972 - NOW	Water Level
					26/10/1972 - NOW	Discharge
					12/11/1991 - NOW	Rainfall
422338A	Canal Creek at Leyburn	Canal Creek	395	412.569	26/10/1972 - NOW	Water Level
					26/10/1972 - NOW	Discharge
					06/06/1991 - NOW	Rainfall
422341A	Condamine River at Brosnans Barn	Condamine River	92	514.613	27/05/1976 - NOW	Water Level
					27/05/1976 - NOW	Discharge
422343A	Charleys Creek at Chinchilla	Charleys Creek	3461	292.282	27/06/2003 - NOW	Water Level
					27/06/2003 - NOW	Discharge
422344A	Condamine River at Bedarra	Condamine River	24340	276.603	13/06/2007 - NOW	Water Level
					13/06/2007 - NOW	Discharge
					13/06/2007 - NOW	Rainfall
422345A	North Condamine River at Lone Pine	North Condamine River	710	365.094	14/10/1978 - NOW	Water Level
					14/10/1978 - NOW	Discharge
422347B	North Condamine River at Pampas	North Condamine River	378	379	01/04/1988 - NOW	Water Level
					01/04/1988 - NOW	Discharge
422350A	Oakey Creek at Fairview	Oakey Creek	1970	338.728	17/10/1980 - NOW	Water Level
					17/10/1980 - NOW	Discharge
422352A	Hodgson Creek at Balgownie	Hodgson Creek	560	404.667	20/05/1987 - NOW	Water Level
					20/05/1987 - NOW	Discharge
					27/11/2009 - NOW	Rainfall
422355A	Condamine River at Talgai Tailwater	Condamine River	3105	400	27/10/1989 - NOW	Water Level
					27/10/1989 - NOW	Discharge
					18/08/2010 - NOW	Rainfall
422359A	Oakey Creek at Jondaryan	Oakey Creek	1353	371.058	18/06/2011 - NOW	Water Level
					18/06/2011 - NOW	Discharge
422394A	Condamine River at Elbow Valley	Condamine River	325	468.837	23/01/1973 - NOW	Water Level
					23/01/1973 - NOW	Discharge
					08/07/1993 - NOW	Rainfall

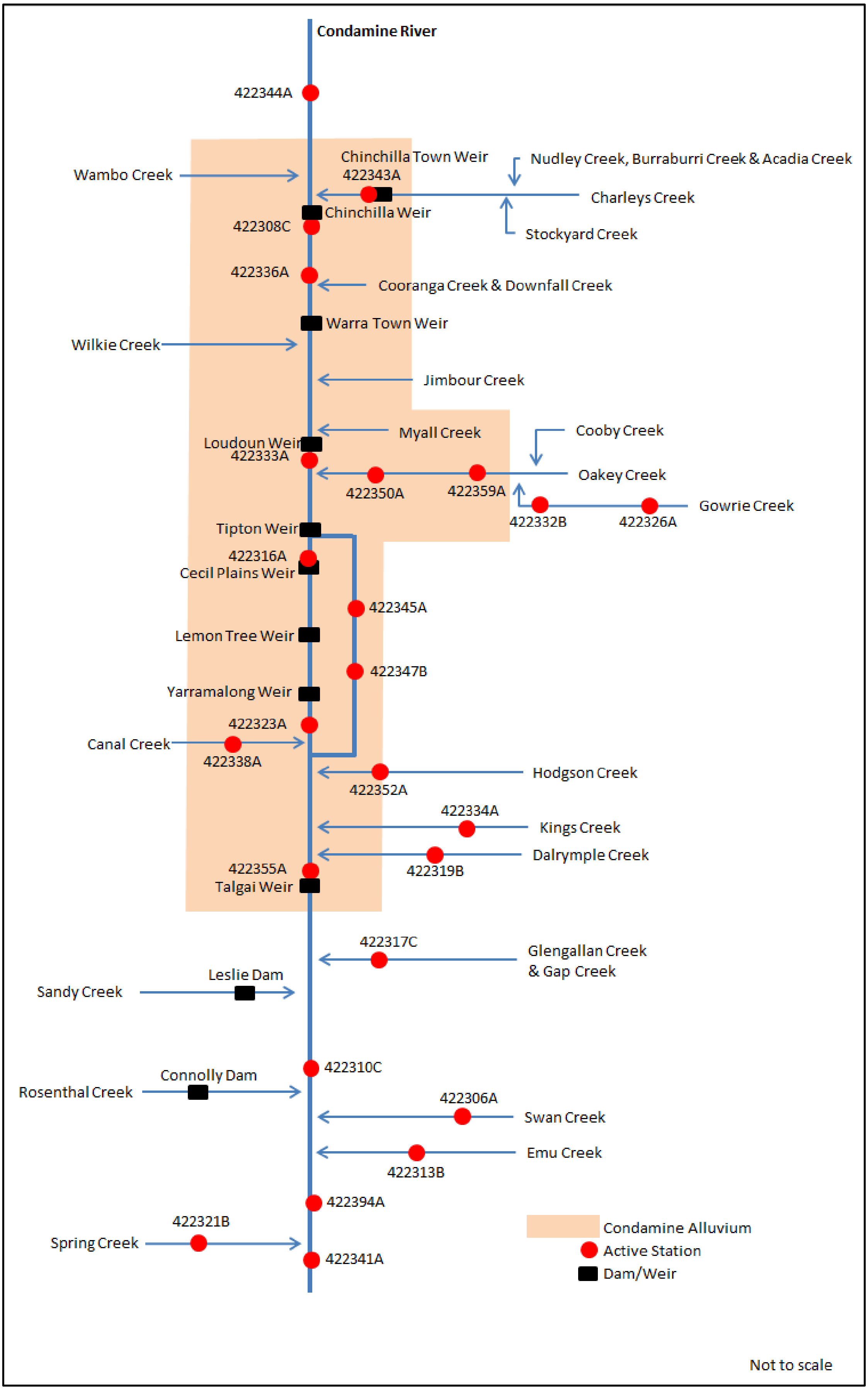

Figure 4-3 Schematic diagram of the Condamine River near the Condamine Alluvium

4.2.3 Flooding

The surface hydrology of the area is dynamic, and flooding is a significant natural hydrological process. The frequency of flooding has led to flood harvesting and storage of water in turkey's nest dams as part of water management to support farming in the area. It can be expected that flooding contributes to the long-term average rate of recharge to aquifers in the Condamine Alluvium.

Flooding is mentioned here not because it is explicitly considered in the analysis that follows. Flooding has not been explicitly considered in any of the regional scale groundwater flow modelling undertaken to date, partly because it is very difficult to do so, and it is unlikely that models could be calibrated. It is important to recognise possible processes, even if they cannot or are not explicitly modelled. Leaving the processes out of models may mean, for example, that a reasonably calibrated groundwater flow model represents recharge from flooding as distributed rainfall-recharge, with essentially the right amount of recharge represented as a long term average process, rather than as an episodic process. The impacts of flooding have not been ignored, but rather, have been included in representation of the recharge process.

Rainfall over the area of the Condamine catchment in excess of 25 mm in 24 hours can result in minor flooding, and rainfall in excess of 50 mm in 24 hours can cause moderate to major flooding (Coffey Environments 2012). Major floods occur regularly, on average once every two years, and generally during late spring, summer and autumn (Coffey Environments 2012).

A number of flood studies have been undertaken within the catchment of the Condamine River since 2004:

- SKM (2004) developed a two-dimensional model of the Upper Condamine River for DNRM. The study area covered the Condamine River from upstream of the northern anabranch downstream to Chinchilla. The study led to development of flood models for the 1976 flood event and for 20- and 100-year Average Recurrence Interval (ARI) design floods.
- SKM (2007, 2011) carried out a flood study for Myall Creek at Dalby. Flood maps for all storm events up to the Probable Maximum Flood (PMF) were produced.
- A hydraulic study was completed by Opus (2007), to investigate flood behaviour in the area where the Condamine River and the Warrego Highway meet (between the towns of Macalister and Warra). Flood levels and flows for 50- and 100-year ARI flood events were determined.
- SKM (2011) undertook a flood study to understand and define flooding behaviour in the floodplain area of the Condamine River from Killarney, through Warwick, and almost to Talgai Weir. The study resulted in flood mapping for 5%, 2% and 1% Average Exceedance Probability (AEP) and PMF flood events.
- BMT WBM Pty Ltd (2012) conducted a flood study to develop mitigation measures designed to reduce the impacts of flooding in the Gowrie Creek catchment. Flood extent maps for 20-, 50-, 100- and 500-year ARI events were produced, and flood mitigation measures were proposed.

As part of Arrow's Surat Gas Project, the following flood models were developed:

- Tipton Gas Fields, Surface Water Study (AECOM 2011). This local study was undertaken to assess the potential impacts of the proposed Tipton Gas Fields development on flood behaviour in the area.
- Surat Gas Project – Concept Select Studies, Surat Basin Flood Mapping (WorleyParsons 2013a) and Surat Basin Design Flood Modelling (WorleyParsons 2013b). For this study, detailed flood models (hydrologic and hydraulic) were developed for 50-, 100-, 500- and 1,000-year ARI design flood events within the Arrow CSG tenements in the Surat Basin.

- Condamine River Flood Inundation Study – Tipton Gas Fields (AECOM 2013a). This work involved a flood assessment of the Condamine River between Cecil Plains Weir and Loudoun Bridge to assess the risk of flooding of the Tipton Gas Field (PL198). The flood assessment produced inundation maps for the 5-, 10-, 20-, 50-, 100- and 1,000-year ARI flood events.
- Condamine River Flood Inundation Study – Daandine Gas fields (AECOM 2013b). This flood assessment was conducted on the Condamine River between Loudoun Bridge and Brigalow to assess the risk of flooding to existing dams of the Daandine Gas Field (PL230). The objective of the assessment was to define the flood inundation maps for 5-, 10-, 20-, 50-, 100-, and 1,000-year ARI flood events.
- Daandine and Kogan North Gas Fields, Local Surface Water Study (AECOM 2013c). At a local scale, a surface water study was undertaken to assess the potential impact of newly constructed dams on flooding behaviour.

Table 4-4 summarises the methodologies and software used to develop some of these models.

Table 4-4 Summary of flood modelling studies

Study	Year	Author	Client	Software	Area
Upper Condamine River Floodplain Broad Scale Hydraulic Model Development Report	2004	SKM	DNRM	URBS MIKE 21	Condamine River and floodplains upstream of Chinchilla weir to Leyburn-Cambooya Road.
Condamine River Flood Inundation Study Tipton Gas Field	2013	AECOM	Arrow Energy	URBS MIKE 21	Condamine River from Cecil Plains up to the confluence with Oakey Creek. Includes an anabranch going into Long Swamp.
Condamine River Flood Inundation Study Daandine Gas Field	2013	AECOM	Arrow Energy	URBS MIKE 11	From Loudoun weir to Warra Town weir, including Wilkie Creek.
Surat Gas Project – Concept Select Studies Surat Basin Design Flood Modelling	2013	Worley Parsons	Arrow Energy	WBNM TUFLOW	Arrow CSG tenements in the Surat Basin.

The Department of Natural Resources and Mines maintains a website that shows the extent of floodplains in Queensland: http://flood.dnrm.esriaustraliaonline.com.au/floodcheck/.

4.2.4 Water Resource (Condamine and Balonne) Plan 2004

The Project area falls within the area covered by the *Water Resource (Condamine and Balonne) Plan 2004* (Queensland Government 2004). The purposes of this Water Resource Plan ("WRP") are:

- "to define the availability of water in the plan area;
- to provide a framework for sustainability managing water and the taking of water;
- to identify priorities and mechanisms for dealing with future water requirements;
- to provide a framework for establishing water allocations;
- to provide a framework for reversing, where practicable, degradation that has occurred in natural ecosystems, for example, in stressed rivers; and

- to regulate the taking of water from overland flow water."

To support the WRP, the Department of Natural Resources and Mines (DNRM) has developed hydrological models (using the Integrated Quantity and Quality Modelling or IQQM software) to simulate surface hydrological processes and allocations of surface water resources. Based on model outputs, performance indicators have been derived to measure and compare the impacts of different management options.

Performance indicators are defined in the Water Resource Plan as Environmental Flow Objectives (EFOs) and Water Allocation Security Objectives (WASOs).

The IQQM datasets for the Condamine region do not explicitly include any flows related to CSG production. They neither include an additional demand on surface flows, to represent possible additional loss of water to groundwater, nor additional supply of water, such as treated produced water discharged under licence to surface water.

4.2.4.1 Environmental Flow Objectives (EFOs)

Environmental Flow Objectives are measured based on the following performance indicators:

- Low flow – the total number of days in the simulation period in which the daily flow is not more than half the pre-development median daily flow.
- Summer flow – the average number of summer flow days in the simulation period, where summer is the period from 1 December in a year until the end of February in the following year.
- Beneficial flooding flow – the median of the wet season 90-day flows for the years in the simulation period.
- 1 in 2 year flood – the daily flow that has a 50% probability of being reached at least once a year.
- 1 in 10 year flood – the daily flow that has a 10% probability of being reached at least once a year.

Environmental Flow Objectives are evaluated at specific locations (defined as nodes in the WRP) along the Condamine and Balonne Rivers. Two of the locations fall within the Central Condamine Alluvium groundwater model area: node K Condamine River at Cecil Plains Weir (Adopted Middle Thread Distance AMTD 891.1 km) and node J Condamine River at the upstream limit of the impounded area of Chinchilla Weir. Nodes located downstream of the Central Condamine Alluvium groundwater model area may also be affected by any change in fluxes in the river caused by CSG production. The two next-closest nodes downstream on the Condamine River are node I, located at the downstream border of the Chinchilla water supply scheme (AMTD 643.7km) and node H at Cotswold (AMTD 537.5 km).

To assess impacts, the EFOs are defined at each node as follows (Queensland Government 2004):

- A performance indicator cannot be less than 66% of the indicator for the pre-development flow pattern. If the indicator is already less than 66% for the Resource Operation Plan (ROP) compared to the pre-development flow pattern, this indicator cannot be allowed to decrease.
- A performance indicator cannot be greater than 133% of the indicator for the pre-development flow pattern. If the indicator is already greater than 133% for the ROP compared to the pre-development flow pattern, this indicator cannot be allowed to increase.

4.2.4.2 Water Allocation Security Objectives (WASOs)

Water Allocation Security Objectives (WASOs) performance indicators are defined for a water allocation group as follows:

- the annual volume probability –
  - for taking unsupplemented water, the percentage of years in the simulation period in which the volume of water that may be taken by the group is at least the total of the nominal volumes for the group, and
  - for taking supplemented allocations, the average annual volume of water that may be taken by the group in the simulation period as a percentage of the total of the nominal volumes for the group.
- the 45% annual volume probability – the percentage of years in the simulation period in which the volume of water that may be taken by the group is at least 45% of the total of the nominal volumes for the group.

"Supplemented water" means water supplied under an interim resource operations licence, resource operations licence or other authority to operate water infrastructure. "Unsupplemented water" means water that is not supplemented water.

These definitions are quite technical, and are quoted here to illustrate the level of detail in the WRP. In principle, a change to water allocation rules should not result in any reductions to the WASO performance indicators. However, at the time of preparation of this report, it seems that this is the first time that the IQQM has been run taking into account possible implications of CSG production on WASOs.

4.2.4.3 Resource Operations Plan

A Resource Operation Plan (ROP) for the Condamine and Balonne was published in 2008 and revised in 2015 (DNRM 2015b). The ROP describes the rules and requirements to achieve the water resource objectives from the Water Resource Plan.

4.2.5 Commonwealth Environmental Water

As part of a suite of national water reforms, the Australian Government created the Commonwealth Environmental Water Holder through the *Water Act 2007*: "*The functions of the Commonwealth Environmental Water Holder are to be performed for the purpose of protecting or restoring the environmental assets of the Murray-Darling Basin ... so as to give effect to relevant international agreements.*"<www.environment.gov.au/water/cewo/about-commonwealth-environmental-water>

Commonwealth water holdings are the direct result of government purchases of entitlements and a substantial investment in more efficient water infrastructure in the Murray-Darling Basin.

The planning, prioritisation, use and monitoring and evaluation of Commonwealth environmental water is informed by a range of stakeholders including the Department of the Environment and other Commonwealth and State government agencies, scientists, catchment and local natural resource management agencies, environmental water advisory groups, water user associations, Indigenous communities and local landholders.

The Condamine-Balonne Rivers region lies with the northern unregulated rivers region. These catchments are predominantly unregulated systems in which the majority of water use occurs by diversion of river and overland flows (water that breaks out of a watercourse as floodwater or runs across the land after rainfall) during episodic flow events. Water taken from unregulated sources is often stored in large, shallow floodplain storages known as “ring tanks” or “turkey’s nest” dams. These can range from hundreds of megalitres (ML) to several hundreds of gigalitres (GL) in capacity.

Commonwealth environmental water is important from the point of view that it provides context, and partly explains the interest of the Federal Government in management of water in the Condamine area. It is also important in that it introduces the notion that river flows are more regulated (hydraulically controlled) further towards the south of the Murray-Darling Basin, and unregulated, with extremely variable flows, in the north.

4.2.6 Surface Water Use

The primary purpose of this section, and indeed of Section 4.2, is to document the magnitude of surface water resources in the Condamine area. The motivation is to provide context for later consideration of the potential impacts of CSG production on surface water resources.

Potential surface water uses in the Condamine catchment include agricultural, pastoral, urban, mining and recreational use.

According to Department of the Environment (2016), registered entitlements in the Condamine-Balonne catchment as at 31 December 2015 are as shown in Table 4-5. Data for the area of the Condamine Alluvium alone are not available.

Table 4-5 Condamine-Balonne catchment entitlements

Security	Registered entitlements (GL)	Nominal volume (GL)	Long term average annual yield (GL)
Condamine-Balonne unsupplemented	0.2	0.2	0.2
Condamine-Balonne water harvesting of overland flow	23.2	10.0	10.0

Unregulated water licences are issued for water management areas. There are four water management areas within the Condamine Alluvium extent (DNRM 2015b):

- the Upper Condamine water management area;
- the Condamine and Balonne water management area;
- the Condamine and Balonne tributaries water management area; and
- the Gowrie and Oakey Creek water management area.

Two water supply schemes fall within the boundary of the Condamine Alluvium: the Upper Condamine water supply scheme and the Chinchilla Weir water supply scheme. Supplemented water licences are issued under the water supply schemes and range from medium to high priority. Table 4-6 and Table 4-7 summarise supplemented water allocations (dated 15 February 2015) within the Project area (Queensland Government 2016).

Table 4-6 Upper Condamine water supply scheme

Location	Minimum volume (GL)	Current volume (GL)	Maximum volume (GL)	Projected volume (GL)
Upper Condamine Zone UCS-01	0	0.3	0.8	0.3
Upper Condamine Zone UCS-02	0.8	2.9	3.3	2.9
Upper Condamine Zone UCS-03	0	7.6	7.2	7.6
Upper Condamine Zone UCS-04	2.9	11.5	11.9	11.5

Table 4-7 Chinchilla Weir Water Supply Scheme

Location	Minimum volume (GL)	Current volume (GL)	Maximum volume (GL)	Projected volume (GL)
Condamine Balonne Zone CBS-01	2.0	2.0	2.9	2.0

Surface water use in the IQQM models, derived from historical data, for the Upper and Middle Condamine catchments, is also summarised in Table 4-8.

Table 4-8 Modelled water use in IQQM (after CSIRO 2008)

	Number of nodes	Medium security licence (GL/y)	Licence (GL/y)	Pump constraints (ML/d)
Upper Condamine IQQM model				
Irrigation				
Medium security	23	30.6		1,551
Unsupplemented	75		66.6[1]	6,335
Floodplain harvesting	5		41.9[2]	8,389[3]
Sub-total	**103**	**30.6**	**108.5**	**16,275**
Town water supplies	4	6.2		
High security 'other demand'	9	0.9		
Sub-total	**13**	**7.1**		
Total	**126**	**37.7**	**108.5**	**16,275**
Middle Condamine IQQM model				
Irrigation				
Medium security	7	3.7		124
Unsupplemented	107		115.0[1]	12,375
Floodplain harvesting	5		150.0[2]	29,991[3]
Sub-total	**119**	**3.7**	**265.0**	**42,490**
Town water supplies	15		5.3	
High security 'other demand'	6		2.3	
Sub-total	**21**		**7.6**	
Total	**140**	**3.7**	**272.6**	**42,490**

1. Based on nominal volume
2. Based on on-farm storage capacity
3. Estimated when gravity diversion used

Given that the IQQM is used by Government to assess the performance of the water allocation system, and would be used to assess applications for new licences, the summary presented in Table

4-8 is the most interesting. The area of the Condamine Alluvium straddles the boundary between the Upper Condamine IQQM model and the Middle Condamine IQQM model, so medium security licences (in the third column) and unsupplemented and floodplain harvesting licences (in the fourth column) cannot be disaggregated from the totals provided in the Table.

The conclusion of this brief exploration of data on surface water resources is that surface water resources in the project area, straddling two IQQM models, is of the order of hundreds of gigalitres per year.

4.3 Groundwater Resources

The Condamine Alluvium is an important groundwater resource for irrigators in the area. The hydrostratigraphy of the alluvium is summarised below, followed by a summary of available data and of groundwater use.

The focus of Section 4.3 is on the Condamine Alluvium, because Section 13(b) refers specifically to the Condamine Alluvium, because most of the licensed abstraction in the region is from the Condamine Alluvium, and because the potential impacts of CSG production are predicted to occur within the area of the Condamine Alluvium. This Section is intended to provide context. Additional information on predicted impacts will be provided below.

Of primary interest is the magnitude of groundwater use. This is important so that possible impacts of CSG production on groundwater availability can be considered relative to existing entitlements.

4.3.1 Hydrostratigraphy

Much has been written on the geology, hydrogeology and hydrostratigraphy of the Condamine Alluvium. Just as its areal extent is uncertain (see Figure 2-2) the internal structure of the Condamine Alluvium is also uncertain.

There is uncertainty regarding the spatial extent of the Condamine Alluvium near its northwestern edge, the occurrence and properties of the transition layer, and the extent of the Jurassic formations underneath the Condamine River Alluvial Aquifer (Dafny and Silburn 2013).

Dafny and Silburn (2013) summarise all previous studies and describe two conceptualisations proposed by different authors:

- A fluvial alluvium unit and a sheetwash alluvium unit, based on depositional environments. The fluvial alluvium unit dominates the lower and western parts and is overlain by the sheetwash alluvium. This is the conceptualisation that was adopted by KCB (2011b) for the Central Condamine Alluvium Groundwater Model (CCAM).
- Three units denoted A, B and C, attributed to transport and sedimentation processes from the eastern tributaries, and forming outwash fans. A is mostly sand and C (termed 'basal layer') is characterised by the appearance of sediments in the lower part. B includes all sediments in-between. This conceptualisation was proposed by SKM (1999).

The Condamine Interconnectivity Research Project (CIRP), as discussed in Section 2.4, prefers reference to a transition layer, which is very clayey and has very low vertical hydraulic conductivity.

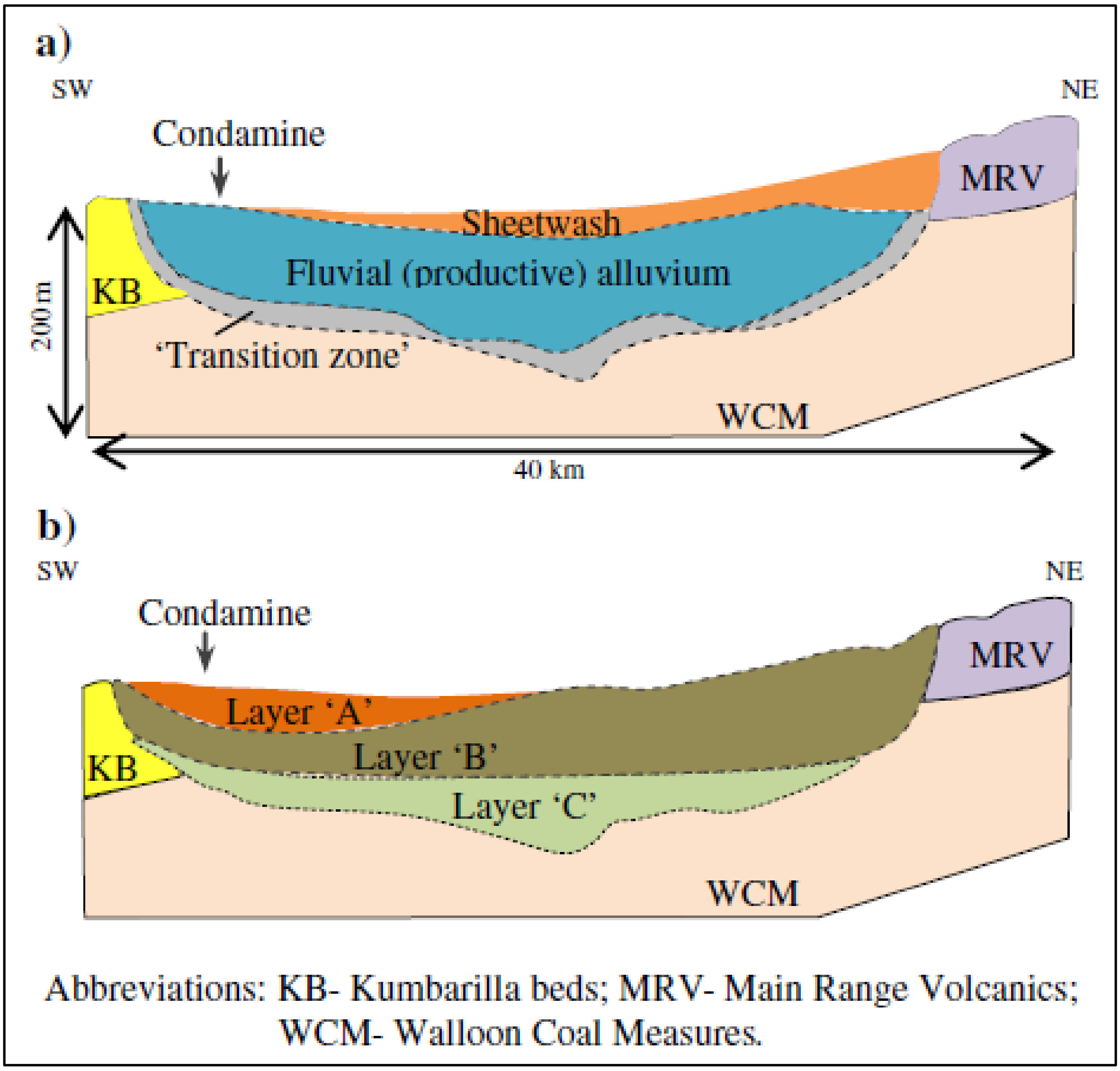

Figure 4-4 Hydrostratigraphic conceptualisations (from Dafny and Silburn 2013)

4.3.2 Groundwater Data

The Groundwater Database Queensland (GWDBQLD, updated on 7 October 2014) has been downloaded from DNRM's website. All data have been extracted for bores located within the plan area of the Condamine Alluvium (as defined by Dafny and Silburn 2013).

At the time of the download, there were 2,827 bore locations with measured depth to water. Groundwater bore locations with water levels are shown in Figure 4-5.

A number of bores do not have records of the elevation of the top of casing from which reduced values of hydraulic head (in mAHD) can be derived. Many bores have only one measurement of depth to water and have been ignored in further analysis. Of the 2,827 bore locations, 601 have transient data (more than two measurements). Of these, 236 bores have no data after 2010. Thus, 375 bores have transient data after 2010.

Groundwater monitoring locations and associated daily water level data have also been downloaded from DNRM's Water Monitoring Portal. Figure 4-5 shows these bore locations as well. Twenty monitoring bores are located in the area of the Condamine Alluvium. Most of these bores (17 of 20) have only a few years of data commencing in 2010-2011, while the remaining three bores have recorded data from 1994-1995.

Dafny (2014) provides a recent systematic analysis of changes in water table elevations in the area of the Condamine Alluvium in recent years. He shows a range of types of responses, including recovery of water table elevations in some areas following changes in abstraction regimes by irrigators. Nevertheless, the water table remains below the bed elevation of the Condamine River and its tributaries in nearly all locations where it is possible to compare the two.

4.3.3 Groundwater Use

Information about active groundwater licences, last updated in October 2015, was downloaded from the Queensland Government data website (Queensland Government 2015). The Condamine River Alluvium aquifer is managed as part of the Central Condamine Alluvium Groundwater Management Area (CCA-GMA). The CCA-GMA is divided into four sub-areas (Figure 4-6) that are themselves separated into transitional zones.

Throughout the CCA-GMA, there are 320 active groundwater abstraction licences with a total entitlement of 87 GL/y. Nominal entitlements for each of the sub-management groups are shown in Table 4-9. Forty percent of the total nominal entitlement is assigned to Central Condamine Subarea 2 – Transitional Zone 3. Overall, about 90% of groundwater abstraction is for irrigation. KCB (2010b) estimated abstraction to be 66 GL/y, including 46 GL/y from metered abstraction and 20 GL/y from unmetered abstraction, for the years 1980 to 2010. In 2012, abstraction was estimated to be 67 GL/y, although sustainable groundwater yield was estimated at the same time to be 40 GL/y (Tan et al. 2012).

The locations of licenced abstraction bores are shown in Figure 4-7. There are concentrations of licences with larger abstraction limits upstream and downstream of Cecil Plains.

Table 4-9 Central Condamine Alluvium GMA active groundwater abstraction licences

Sub-management group	Number of licences	Nominal entitlement (GL)
Central Condamine Subarea 1	55	10
Central Condamine Subarea 2	19	4
Central Condamine Subarea 2 – Group S	1	<1
Central Condamine Subarea 2 – Transitional Zone 3	98	34
Central Condamine Subarea 2 – Transitional Zone 3 – Group S	15	5
Central Condamine Subarea 2 – Urban	2	1
Central Condamine Subarea 3	45	12
Central Condamine Subarea 3 – Transitional Zone 3	16	4
Central Condamine Subarea 4	68	14
Central Condamine Subarea 4 – Urban	1	2
TOTAL	**320**	**87**

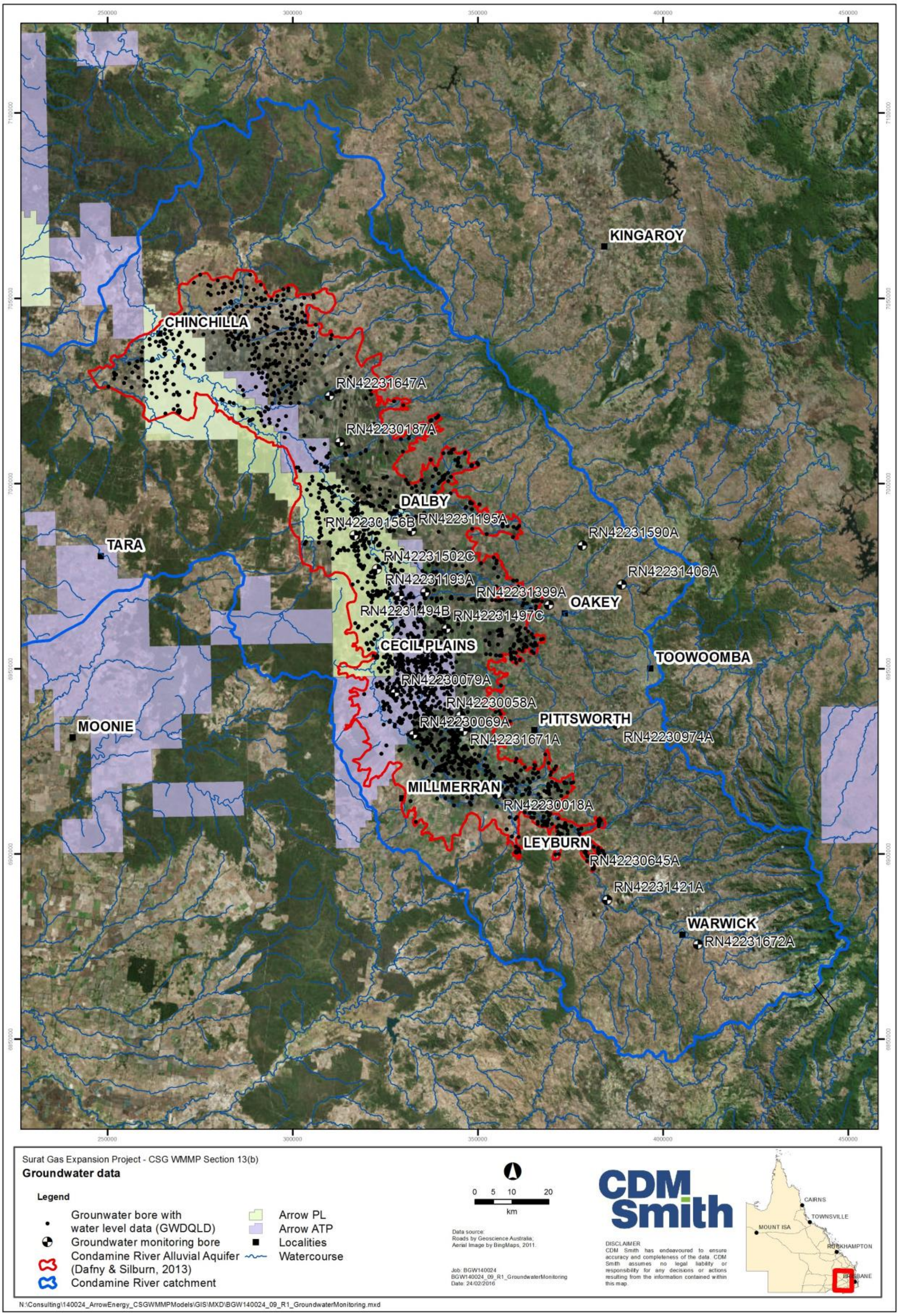

Figure 4-5 Groundwater data

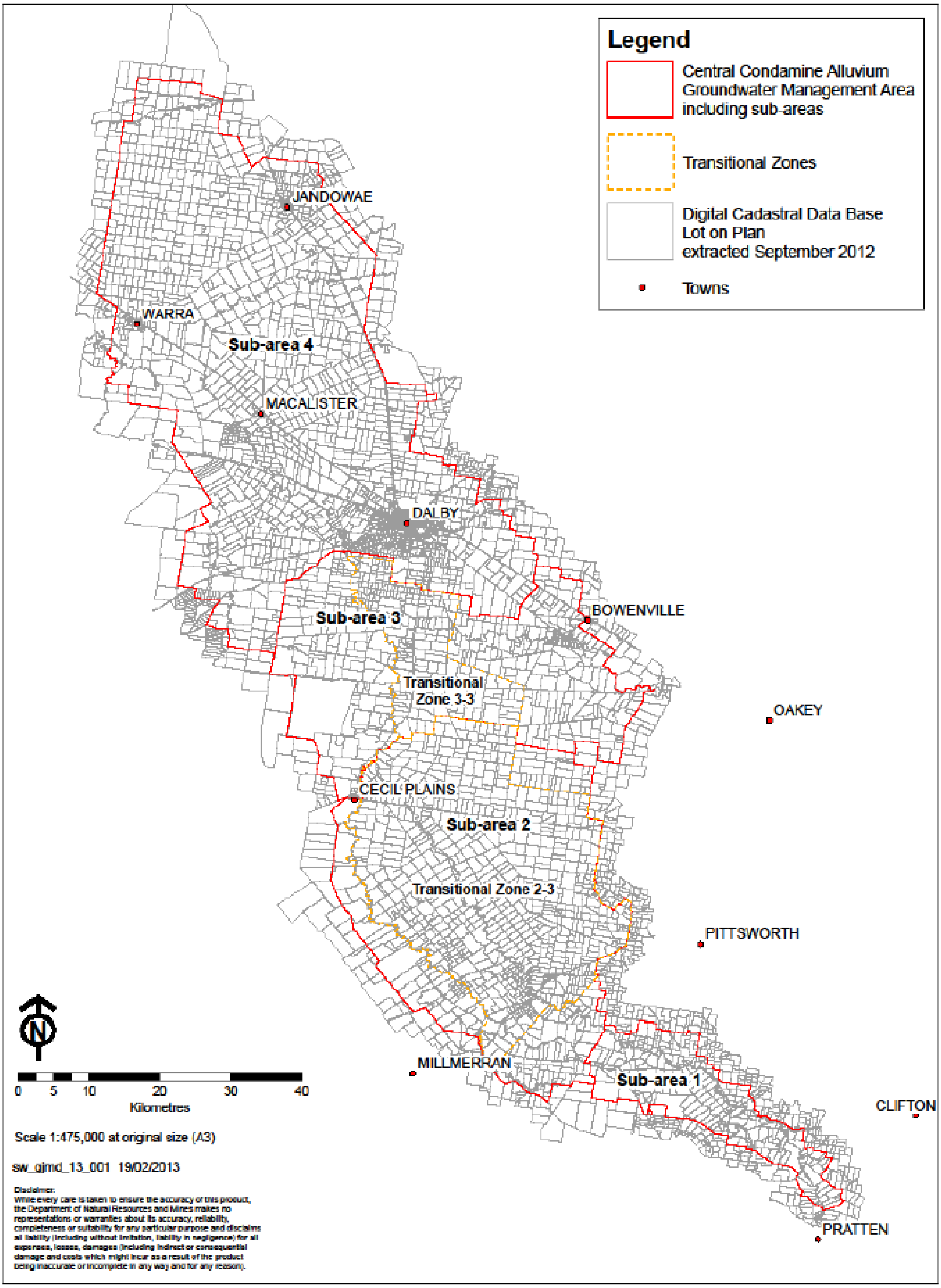

Figure 4-6 Central Condamine Alluvium Groundwater Management Area (DNRM 2015a)

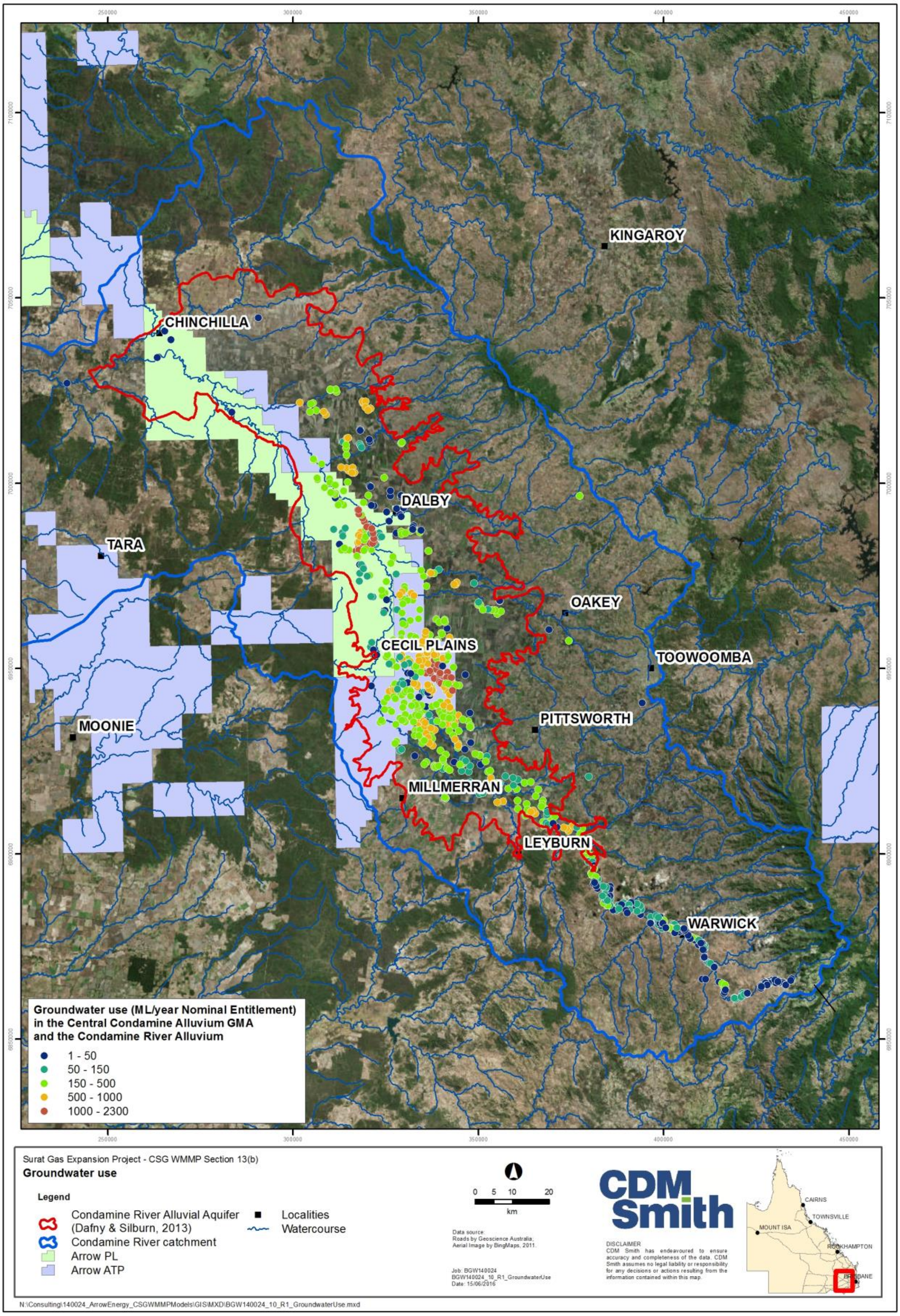

Figure 4-7 Groundwater use within the Condamine Alluvium

Section 5 Surface Water - Groundwater Interaction

5.1 Preamble

The purpose of Section 5 is to discuss concepts of "*surface water – groundwater interaction*", in order to facilitate later discussion of the potential impacts of the "*action in the project area*" on "*surface water – groundwater interactions*" in the "*Condamine Alluvium*".

Surface water – groundwater interaction

"Surface water – groundwater interaction" is any situation where water above the land surface interacts with groundwater below the land surface.

Of greatest interest in the Condamine Alluvium is the interaction between the Condamine River and its tributaries and the water table in the unconfined aquifer in the Condamine Alluvium.

The Condamine River and its tributaries are likely to function as losing disconnected streams over most of their length, such that any lowering of the water table is unlikely to lead to increased leakage from surface water to groundwater.

5.2 Types of Interaction and Terminology

Several definitions of surface water – groundwater interaction and connected water systems have been used in recent Australian literature.

The Australian Groundwater Modelling guidelines (Barnett et al. 2012) define surface water – groundwater interaction as any situation where water above the land surface interacts with groundwater below the land surface.

The terms "connectivity" and "connected water systems" are also frequently used. These are generally defined on the basis of the magnitude and direction of flux between surface and subsurface water bodies and, within the context of water management, the effects imposed on them by stresses such as pumping. Brodie et al. (2007b) and SKM (2012) present stepwise procedures for classifying connectivity. These classifications are broadly consistent, in the sense that the physical connectivity setting (contiguous or non-contiguous) is defined and the impact of pumping on the dynamics of the exchange flux is quantified.

Some of the definitions and classifications of connected water bodies are shown in Table 5-1.

At the highest level, interaction between surface water and groundwater is of three types (e.g. Nield et al. 1994; Townley & Trefry 2000). Surface water bodies such as rivers and streams (including ponds, pool, nearby ox-bow lakes etc.) can be:

- "gaining", e.g. in a typical low-land alluvial valley, or in uplands during or after the wet season, when groundwater supplies baseflow to the stream;
- "losing", e.g. where the water table nearby has dropped below surface water levels, so that the surface water body loses; and
- "flow-through", e.g. in a meandering river, where the slight gradient in river level allows water to flow through the ground inside the loops of the meander, so that surface water flows into adjacent aquifers and returns to the river a short distance downstream.

Figure 11-1 of the Australian Groundwater Modelling Guidelines (Barnett et al. 2012) explains that slightly different terminology is used in surface and groundwater hydrology. The terminology used here, in this report, is that of surface hydrology, considering fluxes from the point of view of the rivers and streams. The Condamine River is perceived to be a "losing stream" (a surface water body losing water to groundwater) rather than a "recharge water body" (with the aquifer below receiving recharge from the river above).

Losing streams can be of two kinds, generally described as "connected" or "disconnected". A stream will lose water to groundwater when the water table on both sides of the stream is lower than the surface water elevation in the stream. When there is a continuous saturated zone at all elevations beneath the streambed, the stream is said to be "connected". When there is an unsaturated zone beneath the stream, it is said to be "disconnected".

The significance of a disconnected stream is that further lowering of the water table does not increase the leakage of water from the "perched" surface water body above.

This phenomenon is described in a number of recent papers with reference to Australian river systems (Brunner et al. 2009a, 2009b, 2010, 2011; Brownbill et al. 2011). In many respects, these recent studies are less informative than earlier work, e.g. by Peterson and Wilson (1988), which explains the role of the unsaturated zone.

The transition from connected to disconnected is such that the rate at which water leaks or is lost from the stream increases and reaches a maximum value. The maximum is controlled by either (i) the vertical hydraulic conductivity of a low conductivity layer that maintains a saturated zone above and allows desaturation below (sometimes called a clogging layer, as in Figure 5-1), or (ii) the unsaturated vertical and horizontal hydraulic conductivities in an unsaturated zone between the bed and the water table at depth (Figure 5-2).

No field studies have been found that show conclusively that this phenomenon occurs beneath the Condamine River overlying the Condamine Alluvium, but because water table elevations are metres lower than bed elevation in many locations, it is believed that the river is largely disconnected.

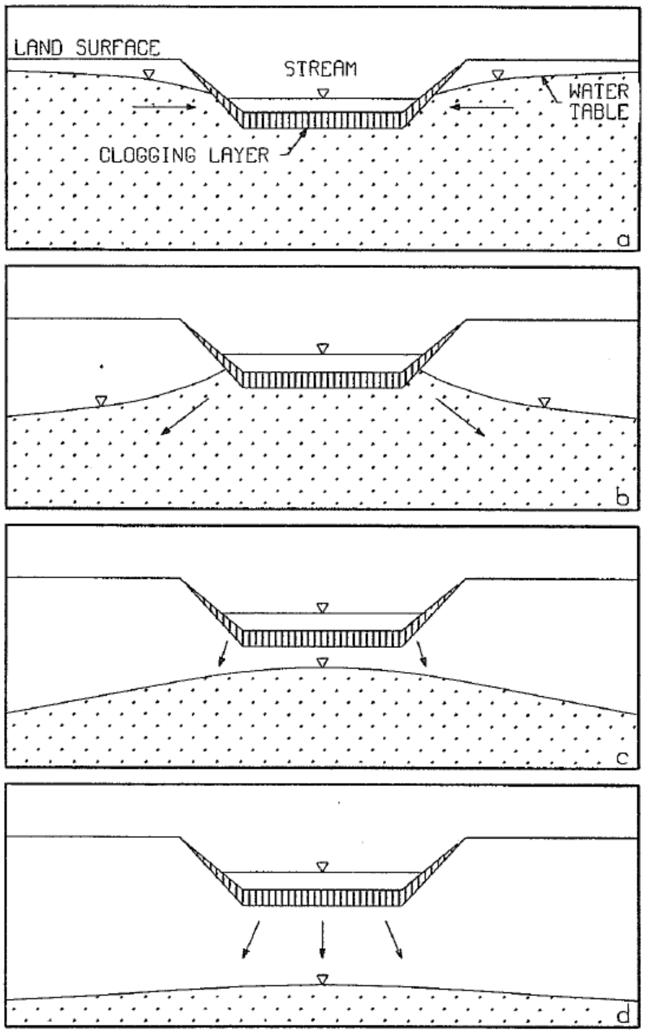

Figure 5-1 Stream-aquifer interaction with a clogging layer (a) connected gaining stream, (b) connected losing stream, (c) disconnected stream with a shallow water table, and (d) disconnected stream with a deep water table (from Peterson and Wilson 1988)

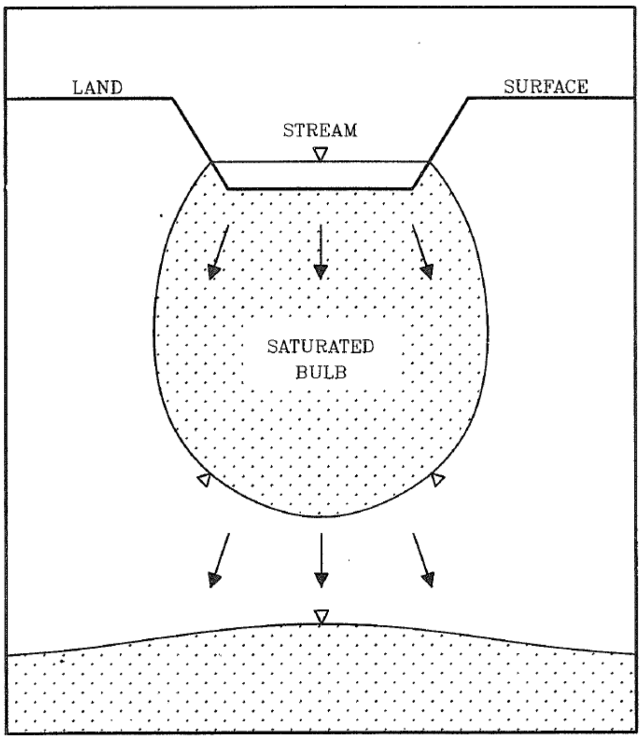

Figure 5-2 Disconnection below a stream without a clogging layer (from Peterson and Wilson 1988)

Table 5-1 Definitions of surface water–groundwater connectivity

Source	Reference	Definition
Bureau of Rural Sciences	Brodie et al. (2007a) An Overview of Tools for Assessing Groundwater-Surface Water Connectivity	Assessment of surface water-groundwater interactions involve the "analysis of the dynamics of water flow between aquifers and surface water features, and the impacts of this interaction in terms of water quantity, quality and ecology"
CSIRO Murray-Darling Basin Sustainable Yields Project	Parsons et al. (2008) Surface–groundwater connectivity assessment: A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project	Similar to the above definition in that the connectivity mapping involved "determining the direction and magnitude of groundwater flux to or from the major rivers."
Department of Primary Industries, Parks, Water and Environment	Sheldon (2011) Groundwater and Surface Water Connectivity in Tasmania: Preliminary Assessment and Risk Analysis.	"Connectivity refers to flows between surface water and groundwater sources".

Source	Reference	Definition
National Water Commission	SKM (2011) National framework for integrated management of connected groundwater and surface water systems	Connected water systems are water systems where: ▪ "abstraction from the groundwater system can affect the quantity (and quality) and reliability/accessibility of abstraction from the surface water system, or ▪ abstraction from the surface water system can affect the quantity (and quality) and reliability/accessibility of abstraction from the groundwater system, or ▪ abstraction of water from either can affect water supply to ecosystems that rely on both surface and groundwater; for example, low flows in rivers and certain wetlands." The terms contiguous and non-contiguous are adopted instead of connected and disconnected to avoid misinterpretation of the latter.
Murray-Darling Basin Authority	SKM (2012) Synthesis of groundwater -surface water connectivity knowledge for the Murray-Darling Basin	Describes that "Groundwater and surface water are intrinsically connected, being part of the one hydrologic cycle" and "there is continual movement of water between groundwater and surface Water". Connectivity refers to "this transfer of water at a given location and timeframe".
Geoscience Australia	http://www.ga.gov.au/groundwater/understanding-groundwaterresources/groundwater-surfacewater-connectivity.html	"Groundwater-surface water connectivity refers to the direction and magnitude of flow between water resources located above and below ground."

5.3 Surface Water and Groundwater in the Condamine Alluvium

CSIRO (2008) describe the Condamine River function as a "losing stream" over most of its length where the river overlies the Condamine Alluvium, and certainly over most of its length inside lease areas held by Arrow. The purpose of Section 5 is to provide evidence that supports this finding.

5.3.1 Streambed Elevation

The level of the bed of a river has an important influence on the nature of surface water – groundwater interaction.

- The depth of surface water in a river or stream can vary from 0 m to many metres, so the elevation of the water surface varies from the bed elevation to an elevation some possibly many metres higher.
- The elevation of the water table on either side of a river or stream can vary from above the water surface elevation to below. It can be a little below the level of the bed or many tens of metres below the level of the bed.
- The elevations of surface water and the water table vary in space and time. One can rise faster than the other in response to rainfall. Surface water generally falls faster than the water table during the recession following an event.

CDM Smith acquired from Arrow the most recent LiDAR data, and processed and analysed the data to infer depth to the water table, as described in Section 5.3.2. The analysis is similar to work undertaken by Ivkovic (2006) in the Namoi catchment in NSW.

The first step was to find all bores in the Groundwater Database Queensland (GWDQLD) located within the Condamine Alluvium, within 1 km of the Condamine River and its tributaries (as defined by an ArcGIS shape file provided by the Queensland Government), and within the LiDAR footprint. Of these, only shallow bores (screened at a depth less than 40 m) and those with transient water level data were chosen. A total of 116 bores were selected.

The closest location along the watercourse to each groundwater bore was extracted using ArcGIS.

A grid of points was generated near each of the "nearest points" on the river or stream found by ArcGIS. LiDAR data were extracted for every point in a 100 m by 100 m grid, at 1 m intervals, i.e. at the resolution of the LiDAR dataset. That is, the LiDAR elevations at 10,000 points near each of the 116 "nearest points" were extracted. For each grid of points, the lowest elevation was found. This lowest point is considered to be the streambed elevation nearest to the bore.

This analysis resulted in estimates of the nearest minimum streambed elevation corresponding to 116 bores within 1 km of the Condamine River or its tributaries.

5.3.2 Depth to Groundwater

The water table elevation in 2010 in the Condamine Alluvium is shown in Figure 5-3. Note the existence of a depression to the east of Cecil Plains. Groundwater allocations are relatively high in this area (see Figure 4-7).

These results are broadly consistent with those shown by DNRM (2012) in 2008. Water table contours cannot be compared directly because the data have been obtained at different times, and because DNRM's contours are not labelled with elevations.

Focusing on the 116 observation bores identified above (within 1 km of the Condamine River and its tributaries), all measurements of water table elevation were analysed to determine the maximum, minimum and average water table elevation at each bore. In areas where the water table elevation is below bed elevation in nearby drainage lines, the maximum water table elevation is of most interest, especially if the latter remains below bed elevation. In areas where the water table elevation is seasonally above and below bed elevation, the maximum and minimum values are of interest.

To illustrate the extent to which data support CSIRO's (2008) conclusion that the Condamine River and its tributaries function as losing streams, depth to groundwater was computed at all 116 locations, using the minimum bed elevation at the nearest location on a river or stream (Section 5.3.1) and the maximum (highest) water table elevation. The results are shown in Figure 5-4.

Brown points in Figure 5-4 show the locations where the water table elevation was higher than the riverbed elevation at some time during the period of available data. Those points are distributed along the Condamine River. They can be seen near Warra Town Weir (just south of Couranga Creek), Loudoun Weir (just south of Myall Creek), at two locations near the confluence of the Condamine River and tributaries (Timbour Creek and another) and at one location on the northern anabranch (possibly affected by a nearby turkey's nest rather than by the river).

Red and orange points in Figure 5-4 show locations where the minimum depth to groundwater is up to 10 m along the Condamine River, i.e. almost everywhere except near the northern anabranch (the North Condamine River) where groundwater is used heavily (Figure 4-7).

Lemon to green points in Figure 5-4 show locations where the minimum depth to groundwater is greater than 10 m.

Overall, the results show that the Condamine River is likely to function as a losing stream with water table elevation below the bed of the river along most of its length within the area of Condamine Alluvium. These results are consistent with those shown by CSIRO (2008).

If more data were available for water table elevation, streambed elevation and surface water elevation, especially on sections orthogonal to the Condamine River and its tributaries, then there would be more support for this conclusion. The available data are sparse, and not in perfect locations, nevertheless the amount of data is significant and allows this conclusion to be drawn.

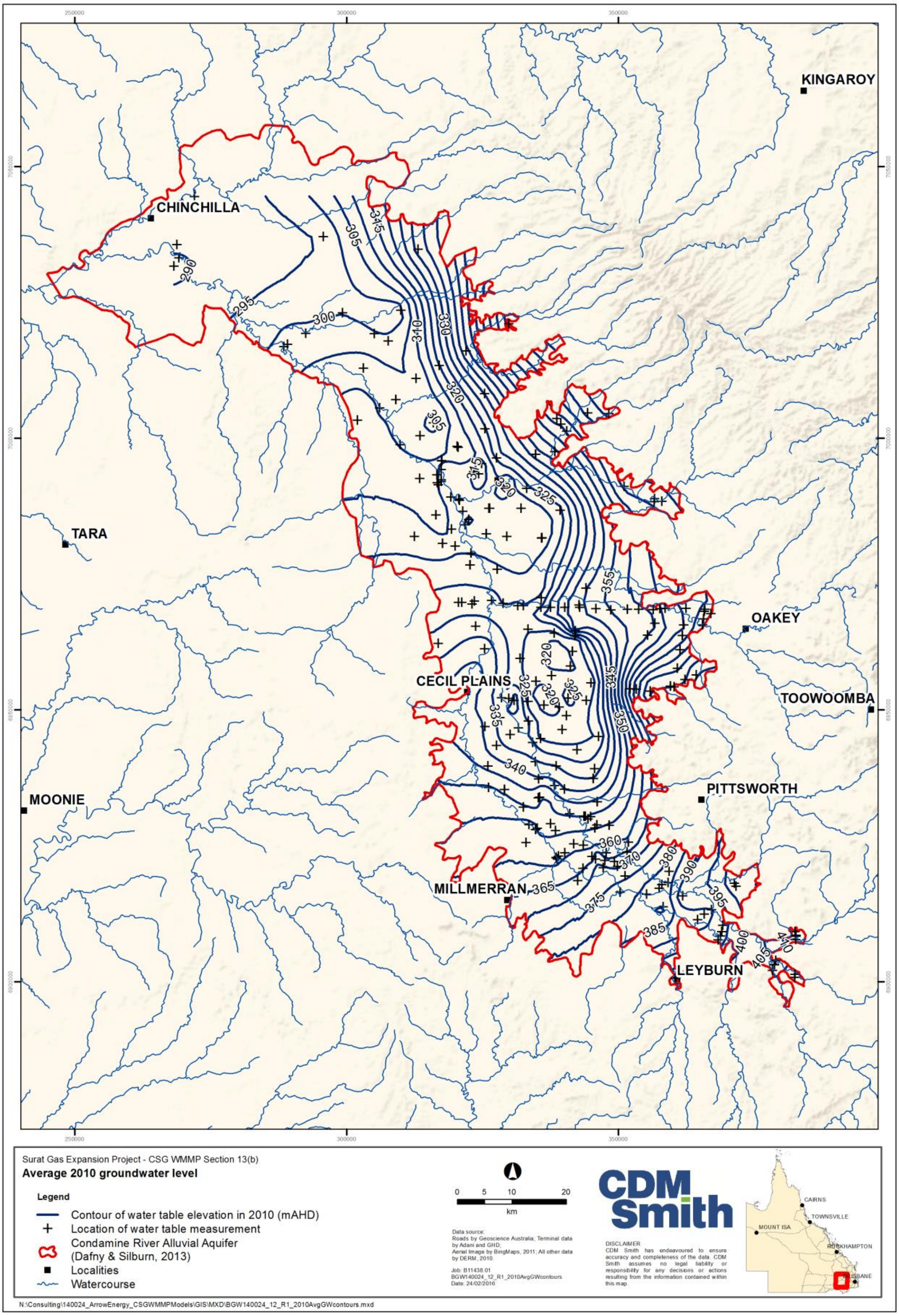

Figure 5-3 Average water table elevation in 2010 in the Condamine Alluvium

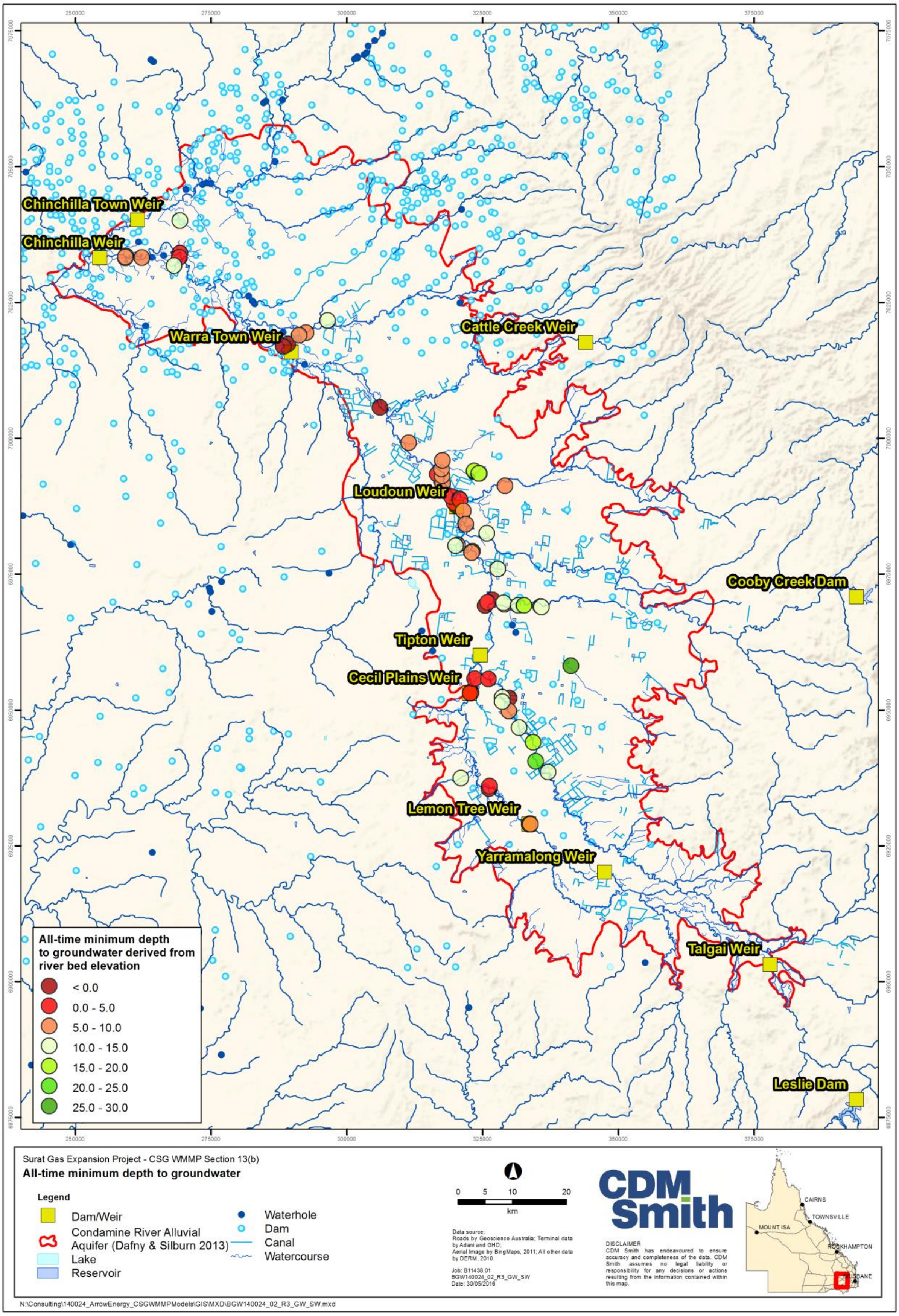

Figure 5-4 Minimum depth to groundwater derived from maximum water table elevation

5.3.3 Water Table Elevations Near Stream Gauging Stations

A comparison of water table elevations and surface water levels along the Condamine River has been made. Only five surface water gauging stations (422316A, 422350A, 422333A, 422308C and 422343A) are close to groundwater bores (within a radius of a few hundred metres) with groundwater level data available. The precise reason for the relative paucity of data is not known, but this situation is not uncommon in inland river systems in Australia. Clusters of observation bores are generally only installed when there is a very specific question to answer, so this suggests that questions have not often been asked about the nature of the connection between the river and the aquifer.

