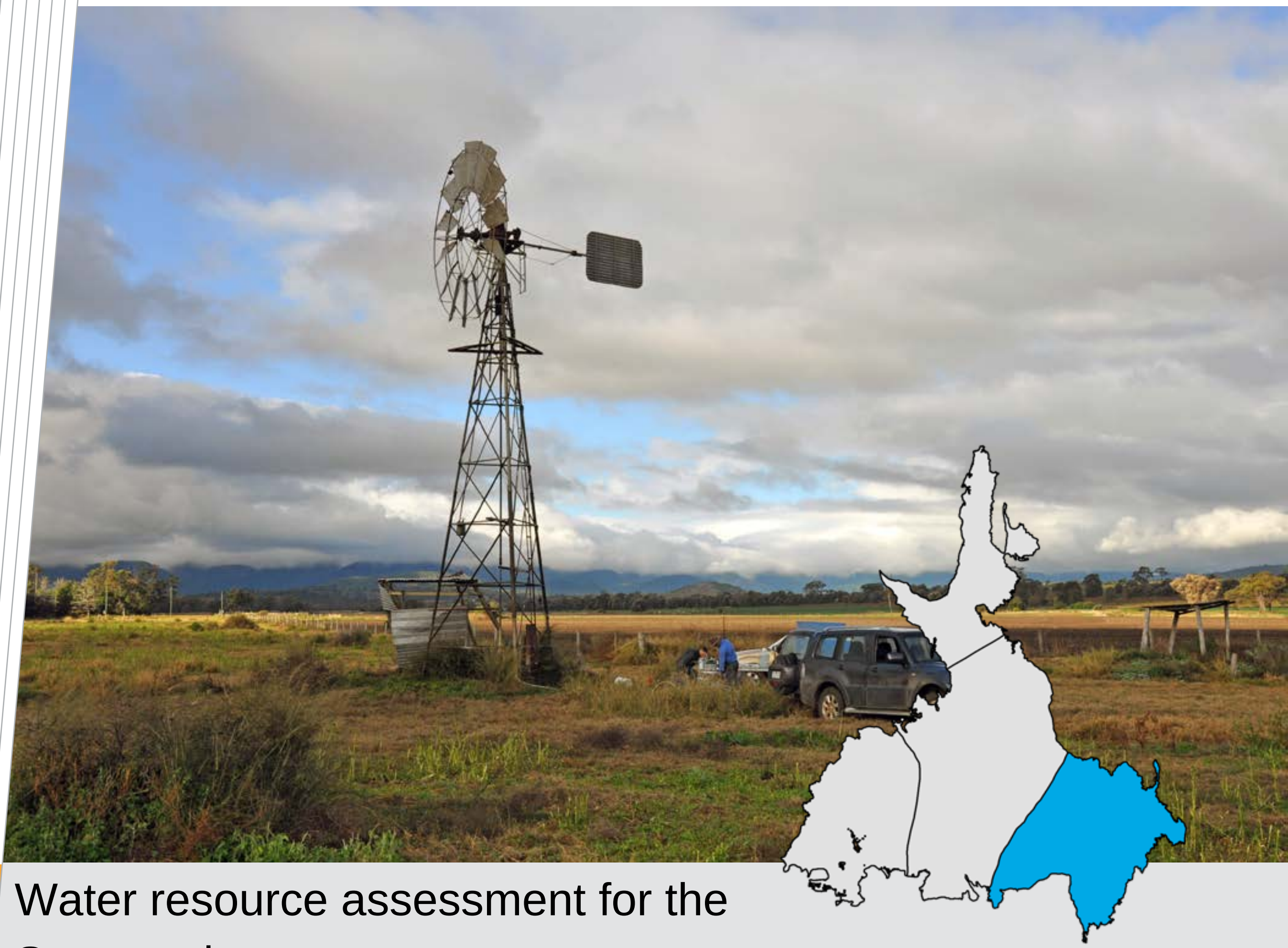

Water resource assessment for the Surat region

A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment

Edited by Smerdon BD and Ransley TR

21 December 2012

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Australian Government
Department of Sustainability, Environment, Water, Population and Communities
National Water Commission

Great Artesian Basin Water Resource Assessment acknowledgments

The Assessment was prepared by CSIRO for the Australian Government under the *Water for the Future* initiative and the National Water Commission (NWC) Raising National Water Standards Program. Geoscience Australia was a significant contributor to the Assessment. Important aspects of the work were undertaken by Sinclair Knight Merz, Flinders University, South Australian Department of Environment, Water and Natural Resources (formerly Department for Water), and MA Habermehl Pty Ltd.

The Assessment was guided and reviewed by a Steering Committee, which had representatives from the following organisations: Australian Government Department of Sustainability, Environment, Water, Population and Communities; National Water Commission; Australian Bureau of Agricultural and Resource Economics and Sciences; New South Wales Office of Water; the Queensland Department of Natural Resources and Mines (formerly the Department of Environment and Resource Management); Queensland Water Commission; South Australian Department of Environment, Water and Natural Resources (formerly Department for Water); and the Northern Territory Department of Land Resource Management (formerly Northern Territory Department of Natural Resources, The Arts and Sport – NRETAS).

Valuable input into this report was provided by the Technical Reference Panel. The Panel included representatives from the same organisations as on the Steering Committee, plus representatives from the following organisations: Australian Government Bureau of Meteorology; CSIRO; and Geoscience Australia. This report benefited from input from Stuart Bunn, Rod Fensham, Travis Gotch, Dale McNeil, Noel Merrick, Claus Otto, and Hugh Wilson.

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Director's foreword

Following the November 2006 Summit on the southern Murray-Darling Basin (MDB), the then Prime Minister and MDB State Premiers commissioned CSIRO to undertake an assessment of sustainable yields of surface water and groundwater systems within the MDB. The project (completed in 2008) was a world first for rigorous and detailed basin-scale assessment of the anticipated impacts of climate change, catchment development and increasing groundwater extraction on the availability and use of water resources.

Following the success of the MDB project, the Council of Australian Governments (COAG) agreed to expand the CSIRO assessments of water yield so that, for the first time, Australia would have a comprehensive scientific assessment of water yield in all major water systems across the country. This would allow a consistent analytical framework for water policy decisions across the nation. Thus in March 2008 COAG commissioned three further Sustainable Yields projects (for northern Australia, south-west Western Australia and Tasmania), providing a nation-wide expansion of the assessments. These were completed in September 2009, December 2009 and February 2010, respectively.

Determinations of sustainable yield and/or over-allocation require choices by communities and governments about the balances of outcomes (environmental, economic and social) sought from water resource management and use. These choices are best made on the basis of sound technical information, with the fundamental underpinning information being a robust description of the extent and nature of the water resource.

The Great Artesian Basin Water Resource Assessment (the Assessment), undertaken by CSIRO and partners together with other consultants, provides this fundamental underpinning information for the Great Artesian Basin (GAB).

Consistent with the previous Sustainable Yields projects, this assessment provides an analytical framework to assist water managers in the GAB to meet National Water Initiative (NWI) commitments. A key outcome of the Assessment is to communicate the best available science to the Australian Government in order to advance basin groundwater management under the NWI water reform agenda. It provides an information base that supports both investment and the environment, and that underpins the capacity of Australia's water management regimes to deal with change both responsibly and fairly (NWI Clause 5). In accordance with NWI Clause 40, the Assessment will inform the implementation of existing water plans through providing information about the status of GAB aquifer systems, data from which could be used to better monitor the performance of water plan objectives, outcomes and water management arrangements. The Assessment will also assist in achieving Action 79 under the NWI in relation to better recognising the different types of surface water – groundwater interactions.

Dr Bill Young

Director, Water for a Healthy Country Flagship

CSIRO

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Data availability

Data produced from the Great Artesian Basin Water Resource Assessment, including map products and GIS data, can be obtained from Geoscience Australia.

For further information on data availability, please visit: <www.ga.gov.au/>.

Acronyms, initialisms and shortened forms

3D	three dimensional
ANAE	Australian National Aquatic Ecosystems
APLNG	Australia Pacific Liquefied Natural Gas
Assessment	the Great Artesian Basin Water Resource Assessment
BRS	Bureau of Rural Sciences (now Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) which itself was formed in 2010 following the merger of the Australian Bureau of Agricultural and Resource Economics (ABARE) and the BRS)
CMB	chloride mass balance
CSG	coal seam gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DERM	Queensland Department of Environment and Resource Management (as per functional capability to 26 March 2012)
DEWNR	South Australian Department of Environment, Water and Natural Resources (formerly DFW: Department for Water)
DFW	Department for Water (now DEWNR)
DLRM	Northern Territory Department of Land Resource Management (formerly Northern Territory Department of Natural Resources, The Arts and Sport – NRETAS)
DWE	New South Wales Department of Water and Energy
EIS	environmental impact statements
EPBC	the Commonwealth’s Environment Protection and Biodiversity Conservation Act 1999
GA	Geoscience Australia
GAB	Great Artesian Basin
GABCC	Great Artesian Basin Coordinating Committee
GABBRP	Great Artesian Basin Bore Rehabilitation Program
GABSI	Great Artesian Basin Sustainability Initiative
GDE(s)	groundwater-dependent ecosystem(s)
GLNG	Gladstone Liquefied Natural Gas
HEVAE	High Ecological Value Aquatic Ecosystems
ICS	International Commission on Stratigraphy
IPCC	Intergovernmental Panel on Climate Change
LGA(s)	local government area(s)
NRETAS	Northern Territory Department of Natural Resources, The Arts and Sport (now Northern Territory Department of Land Resource Management – DLRM)
NWC	National Water Commission
NWI	National Water Initiative
QCLNG	Queensland Curtis Liquefied Natural Gas
QWC	Queensland Water Commission
ROP	resource operations plan
RSF(s)	recharge scaling factor(s)
SAALNRMB	South Australian Arid Lands Natural Resources Management Board
SEWPaC	Australian Government Department of Sustainability, Environment, Water, Population and Communities
SRES	Special Report on Emission Scenarios

Units of measurement

Measurement units	Description
L	litre
kL	kilolitres, 1000 litres
ML	megalitres, 1,000,000 litres
GL	gigalitres, 1,000,000,000 litres
TL	teralitres, 1,000,000,000,000 litres
D	Darcy
mD	milliDarcy
mg	milligrams
mAHD	metres above Australian Height Datum
mASL	metres above sea level
mBGL	metres below ground level
Ma	million years

Executive summary

About the Assessment

Since 2007, CSIRO has been undertaking scientific assessments of current and future water availability in major water systems across Australia through its Sustainable Yields projects. To date, rigorous assessments of the anticipated impacts of climate change, catchment development and increasing groundwater extraction on the availability and use of water resources have been completed for the Murray-Darling Basin, northern Australia, south-west Western Australia and Tasmania. The underlying aim has been to provide consistent water resource assessments to guide water policy and water resources planning.

Determinations of sustainable water resource development and allocations require choices by governments and communities about the balance of outcomes (environmental, economic and social) sought from water resource management and use. These choices are best made on the basis of sound scientific information, particularly a robust description of the extent, variability and nature of the water resource. Consistent with the previous Sustainable Yields projects, the Great Artesian Basin Water Resource Assessment (the Assessment) provides an analytical framework to assist water managers in the Great Artesian Basin (GAB) to meet National Water Initiative commitments.

This report presents the findings of the Assessment for the Surat region – one of four reporting regions in the Assessment, including the Surat, Central Eromanga, Western Eromanga and Carpentaria regions. The region reports are summarised in 16-page summary reports for a general audience. Similarly, the whole-of-GAB report is summarised as a synthesis for a general audience. Five technical reports provide additional scientific detail underpinning the region reports. Other scientific outputs include a computer-coded groundwater flow model, data used and produced in the Assessment (housed at Geoscience Australia), and a three-dimensional visualisation of the GAB.

The Assessment has completed a reappraisal of the latest geological and hydrogeological information for the GAB. This reappraisal has led to an update of the conceptualisation of how the groundwater system operates – an update of the conceptual model. The long-standing conceptualisation by Habermehl (1980) viewed the GAB as a single, large, contiguous groundwater flow system in which aquifers were considered to be laterally continuous across the extent of the entire GAB. Some findings of the Assessment reinforce concepts that have been known previously, whereas others present a new understanding.

The Great Artesian Basin

The GAB contains an extensive and complex groundwater system. It encompasses several geological basins that were deposited at different times in Earth's history, from 200 to 65 million years ago in the Jurassic and Cretaceous periods. These geological basins sit on top of deeper, older geological basins and in turn, have newer surface drainage divisions situated on top of them (e.g. the Lake Eyre and Murray-Darling river basins). In this context – as a groundwater basin – the GAB is a vast groundwater entity stretching across one-fifth of Australia.

Groundwater resources in the GAB support many activities including pastoral, agricultural, mining and extractive industries and inland population centres – and the demand for groundwater is growing. Properly managing these groundwater resources, for often competing interests, requires a better understanding of how the groundwater basin works. The Assessment outlines the current status of groundwater resources in the GAB and the potential impacts of climate change and resource development on those water resources.

Key findings

Knowledge of the GAB has gradually evolved since the late 1800s. The new findings of the Assessment include:

- Establishment of a formal definition of underlying aquifers that are in contact with aquifers of the GAB. In addition to these direct connections, the Assessment has also identified locations where the structure of hydrostratigraphic units in the GAB has been inherited from deeper geological structures.

- Development of new categorisation for GAB hydrostratigraphy. This expands previously defined 'aquifers and aquitards' into five gradations that better represent the variation in geological formations. In combination with these refined categories, existing data for hydraulic properties (i.e. porosity and permeability) have been summarised for specific formations.
- A revised location of the western extent of the GAB in the Coonamble Embayment. The revised boundary has been shifted between 10 and 30 km to the east and approximately 60 km to the south based on the interpretation of geologic data. The current Water Sharing Plans in New South Wales were developed before the revised location of the GAB in the Coonamble Embayment had been identified.
- A revised description of the complex eastern groundwater divide between the Surat and Clarence-Moreton basins. For groundwater in Upper Cretaceous formations, the watertable divide delineates the boundary. For groundwater in the Lower Cretaceous and Jurassic formations, a different groundwater divide exists that is aligned with a structural feature called the Helidon Ridge.
- Preparation of the first ever maps of a regional watertable. These provide a basis to evaluate relationships between groundwater recharge and discharge for non-artesian portions of the GAB, as well as a consistent data source to further investigate interaction between groundwater and surface water.
- Preparation of the first ever maps of groundwater levels representing the Cadna-owie – Hooray Aquifer and equivalents that include faults. The amount of vertical displacement from faulting is variable, but interpolation of groundwater levels where faults act as barriers to groundwater flow has led to a new perspective of groundwater conditions.
- Compilation of groundwater level maps for 20-year intervals beginning in 1900. These maps illustrate the decline in groundwater levels in the early part of the last century, but more recently an increase (recovery) of groundwater levels is evident from bore capping and water piping activities.

Geology of the Surat region

The Surat region (Figure 2.1) is bounded by the Great Dividing Range to the east and the Eulo and Nebine ridges (Figure 5.2) to the west. The extent is defined by the exposure (outcrop) of the Jurassic-aged sediments in the north and the Coonamble Embayment in the south. The region is approximately centred on the geological Surat Basin, which sits on top of the older Bowen Basin.

The geological history underpins the nature of the geological formations observed now – the rock layers that form aquifers and aquitards of the GAB. The sequence of Jurassic to Middle Cretaceous sediments in the Surat region were deposited on top of older geological basins. It is these underlying basins that create the structure and general shape of the GAB. Below the deepest part of the Surat Basin, the older Permian–Triassic Bowen Basin is located within a north-to-south trough and extends southward to the Gunnedah Basin (Figure 5.6). Because the GAB is situated on top of these deeper geological basins, there are some locations where GAB aquifers are connected to aquifers in the deeper basins. The connections form a patchwork across the Surat region. Direct connection of aquifers occurs for approximately 10 percent of the region, and is shown in Figure 5.7.

Properties of aquifers and aquitards

Information about the physical rock properties that describe the ability to store water (porosity) and conduct water (permeability) have been collated from state-agency databases. The geological formations that contain aquifers have average permeability values between 100 and 1000 milliDarcys (mD), with only a few measurements below 10 mD. This is equivalent to approximately 0.1 to 1 m/year of horizontal groundwater movement. The geological formations known to contain aquitards have average permeability values between 10 and 100 mD, which is equivalent to approximately 1 cm/year of horizontal groundwater movement.

Permeability variation for the Surat region aquifers does not appear to differ greatly, with average values being 426 mD for the Hutton Sandstone and 320 mD for Precipice Sandstone (Figure 5.11). The average permeability value for the Surat region aquitards is 67 mD for the Walloon Coal Measures and 87 mD for the Evergreen Formation (Figure 5.12).

There are relatively few measurements for aquitards compared to aquifers in the Surat region. The permeability values reported in existing state-agency databases are predominantly those of sandstone in these formations and are likely to be skewed toward higher values within a particular formation. The permeability values may also not accurately represent in-situ conditions considering the laboratory testing techniques.

Current (2010) groundwater conditions

Primarily, groundwater use in the Surat region has been for pastoralism, with increasing use for stock, town water, and irrigation over the past century. More recently, mining interest has expanded from coal to the potential for coal seam gas (CSG). Extraction of CSG requires pumping groundwater to release gas from the coal, which can lead to decreased water levels in overlying and underlying aquifers. Groundwater resources in the Surat region are managed by two jurisdictions (New South Wales and Queensland), each having different legislation.

The Assessment mapped an approximate regional watertable for the entire GAB. Mapping the watertable in the vicinity of river channels reveals how the groundwater interacts with river water. The watertable is sympathetic with the topography and located within all the GAB aquifers and aquitards that are exposed along the western slopes of the Great Dividing Range. It then passes into the Rolling Downs Group (Winton and Mackunda Formations) which abuts the intake beds and dips gently basinward (Figure 5.14).

Groundwater levels were mapped for the Cadna-owie – Hooray Aquifer and equivalents at 20-year increments, to assess the evolution of groundwater conditions since 1900 (Figure 6.1). Groundwater levels in the Surat region are highest along the northern, eastern and southern margins of the region, where the aquifers are exposed near the intake beds. The resultant maps illustrate the spatial distribution of groundwater levels, from which groundwater flow directions can be inferred, and influence of faults on groundwater levels. For some locations in the region, groundwater levels have increased in the most recent increment (2000 to 2010), illustrating the benefit of bore capping and water piping activities from the Great Artesian Basin Sustainability Initiative (GABSI).

The annual water budget components for the Surat region are shown in Table 7.1 for current (circa 2010) conditions, which have been calculated from existing groundwater data (groundwater levels and chemistry). There is a degree of uncertainty about each piece of the water budget. This can lead to a range of overall water budget values – that have either been determined from a single method (having a range of uncertainty) or from using the findings from different studies. The regional water budget components suggest that in the Surat region, the Cadna-owie – Hooray Aquifer and equivalents are not in equilibrium, having greater outflows then inflows.

Future groundwater conditions

An existing large-scale groundwater model (GABtran) was used to estimate the impact of climate and development on groundwater levels in the GAB by 2070. The model – originally developed for the Great Artesian Basin Sustainability Initiative in 2006 – simulates groundwater levels in the Cadna-owie – Hooray Aquifer as a single layer spanning the GAB and was developed using the Habermehl (1980) conceptualisation of the GAB. Based on the single layer approach and having been calibrated to sparse data, GABtran is a simplified representation of the groundwater conditions of the Cadna-owie – Hooray Aquifer and equivalents and is sensitive to rates of recharge and groundwater extraction. However, this was the only model that considers the main aquifers across the GAB and has been shown to represent the change in groundwater levels at such a large scale.

The modelling considered different scenarios of climate and groundwater development. The future climate scenario included a change in rainfall and evaporation, which would produce different groundwater recharge rates occurring at the intake beds in 2070. The future groundwater development scenarios included consideration of changing rates in groundwater extraction. In the Surat region, these changes include a reduction in extraction due to bore rehabilitation under the GABSI. The modelling scenarios included:

- Scenario A (historical climate and current development)
- Scenario C (future climate and current development)
- Scenario D (future climate and future development).

The future scenarios included the wet extreme, median and dry extreme future climates (i.e. scenarios Cwet, Cmid, Cdry, Dwet, Dmid and Ddry). These future climate scenarios included existing groundwater recharge rates spanning between 38 percent lower under the dry extreme climate and 54 percent higher under the wet extreme climate. In addition to the future climate with current (circa 2010) groundwater development, consideration was given to a scenario of future climate with future development – created by increasing rates of groundwater extraction.

Figure 3.5 shows the change in groundwater levels from 2010 to 2070 under the median future climate scenario and current groundwater development. Under current groundwater development, GASBI and previous Australian Government programs had achieved approximately 75 percent of the total expected groundwater savings, and it is assumed that GABSI had been concluded in 2010. Under the current groundwater development and future climate scenario, groundwater development from bores is 232 GL/year. Groundwater levels decrease in the north and south-west. Under the median future climate and wet extreme future climate, groundwater levels increase in the south-east because groundwater recharge is greater than discharge. Under the dry extreme future climate, groundwater levels decrease in the south-east – because of lower groundwater recharge rates – and the level of groundwater extraction is greater than replenishment.

Figure 3.9 shows the change in groundwater levels from 2010 to 2070 under the median future climate and future groundwater development. Under future groundwater development, GABSI is assumed to run to full completion, achieving 100 percent of the total expected groundwater savings. Under the future groundwater development and future climate scenario, groundwater development from bores is 141 GL/year. For the scenario of median future climate and future groundwater development, at least 50 percent of the region has a gradual recovery of groundwater levels assuming GABSI continues to completion, and that all eligible artesian bores remaining to be controlled at 2010 are controlled.

The GABtran model was suitable for estimating the effects of future climate and development across the GAB, but not the effects of groundwater extraction related to CSG development. CSG development requires extracting groundwater to release gas from the coal. These groundwater extractions occur in different geological formations than are represented in the GABtran model.

For the Surat region, a partnership with the Queensland Water Commission (QWC) was established to use results from the existing groundwater flow model developed by the QWC (Figure 3.2) for assessing the impact of future CSG development (Figures 3.7 and 3.8). The QWC model has a more complex conceptualisation than GABtran, with the hydrostratigraphy represented by 19 layers. The implications of including any of the additional complexities in an updated version of the GABtran model is unknown. It can be reasonably assumed that in order to maintain a calibrated model, significant revision of the parameters of the model would be required. A difference in model layer thickness, hydraulic properties, or leakage from other layers would lead to a different modelling outcome.

Should a new groundwater model be developed for the GAB, the geological features outlined in the Assessment should be considered explicitly. Inclusion of multiple layers, connectivity with overlying and underlying geological formations, and the presence of faults in a new regional-scale groundwater model could potentially improve the predictive ability under future scenarios of climate change and groundwater development. However, such an advanced and complex model would require sufficient data to achieve a representative groundwater condition.

Risks to Great Artesian Basin springs

Many ecosystems depend on groundwater from the GAB aquifers. These groundwater-dependent ecosystems (GDEs) range in size from small vents to large mounds and may be surrounded by wetlands. Spring complexes that are located in major regional clusters are referred to as supergroups, with 13 supergroups found in the GAB and four in the Surat region (Figure 4.3).

The Assessment determined the likely risk and opportunity to artesian springs in the GAB based on the modelled change in groundwater levels from 2010 to 2070 and the conservation value of the spring complexes. A high risk rating means that loss of spring ecological values is highly likely due to a high likelihood that a spring complex would cease to flow. A low risk rating means loss of ecological values is unlikely. Assessment of impact considers both the likelihood of: decline in groundwater level and reduction in spring flow; and increase in groundwater level and recovery of flow to a spring complex.

Under future climate and the current groundwater development (Figure 4.4), some spring complexes are likely to be affected by a decrease in groundwater levels. In the Bourke and Eulo supergroups, many of the spring complexes are currently inactive, so a further decline will not lead to higher risk. However, at the highest ranked spring complex in the Bourke supergroup – Peery Springs complex (ranking 1b) – groundwater levels are likely to decline under the future climate.

Under the future climate with future development (Figure 4.5), the majority of spring complexes (94 percent) are located in areas where the groundwater level is likely to increase. In the region, only six spring complexes are at risk from a decline in groundwater level and only one is active (Peery Springs complex, Bourke supergroup). The groundwater level increase from 2010 to 2070 is determined from groundwater modelling, which assumes that planned GABSI activities continue without change to final completion.

Knowledge and information gaps

The collation, analysis, and interpretation of geological and hydrogeological knowledge for the GAB are ongoing. Because the GAB is defined as a groundwater basin, it encompasses several geological basins, and is also connected with other adjacent geological basins and formations. To continue advancing the understanding of the GAB, refining the conceptual model and developing more robust groundwater models, additional knowledge is needed to define:

- interconnections between different hydrostratigraphic layers within the GAB
- connection of GAB aquifers with underlying and adjacent geological basins
- the variation of hydraulic properties in areas where significant groundwater development is expected
- the role of faulting on groundwater conditions.

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Part I Introduction

1 Preamble

Author: Smerdon BD

1.1 The Great Artesian Basin

The Great Artesian Basin (GAB) is one of the largest groundwater systems in the world and underlies arid and semi-arid regions in Queensland, New South Wales, South Australia and the Northern Territory (Figure 1.1). It is comprised of sedimentary rock layers that form aquifers and aquitards (confining layers) containing groundwater that is mostly under artesian conditions. The GAB is a complex groundwater system that is difficult to visualise and challenging to describe. To help describe the GAB, this report uses scientific terms that may be unfamiliar to some readers – for definitions of these terms, refer to 'Terms and concepts' at the back of the report.

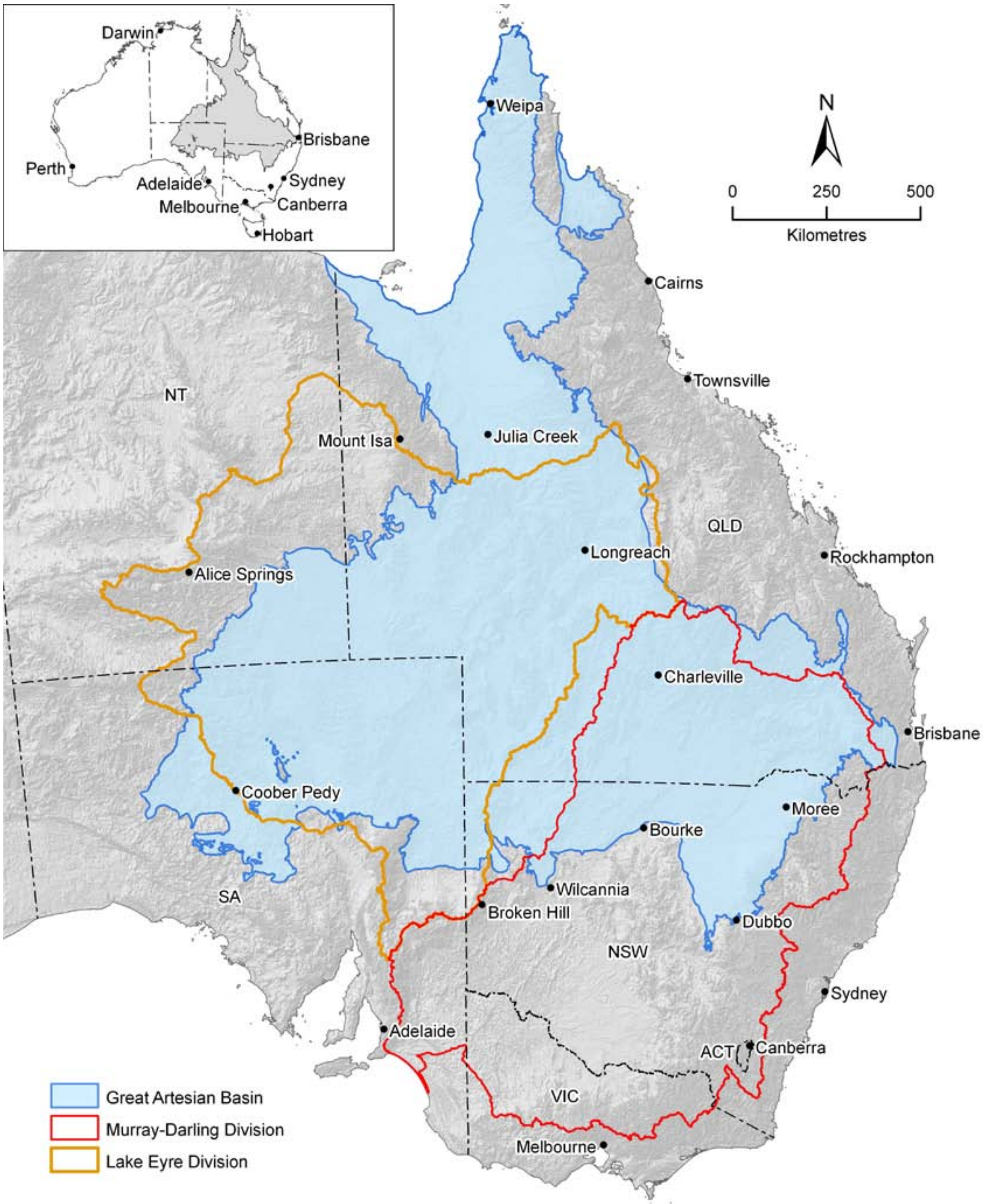


Figure 1.1 Geographic extent of the Great Artesian Basin and selected overlying surface water drainage divisions

The GAB is defined as a groundwater basin, encompassing several geological basins that were deposited at different times in Earth's history, ranging from 200 to 65 million years old, deposited in the Jurassic and Cretaceous periods. These geological basins sit atop deeper, older geological basins (Figure 1.2) and in turn, have newer surface drainage divisions situated on top of them (e.g. the Lake Eyre and Murray-Darling river basins). In this context – as a groundwater basin – the GAB is a vast groundwater entity stretching across one-fifth of Australia (Figure 1.1).