Four of the five comparison sites show that water table elevations are always below the river water levels. Only gauging station 422308C at Chinchilla shows the water table elevation is sometimes higher than surface water levels.

Figure 5-5, Figure 5-6 and Figure 5-7 show hydrographs of surface water and groundwater levels (water table elevations) at three locations (see Figure 4-2). Records at the other two locations are much shorter.

This comparison differs from the comparison of streambed elevation and water table elevation presented in Section 5.3.2 above, in the sense that it uses measured surface water levels. Surface water level will always be above the lowest streambed elevation, so the driving force for leakage from the Condamine River and its tributaries, the difference between surface water level and water table elevation, will always be greater than that shown in Figure 5-4 when there is surface water above the bed.

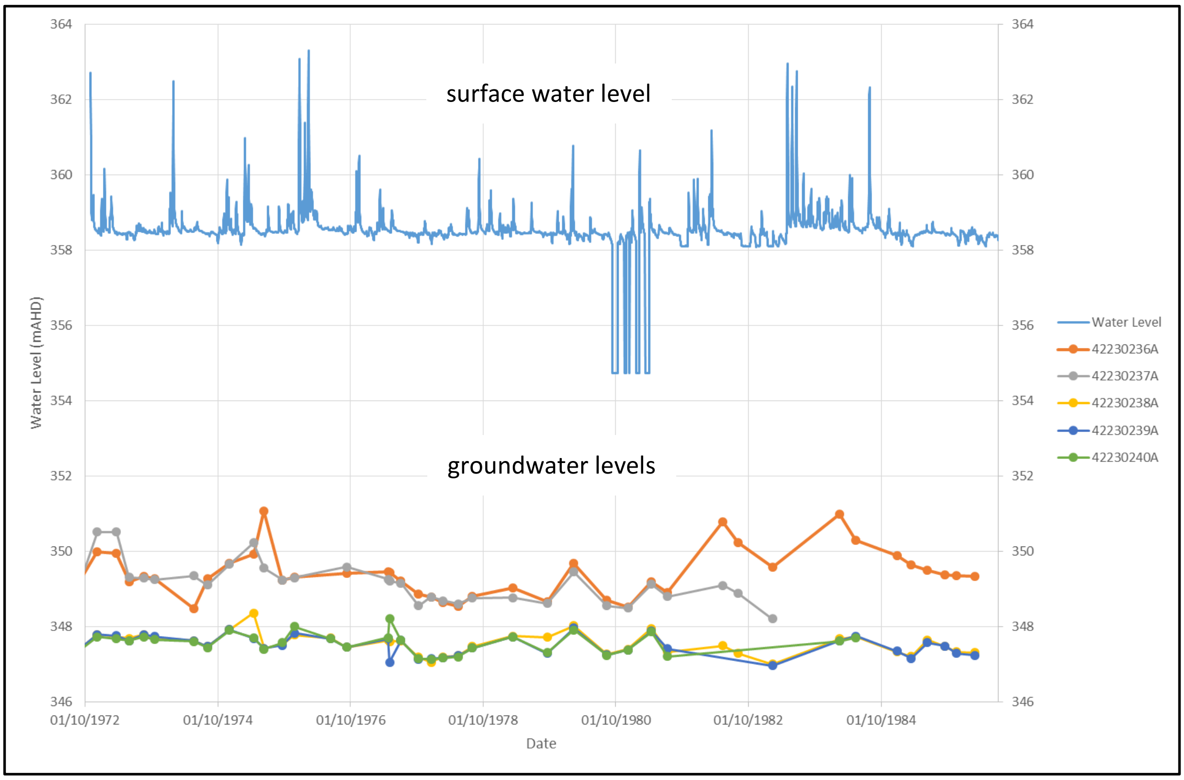

Figure 5-5 Surface water and groundwater levels near station 422316A (Condamine River at Cecil Plains Weir)

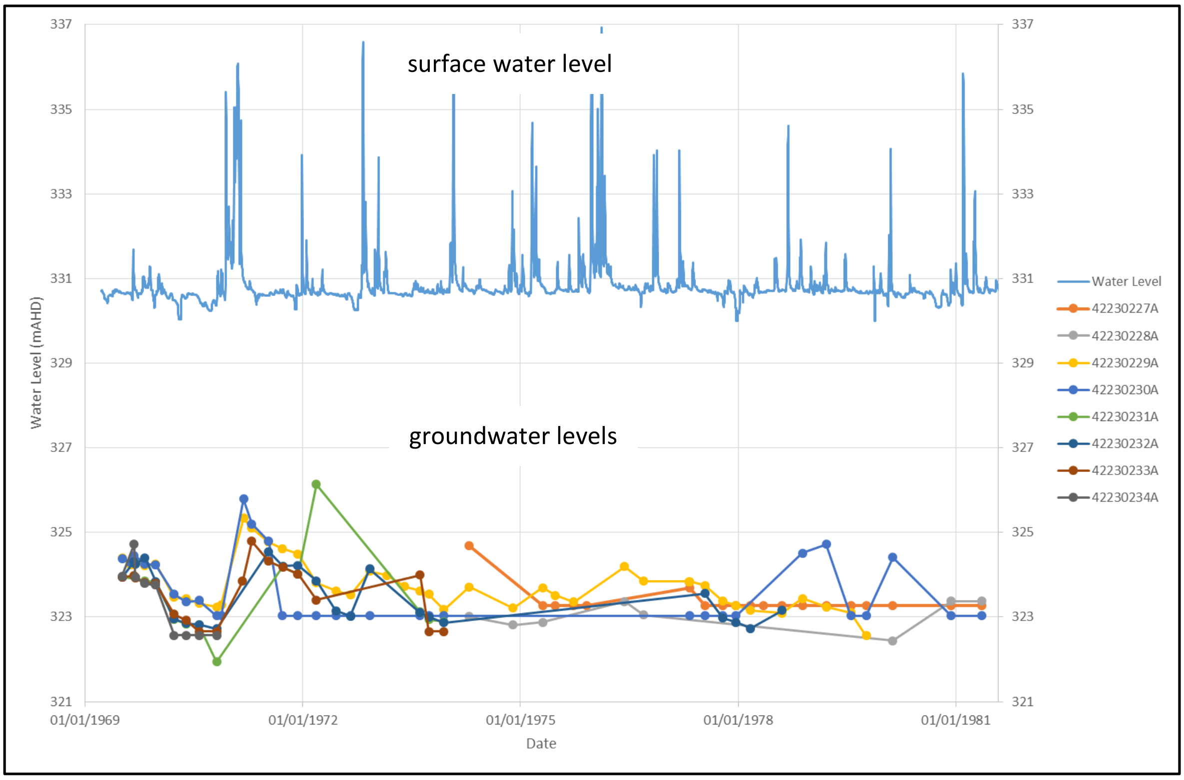

Figure 5-6 Surface water and groundwater levels near station 422333A (Condamine River at Loudons Bridge)

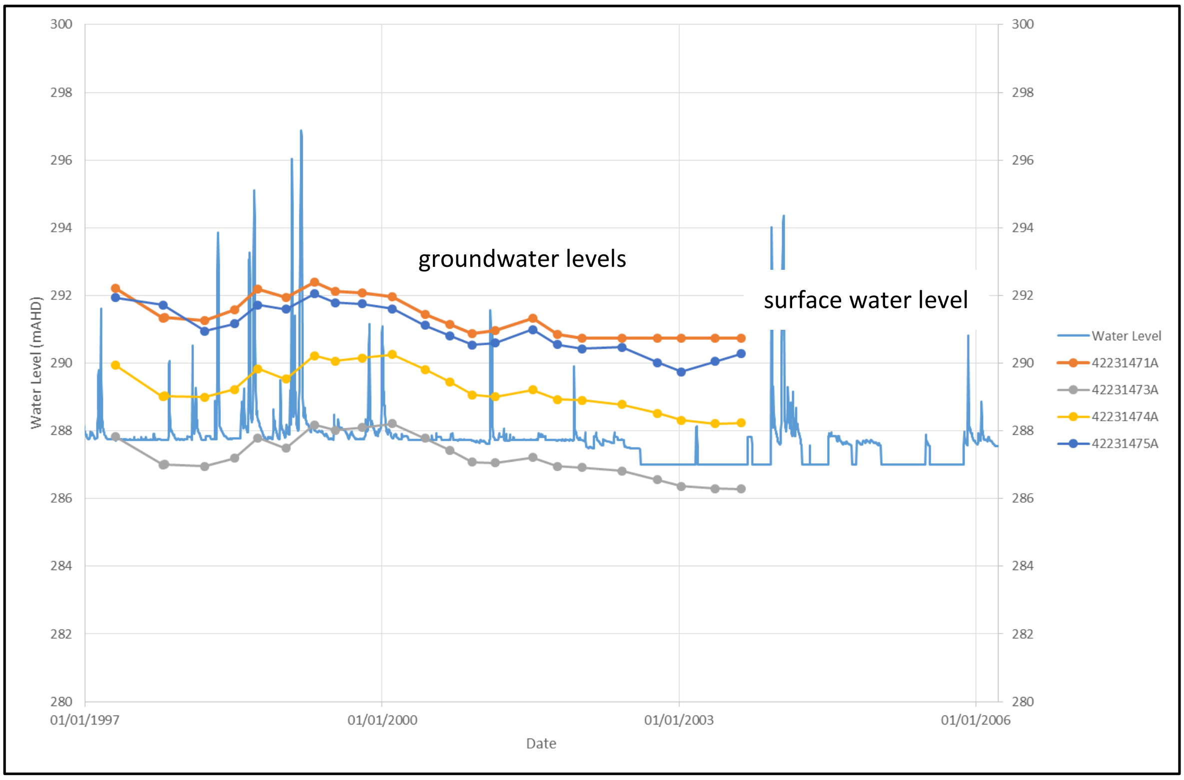

Figure 5-7 Surface water and groundwater levels near station 422308C (Condamine River at Chinchilla)

5.3.4 Stream Dynamics and Flooding

Surface water – groundwater interaction is often considered to be a steady flow phenomenon, with the rate of flow driven by a difference in levels (heads) divided by the distance separating source and sink (a hydraulic gradient), a representative hydraulic conductivity and the cross-sectional area of the flowing region. However, the nature of the interaction can be far more dynamic.

- Surface water – groundwater interaction is possible in all locations where surface water occurs, at some time in the year. Table 4-9 shows that the total length of watercourses within the area of the Condamine Alluvium (Dafny and Silburn 2013) is nearly 3,000 km, while the length of the Condamine Alluvium “as the crow flies” is less than 200 km. The length of streambed that is wet varies seasonally and year to year.
- Figure 4-3 shows that there are nine weirs with permanent weir pools within the area of the Condamine Alluvium. Chinchilla Weir supports the largest pool, being the water supply for the town of Chinchilla. The other storages are relatively small. The wetted area of weir pools varies seasonally and year to year.
- Figure 4-2 shows the percentage of time when there is flow at stream gauging stations. Of the 13 gauging stations inside the area of the Condamine Alluvium (see Section 4.2.2,), only two flow less than half the time, while six flow more than three-quarters of the time. Streamflow is variable in space and time.
- The region is known for episodic flooding. As explained in Section 4.2.3, major floods occur regularly, on average once every two years, and generally during late spring, summer and autumn (Coffey Environments 2012).
- Flooding events are driven by rainfall, which causes runoff, and of course supports the use of flood harvesting as a source of water supply for agriculture.

It is not possible to contemplate simulating and predicting all of the processes described above for a region the size of the Condamine Alluvium, taking into account leakage to groundwater from all wetted areas. This is beyond the capability of current simulation software and computing hardware.

It is not possible to collect data with sufficient resolution in space and time to allow calibration of models of all these processes.

Surface water – groundwater interaction must be represented in an approximate way as a source of recharge to regional scale groundwater flow models.

Section 6 Dependent Ecosystems

6.1 Preamble

The following definition of Dependent Ecosystems (DEs) is sourced from the *Water Act 2007* (Cth) s 4, which is used to oversee water resources planning in the in the Murray-Darling Basin:

> ***water-dependent ecosystem*** *means a surface water ecosystem or a ground water ecosystem, and its natural components and processes, that depends on periodic or sustained inundation, waterlogging or significant inputs of water for its ecological integrity and includes an ecosystem associated with:*
>
> *(a) a wetland; or*
>
> *(b) a stream and its floodplain; or*
>
> *(c) a lake or a body of water (whether fresh or saline); or*
>
> *(d) a salt marsh; or*
>
> *(e) an estuary; or*
>
> *(f) a karst system; or*
>
> *(g) a ground water system;*
>
> *and a reference to a water-dependent ecosystem includes a reference to the biodiversity of the ecosystem.*

The term "water-dependent ecosystem" is very broad and describes a myriad of ecosystems that occur in a range of settings. It is useful to apply a high level classification scheme to DEs to distinguish between broad types of DEs according to their general hydrological setting. This approach is often taken in Groundwater Dependent Ecosystem (GDE) studies where the classification scheme outlined by Eamus et al. (2006) and Eamus (2009) is commonly adopted to separate GDEs into three types, as follows:

- Aquifer and cave ecosystems;
- Ecosystems dependent on the surface expression of groundwater; and
- Ecosystems dependent on the subsurface presence of groundwater.

The Australian GDE toolbox (Richardson et al. 2011), the Australian GDE Atlas (BOM 2012) and the Queensland GDE Atlas (DSITIA 2015) all use this approach.

Currently, there is no widely used classification scheme for DEs so a variant to the GDE scheme has been defined for the purposes of this study which separates DEs into three types as follows:

- **Aquifer Type DEs**: these ecosystems are identical to the Type 1 GDEs described by Richardson et al. (2011) which are underground ecosystems supported by groundwater that provide habitat for stygofauna and other living organisms. The reference to cave ecosystems has been removed for the purposes of this study because they do not occur within the Condamine Alluvium.

- **Aquatic Flora and Fauna Type DEs**: these ecosystems are those that occur within surface water drainage features and are supported by surface water (caused either by groundwater discharge or surface runoff) which provides habitat for aquatic flora and fauna.
- **Terrestrial Vegetation Type DEs**: these ecosystems are those that occur outside of surface water drainage features but may occur on a floodplain. They provide a habitat for vegetation which is supported by either groundwater at depth, the episodic presence of surface water (flood waters) or both.

6.2 Occurrence of DEs in the Condamine Alluvium

The study area is defined by the boundary of the Condamine Alluvium, as defined in Section 2.3.

Maps of DEs in the Condamine Alluvium are provided here for Aquatic Flora and Fauna Type DEs (Figure 6-1) and for Terrestrial Vegetation Type DEs (Figure 6-2). These maps were produced using the data layers listed in Table 6-1. A map of aquifer type DEs is not shown because the existing mapping layer contains no features within the extent of the Condamine Alluvium.

Table 6-1 Spatial layers used to map DEs

Aquifer Type DEs	Aquatic Flora and Fauna Type DEs	Terrestrial Vegetation Type DEs
Queensland GDE mapping (GDE_v1_3.gdb) - Subterranean GDE (Areas)	Queensland Wetland Data v3.0 - Wetland points - Wetland lines - Wetland areas Queensland GDE mapping (GDE_v1_3.gdb) - Surface expression GDE (points) - Surface expression GDE (lines) - Surface expression GDE (areas) Draft refugia (Condamine Alliance 2012)	Queensland GDE mapping (GDE_v1_3.gdb) - Terrestrial GDE (areas)

The Queensland Wetland Data and GDE mapping layers were prepared concurrently with Australian GDE Atlas, but at a finer scale, and these products are frequently updated. The Queensland products are therefore considered to be more accurate than the Australian GDE Atlas for use in Queensland (Mike Ronan DEHP pers. comm.; Katharine Glanville DSITI pers. comm.). The Queensland GDE mapping layer is derived from the Wetlands layer and the Regional Ecosystems (RE) layer that maps vegetation.

6.2.1 Aquifer Type DEs

While the available spatial layers contain no data on Aquifer Type DEs in the Condamine Alluvium, these ecosystems do occur. Stygofauna sampling has taken place in the Condamine and over 70 stygofauna sampling records are recorded in the Queensland Subterranean Fauna Database; however, these records are restricted due to IP agreements (Katharine Glanville, DSITI, pers. comm.). Fauna found include individuals from the *Coleoptera*, *Copepoda*, *Syncarida* and *Oligochaeta* taxonomic groups (Katharine Glanville DSITI pers. comm.).

DISITI has also recently completed their own sampling in the Condamine Alluvium and have confirmed the presence of a variety of stygofauna, but their results are yet to be published (Cameron Schulz, DSITI, pers. comm.). Results from stygofauna sampling in the nearby Border Rivers region of southern Queensland point to the widespread presence of stygofauna in groundwater with varying physico-chemical parameters (Schulz et al. 2013) and rich and diverse stygofauna ecosystems could be expected to occur in the Condamine Alluvium (Cameron Schulz DSITI pers. comm.).

6.2.2 Aquatic Flora and Fauna Type DEs

Aquatic Flora and Fauna Type DEs occur throughout the extent of the Condamine Alluvium. Most of these DEs are associated with the major streams, however some floodplain wetlands are also evident (Figure 6-1).

The Condamine River is characterised by isolated pools in the dry season, which are connected by runs or riffles in the wet season. Large floods can also occur in the wet season. Flow in the Condamine River is regulated by a series of weirs. As discussed in Section 5, the rivers and streams in the study area are generally considered to be losing, and in many cases disconnected (CSIRO, 2008).

The aquatic environment provides habitat for a variety of macrophytes, macroinvertebrates and fish, including the threatened Murray Cod. The Condamine Alliance has drafted a set of environmental values supported by surface water in the Condamine catchment (Condamine Alliance 2012). This review highlights the importance of refugia within the aquatic environment. Refugia are wetlands and pools that stay wet for longer than other waterholes or streams and provide a critical refuge for aquatic flora and fauna in times of low rainfall/flow. The locations of these refugia are included in Figure 6-1.

The ecological health of the Condamine River is considered to be poor to moderate and has been highly modified by agriculture and water resource development (APLNG 2010). The Condamine Alliance has established *The Dewfish Demonstration Reach* as a trial site to restore native fish populations to 60% of pre-European settlement levels. The reach is 110 km long. It begins in central Dalby and incorporates parts of the Myall Creek, Oakey Creek and the Condamine River.

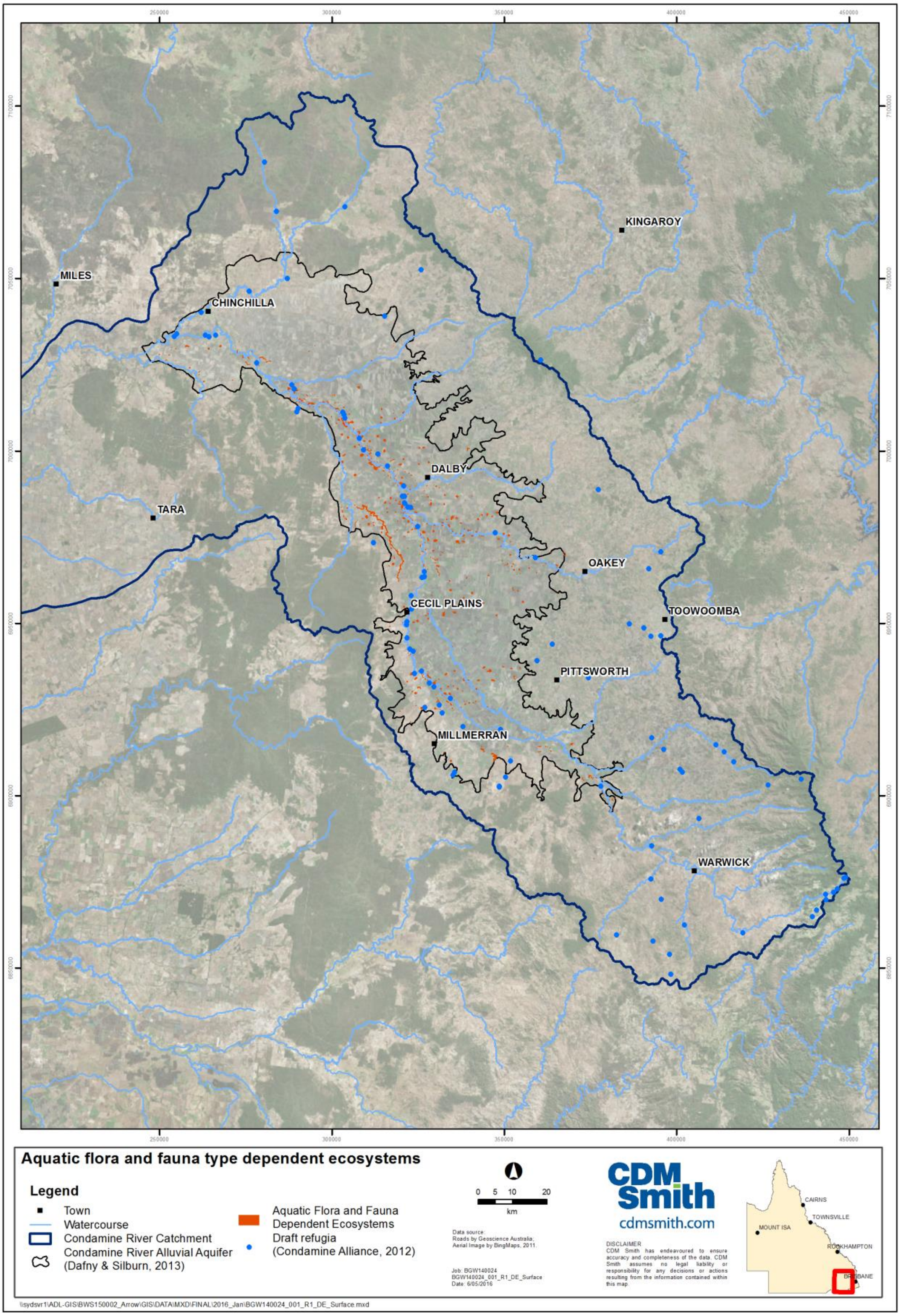

Figure 6-1 Aquatic Flora and Fauna Type DEs in the Condamine Alluvium

6.2.3 Terrestrial Vegetation Type DEs

Before European settlement, the Condamine Alluvium was covered extensively by floodplain grasslands and grassy open woodlands (EPA 2005). There were extensive Queensland bluegrass communities and the woodlands supported poplar box, Queensland blue gums and river red gums. Currently less than 5% of the pre-European vegetation cover on the Upper Condamine Floodplain remains, and all of the floodplain woodland ecosystems are classed as areas 'of concern' (Reardon-Smith 2011).

The Terrestrial Vegetation Type DEs shown in Figure 6-2 correspond to the remnant floodplain woodlands. They are predominantly restricted to riparian corridors and roadside verges. Ecological surveys of these areas have encountered ecosystems under stress with a high incidence of dieback (Reardon-Smith 2011).

The mapped extent of Terrestrial Vegetation Type DEs shown in Figure 6-2 represents 'potential' DEs based on a series of rulesets applied at a regional scale. In general, these rulesets are conservative and likely to result in a number of false positives: the identification of areas classed as a potential DE which have no reliance on groundwater or surface water.

Groundwater has been identified as a potential buffer for these tree species during dry periods, and tree condition (of river red gum) has been correlated to water table elevation, with a groundwater depth of 12-15 m below surface being linked to a decline in tree condition (Kath et al. 2014).

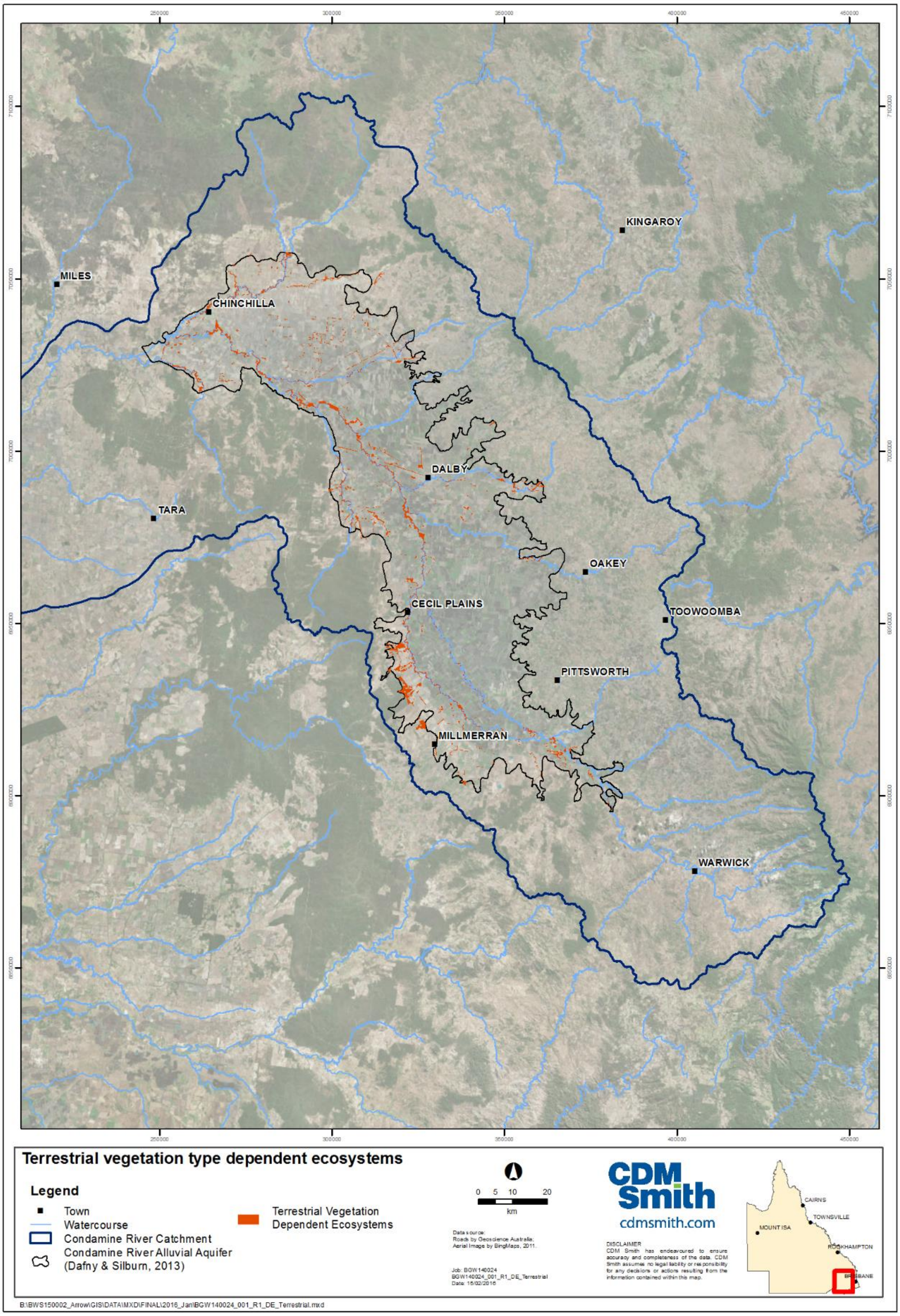

Figure 6-2 Terrestrial Vegetation Type DEs in the Condamine Alluvium

6.3 Conceptualisation of DEs

Eco-hydrological conceptual models are well-established tools for identifying and assessing potential impacts to DEs for proposed developments (Richardson et al. 2011). The objective of the conceptual models is to describe our understanding of how hydrological change can influence ecological functioning and what factors are involved in driving this dynamic. Placing the water-related stressors associated with CSG development into this context assists in identifying and determining the significance of potential threats to the ecosystem from CSG-related activities.

Based on a method outlined by IESC (2015), conceptual models are presented here as control-stressor models. The 'control' element of the model conceptualises the ecosystem-hydrological interaction in the existing environment, which has both natural and anthropogenic drivers. The 'stressor' element of the model pertains to Project-specific activities which have the potential to perturb the existing ecosystem-hydrological interaction.

6.3.1 Aquifer and Cave Type DEs

The scientific understanding of Aquifer and Cave Type DEs is still in its infancy and there are no publically available data for this type of DE in the Condamine Alluvium. It is difficult to construct a conceptual model other than to state the following:

- Stygofauna are assumed to be present throughout groundwater in the Condamine alluvium;
- Stygofaunal functioning is likely to respond to changes in groundwater conditions (quantity and quality) and may be detrimentally affected if these changes are large or sudden;
- The stygofaunal community is probably already in a state of flux (if not severely impacted) given the widespread changes to groundwater conditions in the Condamine Alluvium over the past 50 years in response to the rapid development and high seasonal stress of groundwater resources for agriculture; and
- The project water-related stressors to stygofauna are linked to depressurisation of regional aquifers, which could ultimately manifest in drawdown of the water table. The significance of this threat to stygofauna is related to the rate and magnitude of drawdown relative to existing conditions.

6.3.2 Aquatic Flora and Fauna Type DEs

A control-stressor conceptual model for Aquatic Flora and Fauna Type DEs is presented in Figure 6-3. The model includes the following:

- The major natural and anthropogenic drivers which influence catchment hydrology.
- The major hydrological processes involved and their interaction.
- The 'stressor' component of the model is that which is related to CSG development. Its influence on existing ('control') catchment hydrology occurs via the groundwater regime, which depends on the hydraulic connectivity between the Walloon Coal Measures and the Condamine Alluvium. Its impact on the surface water regime is, in turn, influenced by hydraulic connectivity between the groundwater regime and the surface water regime.
- The ecological effects which may result from changes in the surface water regime depend on the flow element that has been changed. The relationship between ecological effects and flow regime is summarised pictorially in Figure 6-4.

The control-stressor model highlights the fact that the hydrology of the Condamine catchment is highly dynamic and the existing drivers exert considerable influence over the dynamic behaviour. These may substantially outweigh project-related impacts.

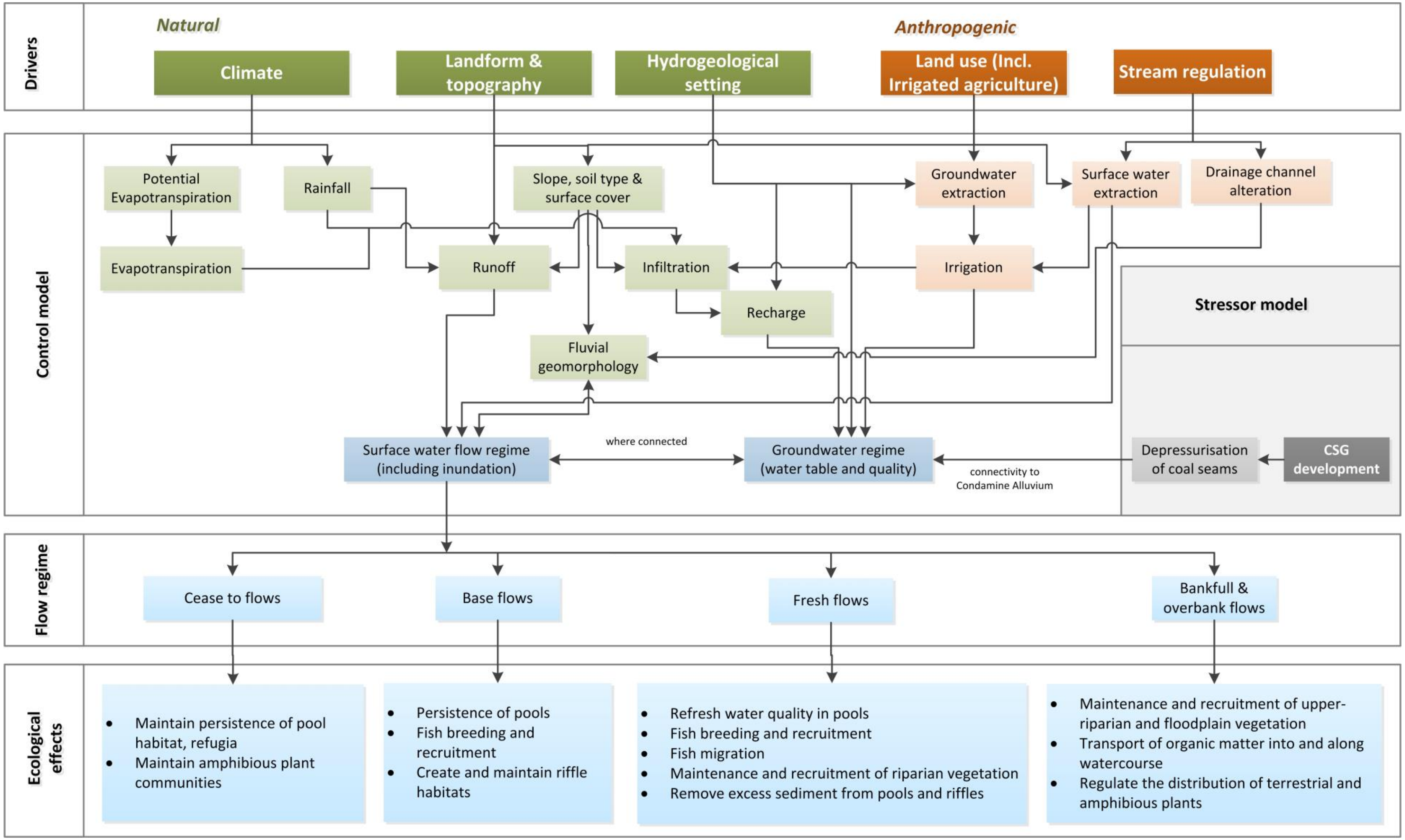

Figure 6-3 Control-stressor conceptual model for Aquatic Flora and Fauna Type DEs

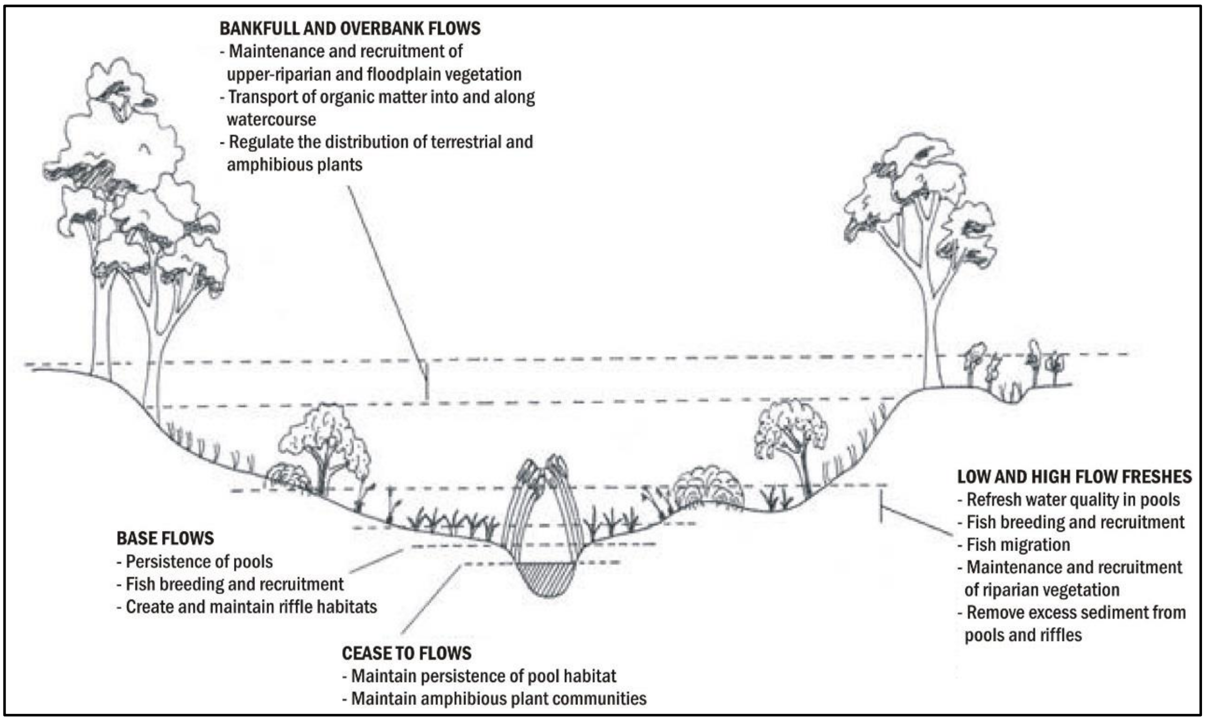

Figure 6-4 Common environmental water requirement processes linked to flow magnitudes (adapted from Favier et al. 2004)

Potential threats to Aquatic Flora and Fauna Type DEs from CSG development occur via the groundwater regime and potential impacts will depend on the connectivity of the Walloon Coal measures to the Condamine Alluvium and of the Condamine Alluvium to surface water.

The influence of the groundwater regime on surface water (where connected) is most significant for low flows and, in particular, cease to flows (periods of no flow) which influence refugia. Therefore, the water-related threats to Aquatic Flora and Fauna Type DEs from CSG development are most significant for refugia that are connected to groundwater.

6.3.3 Terrestrial Vegetation Type DEs

A control-stressor conceptual model for Terrestrial Vegetation Type DEs is shown in Figure 6-5. The model includes the following:

- The major natural and anthropogenic drivers that influence catchment hydrology.
- The major hydrological processes involved and their interaction.
- The 'stressor' component of the model is that which is related to CSG development. Its influence on existing ('control') catchment hydrology occurs via the groundwater regime, which depends on the hydraulic connectivity between the Walloon Coal measures and the Condamine Alluvium, which in turn influences soil water availability according to the depth of groundwater relative to the root zone. It may also influence surface water availability (where groundwater and surface water are connected) which, in turn can influence soil water availability.
- The key hydrological process which influences the ecological function of Terrestrial Vegetation Type DEs is soil water availability, and the model outlines the ecological consequences of different levels of soil water availability. This component of the model is expanded in Figure 6-6, which represents soil water availability on a percentage scale, where 0% represents soil water being unavailable to the plant and 100 % represents non-limiting conditions. It is a function of soil

moisture status (often measured as soil suction) and the relationship shown in Figure 6-6 is a classic model that is common in agronomic literature (e.g. Feddes et al. 1978). Despite it being the key hydrological process for plant function, soil water availability is often not discussed in GDE and DE assessments.

The complexity of the control-stressor model highlights that the hydrology of the Condamine catchment is highly dynamic and the existing drivers exert considerable influence over the dynamic behaviour. These may be more significant than project-related impacts.

Threats to Terrestrial Vegetation Type DEs from CSG development occur via the groundwater regime and potential impacts will depend on the connectivity of the Walloon Coal measures to the Condamine Alluvium, the depth of groundwater relative to the root zone and the connectivity between the Condamine Alluvium and surface water.

The influence of the groundwater regime on soil water availability is most significant at the 'dry end' where groundwater may provide a buffer to soil water availability becoming too dry.

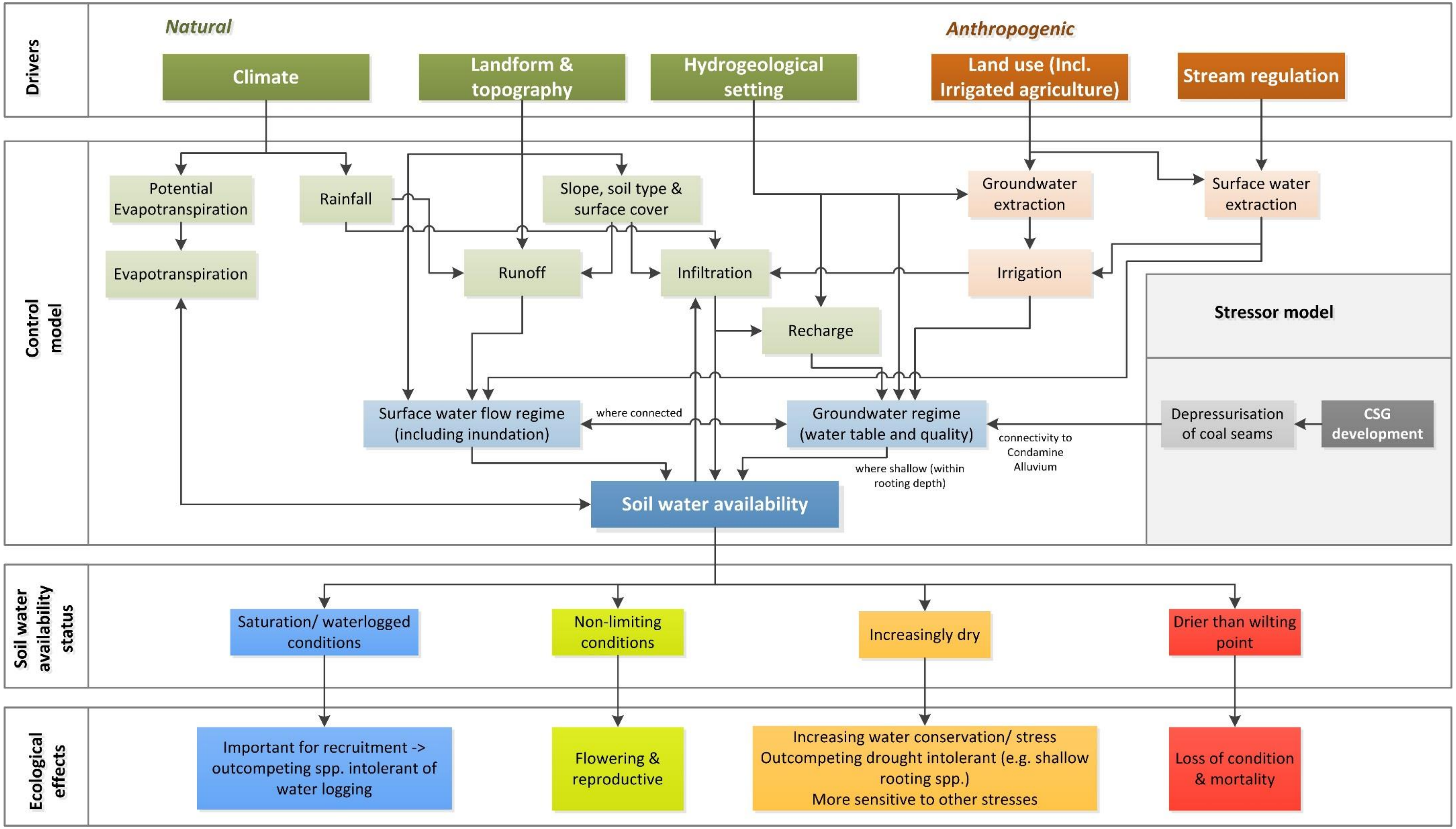

Figure 6-5 Control-stressor conceptual model for Terrestrial Vegetation Type DEs

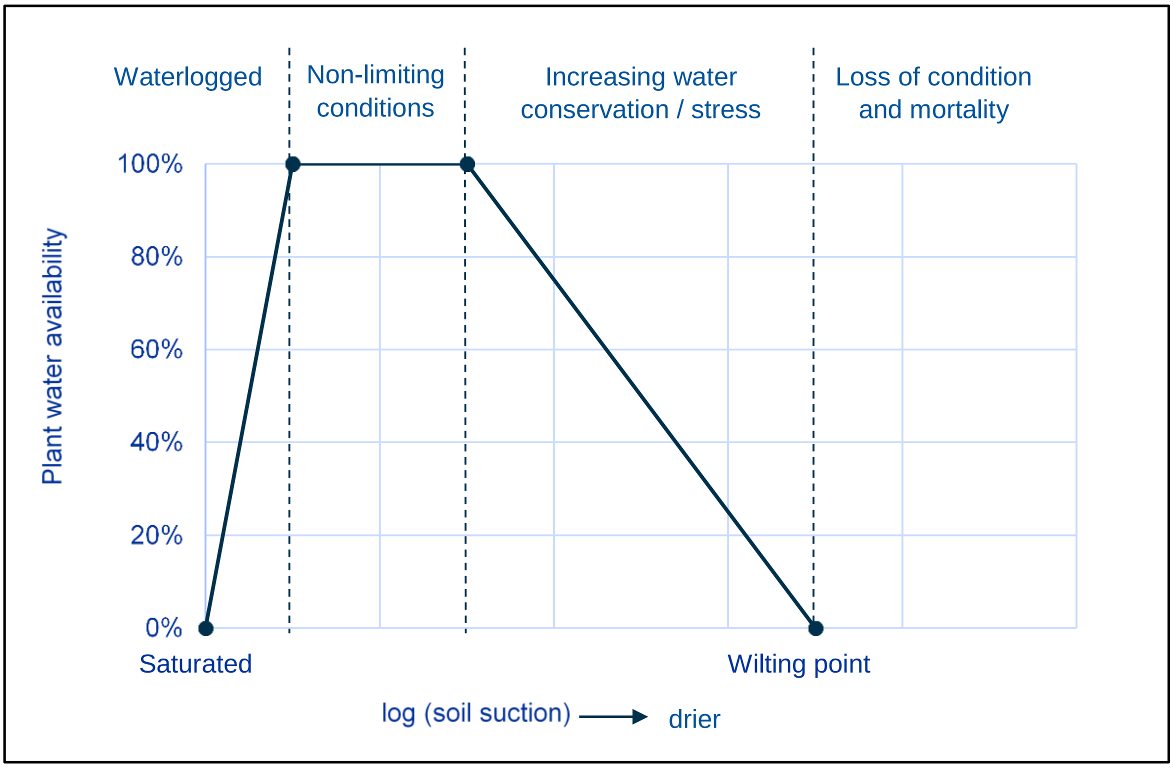

Figure 6-6 Soil water availability as a function of soil suction and its resultant ecological effects[2]

6.4 Threat Pathways

A threat pathway is defined as a possible chain of events, initiated by the water-related CSG stressor that could result in an impact to a DE.

For Aquifer Type DEs, a threat pathway is that depressurisation of groundwater from CSG activities could ultimately manifest in drawdown of the water table which, in turn, could affect stygofauna. The significance of this threat to stygofauna is related to the predicted rate and magnitude of drawdown of the water table relative to existing conditions. If the change is sudden or the overall magnitude of change is large compared to the existing regime (i.e., the change in water levels associated with pumping for irrigation) then this could adversely affect stygofauna.

For the other types of DEs, the control-stressor models (Figure 6-3 and Figure 6-5) can be used to outline threat pathways at a process level, as follows.

<u>Aquatic Flora and Fauna Type DEs:</u>

- The depressurisation of groundwater for CSG development could lead to drawdown in the Condamine Alluvium – this process is influenced by the hydraulic connectivity between the Walloon Coal measures and the Condamine Alluvium.
- Drawdown in the Condamine Alluvium could lead to reduced groundwater discharge to surface water where gaining conditions currently exist either periodically or perennially.

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[2] Plant water availability is low (approaches zero) under saturated conditions due to the anaerobic conditions suppressing root respiration.

- Drawdown in the Condamine Alluvium could lead to increased surface water leakage to groundwater. This process is influenced by groundwater and surface water connectivity and no changes to surface water leakage will occur where they are hydraulically disconnected. Where connected, changes to surface water leakage will depend on the hydraulic conductivity of the streambed and the magnitude of drawdown of the water table.

- Increased surface water leakage could reduce streamflow. How this manifests will depend on the timing and magnitude of the altered leakage rate, and whether or not the stream is regulated. In the case of regulated streams, increased leakage to groundwater does not reduce streamflow if streamflow is supported by upstream storages. In unregulated streams, leakage to groundwater is of most significance for cease to flows and base flows (leakage rates are insignificant in relation to higher flows). Because groundwater depressurisation for CSG development occurs at a regional scale, the timing of any induced leakage rates is unlikely to vary on a seasonal basis but would manifest over long time periods; i.e. it will not be more or less acute at different times of the year when the different flow regimes occur.

- As outlined in Figure 6-4, changes to low flows and cease to flows provide the greatest threat to the maintenance of pool habitat in refugia upon which fish and macrophyte communities depend.

<u>Terrestrial Vegetation Type DEs:</u>

- The depressurisation of groundwater for CSG development could lead to drawdown in the Condamine Alluvium – this process is influenced by the hydraulic connectivity between the Walloon Coal measures and the Condamine Alluvium.

- Drawdown in the Condamine Alluvium could lead to a reduction in soil water availability to plants where the water table is currently shallow enough to be accessed by plants.

- The plants most likely to be associated with this threat pathway are overstorey species such as river red gums, which can access deep water sources.

- As outlined in Figure 6-5, soil water availability is influenced by a number of processes, which include rainfall, flooding events and evapotranspiration. Rainfall and flooding replenish the soil water reserves and are important for the tree recruitment, flowering and reproductive processes, and for ongoing transpiration and nutrient uptake. Evapotranspiration is a control on the rate that soil water reserves are depleted. Groundwater (if shallow) can sustain soil water availability for established trees during dry periods. Threats associated with changes in water table elevation are, therefore, most relevant for established trees.

As indicated in these descriptions of threat pathways, some factors related to existing hydrological conditions stand out as being critical to whether or not a threat pathway exists and will also influence the significance of the potential threat.

- For Aquatic Flora and Fauna Type DEs the threat pathway is influenced by groundwater – surface water connectivity which is, in turn, influenced by:
  - The water table elevation relative to the surface water elevation and the bed elevation; and
  - Whether the stream is regulated or unregulated (a regulated stream will be buffered against the effects of a changing groundwater regime).

- For Terrestrial Vegetation Type DEs the threat pathway is influenced by:
  - The water table elevation relative to the root zone (if the water table is inaccessible to roots, changes in water table elevations do not pose a threat); and

- Whether the stream is regulated or unregulated (a regulated stream will provide a buffer to water table elevation and limit any changes in the water table elevation).

Table 6-2 lists the controls these factors have over threat pathways to DEs. It serves to highlight the hydrological settings where threat pathways occur, where they will be absent (e.g. where groundwater and surface water are disconnected there will be no threat pathway to aquatic flora and fauna type DEs), and where a threat pathway may occur but the threat is buffered by the presence of a regulated stream.

Figure 6-7 shows the different hydrological settings schematically and their occurrence in the landscape has been mapped for Aquatic Flora and Fauna Type DEs (Figure 6-8) and for Terrestrial Vegetation Type DEs (Figure 6-9).

Table 6-2 Relationship between the varying hydrological settings and the threat pathways to DEs

Types of dependent ecosystems	Surface water setting	Weirs and regulated streams			Unregulated, ephemeral streams and channels		
	Water table elevation	Deep: below bed level and deeper than 15m below surface #	Moderate: below bed level but less than 15m below surface	Shallow: above bed level (but below water level)	Deep: below bed level and deeper than 15m below surface	Moderate: below bed level but less than 15m below surface	Shallow: above bed level (but below water level)
Aquifer and Cave Type DEs		Potential threat pathway	Water table elevation will be buffered by surface water regulation where connected	Water table elevation will be buffered by surface water regulation	Potential threat pathway	Potential threat pathway	Potential threat pathway
Aquatic Flora and Fauna Type DEs		No threat pathway (groundwater and surface water disconnected)	Where surface water disconnected: no threat pathway Where surface water connected: buffered by surface water regulation	Buffered by surface water regulation	No threat pathway (groundwater and surface water disconnected)	Where surface water disconnected: no threat pathway Where surface water connected: potential threat pathway	Potential threat pathway
Terrestrial Vegetation Type DEs		No threat pathway (water table too deep for vegetation)	Buffered by surface water leakage where connected	Buffered by surface water leakage	No threat pathway (water table too deep for vegetation)	Potential threat pathway	Potential threat pathway

A water table deeper than 15 m below the surface is assumed to have a limited influence on soil water availability. The 15 m threshold aligns with the findings of Kath et al. (2014).