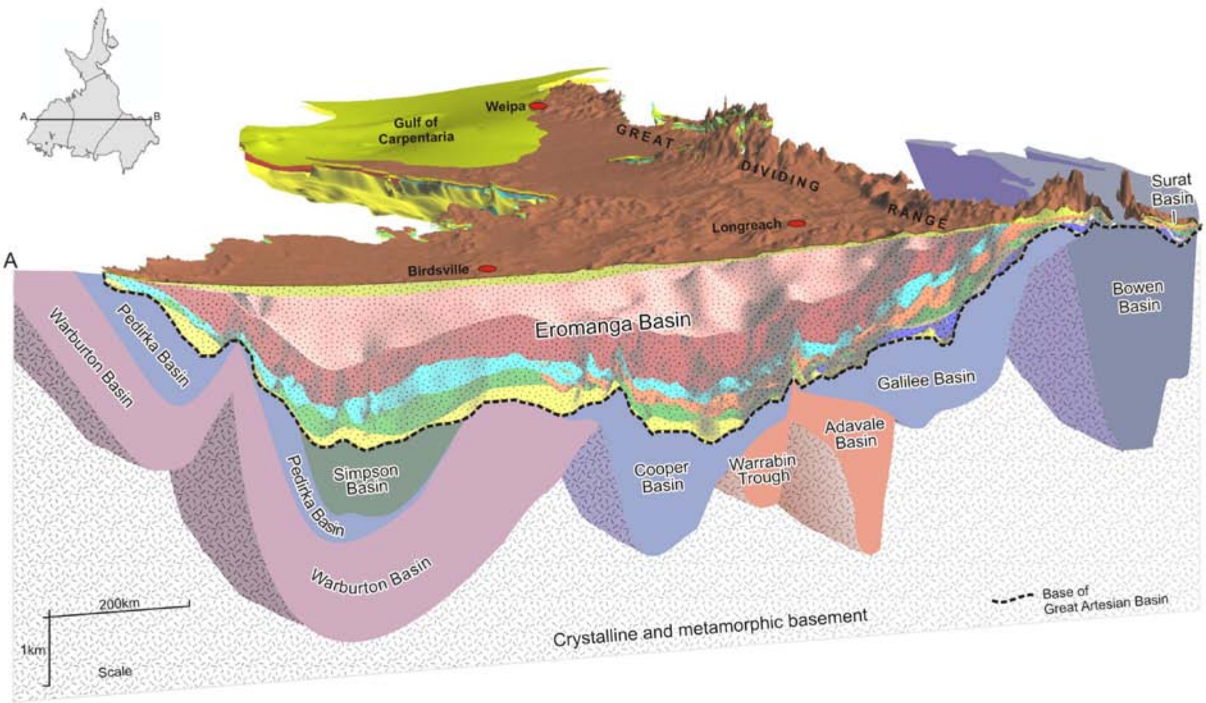


Figure 1.2 Three-dimensional illustration of a slice through the Great Artesian Basin
Note: this diagram shows aquifer layers of the Great Artesian Basin and underlying geological basins. Because the Great Artesian Basin is a groundwater entity, some of the aquifers may be in contact with groundwater in underlying basins

Groundwater resources in the GAB support an extensive pastoral industry, inland population centres, mining activities, and other extractive industries – and demand for these resources is increasing. The consequent management issues require a better understanding of how the whole groundwater system operates. Thus an integrated reappraisal of the latest hydrogeology, hydrochemistry and groundwater modelling is timely.

Such a reappraisal was the aim of the Great Artesian Basin Water Resource Assessment (the Assessment). The Assessment built upon the approach taken by CSIRO and partners in the Murray-Darling Basin, South-West Western Australia, Northern Australia, and Tasmania Sustainable Yields projects. Consistent with these other projects, the Assessment provides an analytical framework to assist water managers in the GAB to meet National Water Initiative (NWI) commitments.

Funded by the Australian Government Department of Sustainability, Environment, Water, Population and Communities and the National Water Commission, the Assessment outlines the current status of water resources in the GAB and the potential impacts of climate change and resource development on those water resources. As a desktop study, no new data were collected. Rather, groundwater modelling using existing data as a base and new interpretations of existing data were undertaken. The Assessment highlights areas that require further investigation, and includes a gap analysis.

1.2 The Assessment area

Groundwater basins are comprised of sedimentary rock layers that form aquifers – the permeable layers that readily transmit water – and aquitards – the confining layers that restrict groundwater flow. Because the GAB is defined as a groundwater basin, it encompasses several geological basins. For reporting purposes of the Assessment, individual regions were aligned with major geological basins, and defined as follows (Figure 1.3):

- Surat region
- Central Eromanga region
- Western Eromanga region
- Carpentaria region.

In the Assessment, terms such as 'Surat region' refer to the reporting regions as shown in Figure 1.3. Terms such as 'Surat Basin' are reserved to mean the geological basin. 'Assessment area' refers to the extent of all four reporting regions combined.

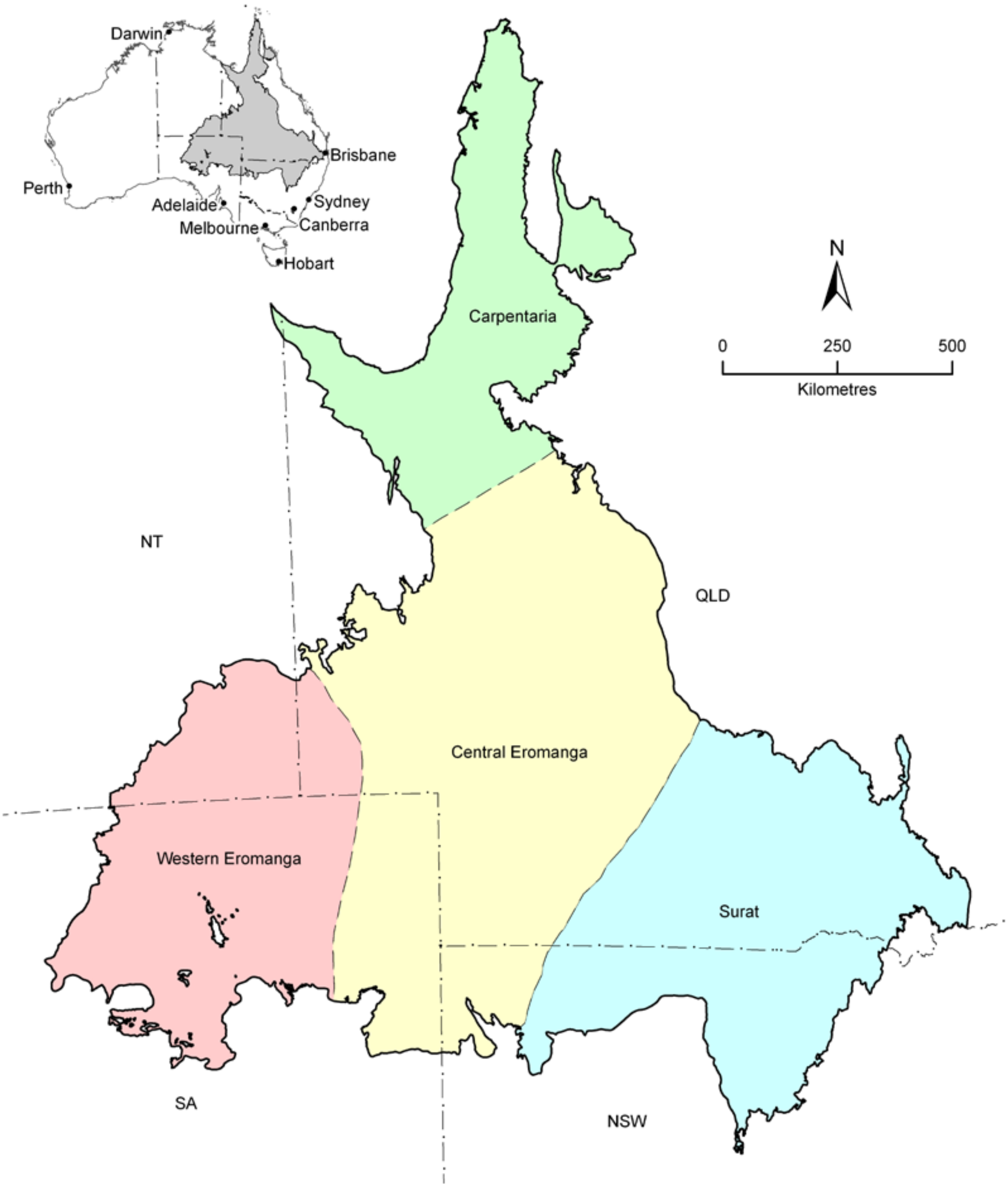


Figure 1.3 Reporting regions of the Great Artesian Basin Water Resource Assessment

The Assessment focused on the aquifers of the Jurassic and Cretaceous periods, which comprise the majority of the GAB and are present across its entirety. In some places, the Jurassic and Cretaceous aquifers are connected with adjacent groundwater systems or underlying geological formations of older geological periods. For this reason, defining a groundwater basin boundary is generally more complicated than defining a boundary for a surface water drainage division (e.g. the Lake Eyre or Murray-Darling river basins) because it requires interpretation of the geological formations.

The Assessment area is defined by the extent of the aquifers of the Jurassic and Cretaceous periods. Older sediments of the Triassic period also form aquifers that may be under artesian conditions in some locations; however, these are differentiated from aquifers of the Jurassic and Cretaceous periods by a major unconformity – a period of geological time where significant erosion occurred before the Jurassic and Cretaceous sediments were deposited.

In addition to layers of different geological periods, large-scale geological structures occur within the GAB. Where a structure separating geological basins was considered to have a significant control on groundwater flow, the geological structure was included in the individual region report. For the Surat region, the boundary between the Surat and Eromanga geological basins coincided with the location of the top of the Eulo and Nebine ridges (see Chapter 5 for more detail). These ridges, and their effects on groundwater conditions described in the Assessment, are included in the Surat region (Figure 1.4).

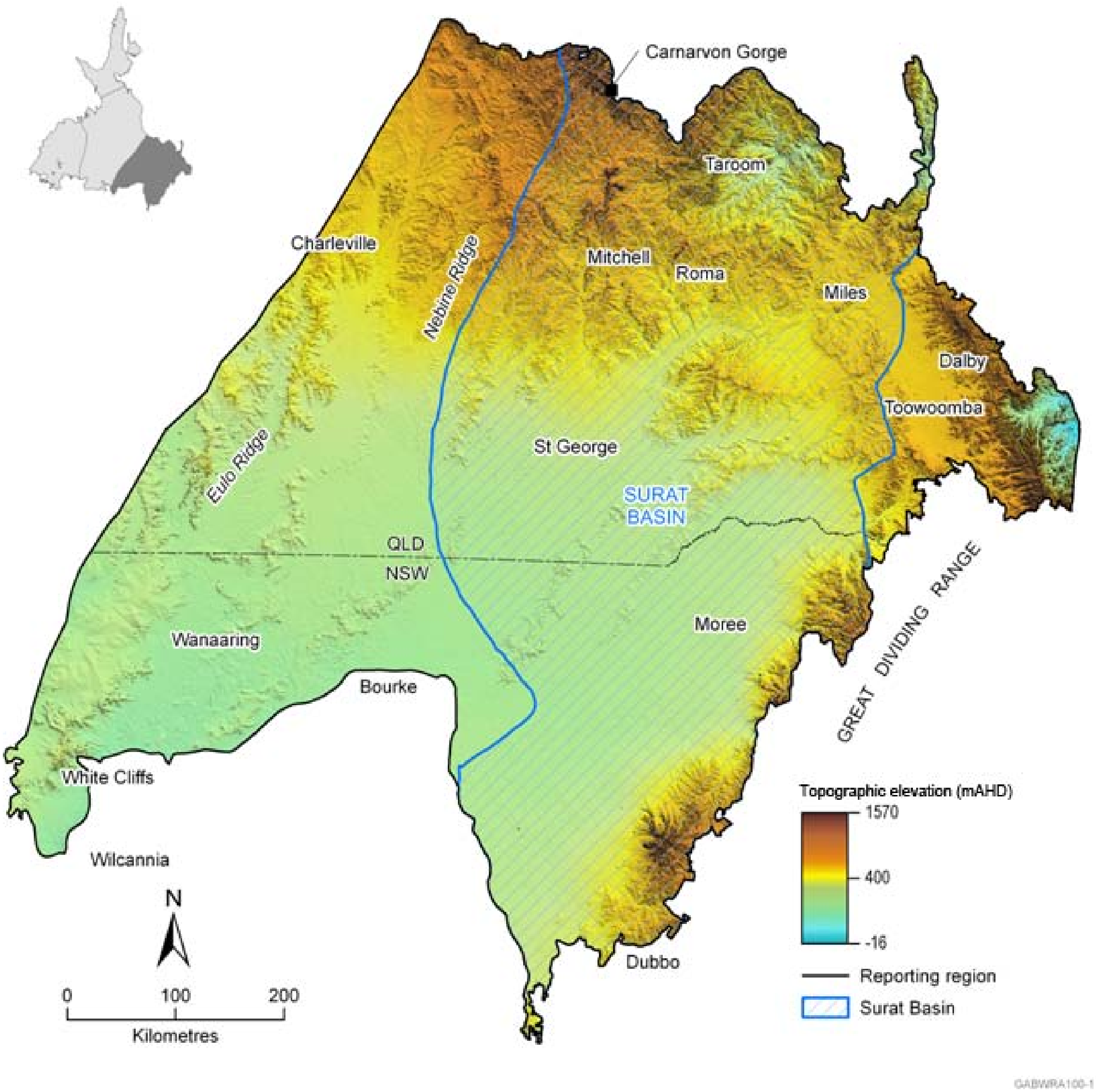


Figure 1.4 Major geological features of the Surat region

1.3 The Assessment approach

The primary aim of the Assessment was to undertake an integrated reappraisal of the latest geological and hydrogeological information and develop a comprehensive description of the GAB aquifers, including the geological history, structure of geological layers, and three-dimensional (3D) visualisation of aquifers and confining layers. To achieve this aim the overall approach of the Assessment was to evaluate the water resources of the GAB from first principles. In parallel with this reappraisal, an existing groundwater flow model was used to assess the effects of future climate and groundwater development on water levels in the Cadna-owie – Hooray Aquifer and equivalents, which are the main aquifers in the GAB, and potential impacts to groundwater-dependent ecosystems.

The GAB contains an extensive and complex aquifer system. The methodology of the Assessment included defining the three-dimensional hydrogeological framework and hydraulic connections, both vertically and laterally, of different parts of the aquifer system. Considering that groundwater is the primary water resource of the reporting regions underlain by the GAB, the Assessment focused on groundwater systems, and surface water was only addressed in terms of interaction with groundwater systems.

1.3.1 Reconceptualising the Great Artesian Basin

Since the late 1800s there has been an evolution of knowledge about this large groundwater system. A comprehensive description of the GAB aquifers was published in 1980 (Habermehl, 1980) and provided the basis for conceptualising how the groundwater system operates. Habermehl's description included aquifers of the Triassic period – formations in the upper part of geological basins underlying the Surat and Central Eromanga basins – which are not present across the entire area of the current Assessment. It conceptualised the GAB as a single, large, contiguous groundwater flow system in which aquifers were considered to be laterally continuous across the extent of the entire GAB (Figure 1.5). In this conceptualisation, aquifers of the Jurassic and Cretaceous periods are recharged where they are exposed or in close proximity to the ground surface, which occurs along the eastern and western margins of the GAB. The greatest recharge occurs where rainfall and ground elevation are highest, which is along the western side of the Great Dividing Range. At these locations, referred to as the 'intake beds', recharge established pressure-driven groundwater flow through aquifers of the Jurassic and Cretaceous periods to natural discharge areas at low elevations and at the location of springs.

Since Habermehl's description of the GAB (Habermehl, 1980), there have been numerous studies in the GAB. However, there has been no comprehensive compilation of this new work. The Assessment reconceptualises how the whole groundwater system operates, as a result of integrating the latest information on hydrogeology and flow system dynamics. The reconceptualisation is described in Part III of this report and in greater detail in a companion technical report about the hydrostratigraphy, hydrogeology and system conceptualisation of the GAB, as listed in Appendix A.

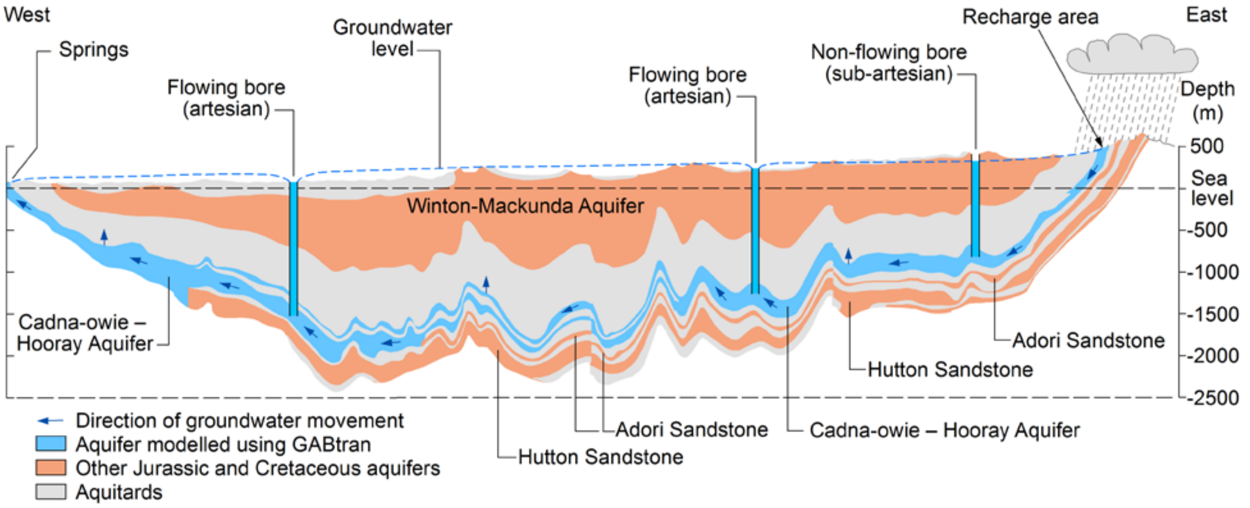


Figure 1.5 Habermehl's 1980 conceptualisation of the Great Artesian Basin (after Radke et al., 2000)
Note: blue shading indicates the aquifer modelled by the Assessment using GABtran, a single-layer transient groundwater model; other aquifers are shaded orange

1.3.2 Overview of the Assessment methodology

Assessments drawing on the Habermehl (1980) conceptualisation of the Great Artesian Basin

The groundwater modelling and the assessment of GDEs utilised groundwater flow models that were based on the Habermehl (1980) conceptualisation of how the whole groundwater system operates – as a laterally continuous flow system across the entire GAB. The groundwater modelling provides a means of assessing future potential impact of climate change and future development on recharge rates, and on the cumulative effects of groundwater abstractions and impact on GDEs. The Assessment objectives required assessments under three separate climate and development scenarios – these are described in detail in Chapter 3.

Assessments drawing on a reconceptualisation of the Great Artesian Basin

The methodology for reconceptualising the groundwater system in the GAB relied on a reappraisal of the geology of the GAB which utilised a three-dimensional (3D) visualisation of aquifers and aquitards, stratigraphy and spatial boundaries. To quantify groundwater flow parameters, physical properties including porosity and permeability were collated and the latest hydrogeological, hydrochemical and isotopic evidence were also used to inform and understand how the whole groundwater system operates. Maps of groundwater levels were produced and combined with an assessment of vertical connection with overlying and underlying aquifers and major surface drainage divisions. The reconceptualisation provided the basis for assessing the rates of recharge and discharge and for assessing water resources across the GAB.

Additional descriptions of approaches used in the Assessment, and results of the Assessment, are described in Part II and Part III of this report. Greater details on the methods are provided in the companion technical reports listed in Appendix A.

1.4 Structure of this report

This report is one of four region reports. The content reflects the key components of the Assessment: data compilation and data management, reconceptualisation of the hydrogeology, an update on the understanding of flow systems dynamics (hydrodynamics) and the water budget, numerical groundwater flow modelling, and impacts on groundwater-dependent ecosystems.

Each region report follows a similar structure, in which the components of the Assessment using the Habermehl (1980) conceptualisation are grouped in Part II and the components of the Assessment that develop the reconceptualisation are grouped in Part III.

The structure of each region report is as follows:

- Part I Introduction
    - Chapter 1 covers the background and information regarding the Habermehl (1980) conceptualisation and reconceptualisation of how the whole groundwater system operates, and the structure of the report.
    - Chapter 2 provides an overview of the region, covering general physiography, climate, land use, and vegetation; key highlights of the geological history; and a summary of the region's water resources and previous studies.
- Part II Assessments drawing on the Habermehl (1980) conceptualisation of the Great Artesian Basin
    - Chapter 3 describes the results of groundwater modelling. Changes in groundwater levels under current and future climate and development scenarios are assessed and discussed.
    - Chapter 4 identifies the different types of aquatic ecosystems and their ecological values, and presents a broad-scale assessment of the causal links between hydrological change and the impacts on groundwater-dependent ecosystems (GDEs) within the GAB.

- Part III Assessments drawing on a reconceptualisation of the Great Artesian Basin
    - Chapter 5 provides a summary of the reconceptualisation of the geological framework and stratigraphy as well as of the boundaries and physical properties of aquifers and aquitards.
    - Chapter 6 describes the reconceptualisation of the flow system dynamics, including collation of groundwater data to develop a historical overview of groundwater levels, analysis of hydrochemical and isotopic data for evaluating flow paths, and interaction of GAB aquifers with adjacent aquifers and surface drainage basins.
    - Chapter 7 provides an estimation of the water budget for the region. Inflows and outflows include recharge and discharge processes.
    - Chapter 8 discusses the new findings of the Assessment and identifies knowledge and information gaps.

1.5 Suite of products

Reporting of the Assessment is covered by a range of products including four region reports, a whole-of-GAB report and a number of detailed technical reports. The region reports are intended for an audience with some policy or scientific background who are interested in the management of water resources. The region reports are summarised in four 16-page summaries intended for a general audience. Similarly, the whole-of-GAB report is summarised in a 12-page synthesis for a general audience.

The series of technical reports contain further scientific detail on the following:

- review of groundwater models and modelling methodologies for the Great Artesian Basin
- hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin
- lithostratigraphic and hydrogeological unit of the Great Artesian Basin
- groundwater modelling to assess the impact of projected climate and development in the Great Artesian Basin.
- potential impacts on groundwater-dependent ecosystems in the Great Artesian Basin

In addition to these technical reports, there are scientific reports describing the development of a three-dimensional computer-generated visualisation of the GAB, and data collected for the Assessment. A list of reports produced by the Assessment is contained in Appendix A.

1.6 References

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Radke BM, Ferguson J, Cresswell RG, Ransley TR and Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra.

2 Overview of the Surat region

Authors: Cresswell RG and Smerdon BD

This chapter provides an overview of the region’s physical characteristics, key highlights of the geological history, and a summary of water resources and previous studies.

2.1 Contextual information

2.1.1 Geography and general geology

The Surat region occupies an area of 440,000 km^2 of south-eastern Queensland and north-central New South Wales (Figure 2.1). The eastern boundary of the region is situated less than 200 km from the Pacific Coast (east of Dalby) and the region extends about 800 km inland to beyond Charleville. The northern boundary is approximately 100 km north of Taroom, and is defined by the outcrop extent of the Jurassic-aged formations, while the southern boundary extends to the Coonamble Embayment near Dubbo, New South Wales.

The Great Dividing Range forms a swathe of high ground around the eastern and northern margins of the Great Artesian Basin (GAB), reaching elevations up to 900 mAHD. The ground surface slopes gently to the south-west to elevations less than 150 mAHD. Some of the geological formations that form aquifers in the GAB are exposed along the western slopes of the Great Dividing Range. These areas – referred to as the ‘intake beds’ – are locations of groundwater recharge for the GAB.

The region’s surface water is drained by tributaries of the Darling River drainage system, which originate in the higher areas along the eastern margin of this region. The Condamine River and associated tributaries have created an extensive, low relief floodplain particularly around the town of Dalby where significant irrigated agriculture occurs. The Condamine River flows north-west before shifting its course towards the west and south-west. It then becomes the Balonne River south of the town of Roma and drainage is almost entirely to the south-west, where it eventually joins the Darling River drainage system. In contrast, rivers originating to the north of the Great Dividing Range flow northwards and eastwards, eventually discharging to the Pacific Ocean. The Barwon River is the confluence of the Macintyre, Gwydir, Namoi, Castlereagh and Macquarie rivers, which drain through the fertile volcanic soils of the northern New South Wales western slopes of the Great Dividing Range. These valleys are highly productive and strategically important agricultural land.

Geologically, the Surat region is dominated by the Surat Basin, an elongate geological basin containing up to 2500 m of continentally-derived sediments deposited in a series of four fining-upward cycles during the Jurassic Period (see Figure 1.4). This depositional sequence is overlain by transgressive marine sediments deposited during the Cretaceous Period (Hennig, 2005). The central Surat Basin overlies the Bowen Basin and extends in east and west orientations to overlap onto the Early Permian basement. The northern margin of the Surat Basin has been exposed and extensively eroded due to orogenic uplift during the Tertiary Period (Exon, 1976). The morphology of the base of the Surat Basin is largely controlled by the underlying basement architecture (i.e. geology and structural features) of the Bowen Basin and older rocks (DERM, 2005).

Sediments of the Surat Basin inter-finger with sediments of the Eromanga Basin across the Eulo and Nebine ridges and the western boundary of the Surat region is defined by these features. Sediments of the Surat Basin also inter-finger with sediments of the Clarence-Moreton Basin across the Kumbarilla Ridge. Detailed examination of the geology and watertable revealed that the Helidon Ridge represents the eastern boundary of the Surat region and the GAB (Chapter 5).

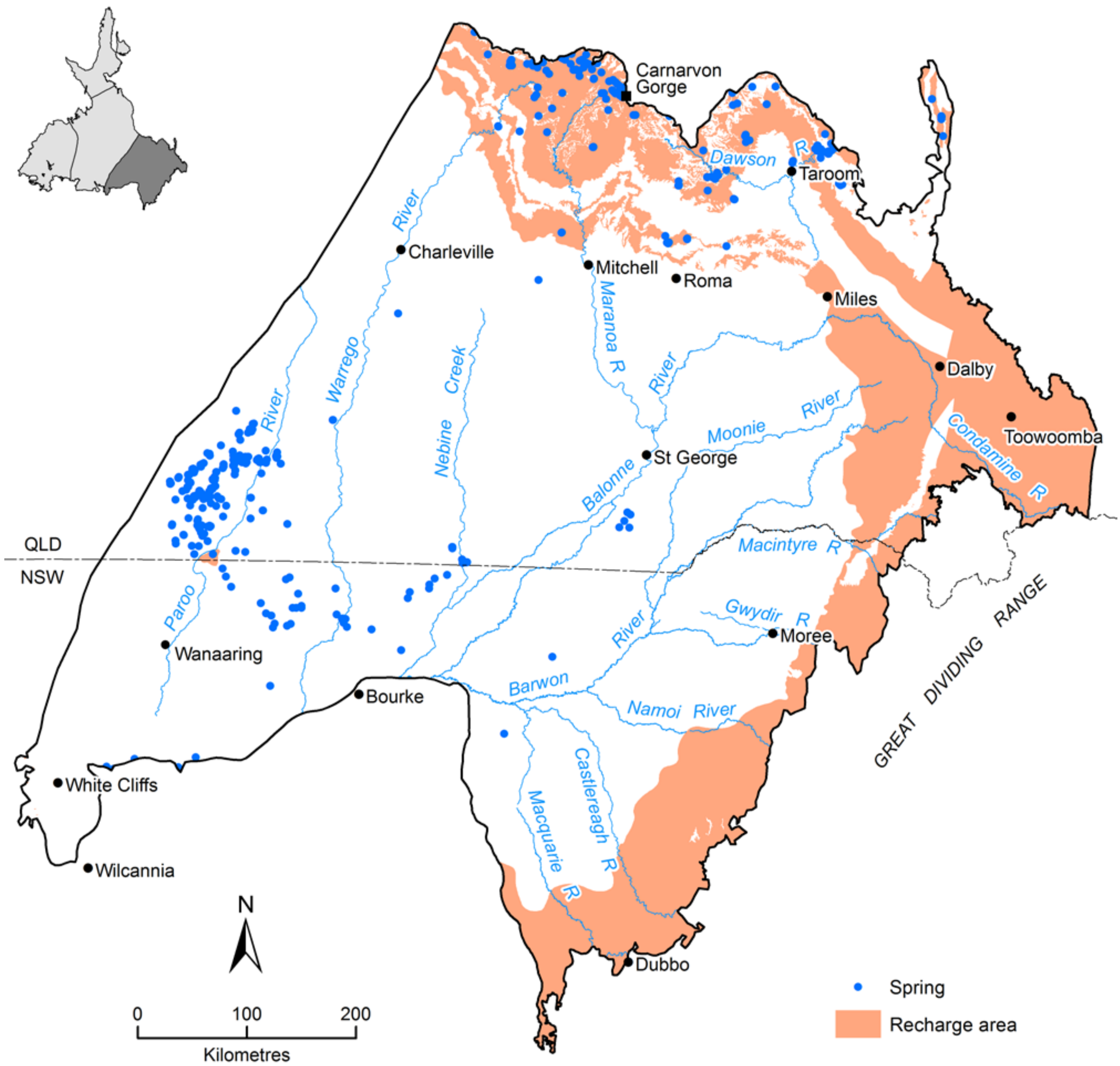


Figure 2.1 The Surat region showing selected rivers and springs and Great Artesian Basin recharge areas

2.1.2 Climate, vegetation and land use

The climate of the Surat region is generally sub-tropical with warm, wet summer months and cooler, drier winter months. The average annual temperature is approximately 20 °C and the typical range of temperatures through the year spans from 0 to 35 °C.