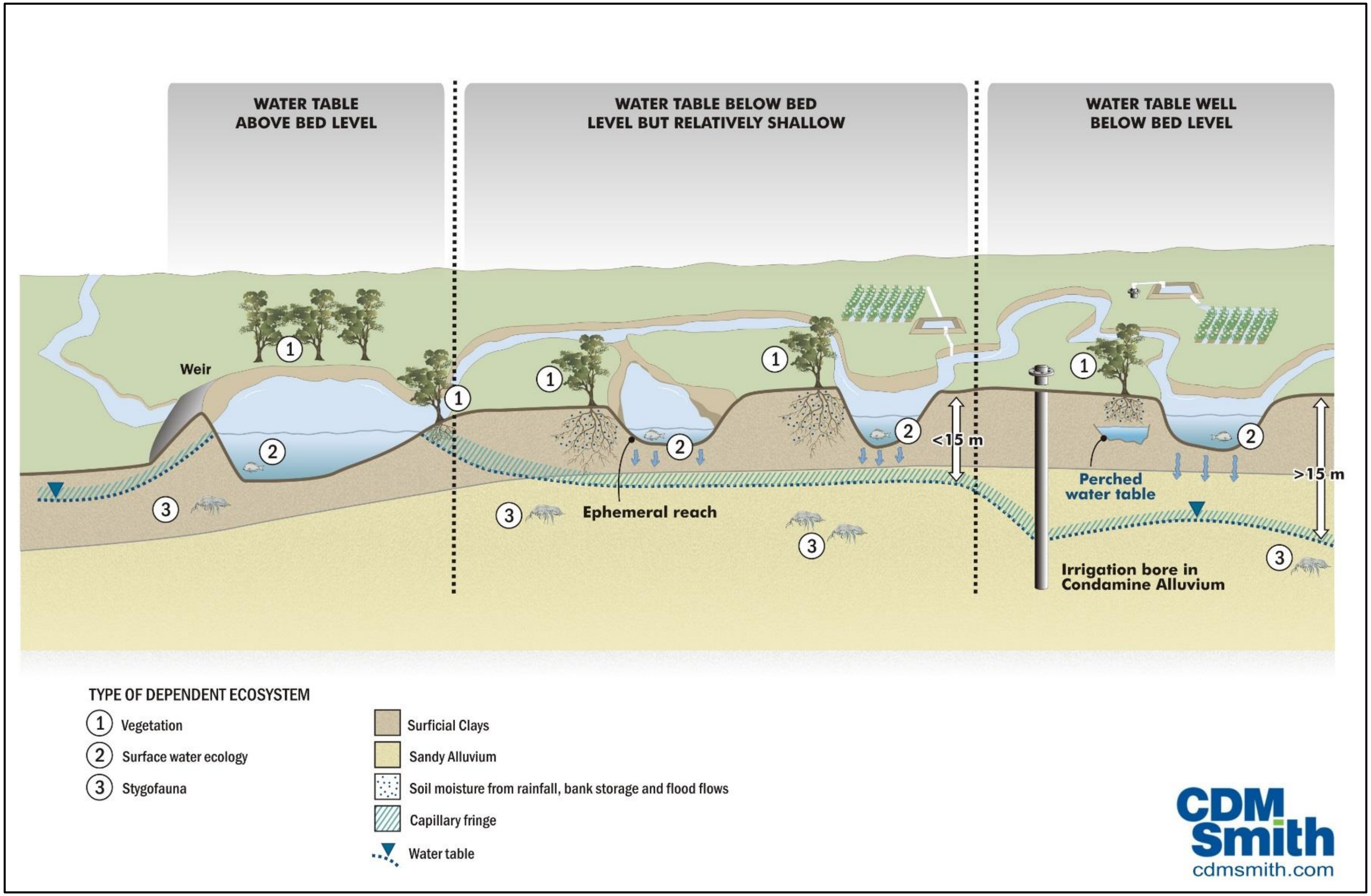


Figure 6-7 Different hydrological settings in the Condamine Alluvium relative to DE Types

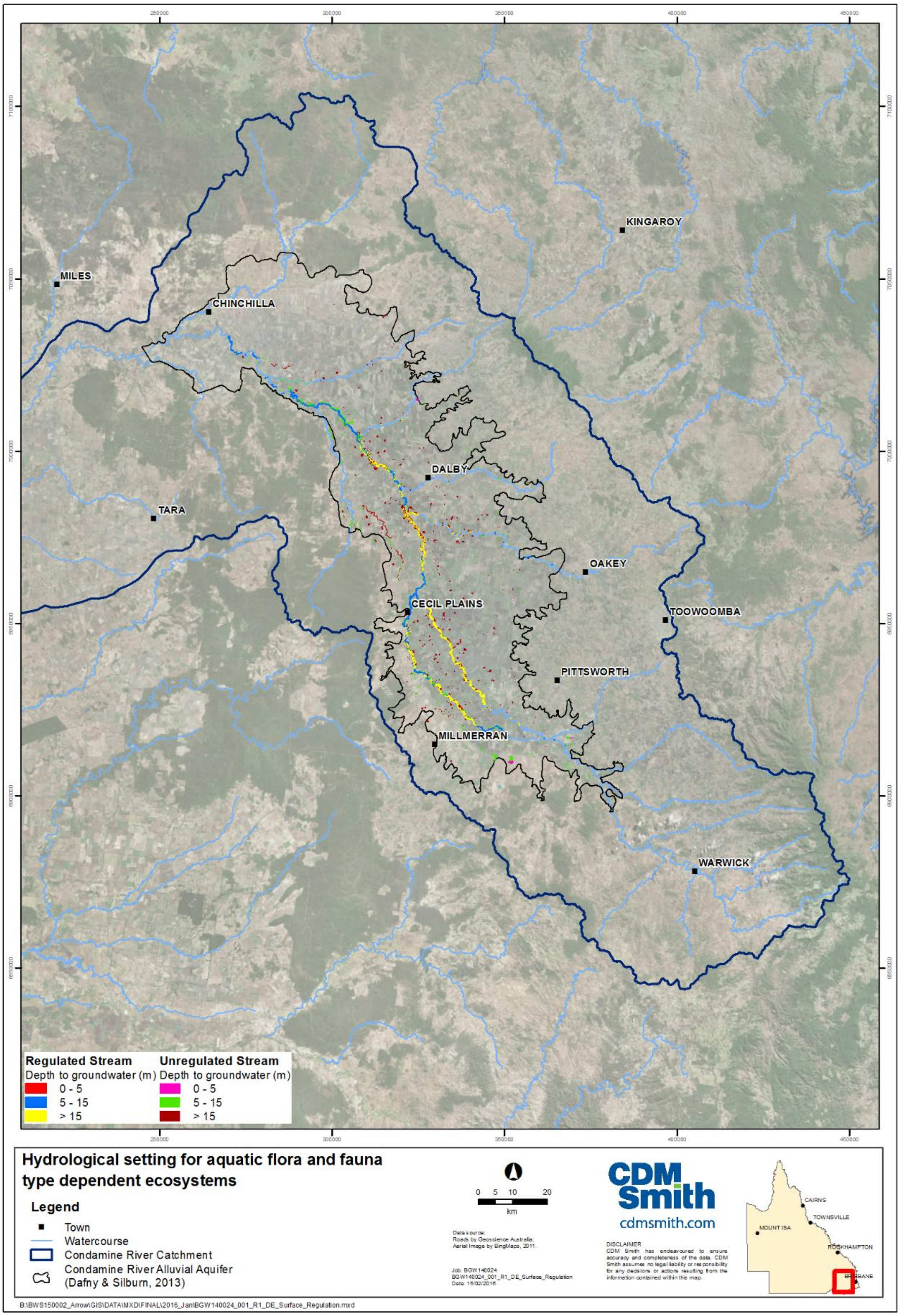


Figure 6-8 Hydrological setting for Aquatic Flora and Fauna Type DEs (see Table 6-2 for relationship between hydrological setting and threat pathway)

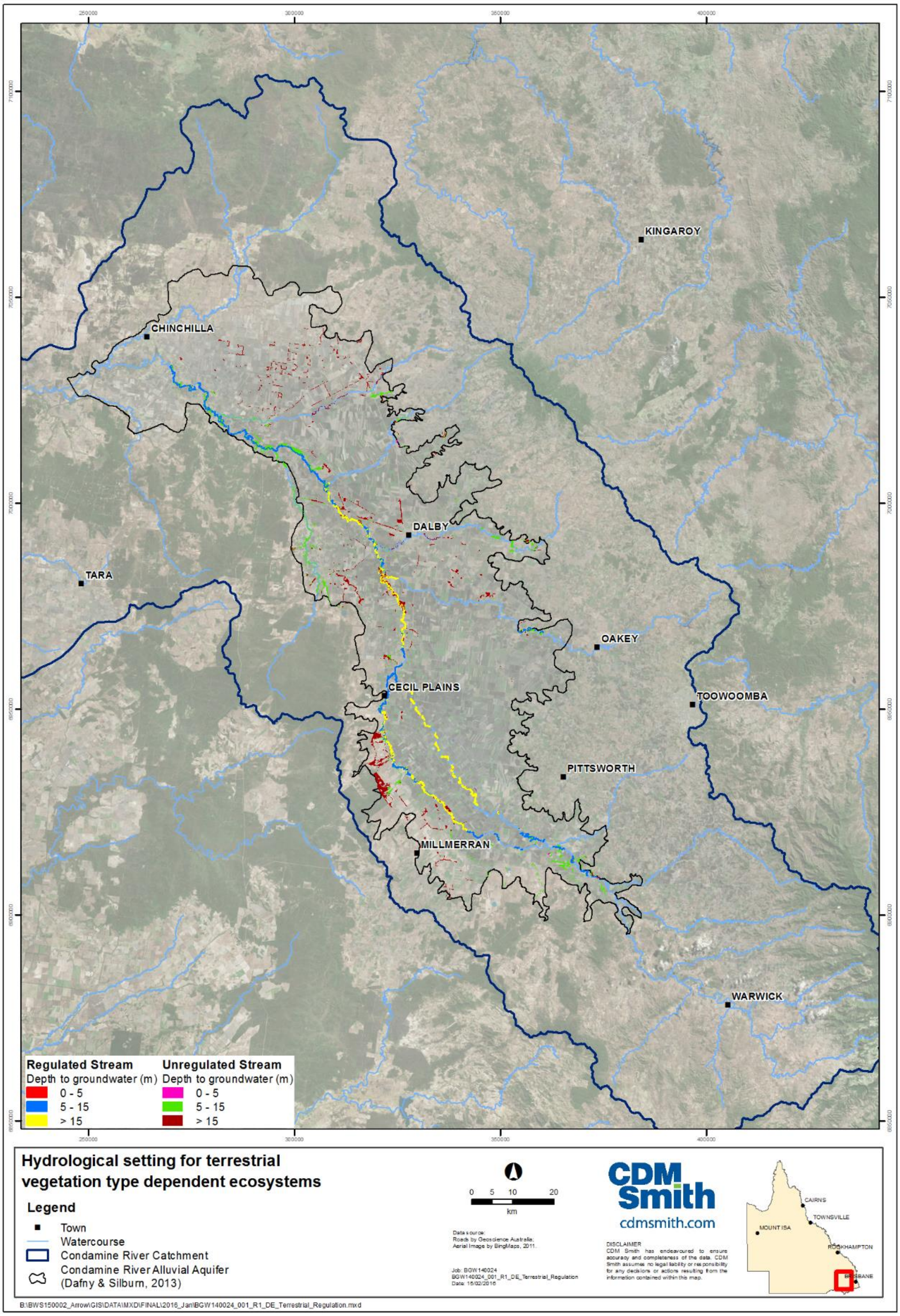


Figure 6-9 Hydrological setting Terrestrial Vegetation Type DEs (see Table 6-2 for relationship between hydrological setting and threat pathway)

Section 7 Fit For Purpose Numerical Simulation

7.1 Preamble

Section 13(b) requires Arrow to develop a "*fit for purpose numerical simulation*".

The purpose of the simulation is "*to assess potential impacts on water resources arising from the action in the project area, subsequent surface water-groundwater interactions in the Condamine Alluvium and impacts to (sic.) dependent ecosystems".*

To meet the requirements of Section 13(b):

- The simulation must represent the production of water by Arrow during the Surat Gas Expansion Project;
- The simulation must be capable of making inferences about potential impacts on both surface water and groundwater resources, perhaps initially on water table elevations in the Condamine Alluvium, then on loss or leakage of water from the Condamine River caused by leakage to groundwater, and finally on flows in the Condamine River in the context of licensed surface water withdrawals and allocation rules;
- The simulation must be capable of making inferences about surface water – groundwater interaction, as implied above; and
- The simulation must be capable of making inferences about changes in water table elevation and surface flows to support subsequent discussion of potential impacts on dependent ecosystems (DEs).

Given the complexity of processes at a wide range of spatial and temporal scales, the existence of models developed by others to address very similar questions, and the fact that Governments have relied on these models to support environmental impact assessment in the past, that using a number of existing models will meet the requirement for a "fit for purpose numerical simulation".

Fit for purpose numerical simulation

A fit for purpose numerical simulation relies on modelling undertaken by a number of organisations in recent years. Different models are used to simulate groundwater flow at regional scale and in the Condamine Alluvium, as proposed by QWC (2012a). Modelling of potential impacts on surface water resources is based on the use of IQQM models prepared previously for the Condamine River.

CDM Smith and Arrow have chosen to rely on:

- the most recent available (regional scale) "OGIA model" (QWC 2012a, 2012b, 2012c; GHD 2012);
- the most recent available (local scale) CCAM run by QWC in parallel with and effectively as part of the "OGIA model" (QWC 2012a, KCB 2011b); and
- the most recent available IQQM models developed by the Department of Natural Resources and Mines (DNRM) for management of surface water resources in the Condamine River and its tributaries (Simons et al. 1996; Paul Harding pers.comm.).

7.2 Previous Modelling

In setting out to develop a fit for purpose numerical simulation, the following information about previous modelling was taken into account.

7.2.1 Surat CMA Groundwater Model

The Surat Cumulative Management Area (CMA) groundwater model (GHD 2012) is now known as the "OGIA model":

- Simulations are run from 1 January 1995 to 31 December 2010, with time-varying boundary conditions, recharge and "evapotranspiration" (using MODFLOW's EVT package to represent production of water);
- Simulations continue from 1 January 2011 to 31 December 4994, with constant (steady) boundary conditions, recharge and EVT;
- During the second period (2011 to 4994), production occurs until ~2065; the net change in flux between the regional aquifers and the Condamine Alluvium peaks in ~2100 and eventually declines to ~5% of the maximum in ~2500; and
- The OGIA model is not a single model but is an ensemble of 200 realisations with different sets of parameters representing hydrogeological properties, recharge and boundary conditions; the ensemble of models deals with some types of model uncertainty but not all.

By way of context, Table 7-1 provides some key results presented previously in Arrow's SREIS. Results from NSMC modelling must be presented based on a statistical analysis of results. One common form of analysis is to present results using probabilities of exceedance.

Table 7-1 Previous modelling results (after Coffey Environments 2013, Appendix D)

Variable	Run	Value
Predicted maximum reduction in rate of net flux at the base of Condamine Alluvium due to CSG water production (ML/d)	Maximum	3.8
	5% probability of exceedance	3.4
	95% probability of exceedance	1.8
Predicted maximum reduction in rate of net flux at the base of Condamine Alluvium due to Arrow water production (ML/d)	Maximum	2.8
	5% probability of exceedance	2.6
	95% probability of exceedance	1.3
Predicted reduction in volume of groundwater flux at the base of Condamine Alluvium due to CSG water production after 100 years (GL)	Maximum	101
	5% probability of exceedance	90
	95% probability of exceedance	44
Predicted reduction in volume of groundwater flux at the base of Condamine Alluvium due to Arrow water production after 100 years (GL)	Maximum	73
	5% probability of exceedance	71
	95% probability of exceedance	34

7.2.2 Central Condamine Alluvium Model

The Central Condamine Alluvium Model (CCAM) was developed originally by Klohn Crippen Berger (KCB 2011b):

- The CCAM was effectively part of the OGIA model, but very few results were reported;
- The CCAM model has one set of model parameters, and when run 200 times using fluxes computed by the OGIA model, leads to 200 predictions of drawdown within the area of the Condamine Alluvium; and

- Representation of surface water – groundwater interaction was simplified, but also relatively sophisticated, in terms of the amount of effort that went into representing different reaches and time series of levels in the river.

7.2.3 Integrated Quantity and Quality Models

The use of Integrated Quantity and Quality Modelling (IQQM) software is required under *the Water Resource (Condamine and Balonne) Plan 2004* (Queensland Government 2004), in order to assess applications for allocation of water in the Condamine River and its tributaries.

7.3 Overview of Modelling

An overview of the groundwater and surface water modelling conducted for this study is provided in Figure 7-1. For practical reasons, the studies undertaken during the preparation of this report to meet the requirements of Section 13(b) were undertaken in a number of stages.

Regional groundwater modelling was conducted using the Surat Cumulative Management Area (CMA) groundwater model, developed originally by the Queensland Water Commission (QWC) (GHD 2012) and now managed and updated by the Office of Groundwater Impact Assessment (OGIA) within the Queensland Department of Natural Resources and Mines (DNRM). The Surat CMA groundwater model is used to simulate potential impacts of Arrow's proposed action on the rate and distribution of vertical groundwater flux between the Surat Basin and overlying Condamine Alluvium. Figure 7-2 shows the boundaries of the Surat CMA and the Surat CMA groundwater model.

Predictions of **changes in** vertical groundwater flux are then used as inputs to the Central Condamine Alluvium Model (CCAM) to assess potential impacts of development of CSG resources in the Surat Basin on groundwater and surface water resources in the Condamine Alluvium. The CCAM was originally developed by Klohn Crippen Berger (KCB 2011b) and is now managed and updated by DNRM. The boundary of the CCAM is also shown in Figure 7-2.

The predicted impacts on groundwater and surface water resources in the Condamine Alluvium are used as inputs to the Condamine Integrated Quantity and Quality Modelling (IQQM) software to assess potential impacts of CSG development on the availability of surface water in the Condamine Alluvium.

Figure 7-3 shows a timeline of the existing modelling conducted using the Surat CMA groundwater model, CCAM and Condamine IQQM. Further descriptions of the models, and how they have been used in this study, are provided below.

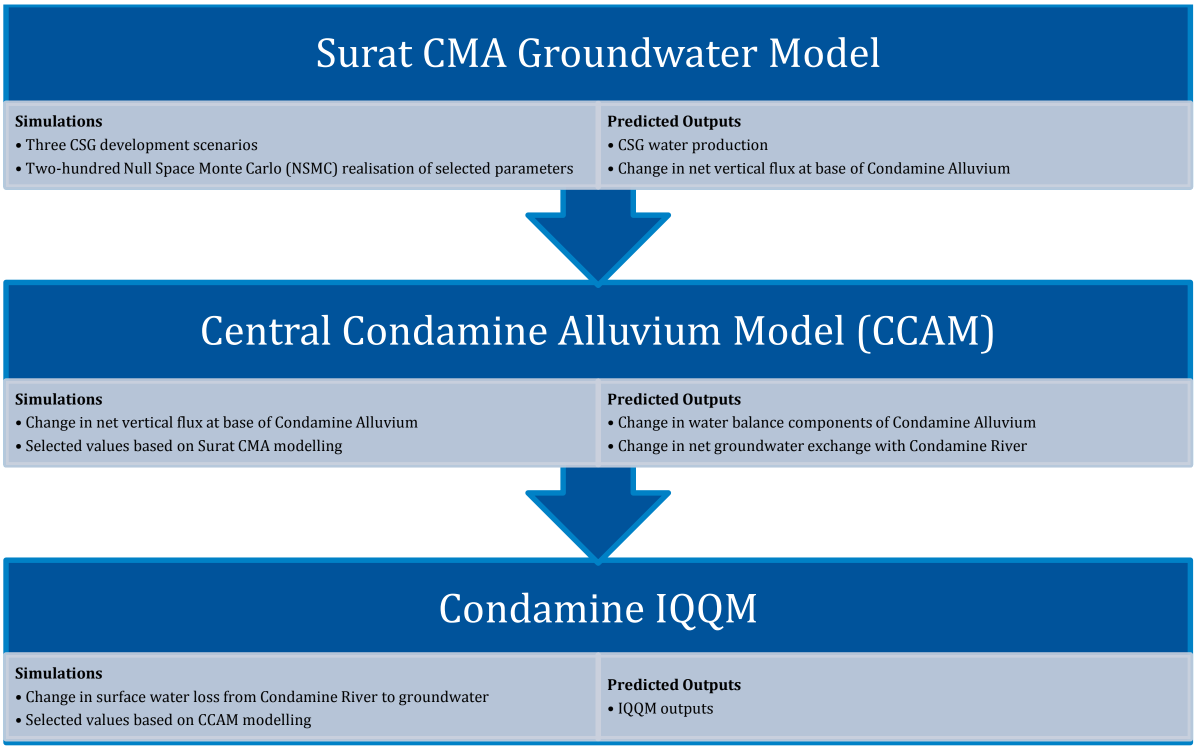


Figure 7-1 Modelling stages in this study

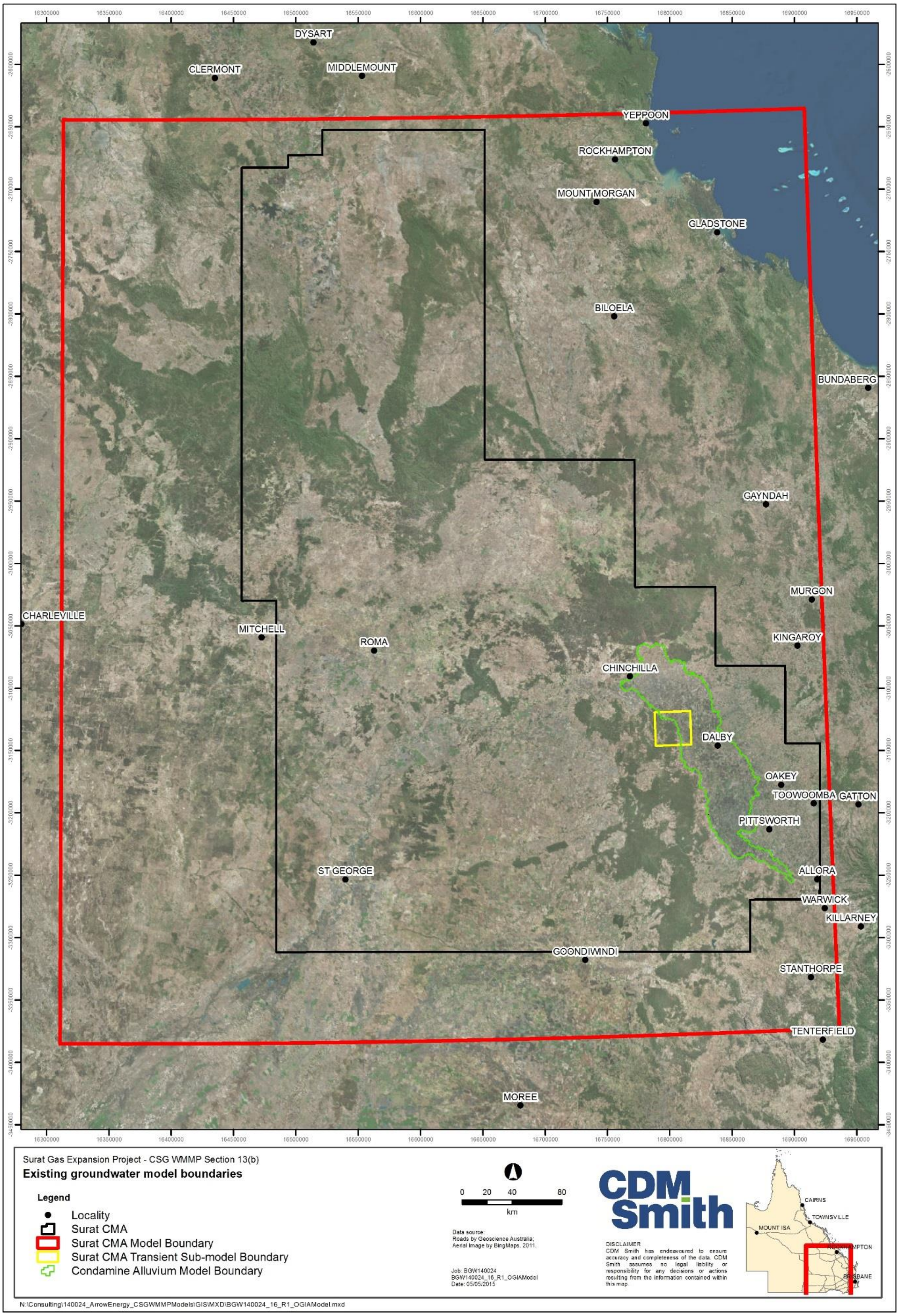


Figure 7-2 Existing groundwater model boundaries

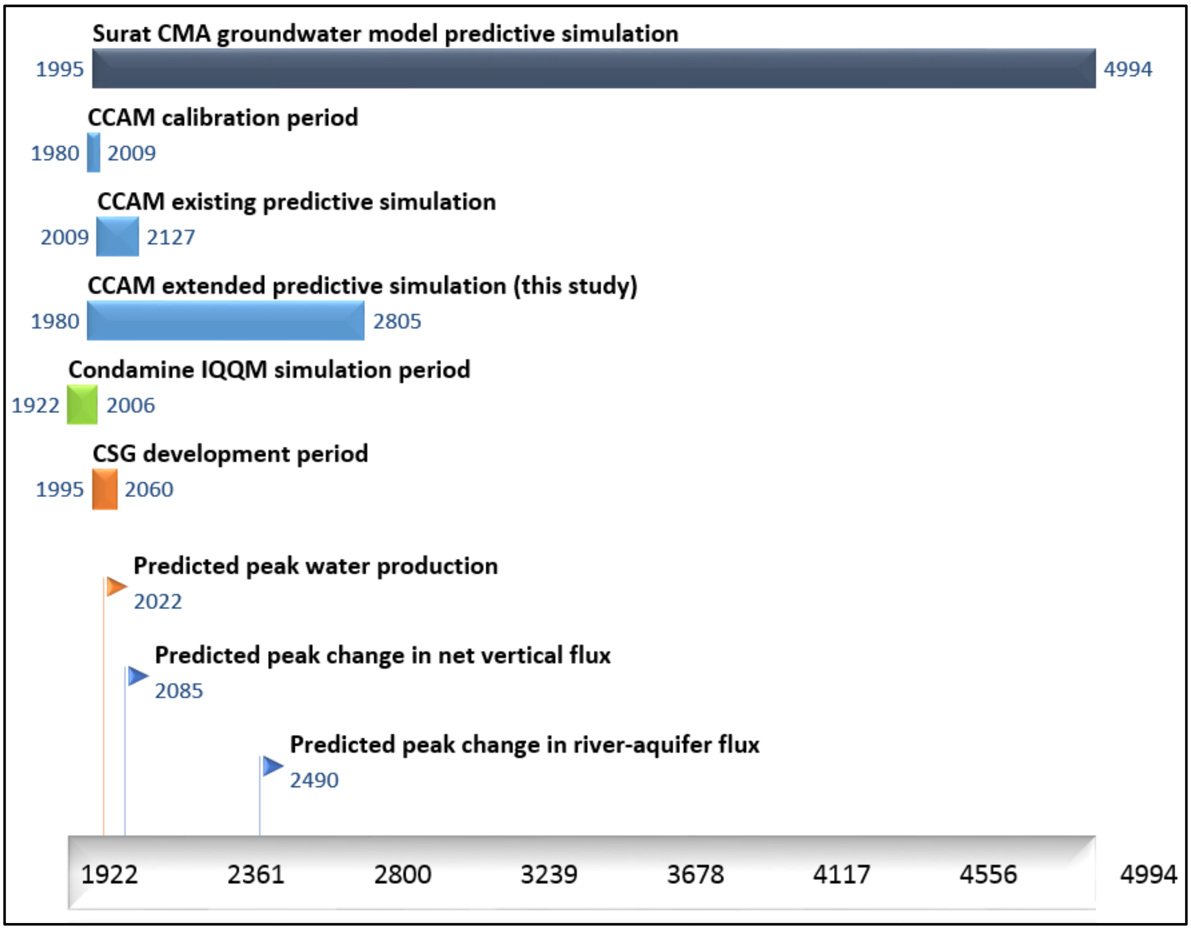


Figure 7-3 Modelling simulation timeline and indicative timing of induced groundwater fluxes

7.4 Regional Scale Groundwater Modelling

7.4.1 Overview of the Surat CMA Groundwater Model

The Surat Cumulative Management Area (CMA) groundwater model (GHD 2012) was developed by the Queensland Water Commission ([3]QWC) for the Surat CMA Underground Water Impact Report ([4]UWIR) (QWC 2012a). The Surat CMA model was constructed using MODFLOW 2005 (Harbaugh 2005) and PEST calibration tools.

The geographic extent of the Surat CMA model can be seen in Figure 7-2. In order to predict the response of the Condamine Alluvium, the Surat CMA model was originally run in tandem with a local-scale model of groundwater flow in the Condamine Alluvium, which was developed by KCB (2011) and is now managed by DNRM.

The Surat CMA model is based on the hydrogeology of the Surat CMA as compiled by the QWC (2012b) for the Surat CMA UWIR. Predictive uncertainty of the Surat CMA model was assessed by Watermark Numerical Computing (WNC) in a separate report for the QWC (2012c).

[3] Now the Office of Groundwater Impact Assessment (OGIA) - http://www.dnrm.qld.gov.au/ogia
[4] http://www.dnrm.qld.gov.au/ogia/surat-underground-water-impact-report

The Surat CMA model consists of a regional-scale groundwater flow model and a sub-model of the existing Kogan North-Daandine coal seam gas (CSG) fields within the Walloon Coal Measures. For the Surat CMA UWIR, the Kogan North-Daandine sub-model was used for local-scale transient calibration, and the calibrated hydrogeological properties were passed back to the regional-scale model, which was then used for the predictive simulations. Thus, unless there is a need to re-calibrate the Kogan North-Daandine sub-model, there is no need to re-run the sub-model each time the Surat CMA model is run. The Kogan North-Daandine sub-model is not run in this study.

Notably, the Surat CMA regional-scale model was not designed to predict impacts on the water table in the Condamine Alluvium. For the Surat CMA UWIR, the water table elevation in the area of the Condamine Alluvium was represented as a head-dependent boundary condition, with the water table elevation set equal to a previous estimate of the water table derived from local-scale modelling of the alluvium (KCB 2011b). By this approach, the Surat CMA model was used to predict changes in groundwater flow from the base of the Walloon Coal Measures to the Condamine Alluvium as a consequence of proposed CSG water production, but the Surat CMA model was not used to simulate head responses in the alluvium, or the associated impacts on the exchange of groundwater between the alluvium and the Condamine River.

The geographic extent of the Surat CMA model is approximately 360,000 km^2 (550 × 660 km). The model's finite different grid has uniform row and column spacing of 1500 m (441 rows and 365 columns) and is divided into 19 layers that extend from the ground surface to the base of the Bandanna Formation. The upper 14 layers are used to represent the stratigraphic sequence of the Surat Basin and the lower 5 layers are used to represent the uppermost hydrostratigraphic sequence of the underlying Bowen Basin.

The use of the Surat CMA groundwater model as part of a "fit for purpose numerical simulation" is based partly on the effort that has already been made to develop a model that supports the UWIR for the Surat CMA. The Surat CMA model represents the most comprehensive consolidation of data and experience available at the time of its development. In the sections that follow, the complexity and degree of sophistication of the existing Surat CMA model will be described.

7.4.2 Previous Use of the Surat CMA Model

7.4.2.1 Surat CMA UWIR

The Surat CMA model was calibrated in steady state to replicate groundwater conditions in 1995 based on the assumption that a reasonable dynamic balance existed at that time (QWC 2012a, p.51). The calibration incorporated extraction rates from known stock and domestic bores, licensed entitlements and water extraction associated conventional petroleum and gas production bores.

Two predictive simulations commencing in 1995 were undertaken, with initial conditions from the steady state calibration:

- "Base Run" – representing a base case predictive simulation with continuation of the rates of groundwater extraction in 1995 but without future petroleum or gas development; and
- "P&G Production Run" – representing the Base Run simulation plus forecasted water extraction from current and proposed petroleum and gas (P&G) developments.

Potential impacts on groundwater resources were assessed by QWC based on the predicted differences in hydraulic head for the Base Run and P&G Production Run. Neither of these simulations has been used in this study. They are reported here to provide context.

7.4.2.2 Predictive uncertainty

Predictive uncertainty of the Surat CMA model was assessed by WNC (QWC 2012c). A Null Space Monte Carlo (NSMC) methodology was applied to generate 200 realisations of spatial distributions of selected model parameters. Each realisation of the parameter distributions was considered to represent a calibration-constrained parameter set that was within an allowable margin of the original calibration conducted for the Surat CMA UWIR.

Two hundred realisations were generated to represent distributions of horizontal hydraulic conductivity (K_h), vertical hydraulic conductivity (K_v), storage coefficient (S), recharge rate and conductance values for general head boundary conditions. Predictive uncertainty was assessed by running the Surat CMA model 200 times using these realisations and analysing the statistics of the results.

Two future scenarios were considered by WNC:

- "MODEL_BASE" – representing a base case predictive simulation with continuation of current groundwater stresses but without future CSG development; and
- "MODEL_CSG" – representing the MODEL_BASE plus forecasted groundwater extraction for progressive expansion and contraction of CSG operations over a period of 50 to 60 years.

Each scenario was run 200 times using the different realisations of model parameters. Each simulation covered a period of 3,000 years from the start of 1995 to the end of the year 4994.

7.4.3 Model Files

For this study to address the requirements of Section 13(b), model files and datasets from the Surat CMA modelling were provided by OGIA under agreement with Arrow.

The modelling files and datasets consist of existing MODFLOW input files from the Surat CMA model (GHD 2012, QWC 2012a); 200 realisations of parameter sets from the predictive uncertainty assessment by WNC (QWC 2012c); and updated water production data for current and approved CSG development based on the 2014 review of the Surat CMA model. A modified MODFLOW 2005 executable ("mf2005d32_alt.exe") for running the Surat CMA groundwater model was also provided with the MODFLOW input files.

Appendix A contains a listing of the model files acquired for this study and their version dates.

7.4.4 Model Inputs and Settings

7.4.4.1 Geographic datum and coordinates

The geographic datum is Geocentric Datum of Australia (GDA) 1994, and the model coordinate system is Map Grid of Australia (MGA) Zone 55. The lower left model cell (the southwest corner of the model grid) is the local MODFLOW coordinate origin (0, 0), which corresponds to grid row 441 and grid column 1, with MGA easting 453,500 m and MGA northing 6,783,500 m.

7.4.4.2 Model layers

The Surat CMA groundwater model was constructed with 19 model layers to represent the hydrostratigraphic sequence shown in Table 7-2.

Model layer 1 was used to represent the Condamine Alluvium, other shallow alluvial sediments outside the extent of the Condamine Alluvium, and the Main Range Volcanics.

Table 7-2 Surat CMA model layers

Model Layer	Hydrostratigraphic Unit
1	Condamine Alluvium Alluvium outside of Condamine Alluvium Main Range Volcanics
2	Rolling Downs Group
3	Bungil Formation / Mooga Sandstone
4	Orallo Formation
5	Gubberamunda Sandstone
6	Westbourne Formation
7 and 8	Springbok Sandstone
9	Walloon Coal Measures upper aquitard
10	Walloon Coal Measures coals
11	Walloon Coal Measures lower aquitard
12	Hutton Sandstone
13	Evergreen Formation
14	Precipice Sandstone
15	Moolayember Formation
16	Clematis Group
17	Rewan Formation
18	Bandanna Formation
19	Pre-Bandanna age units

7.4.4.3 Stress periods

The existing predictive simulations were set up with 259 stress periods spanning approximately 3,000 years (1,095,728 days). A summary of the stress periods is provided in Table 7-3, where stress period 1 represents a steady state solution.

Four types of model stresses were transient for some periods during the predictive simulations. A timeline showing how stresses varied over time can be seen in Figure 7-4. Recharge, groundwater extraction (Well BCs) and the River boundary conditions used to represent the Condamine Alluvium all varied from 1995 to 2010 (a period of 16 years). The evapotranspiration boundary conditions used to represent CSG water production varied over a longer period from 1995 to 2060 (66 years), this being the forecast period of CSG production. All model stresses but one (CSG water production) were constant from 2011 onwards, and all model stresses were constant from 2061 onwards. Further details are provided in sections 7.4.4.7 to 7.4.4.9 below.

Table 7-3 Surat CMA model stress periods

Date Span	Time Period, y	Stress Period Length, d	Stress Period Number
1/1/1995 to 31/12/2010	0 to 16	90, 91 or 92	2 to 65
1/1/2011 to 31/12/2094	17 to 100	365	66 to 149
1/1/2095 to 31/12/2994	101 to 1000	3652 or 3653	150 to 239
1/1/2995 to 31/12/4994	1000 to 3000	36,524 or 36,525	240 to 259

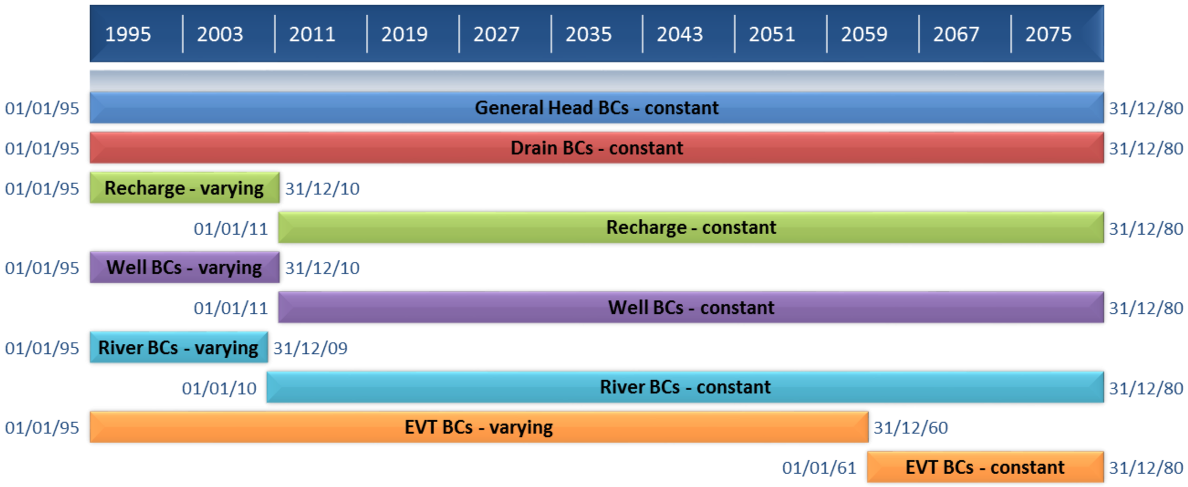


Figure 7-4 Surat CMA model stresses

7.4.4.4 Time stepping

Predictive simulations were performed using the time stepping shown in Table 7-4. The total number of time steps was 332 over 3,000 years.

Table 7-4 Surat CMA model timing stepping

Stress Period	Time Period, y	Time Step Length, d	Time Steps per Stress Period	Time Step Multiplier
2 to 65	0 to 16	90, 91 or 92	1	N.A.
66 to 70	17 to 21	6.2 to 66	14	1.2
71 to 76, 80, 87, 88	22 to 39	166, 199	2	1.2
77 to 79, 81 to 86, 89 to 149	28 to 100	365 or 366	1	1.2
150 to 239	101 to 1000	3652 or 3653	1	N.A.
240 to 259	1001 to 3000	36524 or 36525	1	N.A.

7.4.4.5 Flow processes

The Surat CMA groundwater model uses the Layer-Property Flow (LPF) Package of MODFLOW. The LPF Package permits two types of model layers: (i) confined (layer type = 0) and (ii) convertible (layer type ≠ 0). If the confined layer option is used, then the cell drying and re-wetting capabilities of MODFLOW are not active.

All model layers in the Surat CMA groundwater model were specified as confined (cell drying and re-wetting inactive), including outcrop units containing a water table. That choice eliminated the potential for numerical instability associated with drying and re-wetting of model cells but required the values of transmissivity and storage coefficients to be held constant within all layers over the duration of simulations.

The groundwater modelling report (GHD 2012, p.55) noted: "It would have been preferable to simulate the Quaternary alluvium and Main Range Volcanics in particular as variable transmissivity layers (i.e. MODFLOW layer type 3). Unfortunately, this would have prevented parameter optimisation and uncertainty analysis being carried out, by reducing the overall stability of the model and increasing model run times." The implications of this approach, and the occurrence of dry cells (simulated hydraulic head below the bottom of model cells) within the Condamine Alluvium are discussed in Section 7.4.5.

An approximate method was used to assign the values of storage coefficient in areas of the model where a water table was known to be present. Prior to calibration using PEST (GHD 2012, p.70):

- For model cells in areas of outcrop, where unconfined conditions were assumed, the initial values of specific storage were calculated by dividing the initial estimates of specific yield by the layer (cell) thickness; and
- For the remaining model cells, where confined conditions were assumed, the initial values of specific storage were assigned normally.

7.4.4.6 Initial heads

Transient simulations commence in 1995 using initial heads from the steady state calibration (Section 7.4.2) which is run as stress period 1.

7.4.4.7 Groundwater recharge

Twenty-one groundwater recharge zones were used, with recharge applied to the highest active cell in each vertical column of model cells. Rates of recharge were time varying for the first 65 stress periods (0 to 16 years) and then constant for the remaining 193 stress periods (17 to 3,000 years).

Two hundred realisations of the spatial distribution of recharge were generated for the assessment of predictive uncertainty (QWC 2012c, p.20). A single long-term average distribution of groundwater recharge was used for the period of constant recharge from 17 to 3,000 years.

7.4.4.8 Groundwater discharge

Extraction from bores

For the steady state calibration of the Surat CMA groundwater model, groundwater extractions from approximately 19,000 bores in 1995 were represented using the Well (WEL) Package, including licensed volumetric entitlements, estimated groundwater extractions from stock and domestic bores, and estimated water production from conventional gas and oil production wells (GHD 2012, p.59).

CDM Smith has analysed the contents of the well file to understand how the total groundwater extraction was varied over time. A summary of this analysis is provided in Table 7-5, based on the well file "AllExtraction_BSv2TRPred12v2_production_FREE_noBGT.wel" used for CSG development scenarios (Appendix A). The total rate of pumping was time varying over the initial 16 years of predictive simulations (1995 to 2010) and then effectively constant from 2011 onwards.

Some differences existed between the well files that were generated by OGIA for the MODEL_BASE[5] and MODEL_CSG[6] simulations (section 7.4.2.2). It is understood that the differences are due to inclusion of water production for conventional oil and gas production in the MODEL_CSG simulation. During the first 100 years, there were 50 to 125 fewer wells for MODEL_CSG simulations. From 0 to 36 years the total volume of extraction for MODEL_CSG simulations was approximately 30.5 GL greater than the total extraction for MODEL_BASE simulations, and from 37 to 100 years the total

[5] AllExtraction_BSv2TRPred23_basecase_REV_NOBGT.wel
[6] AllExtraction_BSv2TRPred12v2_production_FREE_noBGT.wel

extraction for MODEL_CSG simulations was approximately 14 GL less than the total extraction for MODEL_BASE simulations; with an overall difference of approximately 16.5 GL over the initial 100 years of extraction. From 100 years onward the number of wells and the rates of extraction are identical in both well files.

Table 7-5 Surat CMA groundwater model extraction

Stress Period	Time Period, y	Number of Wells	Total Extraction, ML/d
1 - 65	1/1/1995 to 31/12/2010	14,400 - 19,415	343 - 497
66 - 85	1/1/2011 to 31/12/2030	19,141	489
86 - 259	1/1/2031 to 31/12/4994	18,914 – 18,970	485

CSG water production

Water production for CSG development was simulated using the Evapotranspiration (EVT) Package and the methodology described by QWC (2012c, p.19). Maximum potential rates of evapotranspiration were set equal to the maximum potential rates of water production in the Walloon Coal Measures (model layer 10) and Bandanna Formation (model layer 18). These maximum rates of water production occur while the simulated heads in the coal seams are above the elevation of the evapotranspiration surface, which is defined to be 30 m to 50 m above the top of the coal seams. The rates of water production are reduced relative to the maximum potential rates by the EVT Package if the simulated heads fall below the evapotranspiration surface; reducing linearly from the maximum rate to zero at an extinction depth of 20 m below the evaporation surface.

Maximum potential rates of water production from the 2014 review of the Surat CMA groundwater model have been provided for this project in the EVT file "scenario_update_2014.evt" (Appendix A). The potential rates of evapotranspiration were time varying and spanned a period of 66 years (115 stress periods) consisting of the historical period of water production from 1995 to 2013 (19 years) and the forecast period of water production from 2014 to 2060 (47 years).

Discharge from the Condamine Alluvium

The Condamine Alluvium was assumed to be a discharge area for groundwater and was represented using the River (RIV) Package applied to cells in model layer 1. The parameter values of the RIV Package were specified in a way that made them mimic drain boundary conditions, which only allowed groundwater to be removed from the alluvium. This was achieved by setting the values of river stage (HRIV) and river bottom (RBOT) equal to one another (GHD 2012, p.57). The values of HRIV and RBOT were set equal to an estimate of the elevation of the water table in the alluvium that was derived from smaller-scale modelling of groundwater flow in the Condamine Alluvium.

The RIV Package was used to mimic drain boundary conditions and could only remove water from the alluvium according to the following rules:

- When simulated head in the Condamine Alluvium was above the estimated water table elevation in the alluvium (HRIV), groundwater discharge from the alluvium to the river boundary conditions occurred; and
- When simulated head in the Condamine Alluvium was below the estimated water table elevation (HRIV), recharge of groundwater into the alluvium from the river boundary condition was prevented.

All conductance terms for the river boundary conditions were set equal to 2,500 m/d. The river boundary conditions were time-varying for the first 58 stress period (from 1995 to 2009) and constant for the remaining stress periods.

Discharge from other areas of alluvium

Areas of alluvium outside of the Condamine Alluvium were also assumed to be discharge areas for groundwater and were similarly represented using the RIV Package applied to cells in model layer 1. The same methodology was used as for representing discharge from the Condamine Alluvium, but the elevation values of the tops of river cells, river stage (HRIV) and river bottom (RBOT) were set equal to ground surface elevation. Thus, the RIV Package was used to mimic drain boundary conditions corresponding to topographic elevation, and could only remove water from the alluvium.

All conductance terms for these river boundary conditions were set equal to 2,500 m/d. The river boundary conditions were time varying for the first 58 stress period (from 1995 to 2009) and constant for the remaining stress periods.

Discharge from ground surface

Groundwater discharge to the atmosphere outside of the alluvium was represented using the Drain Package (DRN) applied to the uppermost active model layer. Drain cell elevations were constant and set equal to ground surface elevation and the conductance terms were set equal to 2,500 m/d.

7.4.4.9 Lateral model boundaries

The western and northern boundaries of the Surat CMA model were specified as no-flow boundary conditions. General Head boundary conditions (GHB) were used along portions of the eastern and southern boundaries of the model (GHD 2012, p.57) and were all steady state.

- On the eastern boundary, GHB conditions representing lateral groundwater flow between the Surat Basin and Clarence Morton Basin were specified within the Walloon Coal Measures (layer 10), Hutton Sandstone (layer 12) and Precipice Sandstone (layer 14); and
- On the southern boundary, GHB conditions representing lateral groundwater flow within the Surat Basin were specified within the Bungil Formation and Mooga Sandstone (layer 3), Gubberamunda Sandstone (layer 5), Springbok Sandstone (layers 7 and 8), Walloon Coal Measures coals (layer 10), Hutton and Marbung Sandstone (layer 12), Precipice Sandstone (layer 14) and Clematis Sandstone (layer 16).

Two hundred realisations of the GHB conductance values on the eastern and southern boundaries were generated for the assessment of predictive uncertainty (QWC 2012c, p.18).

7.4.4.10 Solver options

The Preconditioned Conjugate Gradient Solver with Improved Nonlinear Control (PCGN) Package solver was used.

7.4.4.11 Output control

The water balance (budget) was printed to output files and saved at 259 selected time steps, and head was saved for layers 1, 3, 5, 7, 8, 10, 12, 14, 16 and 18 at the same times.

7.4.5 Model Outputs and Results

This Section considers outputs from the Surat CMA groundwater model that are relevant to predicting groundwater flux between the Condamine Alluvium and underlying hydrostratigraphic units of the Surat Basin. In Section 7.4.6 of this report, the Surat CMA groundwater model is used to assess the potential impact of Arrow's proposed action on the exchange of groundwater between the Condamine Alluvium and Surat Basin. Within this context, it is important to understand how these fluxes are generated by the Surat CMA groundwater model, and how they can be used appropriately in this study.

Several features of the existing modelling results that are not documented in the earlier reports (GHD 2012, QWC 2012c) are considered below.

7.4.5.1 Predicted vertical flux at the base of the Condamine Alluvium

The footprint area of the Condamine Alluvium in the Surat CMA groundwater model is represented by 2,624 model cells that cover an area of approximately 5,902 km^2 (2.25 km^2 per cell). The predicted groundwater flux between the Condamine Alluvium and underlying strata of the Surat Basin can be quantified by summing the simulated groundwater fluxes across the faces of these cells over time.

With the exception of Figure 5-100 in the existing report on predictive uncertainty (QWC 2012c, p.289), analyses of the simulated groundwater fluxes at the base of the Condamine Alluvium do not appear in previous modelling reports. Figure 5-100 showed the simulated "impact" (change in "total net vertical leakage flux" between the Condamine Alluvium and Surat Basin) over time for the 200 Null Space Monte Carlo (NSMC) simulations conducted for that study. The results were presented as change (or difference) in total net vertical flux due to forecast CSG development relative to an otherwise equivalent future with no CSG development. The absolute values of the vertical fluxes and their spatial distributions were not described.

An example of the simulated distribution of vertical flux at the base of the Condamine Alluvium from the Surat CMA groundwater model can be seen in Figure 7-5, which shows the steady state initial condition for NSMC realisation r1. The results in Figure 7-5 have been generated in this study using the Surat CMA groundwater model and datasets provided by OGIA from the assessment of predictive uncertainty (QWC 2012c). The following observations are made in relation to these results:

- Although the model predicts net vertical flux from the Surat Basin to the Condamine Alluvium summed over the entire footprint area of the alluvium, the direction of vertical flux is downward from the alluvium into underlying strata over approximately 62 percent of the footprint area (1,626 cells) and upward from underlying strata into the alluvium over the remaining 38 percent of the footprint area (997 cells);
- Inflow to the Condamine Alluvium from underlying strata of the Surat Basin (blue tones in Figure 7-5) is predicted mainly around the margins of the alluvium where flow is topographically controlled and in the south of the footprint area;
- Outflow from the alluvium to underlying strata of the Surat Basin (red tones in Figure 7-5) is predicted in the central and northern parts of the footprint area; and
- The model predicts values of hydraulic head that are below the bottom elevation of the alluvium (hatched areas in Figure 7-5) over approximately 15 percent of the footprint area (387 model cells); these 'dry cells' are ignored by the LPF Package, which deactivates MODFLOW's cell drying and wetting capabilities in layers that are specified as confined (refer to Section 7.4.4.5);

- the LPF Package continues to compute and report groundwater fluxes into and out of 'dry cells' in confined layers based on the simulated hydraulic gradient, assigned hydrogeological properties and cell geometries (e.g. cell thickness and face dimensions);
- dry cells in the alluvium appear to be caused by excessive drawdown in underlying strata that is induced by simulated pumping from groundwater bores in the Surat Basin; the model calibration (GHD 2012, Appendix H) showed simulated hydraulic head in these areas that was 10 m to 100 m lower than observed hydraulic head.

Figure 7-6 shows the temporal patterns of total net vertical flux simulated by the Surat CMA groundwater model for NSMC realisation r1. The graphs in Figure 7-6 compare results from simulations with and without CSG development, summed over the entire footprint area of the alluvium (blue tones), and results from simulations with and without CSG development summed over the portion of the footprint area that excludes 'dry cells' (red tones). Forecast CSG development is simulated using the 2014 update of water production data contained in "scenario_update_2014.evt" (Appendix A). The following observations are made in relation to these results:

- Predicted total net vertical flux summed over the entire footprint area of the alluvium decreases from approximately 20 ML/d to less than 5 ML/d over the 3000-year simulation period (Figure 7-6(a)); this decrease in the rate of net vertical flux is caused by larger simulated rates of groundwater pumping in the Surat Basin from around 16 years onwards relative to the steady state initial condition.
- The predicted impact on net vertical flux at the base of the alluvium due to forecast CSG development is smaller than the effect predicted due to the simulated increase in the long-term rate of groundwater pumping from the Surat Basin; it can be seen that recovery of impacts caused by simulated CSG development is predicted from around 100 years onwards due to the temporary lifecycle of CSG development; in contrast the total water balance of the model is progressing toward a new equilibrium with smaller net vertical flux from the Surat Basin to the Condamine Alluvium due to the permanent change in simulated groundwater pumping from the Surat Basin.
- Between 35 and 80 percent of total net vertical flux from the Surat Basin to the Condamine Alluvium occurs via cells that the model predicts to be 'dry'; it is not expected that these areas of the alluvium are dry (do not contain a water table) in reality, and in this sense the model is expected to be consistent with observations; however, the simulated fluxes should be considered to be less reliable because simulated hydraulic head and aquifer transmissivity are not consistent with observations.

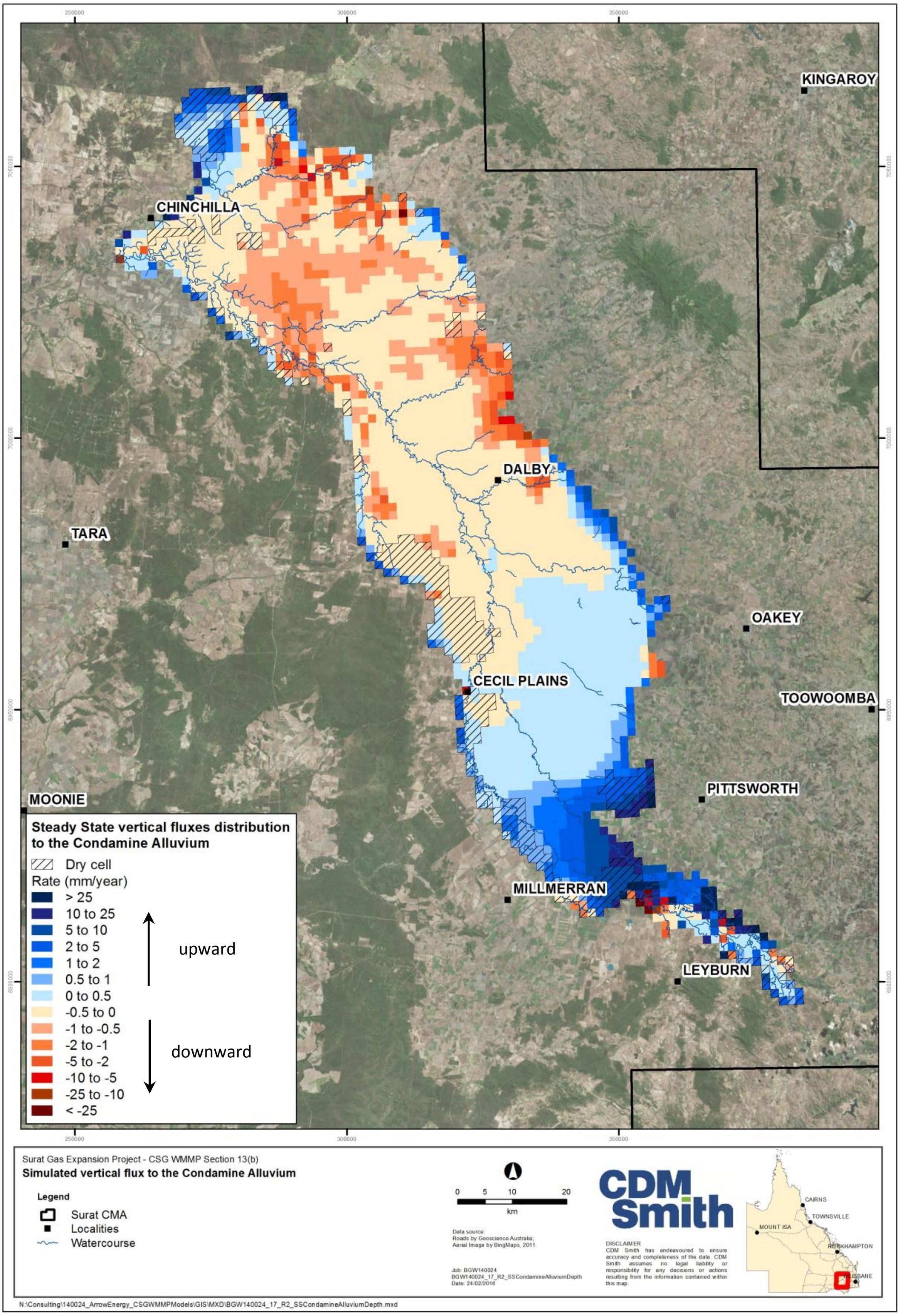
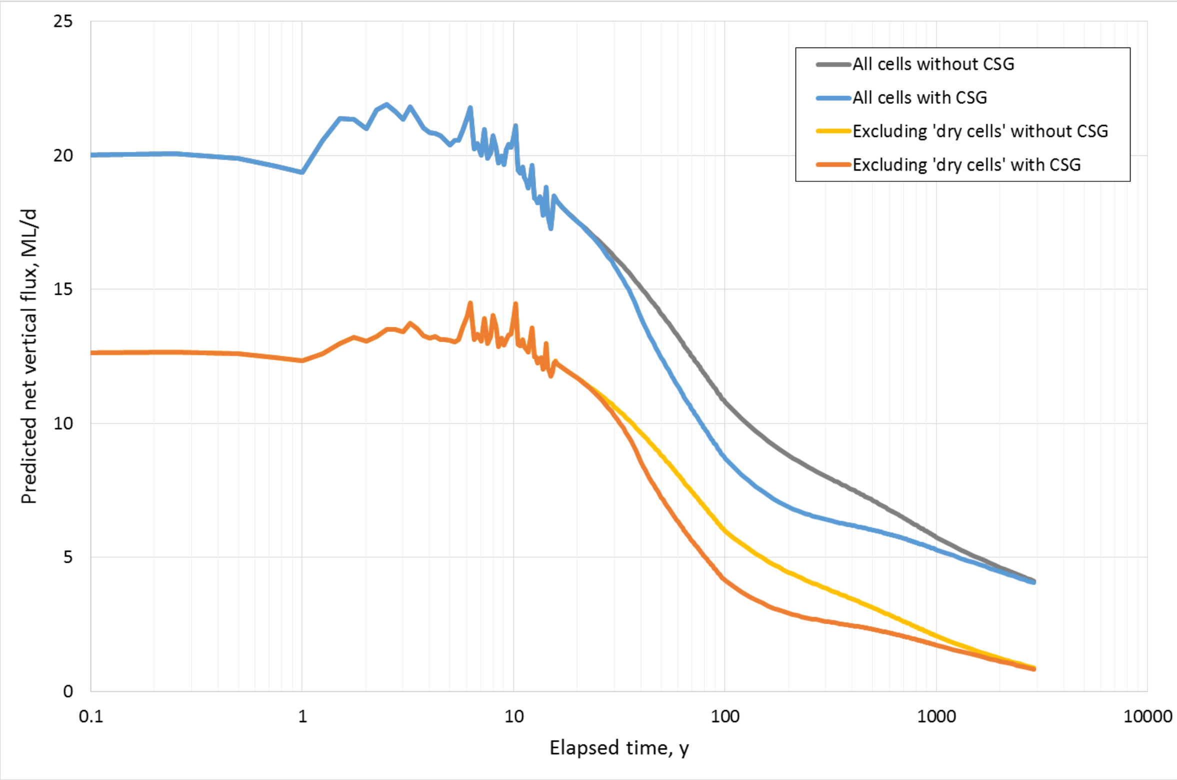


Figure 7-5 Surat CMA groundwater model, NSMC realisation r1 - simulated vertical flux to the Condamine Alluvium for the steady state initial condition

a.



b.

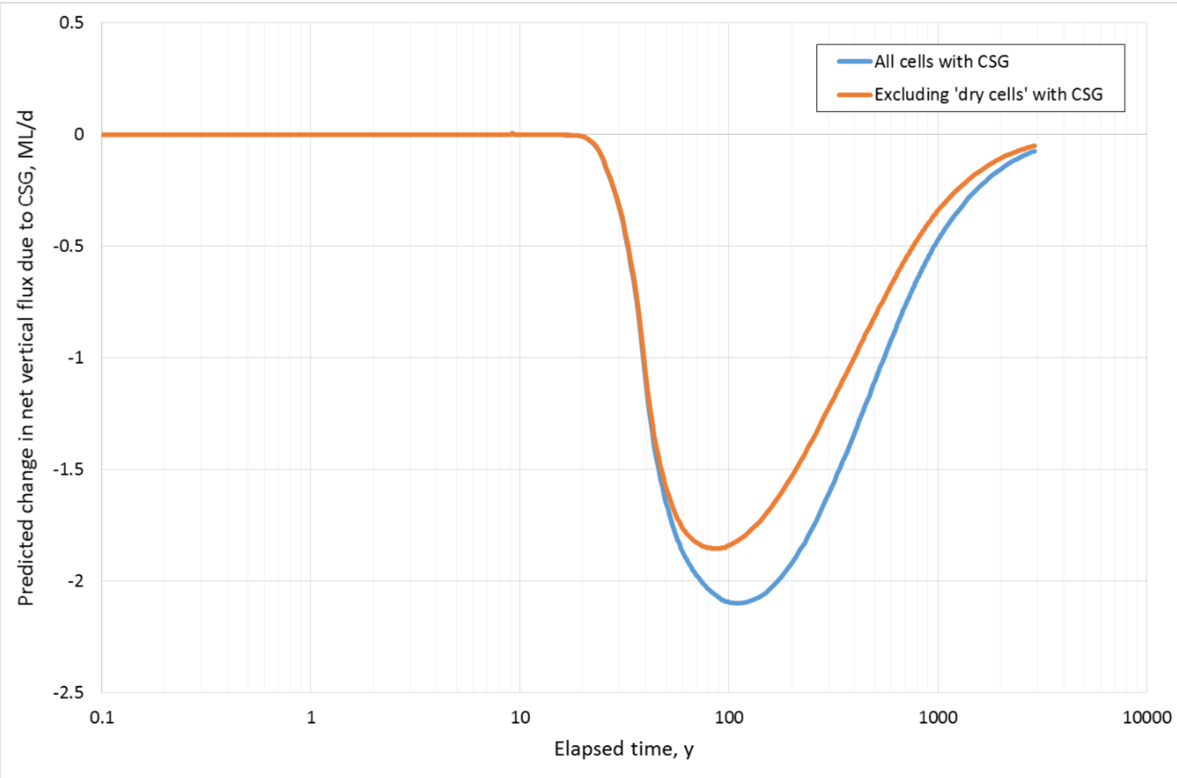


Figure 7-6 Surat CMA groundwater model, NSMC realisation r1 - predicted net vertical flux from the Surat Basin to the Condamine Alluvium: a. Total net vertical flux with and without CSG development; b. Change in net vertical flux due to CSG development

7.4.6 Predictive Simulations

This section describes the application of the Surat CMA groundwater model in this study to predict potential impacts of CSG development on vertical groundwater flux at the base of the Condamine Alluvium. The preceding sections (Section 7.4.1 to Section 7.4.5) contain an overview of the Surat CMA groundwater model, and its input requirements and outputs.

7.4.6.1 Methods

The Surat CMA groundwater model has been run using 200 realisations of selected model parameters that were developed by WNC for assessment of predictive uncertainty; this work is summarised in Section 7.4.2.2 and is fully described by QWC (2012c). WNC's assessment of predictive uncertainty involved the application of a Null Space Monte Carlo (NSMC) method to generate 200 realisations of the following model parameters:

- horizontal hydraulic conductivity;
- vertical hydraulic conductivity
- aquifer storativity (as storage coefficients);
- groundwater recharge rate, and
- conductance values for general head boundary conditions.

Each NSMC realisation has unique distributions of hydraulic conductivity, aquifer storativity, groundwater recharge and general head boundary conditions.

Predictive uncertainty analysis has previously been undertaken twice: the first time by WNC for QWC's 2012 UWIR (QWC 2012c), and the second time by GHD for Arrow's SREIS (Coffey Environments 2013). These analyses are similar but slightly different:

- Since QWC was focused on the potential impacts of all CSG production, WNC ran two sets of 200 simulations:
  - MODEL_BASE, being 200 base case predictive simulations with no CSG development; and
  - MODEL_CSG, being 200 predictive simulations incorporating all existing and proposed CSG development; these simulations used a version of water production data contained in a file called "evt_varQmax_final_BGT.dat".
- GHD considered a so-called "Arrow-only Case". GHD also ran two sets of 200 simulations, and computed potential impacts by differencing the results of these two sets of runs:
  - Cumulative Case, equivalent to WNC's MODEL_CSG case, incorporating all existing and proposed CSG development, but using used a 2012 version of water production data contained in an .evt file; and
  - Base Case, equivalent to WNC's MODEL_CSG case, but with another modified .evt file leaving out Arrow's water production.