Average annual rainfall across the region is variable, increasing from west (500 mm/year in Charleville) to east (627 mm/year in Dalby) and south (350 mm/year in Bourke, 581 mm/year in Dubbo) to north (675 mm/year in Taroom). Peak rainfalls generally occur between the months of October and March (Figure 2.2). Over the past fifty years, the region has experienced periods of above-average rainfall (i.e. the early 1960s, 1971 to 1984, and 1996 to 2000) and below-average rainfall (i.e. 1963 to 1970, 1984 to 1996 and 2000 to 2009).

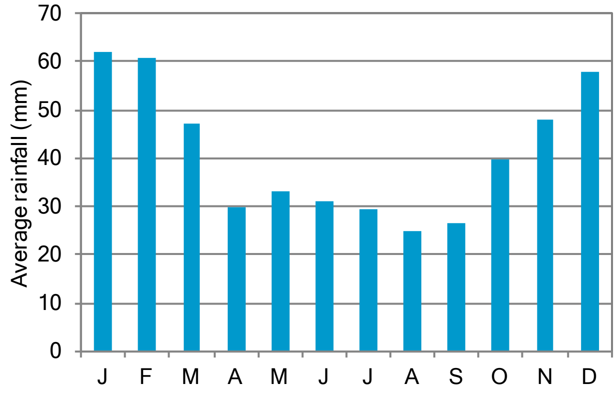


Figure 2.2 Average monthly rainfall (mm) for the Surat region

Average annual evaporation is between 1800 mm/year and 2400 mm/year, and exceeds the precipitation received throughout the region. The annual rainfall deficit increases with increasing distance from the coastline.

Vegetation communities of the Surat region are highly varied – relating to the variability in climate, soil type and topography. Vegetation communities reflect the arid to semi-arid conditions of the region and have developed a number of adaptations to survive in climatic extremes. Dominant vegetation types include eucalypt woodland and open grassland. Small shrubs and tussock grasses are common in the east. The region includes the threatened Brigalow ecological community which is listed as endangered under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act). The community of native species dependent on natural discharge of groundwater from the GAB is also listed as endangered under the EPBC Act and includes 11 species that are listed as threatened nationally and/or in Queensland, New South Wales and South Australia (SEWPaC, 2010). Seven of these species are plants.

Large areas of native vegetation have been cleared for industry and agriculture (Figure 2.3). Pastoralism, cotton growing and crop production are major industries in the region and there is increasing interest in mining and coal seam gas (CSG) development, particularly in Queensland (see Section 2.1.6).

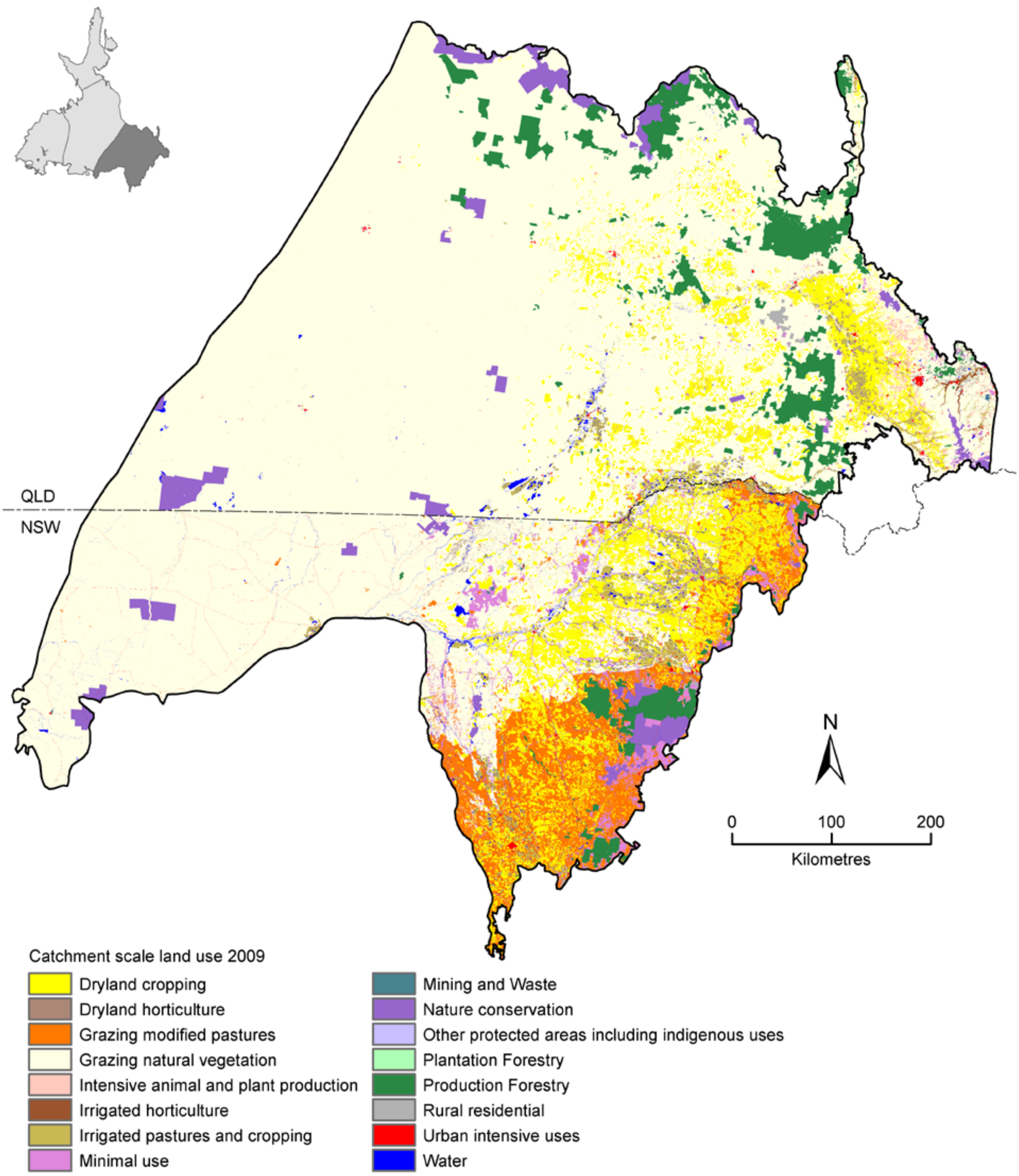


Figure 2.3 Land use across the Surat region

2.1.3 Surface water

The surface waters of the Surat region (Figure 2.1) incorporate the catchments of the Condamine, Balonne, Barwon, Dawson, Macintyre, Maranoa, Moonie, Macquarie-Castlereagh, Gwydir, Namoi, Paroo and Warrego rivers. The Paroo River traverses the western-most margin of the Surat region.

2.1.4 Groundwater

The New South Wales portion of the Surat region extends across 160,000 km^2 and the groundwater flow and pressure in this part of the region is influenced by recharge from the south and east. This directs flow in a northerly and westerly direction where it converges with south-west flowing groundwater originating from Queensland (DWE, 2009). The convergence of groundwater flow and presence of the Nebine Ridge have caused numerous springs to develop north-west of Bourke. Numerous water bores tap into this part of the Surat region to take advantage of high groundwater flows and provide for free-flowing conditions (DWE, 2009). These bores are generally used for stock and domestic purposes, but also by industry and mining, and for mineral health spa baths by local tourism and leisure industries.

Groundwater discharge may also occur through upward leakage into surface waters. Radke et al. (2000) suggests that streams of the lower reaches of the Macquarie, Bogan and Barwon systems are subject to upward leakage.

The Queensland portion of the Surat region covers an area of approximately 280,000 km^2. Groundwater recharge occurs in the north-east and typically groundwater flows to the south-west. This recharge provides water for bores and springs in the sub-artesian recharge areas as well as further south and west in artesian zones (DERM, 2005). There are three different recharge processes that occur in the north-east of the region: diffuse rainfall recharge, preferred pathway flow and river/aquifer leakage (DERM, 2005).

2.1.5 People

The Queensland portion of the Surat region includes the local government areas (LGAs) of Toowoomba, Western Downs and Maranoa and extends through parts of Banana and Gladstone shires. Major regional centres of this part of the region include Toowoomba, Dalby, Warwick and Roma. The majority of the resident population of the Queensland portion of the Surat region is based in the Toowoomba Regional Council area (DEEDI, 2011). As at June 2008, the population of this LGA was 155,000 and the Western Downs and Maranoa LGAs had populations of 31,000 and 13,000 respectively (DEEDI, 2011). The estimated population in the Queensland portion of the region for 2011 was 209,961, equivalent to 4.6 percent of Queensland's population (DEEDI, 2011).

The population of the part of the region within New South Wales is primarily concentrated in the central and north-west of the state. Local water utilities in many New South Wales towns source water from the Surat Groundwater Source (DWE, 2009). Townships include Coonamble, Moree, Lightning Ridge and Gilgandra (DWE, 2009).

Indigenous values of the landscape of the Surat region are associated with cultural and spiritual beliefs and the importance of groundwater discharge in supporting plants, animals and people. Government agencies recognise cultural and heritage features in water resource planning instruments.

2.1.6 Current and proposed water resource development

Historically, pastoralism has been the primary land use in the Surat region (Figure 2.3). Whilst sub-artesian water along the eastern margins has supported intensive stock enterprises, town water, irrigation, aquaculture and mining, realisation of a reliable water source once bores were sunk in western New South Wales resulted in pastoralists moving further west (DWE, 2009). Springs, which discharge from aquifers of the Surat Basin, are also an important water source for environmental and pastoral purposes.

High volumes of artesian water are also used by the spa industry. These tourist and community facilities are important to rural town economies. Several are located in the Surat region including those situated in Moree and Lightning Ridge (DWE, 2009).

Mining interests in the Surat region are predominantly centred on coal and, to a lesser extent, deposits of opal (GABCC, 2010). In New South Wales, the only mining activity which uses artesian water is opal mining around Lightning Ridge.

Petroleum exploration is also underway in the Surat Basin. In excess of 3500 wells have been drilled across the GAB, the majority of which are in the Surat and Eromanga basins for conventional oil and gas (GABCC, 2010). Crude oil production began in 1969 following the discovery of oil at Moonie (GABCC, 2010). Oil production peaked in the 1980s but has fallen since. Minor oil shale deposits occur in the Jurassic Walloon Coal Measures.

In recent years, there has been a focus on the potential for CSG development in the Surat Basin. Production of CSG in the GAB first commenced in 1998 near Injune and has increased since. A primary focus is on the seams of the Walloon Coal Measures, which are part of the Jurassic-aged sediments of the GAB. The Walloon Coal Measures are situated in the Surat and Clarence-Moreton basins where CSG development is currently underway in the McAlister-Brigalow CSG area of south-eastern Queensland. Kogan North CSG area west of Dalby was the site of the first CSG production from the Surat Basin, commencing in January 2006 (Basin Sustainability Allience, 2011). Production from the Berwyndale South CSG area followed in May 2006 and several other production areas between Dalby, Chinchilla and further south have subsequently emerged (Basin Sustainability Allience, 2011).

Pumping of water from coal seams is required to reduce overlying groundwater levels and allow gas to release from coal pores. This practice, termed depressurisation, results in a drawdown of water levels in the producing beds (the Walloon Coal Measures in the Surat Basin) and can lead to drawdown of water levels in overlying and underlying aquifers. Companies exploring for CSG in the Surat Basin draw down the hydraulic head within 35 m of the upper coal seam which can impact on areas beyond the gas field production area (Moran and Vink, 2010).

Groundwater extraction for mine dewatering is also required for coal mines that are being developed in the region (GABCC, 2010).

2.1.7 Legislation, water use, entitlements and purpose

The Surat region straddles two jurisdictions of Australia (New South Wales and Queensland), hence two different sets of legislative instruments apply to the management of groundwater resources. The most up to date information on water legislation and allocation may be obtained from each jurisdiction. The information provided here is intended as an overview that is relative for the Surat region. Groundwater resource units – specific areas associated with water management – are shown in Figure 2.4 and Figure 2.5 for the Surat region. These units may span more than one region and also extend beyond the region reported by the Assessment.

New South Wales

Water entitlements and use are governed by the *Water Sharing Plan for the New South Wales Great Artesian Basin Groundwater Sources 2008* and the *Water Sharing Plan for the New South Wales Great Artesian Basin Shallow Groundwater Sources 2011* under the New South Wales *Water Management Act 2000*. The *Water Sharing Plan for the New South Wales Great Artesian Basin Groundwater Sources 2008* applies to five defined groundwater sources (identified as groundwater resource units in Figure 2.4):

- the Eastern Recharge Groundwater Source (unit 29)
- the Southern Recharge Groundwater Source (unit 30)
- the Surat Groundwater Source (unit 28)
- the Warrego Groundwater Source (unit 27)
- the Central Groundwater Source (unit 26).

The New South Wales portion of the Surat region includes all five GAB groundwater sources (Figure 2.4), and three shallow GAB groundwater sources that include the uppermost 60 m of GAB sediments. There are several shallow groundwater sources that overlie the GAB (Figure 2.5) and four deep groundwater sources that underlie the GAB. The Kanmantoo Fold Belt MDB, Lachlan Fold Belt MDB and the New England Fold Belt MDB groundwater sources form the deep groundwater sources underneath the GAB groundwater sources (except in the eastern portion of the region where the Gunnedah Basin MDB groundwater source sits between the GAB and the Lachlan Fold Belt MDB). As outlined in Sections 12(2) and 12(3)(a) of the plan, the basis for water sharing in the New South Wales portion of the region is 70 percent of the estimated long-term average annual net recharge for the Eastern Recharge and Southern Recharge Groundwater Sources and the volume of water required to maintain pressure levels experienced under the level of water extraction associated with the water entitlements, infrastructure and management rules in place at 1990 (sustainable pressure entitlement equivalent) for the Surat, Warrego and Central Groundwater Sources. This is estimated to be 19,000 ML/year and 42,400 ML/year for the Eastern Recharge and Southern Recharge Groundwater Sources and 75,000 ML/year, 22,400 ML/year, and 7,900 ML/year for the Surat, Warrego and Central Groundwater Sources.