Simulations

In this study, CDM Smith has also run two sets of 200 simulations (400 total simulations) using the Surat CMA groundwater model and the 200 NSMC parameter realisations (QWC 2012c):

1. MODEL_CSG, being 200 predictive simulations incorporating all existing and proposed CSG development; these simulations use the 2014 update of water production data contained in "scenario_update_2014.evt" (Appendix A); and

2. MODEL_XARROW, being 200 predictive simulations incorporating all existing and proposed CSG development but excluding Arrow's proposed activities; these simulations use a modified version the 2014 update of water production data named "scenario_update_2014_withoutArrow", which has all CSG water production in Arrow's tenements removed.

The three sets of NSMC analysis undertaken by WNC, GHD and CDM Smith cannot be directly compared. Different questions have been asked at different times, and different estimates of Arrow's water production have been used in all three. Any change affects rankings, so not only is it possible for the same realisation to have different ranking in terms of drawdown, fluxes or any other measure, but changes in Arrow's production data mean that rankings for any measure are also likely to vary between the three sets of NSMC analysis.

Stress Periods

The setup of stress periods for the predictive simulations is unchanged from the previous modelling for the Surat CMA UWIR (see Section 7.4.2.1). Each simulation spans 3,000 years from 1995 to the end of 4994.

7.4.7 Results

7.4.7.1 Existing and proposed CSG development (MODEL_CSG)

Predicted water production for existing and proposed CSG development

The following water production data have been extracted from the predictive simulations incorporating all existing and proposed CSG development, and are archived in csv formatted data files:

- Net rates of water production at the end of each stress period (259 times) by all operators (total water production), by others (non-Arrow water production) and by Arrow, for all realisations;

- Maximum rates of water production, and times of maximum rates, by all operators (total water production), by others (non-Arrow water production) and by Arrow, for each realisation; and

- Total volumes of water production over the 65-year period of simulated CSG development, by all operators (total water production), by others (non-Arrow water production) and by Arrow, for each realisation.

Figure 7-7, Figure 7-8 and Figure 7-9 show summaries of the predicted rates of CSG water production by all operators, and the contributions to those totals by other operators (non-Arrow) and Arrow. The curves on each graph show the minimum and maximum rates of water production for all realisations over time (grey dashed lines), the median rate of water production for all realisations (black dashed line), and the rates of water production that are exceeded in 95% and 5% of realisations (blue and red solid lines).

In broad terms, it can be seen that the predicted maximum rate of water production by all operators is around 500 ML/d (approx. 180 GL/y), and that the predicted maximum contributions by non-Arrow operators and Arrow are around 450 ML/d (approx. 165 GL/y) and 150 ML/d (55 GL/y), respectively.

More detailed summaries of the predicted water production volumes and the maximum rates of water production are given in the following sections.

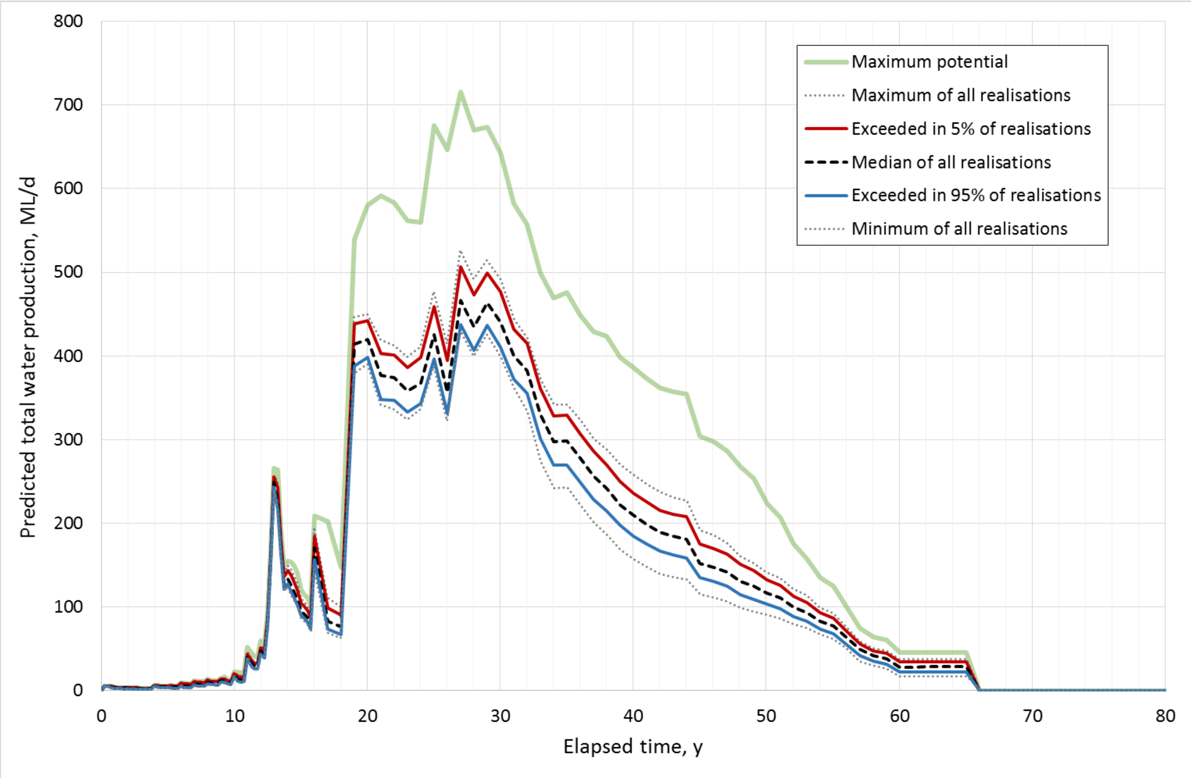


Figure 7-7 Predicted total water production for existing and proposed CSG development

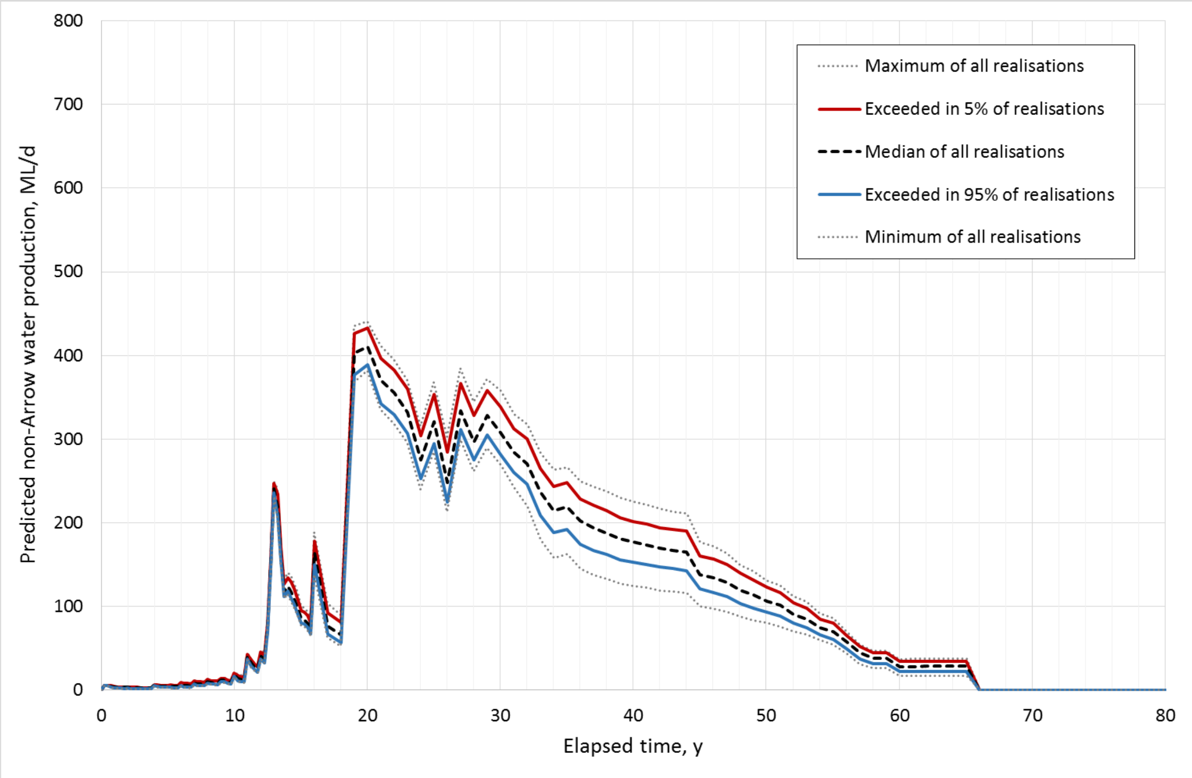


Figure 7-8 Predicted non-Arrow water production for existing and proposed CSG development

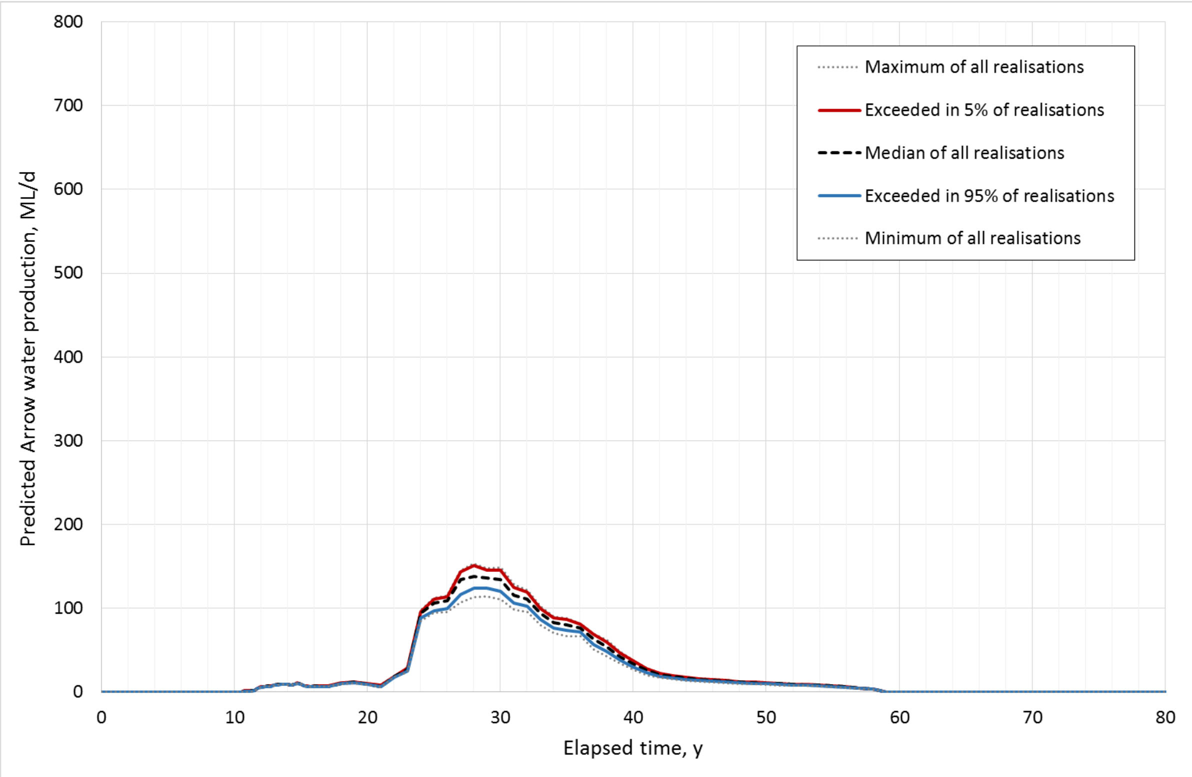


Figure 7-9 Predicted Arrow water production for existing and proposed CSG development

Predicted water production volumes for existing and proposed CSG development

Table 7-6 to Table 7-8 are statistical summaries of the predicted total water production volumes over the 65-year period of simulated CSG development. The data that these statistics represent are shown as graphs of predicted water production in Figure 7-10 to Figure 7-12

With respect to total water production by all operators, 90% of realisations have predicted volumes between 3,738 GL and 4,395 GL, with a median value of 4,032 GL and a mean value of 4,052 GL. The mean value of 4,052 GL over 65 years is equivalent to average annual rate of water production of 62 GL/y. The range of 1,035 GL is approximately 26% of the mean.

With respect to the contributions by others (non-Arrow), 90% of realisations have predicted volumetric contributions between 3,036 GL and 3,663 GL, with a median contribution of 3,324 GL and mean contribution of 3,346 GL over 65 years (51 GL/y). The median contribution of 3,324 GL is 83% of the total water production by all operators for that realisation (r152). The range of 1,090 GL is approximately 33% of the mean.

With respect to the contributions from Arrow, 90% of realisations have predicted volumetric contributions between 653 GL and 755 GL, with a median contribution of 710 GL and mean contribution of 706 GL over 65 years (11 GL/y). The median contribution of 710 GL is 19% of the total water production by all operators for that realisation (r102). The range of 157 GL is approximately 22% of the mean.

Table 7-6 Predicted total water production volumes for existing and proposed CSG development

Measure for 200 realisations	Total water production volume, GL	Realisation number
Maximum	4,527	53
Exceeded in 5% of realisation	4,395	83
Mean	4,052	8
Median	4,032	140
Exceeded in 95% of realisation	3,738	81
Minimum	3,492	191

Table 7-7 Predicted non-Arrow water production volumes for existing and proposed CSG development

Measure for 200 realisations	Non-Arrow water production volume		Realisation Number
	GL	Fraction total WP volume, %	
Maximum	3,859	85	138
Exceeded in 5% of realisation	3,663	83	37
Mean	3,346	82	148
Median	3,324	83	152
Exceeded in 95% of realisation	3,036	82	82
Minimum	2,768	79	191

Table 7-8 Predicted Arrow water production volumes for existing and proposed CSG development

Measure for 200 realisations	Arrow water production volume		Realisation Number
	GL	Fraction of total WP volume, %	
Maximum	766	19	34
Exceeded in 5 % of realisation	755	19	154
Median	710	19	102
Mean	706	18	89
Exceeded in 95% of realisation	653	17	24
Minimum	609	16	25

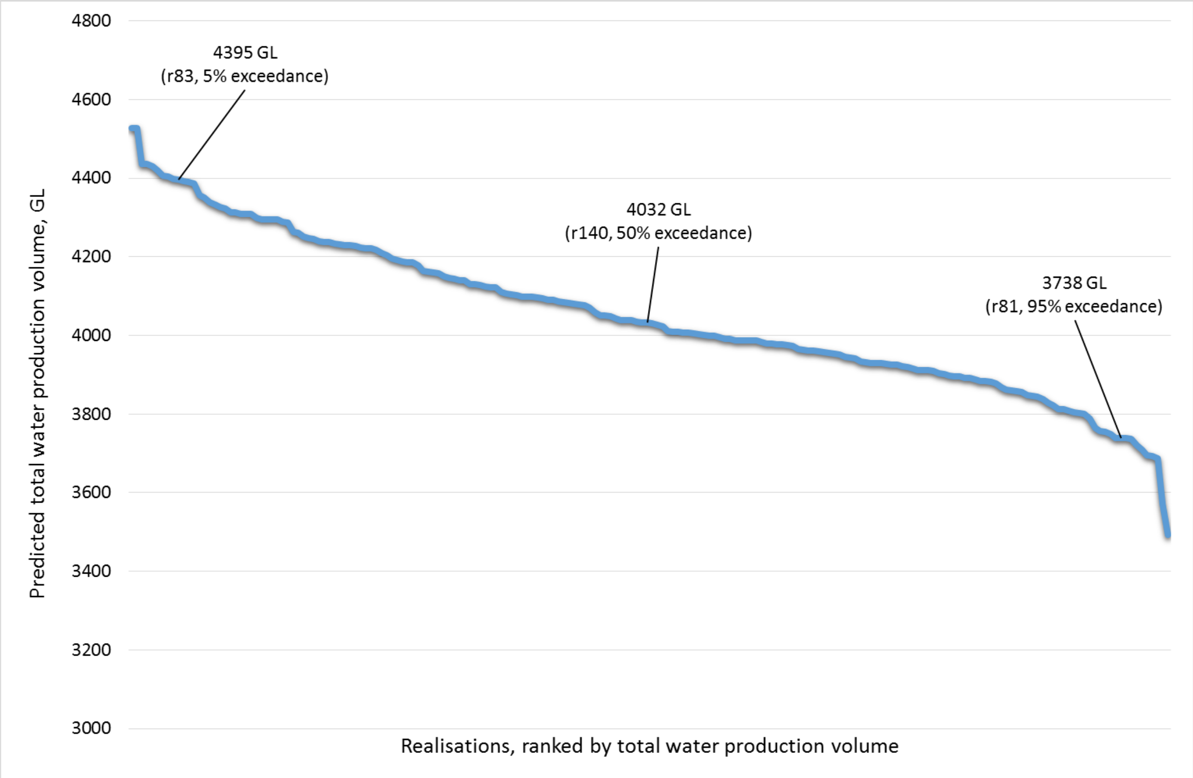


Figure 7-10 Predicted total water production volumes for existing and proposed CSG development

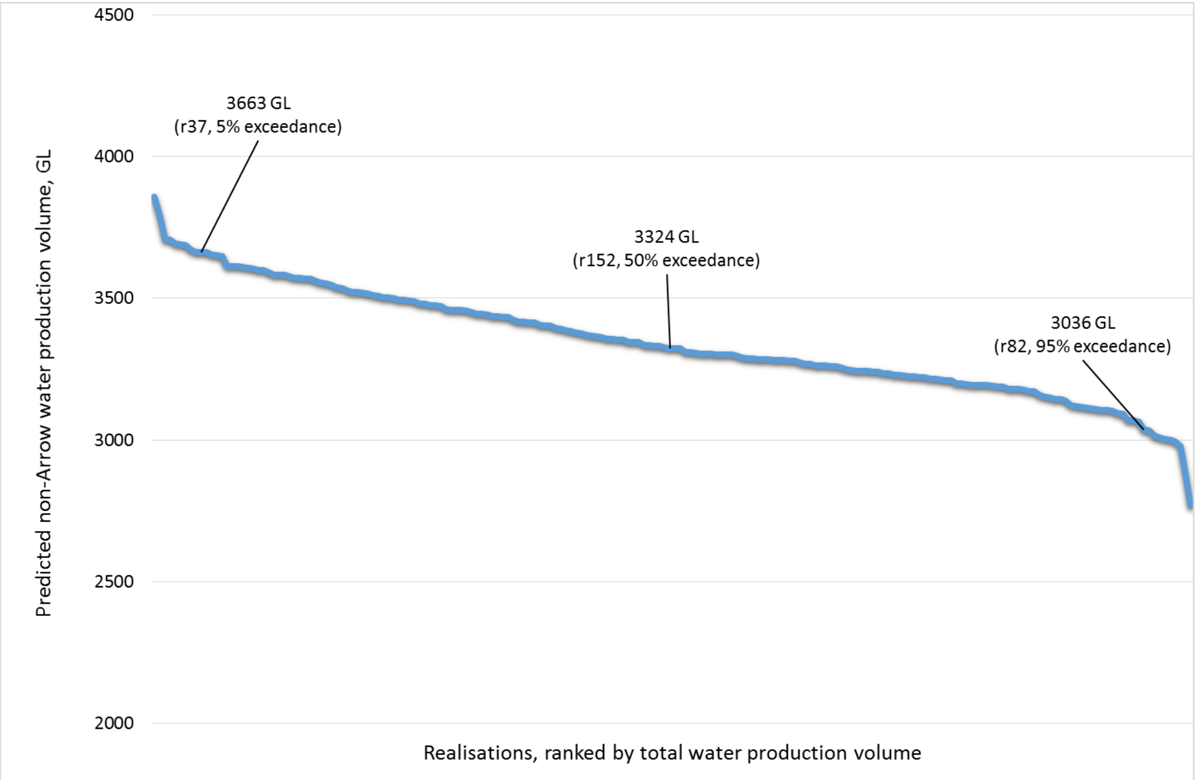


Figure 7-11 Predicted non-Arrow water production volumes for existing and proposed CSG development

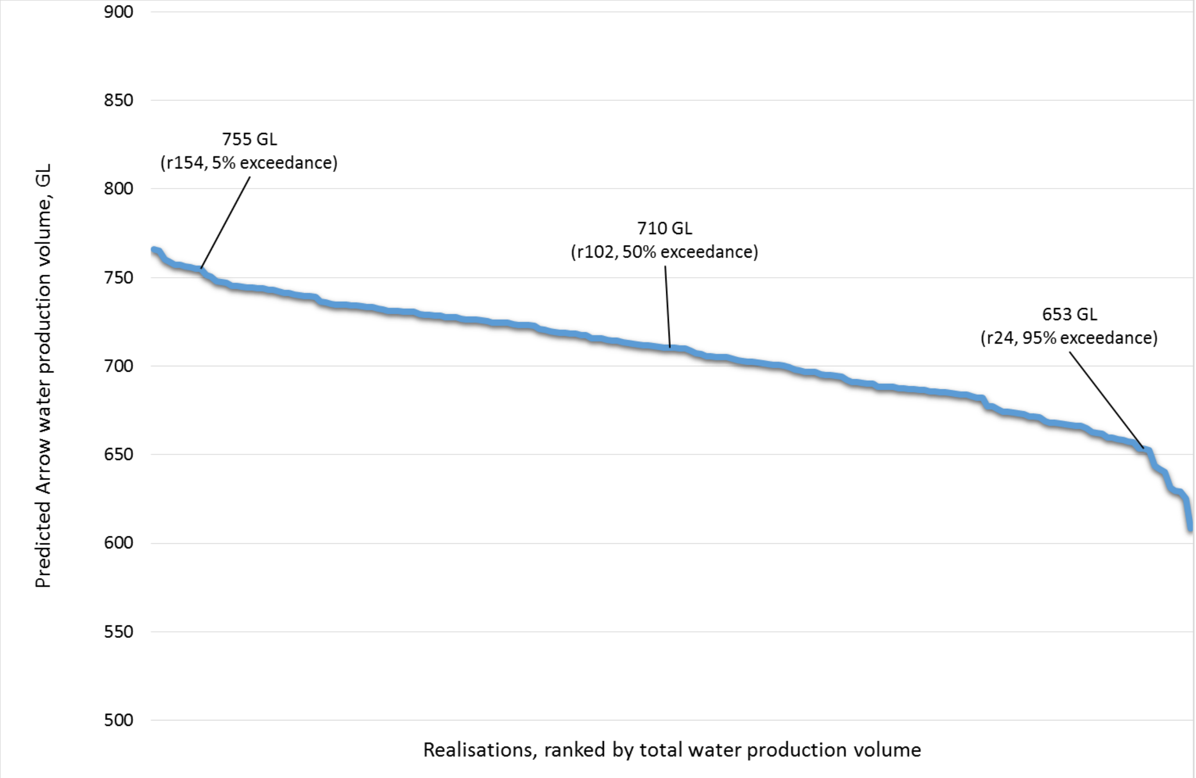


Figure 7-12 Predicted Arrow water production volumes for existing and proposed CSG development

Predicted maximum rates of water production for existing and proposed CSG development

Table 7-9 to Table 7-11 are statistical summaries of the predicted maximum rates of water production over the 65-year period of simulated CSG development. The data that these statistics represent are shown as graphs in Figure 7-13 to Figure 7-15.

With respect to maximum rates of water production by all operators, 90% of realisations have maximum rates between 440 ML/d and 506 ML/d, with a median value of 467 GL and mean value of 469 ML/d. The range of 96 ML/d is approximately 21% of the mean.

With respect to maximum rates of water production by other operators (non-Arrow), 90% of realisations have maximum rates between 390 ML/d and 433 ML/d, with a median value of 411 ML/d and mean value of 410 ML/d. The median maximum value of 411 ML/d is 87% of the rate of the total water production by all operators for that realisation (r184) at that time. The range of 59 ML/d is approximately 14% of the mean.

With respect to maximum rates of water production by Arrow, 90% of realisations have maximum rates between 124 ML/d and 151 ML/d, with a median value of 138 ML/d and mean value of 138 ML/d. The median maximum value of 138 ML/d is 30% of the rate of the total water production by all operators for that realisation (r35) at that time. The range of 40 ML/d is approximately 29% of the mean.

Table 7-9 Predicted maximum rates of water production for existing and proposed CSG development

Measure for 200 realisations	Maximum water production rate, ML/d	Realisation number
Maximum	527	53
Exceeded in 5 % of realisation	506	20
Mean	469	2
Median	467	34
Exceeded in 95% of realisation	440	26
Minimum	430	173

Table 7-10 Predicted maximum rates of water production by non-Arrow operators for existing and proposed CSG development

Measure for 200 realisations	Non-Arrow maximum water production rate		Realisation Number
	ML/d	Fraction of total WP rate, %	
Maximum	441	87	83
Exceeded in 5 % of realisation	433	88	101
Median	411	87	184
Mean	410	88	172
Exceeded in 95% of realisation	390	89	190
Minimum	382	82	48

Table 7-11 Predicted maximum rates of water production by Arrow for existing and proposed CSG development

Measure for 200 realisations	Arrow maximum water production rate		Realisation Number
	ML/d	Fraction of total WP rate, %	
Maximum	154	32	182
Exceeded in 5 % of realisation	151	31	171
Median	138	30	35
Mean	138	31	64
Exceeded in 95% of realisation	124	27	179
Minimum	114	26	19

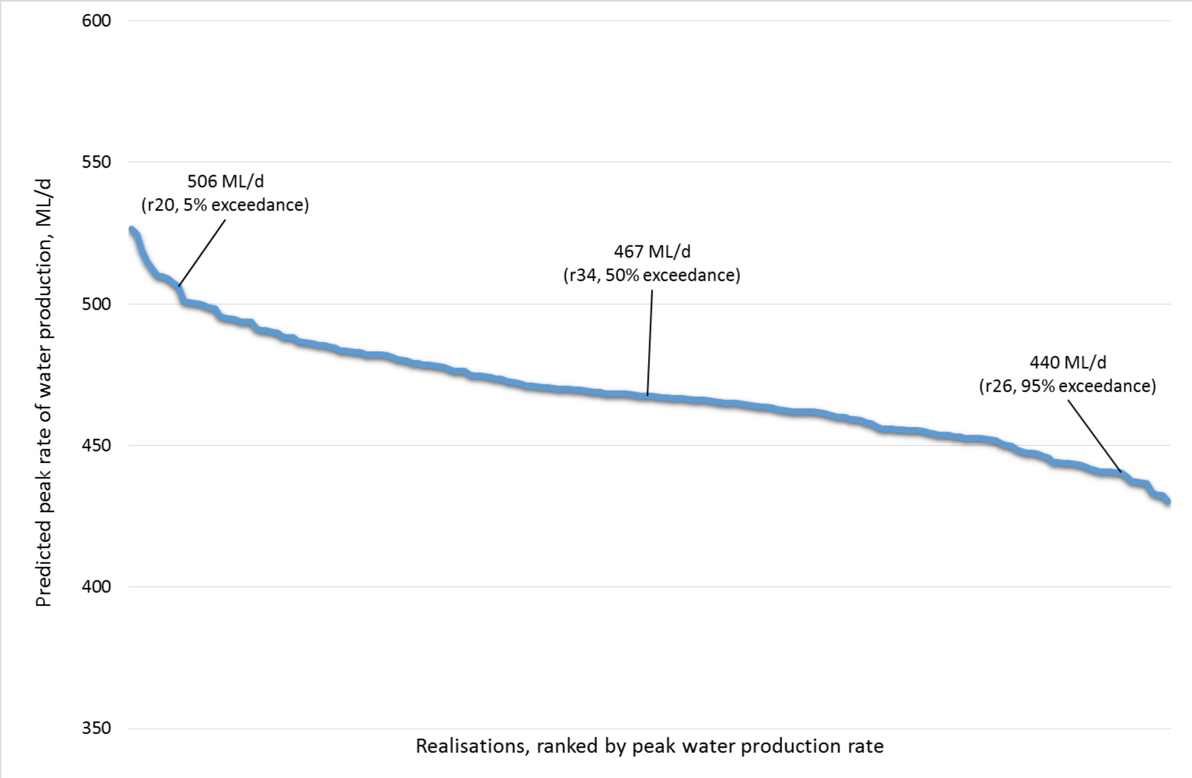


Figure 7-13 Predicted maximum rates of water production for existing and proposed CSG development

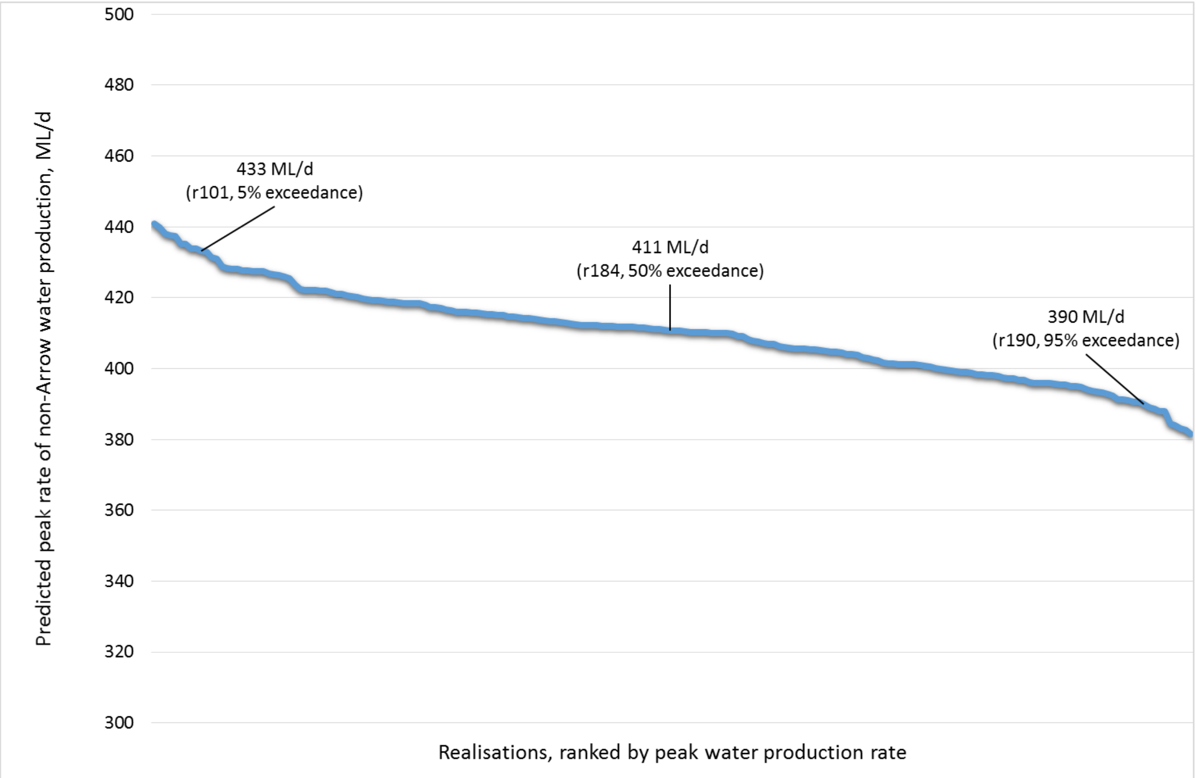


Figure 7-14 Predicted maximum rates of water production by non-Arrow operators for existing and proposed CSG development

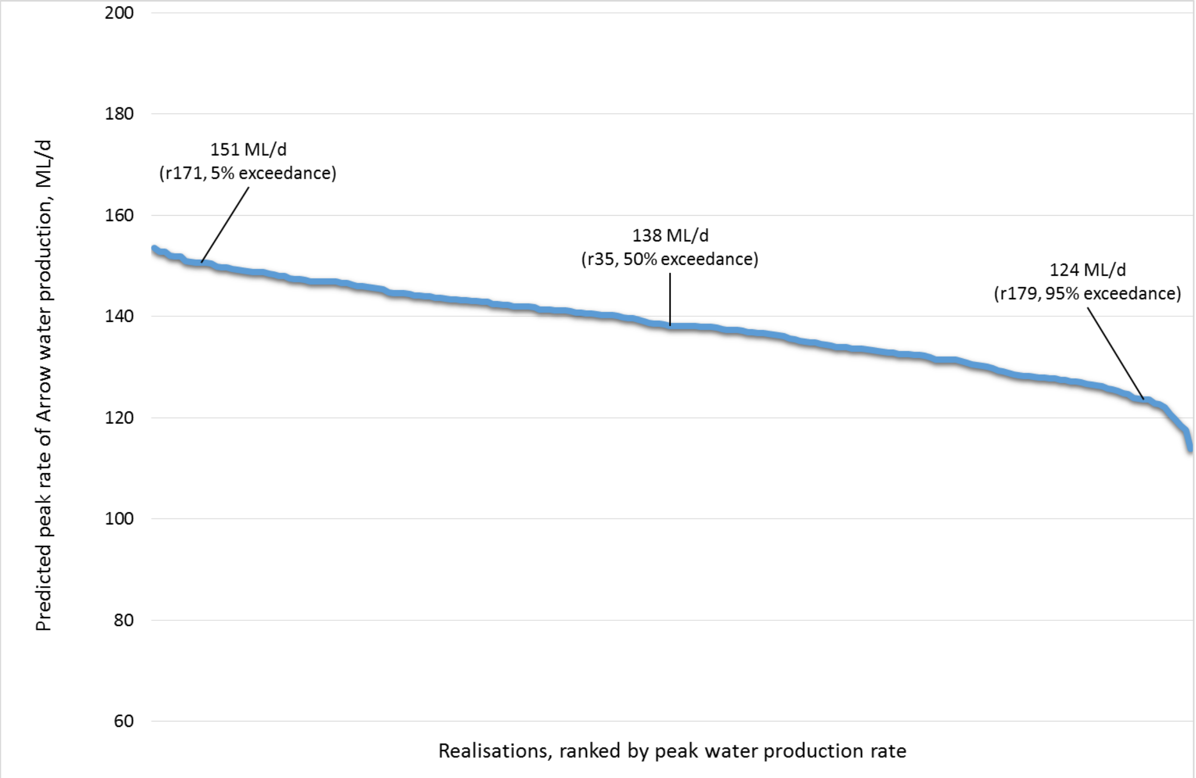


Figure 7-15 Predicted maximum rates of water production by Arrow for existing and proposed CSG development

7.4.7.2 Existing and proposed non-Arrow CSG development (MODEL_XARROW)

Predicted water production for existing and proposed non-Arrow CSG development

The following water production data have been extracted from the predictive simulations incorporating all existing and proposed CSG development but excluding Arrow's proposed activities, and are archived in csv formatted data files:

- Net rates of water production at the end of each stress period (259 times) by all non-Arrow operators, for all realisations;
- Maximum rates of water production, and times of maximum rates, by all non-Arrow operators, for each realisation; and
- Total volumes of water production over the 65-year period of simulated CSG development by all non-Arrow operators, for each realisation.

Figure 7-16 shows predicted rates of CSG water production by all non-Arrow operators with no concurrent CSG development by Arrow. The curves on each graph show the minimum and maximum rates of water production for all realisation over time (grey dashed lines), the median rates of water production for all realisations (black dashed line), and the rates of water production that are exceeded in 95% and 5% of realisations (blue and red solid lines). The predicted maximum rate of water production by all non-Arrow operators is around 441 ML/d (approx. 161 GL/y).

Comparison of Figure 7-16 (MODEL_XARROW) and Figure 7-8 (MODEL_CSG) shows similar rates of predicted water production for all non-Arrow operators, both with and without concurrent development of CSG by Arrow. Slight differences might be expected because the numerical model is slightly nonlinear in its behaviour, and production by one operator at one time will influence how much water might be produced by another nearby operator at the same or a different time. More detailed summaries of the predicted water production volumes and the maximum rates of water production are given in the following sections.

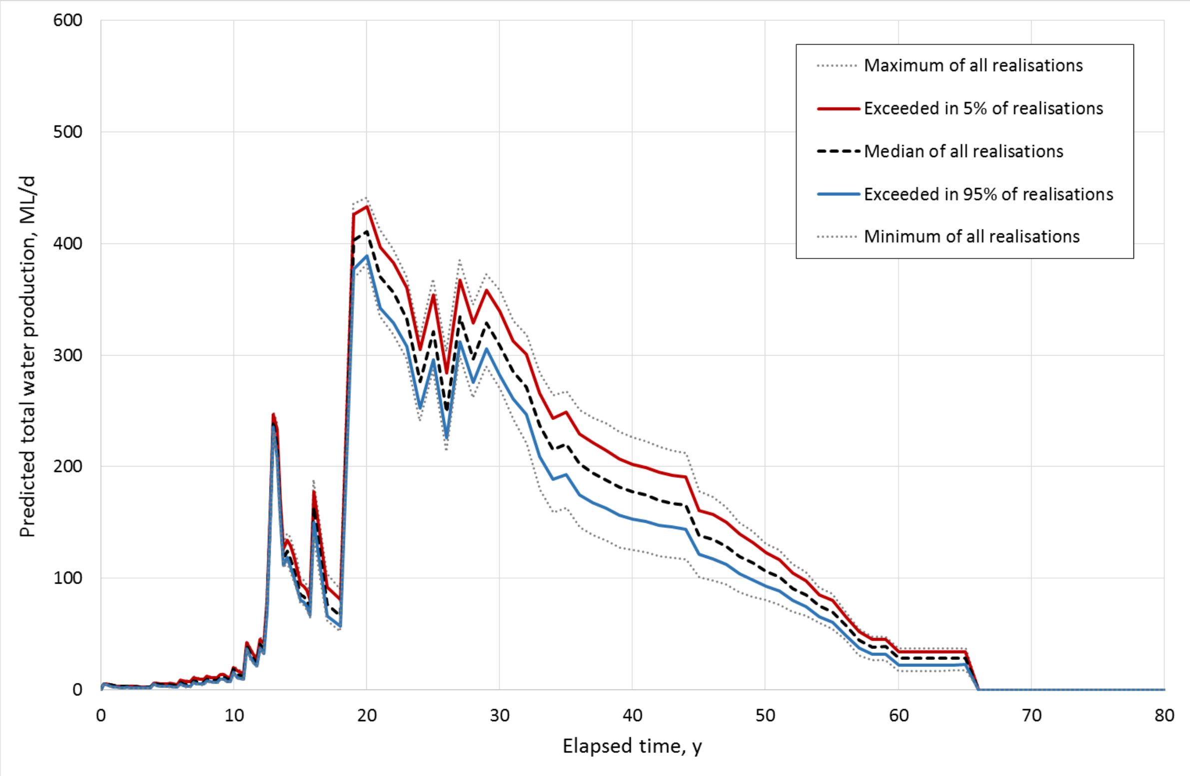


Figure 7-16 Predicted total water production for existing and proposed non-Arrow CSG development

Predicted water production volumes for existing and proposed non-Arrow CSG development

Table 7-12 is a statistical summary of the predicted water production volumes by non-Arrow operators, and with no water production by Arrow, over the 65-year period of simulated CSG development for all realisations. It can be seen that 90% of realisations have predicted volumes between 3,044 GL and 3,668 GL, with a median value of 3,333 GL and mean value of 3,353 GL. The mean value of 3,353 GL over 65 years is equivalent to average annual rate of water production of approximately 52 GL/y. The range of 1,094 GL is approximately 33% of the mean.

Comparison of Table 7-12 (MODEL_XARROW) and Table 7-7 (MODEL_CSG) shows similar predicted volumes of water production by non-Arrow operators both with and without concurrent CSG development by Arrow. The total volumes of water production by non-Arrow operators are predicted to be slightly larger when there is no concurrent CSG development by Arrow because there is no contribution from Arrow's operations to depressurisation in non-Arrow tenements.

Table 7-12 Predicted water production volumes for existing and proposed non-Arrow CSG development

Measure for 200 realisations	Total water production volume, GL	Realisation number
Maximum	3,872	138
Exceeded in 5 % of realisation	3,668	37
Mean	3,353	132
Median	3,333	31
Exceeded in 95% of realisation	3,044	82
Minimum	2,777	191

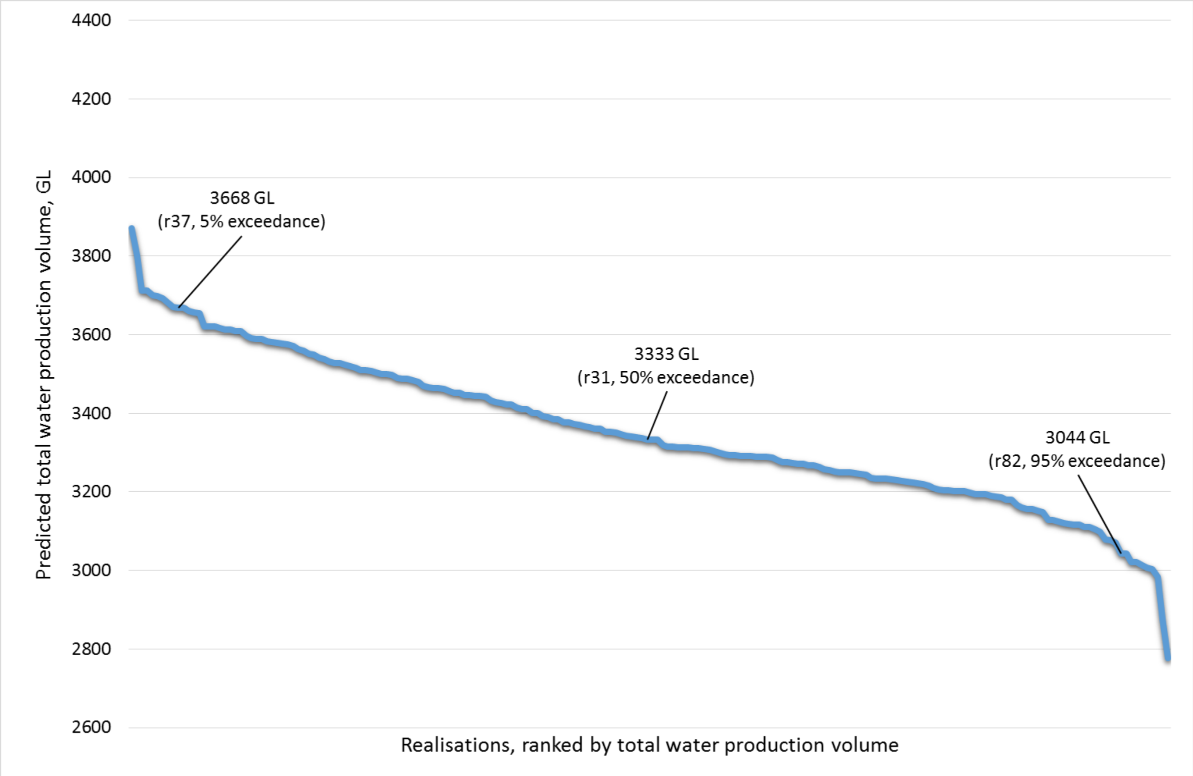


Figure 7-17 Predicted total water production volumes for existing and proposed non-Arrow CSG development

Predicted maximum rates of water production for existing and proposed non-Arrow CSG development (MODEL_XARROW)

Table 7-13 is a statistical summary of the predicted maximum rates of water production over the 65-year period of simulated CSG development. With respect to maximum rates of water production by all non-Arrow operators, 90% of realisations have maximum rates between 390 ML/d and 433 ML/d, with a mean value of 410 ML/d. The range of 59 GL is approximately 14% of the mean.

Comparison of Table 7-13 (MODEL_XARROW) and Table 7-10 (MODEL_CSG) shows identical results, and indicates that the predicted maximum rates of water production by non-Arrow operators are the same both with and without concurrent CSG development by Arrow.

Table 7-13 Predicted maximum rates of water production for existing and proposed non-Arrow CSG development

Measure for 200 realisations	Non-Arrow maximum water production rate	Realisation number
Maximum	441	83
Exceeded in 5 % of realisation	433	101
Mean	410	125
Median	411	184
Exceeded in 95% of realisation	390	190
Minimum	382	48

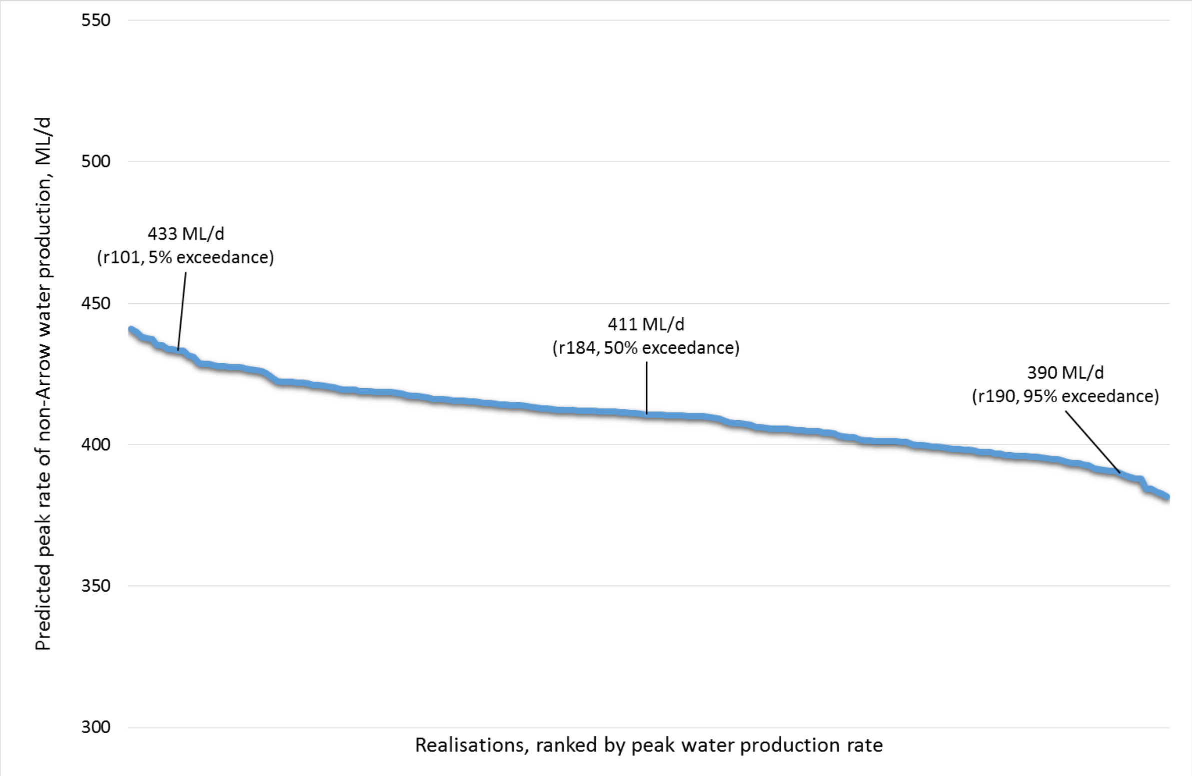


Figure 7-18 Predicted maximum rates of water production for existing and proposed non-Arrow CSG development

7.4.7.3 Predicted change in vertical flux at the base of Condamine Alluvium due to existing and proposed CSG development (MODEL_CSG)

The following vertical flux data have been extracted from the predictive simulations and are archived in csv formatted data files:

- Net rates of vertical flux in each model cell at the base of the Condamine Alluvium (2,624 cells) at the end of each stress period (259 times) for each realisation (135.9 million values);
- Net volumes of vertical flux in each model cell at the base of the Condamine Alluvium (2,624 cells) over each stress period (259 times) for each realisation (135.9 million values);
- Total rates, volumes and cumulative volumes of net vertical flux at the base of the Condamine Alluvium (summed over 2,624 cells) over each stress period (259 times) for each realisation; and

- Total rates, volumes and cumulative volumes of net vertical flux at the base area of the Central Condamine Alluvium Model (CCAM) (summed over 2,365 cells) over each stress period (259 times) for each realisation.

Additional data processing has been performed to compute differences in the above rates, volumes and cumulative volumes of net vertical flux for simulations with and without CSG development, and for all realisations. These results are also archived in csv formatted data files.

The footprint area of the Condamine Alluvium in the Surat CMA groundwater model extends over 2,624 model cells (5,904 km^2). An example of the spatial distribution of simulated net vertical flux at the base of the Condamine Alluvium within the footprint area is shown in Figure 7-5.

The area of alluvium in the Central Condamine Alluvium Model (CCAM) where connection to underlying strata of the Surat Basin was simulated corresponds to an area of 2,365 cells of the Surat CMA groundwater model (5,321 km^2), which are a subset of the footprint area of 2,624 cells. Thus, the area of connection between alluvium and underlying strata in the CCAM is approximately 90% of the footprint area of alluvium in the Surat CMA groundwater model.

Figure 7-19 is an example map showing the predicted spatial distribution of maximum change in vertical flux over the whole simulation period at the base of the Condamine Alluvium for NSMC realisation r1 due to simulated water production by all CSG operators. Negative values indicate that the predicted rate of vertical flux from the Surat Basin to the alluvium is reduced by a maximum of that amount as a result of the simulated water extraction. In this example, the pattern of change in vertical flux reflects the CSG field development plan and the spatial distributions of parameters for NSMC realisation r1; particularly the spatial pattern of vertical hydraulic conductivity. While the predicted maximum reduction in vertical flux to the alluvium is approximately 4.7 mm/y in one model cell, the maximum reductions in vertical flux are less than 1 mm/y over approximately 96% of the alluvium, and less than 0.1 mm/y over approximately 60% of the alluvium. At all other times during the simulation the changes in net vertical flux are smaller than the maximum values. Similar maps have been produced for other NSMC realisations later in this report (Figure 7-44).

Figure 7-20 shows the predicted change in total net vertical flux at the base of the Condamine Alluvium due to CSG water production by all operators (i.e. vertical flux summed over all model cells within the footprint area of the alluvium). As above, negative values indicate a reduction in the predicted net total groundwater flow from the Surat Basin to the Condamine Alluvium. The curves on each graph show the minimum and maximum change in net vertical flux for all realisations over time (grey dashed lines), the median change in net vertical flux for all realisations (black dashed line), and the changes in net vertical flux that are exceeded in 95% and 5% of realisations (blue and red solid lines).

It can be seen in Figure 7-20 that the simulated impacts from CSG development over a period of 65 years take around 3,000 years to finish propagating from the Surat Basin to the Condamine Alluvium.

Figure 7-21 is similar to Figure 7-20 but shows the predicted change in net vertical flux over a smaller area, which represents the area of alluvium in the Central Condamine Alluvium Model (CCAM) where connection to underlying strata of the Surat Basin was simulated.

More detailed summaries of the predicted volumes and maximum rates of net vertical flux at the base of the Condamine Alluvium and CCAM are given below.

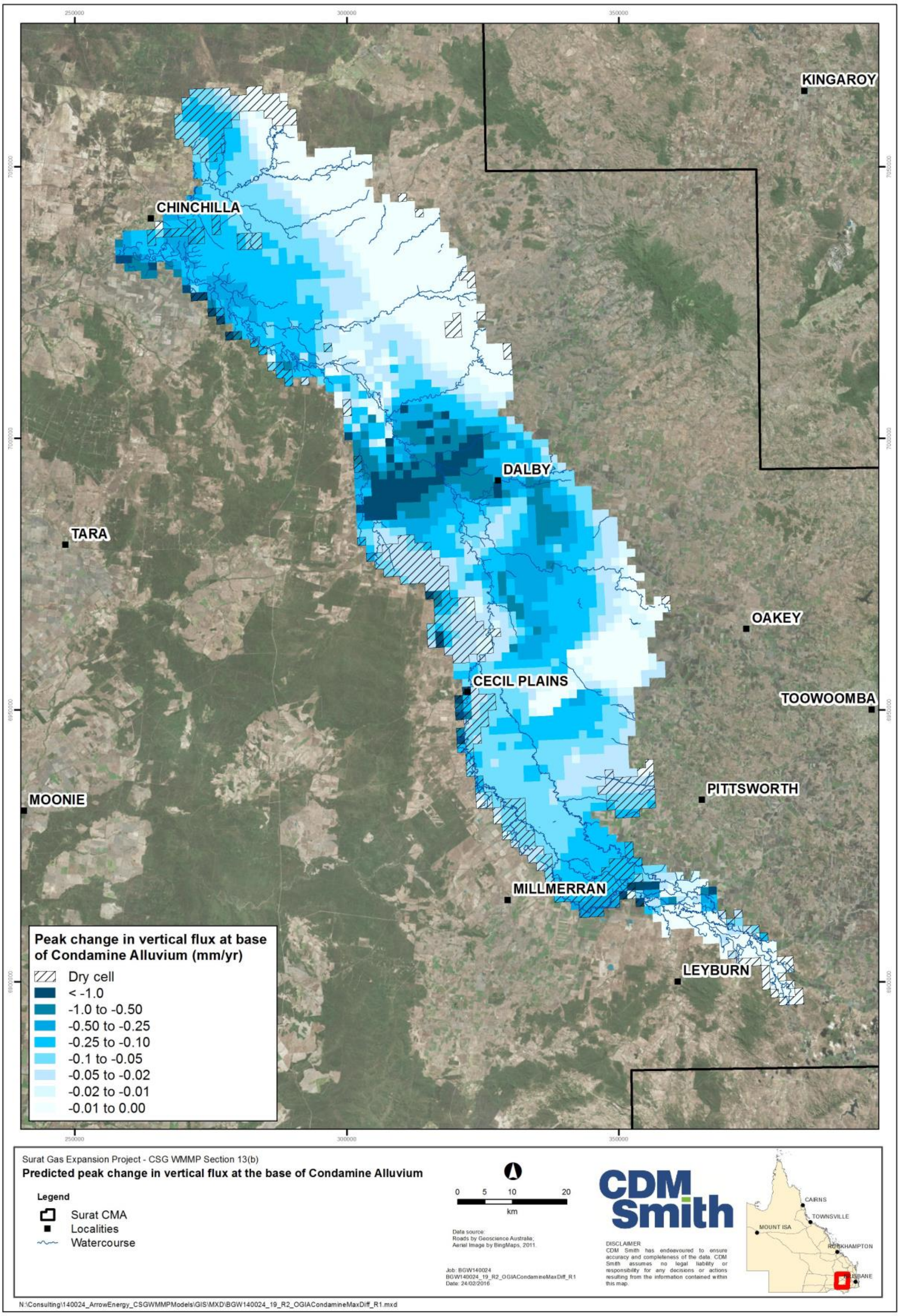


Figure 7-19 Surat CMA groundwater model, NSMC realisation r1 – maximum change in vertical flux at the base of Condamine Alluvium during the simulation period

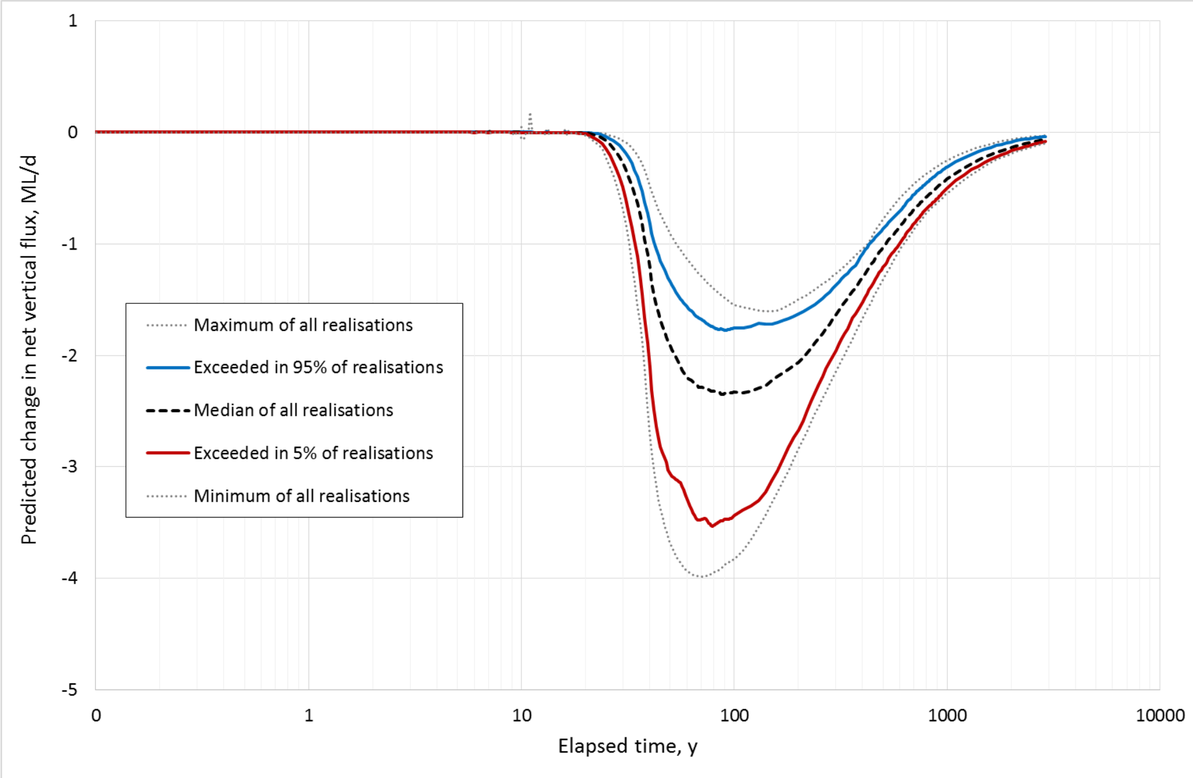


Figure 7-20 Predicted change in net vertical flux at the base of the Condamine Alluvium due to existing and proposed CSG development

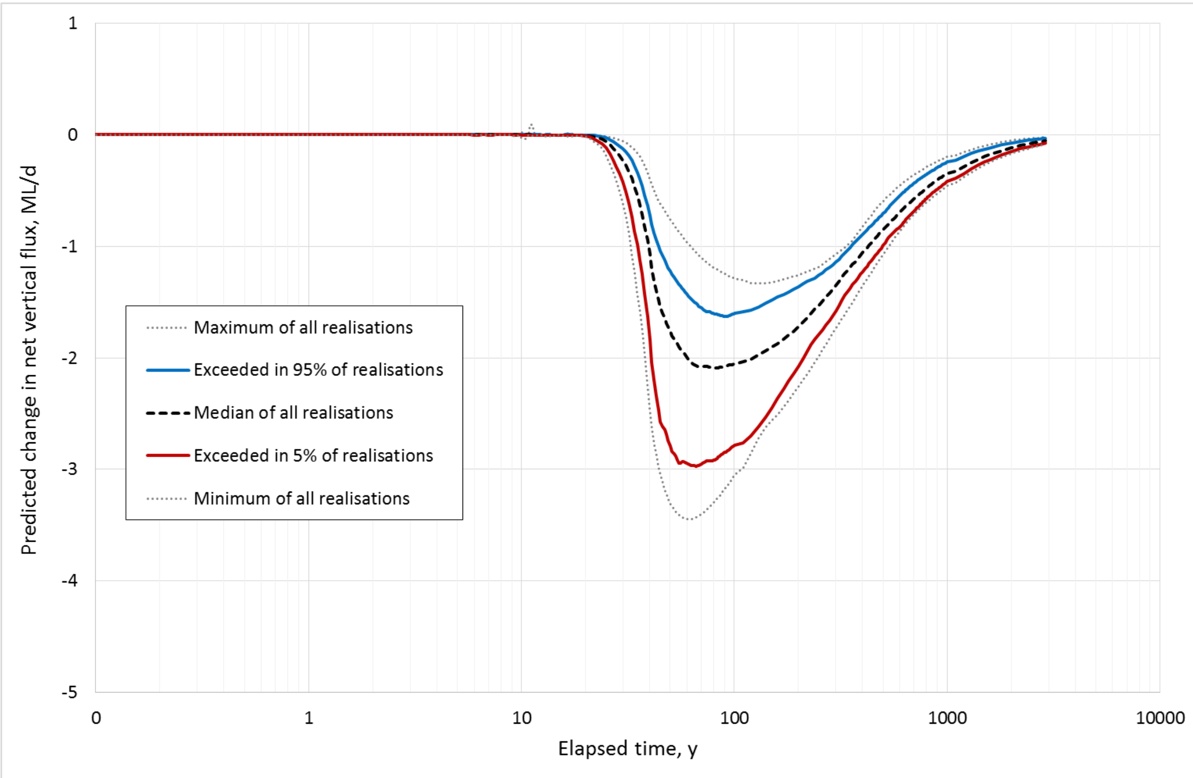


Figure 7-21 Predicted change in net vertical flux at the base of the CCAM due to existing and proposed CSG development

Condamine Alluvium footprint area

Table 7-14, Table 7-15, Figure 7-22 and Figure 7-23 summarise the predicted change in net vertical flux at the base of the Condamine Alluvium due to the simulated CSG water production by all operators over the 3,000-year simulation period.