The plan takes into consideration the variability of the climate and its impact on recharge through a range of provisions that manage water sharing within the limits of water availability over the long-term and restrict water extractions so that groundwater-dependent ecosystems (GDEs) and groundwater quality are protected. It also provides a list of high priority GDEs that are situated in the New South Wales portion of the GAB.

Queensland

In Queensland, a Water Resource Plan (WRP) and supporting Resource Operations Plan (ROP) have been developed for the GAB under Queensland's *Water Act 2000*. In the *Water Resource (Great Artesian Basin) Plan 2006*, the Surat region comprises several management areas (groundwater resource units 13, 14 and 18 to 25 as shown in Figure 2.4). Each management area includes a series of management units associated with the major GAB aquifers or formations. General reserves for each management area – the total volume of water available for allocation – are as listed below:

- Barcaldine East (unit 13): 0 ML
- Barcaldine South (unit 14): 1500 ML
- Warrego East (unit 18): 4000 ML
- Surat (Qld) (unit 19): 5000 ML
- Surat North (unit 20): 200 ML
- Surat East (unit 21): 2000 ML
- Mimosa (unit 22): 500 ML
- Mulgildie (unit 23): 0 ML
- Eastern Downs (unit 24): 0 ML
- Clarence Moreton (unit 25: 0 ML.

The ROP outlines the arrangement for implementing the water resource plan and details how unallocated water is made available through the granting of a water licence.

The extraction of petroleum resources – including CSG – is governed by the *Petroleum and Gas (Production and Safety) Act, 2004*. The *Petroleum and Gas (Production and Safety) Act, 2004* includes groundwater extracted as 'associated water', which is classified as a waste product and must be handled in accordance to the state and federal government approval conditions.

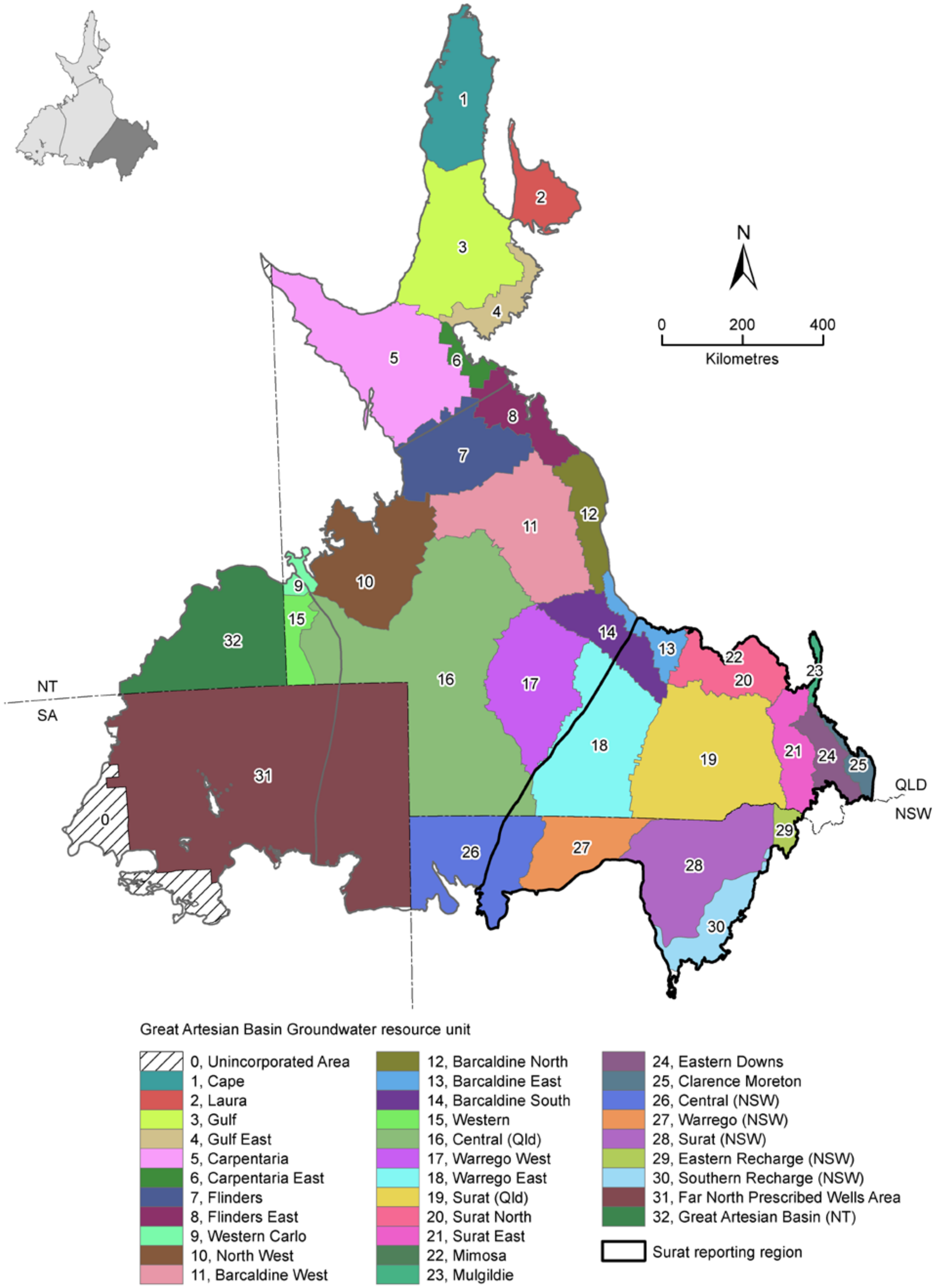


Figure 2.4 Groundwater resource units of the Great Artesian Basin, shown only for the area of the Assessment

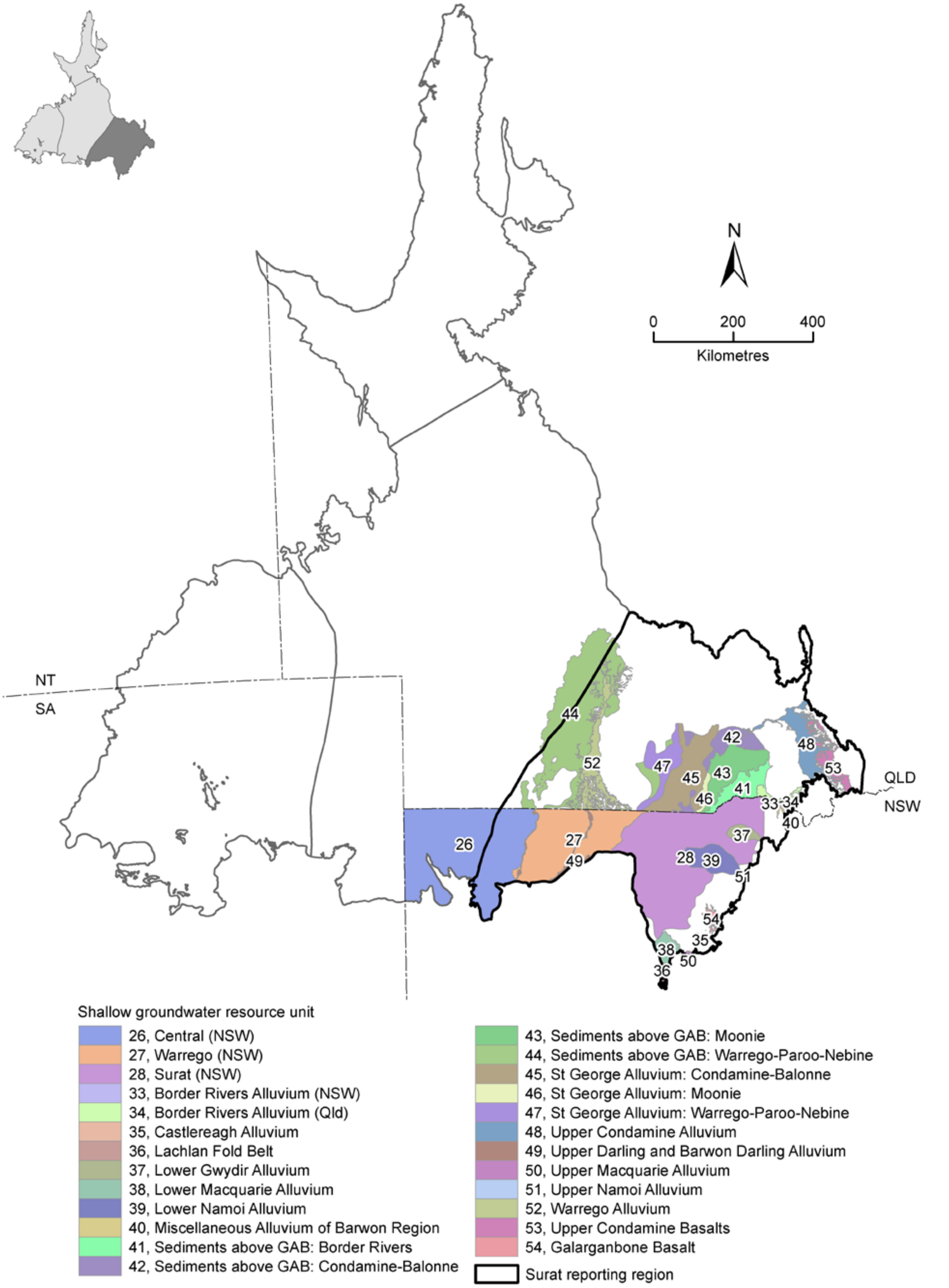


Figure 2.5 Shallow groundwater resource units, shown only for the area of the Assessment

2.2 History of understanding of the Surat region

In 1818, John Oxley travelled downstream along the Macquarie River and entered an 'ocean of reeds' that is now known as the Macquarie Marshes. This stymied his expedition and, unbeknownst to him, he had entered the geographic area of the GAB (Blake and Cook, 2006).

In 1846, Thomas Mitchell journeyed to the source of the Balonne and Warrego river systems, and observed springs in the headwaters of the Warrego and Nogoa rivers on the Great Dividing Range. Springs were an invaluable source of water for early pastoralists in western Queensland – as they had been for the Aboriginal people across the GAB for millennia.

The first artesian bore in the region, and indeed across the entire GAB, was drilled in 1878 close to one of these springs, on Kallara Station, near Tilpa, north-western New South Wales, on the floodplain of the Darling River. Searching for a reliable water supply, the bore tapped an artesian water source at about 65 m and water rose 12 m above the ground surface. The first artesian bores in the Queensland part of the region were drilled a year later, in 1879, to the east of Toowoomba, at Helidon Springs in the Lockyer Valley. These first artesian bores produced water from the lower Jurassic aquifers.

The rapidly expanding Queensland pastoral industry required water along stock routes, but shallow drilling and tanks for water supply was proving unsatisfactory through the 1880s and a severe drought across central western Queensland in 1885 prompted further drilling for deeper water. Blackall was chosen as a trial site as it was deemed to have greatest need for water. The first attempt was unsuccessful, but in 1888 a successful artesian bore was sunk. Meanwhile, a successful attempt to drill for artesian water was made to the south on Thurulgoonia Station, near Cunnamulla, in 1887. This success led to government sponsorship of Loughead in 1887 for a bore at Barcaldine where at 300 m, a flow of 700 kL/day was achieved. Drilling continued across the region and, by 1892, 19 Queensland government bores were either completed or in progress and by 1899, 542 bores had been sunk with 505 successes. By 1910, New South Wales had developed 364 artesian bores producing 600 ML per day (Blake and Cook, 2006).

As an interesting aside, gas was accidentally discovered during water drilling in Roma in 1901, and a plant for separating gas from water was established by 1906. Ensuing drilling tapped an extraordinary gas flow (300 ML per day), but this caught fire and consumed various buildings. This disaster discouraged further exploration for 20 years and even then the Depression thwarted recovery. Earnest oil exploration only recommenced in the 1950s (Blake and Cook, 2006).

2.2.1 Previous studies

Knowledge about groundwater levels enable a better understanding of the artesian groundwater system and is consequently used for a range of resource management purposes to assist groundwater management (Habermehl, 1980; 1982). The groundwater levels at artesian bores in the Surat region has been repeatedly measured; many measurements at regular time intervals, but a large number at irregular time intervals. Water levels in non-flowing artesian (sub-artesian) water bores have generally only been measured at the time of drilling and bore completion.

Since the early 1900s measurements of artesian groundwater levels have been carried out by the state water and geological authorities of Queensland and New South Wales. Legislation was passed to control the use of subsurface water in Queensland in 1910 and 1912 in New South Wales – after several earlier attempts to legislate had been made since 1891. With the introduction of government control, came requirements for bores to be licensed, for the provision of detailed information about the bores and for bores to be completed according to prescribed standards.

Systematic investigations by state water authorities of the artesian groundwater conditions in the GAB increased markedly as a result of the five Interstate Conferences on Artesian Water, held between 1912 and 1928 (ICAW, 1913; 1914; 1922; 1925; 1929). Measurements of groundwater levels from these early studies and a number of subsequent studies have provided valuable datasets for understanding the nature of the GAB. Interpretation of groundwater level data has also informed the development of the GAB-wide Great Artesian Basin Strategic Management Plan (GABCC, 2000), the Great Artesian Basin Bore Rehabilitation Program (GABBRP) and the Great Artesian Basin Sustainability Initiative Program (GABSI) (GABCC, 2000).

The Surat region contains at least 10 contemporary part-GAB groundwater models that individually cover between 0.2 percent and 37 percent of the region (Smith and Welsh, 2011) (Figure 2.6). The GABtran model covers approximately 84 percent of the region, including the main Cretaceous aquifers and their recharge beds, but omits the deeper Jurassic, Triassic stratigraphic units including those that contain CSG resources. During the past few years, a number of large groundwater models of the north-east Surat region have been developed to support environmental impact statements (EIS) for proposed CSG projects. They include large multi-layered groundwater models for the Australia Pacific Liquefied Natural Gas (APLNG) Project (WorleyParsons, 2010), Gladstone Liquefied Natural Gas (GLNG) Project (Matrixplus, 2009) and Queensland Curtis Liquefied Natural Gas (QCLNG) Project (Golder Associates, 2009). Updated and new groundwater models are also under development for supplementary EIS within these projects, and for other CSG development proposals that are currently in preparation (e.g. Arrow Energy's Surat Gas Project).

Despite the existence of large contemporary groundwater models within the Surat region, a review of those models (GHD, 2010) for the Queensland Water Commission (QWC) found that none were suitable for assessing and managing the regional cumulative impacts that are anticipated to arise from multiple CSG projects involving multiple operators. Based on the recommendations of the review, the QWC developed a regional groundwater model for the Surat Cumulative Management Area (QWC, 2010). The QWC model focussed on a regional assessment and covers a larger area than the combined individual proponents' models to enable assessment of cumulative impacts from concurrent gas and petroleum developments.