With respect to changes in net vertical flux volumes induced by the simulated CSG development, 90% of realisations have predicted volumetric changes between 465 GL and 608 GL, with a median value of 537 GL and mean value of 537 GL. The mean volumetric change of 537 GL is 14% of the total volume of CSG water production by all operators for that realisation (r158). The range of 245 GL is 46% of the mean.

With respect to the maximum changes in net vertical flux induced by the CSG development, 90% of realisations have predicted maximum changes in net vertical flux between 1.79 ML/d and 3.57 ML/d, with a median value of 2.36 ML/d and mean value of 2.47 ML/d. The range of 2.38 ML/d is approximately 96% of the mean. The mean maximum change in net vertical flux of 2.47 ML/d is equivalent to a single high-yielding groundwater bore pumping continuously at a rate of 29 L/s; noting that groundwater users in the Condamine Alluvium experience bore yields of between 2 and 60 L/s (Murray-Darling Basin Authority[7]).

Table 7-14 Predicted change in net vertical flux volumes at the base of the Condamine Alluvium due to existing and proposed CSG development

Measure for 200 realisations	Change in net vertical flux volume		Realisation Number
	GL	Fraction of total water production, %	
Maximum	685	17	154
Exceeded in 5 % of realisation	608	14	96
Median	537	13	8
Mean	537	14	158
Exceeded in 95% of realisation	465	11	168
Minimum	440	12	82

Table 7-15 Predicted maximum change in the rate of net vertical flux at the base of the Condamine Alluvium due to existing and proposed CSG development

Measure for 200 realisations	Maximum change in vertical flux rate, ML/d	Realisation number
Maximum	3.98	132
Exceeded in 5 % of realisation	3.57	123
Mean	2.47	30
Median	2.36	34
Exceeded in 95% of realisation	1.79	183
Minimum	1.60	5

[7] http://www.mdba.gov.au/sites/default/files/archived/proposed/GW-reportcards-QLD.pdf

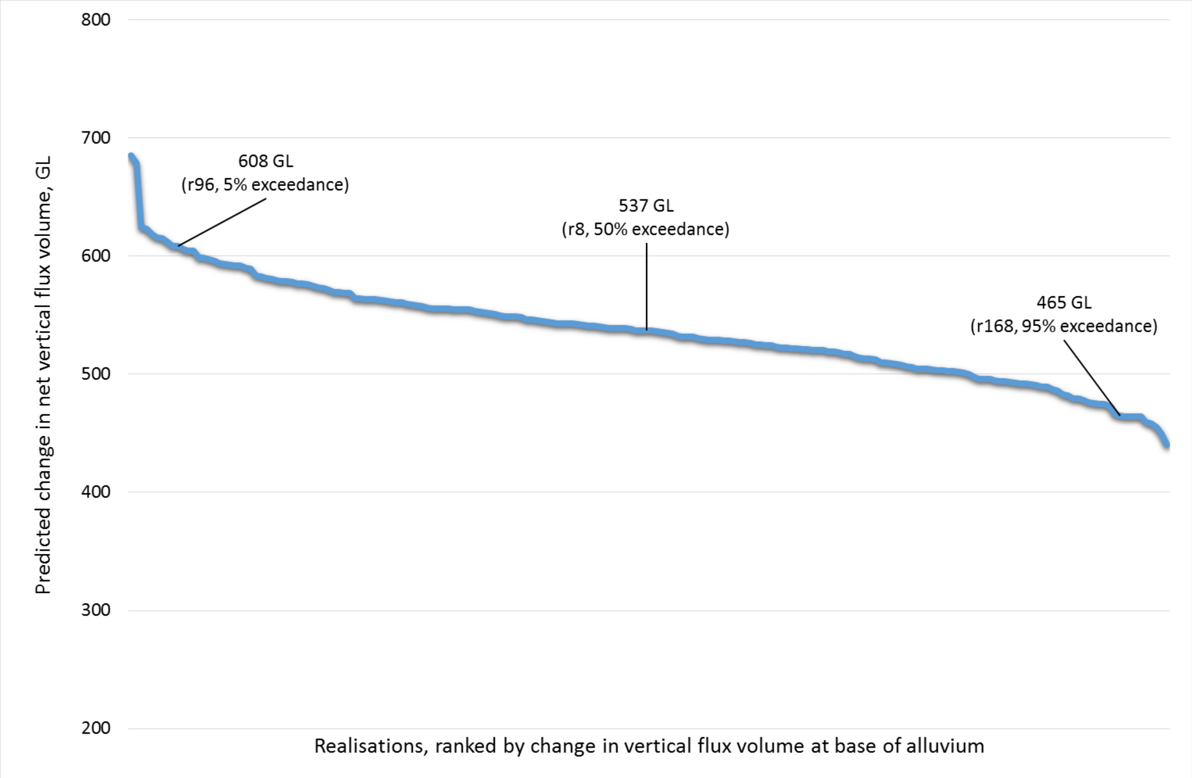


Figure 7-22 Predicted change in net vertical flux volumes at the base of the Condamine Alluvium due to existing and proposed CSG development

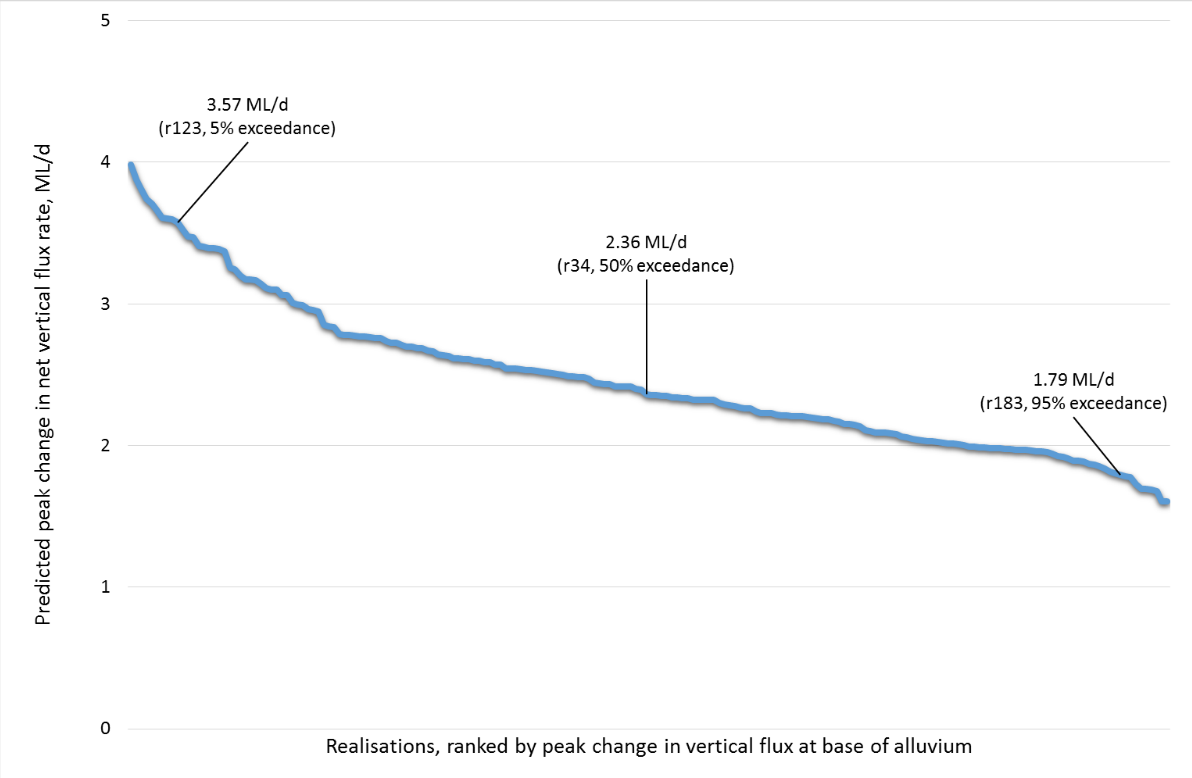


Figure 7-23 Predicted maximum change in the rate of net vertical flux at the base of the Condamine Alluvium due to existing and proposed CSG development

Central Condamine Alluvium Model (CCAM) area

Table 7-16, Table 7-17, Figure 7-24 and Figure 7-25 summarise the predicted change in net vertical flux at the base of the CCAM due to the simulated CSG water production by all operators over the 3,000-year simulation period.

With respect to changes in net vertical flux volumes induced by the simulated CSG development, 90% of realisations have predicted volumetric changes between 384 GL and 508 GL, with a median value of 445 GL and mean value of 443 GL. The median volumetric change of 445 GL is 11% of the total volume of CSG water production by all operators for that realisation (r27). The range of 210 GL is 47% of the mean.

With respect to the maximum changes in net vertical flux induced by the CSG development, 90% of realisations have predicted maximum changes in net vertical flux between 1.64 ML/d and 2.99 ML/d, with a median value of 2.11 ML/d and mean value of 2.15 ML/d. The range of 2.11 ML/d is approximately 98% of the mean. The mean maximum change in net vertical flux of 2.15 ML/d is equivalent to a single high-yielding groundwater bore pumping continuously at a rate of 25 L/s.

Table 7-16 Predicted change in net vertical flux volumes at the base of the CCAM due to existing and proposed CSG development

Measure for 200 realisations	Change in vertical flux volume at base of CCAM		Realisation Number
	GL	Fraction of total water production, %	
Maximum	556	14	154
Exceeded in 5 % of realisation	508	13	35
Median	445	11	27
Mean	443	12	119
Exceeded in 95% of realisation	384	10	26
Minimum	346	9	164

Table 7-17 Predicted maximum change in the rate of net vertical flux at the base of the CCAM due to existing and proposed CSG development

Measure for 200 realisations	Maximum change in vertical flux rate at base of CCAM, ML/d	Realisation number
Maximum	3.45	132
Exceeded in 5 % of realisation	2.99	87
Mean	2.15	170
Median	2.11	145
Exceeded in 95% of realisation	1.64	59
Minimum	1.33	58

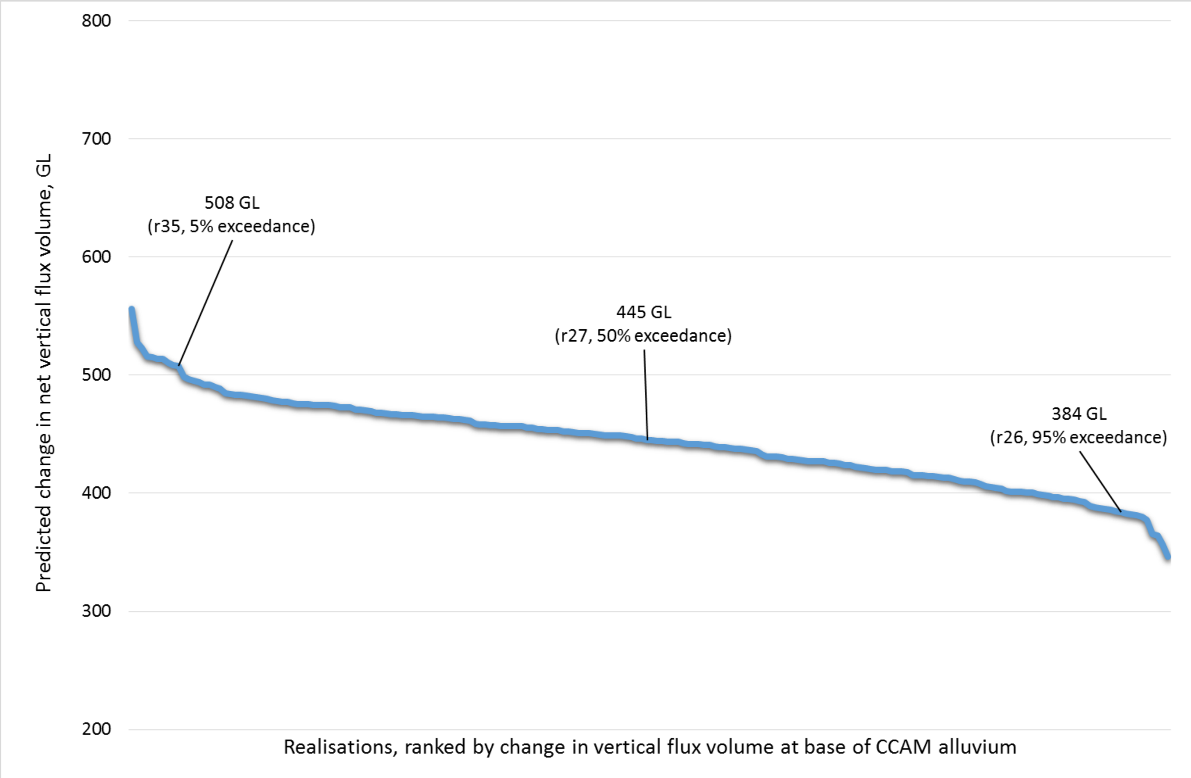


Figure 7-24 Predicted change in net vertical flux volumes at the base of the CCAM due to existing and proposed CSG development

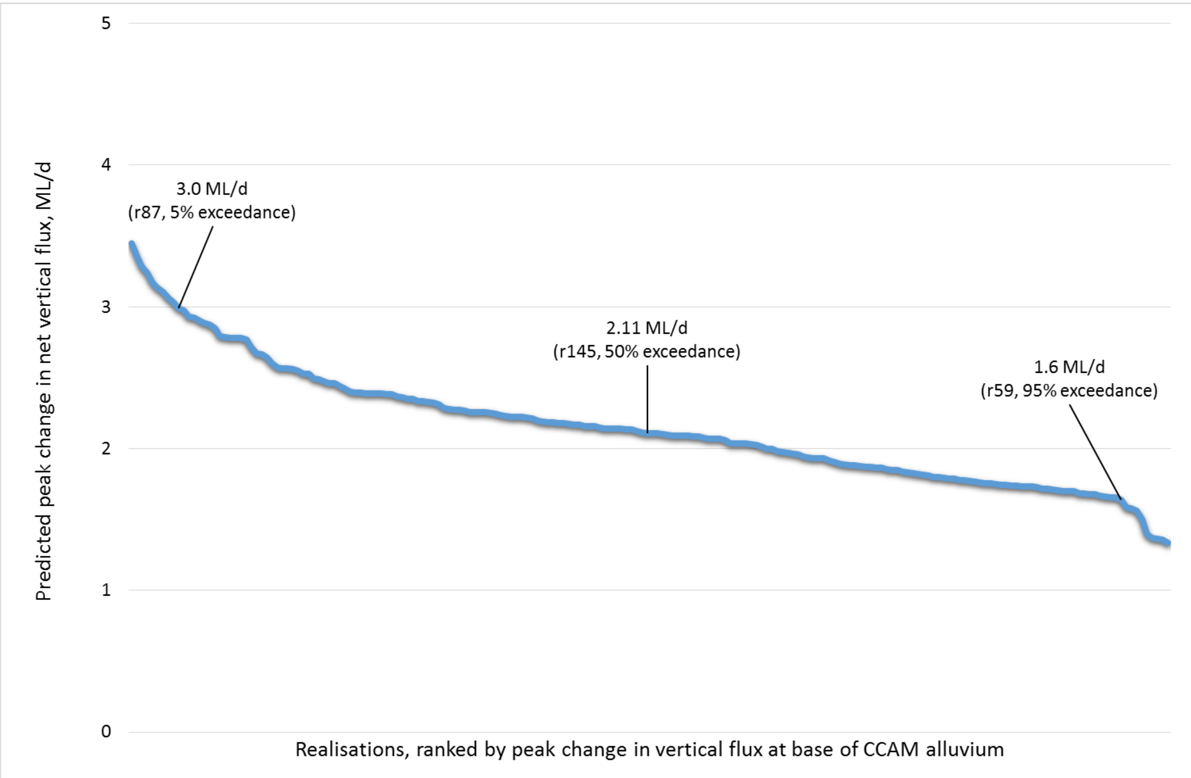


Figure 7-25 Predicted maximum change in the rate of net vertical flux at the base of the CCAM due to existing and proposed CSG development

7.4.7.4 Predicted change in vertical flux at the base of Condamine Alluvium due to existing and proposed non-Arrow CSG development (MODEL_XARROW)

Figure 7-26 shows the predicted change in net vertical flux at the base of the Condamine Alluvium due to existing and proposed non-Arrow CSG development. The graph shows the reduction in groundwater flow from the Surat Basin to the Condamine Alluvium predicted by the Surat CMA groundwater model. The curves on each graph show the minimum and maximum change in net vertical flux for all realisations over time (grey dashed lines), the median change in net vertical flux for all realisations (black dashed line), and the changes in net vertical flux that are exceeded in 95% and 5% of realisations (blue and red solid lines). The simulated impacts from CSG development over a period of 65 years take around 3,000 years to propagate from the Surat Basin to the Condamine Alluvium.

Figure 7-27 is similar to Figure 7-26 but shows the predicted change in net vertical flux over the area of alluvium in the Central Condamine Alluvium Model (CCAM) where connection to underlying strata of the Surat Basin is simulated. A difference exists between the figures because the CCAM does not have transfer boundary conditions over the entire footprint area of the Condamine Alluvium. Approximately 10% of the footprint area of the CCAM has no-flow boundary conditions that prevent transfers, and therefore the values of change in net vertical flux in Figure 7-27 are around 10% smaller than the values in Figure 7-26.

More detailed summaries of the predicted volumes and maximum rates of net vertical flux at the base of the CCAM are given in the following sections.

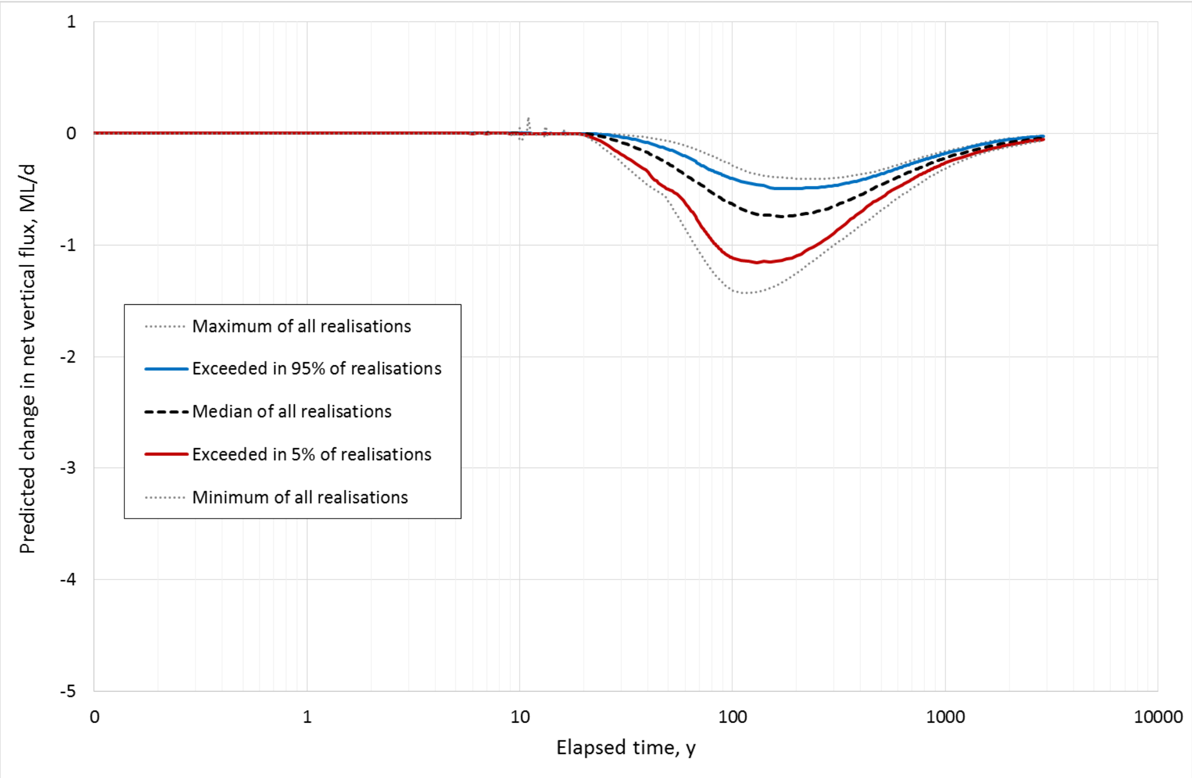


Figure 7-26 Predicted change in net vertical flux at the base of the Condamine Alluvium due to existing and proposed non-Arrow CSG development

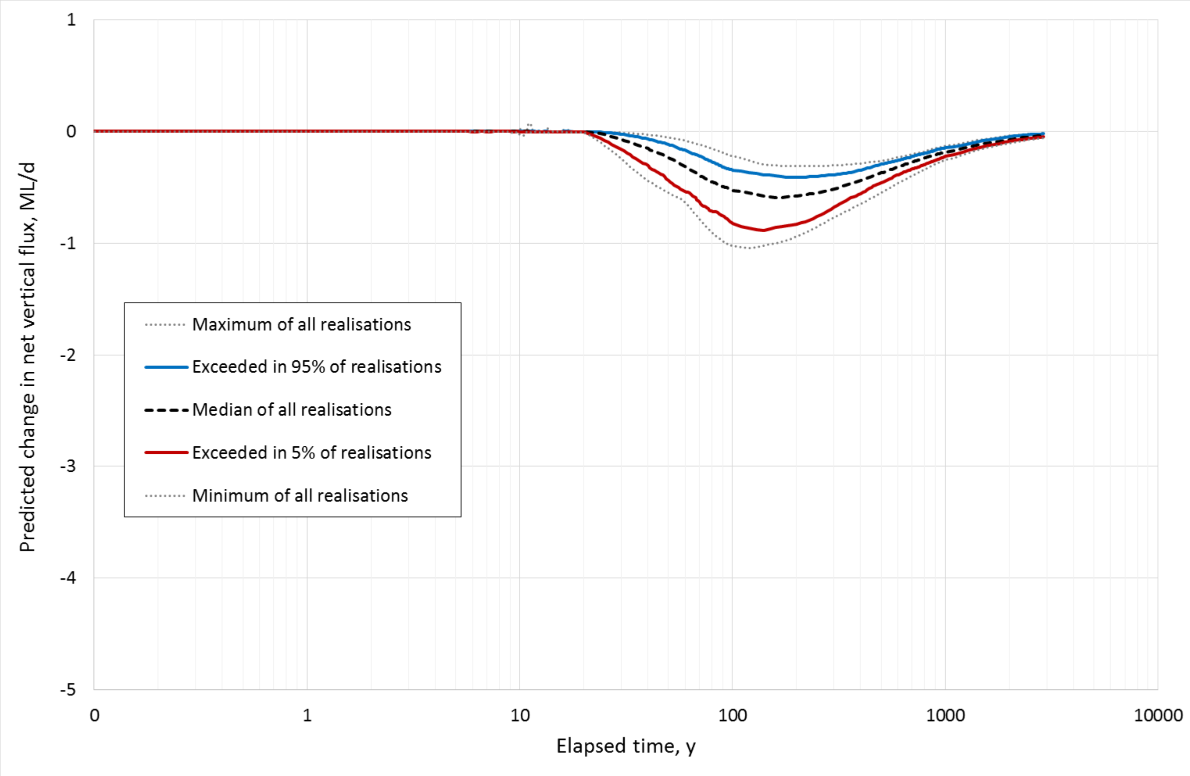


Figure 7-27 Predicted change in net vertical flux at the base of the CCAM due to existing and proposed non-Arrow CSG development

Condamine Alluvium footprint area

Table 7-18, Table 7-19, Figure 7-28 and Figure 7-29 summarise the predicted change in net vertical flux at the base of the Condamine Alluvium due to the simulated CSG water production by non-Arrow operators.

With respect to changes in net vertical flux volumes, 90% of realisations have predicted volumetric changes between 191 GL and 285 GL, with a median value of 232 GL and mean value of 234 GL. The mean volumetric change of 234 GL is 7% of the total volume of CSG water production for that realisation (r45) and approximately 44% of the mean value of predicted changes in net vertical flux volumes for existing and proposed CSG development including Arrow's activities.

With respect to the maximum changes in net vertical flux rate, 90% of realisations have predicted maximum changes in net vertical flux between 0.50 ML/d and 1.16 ML/d, with a median value of 0.75 ML/d and mean value of 0.80 ML/d. The mean maximum change in net vertical flux of 0.80 ML/d is equivalent to a single moderate-yielding groundwater bore pumping continuously at a rate of 9.3 L/s; noting that groundwater users in the Condamine Alluvium experience bore yields of between 2 and 60 L/s.

Table 7-18 Predicted change in net vertical flux volumes at the base of the Condamine Alluvium due to existing and proposed non-Arrow CSG development

Measure for 200 realisations	Change in net vertical flux volume		Realisation Number
	GL	Fraction of non-Arrow WP, %	
Maximum	346	11	154
Exceeded in 5 % of realisation	285	8	96
Mean	234	7	45
Median	232	7	145
Exceeded in 95% of realisation	191	6	126
Minimum	164	5	26

Table 7-19 Predicted maximum change in the rate of net vertical flux at the base of the Condamine Alluvium due to existing and proposed non-Arrow CSG development

Measure for 200 realisations	Maximum change in vertical flux rate, ML/d	Realisation number
Maximum	1.43	69
Exceeded in 5 % of realisation	1.16	146
Mean	0.80	168
Median	0.75	88
Exceeded in 95% of realisation	0.50	56
Minimum	0.41	58

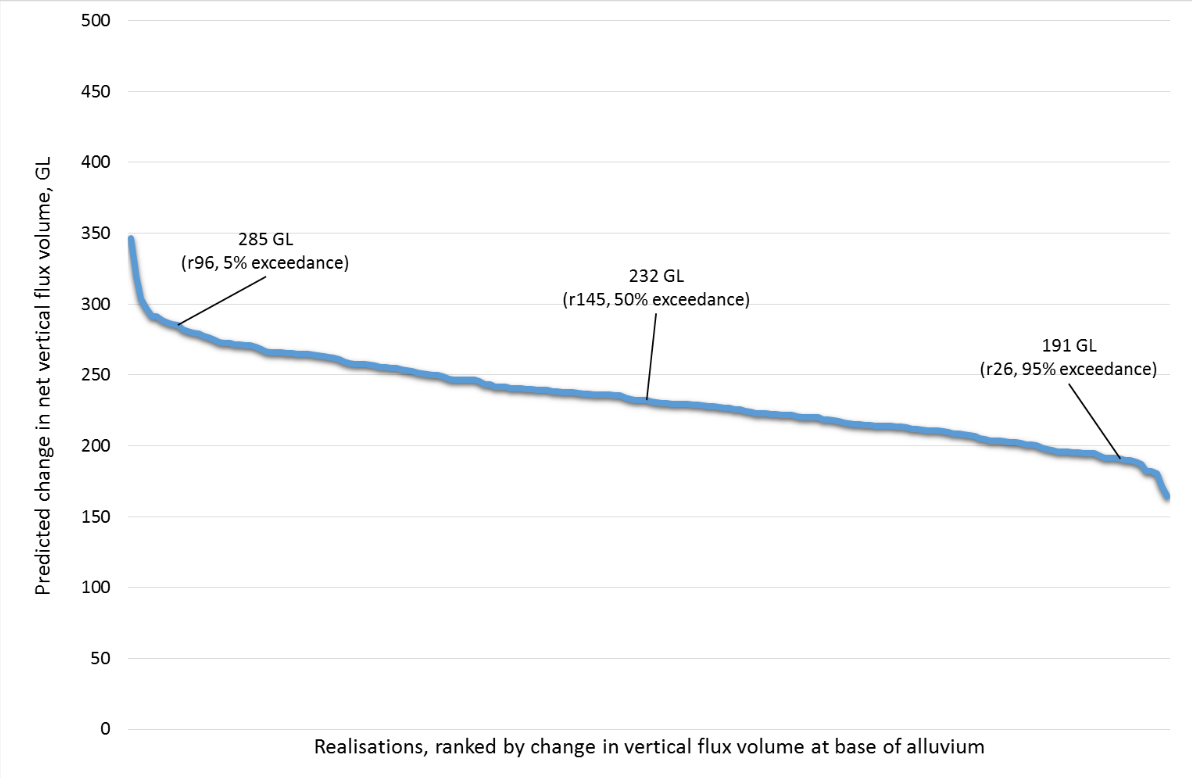


Figure 7-28 Predicted change in net vertical flux volumes at the base of Condamine Alluvium due to existing and proposed non-Arrow CSG development

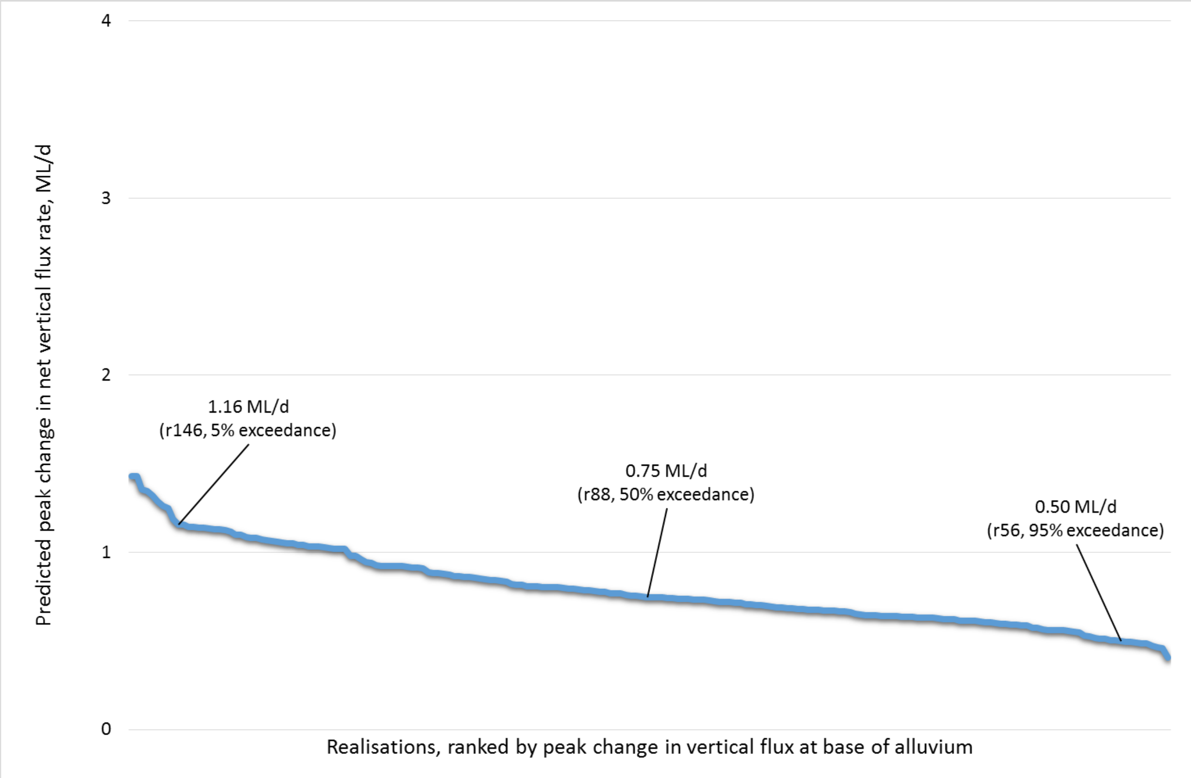


Figure 7-29 Predicted maximum change in the rate of net vertical flux at the base of the Condamine Alluvium due to existing and proposed non-Arrow CSG development

Central Condamine Alluvium Model (CCAM) area

Table 7-20, Table 7-21, Figure 7-30 and Figure 7-31 summarise the predicted change in net vertical flux at the base of the CCAM due to the simulated CSG water production by non-Arrow operators.

With respect to changes in net vertical flux volumes, 90% of realisations have predicted volumetric changes between 157 GL and 236 GL, with a median value of 185 GL and mean value of 188 GL. The mean volumetric change of 188 GL is 5% of the total volume of CSG water production for that realisation (r71) and approximately 42% of the mean value of predicted changes in net vertical flux volumes for existing and proposed CSG development including Arrow's activities (Table 7-16).

With respect to the maximum changes in net vertical flux rate, 90% of realisations have predicted maximum changes in net vertical flux between 0.42 ML/d and 0.89 ML/d, with a median value of 0.60 ML/d and mean value of 0.62 ML/d. The mean maximum change in net vertical flux of 0.62 ML/d is equivalent to a single moderate-yielding groundwater bore pumping at a rate of 7.2 L/s; noting that groundwater users in the Condamine Alluvium experience bore yields of between 2 and 60 L/s.

Table 7-20 Predicted change in net vertical flux volumes at the base of the CCAM due to existing and proposed non-Arrow CSG development

Measure for 200 realisations	Change in net vertical flux volume		Realisation Number
	GL	Fraction of total water production, %	
Maximum	272	8	154
Exceeded in 5 % of realisation	236	7	163
Mean	188	5	71
Median	185	5	95
Exceeded in 95% of realisation	157	5	126
Minimum	140	4	58

Table 7-21 Predicted maximum change in the rate of net vertical flux at the base of the CCAM due to existing and proposed non-Arrow CSG development

Measure for 200 realisations	Maximum change in vertical flux rate, ML/d	Realisation number
Maximum	1.04	8
Exceeded in 5 % of realisation	0.89	74
Mean	0.62	115
Median	0.60	145
Exceeded in 95% of realisation	0.42	56
Minimum	0.31	58

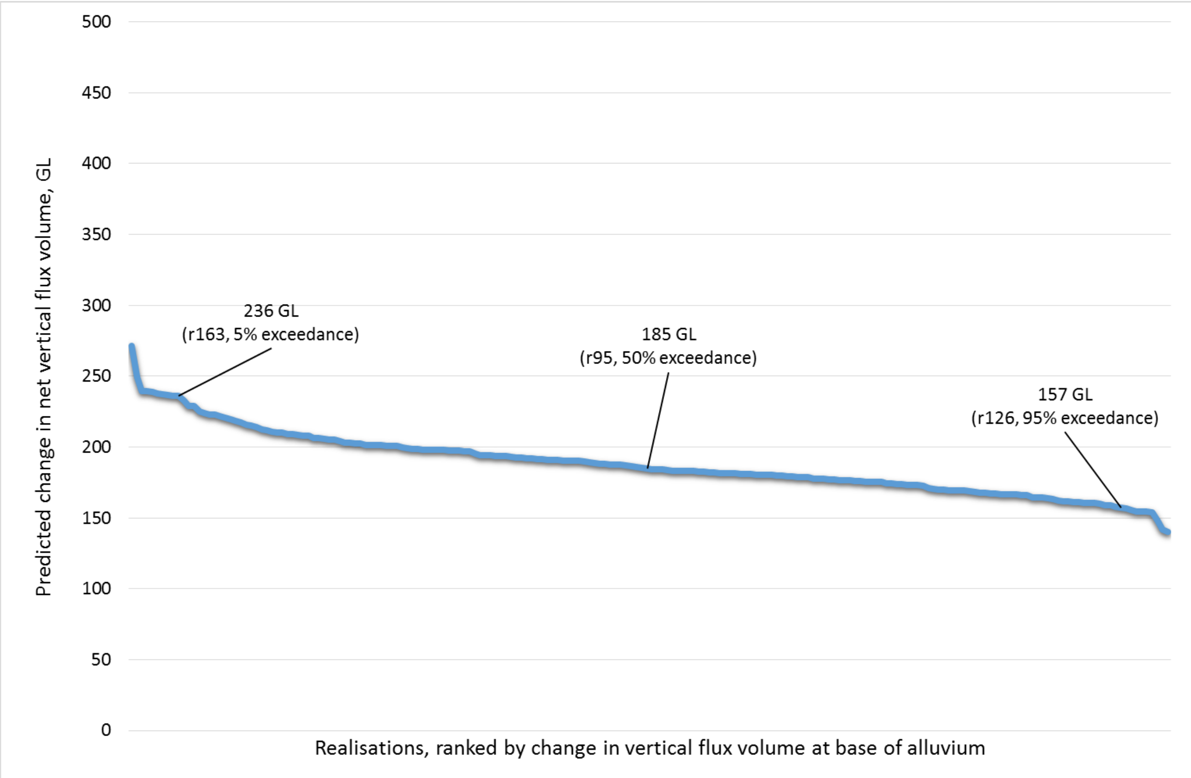


Figure 7-30 Predicted change in net vertical flux volumes at the base of the CCAM due to existing and proposed non-Arrow CSG development

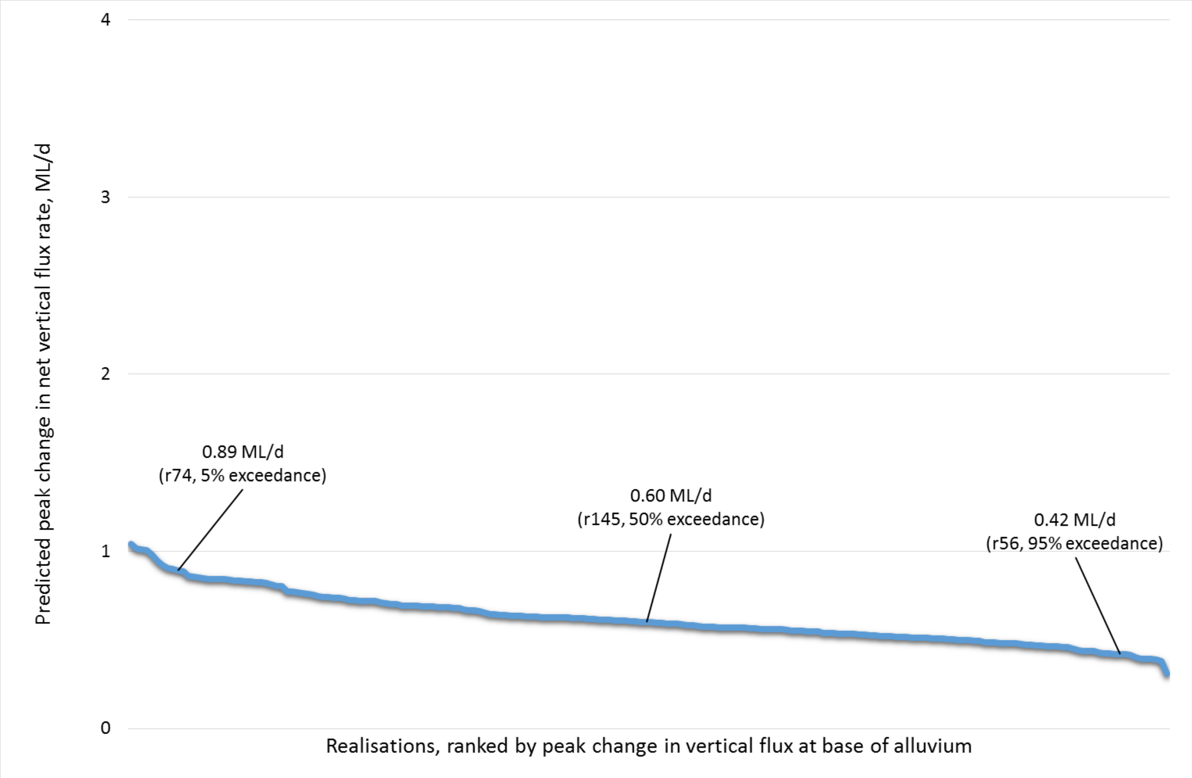


Figure 7-31 Predicted maximum change in the rate of net vertical flux at the base of the CCAM due to existing and proposed non-Arrow CSG development

7.4.7.5 Arrow contribution to predicted change in vertical flux at the base of Condamine Alluvium for existing and proposed CSG development

Results in this section are derived from results in the preceding sections for existing and proposed CSG development (MODEL_CSG simulations) and for existing and proposed non-Arrow CSG development (MODEL_XARROW simulations). Arrow's predicted contributions to change in net vertical flux at the base of the Condamine Alluvium are computed as the difference between the above two sets of simulations.

Figure 7-32 shows Arrow's contributions to predicted change in net vertical flux at the base of the Condamine Alluvium. The graph shows Arrow's contribution to reduction in groundwater flow from the Surat Basin to the Condamine Alluvium predicted by the Surat CMA groundwater model. The curves on each graph are the minimum and maximum change in net vertical flux for all realisations over time (grey dashed lines), the median change in net vertical flux for all realisations (black dashed line), and the changes in net vertical flux that are exceeded in 95% and 5% of realisations (blue and red solid lines).

Figure 7-33 is similar to Figure 7-32 but shows Arrow's contribution to predicted change in net vertical flux over the area of alluvium in the Central Condamine Alluvium Model (CCAM) where connection to underlying strata of the Surat Basin was simulated.

More detailed summaries of the predicted volumes and maximum rates of net vertical flux at the base of the CCAM are given in the following sections.

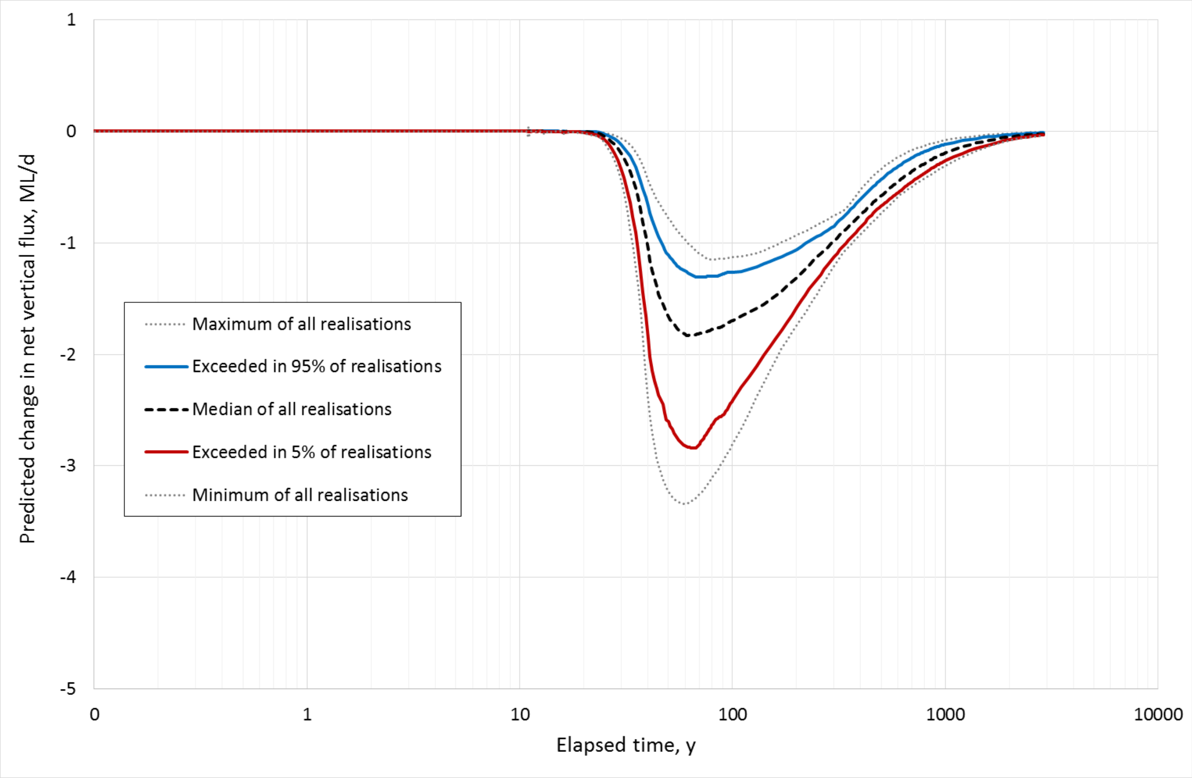


Figure 7-32 Arrow's contribution to predicted change in net vertical flux at the base of the Condamine Alluvium for existing and Proposed CSG development

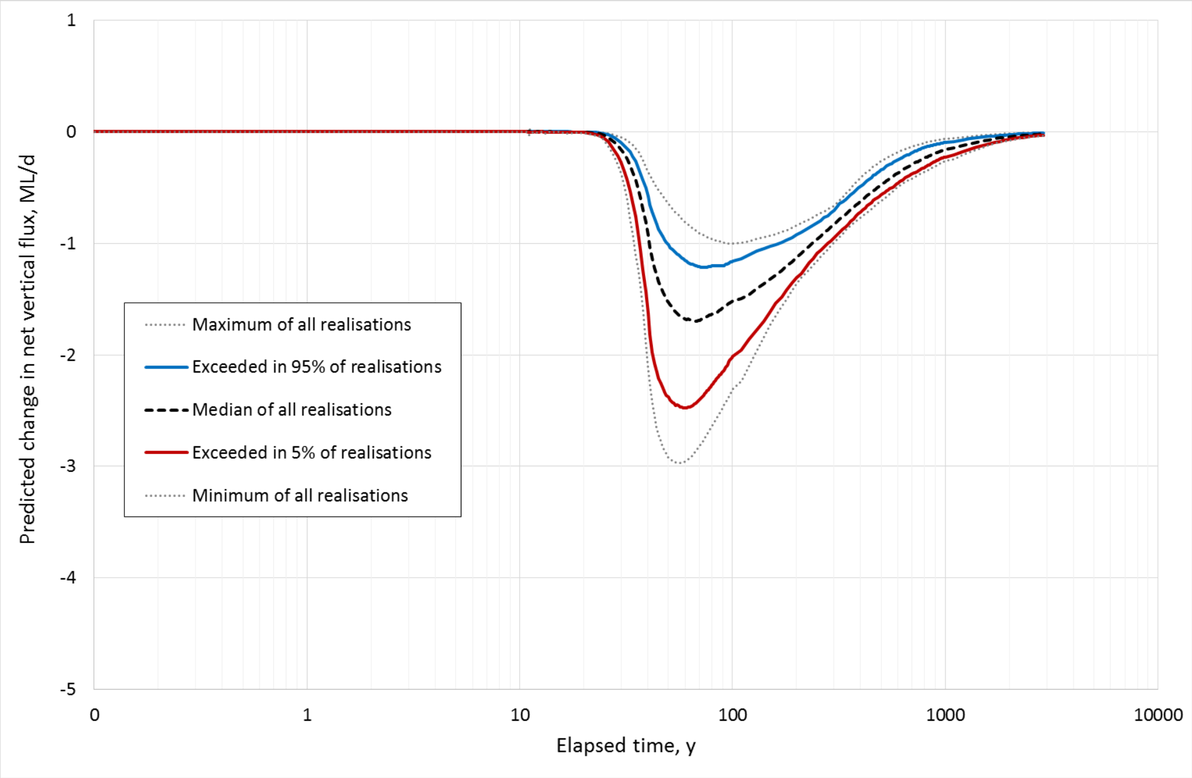


Figure 7-33 Arrow's contribution to predicted change in net vertical flux at the base of the CCAM for existing and Proposed CSG development

Condamine Alluvium footprint area

Table 7-22 and Figure 7-34 summarise Arrow's contributions to predicted change in net vertical flux at the base of the Condamine Alluvium. The results show that 90% of realisations have predicted volumetric changes between 264 GL and 341 GL, with a median value of 303 GL and mean value of 302 GL. The mean volumetric change of 302 GL is 41% of Arrow's predicted water production volume for that realisation (r73).

Table 7-22 Arrow's contribution to predicted change in net vertical flux volumes at the base of the Condamine Alluvium for existing and proposed CSG development

Measure for 200 realisations	Change in net vertical flux volume		Realisation Number
	GL	Fraction of Arrow's WP, %	
Maximum	359	47	69
Exceeded in 5 % of realisation	341	47	37
Mean	302	41	73
Median	303	43	63
Exceeded in 95% of realisation	264	37	103
Minimum	244	39	19

Central Condamine Alluvium Model (CCAM) area

Table 7-23 and Figure 7-35 summarise Arrow's contributions to predicted change in net vertical flux at the base of the CCAM. The results show that 90% of realisations have predicted volumetric changes between 216 GL and 292 GL, with a median value of 256 GL and mean value of 255 GL. The mean volumetric change of 255 GL is 37% of Arrow's predicted water production volume for that realisation (r175).

Table 7-23 Arrow's contribution to predicted change in net vertical flux volumes at the base of the CCAM for existing and proposed CSG development

Measure for 200 realisations	Change in net vertical flux volume		Realisation Number
	GL	Fraction of Arrow's WP, %	
Maximum	305	41	20
Exceeded in 5 % of realisation	292	41	23
Median	256	37	47
Mean	255	37	175
Exceeded in 95% of realisation	216	34	116
Minimum	195	31	19

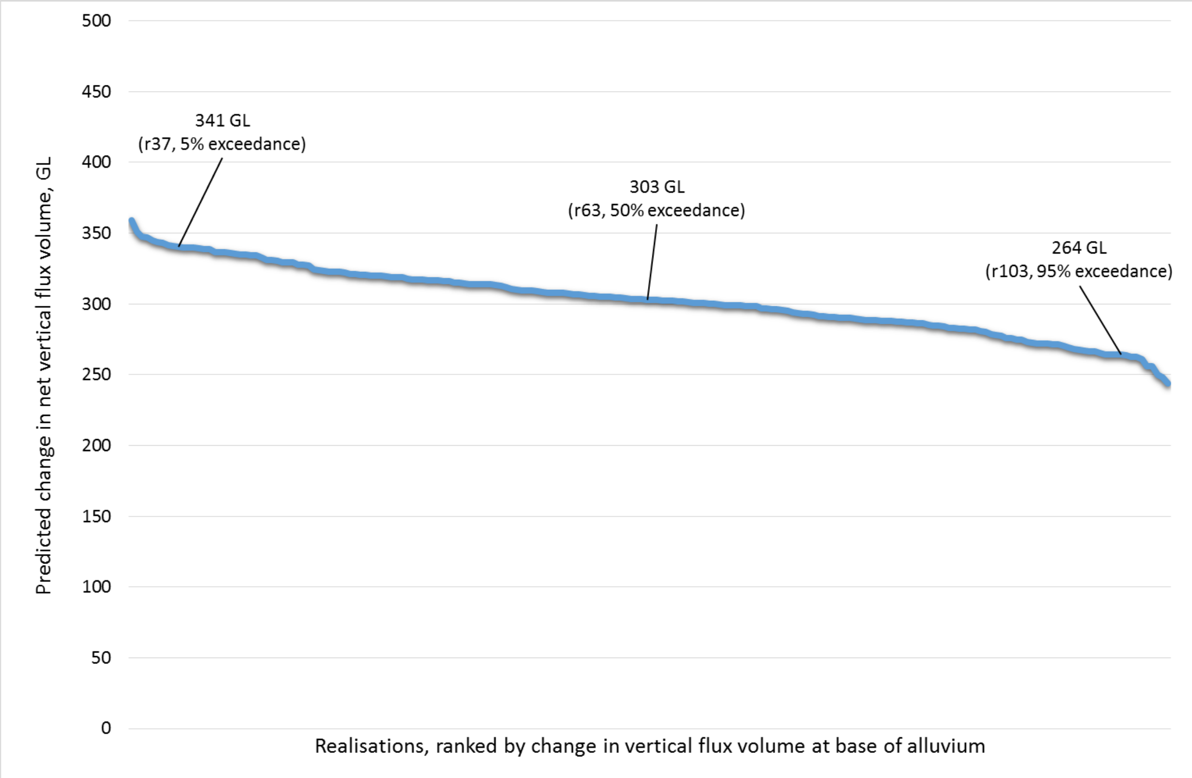


Figure 7-34 Arrow's contribution to predicted change in net vertical flux volumes at the base of Condamine Alluvium for existing and proposed CSG development

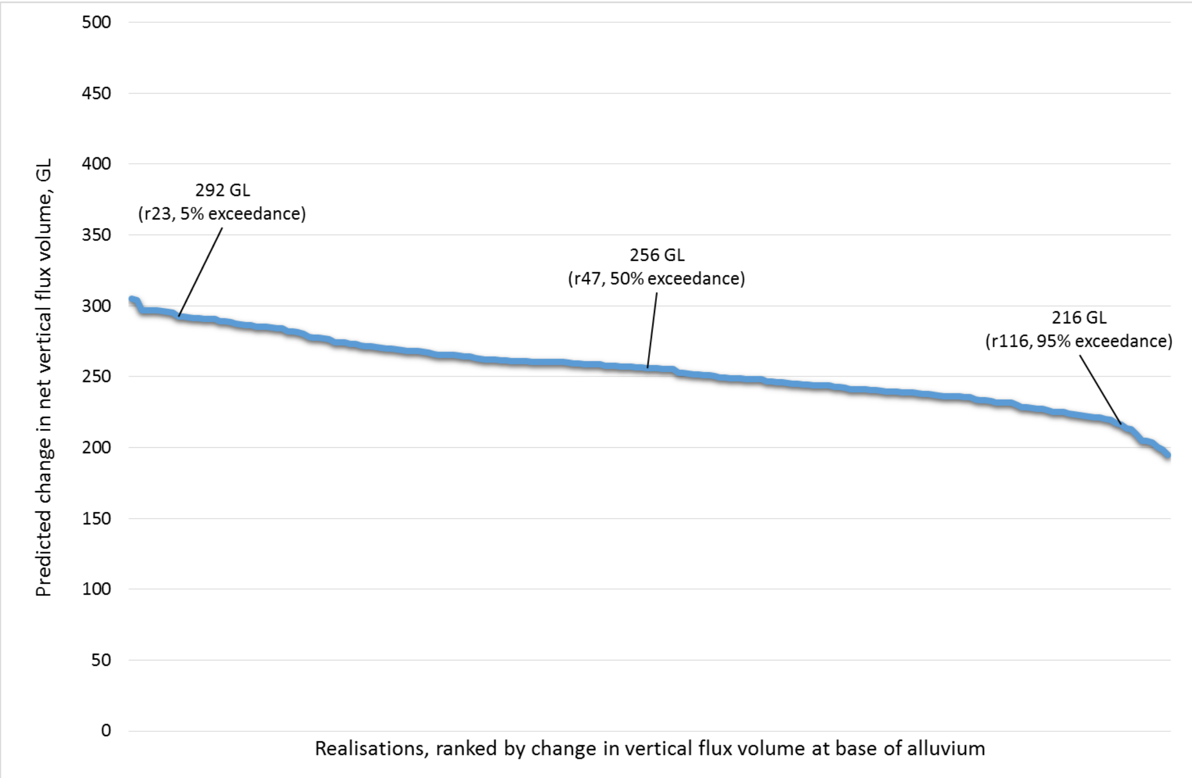


Figure 7-35 Arrow's contribution to predicted change in net vertical flux volumes at the base of CCAM for existing and proposed CSG development

7.5 Surface Water – Groundwater Interactions

7.5.1 Simulation of Losing Streams

Rivers and streams that have water level higher than water table elevation on both sides will lose or leak surface water to groundwater. They are classified as "losing" surface water bodies.

When the water table is not far below the surface water level, the rate of leakage is controlled largely by lateral flow, i.e. by the transmissivity of the aquifer nearby.

When the water table is far below, the rate of leakage is controlled more by vertical flow. In some circumstances, the rate of leakage can be close to the value of vertical hydraulic conductivity, because the vertical gradient in piezometric head is close to unity.

There are several mechanisms by which unsaturated conditions can develop beneath the bed of a river or stream. In these circumstances, rivers and streams can be classified as "losing disconnected", and the rate of leakage can reach a maximum value that is not exceeded is the water table falls further.

7.5.2 Modelling Methodologies

Nearly all modelling undertaken by consultants and Government agencies to simulate regional scale hydrological systems, and to assess the potential impacts of proposed projects, uses the same kind of approach for representation of rivers, streams, ponds and other surface water bodies. The approach relies on the use of a difference in heads (a driving force), a separation (in order to define a gradient) and a leakage coefficient or leakance based on hydraulic conductivity and a cross-sectional area through which flow occurs.

This approach has been popularised by the use of MODFLOW to simulate groundwater flow. The methodology is described by Anderson and Woessner (1992), which references descriptions by Townley & Wilson (1980, the user manual for AQUIFEM-1) of various methods for representing surface water bodies depending on their size relative to finite elements (or finite difference cells).

The general approach is to represent surface water – groundwater interaction using a mixed or third type boundary condition. With this type of boundary condition, neither the head in the aquifer nor the flux across the boundary is known, but rather an additional equation is added to allow both head and flux to be computed during the process of solving water balance equations in space and time.

This approach works best when a simple linear relationship is assumed, i.e. for connected rivers and streams. Losing disconnected rivers and streams add a degree of nonlinearity to the boundary condition, because when the water table drops below the base of a notional clogging layer, leakage no longer depends on water table elevation, but depends only on the thickness of the clogging layer, its hydraulic conductivity and the gradient across it. MODFLOW and AQUIFEM-1 (among other software) have always included the possibility that leakage flux reaches a maximum when head drops below the clogging layer at the bed of a stream. This capability is included in the MODFLOW's River package, which is used in the CCAM.

Recent work by Brunner et al. (2009a, b) has led to a perception that some new understanding has been gained about losing disconnected rivers and streams. The authors assert that disconnection can only occur if a clogging layer is present. This notion seems unintuitive, because many rivers and streams have gravel beds and appear not to have a layer of lower hydraulic conductivity at or near the bed. Brunner et al. (2011) soften their earlier assertion, by recognising that disconnection may also occur without the presence of a clogging layer.

CDM Smith has a clear understanding of the work by Brunner et al. In essence, if leakage is controlled by a clogging layer, Brunner et al. claim that the maximum leakage should be computed as follows:

- Leakage through the clogging layer is equal to the product of the saturated conductivity of the clogging layer and the hydraulic gradient through that layer.
- The hydraulic gradient is equal to the difference between the elevation of surface water and the head at the base of the clogging layer, divided by the thickness of the clogging layer.
- The head at the base of the clogging layer is equal to the elevation of the base of that layer plus the pressure head at that location, but since pressure at the saturation of the underlying (aquifer) material is negative relative to gauge pressure, the pressure head is less than zero, and head is lower than elevation. This is the change recommended by Brunner et al., because most previous work assumes that pressure is zero at the base of the clogging layer.
- The pressure head at the base of the clogging layer depends on soil matric potential, which in turn depends on moisture content or saturation, via a moisture retention curve $\psi(\theta)$.
- The moisture content at the base of the clogging layer is that value that causes vertical hydraulic conductivity Kv in the underlying material to be equal to the rate of leakage through the clogging layer.

This algorithm has not been implemented in recent modelling of regional systems, but is not believed to make a significant difference, because there are many other causes of uncertainty in regional scale modelling that are likely to dominate this effect.

MODFLOW's river package, as used in the CCAM, is currently best practice. MODFLOW's representation of leakage from losing disconnected streams is consistent with the discussion in Peterson and Wilson (1988), who also discuss leakage without a clogging layer.

CDM Smith has undertaken exploratory modelling of unsaturated flow using the properties of clayey soils found in the Condamine Alluvium. The results are presented in Appendix B.

7.6 Modelling Groundwater in the Condamine Alluvium

7.6.1 Overview of the CCAM

The Central Condamine Alluvium Model (CCAM) was developed originally by Klohn Crippen Berger (KCB 2011b) for the former Queensland Department of Environment and Resource Management, and is now managed by the Queensland Department of Natural Resources and Mines (DNRM). The CCAM was developed using MODFLOW-SURFACT (HydroGeoLogic 1998).

Associated reports for the CCAM include:

- "Central Condamine Alluvium Data Availability Review" (KCB 2010a);
- "Condamine Alluvium Stage II – Conceptual Hydrogeological Summary" (KCB 2010b);
- "Central Condamine Alluvium Stage III – Detailed Water Balance" (KCB 2011a); and
- "Central Condamine Alluvium Stage IV – Numerical Modelling" (KCB 2011b).

The geographic extent of the CCAM can be seen in Figure 7-2. The model domain covers an area of approximately 11,055 km^2 (55 × 201 km) inclusive of inactive model cells, and has an active area of approximately 5,468 km^2. The model's finite-difference grid has uniform row and column spacing of 500 m, consisting of 402 rows and 110 columns, and is divided into two layers that extend vertically from ground surface to the base of the alluvium.

The CCAM was calibrated over a 29.5-year period from 1 January 1980 to 1 July 2009 (KCB 2011b). Predictive simulations have been run in the past for a 118-year period from 1 July 2009 to 1 July 2127 (QWC 2012c).

7.6.2 Model Files

For this study, model files and datasets from the CCAM were provided by DSITIA (now DSITI) under agreement with Arrow. The modelling files consist of MODFLOW-SURFACT input files, which are listed in Appendix C along with their version dates.

7.6.3 Original Model Inputs and Settings

7.6.3.1 Geographic datum and coordinates

The geographic datum for the CCAM is the Geocentric Datum of Australia (GDA) 1994, and the model coordinate system is Map Grid of Australia (MGA) Zone 56. The rows and columns of the model grid are rotated 33 degrees anticlockwise from due north to align with the dominant orientation of the Condamine River valley. The lower left model cell (southwest corner of the model grid) is the local MODFLOW coordinate origin (0, 0), which corresponds to grid row 402 and grid column 1, with MGA easting 357,000 m and MGA northing 6,879,500 m.

7.6.3.2 Model layers

The model was constructed with two layers representing “sheetwash” and alluvium (Table 7-24).

Table 7-24 Central Condamine Alluvium Model layers

Model Layer	Hydrostratigraphic Unit
1	Sheetwash – wedge of typically finer grained sediments onlapping the Condamine Alluvium along its eastern edge
2	Alluvium

7.6.3.3 Stress periods

The CCAM used monthly stress periods of 30.4375 days (365.25 d/y ÷ 12 months/y). The calibration period consisted of 354 monthly stress periods of total duration 29.5 years. The predictive simulations consisted of 1,416 stress periods of total duration 118 years and made up of 4 cycles of 29.5-year calibration period (QWC 2012c).

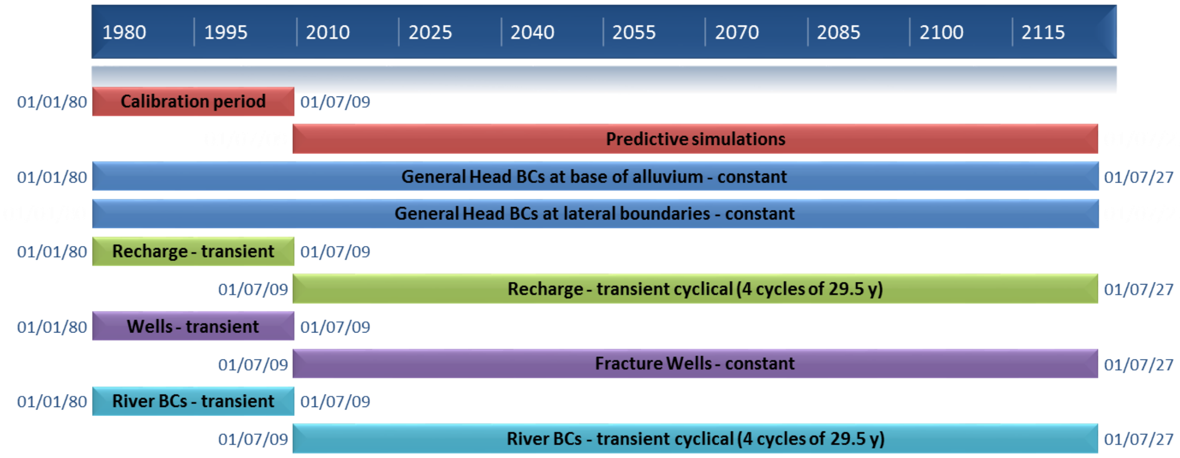


Figure 7-36 Transient and constant stresses of CCAM

7.6.3.4 Flow processes

Groundwater flow processes were simulated using the Block-Centered Flow (BCF4) package of MODFLOW-SURFACT. Both model layers were specified as unconfined. Variable saturation and drying and re-wetting of cells was simulated using the "pseudo-soil functions" of the BCF4 package.

7.6.3.5 Initial heads

It appears that the initial heads supplied with the CCAM are from the end of the calibration period (1 July 2009).

7.6.3.6 Groundwater recharge and discharge

Diffuse recharge

Groundwater recharge was continuously distributed in space and transient during the 29.5-year calibration period (354 stress periods). During predictive simulations the recharge pattern from the calibration period was repeated cyclically over a period of 118 years (4 cycles of 29.5 years each, specified by 1,416 stress period) (see Figure 7-36).

Evapotranspiration

The CCAM did not simulate evapotranspiration (KCB 2011b, p.40).

Groundwater bores

The CCAM was originally constructed with 749 groundwater bores with transient pumping rates over the calibration period. The average total extraction was estimated to be approximately 182,000 m^3/d (KBC 2011a, p.5). It is understood that the assigned pumping rates for unmetered groundwater usage were set equal to 100% of the allocation limits (KBC 2011b, p.18).

For predictive simulations, extraction from groundwater bores was represented using the Fracture Well (FWL) package of MODFLOW-SURFACT; total withdrawal at a well is adjusted dynamically during a simulation if the water level in the well reaches the elevation of the well bottom. Predictive simulations were specified with 605 fracture wells and constant rates of pumping that were set equal to 50% of the annual allocation limits in 2009 (QWC 2012c, p.23). The maximum potential rate of pumping from all fracture wells was 97,598 m^3/d, which was less than half the average total pumping rate during the calibration period, as given above.

7.6.3.7 Vertical flux at base of Condamine Alluvium

Vertical flux between the Condamine Alluvium and underlying strata of the Surat Basin was represented using General Head (GHB) boundary conditions within layer 2 of the CCAM. The external head values assigned in GHB cells (representing hydraulic head in the strata immediately underlying the alluvium) were continuously distributed in space and constant in time.

The conductance values in all GHB cells were assigned the value 0.005 m^2/d and the modelling report states that the values of external head in GHB cells were based on "Available head data from DERM GWDB for bores screened within WCM surrounding the CCRA; merged with earliest available head data for CCRA" (KCB 2011b, Table 3.1, p.14).

7.6.3.8 Surface water – groundwater interaction

The Condamine River and its northern anabranch were represented using the River (RIV) package of MODFLOW (KCB 2011b, p.15); no other tributaries or streams were simulated. All river cells were specified in layer 2 of the model, which represents the Condamine Alluvium. Model layer 1 represents sheetwash and pinches out to the east of the Condamine River, with the result that model cells in layer 1 can be dry in this region.

The bed elevations of river cells were derived from topographic analyses.

River stage values were transient, with the time series for the calibration period of 29.5 year (354 stress periods) repeated cyclically over 118 years for predictive simulations (4 cycles of 29.5 years each, specified by 1,416 monthly stress period) (see Figure 7-36).

River bed conductance values were varied by river reach with values ranging between 20 and 400 m^2/d.

7.6.3.9 Lateral model boundaries

Lateral groundwater flows across specified sections of the model boundary were represented using general head (GHB) boundary conditions (KCB 2011b, Table 3.1, p.14). The GHBs included subsurface flow from upstream alluvium of the Condamine River, subsurface flow from alluvial tributaries on the eastern side of the Condamine River, subsurface flow into the alluvium from basement rocks to the east, and subsurface outflow from the alluvium at Chinchilla Weir.

7.6.4 Predictive Simulations for this Study

This section describes the application of the CCAM to predict potential impacts of CSG development in the Surat Basin on the exchange of water to the Condamine Alluvium and subsequent interactions with the Condamine River. The preceding section (Section 2) contains an overview of the CCAM and its input requirements and outputs.

7.6.4.1 Methods

Modifications to the CCAM

The structure and parameterisation of the CCAM are unchanged for the predictive simulations in this study; however, a number of changes have been made to allow the predictive simulations to be conducted over a longer period of time than the model has previously been run. These changes were necessary to simulate the potential maximum impact (maximum impact over time) of CSG development on the Condamine River, which is expected to occur more than 500 years in the future.

The types of boundary conditions used to represent net vertical flux at the base of the Condamine Alluvium in the CCAM are also modified so that the changes in net vertical flux predicted using the Surat CMA groundwater model can be represented with the CCAM. These changes are described in more detail in the following sections.

Figure 7-37 shows the time periods spanning the CCAM calibration, the existing predictive simulations, and the extended predictive simulations in this study. Under the current scenario for CSG development in the Surat Basin, the Surat CMA groundwater model predicts that the maximum in water production will occur in around 2022, and the maximum change in net vertical flux at the base of the Condamine Alluvium will occur in around 2085 – approximately 63 years later. Based on these results from the Surat CMA groundwater model, the CCAM predicts that the maximum impact on the Condamine River from CSG development in the Surat Basin will occur approximately 468 years after the maximum in water production (these results are presented later in section 7.6.4.6).

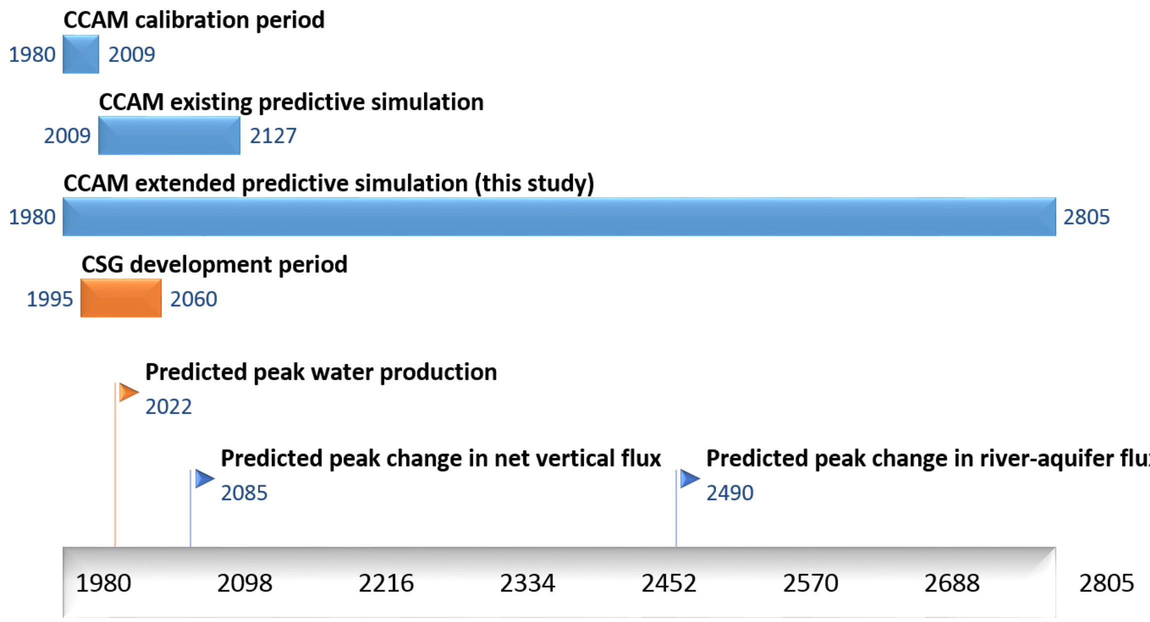


Figure 7-37 Modelling timeline

7.6.4.2 Simulations

The following simulations using the CCAM have been undertaken in this study:

- The CCAM has been run for a period of 826 years, from 1980 to 2805, using annual stress periods; this simulation is used to extract net vertical flux at the base of the Condamine Alluvium, which is represented using the original general head (GHB) boundary conditions;
- The CCAM has then been run again using pumping well (WEL) boundary conditions in place of the original GHB boundary conditions, with the well pumping rates set equal to the flux rates extracted from the GHB cells; this simulation checks that the fluxes are correctly extracted from the GHB model cells, are correctly transferred to their counterpart pumping well cells, and that the pumping wells correctly represent the rate of vertical flux at the base of the alluvium predicted by the CCAM;

- The CCAM has been run for the above-mentioned period of 826 years to predict the potential impacts of CSG development predicted by the Surat CMA groundwater model for three selected realisations; this is achieved by changing the flux rates at the pumping wells by the amount of change in net vertical flux predicted by the Surat CMA model from CSG water production;
  - For realisation r35 of the Surat CMA model – representing a high-case prediction of change in net vertical flux volumes at the base of the Condamine Alluvium (5% probability of exceedance in 200 realisations);
  - For realisation r27 of the Surat CMA model – representing the median case prediction of change in net vertical flux volumes at the base of the Condamine Alluvium (50% probability of exceedance in 200 realisations); and
  - For realisation r26 of the Surat CMA model – representing a low-case prediction of change in net vertical flux volumes at the base of the Condamine Alluvium (95% probability of exceedance in 200 realisations).
- For each of the above realisations the CCAM model is run twice to predict the potential impact of Arrow water production on the Condamine Alluvium, as follows;
  - With the predicted water production by all CSG operators – giving the predicted cumulative impact of all CSG operators on the Condamine Alluvium; and
  - With the predicted water production by all CSG operators other than Arrow – giving the predicted cumulative impact of all non-Arrow CSG operators on the Condamine Alluvium

The predicted impact of Arrow water production is calculated as the difference between the predicted impact of all CSG operators (including Arrow) and all non-Arrow CSG operators.

All results from the Surat CMA model have been obtained using the updated water production data for 2014 ("scenario_update_2014.evt"). The potential rates of evapotranspiration are time-varying over a period of 66 years, consisting of the historical period of water production from 1995 to 2013 (19 years) and the forecast period of water production from 2014 to 2060 (47 years).

7.6.4.3 Conversion from monthly to annual stress periods

The existing predictive simulations conducted using the CCAM had 1,416 monthly stress periods that consisted of 4 cycles of 29.5-year each, yielding a total simulation time of 118 years (section 7.6.3.3). For the current CSG development scenario, the Surat CMA groundwater model predicts that the maximum impact on net vertical flux at the base of the Condamine Alluvium will occur in around 2085. The maximum impact on the Condamine River due to this change in net vertical flux at the base of the alluvium will thus be later than 2085 and is unlikely to be reached within the 118-year timeframe of the existing CCAM predictive simulations.

To predict the maximum impact of CSG development on the Condamine River it is necessary to run the CCAM for more than 500 years. In this situation, monthly stress periods are unnecessary – because cyclical monthly variations are not relevant to the system's behaviour over hundreds of years – and from a practical point of view it is also preferable to use longer stress periods to help manage the size of model input and output files.

Within this context, the CCAM inputs have been modified as follows:

- Stress periods – 826 annual stress period are defined for the period spanning 1980 to 2805;

- Recharge – monthly values of groundwater recharge in each model cell have been aggregated to annual average values over 29.5 years, and a new recharge (RCH) file with annual stress periods has been produced for the period 1980 to 2805 using 28 cycles of 29.5 years each;
- Fracture wells – monthly extraction rates for 605 fracture wells (556 unique row and column locations) have been aggregated to annual extraction rates over 29.5 years, and a new fracture well (FWL) file with annual stress periods has been produced for the period 1980 to 2805 using 28 cycles of 29.5 years each; and
- River cells – monthly values of river stage, river bed elevation and river bed conductance for 565 unique row and column locations have been aggregated to annual average values over 29.5 years, and a new river (RIV) file with annual stress periods has been produced for the period 1980 to 2805 using 28 cycles of 29.5 years each.

The GHB boundary conditions that were not replaced by pumping wells (i.e., GHD cells representing lateral flows on the boundary of the CCAM) are constant in time and have not been modified. The CCAM does not use the evapotranspiration (EVT) package.

7.6.4.4 Representation of vertical flux at base of Condamine Alluvium

The method used to simulate change in net vertical flux at the base of the Condamine Alluvium due to the development of CSG resources in the Surat Basin is described above in section 7.6.4.2.

Further to that description, it is noted that:

- The footprint area of the Condamine Alluvium in the Surat CMA model is approximately 5,904 km^2, while the area of Condamine Alluvium in the CCAM is approximately 5,468 km^2, which is around 7% smaller;
- The area of connection between the Condamine Alluvium and Surat Basin in the CCAM (as represented by GHB boundary conditions) is approximately 5,321 km^2, which is approximately 10% smaller than the area of Condamine Alluvium in the Surat CMA groundwater model;
- Changes in net vertical flux predicted by the Surat CMA groundwater model are only passed to the CCAM at locations where Condamine Alluvium is present in both models and the CCAM was assigned GHD boundary conditions to represent groundwater exchange with the Surat Basin; and
- Changes in net vertical flux predicted over the entire footprint area of Condamine Alluvium in the Surat CMA groundwater model and over the area of connection represented in the CCAM are presented in Sections 7.4.7.3 to 7.4.7.5 above.

7.6.4.5 Time stepping

The extended predictive simulation conducted in this study use the Adaptive Time stepping and Output (ATO) control package of MODFLOW-SURFACT, with the following settings for each stress period: initial time step size of 5 d; minimum time step size of 1 d; maximum time step size of 10 d; time step multiplier of 1.2; and reduction factor for time step size of 1.2. These settings resulted in 38 time steps per year.

7.6.4.6 River locations in the CCAM where impacts from CSG development are possible

The CCAM can predict impacts on the Condamine River only at locations where the river is represented by a river boundary condition (i.e. at river cells) and only in those river cells where the assigned value of the river bed elevation is below the simulated elevation of the water table.

When the above situation occurs, the MODFLOW River package considers the river and aquifer to be 'connected' and computes a rate of flux between the alluvium and the river that is based on the difference in elevation between the river level and water table. Activities that may potentially change the water table elevation also have a potential to change the rate at which groundwater is exchanged between the alluvium and river at these locations. The direction of flow between the alluvium and river in these river cells is controlled by the relative elevations of the river level and water table, with the flow occurring in the direction from highest to lowest elevation. The direction of flow can change dynamically during a simulation in response to changes in the assigned river level and computed water table elevation; thus, the river can sometimes gain groundwater from the alluvium (gaining condition) and sometimes lose water to the alluvium (losing condition).

A different situation exists at river cells where the assigned elevation of the river bed is above the simulated elevation of the water table (i.e., at locations where there is a zone of unsaturated soil between the river bed and underlying water table). When these conditions occur, the MODFLOW River package considers the river and aquifer to be 'disconnected' and computes a rate of flux from the river to groundwater that is based only on the depth of river water above the river bed and the value assigned to the river-bed conductance. The computed rate of flow between the river and alluvium is independent of the simulated water table elevation, and it follows that activities with potential to change the elevation of the water table do not affect the rate at which groundwater is exchanged at these locations.

The above discussion can be summarised as follows:

- There is potential for the CCAM to predict an impact on the Condamine River at locations where the river cells are 'connected', meaning that the assigned values of the river bed elevation are below the simulated water table elevation; and
- There is no potential for the CCAM to predict an impact on the Condamine River at locations where the river cells are 'disconnected', meaning that the assigned values of the river bed elevation are above the simulated water table elevation.

Figure 7-38 shows the depth of the water table below the assigned values of river bed elevation in river cells of the CCAM. Negative values of depth (blue tones in the legend) signify that the water table is above the river bed, and the river cells are 'connected'. Positive values of depth (red tones) signify that the water table elevation is below the river bed, and the river cells are 'disconnected' and losing. From visual inspection of this Figure, it is clear that the majority of the Condamine River is represented by a 'disconnected' losing condition in the CCAM. There are only three relatively small areas (northwest, central and southeast) where the river is 'connected' and where potential drawdown of the water table would cause an impact on the river. Over the simulation period, the transient recharge and river boundary conditions (the cycle of 29.5 years repeated) can potentially influence and slightly change the connection between the river and the water table shown in Figure 7-38. The implications of disconnection and the influence on the predicted impacts are discussed in the following sections.

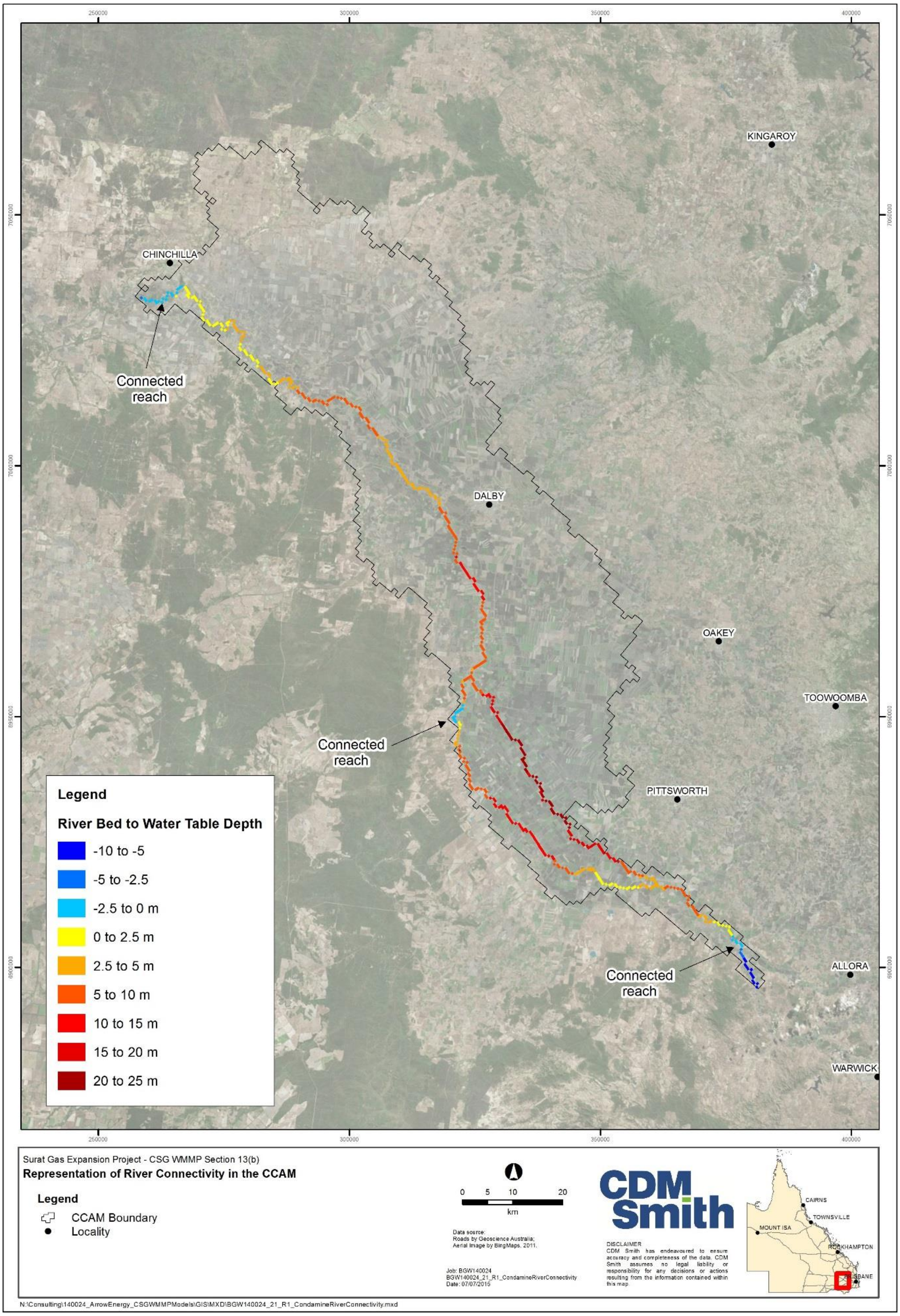


Figure 7-38 Representation of river connectivity in the CCAM

7.6.5 Results

The Surat CMA groundwater model predicts that impacts on the Condamine Alluvium from the development of CSG resources in the Surat Basin will occur over a period of more than 3,000 years. The maximum impacts are predicted to occur within the first 1,000 years.

Results presented in this section have been generated for a simulation period spanning 826 years from 1980 to 2805 (consisting of 28 cycles of 29.5 years each). The maximum potential impact on the Condamine Alluvium caused by Arrow alone is predicted to occur during this period. Around 70% of the total volumetric change in net vertical flux at the base of the Condamine Alluvium is predicted to occur slowly during the simulation period, while the remaining 30% occurs even more slowly over the subsequent 2,174 years or more.

7.6.5.1 Baseline water balance without CSG development

Water balance components for the CCAM simulation with no CSG development are presented in Table 7-25. Rates "IN" and "OUT" of the system provide the baseline against which to calculate the changes induced by CSG development.

The main outflow component is groundwater extraction, which is approximately 96% of the total outflow. Recharge and inflow from river cells account for 82.7% of the total inflow volume, and leakage at the base of the Condamine Alluvium accounts for approximately 9.4% of the total inflow volume.

Table 7-25 CCAM "baseline" cumulative water balance to 2805 (after 826 years)

Flow component	IN		OUT	
	Maximum rate (ML/d)	Total volume in year 2805 (GL)	Maximum rate (ML/d)	Total volume in year 2805 (GL)
Recharge	72.0	8,506	0.0	0
River cells	62.5	9,731	5.0	901
Leakage from adjacent aquifers (lateral) (GHB)	6.2	1,730	0.2	70
Leakage from adjacent aquifer at the base of Condamine (well)	7.9	2,066	0.3	74
Groundwater extraction (fracture wells)	0.0	1	97.2	26,564

7.6.5.2 Predicted impacts of Arrow CSG development on flux rates in the Condamine Alluvium

Table 7-26 shows predicted maximum changes (reductions) in the components of flow in the CCAM for the period of 811 years after the start of CSG development due to Arrow's water production. Arrow's contribution to the total water production is calculated as the difference between water production by all CSG operators (including Arrow) and water production by all non-Arrow CSG operators.

An assumption in the presentation of these results is that the stakeholders and community are foremost concerned with the potential cumulative impacts of CSG development in the Surat Basin on groundwater in the Condamine Alluvium, and within that context, Arrow's contributions to those impacts. Thus, the high median and low cases for predicted total water production are considered in Table 7-26. An alternative approach would be to rank Arrow water production for the two-hundred realisations and identify the low, median and high case predictions; however, it is felt that this approach lacks context within the ranking and analysis of cumulative impacts.

The maximum rate of Arrow water production in the Surat CMA groundwater model occurs around the same time (between year 2023 and 2024) for the high, median and low case realisations. Depressurisation in the target coal seams takes time to propagate through the strata of the Surat Basin to the base of the Condamine Alluvium. The simulated maximum change in net (vertical) flux at the base of the alluvium (a reduction in flow to the Condamine Alluvium) occurs 29 to 45 years after the maximum in Arrow water production, which is between year 2052 and 2069 depending on the realisation.

The predicted maximum change in flux at the base of the Condamine Alluvium due to Arrow water production is greater for the median case than the high case, i.e. 2.67 ML/d compared to 2.11 ML/d, even though the corresponding maximum in water production is smaller (for both Arrow and non-Arrow CSG development). This is caused by the distribution and magnitudes of hydraulic conductivities in this realisation, creating stronger connections between the Surat Basin and the Condamine Alluvium in the area of Arrow's CSG activities. The three realisations presented in this section were ranked based on the total impact from all existing and proposed CSG water extraction on the Condamine Alluvium, not only Arrow.

The maximum rate of change (reduction) in storage in the Condamine Alluvium occurs before or just after the maximum change in net vertical flux at the base of the alluvium. Other sources of water also partially counterbalance the indirect draw on alluvial groundwater from CSG water production (e.g. head-dependent changes in lateral inflow to the alluvium through GHB boundaries, and head-dependent changes in groundwater extraction from fracture wells).

At the Condamine River, the maximum rate of change (reduction) in groundwater flux from the Condamine Alluvium to the Condamine River due to Arrow water production is predicted to occur between years 2137 and 2146 for the high, median and low case realisations, 113 to 123 years after the maximum in simulated water production. Predicted impacts on the Condamine River are discussed in more detail in Section 7.6.5.5.

Table 7-26 Predicted maximum changes in groundwater fluxes due to Arrow CSG development

Flow component	Surat CMA Groundwater Model realisation					
	r35 (high case)		r27 (median case)		r26 (low case)	
	ML/d	Year	ML/d	Year	ML/d	Year
Maximum rate of Arrow water production	138	2023	128	2023	123	2024
Maximum reduction in rate of net flux at base of Condamine Alluvium from Walloon Coal Measures and other HSUs to the Condamine Alluvium due to Arrow water production	2.11	2054	2.67	2052	1.34	2069
Maximum reduction in groundwater storage in Condamine Alluvium due to Arrow water production	2.04	2049	2.12	2057	1.32	2063
Maximum reduction in net groundwater flux from Condamine Alluvium to the Condamine River due to Arrow water production	0.12	2146	0.13	2146	0.09	2137

Figure 7-39 shows the distributions of maximum change in flux across the base of the Condamine Alluvium due to Arrow water production for the high, median and low cases realisations (from existing and proposed CSG development). Differences in the maximum responses are caused by the differences in the magnitudes and distributions of hydrogeological properties in different realisations. More generally, the patterns of maximum change in flux are similar, with larger impacts observed in the northwest and central parts of the Condamine Alluvium (darker blue).

Note the grey area along the western edge of the Condamine Alluvium where there is no general head boundary (GHB) condition to allow leakage from or to the underlying aquifers. This means that the Condamine Alluvium is not connected to the underlying Surat Basin in this area of the model.

The distribution of maximum change in flux across the base of the Condamine Alluvium due to Arrow water production at all times and for all realisations is shown in Figure 7-40. The Figure also shows the corresponding time of maximum change in vertical flux and the associated realisation number. A total of 138 realisations have, at some point, predicted the maximum change in flux due to CSG activities in a given cell. The Figure displays the worst impact in terms of maximum change in groundwater flux at every cells but doesn't represent an actual modelling result that is physically possible and reproducible.

Comparison of the legends in Figure 7-40 with Figure 7-39 shows that the maximum change in vertical flux over all realisations and all times is as high as 13.14 mm/y. This is about three times larger than the maximum flux in the three realisations of interest (the high, median and low cases), where the maximum change in vertical flux is as high as 4.6 mm/y. This is not surprising. Even the high case (realisation r35, having a 5% probability of exceedance of total change in volume of vertical flux, as explained in Section 7.6.4.2) can have values exceeded in individual cells, and the ranking on which r35 was chosen is based on volumes not rates of flux. Interpretation of the results of NSMC simulations requires care.

Figure 7-41, Figure 7-42 and Figure 7-43 show the global water balance response in the Condamine Alluvium over time due to the simulated Arrow water production. Initially, all of the additional draw at the base of the alluvium is taken directly from groundwater storage. Over time, as depressurisation at the base of the alluvium propagates into other areas, other sources of water contribute additional inflow and the rate of storage decline in the alluvium slows. The counterbalancing changes in fluxes include: river cells, representing slightly increased recharge from the Condamine River; pumping wells (represented as so-called "fracture wells" in MODFLOW-SURFACT) representing less extraction from the alluvium; and general head boundaries, representing increased lateral inflow from areas outside of the alluvium. These changes in fluxes are small and occur very slowly.

After the year 2400 the rate of change in storage becomes negative and the alluvium begins to gain storage and recover. By the end of the simulation in year 2806 the alluvium has not fully recovered but the maximum changes in the other components of the water balance have been reached, including exchange between the river and alluvium. The Surat CMA groundwater model predicts that impacts on the Condamine Alluvium from the development of CSG will occur over a period of more than 3,000 years. The CCAM would need to be run for longer than 3,000 years to see full recovery of storage in the Condamine Alluvium.

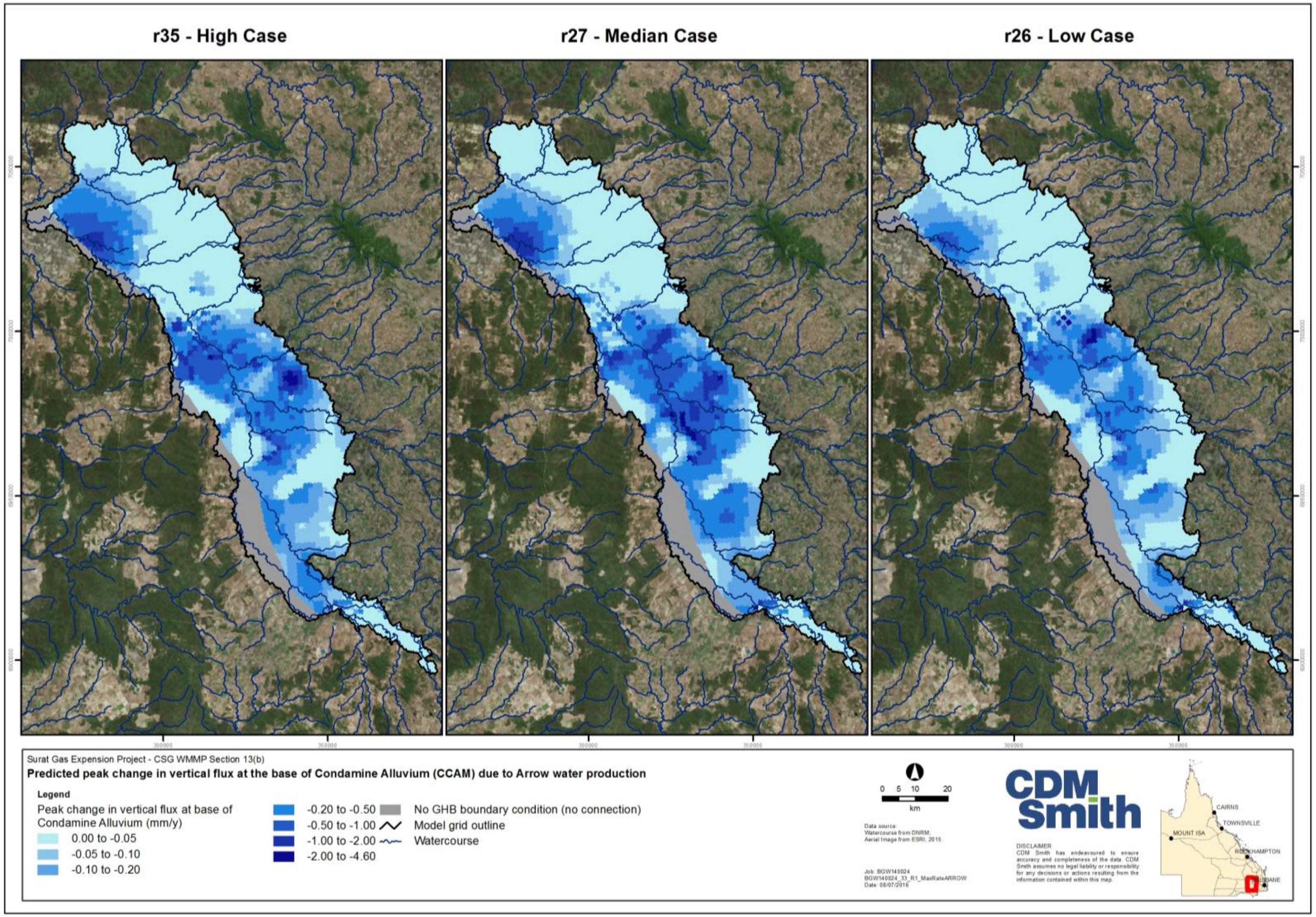


Figure 7-39 Predicted distribution of maximum change in flux at the base of the Condamine Alluvium due to Arrow water production during the simulation period

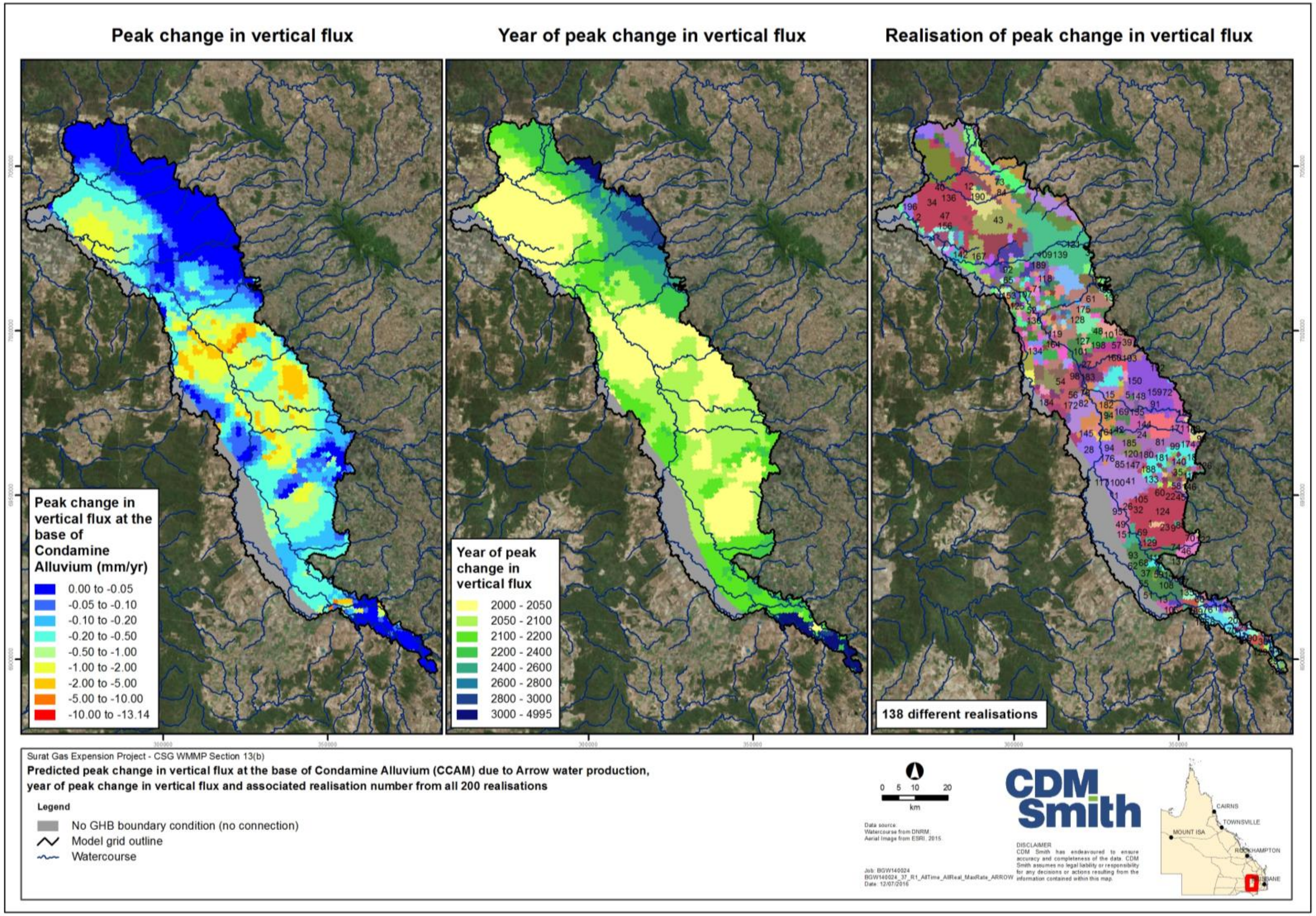


Figure 7-40 Predicted distribution of maximum change in flux at the base of the Condamine Alluvium due to Arrow water production from all 200 realisations

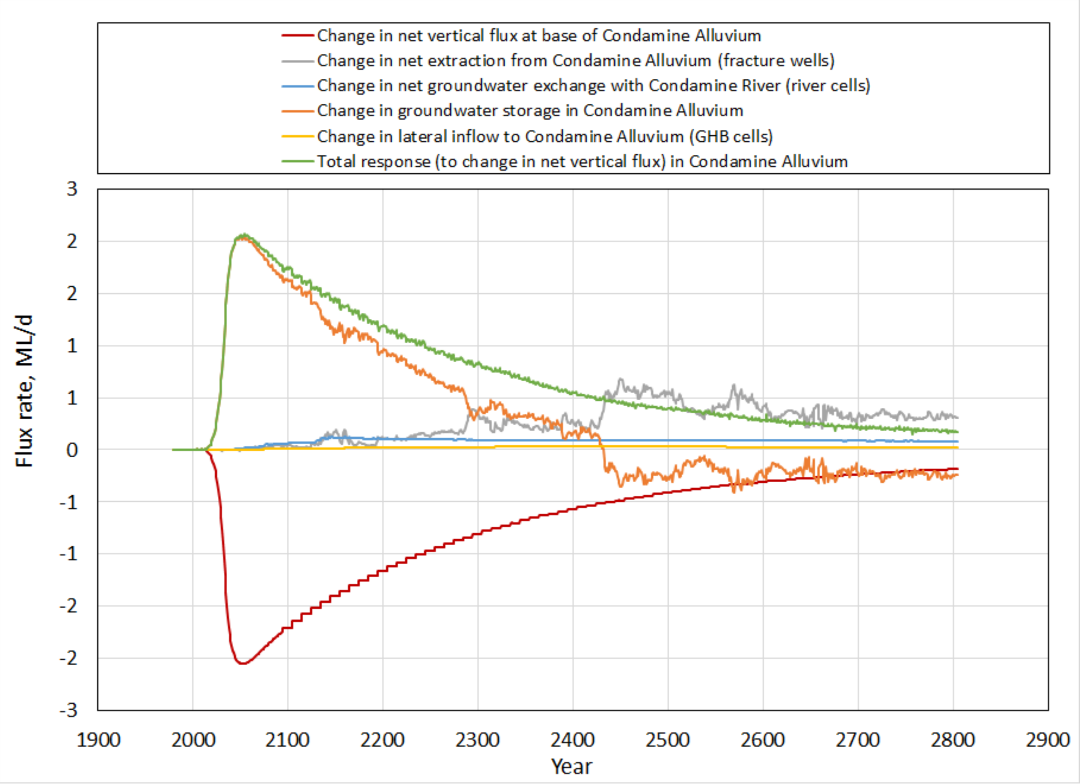


Figure 7-41 Predicted change in groundwater fluxes due to Arrow water production for realisation r35 (high case)

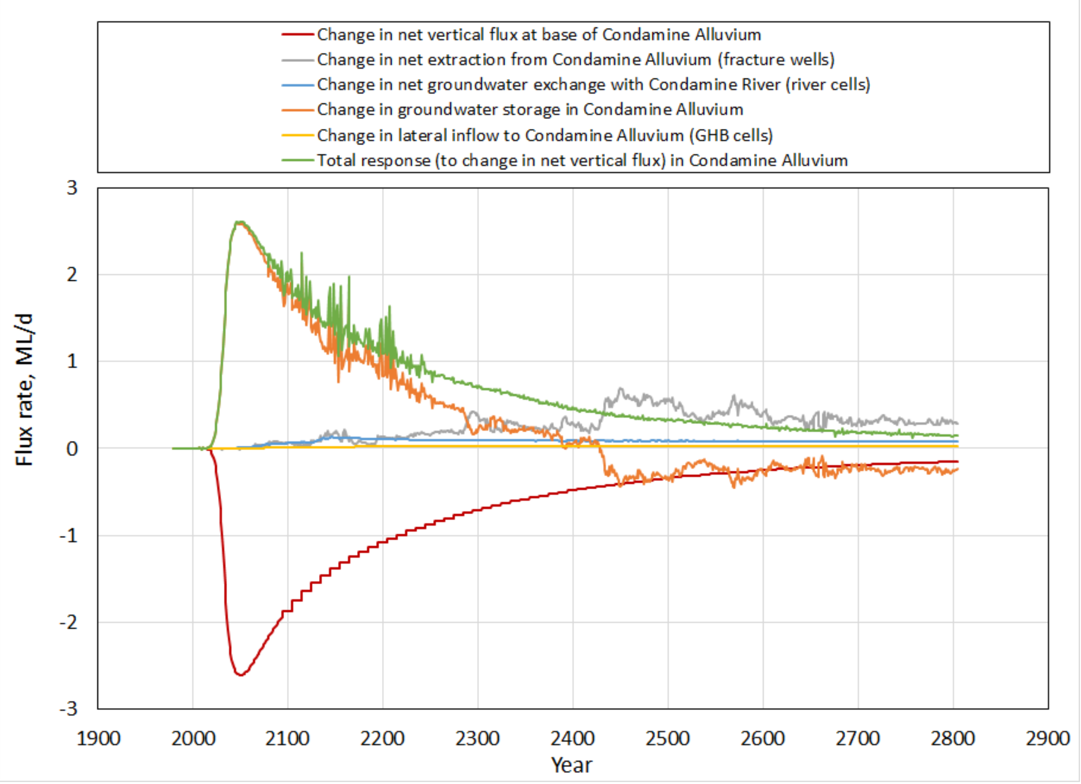


Figure 7-42 Predicted change in groundwater fluxes due to Arrow water production for realisation r27 (median case)

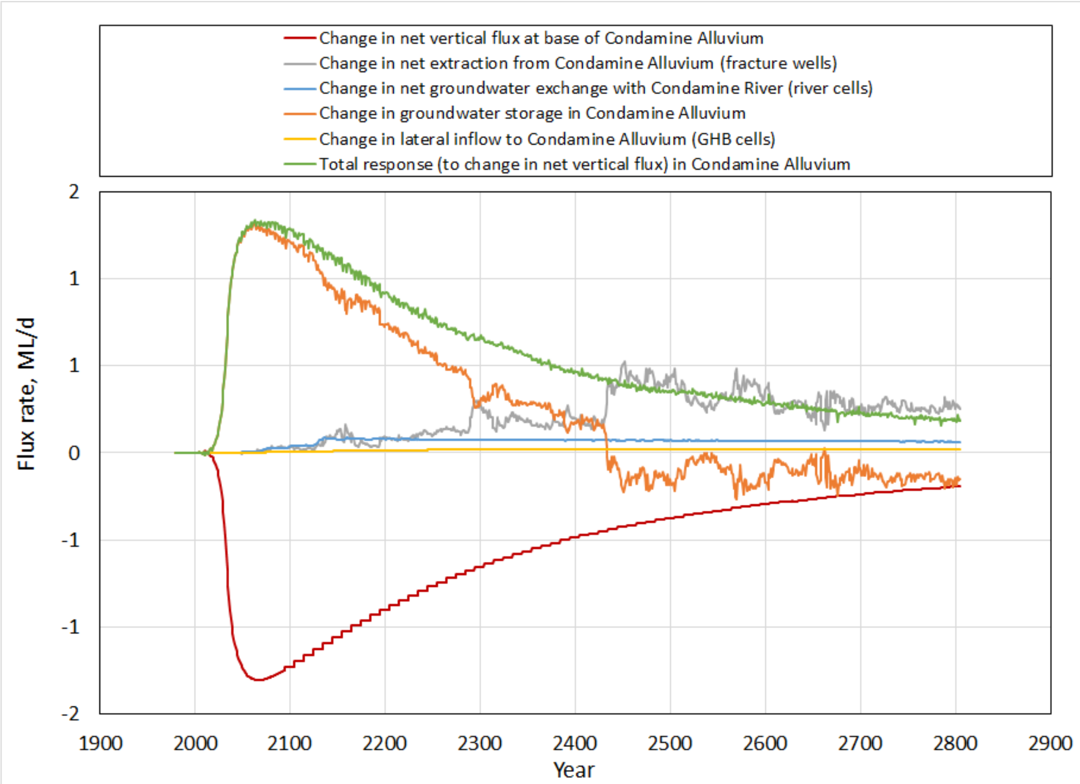


Figure 7-43 Predicted change in groundwater fluxes due to Arrow water production for realisation r26 (low case)

7.6.5.3 Predicted impacts of CSG development on flow volumes in the Condamine Alluvium

The CCAM is run until the year 2805 (811 years after the start of CSG water production and 826 years in total) but at the end of the simulation the system has not fully recovered. Table 7-27 summarises the predicted changes in volumetric fluxes at the end of the simulation in year 2805 due to Arrow water production. The results are also shown on Sankey diagrams in Figure 7-44, Figure 7-45 and Figure 7-46; the Sankey diagrams show the predicted water balance components using arrow sizes that are proportional to Arrow water production volumes.

Between 25.1% (164 GL) and 29.1% (208 GL) of simulated Arrow water production is predicted to be drawn from the Condamine Alluvium up to year 2805 for the high, median and low case realisations; thus, the majority of water production is predicted to be drawn in the long-term from the Surat Basin. The changes in net flux at the base of the Condamine Alluvium are predicted to be 8% to 10% relative to the baseline flux without CSG development (refer Table 7-25).

Groundwater discharge to the Condamine River is predicted to decrease by 18.6 GL to 24.4 GL over the simulation period of 826 years. These decreases account for up to 5.2% of Arrow CSG water production volume (between 3.8% and 5.2%).

Figure 7-47 shows the distribution of total change in volumes passing across the base of the Condamine Alluvium for the high, median and low case realisations. The slight differences in the response between realisations are attributable to the different distributions of hydrogeological properties. Model cells shown in tan (colour) have extremely small positive values but are effectively zero.

The distribution of total change in volumes across the base of the Condamine Alluvium due to Arrow water production at all times and for all realisations is shown in Figure 7-48. The Figure also shows the associated realisation number. A total of 164 realisations out of 200 exhibit, at some point in time, the maximum change in groundwater volume due to CSG activities in one or more cells. The Figure shows the greatest impact in terms of maximum change in groundwater volume in every cell but does not represent an actual modelling result that is physically possible; the Figure combines results from 200 realisations.

Table 7-27 Predicted volumetric contributions to Arrow water production in year 2805

Predicted volumes in year 2805, GL	Surat CMA Groundwater Model realisation		
	r35 (high case)	r27 (median case)	R26 (low case)
Total water production	4,023	3,896	3,902
Non-Arrow water production	3,308 (82.2%)	3,234 (83.0%)	3,248 (83.2%)
Arrow water production	715 (17.8%)	662 (17.0%)	654 (16.8%)
Component of Arrow water production derived from the Surat Basin	507 (70.9)	459 (69.3%)	490 (74.9%)
Component of Arrow water production derived from Condamine Alluvium	208 (29.1%)	203 (30.7%)	164 (25.1%)
Component of Arrow water production derived from change in groundwater storage in Condamine Alluvium	100 (14.0%)	97.6 (14.7%)	81.5 (12.5%)
Component of Arrow water production derived from reduced groundwater extraction from Condamine Alluvium (fracture wells)	75.5 (10.6%)	77.3 (11.7%)	58.7 (9.0%)
Component of Arrow water production derived from reduced groundwater discharge to Condamine River (river cells)	24.4 (3.4%)	23.9 (3.6%)	18.6 (2.8%)
Component of Arrow water production derived from increased lateral groundwater inflow to Condamine Alluvium (GHB cells)	6.6 (0.9%)	6.8 (1.0%)	4.9 (0.8%)
Unaccounted for components of Arrow water production due to water balance discrepancy of CCAM[1]	1.5 (0.2%)	-2.6 (-0.4%)	0.3 (0.0%)

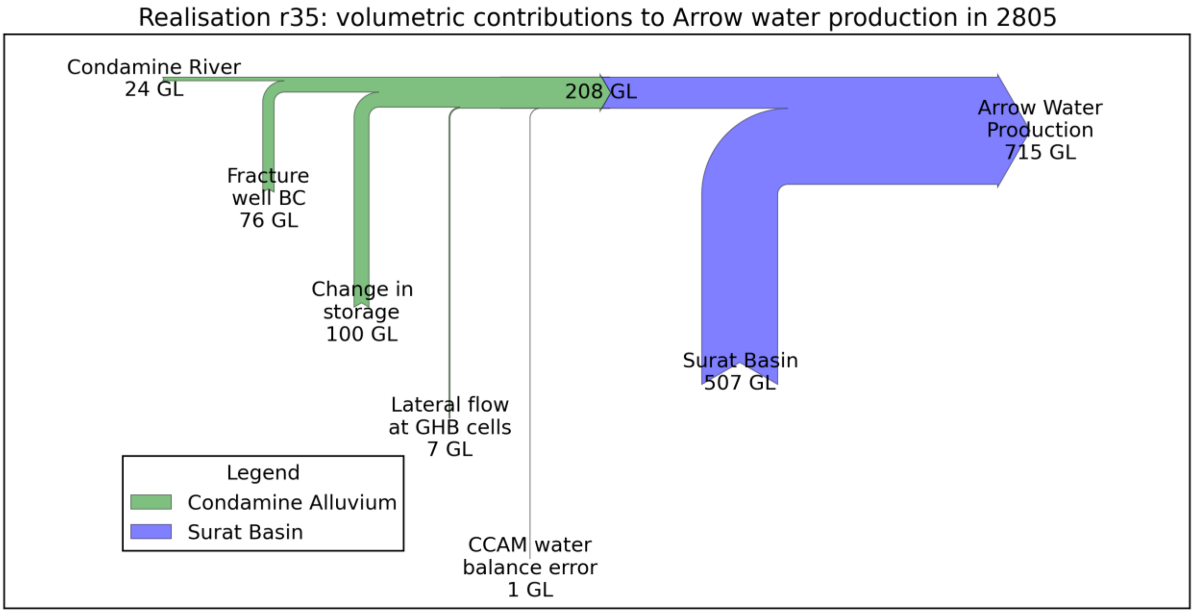


Figure 7-44 Sankey diagram for realisation r35 (high case) showing the predicted volumetric contributions to Arrow water production from the Surat Basin and Condamine Alluvium in year 2805

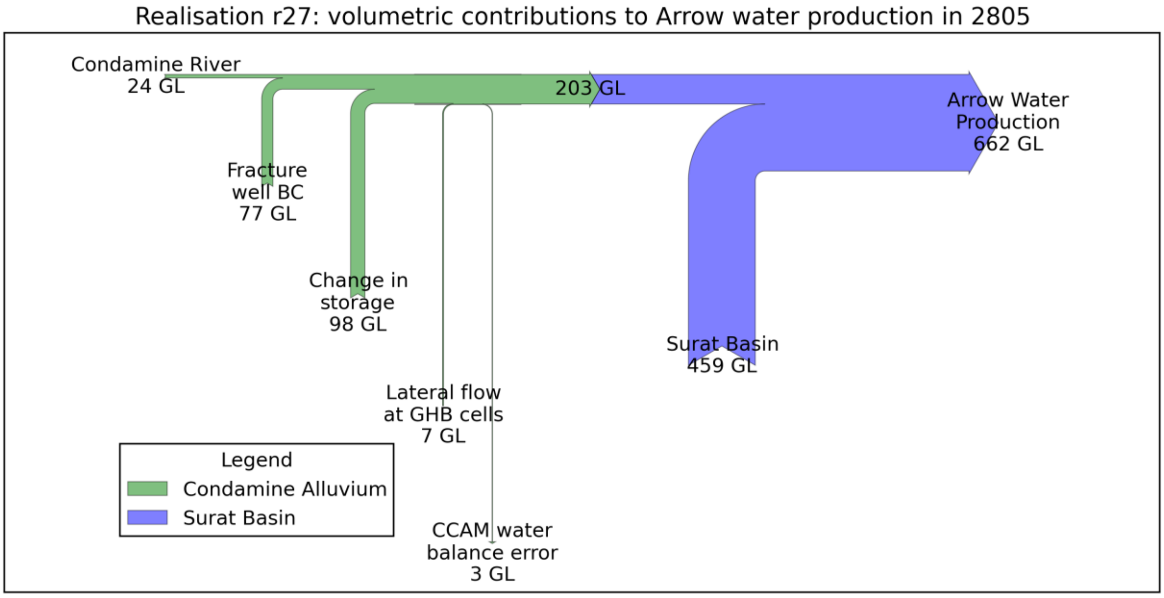


Figure 7-45 Sankey diagram for realisation r27 (median case) showing the predicted volumetric contributions to Arrow water production from the Surat Basin and Condamine Alluvium in year 2805

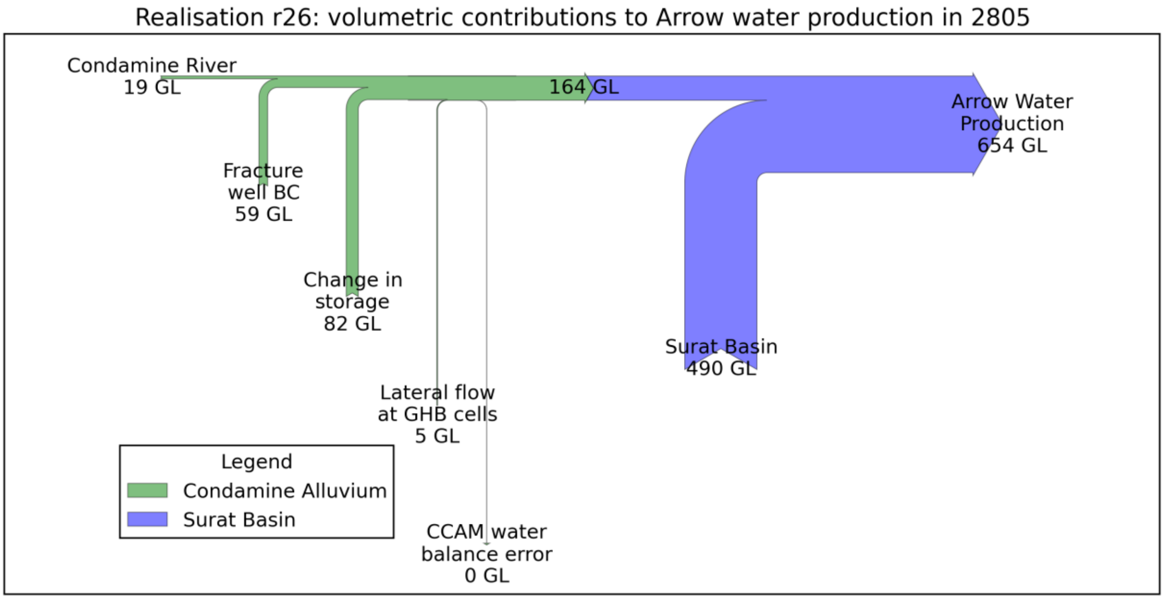


Figure 7-46 Sankey diagram for realisation r26 (low case) showing the predicted volumetric contributions to Arrow water production from the Surat Basin and Condamine Alluvium in year 2805

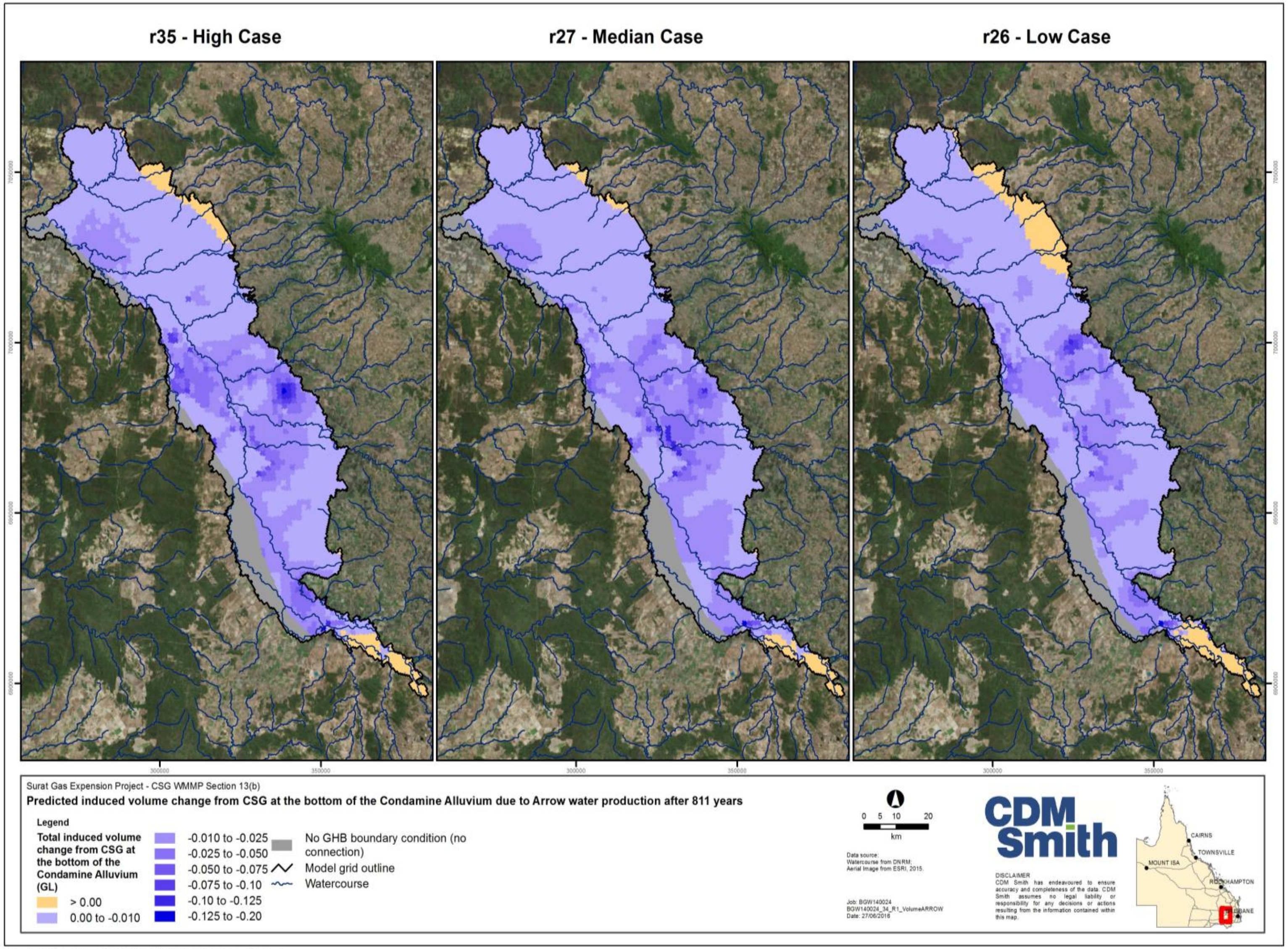


Figure 7-47 Predicted distribution of total change in volume at the base of the Condamine Alluvium due to Arrow water production

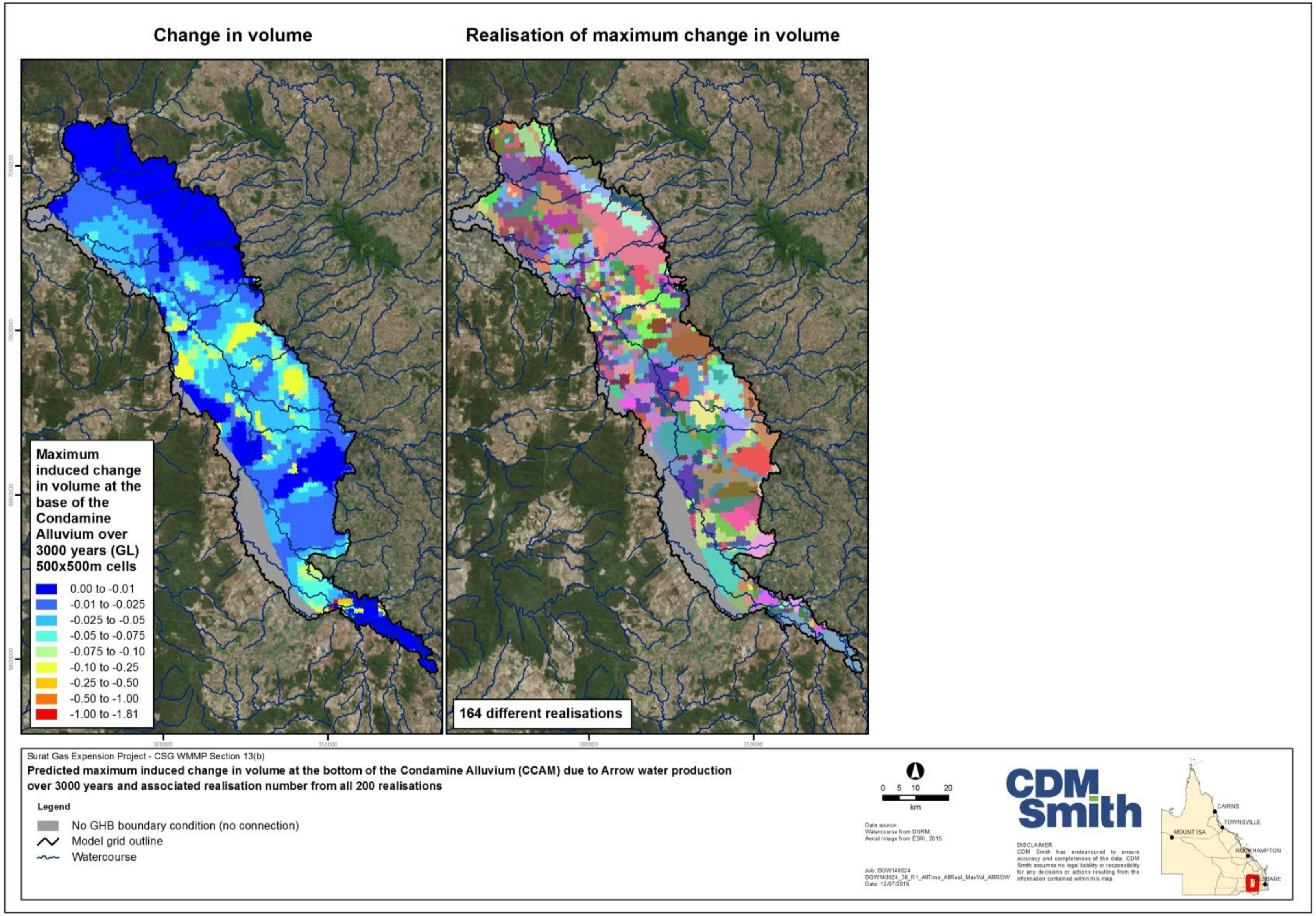


Figure 7-48 Predicted distribution of total change in volume at the base of the Condamine Alluvium due to Arrow water production

7.6.5.4 Predicted drawdown of the water table due to CSG development

Figure 7-49 shows maximum drawdown at the water table due to Arrow CSG development for the high, median and low case realisations. The predicted values of maximum drawdown (the largest values of drawdown in each model cell over the period of the simulation) are indicated by the contour lines and the times at which the maximum values occur are indicated by colour. It can be seen that maximum drawdown is predicted to occur at different times within the simulation period at different locations within the alluvium; however, maximum drawdown is not reached in some areas of the alluvium by year 2805 at the end of the simulation period (dark blue areas).