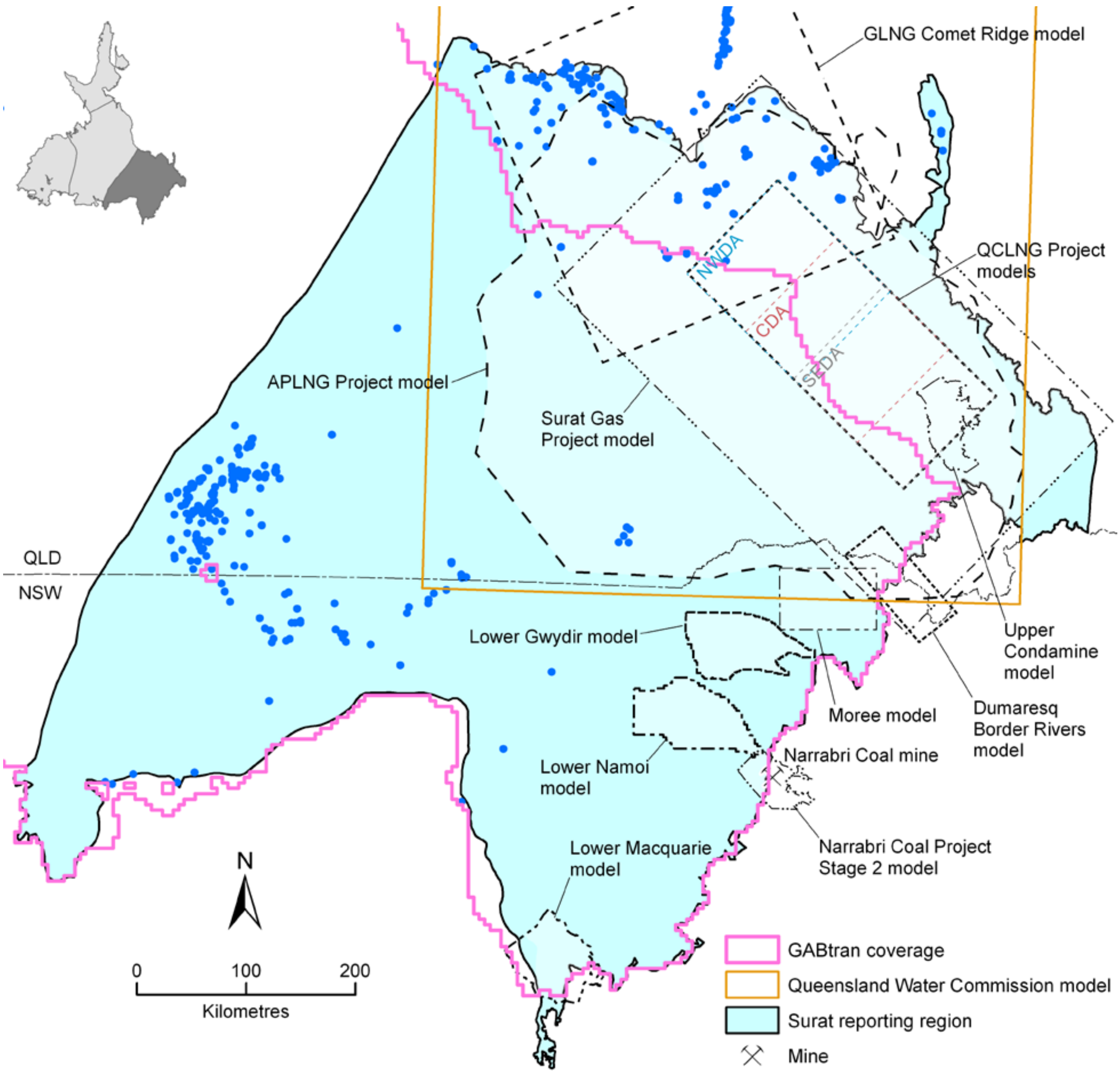


Figure 2.6 Areas covered by groundwater models within the Surat region

2.3 References

Basin Sustainability Allience (2011) Basin Sustainability Alliance Annual Report 2010-2011. Basin Sustainability Allience. <http://www.basinsustainabilityalliance.org/cms-assets/documents/28370-8267.bsa-annual-report-july2011.pdf>.

Blake T and Cook M (2006) Great Artesian Basin: historical overview. Department of Natural Resources, Mines and Water, Queensland.

DEEDI (2011) Surat Basin future development strategy. Department of Employment, Economic Development and Investment, Brisbane. <http://203.210.126.185/dsdweb/v4/apps/web/secure/docs/4547.pdf>.

DERM (2005) Hydrogeological framework report for the Great Artesian Basin Water Resource plan area: version 1.0. Unpublished report. Queensland Department of Environment and Resource Management. Prepared by the Queensland Department of Natural Resources and Mines, Brisbane.

DWE (2009) Water Sharing Plan NSW Great Artesian Basin Groundwater Sources: background document. NSW Department of Water and Energy, Sydney.

Exon NF (1976) Geology of the Surat Basin in Queensland. Bulletin 166. Bureau of Mineral Resources, Geology and Geophysics, Canberra.

GABCC (2000) Great Artesian Basin strategic management plan. Great Artesian Basin Consultative Council for the Australian Government Department of Agriculture, Fisheries and Forestry, Canberra. Viewed 27/09/2008.

GABCC (2010) Great Artesian Basin resource study update. Great Artesian Basin Coordinating Committee, Brisbane. Viewed 17 October 2011, <http://www.gabcc.org.au/tools/getFile.aspx?tbl=tblContentItem&id=412>.

GHD (2010) Report for QWC 17–10 Surat: Basin groundwater modelling: Stage 1 model review (Draft). GHD report to Queensland Water Commission, Brisbane.

Golder Associates (2009) Groundwater assessment. Supplementary appendix 3.2 in: Queensland Curtis LNG Project environmental impact statement, Volume 3 – environmental impacts of the gas field component. Golder Associates on behalf of QGC – A BG Group business, Brisbane.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Habermehl MA (1982) Investigations of the geology and hydrology of the Great Artesian Basin, 1878–1980. Report 234. Bureau of Mineral Resources, Canberra.

Hennig A (2005) A Summary of the Hydrogeology of the Southern Eromanga and Surat Basins of the Great Artesian Basin. CO2CRC/CSIRO Petroleum, Australia. CO2CRC Report Number RPT05-0024. <https://extra.co2crc.com.au/pts/index.php/extDown/getFile/31>.

ICAW (1913) Report on the interstate conference on artesian water, Sydney, 1912. Interstate Conference on Artesian Water, Government Printer, Sydney.

ICAW (1914) Report on the second interstate conference on artesian water, Brisbane, 1914. Interstate Conference on Artesian Water, Government Printer, Brisbane.

ICAW (1922) Report on the third interstate conference on artesian water, Adelaide, 1921. Interstate Conference on Artesian Water, Government Printer, Adelaide.

ICAW (1925) Report on the fourth interstate conference on artesian water, Perth, 1924. Interstate Conference on Artesian Water, Government Printer, Sydney.

ICAW (1929) Report on the fifth interstate conference on artesian water, Sydney, 1928. Interstate Conference on Artesian Water, Government Printer, Sydney.

Matrixplus (2009) Groundwater (deep aquifer modelling) for Santos GLNG Environmental Impact Statement. Matrixplus. Viewed 28 March 2012, <http://www.glng.com.au/library/EIS/Appendices/P2_Groundwater%20%28Deep%29%20FINAL%20PUBLIC.pdf>.

Moran C and Vink S (2010) Assessment of impacts of the proposed coal seam gas operations on surface and groundwater systems in the Murray-Darling Basin. Centre for Water Management in the Mineral Industry, University of Queensland, Brisbane.

QWC (2010) Annual Report 2009–10. Queensland Water Commission, Brisbane. <http://www.qwc.qld.gov.au/about/pdf/corpdoc/annual-report-0910-full.pdf>.

Radke BM, Ferguson J, Cresswell RG, Ransley TR and Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra.

SEWPaC (2010) The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin. In community and species profile and threats database. Department of Sustainability, Environment, Water, Population and Communities, Canberra. Viewed 23 August 2011, <http://www.environment.gov.au/sprat>.

Smith AJ and Welsh WD (2011) Review of groundwater models and modelling methodologies for the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

WorleyParsons (2010) Ground water technical report – gas fields. Chapter 21 in: Australia Pacific LNG Project environmental impact statement, Volume 5 attachements. Worley Parsons on behalf of Australia Pacific LNG, Brisbane. <http://www.aplng.com.au/environment/our-environmental-impact-statement>.

Part II Assessments drawing on the Habermehl (1980) conceptualisation of the Great Artesian Basin

3 Numerical groundwater flow modelling

Authors: Welsh WD, Moore CR and Turnadge CJ

The primary aim of the Great Artesian Basin Water Resource Assessment (the Assessment) is to undertake an integrated reappraisal of the latest hydrogeology, hydrochemistry and groundwater modelling of the Assessment area. Included in this is a consideration of current and future climate and development through groundwater model scenarios.

The objective of the modelling is to investigate the consequences to groundwater resources under different scenarios (as described in Section 3.1.1), such as might occur under climate change, or changed development regimes. Thus, estimates can be made of future hydrogeological attributes, such as the changes in groundwater levels. The future climate scenarios included a change in rainfall and evaporation, which would produce different groundwater recharge rates occurring at the intake beds in 2070. A spectrum of three different climate scenarios was selected, representing a wet extreme, median and dry extreme future climate. The future groundwater development scenarios included consideration of changing rates in groundwater extraction. In the Surat region, these changes will include a reduction in extraction due to bore rehabilitation under the Great Artesian Basin Sustainability Initiative (GABSI) and development of other potential extractive industries.

A review of groundwater models and modelling methodologies was conducted as part of the Assessment (Smith and Welsh, 2011). This review compiled a current list of contemporary groundwater models within the Assessment area with the aim of identifying those models potentially suitable for the purpose of the Assessment. The review found the GABtran model to be the most suitable existing groundwater model. It also found that insufficient time and resources preclude the extension of the single-layer GABtran model to a multilayered groundwater flow model that would be more suitable for the Assessment. It recommended that any future re-development of GABtran should be based on the reconceptualisation of the Great Artesian Basin (GAB) that will be a product of this Assessment.

For the Surat region, the review found that GABtran is capable of simulating the effects of future climate, but not the effects of groundwater development related to coal seam gas (CSG) development. This is because CSG production will originate from geological formations underlying the modelled aquifers and hence is not represented in GABtran. A collaboration was established between CSIRO and the Queensland Water Commission (QWC) to use the existing groundwater flow model developed by QWC, together with GABtran, for assessing the impact of CSG developments under the climate and development scenarios. This model is based on a more recent conceptualisation of the GAB.

3.1 Methodology

The reconceptualisation of the GAB was not completed before the modelling was required to begin. Hence the numerical modelling was based on Habermehl's (1980) conceptualisation (see Section 1.3.1).

The following sections summarise the modelling methods used in the Assessment. They cover future climate and development scenarios, recharge scaling factors, and the GABtran and QWC models. For more detailed descriptions of the modelling process, refer to the companion technical report about modelling as listed in Appendix A.

3.1.1 Future climate and development scenarios

The list below summarises the scenarios used in the Assessment.

- Base run – historical climate and development to 31 December 2010
- Scenario A – same as base run to 31 December 2010, then historical climate and current (2010) development to 31 December 2070
- Scenario C – same as base run to 31 December 2010, then future climate and current (2010) development to 31 December 2070

- Scenario D – same as base run to 31 December 2010, then future climate and future development to 31 December 2070.

The modelling scenarios have been designated Scenario A, Scenario C and Scenario D following the convention established for previous Sustainable Yields projects. Results of a particular scenario are reported relative to another scenario to minimise uncertainty in model results. Scenarios A, C and D are always reported relative to the base run. Also Scenario C is sometimes reported relative to Scenario A, and Scenario D is sometimes reported relative to Scenario C. Thus, results are never reported just under the base run.

To represent climate change, recharge scaling factors (Section 3.1.2) derived from global climate models were applied to recharge cells representing rain-derived model inflows under scenarios C and D.

Previous Sustainable Yields projects in the Murray-Darling Basin, northern Australia, south-west Western Australia and Tasmania also modelled and reported a Scenario B (CSIRO, 2008; 2009a; 2009b; 2009c) – a short recent climate scenario (past 10 or 11 years) which was used to evaluate the consequences of recent climate variations on surface water resources. As the Assessment does not consider the consequences to surface water supplies, (except those generated through discharge of GAB groundwater), a short recent past scenario like this is unlikely to exhibit any difference (within statistical uncertainty) to the longer-term (100-year plus) record for groundwater levels. This reflects the longer time frames for adjustment of groundwater systems relative to surface water systems. Thus the Assessment did not model or report Scenario B.

Also unlike the previous Sustainable Yields projects that reported the results of dynamic steady state model simulations, the scenarios in this Assessment are run in transient mode. This is an increased level of sophistication that incrementally applies future climate and future development so the scenario results apply to 2070, regardless of whether the system has reached equilibrium by this time.

3.1.2 Recharge scaling for future scenarios

Changes in climate conditions will result in changes to rainfall and potential evapotranspiration, which in turn will produce changes in groundwater recharge rates. Under scenarios C and D, groundwater recharge was altered relative to the baseline (historical) recharge. As in previous Sustainable Yields projects, the coupled soil, vegetation and atmosphere WAVES model (Zhang and Dawes, 1998) was used to develop relationships between the future climate scenario and groundwater recharge (Crosbie et al., 2010a). WAVES includes plant physiological feedbacks in response to increased CO_2 of future climate scenarios and recharge fluxes. The WAVES model was run for a set of control points that represent a range of soil types and land uses. The results of this point-scale modelling were then upscaled based on gridded climate, soil and vegetation data to create a recharge raster across the entire Assessment area. To investigate the impact of climate scenarios, modelled recharge estimates based on historical climate data are compared with results generated from future climate scenarios. This comparison is referred to as a recharge scaling factor, defined as the ratio of future recharge to historical recharge.

The Assessment used the results from a National Water Commission (NWC) funded project ‘Investigating the Impact of Climate Change on Groundwater Resources’ (Crosbie et al., 2010b), which used the same recharge scaling factor approach. The NWC project generated recharge rasters for all of Australia using historical and future climates (2050), and soil and vegetative groups across the entire country. For the national-scale recharge rasters, the historical period considered was the 80-year period from 1930 to 2009, and future climate sequences were generated from 16 global climate models with three different global warming cases: low = +1.0 °C, medium = +1.7 °C, and high = +2.4 °C (all relative to 1990). The global warming cases for the 2050 climate were inferred from the Special Report on Emission Scenarios (SRES) scenarios (IPCC, 2000).