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

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

7.6.5.5 Predicted impacts of CSG development on the Condamine River

Impacts to the Condamine River from CSG water extraction can only be modelled where river cells are considered to be ‘connected’ to groundwater and where potential drawdown is predicted (refer Section 7.6.5.4). The predicted magnitude and timing of impacts to the river is therefore dependent on the location of ‘connected’ river cells and the drawdown induced by the simulated water production.

Figure 7-50 shows the distributions of the all-time maximum changes in groundwater flux in river cells representing the Condamine River for the high, median and low case realisations. Analysis of these results shows that more than 75% of river cells (white coloured cells) experience no discernible change in groundwater flux over the simulation period because they are ‘disconnected’ from groundwater; thus, the rates of leakage from these river cells are constant and independent of the water table elevation. Most of the predicted impact on the Condamine River due to Arrow CSG water production occurs in river cells located downstream of Warra Town Weir (see map inserts in Figure 7-50) with maximum changes in groundwater flux of between 0.001 ML/d and 0.004 ML/d; these are very small fluxes (less than 0.1 L/s for a cell 500 m x 500 m in size along the alignment of the river) and arguably beyond the expected accuracy of the CCAM. Very small impacts (less than 0.001 ML/d) are also predicted just upstream of Talgai Weir, Yarramalong Weir, Cecil Plains Weir and Chinchilla Weir. For all practical purposes the predicted impacts are negligible.

The predicted maximum changes in total groundwater flux to the Condamine River due to Arrow water production were 0.12 ML/d, 0.13 ML/d[8] and 0.08 ML/d for the high, median and low case realisations, respectively (Table 7-26). Over the simulation period (up to 811 years after the start of simulated water production) the predicted total change in volumetric flux between the Condamine River and Condamine Alluvium is between 18.6 GL and 24.4 GL (Table 7-27).

[8] Note that the change for the median case is larger and appears out of order, but this is because the high, median and low cases were selected based on total change in volume of vertical flux, rather than maximum change in flux, and furthermore the ranking was based on runs of the OGIA model that included all CSG production, not only Arrow’s.

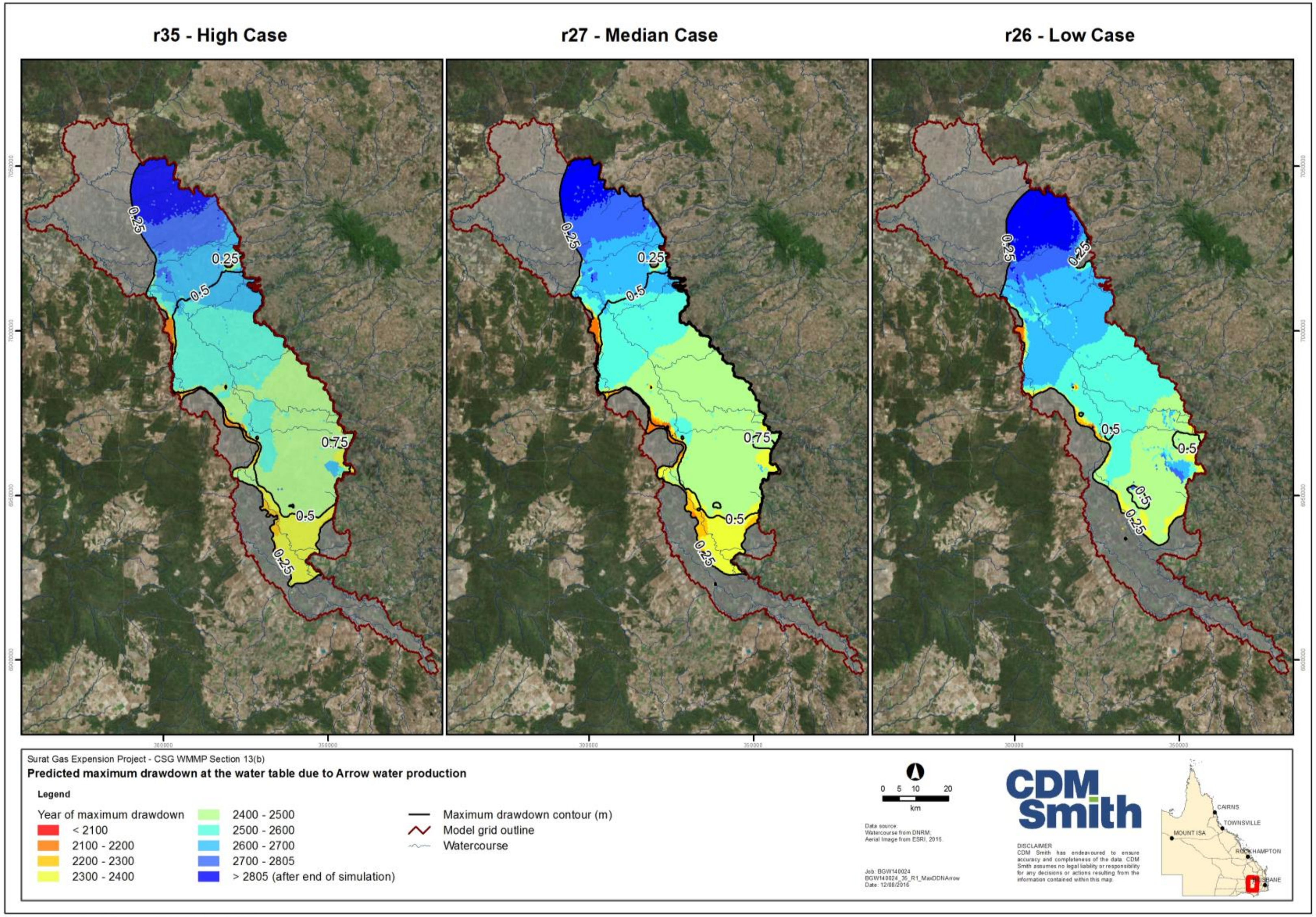


Figure 7-49 Predicted maximum drawdown at the water table due to Arrow water production

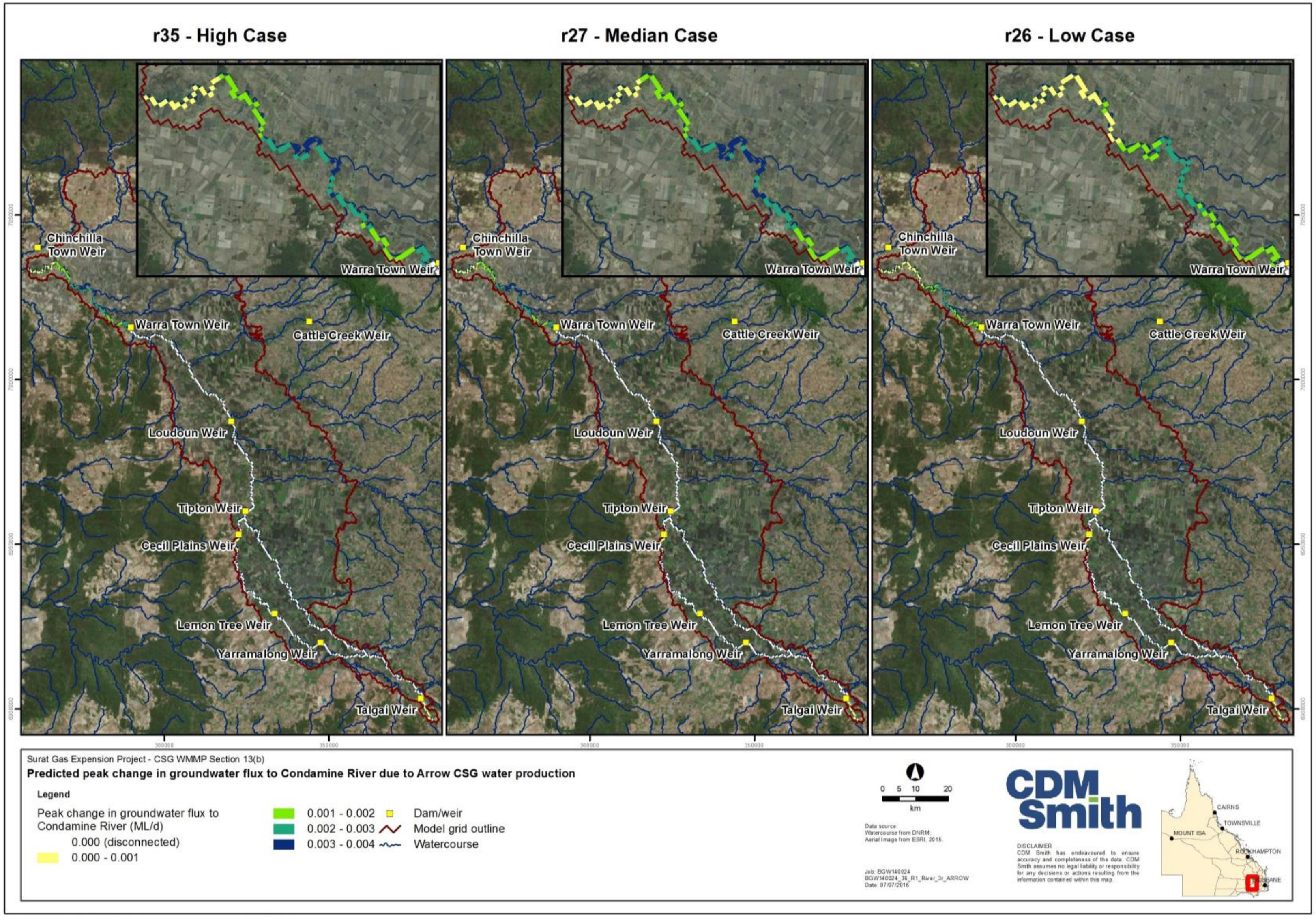


Figure 7-50 Distribution of maximum change in groundwater flux to the Condamine River due to Arrow water production

7.6.5.6 Conclusions

The CCAM has been run using the results from three of the 200 realisations of the Surat CMA groundwater model, which predicts change in net vertical flux at the base of the Condamine Alluvium due to simulated CSG water production in the Surat Basin. The three realisations consist of a high case (5% probability of exceedance), median case (50% probability of exceedance) and low case (95% probability of exceedance).

The footprint of the CCAM where connection between the Condamine Alluvium and Surat Basin is represented by GHB boundary conditions is 10% smaller than the footprint area of the Condamine Alluvium in the Surat CMA groundwater model. Predicted change in flux at the base of the Condamine Alluvium from the Surat CMA model is only transferred to the CCAM in the area where the model footprints overlap and both models simulate leakage at the base of the alluvium.

With no CSG development, the CCAM predicts net vertical leakage at the base of the Condamine Alluvium that is approximately 9.4% of the total simulated inflow to the alluvium over the simulation period of 826 years. Relative to this baseline, the predicted change in net vertical flux due to Arrow simulated water production is 8% to 10%, which is equivalent to an induced change in total inflow to the alluvium of 0.7% to 1%.

For the high, median and low case realisations the impacts of CSG development on water fluxes in the Condamine Alluvium that are predicted by the CCAM include:

- Maximum change in net vertical flux at the base of the Condamine Alluvium due to Arrow water production of 2.11 ML/d, 2.67 ML/d and 1.34 ML/d for the high, median and low case realisations, respectively; the times at which the predicted maxima occur vary between 29 and 49 years after the simulated maximum in water production; and the spatial distributions of the maximum change in fluxes vary between the three realisations but the general patterns are similar;
- Volumetric change in net groundwater flux at the base of the Condamine Alluvium over the simulation period of 826 years of between 164 GL for the low case realisation and 208 GL for the high case realisation, which is between 25% and 30% of Arrow simulated water production;
- Maximum drawdown at the water table of approximately 1.1 m for the high and median case realisations, and maximum drawdown of approximately 0.8 m for the low case realisation; with maximum drawdown at most locations occurring more than 275 years after the simulated maximum in water production, and maximum drawdown not reached after 826 years at the end of simulation in some areas;
- Maximum change in net groundwater flux to the Condamine River of 0.12 ML/d, 0.13 ML/d and 0.09 ML/d for the high, median and low case realisations, respectively; the time at which the maximum values occur vary between 113 and 123 years after the maximum in simulated water production; and
- Volumetric change in groundwater exchange with the Condamine River of 18.6 GL for the low case realisation up to 24.4 GL for the high case realisation over the simulation period of 826 years; representing between 2.8% and 3.6% of Arrow simulated total water production.

7.7 IQQM Modelling

7.7.1 Overview of the IQQM

The Integrated Quantity and Quality Modelling (IQQM) computer program is a hydrological modelling tool (a computer model) developed by the New South Wales Department of Primary Industries (DPI) for use in planning and evaluating water resource management policies (Simons et al. 1996). The major processes represented in IQQM are flow routing, reservoir operation, resource assessment, irrigation, urban water supply and other consumptive uses, and wetland and environmental flow requirements.

IQQM is widely used to assess the impact of changes in surface water inflows or outflows on water resources at the basin scale in New South Wales and Queensland. In Queensland, IQQM data sets are developed and maintained by the Department of Natural Resources and Mines (DNRM). Data sets encapsulate licensing conditions, so that the model can be used to manage allocations.

CDM Smith obtained permission to use the IQQM software and was trained to do so. Appendix D lists data files obtained for IQQM.

Two IQQM models are used for the area defined by the extent of the Condamine Alluvium groundwater model (CCAM). The Upper Condamine model covers the upstream part of the Condamine River catchment up to Cecil Plains. The Middle Condamine model starts from Cecil Plains and finishes at Beardmore Dam. Data for these two IQQM models were supplied by DSITI.

7.7.1.1 Model description

Two scenarios were provided with the IQQM model files: a Pre-Development case and the Resource Operation Plan (ROP).

The Pre-Development scenario represents natural flow conditions. This simulates the flow regime without any development of water resources, i.e. without any water infrastructure and water extraction. The ROP scenario includes full entitlements. This means that all water resource development and allocations that existed at the time the two models were developed are included, and these allocations are fully utilised.

The Upper Condamine and Middle Condamine Resource Operation Plan (ROP) IQQM models are used as the base case to assess the potential impacts of CSG production on surface water resources.

Both IQQM models use a fixed monthly demand pattern and represent 2000/2001 levels of infrastructure combined with fully utilised medium security licences. Water harvesting licences are modelled by a soil moisture accounting model with fixed areas determined as a function of on-farm storage capacity. Irrigation demands vary as a function of climatic conditions (CSIRO 2008).

Groundwater interaction is not explicitly simulated in the IQQM. On the other hand, stream transmission losses were estimated and are therefore included in each IQQM model. This was done by comparing recorded and simulated flows at a downstream gauge. Losses can be attributed to groundwater recharge, breakout around the downstream gauge, infiltration during periods of overland flooding, and uncertainty in the measurements (too small or too large flows) and water extraction estimates (Ryan 2002).

Upper Condamine

The Upper Condamine model was built using version 6.73.4 of IQQM (Ryan 2002). The model starts at Killarney Weir and finishes at Cecil Plains Weir gauge 422316A on the Condamine River, and at the Lone Pine gauge 422345A on the North Condamine River (the northern anabranch).

The model contains 424 nodes distributed over 11 river reaches. The model has eight supply storages, starting from upstream: Killarney Weir, Connolly Dam, North Toolbura Weir, Leslie Dam, Talgai Weir, Yarramalong Weir, Lemon Tree Weir, and Cecil Plains Weir. Water use is represented by 116 nodes, representing 23 medium security irrigators, 75 unsupplemented access irrigators, five floodplain harvesters, four town water supplies, and nine high security 'other demand' users (CSIRO 2008).

The scenario name for the ROP is 909B. The simulation period extends from January 1895 to the end of June 2006. For the purpose of this assessment, the period from July 1922 to the end of June 1995 has been used to derive the performance indicators described in Section 4.2.4 for the ROP.

Only one EFOs reporting site, node K on the Condamine River at Cecil Plains Weir (see Section 4.2.4.1), is located within the extent of the Central Condamine Alluvium groundwater model (CCAM) for the Upper Condamine IQQM model (see Figure 4-2). Table 7-28 shows the simulated mean annual flow at that node from 1 July 1922 to 30 June 1995. The ROP full entitlement scenario reduces the Pre-Development mean annual flow at node K by 30%.

Table 7-28 Simulated mean annual flow at node K on the Condamine River at Cecil Plains Weir

Node	River	AMTD (km)	Mean Annual Flow (ML/yr)		% of reduction
			Pre-development	ROP	
K	Condamine River	891.1	267,608	188,544	30

Middle Condamine

The Middle Condamine model was built using version 6.73.4 of IQQM and contains a total of 410 nodes (Anderson et al. 2002). The model starts at Cecil Plains Weir and Lone Pine gauges, where outflows from the Upper Condamine model are passed through as inflows to the Middle Condamine model, and finishes at Beardmore dam headwater gauge 422212B.

The model has 17 regulated storages: Tipton Weir, Cooby Creek Dam, Loudon Weir, Bell Town water storage, Jandowae town water storage, Warra Weir, Chinchilla Weir, Condamine Weir, Riley's Weir, Tara town water storage, Brigalow Creek Weir, Freers Weir, Dogwood Creek Weir, Drillham Creek Weir, Dufacca town water storage, Surat Weir and Neil Turner Weir. Water use is simulated by 140 nodes, representing seven medium security irrigators, 107 unsupplemented access irrigators, five floodplain harvesters, 15 high security town water supplies and six high security stock and domestic users (CSIRO 2008).

The scenario name for the ROP is 106A. The simulation period extends from January 1895 to the end of June 2006. For the purpose of this assessment, the period from July 1922 to the end of June 1995 has been used to derive the performance indicators described in Section 4.2.4 for the ROP.

Only one EFOs reporting site on the Condamine River, node J at the upstream limit of the impounded area of Chinchilla Weir, is located within the extent of the Central Condamine Alluvium groundwater model (CCAM) for the Middle Condamine IQQM model. The two next nodes, I and H, are located further downstream on the Condamine River and are considered as part of this study to look at potential impacts further downstream (Figure 4-2 shows the location of node I, but node H is further downstream, well downstream of the Condamine Alluvium). Table 7-29 shows the simulated mean annual flows at nodes J, I and H from 1 July 1922 to 30 June 1995. The ROP full entitlement scenario reduces the Pre-Development mean annual flows in the Condamine River by 29-37%.

Table 7-29 Simulated mean annual flow at nodes J, I and H on the Condamine River

Node	River	AMTD (km)	Mean Annual Flow (ML/y)		% of reduction
			Pre-development	ROP	
J	Condamine River	-	440,462	278,276	37
I	Condamine River	643.7	555,433	376,428	32
H	Condamine River	537.5	589,925	416,428	29

7.7.2 CCAM Predictions of Impacts on the Condamine River

As discussed in Section 7.6, three simulations out of the 200 NSMC realisations of the Surat CMA groundwater model were run with the CCAM (CDM Smith 2015b) to predict impacts on the Condamine River between Talgai Weir and Chinchilla Weir. These simulations were selected based on the predicted change in net vertical flux volumes at the base of the Condamine Alluvium, and are defined as the high case (5% probability of exceedance in 200 realisations), the median case (50% probability of exceedance in 200 realisations) and the low case (95% probability of exceedance in 200 realisations). It is assumed that the predicted change in net vertical flux volume at the base of the Condamine is directly related to the predicted magnitude of impact at the Condamine River.

Because potential impacts will vary in space and time, a decision was needed regarding what fluxes would be used to assess the impact on the surface water system. A conservative decision was made, i.e. to use the IQQM to assess the potential impact of the all-time maximum change in groundwater flux to the Condamine River predicted within the CCAM groundwater model. Predicted maximum changes in groundwater flux based on the CCAM are provided in Table 7-30 for the three cases referred to above.

Table 7-30 Predicted maximum changes in groundwater fluxes to the Condamine River due to Arrow water production (from Table 7-26)

Surat CMA groundwater model realisation	High case (r35) ML/d	Median case (r27) ML/d	Low case (r26) ML/d
Maximum change in groundwater flux to the Condamine River	0.12	0.13	0.09

7.7.3 Results

The Integrated Quantity and Quality Modelling (IQQM) software has been used to assess the potential impacts of the proposed CSG extraction on surface water users. The effects are represented in IQQM by the change in fluxes (loss) between the Condamine River and the underlying aquifer. The impacts on downstream users and Environmental Flow Objectives (EFOs) nodes are then assessed, as specified in the Condamine and Balonne Water Resource Plan (WRP) (Queensland Government, 2004).

Impacts to the Condamine River are predicted to occur almost entirely between Warra Town Weir and Chinchilla Weir (see Figure 7-50). This falls within the Middle Condamine IQQM model. No impacts are predicted in the area covered by the Upper Condamine IQQM model. Results are therefore only reported for the Middle Condamine IQQM model.

To evaluate the impacts on water resources, an additional node (called an unsupplemented node in the language of IQQM) has been included in the IQQM Middle Condamine ROP model. This node is set to remove up to the predicted maximum change in groundwater fluxes to the Condamine River (see Table 7-30) when water is available in the system.

The node is located in the middle of the reach from Warra Town Weir to Chinchilla Weir, between IQQM nodes 132 and 188. The sensitivity to the location of the loss node has been tested to make sure that the predicted impacts were consistent.

Whether or not this additional flux could actually occur would depend on whether the Condamine River is already disconnected in the area where the effects might be felt, because if disconnected, any tendency for the water table to be lowered might not cause any additional loss of water from the river.

7.7.3.1 Environmental Flow Objectives (EFOs)

The environmental flow objectives (EFOs) performance indicators for the Condamine and Balonne Water Resource Plan (Queensland Government, 2004) are described in Section 4.2.4.1. Table 7-31 shows the predicted impacts on the performance indicators at the three EFOs reporting nodes downstream of the simulated groundwater loss (a single additional unsupplemented node in the IQQM model).

Results for the three simulations are compared to the base case ROP scenario. Cells highlighted in orange are for performance indicators that are already below their targets for the ROP scenario. These indicators do not get worse.

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

Daily flow duration curves at Nodes J, I and H are plotted in Figure 7-51, Figure 7-52 and Figure 7-53. Each of the Figures shows the flow duration curve for the ROP base case, and the ROP base case with the high, median and low scenario impacts from CSG production. The curves are nearly identical in every case, showing that there is almost no discernible impact of CSG production.

A very slight change in the low flow regime can be observed at node J, the closest EFO node downstream, for the High case scenario. This can be seen where the curves meet the horizontal axis at about 55% of days. No discernible change is predicted for the median and low cases.

Table 7-31 Environmental flow objectives results - high case, median case and low case

	WRP EFOs objective	ROP	High case (0.31 ML/d)	Median case (0.28 ML/d)	Low case (0.17 ML/d)
Node J Condamine River at the upstream limit of the impounded area of Chinchilla Weir (IQQM node 063)					
Low Flow (days)	< 133%	112.5%	112.6%	112.6%	112.6%
Summer Flow (days)	> 66%	56.3%	56.3%	56.3%	56.3%
Beneficial Flooding Flow (ML)	> 66%	60.0%	60.0%	60.0%	60.0%
1 in 2 year Flood (ML/day)	> 66%	76.1%	76.1%	76.1%	76.1%
1 in 10 year Flood (ML/day)	> 66%	80.5%	80.5%	80.5%	80.5%
Node I Condamine River downstream of CWWSS AMTD 643.7 km (IQQM node 360)					
Low Flow (days)	< 133%	105.4%	105.4%	105.4%	105.4%
Summer Flow (days)	> 66%	61.2%	61.2%	61.2%	61.2%
Beneficial Flooding Flow (ML)	> 66%	65.6%	65.6%	65.6%	65.6%
1 in 2 year Flood (ML/day)	> 66%	77.1%	77.1%	77.1%	77.1%
1 in 10 year Flood (ML/day)	> 66%	90.7%	90.7%	90.7%	90.7%
Node H Condamine River at Cotswold AMTD 537.5 km (IQQM node 069)					
Low Flow (days)	< 133%	104.3%	104.3%	104.3%	104.3%
Summer Flow (days)	> 66%	61.4%	61.4%	61.4%	61.4%
Beneficial Flooding Flow (ML)	> 66%	76.2%	76.2%	76.2%	76.2%
1 in 2 year Flood (ML/day)	> 66%	74.2%	74.2%	74.2%	74.2%
1 in 10 year Flood (ML/day)	> 66%	85.8%	85.8%	85.8%	85.8%

Note: Orange cells show performance measures that already fail to meet EFOs under the ROP scenario.

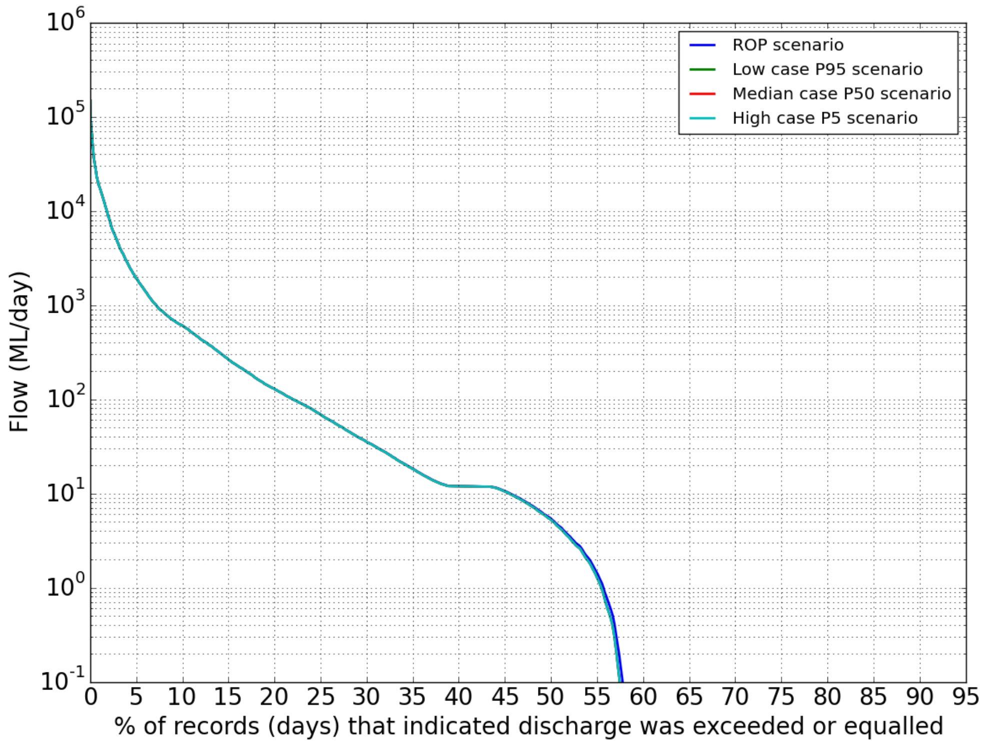


Figure 7-51 Flow duration curve for EFO node J

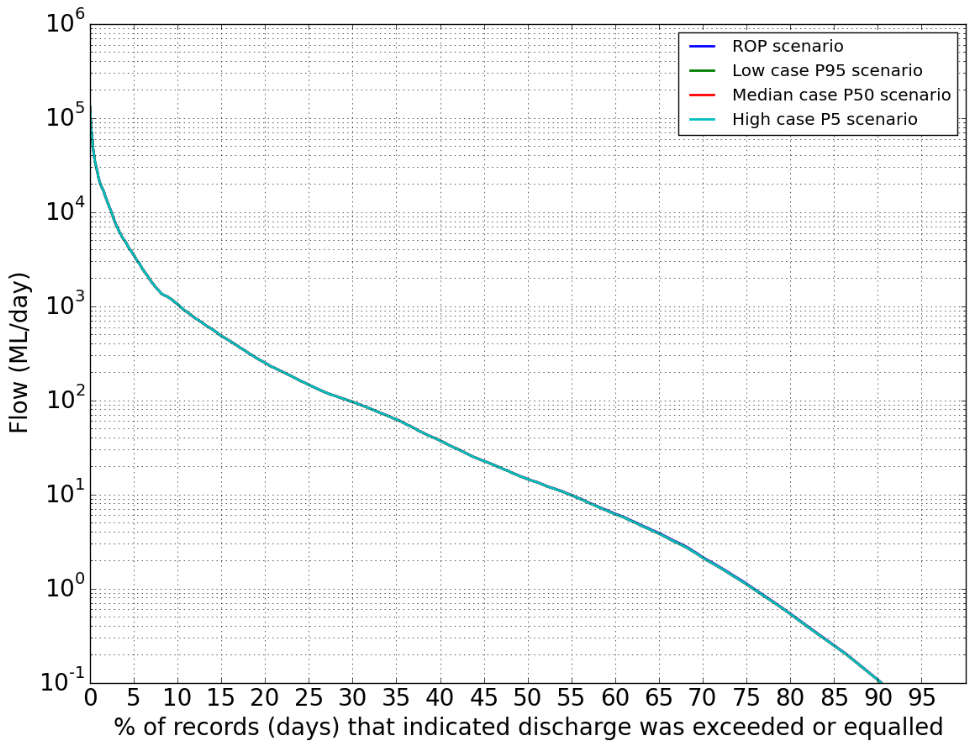


Figure 7-52 Flow duration curve for EFO node I

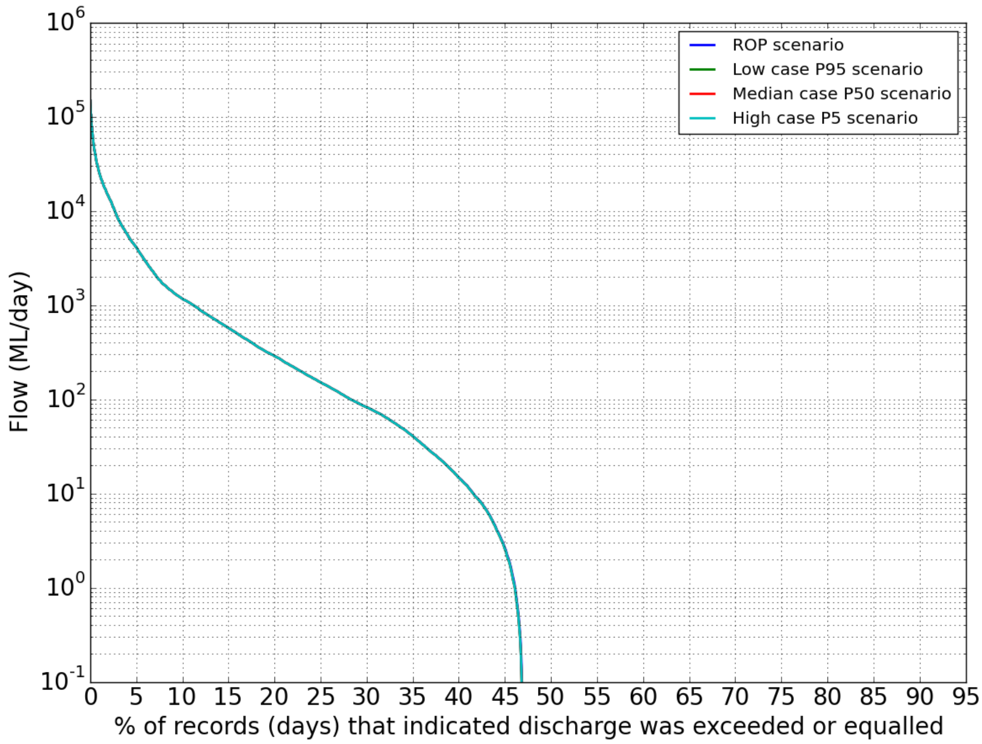


Figure 7-53 Flow duration curve for EFO node H

7.7.3.2 Potential impacts on other users

Potential impacts of groundwater losses from CSG extraction on downstream users also have to be assessed. The associated Water Allocation Security Objectives (WASOs) are described in Section 4.2.4.2. All WASO performance indicators were checked for users downstream of the loss node. Table 7-32 presents the predicted impacts on the next four downstream water users. There were no reductions in the performance indicators except at IQQM node 184 (Brigalow Town Water Supply). At this node, the Annual Volume Probability has decreased by 0.3% for the high, median and low cases.

Table 7-32 Water Allocation Security Objectives

Node	ROP		High case (0.31 ML/d)		Median case (0.28 ML/d)		Low case (0.17 ML/d)	
	45% Annual Volume Reliability (%)	Annual Volume Probability (%)	45% Annual Volume Reliability (%)	Annual Volume Probability (%)	45% Annual Volume Reliability (%)	Annual Volume Probability (%)	45% Annual Volume Reliability (%)	Annual Volume Probability (%)
184 Brigalow Town Water Supply	67.1	55.0	67.1	54.7	67.1	54.7	67.1	54.7
183 Chinchilla Town Water Supply	100	99.7	100	99.7	100	99.7	100	99.7
78 Irrigation	89.0	84.6	89.0	84.6	89.0	84.6	89.0	84.6
218 Irrigation	94.5	95.3	94.5	95.3	94.5	95.3	94.5	95.3

7.8 Fit For Purpose Numerical Simulation

The numerical modelling described in Section 7 is a "fit for purpose numerical simulation", as required in Section 13(b) of the Approval.

The purpose of the modelling is to support assessment of the "*potential impacts on water resources arising from the action in the project area*, *subsequent surface water-groundwater interactions* in *the Condamine Alluvium* and *impacts to (sic.) dependent ecosystems*". Already it can be seen that:

- Section 7.4 and Section 7.6 allow assessment of impacts on groundwater resources;
- Section 7.5 supports the interpretation of connected and disconnected rivers in Section 7.6; and
- Section 7.7 allows assessment of potential impacts on surface water resources.

Section 8 will summarise the potential impacts on water resources and surface water – groundwater interactions, and present an assessment of potential impacts on dependent ecosystems.

Section 8 Potential Impacts

8.1 Preamble

Section 13(b) requires an assessment of potential impacts on *"water resources …, subsequent surface water-groundwater interactions in the Condamine Alluvium* and *impacts to (sic.) dependent ecosystems*". This section addresses these three types of potential impacts.

Potential impacts

Production of CSG will require pumping of water from and depressurisation within the Walloon Coal Measures, with pressures lowered so that piezometric heads measured in deep monitoring bores screened near production wells would be tens of metres above the elevations of screens. These impacts are not potential impacts – they are necessary for the desorption and production of gas. However, these impacts are far from water-producing bores licensed to other users.

Some depressurisation may ultimately be observed in other HSUs above and below the Walloon Coal Measures. Some units may be classified as confined aquifers, in which case the lower pressures and heads could affect some bores in these confined groundwater resources.

Depressurisation in the Walloon Coal Measures will ultimately cause changes in vertical fluxes between the Walloon Coal Measures and the Condamine Alluvium.

The potential impact of a reduction in net discharge of groundwater to the Condamine Alluvium is lowering of the water table in the Condamine Alluvium, which would be considered to be an impact on these unconfined groundwater resources.

Any lowering of the water table in the Condamine Alluvium could have a potential impact on the nature of surface water – groundwater interaction near the Condamine River and its tributaries.

Any reduction of discharge from the Condamine Alluvium to the Condamine River and its tributaries could have a potential impact on surface water resources in the Condamine River.

Any lowering of the water table in the Condamine Alluvium or reduction of water levels or flows in the Condamine River or its tributaries could have a potential impact on dependent ecosystems.

All of these possible potential impacts will be evaluated and discussed in this section.

8.2 Potential Impacts on Water Resources

8.2.1 Summary of Predicted Water Production

Predicted water production

Water production is first estimated by reservoir engineers on behalf of CSG producers. These estimates are provided to QWC and OGIA, who then prepare datasets for the OGIA model.

Water production is simulated using MODFLOW's EVT package, which represents pumping as a mixed boundary condition, neither imposing pumping rate nor head, but rather a relationship between the two. When 200 realisations of the OGIA model are run, the results include 200 sets of water production curves, influenced by uncertainty in hydraulic conductivities and other model parameters. The range helps to demonstrate that initial estimates are reasonable.

This study suggests that water production will be less than was estimated by QWC (2012c). This is largely because all producers have been decreasing their predicted pumping requirements each year, as more knowledge is gained.

Based on 200 realisations, this study suggests that Arrow's median average annual water production will be 11 GL/y.

Table 8-1, and Figure 8-1, Figure 8-2 and Figure 8-3 are summaries of predicted water production from groundwater modelling, including the total volume of water production, the average annual rate of water production (over 65 years) and the maximum rate of water production. These results are tabulated as totals for all CSG operators, for non-Arrow CSG operators, and for Arrow alone. The ranges are based on values with 5% and 95% probabilities of exceedance from 200 NSMC realisations (QWC 2012c), where 95% probability of exceedance represents a notional lower bound, and 5% probability of exceedance represents a notional upper bound.

Arrow's predicted water production of 653 to 755 GL (average 10 to 12 GL/y) is approximately 17% of the total predicted water production of 3,738 to 4,395 GL (average 58 to 68 GL/y) and approximately 21% of the predicted water production by other CSG operators of 3,036 to 3,663 GL (47 to 56 GL/y).

Using the Surat CMA groundwater model, QWC (2012a, p.58) predicted average annual water production for all existing and proposed CSG developments of approximately 95 GL/y, which is about 50% larger than the median value of 62 GL/y predicted in this study using the same model and the 2014 update of water production data. Other estimates of average annual water production provided by QWC (2012a, p.58) vary in the range 75 GL/y to 98 GL/y.

Table 8-1 Predicted water production volumes

Scenario	Operator	Range based on values with 5% and 95% probabilities from 200 realisations		
		Total volume, GL (in 65 y)	Average annual rate, GL/y	Maximum rate, ML/d
Existing and proposed CSG development[1]	All Non-Arrow Arrow	3,738 – 4,395 3,036 – 3,663 653 – 755	58 – 68 47 – 56 10 – 12	440 – 506 390 – 433 124 – 151
Existing and proposed non-Arrow CSG development[2]	Non-Arrow	3,044 – 3,668	47 – 56	390 – 433

[1]MODEL_CSG, [2]MODEL_XARROW

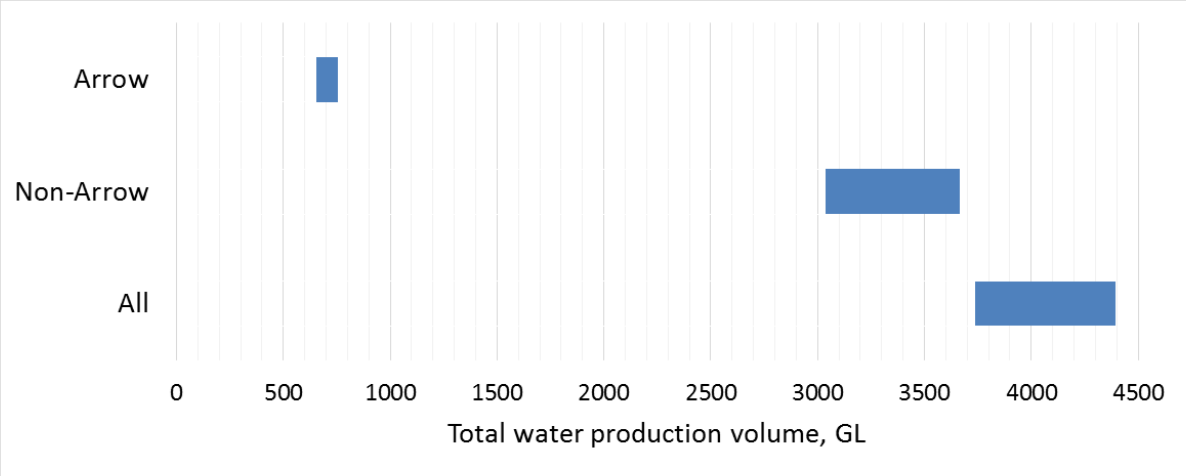


Figure 8-1 Predicted water production volumes based on 5% and 95% probabilities of exceedance from 200 realisations

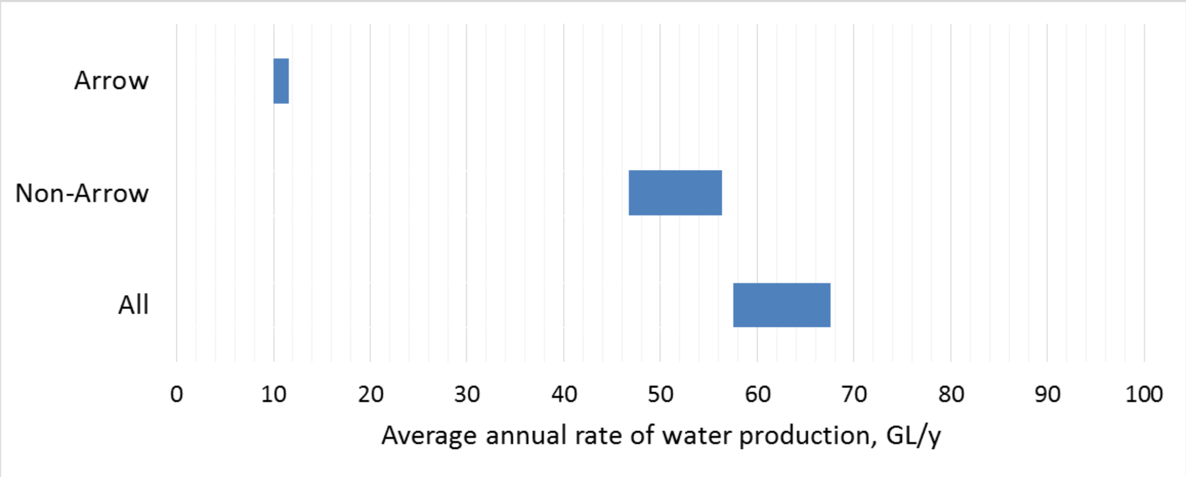


Figure 8-2 Predicted average annual rate of water production based on 5% and 95% probabilities of exceedance from 200 realisations

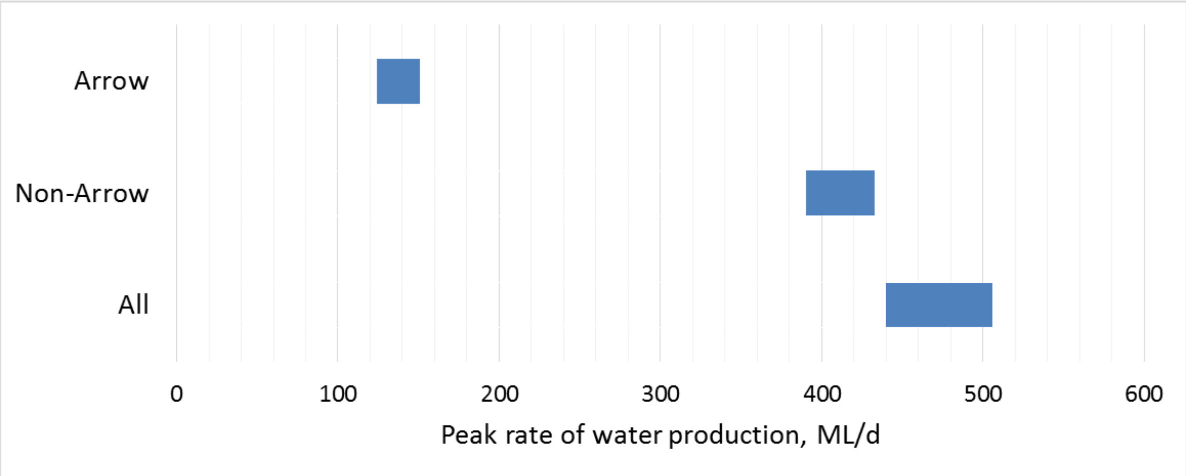


Figure 8-3 Predicted maximum rate of water production based on 5% and 95% probabilities of exceedance from 200 realisations

8.2.2 Summary of Predicted Changes in Vertical Flux at the Base of Condamine Alluvium

Predicted changes in vertical flux at base of the Condamine Alluvium

Changes in the rates of vertical flux through the base of the Condamine Alluvium are computed in each of 200 realisations of the OGIA model.

Focusing on the area of the CCAM, because subsequent modelling of groundwater in the Condamine Alluvium is based on use of the CCAM, Arrow's predicted contribution to change in net vertical flux is 216 to 292 GL over 3,000 years, which is approximately 55% of the total change in net vertical flux volume caused by all CSG producers and 37% of Arrow's predicted water production volume.

Regional scale modelling leads to the prediction that water extracted during CSG development will be replenished slowly over a period of around 3,000 years, and that only part of the total water production will be replenished by a change in vertical flux at the base of the Condamine Alluvium. The combination of slow replenishment of water extracted from the target coal seams, and the large area of alluvium affected by CSG water production, results in very small predicted changes in flux rate at the base of the alluvium.

Table 8-2, Table 8-3 and Figure 8-4 summarise the predicted changes in vertical flux at the base of the Condamine Alluvium. Arrow's predicted contributions to change in net vertical flux volumes are computed as the difference between simulations conducted for all existing and proposed CSG development and simulations conducted for existing and proposed non-Arrow CSG development. Arrow's contributions to predicted maximum changes in vertical flux rates cannot be computed by this method because the maximum rates may occur at different times.

The ranges are based on values with 5% and 95% probabilities of exceedance from 200 NSMC realisations (QWC 2012c), where 95% probability of exceedance represents a notional lower bound, and 5% probability of exceedance represents a notional upper bound.

Over the entire footprint area of the Condamine Alluvium, and for existing and proposed CSG development:

- The predicted change in total net vertical flux volume passing through the base of the alluvium during a period of 3,000 years is 465 to 608 GL (maximum rate 1.79 to 3.57 ML/d) which is around 13% of the total water production volume;
- The predicted maximum change in total vertical flux is 3.57 ML/d, which when distributed over 5,904 km^2 of alluvium is equivalent to an average change in flux of 0.22 mm/y in the year when the maximum occurs.
- Arrow's predicted contribution to change in net vertical flux is 264 to 341 GL, which is approximately 45% of the total change in net vertical flux volume and 43% of Arrow's predicted water production volume.

Over the connected area of alluvium in the Central Condamine Alluvium Model (CCAM), and for existing and proposed CSG development:

- The predicted change in total net vertical flux volume passing through the base of the alluvium during a period of 3,000 years is 384 to 508 GL (maximum rate 1.64 to 2.99 ML/d) which is around 12% of the total water production volume.

- The predicted maximum change in total vertical flux of 2.99 ML/d, which when distributed over 5,321 km^2 of alluvium is equivalent to an average change in flux rate of 0.21 mm/y in the year when the maximum occurs.
- Arrow's predicted contribution to change in net vertical flux is 216 to 292 GL over 3,000 years, which is approximately 55% of the total change in net vertical flux volume and 37% of Arrow's predicted water production volume.

Table 8-2 Predicted change in net vertical flux at the base of Condamine Alluvium

Scenario	Contribution	Range based on 5% and 95% probabilities of exceedance from 200 realisations	
		Volume change, GL (in 3,000 y)	Maximum rate change, ML/d
Existing and proposed CSG development[1]	All Arrow	465 – 608 264 – 341	1.79 – 3.57 Cannot be computed
Existing and proposed non-Arrow CSG development[2]	Non-Arrow	919 – 285	0.5 – 1.16

[1]MODEL_CSG, [2]MODEL_XARROW

Table 8-3 Predicted change in net vertical flux at the base of CCAM

Scenario	Contribution	Range based on 5% and 95% probabilities of exceedance from 200 realisations	
		Volume change, GL (in 3,000 y)	Maximum rate change, ML/d
Existing and proposed CSG development[1]	All Arrow	384 – 508 216 – 292	1.64 – 2.99 Cannot be computed
Existing and proposed non-Arrow CSG development[2]	Non-Arrow	157 – 236	0.42 – 0.89

[1]MODEL_CSG, [2]MODEL_XARROW

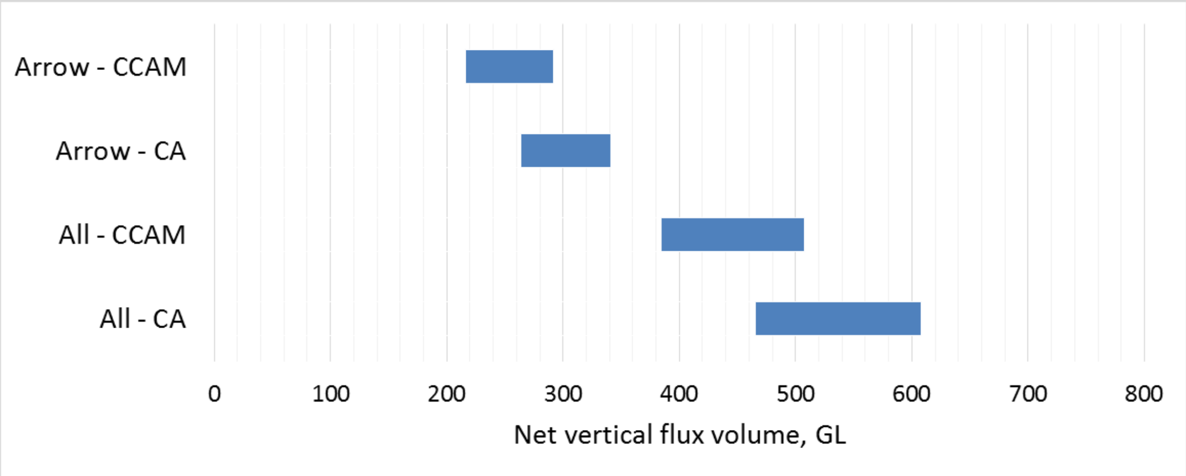


Figure 8-4 Predicted change in net vertical flux: CA – Condamine Alluvium footprint area; CCAM – Central Condamine Alluvium Model

The results presented above have been obtained by regional sale modelling, with 200 realisations of model parameters. Local scale modelling of the Condamine Alluvium with the CCAM is based on only three realisations. Changes in flux across the base of the alluvium are computed in the regional scale OGIA model and imposed as boundary conditions in the CCAM.

For the high, median and low case realisations used in the CCAM, the impacts of CSG development include:

- Maximum change in net vertical flux at the base of the Condamine Alluvium of 2.95 ML/d, 2.60 ML/d and 1.64 ML/d for the high, median and low case realisations, respectively; the times at which the predicted maxima occur vary between 34 and 61 years after the simulated maximum in water production; and
- Volumetric change (a reduction) in net groundwater flux through the base of the Condamine Alluvium over the simulation period of 826 years of between 248 GL for the low case realisation and 349 GL for the high case realisation, which is between 6.4% and 9.7% of the simulated total water production.

8.2.3 Summary of Potential Drawdown Within the Condamine Alluvium

Predicted potential drawdown within the Condamine Alluvium

The CCAM has been run three times for high, median and low cases, based on total change in the volume of vertical flux through the base of the Condamine Alluvium.

The CCAM predicts maximum drawdown due to Arrow water production of approximately 1.1 m for the high and median case realisations, and 0.8 m for the low case realisation. The maximum drawdown at most locations will occur more than 275 years after the simulated maximum in water production, and maximum drawdown is not reached after 826 years (at the end of the CCAM simulation) in some areas.

The CCAM has been run using the results from three of the 200 realisations of the Surat CMA groundwater model, which predicts change in net vertical flux at the base of the Condamine Alluvium due to simulated CSG water production in the Surat Basin. The three realisations consist of a high case, median case and low case, where the high case is based on total change in the volume of vertical flux through the base of the Condamine Alluvium being exceeded in only 5% of realisations, the median case is based on total change in the volume of vertical flux being exceeded in 50% of realisations, and the low case is based on total change in the volume vertical flux being exceeded in 95% of realisations.

The footprint of the CCAM, where connection between the Condamine Alluvium and Surat Basin is represented by a GHB boundary conditions, and is 10% smaller than the footprint area of the Condamine Alluvium in the Surat CMA groundwater model. Predicted changes in flux at the base of the Condamine Alluvium from the OGIA model are only transferred to the CCAM in the area where the model footprints overlap and both models simulate leakage at the base of the alluvium.

With no CSG development, the CCAM predicts net vertical leakage at the base of the Condamine Alluvium that is approximately 9.4% of the total simulated inflow to the alluvium over the simulation period of 826 years. Relative to this baseline, the predicted change in net vertical flux due to the simulated Arrow water production is 8% to 10%, which is equivalent to an induced change in total inflow to the alluvium of 0.7% to 1%.

For the high, median and low case realisations, the impacts of Arrow CSG development on the water table in the Condamine Alluvium are predicted by the CCAM to be:

- Maximum drawdown at the water table of approximately 1.1 m for the high and median case realisations, and maximum drawdown of approximately 0.8 m for the low case realisation. The maximum drawdown at most locations occurs more than 275 years after the simulated maximum in water production, and maximum drawdown is not reached after 826 years (at the end of the CCAM simulation) in some areas.

- Figure 7-49 shows a smooth spatial distribution in drawdown for the three cases simulated, with maximum drawdown of 0.5 m near the eastern and western boundaries of the Condamine Alluvium, enclosing approximately half of the area of the Condamine Alluvium.

8.2.4 Summary of Potential Impacts on Surface Water Resources

Predicted potential impacts on surface water resources

The CCAM has been run three times for high, median and low cases, based on total change in the volume of vertical flux through the base of the Condamine Alluvium.

The CCAM predicts changes in the rate of discharge from the Condamine Alluvium to the Condamine River. The predicted maximum changes in groundwater flux to the Condamine River due to Arrow water production are 0.12 ML/d for the high case realisation, 0.13 ML/d for the median case realisation and 0.08 ML/d for the low case realisation. Over the simulation period (up to 811 years after the start of simulated water production) the predicted total reduction in volumetric flux from the Condamine Alluvium to the Condamine River is between 16.2 GL and 24.4 GL.

The potential impact of reduced discharge due to Arrow water production to the Condamine River on surface water resources has been evaluated using the IQQM. The results show that required performance indicators for the Environmental Flow Objectives (EFOs) are achieved for the high, median and low case realisations. The modelling also shows that there were no reductions in the performance indicators on downstream users except at Brigalow Town Water Supply, where the Annual Volume Probability decreases by 0.3% for all case realisations.

The CCAM has been run using the results from three of the 200 realisations of the Surat CMA groundwater model, which predicts change in net vertical flux at the base of the Condamine Alluvium due to simulated CSG water production in the Surat Basin. The three realisations consist of a high case, median case and low case, where the high case is based on total change in the volume of vertical flux through the base of the Condamine Alluvium being exceeded in only 5% of realisations, the median case is based on total change in the volume of vertical flux being exceeded in 50% of realisations, and the low case is based on total change in the volume vertical flux being exceeded in 95% of realisations.

The CCAM predicts that the maximum changes in groundwater flux to the Condamine River are 0.12 ML/d, 0.13 ML/d and 0.08 ML/d for the high, median and low case realisations, respectively. The predicted total change in groundwater volume to the Condamine Alluvium over the simulation period (811 years after the start of CSG water production) is predicted to be between 16.2 GL and 24.4 GL.

The maximum changes in groundwater flux predicted in the CCAM for the three realisations were introduced into IQQM as loss nodes to evaluate the potential impact to surface water resources. Results show that no impacts are predicted and all required performance indicators are achieved for the Environmental Flow Objectives (EFOs) for the high, median and low case realisations. The only predicted impact is to the next downstream user, Brigalow Town Water Supply, where the Annual Volume Probability is predicted to decrease by 0.3% for all three case realisations.

Consideration of potential impacts on surface water resources relies on an understanding of potential impacts on surface water – groundwater interactions summarised in Section 8.3 below.

Potential impacts are discussed here to keep discussion of potential impacts on water resources within Section 8.2.

It should be noted that CCAM and IQQM modelling do not take into account the potential beneficial effects of discharge of treated CSG production water by QGC. Such discharge will occur during the life of QGC's operations, and is unlikely to continue until the time of maximum potential impacts in the Condamine Alluvium. Nevertheless, the discharge may cause additional recharge and increases in water table elevations in some areas in the interim.

8.3 Potential Impacts on Surface Water – Groundwater Interactions

Modelling undertaken in Section 7.6 using the CCAM shows that the Condamine River and its tributaries act as losing streams over most of their length, within the area of the Condamine Alluvium.

The Condamine River is represented in MODFLOW using a river boundary condition; the results show that the water table is below bed level in most locations, such that in each such cell the river functions as a losing disconnected stream.

Tributaries of the Condamine River (i.e. the 12 tributaries identified in Table 4-2 and shown in Figure 4-1 and elsewhere) are no represented explicitly in the CCAM. A decision was made not to add them to the CCAM, because doing so would have required recalibration and further review. In essence, it is believed that the CCAM uses distributed recharge as a surrogate for leakage from tributaries, so even through the tributaries are not represented explicitly, the fact that the water table is well below bed level along the alignment of tributaries means that they operate as losing disconnected streams, and further lowering of the water table would not cause additional leakage.

Figure 8-5 shows a comparison of two distributions of initial depth to water table, being the difference between surface elevation and the initial water table elevation in runs of the CCAM. The first Figure (on the left) uses surface elevation as defined in individual finite difference cells in the CCAM. The second (on the right) uses SRTM data. There are few locations where the initial depth to water table is not positive, i.e. where the water table is not below the land surface. The water table is generally closer to the surface along the Condamine River than beneath tributaries.

Figure 8-6 shows the same initial depth to water table using top elevations of cells on the left, and the predicted Arrow contribution to maximum drawdown at the time of greatest drawdown on the right. Depth to water table is shown with different contour intervals, emphasising the ranges 0-2 m, 2-5 m, 5-10 m and more than 10 m. The water table is predicted to decline slightly in nearly all model cells beneath the Condamine River and its tributaries. The time at which the greatest change occurs is different in all cells (see Figure 7-49).

The modelling shows that the distribution of "losing disconnected" cells is unlikely to change significantly due to long slow changes in water table elevation in the Condamine Alluvium and its tributaries.

- In many cells the depth to water table is 10 or more metres (shown in grey on the left of Figure 8-6), and CSG production will cause a slight increase in depth to water table. This applies to most tributaries of the Condamine River and along some reaches of the Condamine River.
- In many cells along the Condamine River, the depth to water table is in the range 5-10 m, and the river may also already function as a losing disconnected river. In these areas (shown in blue on the left of Figure 8-6), additional drawdown of up to 0.25 m (green at right) or 0.5 m (yellow

at right) or 0.75 m (brown at right) over 100 years or more may not change the rate of leakage, i.e. the degree of disconnectedness may be sufficient already to mean that leakage fluxes will not increase.

- There are some cells along the Condamine River where the simulated depth to water table is 2 to 5 m (shown in yellow on the left of Figure 8-6) where additional drawdown of 0.5-0.75 m (brown at right) or 0.25-0.5 m (yellow at right) is predicted. Because so little is known about the precise nature of bed of the Condamine River, it is difficult to argue conclusively that the river is already acting as a losing disconnected river, and that the additional drawdown will not change the nature of leakage. However, based on the likelihood of the river bed being incised in clayey sediments and the experience gained with exploratory modelling of unsaturated flow (see Appendix B), it is believed that the approach taken to date, using MODFLOW's river package to implement a behaviour consistent with disconnected losing behaviour, is reasonable.

None of the modelling undertaken is capable of predicting the impact of CSG production on the likelihood that the frequency or nature of surface flooding would in any way be changed, or the likelihood that infiltration and recharge from overland flooding, which may not be represented adequately in the CCAM, would change. The CCAM includes distributed recharge as a surrogate for all kinds of recharge, including the cumulative effects of episodic flooding and subsequent recharge to the water table.

Changes in flux between the Condamine River and its tributaries and the water table are computed by the CCAM. For the high, median and low case realisations, the impacts of Arrow CSG development on leakage from the Condamine River are predicted by the CCAM to be:

- Maximum change in net groundwater flux to the Condamine River due to Arrow water production of 0.12 ML/d, 0.13 ML/d and 0.08 ML/d for the high, median and low case realisations, respectively; the time at which the maximum values are predicted to occur varies between 140 and 348 years after the maximum in simulated water production; and

- Volumetric change in groundwater exchange with the Condamine River of 18.6 GL for the low case realisation, and 24.4 GL for the high case realisation over the simulation period of 826 years, representing between 3.0% and 3.5% of Arrow simulated water production.

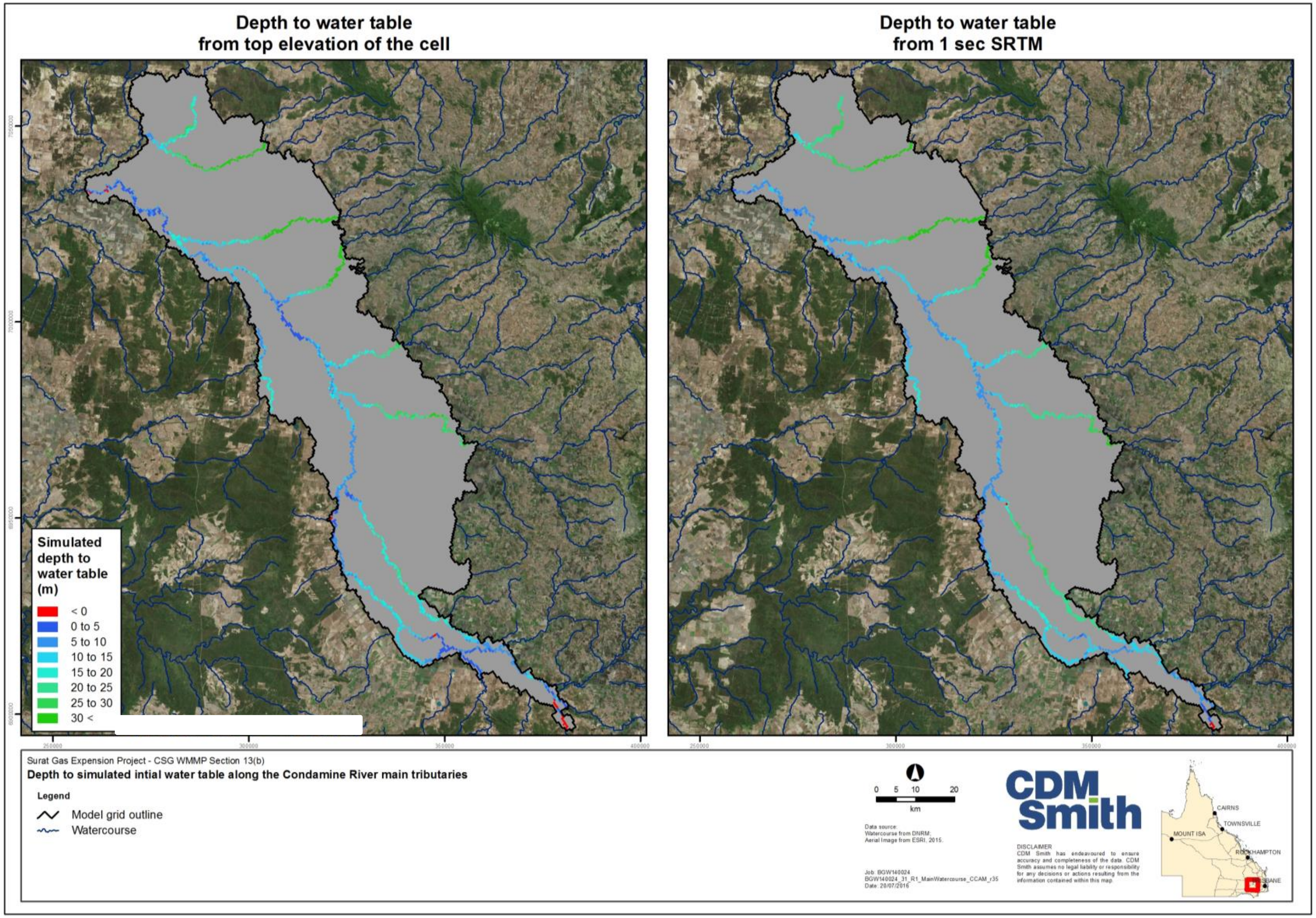


Figure 8-5 Simulated depth to groundwater along the Condamine River and its main tributaries

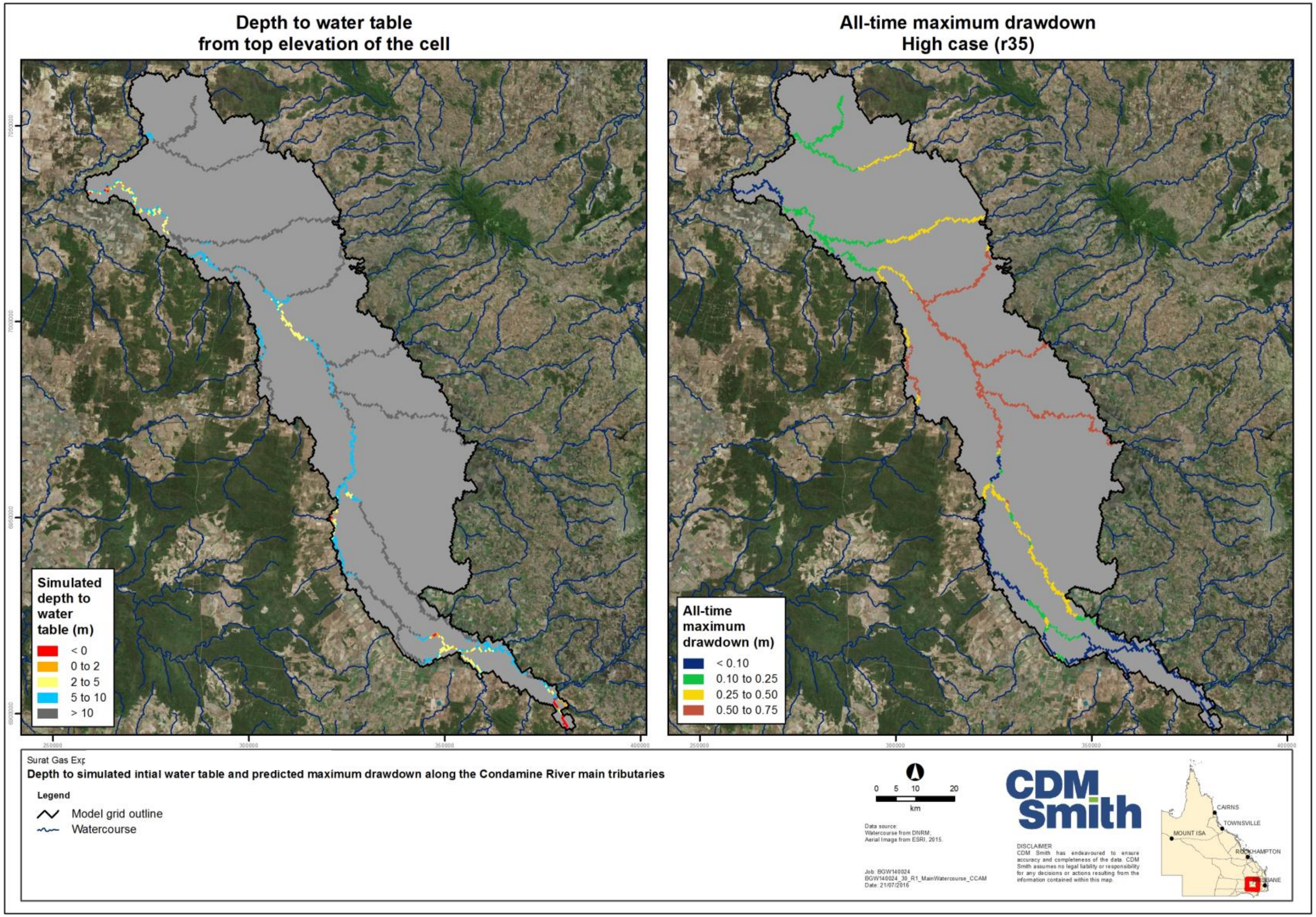


Figure 8-6 Simulated depth to groundwater and predicted maximum drawdown (case r35) along the Condamine River and its tributaries

8.4 Potential Impacts on Dependent Ecosystems

The purpose of this assessment is to investigate the potential for ecological consequences to arise from the hydrological effects caused by the groundwater depressurisation associated with CSG production.

An impact assessment is undertaken for each of the threat pathways identified. No potential impacts are predicted where threat pathways are absent. The impact assessment proceeds by examining the predicted hydrological changes (from the numerical simulations), comparing these to current trends in the surface and groundwater regime, and outlining the potential ecological effects that may result from these changes based on the conceptualisations presented.

8.4.1 Aquifer Type DEs

The potential threat pathways identified for Aquifer DEs are linked to the depressurisation of groundwater which could manifest in water table drawdown. The significance of this threat to stygofauna is related to the predicted rate and magnitude of drawdown relative to existing conditions. If the change is sudden or the overall magnitude of change is large then this could adversely affect stygofauna.

The depressurisation of groundwater from CSG development is predicted to lead to a decline in the water table of the Condamine Alluvium, but one that is small in magnitude and very gradual (see Section 7.6). The predicted rate of change is of the order of 1 to 2 mm/y and will be almost imperceptible compared to background rates of change which can be more than 1 m per year, with fluctuations of up to tens of metres during an irrigation season, based on historic trends (MDBA, 2012). The very low rate of change compared to other influences indicates negligible impacts to stygofauna from CSG development.

8.4.2 Aquatic Flora and Fauna Type DEs

The predicted changes to surface water-groundwater flux are outlined in Section 7.6.

No changes to surface water-groundwater flux are predicted where groundwater and surface water are disconnected, along most of the length of the Condamine River and its tributaries. Impacts to Aquatic Flora and Fauna Type DEs in these settings are therefore considered highly unlikely.

Threats to Aquatic Flora and Fauna Type DEs will be buffered where stream flows are regulated by surface water storages (see Section 6.4). The predicted maximum change in surface water-groundwater flux along the Condamine River as a result of CSG development is of the order of 0.2–0.3 ML/d. When introduced to the IQQM hydrological model, this change in flux results in negligible changes to surface water flow. The only detected change was an increase in low flow days by 0.1% at one of the model nodes. The very minor change to flow rates, which is only predicted to occur at one location, indicates negligible impacts to Aquatic Flora and Fauna Type DEs in regulated settings.

In unregulated settings (e.g. in tributaries not captured by the IQQM modelling) where groundwater and surface water are connected, water table drawdown may induce some additional surface water leakage which is not buffered by upstream flows. As outlined in Section 6, refugia in these hydrological settings are the most sensitive components of Aquatic Flora Fauna Type DEs to such a threat.

The numerical modelling undertaken is unable to assess changes to surface water conditions in unregulated settings because they are not included in the IQQM modelling[9]. Therefore, a conceptual approach has been used to assess the significance of potential impacts, as follows:

- Increased surface water leakage as a result of an increased hydraulic gradient from the stream to the water table will be controlled by the hydraulic conductivity of the streambed and the strata which underlie it.
- Investigations undertaken by Lane (1978) confirmed the presence of clayey strata underlying drainage channels throughout the Condamine Alluvium.
- Given that the magnitude of predicted drawdown due to Arrow water production peaks at 1.1 m or less, any increased leakage from surface water would be less than the vertical flux through the clayey strata underlying the drainage channels under a vertical hydraulic gradient of 1.5.
- A conservative estimate of the k_v of clayey sediments is in the order of 0.001 m/d (Fetter 1980) implying that any increased leakage would be no more than 1.5 mm/d greater than the baseline leakage rate.
- The altered leakage would manifest over hundreds of years, such that the rate of change is of the order of 0.0015 mm/d – an undetectable change compared to other influences such as climatic variation.
- These very minor changes in surface water leakage rates indicates negligible impacts to Aquatic Flora and Fauna Type DEs in these settings.

8.4.3 Terrestrial Vegetation Type Des

As discussed in Section 6.4, predicted drawdown to the water table in Condamine Alluvium in response to CSG development presents a potential threat pathway to Terrestrial Vegetation Type DEs where the water table is reasonably shallow. For the impact assessment, the threat pathway is assumed to occur when the water table is within 15 m of the land surface, based on the work of Kath et al. (2014).

The predicted drawdown is small in magnitude (less than 1.5 m in total) and very gradual (of the order of 1 to 2 mm/y) and will be almost imperceptible compared to background rates of change which can be more than 1 m per year with fluctuations of up to tens of metres during an irrigation season, based on historic trends (MDBA 2012). It has been shown the phreatophytic vegetation can adjust to gradual changes in the water table and measured root elongation rates far exceed these predicted rate of drawdown (Canham 2011). Impacts to Terrestrial Vegetation Type DEs are therefore indicated to be negligible.

[9] Unregulated streams, which include a number of tributaries to the main Condamine channel, are also not represented in the CCAM through a specified boundary condition, such as a River cell. Their lack or representation in the CCAM means that (locally) any predicted drawdown is not buffered by increased surface water leakage and, as such, predicted drawdown is overstated. The results, therefore, provide a conservative basis with which to assess potential impacts to DEs in these settings.

Section 9 Summary and Conclusions

The purpose of this report is to help Arrow to meet the requirements of Section 13(b) of the Approval.

The Approval
Section 13(b) of the Approval requires Arrow to prepare "a *fit for purpose numerical simulation* to assess *potential impacts on water resources arising from the action in the project area*, *subsequent surface water-groundwater interactions* in *the Condamine Alluvium* and *impacts to (sic.) dependent ecosystems*".

9.1 Introduction and Conceptualisation

Section 1 of the report explains the requirements of Section 13(b). Section 1.3 describes the approach to responding to the requirements, including selection of a suitably qualified reviewer, and a site visit in August 2015. Section 1.4 provides an introduction to the magnitude of potential impacts, by reference to results presented in the UWIR prepared by QWC (2012a).

Section 2 discusses the importance of conceptualisation: the geometry of the system (including topography), the extent of the Condamine Alluvium, hydrogeology and connectivity, and groundwater flow processes before, during and after CSG production.

9.2 The Action

Section 3 describes the Surat Gas Expansion Project, being "*the action*" whose potential impacts Arrow is required to assess.

9.3 Water Resources

Section 4 Section 3describes surface water and groundwater resources, in order to explore what is known about "*water resources*" in and near the Project area.

9.4 Surface Water – Groundwater Interaction

Section 5 describes the nature of "*surface water – groundwater interactions*" in the area of the Condamine Alluvium.

9.5 Dependent Ecosystems

Section 6 describes "*dependent ecosystems*" (DEs). The primary focus is on Aquatic Flora and Fauna Type DEs and Terrestrial Ecosystem Type DEs.

9.6 Fit for Purpose Numerical Simulation

Section 7 describes the modelling that has been undertaken, and explains how the modelling satisfies the requirement for a "*fit for purpose numerical simulation*". Four types of modelling have been undertaken, including:

- regional scale groundwater modelling, using the Surat CMA groundwater model (the most recent "OGIA model");
- exploratory near field simulation of surface water – groundwater interaction, in order to explore the phenomenon of losing disconnected streams (see Appendix B);
- simulation of groundwater in the Condamine Alluvium using the CCAM; and
- surface water allocation modelling using IQQM.

It seems worthwhile at this stage to revisit the conceptualisation presented at the start of this report, to show that the fit for purpose numerical simulation is consistent with the initial conceptualisation, and to summarise potential impact of Arrow's CSG production on groundwater flows and groundwater in the Condamine Alluvium, before specifically addressing the potential impacts referred to in Section 13(b).

Figure 9-1 shows an idealised schematic cross-section from west to east through the region of interest, showing major hydrostratigraphic units and the Condamine River. This cross-section is conceptually similar to those presented in Section 2.4.

Coal seam gas will be produced from the Walloon Coal Measures, to the west of and beneath the Condamine Alluvium. The process of producing gas requires the removal of water by pumping, during the period of production, in order to lower pressures in the coal seams to levels low enough to cause gas to be released (desorbed). The top of Figure 9-1 shows that the maximum rate of production by Arrow approaches 150 ML/d, that the maximum rate of production will be about 15 years from now, and that production will cease after 65 years. Note that the vertical axis is "broken" and has two scales. This explains the change in slope on the recession side of the orange curve.

Water production curves are based on estimates by CSG producers, but they are simulated by the OGIA model, in such a way that 200 realisations of the OGI model with 200 sets of model parameters leads to 200 sets of water production curves for each producer and the industry as a whole.

Lower pressures in the Walloon Coal Measures will affect regional scale groundwater flows. Running the OGIA model 200 times leads to 200 sets of responses, allowing model uncertainty to be expressed statistically. Historically, groundwater flowed from the coal measures towards the Condamine Alluvium. The Condamine River was the "drain" for the region, and water recharging regional aquifers flowed towards the alluvium and the river. The river no longer receives groundwater over most of its length because of the impact of groundwater abstraction. Lowering pressures in the Walloon Coal Measures will either reduce the rate of groundwater flow towards the alluvium, or in some places reverse the direction of flow so that groundwater flows from the alluvium to the coal measures. The top of Figure 9-1 shows that Arrow's contribution to the maximum change in flux between the Walloon Coal Measures and the Condamine Alluvium will be slightly less than 3 ML/d (based on the so-called high case, r35), over the area of the whole of the Condamine Alluvium, peaking about 45 years from now, with a long slow decline in impact thereafter.

Because of a slight reduction in groundwater inflows to the Condamine Alluvium, there will be a tendency for the water table in the Condamine Alluvium to be lowered further. However, because the water table is already below the bed of the river, leakage from the river to groundwater will increase very little, if at all. The top of Figure 9-1 shows that the maximum increase in losses from the Condamine River to groundwater will be less than 0.13 ML/d, peaking in about 145 years, with a long slow decline in impact lasting almost 3,000 years (again based on the so-called high case, r35).

The fit for purpose numerical solution presented in this report relies on previous models and modelling developing and reviewed by others. The approach includes effects of uncertainty, especially at a regional scale where 200 realisations of aquifer properties were generated, and 200 simulations were performed to predict a range of possible responses to CSG production. That approach has been extended here not by changing the representation of uncertainty but by extending the length of simulations, especially in the Condamine Alluvium Aquifer Model, to allow better appreciation of the impacts on the Condamine Alluvium over a longer period of time.

9.7 Potential Impacts

Section 8 addresses "*potential impacts*" of the Surat Gas Expansion Project, under three headings: water resources, surface water – groundwater interaction and dependent ecosystems. The following conclusions can been made:

Potential impact on groundwater resources

- Production of water to produce CSG will cause depressurisation in the Walloon Coal Measures, and the depressurisation will cause a tendency for groundwater to flow towards the target seams for hundreds and thousands of years until pressures equilibrate at values near those prior to production of CSG.
- Over the footprint of the CCAM, Arrow's contribution to the predicted maximum change in total vertical flux through the base of the Condamine Alluvium for the realisation closest to a median case is predicted to be 2.67 ML/d, which when distributed over 5,321 km^2 of alluvium is equivalent to an average change in flux of 0.18 mm/y in the year when the maximum occurs.
- About 40% of Arrow's water production volume will ultimately come from the Condamine Alluvium (Section 8.2.2), over a period of about 3,000 years.
- The maximum drawdown at the water table in the Condamine Alluvium due to Arrow water production is predicted to be approximately 1.1 m for so-called high and median case realisations (running the CCAM), and approximately 0.8 m for the low case realisation. The maximum drawdown at most locations will occur more than 275 years after the simulated maximum in water production, and may not be reached after 826 years (the end of the CCAM simulation) in some areas (Section 7.6.5.6).
- Potential impacts on groundwater resources can be considered by comparing the predicted maximum change in total vertical flux through the base of the Condamine Alluvium over the footprint of the CCAM due to Arrow water production, which is 2.67 ML/d or 0.98 GL/y for the realisation closest to the median case, with groundwater entitlements of the order of 87 GL/y (Section 4.3.3). It should be noted that groundwater abstraction occurs year after year, while the impact of CSG production will rise slowly over ~150 years and then decline again to zero.

Potential impact on surface water – groundwater interaction

- The water table in the Condamine Alluvium lies below the bed of the Condamine River and its tributaries in nearly all locations. The depth to groundwater is believed to be such that the river and its tributaries function as "losing disconnected" streams. This means that further lowering of the water table is unlikely to cause additional leakage of surface water to groundwater. This is especially the case given that additional lowering of the water table is predicted be of the order of 1 m, less than the threshold required for an unconsolidated aquifer to be classified as a long-term affected area (LAA).

Potential impact on surface water resources

- The maximum change in net groundwater flux to the Condamine River is predicted to be 0.31 ML/d, 0.28 ML/d and 0.17 ML/d for the high, median and low case realisations, respectively (Section 7.6.5.6). The times at which maximum changes in flux are likely to occur vary between 140 and 348 years after the maximum in simulated water production. Note that in spite of the Condamine River being disconnected and losing over most of its length, the CCAM still predicts a net movement of water towards the river, because of connected gaining reaches near the downstream end of the Condamine Alluvium.

- Surface water allocations are managed using the IQQM. When assessed using the IQQM, using the three values of maximum change in net flux to the Condamine River, performance indicators with respect to Environmental Flow Objectives (EFOs) were achieved for all three cases (Section 7.7.3.1) and there were no reductions in the performance indicators with respect to Water Allocation Security Objectives (WASOs) except at IQQM node 184 (Brigalow Town Water Supply), where the Annual Volume Probability is decreased by 0.3% for the high, median and low case realisations (Section 7.7.3.2).

Potential impact on dependent ecosystems

- Consideration of potential impacts on dependent ecosystems (DEs) leads to the conclusion that impacts will depend on the amount of change in water table elevation and the rate of change. The rate of change will be unnoticeable and the amount is so much less than background variations that it is unlikely to affect DEs. As such, the results of the modelling in this study advocate that monitoring of DEs would not be necessary.

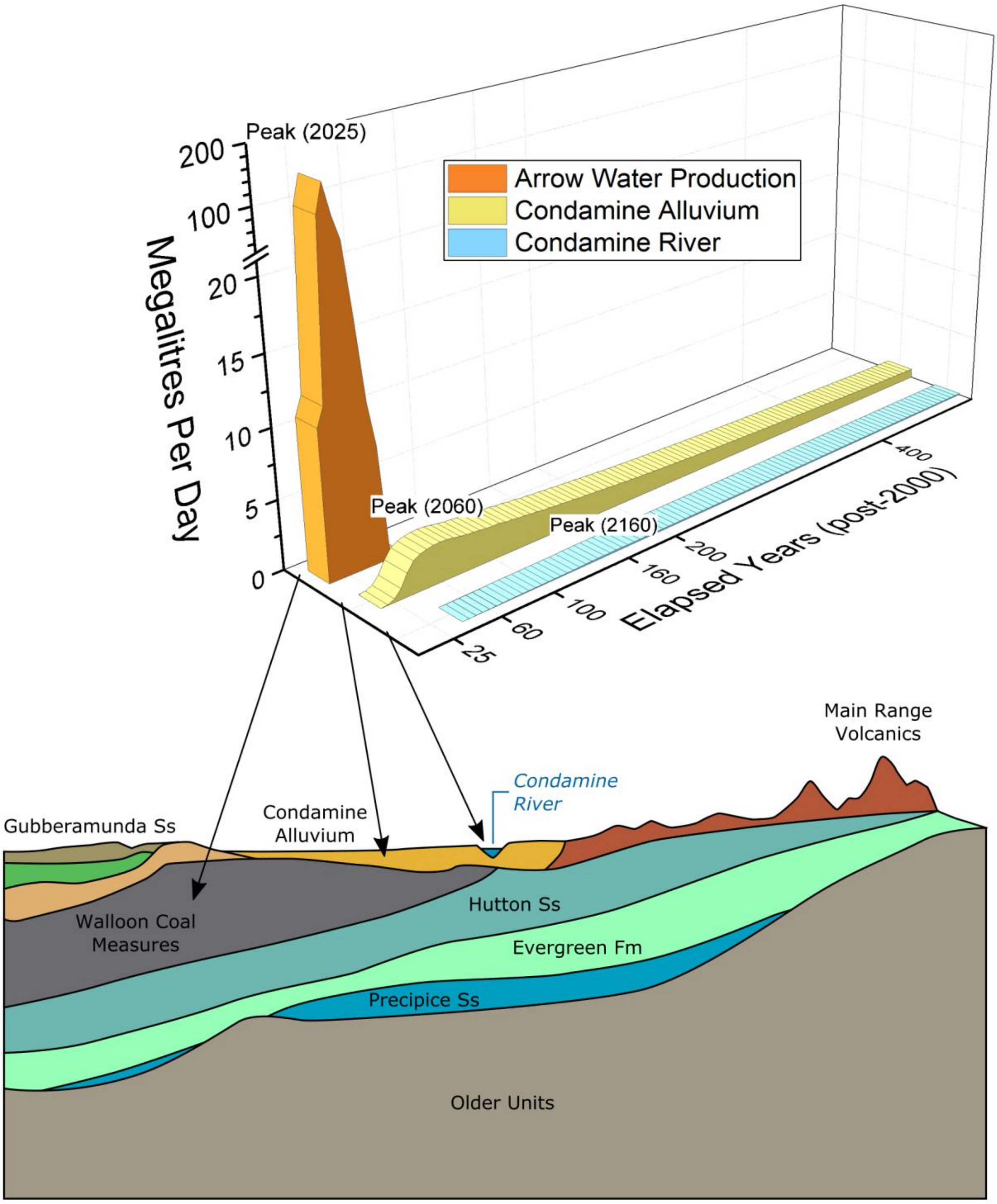


Figure 9-1 Schematic diagram showing fluxes in different parts of the hydrogeological system

Acknowledgements

The modelling results in this report are derived from existing numerical models that were developed by the State of Queensland (State) and supplied to Arrow for use in this study. The models used in this study include the Surat CMA Groundwater Model (Section 7.2.1); the Central Condamine Alluvium Model (Section 7.2.2); and Integrated Quality and Quantity Models (IQQM, Section 7.2.3).

In respect to the State permitting use of the afore mentioned models, it is acknowledged that the State gave no warranty in relation to the models and associated licensed data (including accuracy, reliability, completeness, currency or suitability) and accepted no liability (including without limitation, liability in negligence) for any loss, damage of costs (including consequential damage) relating to any use of the models and associated licenced data. It is further acknowledged that the models and licensed data must not be used for direct marketing or be used in breach of any privacy laws.

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Appendix A
Surat CMA Model Files

Folders

```
\---UWIR_MODEL_V1
    +---EXE
    +---GHB_Realisations
    +---Kx_Realisations
    +---Kz_Realisations
    +---MODEL_BASE
    |   \---MODEL_BASE
    |       \---InitialHeads_bsv2SS023bpa5
    +---MODEL_CSG
    |   \---MODEL_CSG
    |       \---InitialHeads_bsv2SS023bpa5
    +---RCH_Realisations
    \---S_Realisations
```

Files

\---UWIR_MODEL_V1
scenario_update_2014.evt

\---UWIR_MODEL_V1\EXE
allcells.inf
layers.dat
mulmax.exe
mulmax.in

\---UWIR_MODEL_V1\GHB_Realisations
General Head Boundary realisations – 200 files, 1 per realisation (BSv2TRPred019_noBGT.ghb.#)

\---UWIR_MODEL_V1\Kx_Realisations
Horizontal hydraulic conductivity realisations – 200 files, 1 per realisation (Kx.#)

\---UWIR_MODEL_V1\Kz_Realisations
Vertical hydraulic conductivity realisations – 200 files, 1 per realisation (Kz.#)

\---UWIR_MODEL_V1\RCH_Realisations
Recharge realisations – 200 files, 1 per realisation (BSv2TRPred019_noBGT.rch.#)

\---UWIR_MODEL_V1\S_Realisations
Storage coefficent realisations – 200 files, 1 per realisation (S.#)

\---UWIR_MODEL_V1\MODEL_BASE\MODEL_BASE
AllExtraction_BSv2TRPred23_basecase_REV_NOBGT.wel
BSv2TRPred001_noBGT.drn
BSv2TRPred006_noBGT.riv
BSv2TRPred019.bas
BSv2TRPred019_noBGT.lpf
BSv2TRPred023.dis

```
BSv2TRPred023.pcgn
bsv2trpred023_compact.oc
mf2005d32_alt.exe
UWIR_BASE_noBGT.nam
```

\---UWIR_MODEL_V1\MODEL_BASE\MODEL_BASE\InitialHeads_bsv2SS023bpa5

```
Initial heads – 19 files, 1 per model layer (InitHlay#.ref)
```

\---UWIR_MODEL_V1\MODEL_CSG\MODEL_CSG

```
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BSv2TRPred023.dis
BSv2TRPred023.pcgn
bsv2trpred023_compact.oc
evt_varQmax_final_BGT.dat
mf2005d32_alt.exe
UWIR_CSG_noBGT.nam
```

\---UWIR_MODEL_V1\MODEL_CSG\MODEL_CSG\InitialHeads_bsv2SS023bpa5

```
Initial heads – 19 files, 1 per model layer (InitHlay#.ref)
```

File Versions

Discretization (DIS) file - dated 25/03/2013;

Basic (BAS) package file - dated 02/11/2011;

Layer Property Flow (LPF) package, River (RIV) package, Drain (DRN) package, and Well (WEL) package files - dated 14/8/2012;

PCNG solver file - dated 11/11/2014;

Output Control (OC) file - dated 15/11/2011;

Initial head files (one for each model layer) - dated 31/10/2013;

NSMC realisations files - dated 04/04/2014;

Evapotranspiration (EVT) package file, containing the 2014 update of water production data for current and approved petroleum and gas development - dated 29/11/2014;

MODFLOW 2005 executable “mf2005d32_alt.exe” - dated 09/08/2011.

Appendix B
Unsaturated Flow Modelling

CDM Smith

Unsaturated Flow Modelling Near Disconnected Streams

CDM Smith has undertaken some exploratory modelling to assess the phenomenon of disconnected losing streams, in particular to test whether the rate of leakage can reach a maximum even without a clogging layer.

One of the questions of interest was whether or not the initial assertion by Brunner et al. that a clogging layer is needed for disconnection to occur is correct. For this reason, CDM Smith's first exploratory modelling was based on simulating a system similar to that considered by Brunner et al. (2009a), with a clogging layer.

In some respects, Peterson and Wilson (1988) went much further in developing an understanding of unsaturated flow beneath disconnected streams, albeit with software much less sophisticated than current version of FEFLOW. Modelling unsaturated flow at field scale remains challenging.

Hydrogeological properties

Modelling and simulation of variably-saturated groundwater flow requires information about how the hydraulic conductivity varies with degree of saturation. Strata located below the water table are normally assumed to be fully saturated, such that the flow of groundwater in this region represents a special case of variably saturated flow in which only the value of hydraulic conductivity at saturation needs to be known.

To simulate variably-saturated flow, empirical or mathematical relationships are needed to describe how the water content of porous media vary with changes in pressure head (matric potential) and how the hydraulic conductivity varies simultaneously with these changes in the water content.

Relationships between pressure head, water content and hydraulic conductivity can be derived directly from experimental data; from empirical or theoretical mathematical models; or by fitting these models to experimental data. Well-known examples include the models developed by Brooks and Corey (1964), Mualem (1976) and van Genuchten (1980).

The relationship between pressure head and water content in a porous medium is commonly referred to as the water retention curve (WRC) which is often represented as a graph. The value of unsaturated hydraulic conductivity for a specified water content is then evaluated using the WRC and a hydraulic conductivity model that defines the relationship between unsaturated hydraulic conductivity and water content.

Figure B-1a shows examples of WRCs after van Genuchten (1980). Figure B-1b shows hydraulic conductivity values estimated using the conductivity model of Mualem (1976), and typical soil types defined by van Genuchten et al. (1991). The horizontal axes of the plots show volumetric water content in units of volume of water per volume of porous medium, and the vertical axes show pressure head in units of metres of water and relative permeability, where relative permeability is the ratio of unsaturated hydraulic conductivity to saturated hydraulic conductivity.

Figure B-1 shows that when the water content in sand is around 0.2 (approximately 70% of the saturated water content), the pressure head is about 0.1 m, and the relative permeability at that water content is less than 0.05 (i.e. the unsaturated hydraulic conductivity is less than 5% of the saturated hydraulic conductivity). The pressure head is a suction, so water at this water content occurs roughly 0.1 m above the water table (where pressure is atmospheric, or zero relative to gauge).

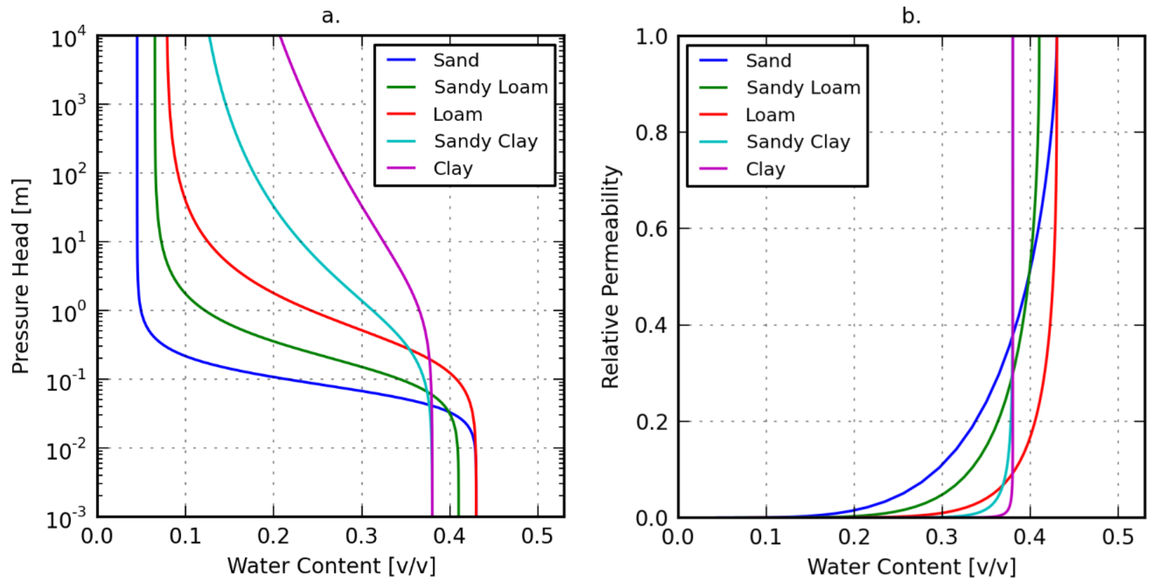

Figure B-1 Example soil moisture characteristics for typical soil types: a. water retention curves after van Genuchten (1980), b. hydraulic conductivity model after Mualem (1976)

Soils of Southeast Queensland

Information about the unsaturated hydrogeological properties of rocks and hydrogeological strata can be sparse within large regional settings, and this is the case within the Condamine alluvium. A review has been undertaken to assess the availability of water retention data for the major soil types of southeast Queensland, with the finding that these data are mostly limited to experimental results contained in Connolly et al. (1997).

The study by Connolly et al. (1997) considered the five most commonly cropped soils in southeast Queensland: Sodosols, Light Vertosols with ≤55% clay, Heavy Vertosols with >55% clay, Red Ferrosols and Red Chromosols-Kandosols. The soils of the Condamine Alluvium are predominantly vertosols (clay soils with shrinking and swelling characteristics that develop deep cracks when dry) with small areas of sodosols and chromsols. Connolly et al. (1997) presented soil moisture characteristics based on experimental data for these five major soil types, which were sampled to a depth of 0.2 m. Pressure heads up to a maximum value of approximately 15 kPa (equivalent to 153 m of suction) were applied to the soil samples.

Figure B-2 shows the experimental results for vertosols, sodosols and red chromosols, which occur over the Condamine Alluvium. The data have been fitted to the van Genuchten-Mualem model using the RECT (v.6.02) code (van Genuchten et al. 1991) and the results are summarised in Table B-1. The water retention data have been fitted to the van Genucthen model with the fitting parameter $m = 1 - 1/n$ (van Genuchten 1980), and the estimated values of hydraulic conductivity are calculated from Mualem's conductivity model (Mualem 1976).

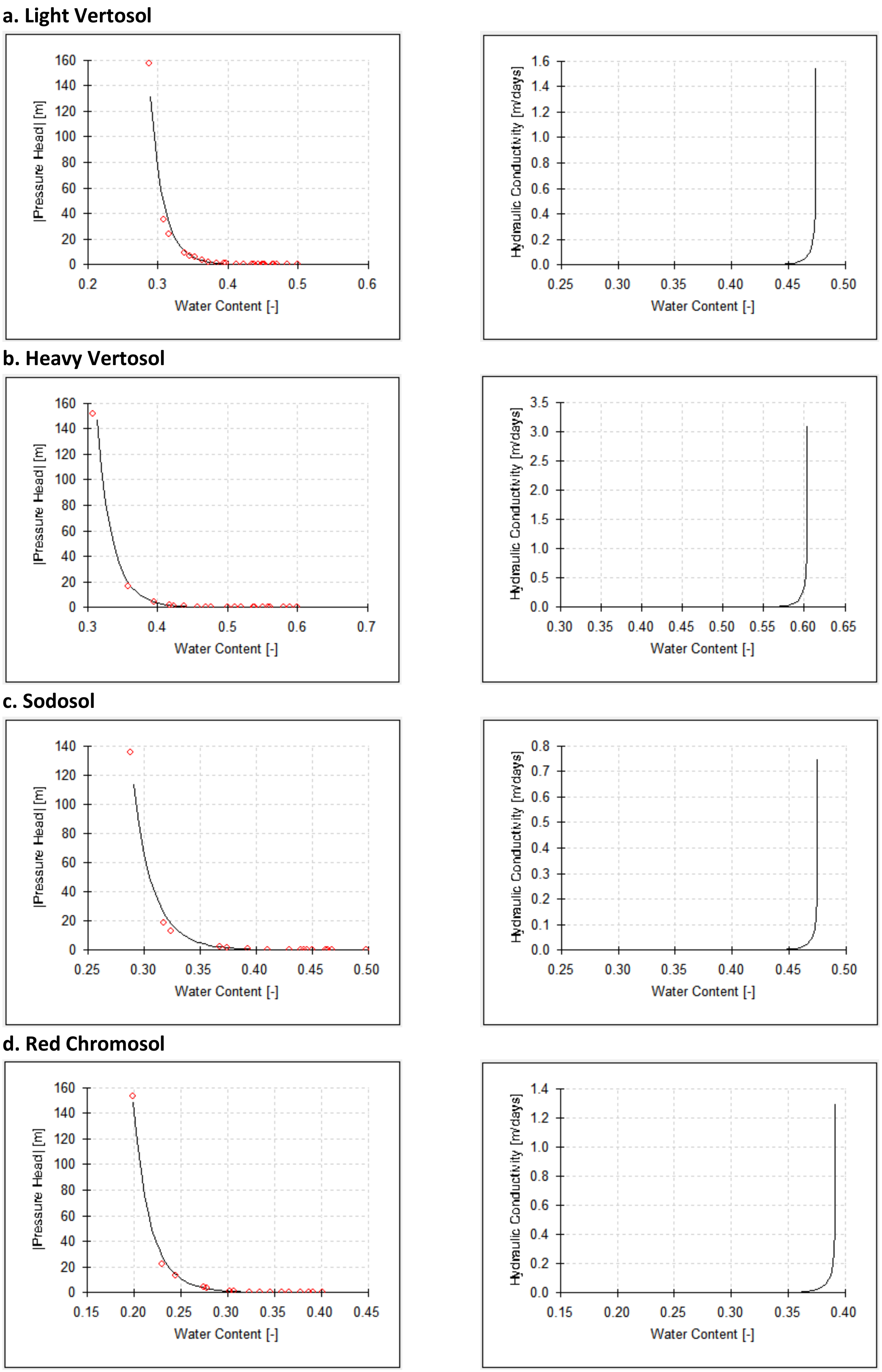

Figure B-2 Measured water retention data (red symbols) from Connolly et al. (1997) fitted to the van Genuchten-Mualem model using the RETC code

For each soil type it can be seen that the estimated values of hydraulic conductivity decrease markedly for values of water content even slightly less than saturation. If the results are compared to the WRCs for typical soil types ranging from sand through loam to clay, the data from Connolly et al. (1997) present as extreme examples of clay soils. If the data are considered to be representative of the major soil types within the Condamine Alluvium, then it follows that even mild desaturation of these soils will cause dramatic decreases in their unsaturated hydraulic conductivity, and very low rates of unsaturated flow can be expected under such circumstances.

Table B-1 Fit of measured water retention data from Connolly et al. (1997) to the van Genuchten-Mualem model using RETC

Soil Moisture Parameter	Unit	Value	Description
Light Vertosol			
α	m^{-1}	22.6	Van Genuchten fitting parameter (fitted)
n	1	1.06	Van Genuchten fitting parameter (fitted)
σ	1	0.5	Mualem model parameter (fixed)
ε	1	0.47	Porosity (fitted)
K_{sat}	$m.d^{-1}$	10	Saturated hydraulic conductivity (estimated from Fig.2)
Heavy Vertosol			
α	m^{-1}	141.3	Van Genuchten fitting parameter (fitted)
n	1	1.07	Van Genuchten fitting parameter (fitted)
σ	1	0.5	Mualem model parameter (fixed)
ε	1	0.60	Porosity (fitted)
K_{sat}	$m.d^{-1}$	18	Saturated hydraulic conductivity (estimated from Fig.2)
Sodosol			
α	m^{-1}	30.69	Van Genuchten fitting parameter (fitted)
n	1	1.06	Van Genuchten fitting parameter (fitted)
σ	1	0.5	Mualem model parameter (fixed)
ε	1	0.47	Porosity (fitted)
K_{sat}	$m.d^{-1}$	5	Saturated hydraulic conductivity (estimated from Fig.2)
Red Chromosol			
α	m^{-1}	16.09	Van Genuchten fitting parameter (fitted)
n	1	1.09	Van Genuchten fitting parameter (fitted)
σ	1	0.5	Mualem model parameter (fixed)
ε	1	0.39	Porosity (fitted)
K_{sat}	$m.d^{-1}$	10	Saturated hydraulic conductivity (estimated from Fig.2)

Other studies

Connolly et al. (2001) used APSIM (Agricultural Productions Systems Simulator) to predict effects of changing soil condition on crop growth and yield for the five major soil types in southeast Queensland. The modelling relied on the experimental results from Connolly et al. (1997) with Table 3 of that paper presenting the values of WRC parameters used for the modelling.

Yee and Silburn (2003) undertook water balance modelling to estimate rates of deep drainage under various land uses within the Queensland portion of the Murray-Darling Basin. The study area incorporated ten river catchments, including the Condamine River catchment. No experimental data or field-based WRCs were presented. The report stated that "Soil parameters were extracted from a large number of measurements made by CSIRO, NR&M and DPI". The report also notes that measurements of saturated hydraulic conductivity were sourced from Bell et al. (1997); however, the study by Bell et al. is specific to Red Ferrosols that are not found within the Condamine Alluvium.

Consideration of previous work

Preliminary modelling of interaction between a river channel and an underlying water table in vertical section has been undertaken to explore the results presented in the series of papers by Brunner et al. (2009a, 2009b, 2010, 2011) and to understand how these results could in principle be applied to the Condamine River and the underlying alluvial aquifer. The papers explore the process of transition from a connected state to a disconnected state, associated with the development of an unsaturated zone beneath a clogging layer at the base of the river bed.

The river and water table are said to be "connected" if the water table is in direct contact with the river bed (gaining or losing conditions); the river is said to be "disconnected" if the depth of the water table below the river bed is sufficiently large that variation in the elevation of the water table does not significantly affect the rate of infiltration from the river bed (losing conditions only); a state of "transition" from connected to disconnected is said to occur within a range of water table elevations within which variation of elevation causes significant variation in the rate of infiltration from the river bed (losing conditions only).

A potentially restrictive aspect of the conceptualisation forming the basis for these studies is the assumption of uniform and isotropic hydrogeological properties in the subsurface, with the exception of the introduced "clogging" layer at the base of the river bed, and steady state flow.

The authors concluded that without a clogging layer the river and water table cannot disconnect, and that the presence of the clogging layer was a "necessary but not sufficient criterion for disconnection to occur."

This conclusion can be interpreted as saying that there is a lack of potential for disconnection to occur in isotropic and homogeneous systems under steady flow conditions. If correct, then the lack of potential for disconnection in an isotropic, homogeneous and steady flow system leads to questions about the types of heterogeneity and flow dynamics that could create a potential for disconnection. The authors have considered one specific example of a clogging layer, but have not explored other possibilities.

Within the context of a homogeneous and isotropic system that cannot otherwise disconnect, Brunner et al. first impose a clogging layer as a mechanism for disconnection, and then subsequently identify the clogging layer as the key hydrologic control on the potential for disconnection. This approach appears to be circular.

Within the above context, it follows that:

- There could be other conceptualisations of layered heterogeneity beneath the river that could also lead to unsaturated flow conditions and potential for disconnection between the river and water table;
- Vertical anisotropy could also create a potential for disconnection; and
- Flow dynamics in the river (e.g. fluctuations between wet and dry conditions) could similarly create a potential for disconnection, even for homogeneous and isotropic conditions.

Brunner et al. (2009a) base their work on the following:

- Conceptualisation is based on a straight river, with homogeneous hydrogeological properties, steady state flow, and the presence of a clogging layer at the base of the river bed;
- The clogging layer is considered to be a "necessary but not sufficient criterion for disconnection to occur", but the paper does not consider other examples of vertical heterogeneity or

anisotropy that are characteristic of interbedded fluvial sediments, and how these characteristics might similarly influence the potential for disconnection;

- A precise criterion (eq. 5) is developed (almost by assumption), which allows determination of whether the river and water table can disconnect; and which depends on the thickness and conductivity of the clogging layer; thus, it follows that other examples of heterogeneity would lead to different criteria for disconnection;
- If the water table below a river is sufficiently deep, then changes in the depth of the water table are believed not to influence the infiltration rate from the river (disconnected state); and
- The unsaturated soil properties (van Genuchten parameters) used for these simulations appear to be the default properties in RETC, without any consideration of whether or how these material properties might apply in Australia or elsewhere.

Exploratory FEFLOW modelling

Three modelling approaches have been tested using FEFLOW, to explore the processes of connection and disconnection beneath losing rivers. Prescribed head boundary conditions are defined on the river bed (the inflow boundary) and lateral boundaries of the aquifer (the outflow boundaries).

Three types of situations have been considered:

Saturated flow (e.g. Figure B-1):

- specified as a free and movable water table with saturated hydraulic conductivity;
- no disconnection can occur;
- vertical anisotropy causes 'necking' of the water table geometry beneath the river bed, with larger anisotropy resulting in a longer 'neck', and smaller vertical hydraulic conductivity resulting in smaller infiltration rates from the river; and
- a clogging layer has not yet been simulated but specification of a clogging layer would be imprecise due to the BASD (Best Adaptation to Stratigraphic Data) method used by FEFLOW with associated variations in mesh geometry and undesirable averaging of properties.

Variably-saturated approach (e.g. Figure B-2):

- specified as a phreatic water table with saturated hydraulic conductivity;
- using a variably-saturated approach, model elements can become dry, causing disconnection, but unsaturated flow is not simulated; thus, when dry cells occur between the river bed and water table the river and water table effectively disconnect and there is no simulation of water movement from the river to the water table;
- vertical anisotropy causes 'necking' of the water table geometry beneath the river bed;
- a clogging layer is not yet simulated; the geometry of the clogging layer could be specified precisely, but there is little point if it causes dry elements;

Unsaturated flow (e.g. Figure B-3):

- Richards' Equation with hydraulic conductivity varying with saturation;
- saturation of elements can vary, with variably-saturated flow occurring from the river bed to the water table;

- steady state solutions are difficult to obtain (do not converge) without quasi-steady initial conditions;
- progress toward quasi-steady solutions can be very (impractically) slow due to small time steps required to achieve convergence and numerical stability (some simulations ran for a week on fast 12-core workstations with very little change); and
- vertical anisotropy can cause desaturation beneath the river and disconnection from the water table without the presence of a clogging layer.

The purpose of this work was to explore whether or not it would be feasible to undertake systematic modelling to test the dynamics of disconnected losing streams, and in particular to test whether lowering the water table by say 1 m beneath the Condamine River, when the water table is already metres below the river bed, would have a significant effect on rates of leakage from the river.

The work is incomplete, but was started in the hope that it may contribute to the development of a fit for purpose numerical simulation for the purposes of meeting the requirements of Section 13(b) of the Approval. The results of this effort so far suggest that while this approach may help in the longer term, the work is sufficiently theoretical and difficult, that it is not ready for application. The results so far suggest that rates of leakage into clays beneath the Condamine Aquifer are already very small, perhaps smaller than expected.

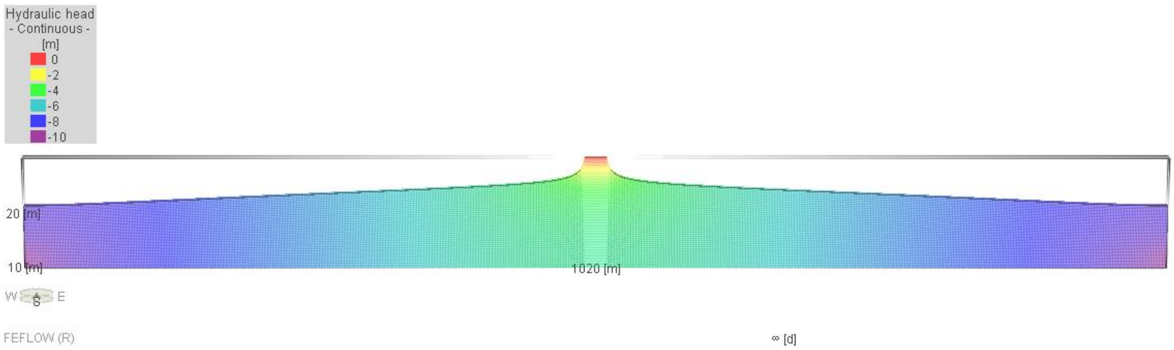

Figure B-3 Example FEFLOW result for saturated flow (free and movable water table) and anisotropy ratio 100

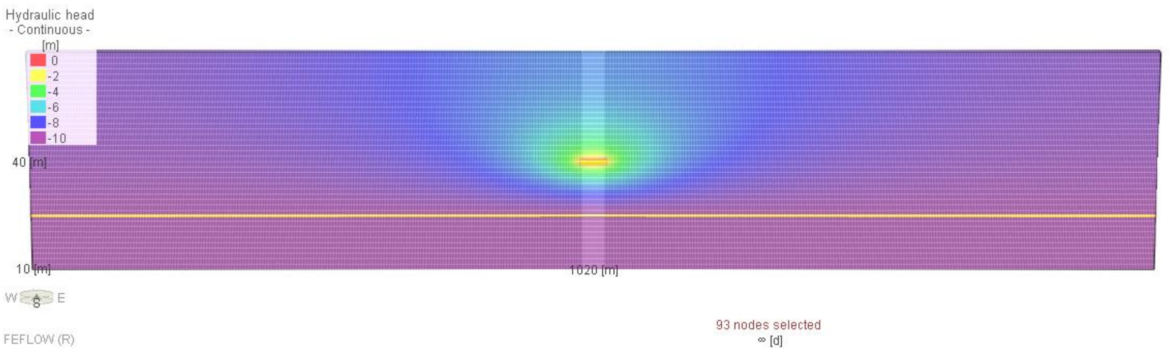

Figure B-4 Example FEFLOW result for variably-saturated approach (phreatic water table) and anisotropy ratio 100

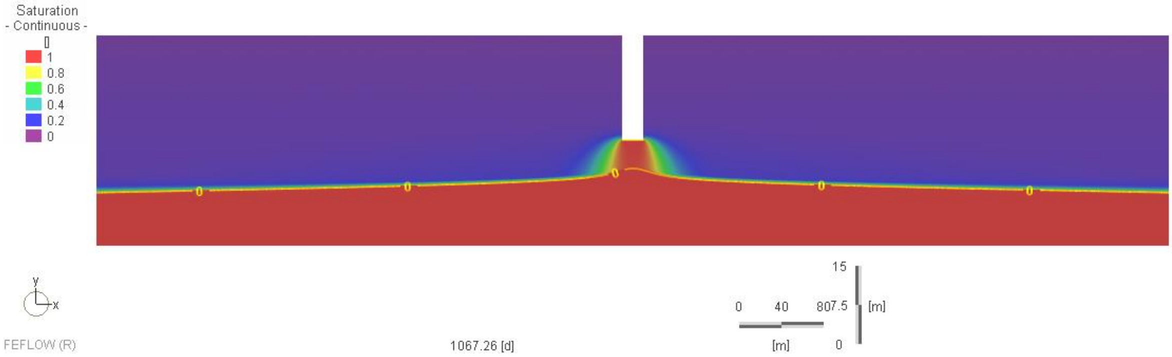

Figure B-5 Example FEFLOW result for unsaturated flow (Richards Equation) and anisotropy ratio 100

Appendix C

CCAM Files

Files

The following CCAM files were supplied for use in this study:

```
ccatr5v1.bcf
ccatr5v1.pg5
ccatr5v1_pred.ato
ccatr5v1_pred.bas
ccatr5v1_pred.fwl
CCATR5v1_pred.ghb
ccatr5v1_pred.obs
CCATR5v1_pred.RCH
CCATR5v1_pred.riv
ccatr5v1_pred_base.hds
ccatr5v1_pred_base.nam
ccatr5v1_pred_base.out
cdmn_derm_ibound.inf
layers_cdmn.dat
```

File Versions

MODFLOW Block-Centered Flow (BCF) package file – dated 19/04/2011;

MODFLOW Name (NAM) file, Basic (BAS) package file, Recharge (RCH) package file, River (RIV) package file, General Head (GHD) package file, and Observations (OBS) input file – dated 10/05/2013;

SURFACT PCG5 solver (PG5) file – dated 13/04/2011;

SURFACT Adaptive Time Stepping and Output Control (ATO) package, Fracture Well (FWL) package file – dated 10/05/2013.

Appendix D
IQQM Files

Files

The following IQQM files were supplied for use in this study:

IQQM Basin 422 – Middle Condamine (ROP)

```
IQQM executable and system files: RLIQQM6NT.exe
Pre-Development Model files
Middle ROP Model – 1106A files
Post-processing programs BigLQ, MADCAL (MC) and CONFLOT
Batch files to run IQQM and processing programs
SW_Middle_IQQM_Summary.xlsm to summarise results
```

IQQM Basin 422 – Upper Condamine (ROP)

```
IQQM executable and system files: RLIQQM6NT.exe
Pre-Development Model files
0909B – Upper ROP Model files
Post-processing programs BigLQ, MADCAL (MC) and CONFLOT
Batch files to run IQQM and processing programs
SW_RESULTS_Upper_Condamine_Summary.xlsm to summarise results
```

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