Considering that median global warming for the 2070 climate and SRES emission scenarios is approximately 2.2 °C (Wigley and Raper, 2001), modelled recharge scaling factor rasters from the high global warming case (2.4 °C) for the 2050 climate and SRES emission scenarios are being used as a proxy for new recharge modelling. The implications of using recharge scaling factor rasters determined for a high global warming case for 2050 as a proxy for median global warming for 2070 are expected to be minimal.

In the Assessment the range of future scenarios is represented using a weighted probability distribution. The range includes the wet extreme, median and dry extreme future climates (i.e. scenarios Cwet, Cmid, Cdry, Dwet, Dmid and D dry). The wet scenarios use results from the 90th percentile, mid from the 50th percentile and dry from the 10th percentile of the 2050 high global warming case. The rain-derived recharge cells in the groundwater models are multiplied by proportions of the recharge scaling factors, from zero in 2010, linearly increasing to the full values in 2070.

The definition of recharge areas is taken from Habermehl and Lau (1997) .Recharge is mostly around the northern and eastern margin of the Surat region (Figure 3.1). Under the wet scenarios, recharge increases in all areas. Under the mid scenarios, recharge decreases in the west and parts of the south, east and north. Under the dry scenarios, recharge decreases everywhere. Since the GAB flow systems are large, the full impact of climate change to 2070 might not be observed in this timeframe.

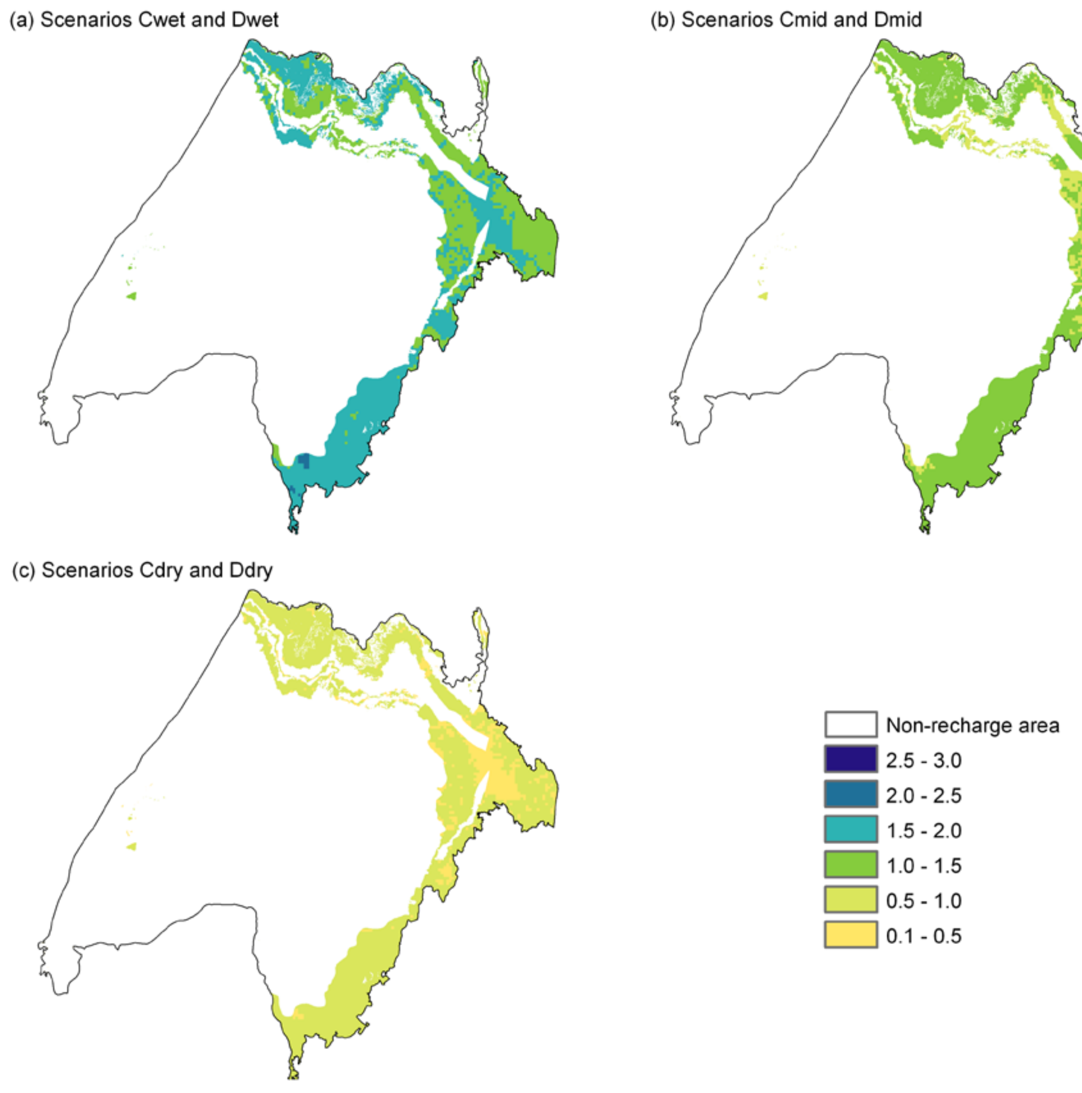


Figure 3.1 WAVES recharge scaling factors under scenarios C and D
Note: legend shows recharge scaling factors

3.1.3 GABtran model

The GABtran model was developed to estimate water level recoveries under different GABSI bore rehabilitation scenarios and model results are sensitive to rates of groundwater recharge and groundwater extraction. GABtran is a single layer model that includes net leakage from vertically adjacent aquitards. The model is described in detail in Welsh (2006; 2007) and summarised in the companion technical report about modelling as listed in Appendix A. The GABtran model used for the Assessment was not modified from its original 2006 parameterisation, except as required to run the scenarios.

GABtran was not able to model 100 percent of the climate and development impacts because it does not extend over the entire GAB. It covers 80 percent of the Surat region (Figure 3.2). GABtran models the uppermost artesian aquifer, which has been eroded by natural processes over geological time along the eastern boundary – so the spatial extent does not cover the northeastern portion of the Surat region. The impact of climate and development changes in the aquifers and aquitards both above and below the modelled aquifer are also not addressed in GABtran. Conventional petroleum extractions from the uppermost artesian aquifer are included in the GABtran simulations, but these are zero in the Surat reporting region. The impacts of CSG extraction are modelled using the QWC model for the climate and development scenarios (Section 3.1.4).

To run the scenarios, historical development conditions were extended from the original GABtran model to 31 December 2010 using the available water bore and petroleum well discharge measurements and estimates, including those for bores rehabilitated under capping and piping schemes. This includes estimates of spring discharge rates. Scenarios A and C extended 31 December 2010 development unchanged to 2070. Under Scenarios A and C, GASBI and previous Australian Government programs had achieved approximately 75% of the total expected groundwater savings for the GAB, and it is assumed that no additional groundwater savings would occur. Scenario D used future estimates for flow from springs, water bores and petroleum wells. Under Scenario D, GABSI is assumed to run to full completion, achieving 100% of the total expected groundwater savings. Table 3.1 summarises development under the different scenarios. Under Scenario D, total discharge is estimated to decrease by nearly 40 percent due to ongoing capping and piping of stock and domestic water bores.

Table 3.1 Current and future development discharge estimates for the Surat region in GABtran

Scenario	Year	Water bores	Petroleum wells	Springs	Total
		ML/y			
A and C	2070	231,532	0	2,644	234,176
D	2070	140,747	0	2,644	143,391

Under scenarios C and D the recharge scaling factors were applied to all recharge cells representing rain-derived model inflows. Statistics of the recharge scaling factors and their impact on model recharge in the Surat region are shown in Table 3.2. Note that the average impact of these, as shown in the change in recharge relative to Scenario A, differs from the mean recharge scaling factor because recharge scaling factors are multiplied by different rates of recharge in each cell. For example, under Scenario Cmid, average groundwater recharge increases by 6 percent.

Table 3.2 Statistics of the recharge scaling factors applied in the Surat region in GABtran under scenarios C and D

Scenario	Recharge scaling factor range	Recharge scaling factor mean	Mean change in recharge in 2070 relative to Scenario A
Cwet and Dwet	1.01 – 2.05	1.59	1.54
Cmid and Dmid	0.74 – 1.31	1.10	1.06
Cdry and Ddry	0.13 – 0.90	0.66	0.62

In summary, the scenarios modelled in the Assessment are:

- Scenario A is run for 60 years (to 2070) using the 2010 climate and the 2010 level of development.
- Scenario C linearly transitions to the aggregated recharge rates under scenarios Cwet, Cmid and Cdry over 60 years to 2070. The 2010 level of development is continued from 2010 to 2070.
- Scenario D linearly transitions to the aggregated recharge rates under scenarios Dwet, Dmid and Ddry over 60 years to 2070. Abstractions are modified as per the projected development from 2010 to 2070.

The locations of the calibration bores used in the modelling are superimposed on the results (e.g. Figure 3.3) to show where confidence in the results is greatest. GABtran was not calibrated over the recharge areas.

A generally-accepted rule of groundwater modelling is that scenario results are more reliable when scenarios extend into the future for up to the length of the calibration period. The scenarios used in the Assessment extend the GABtran model by 70 years, while GABtran was calibrated over a 35 year period (1965 to 1999), therefore GABtran results should be regarded as approximations only.

Additional details regarding the scenarios for groundwater modelling are given in the companion technical report about modelling as listed in Appendix A.

3.1.4 Queensland Water Commission model

The QWC developed a numerical groundwater model (GHD, 2011) to simulate the potential impacts of the fast-developing CSG industry in the Surat Basin in Queensland. This model lies entirely within the Surat reporting region. The depressurisation of coal seams to release the natural gas occurs in the Walloon Coal Measures aquitard that underlies the artesian aquifer modelled by GABtran. Impacts on adjacent aquifers from CSG-related abstractions are likely to be via vertical leakage as groundwater is drawn from higher-pressure to lower-pressure areas.

The QWC model has a more complex conceptualisation than GABtran. It has 19 layers. Layer 5 of this model represents the Gubberamunda Sandstone, which is equivalent to the centre to lowest of the GABtran model layer. The QWC model does not extend beyond the New South Wales – Queensland border. The Gubberamunda layer in the QWC model extends further than GABtran in the north-east because the GABtran model boundary follows a local groundwater divide in this area (Figure 3.2). Other minor differences between GABtran, the QWC model and the region boundary are due to improved knowledge since GABtran was developed.

The QWC model was calibrated as a steady state model, then modified to allow transient predictive simulations within a probabilistic context. For its transient predictions, the QWC model uses 200 realisations of model parameters and boundary conditions that are all valid for the calibration of the steady state model. Because the QWC model is designed to estimate only CSG impacts, water bore and spring flows do not change over time in the transient predictive simulations. A summary of the model conceptualisation and development is provided in the companion technical report about modelling as listed in Appendix A.

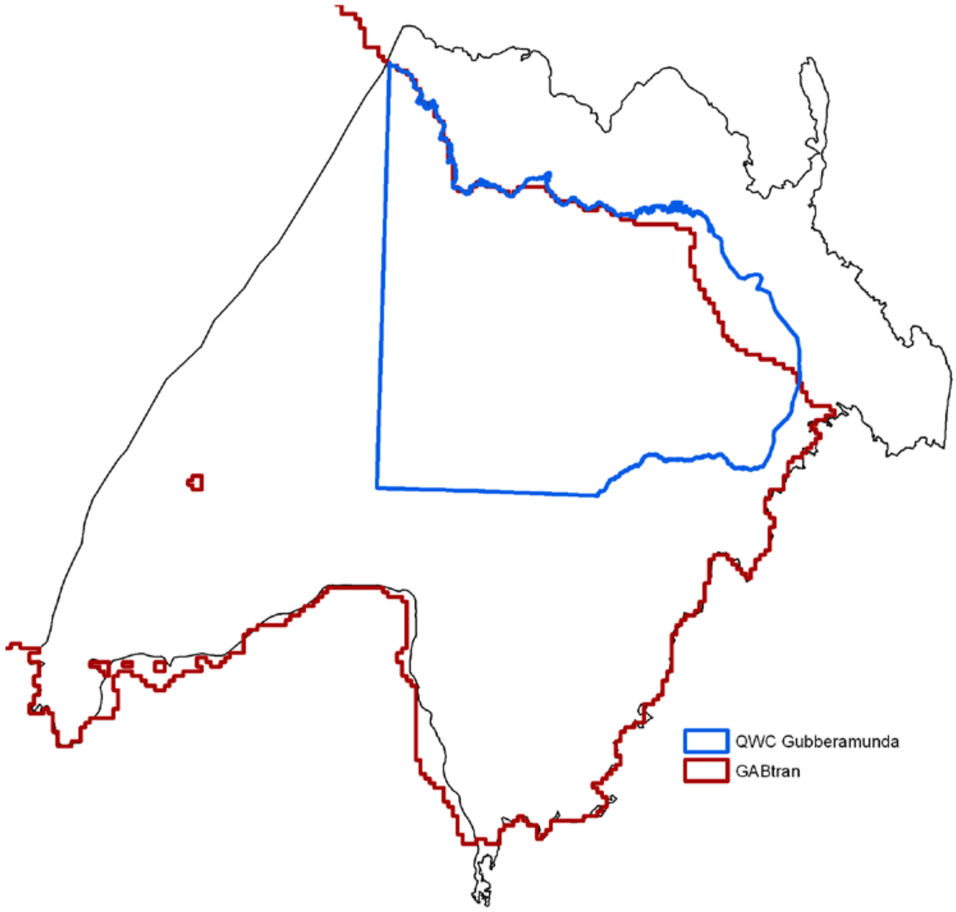


Figure 3.2 Extent of the Gubberamunda Sandstone in the QWC model and GABtran active model cells

Historical development conditions in the QWC model were extended from 1 January 1995 to 31 December 2010 using the available water bore and petroleum well discharge measurements and estimates. This included estimates of spring discharge rates. Scenario C extends 31 December 2010 development unchanged to 2075. Scenario D used estimates of future flow from CSG pumping to achieve depressurisation. Results are reported for Layer 5. CSG extraction is simulated as the extraction rate required to reduce the groundwater level to approximately 40 m above the uppermost coal horizon. Extraction rates decrease with time as more gas begins to flow. CSG depressurisation is expected to cease by 2050, so CSG depressurisation reduces to zero before 2070. However, the impacts of the depressurisation are likely to continue beyond 2070.

The QWC model results are only used in the Assessment for the impact of CSG development on the main artesian aquifers. QWC provided the results from simulating the impacts on the GAB from CSG activities under Scenario D relative to Scenario C at 2075 (Section 3.4.2).

3.2 Scenario A: historical climate and current development

3.2.1 GABtran

Figure 3.3 shows the change in groundwater level under Scenario A at 2070. The results show the impact of continuing historical climate and current development from 2010 to 2070 assuming that GABSI had concluded in 2010 at approximately 75% of the total expected groundwater savings for the GAB.

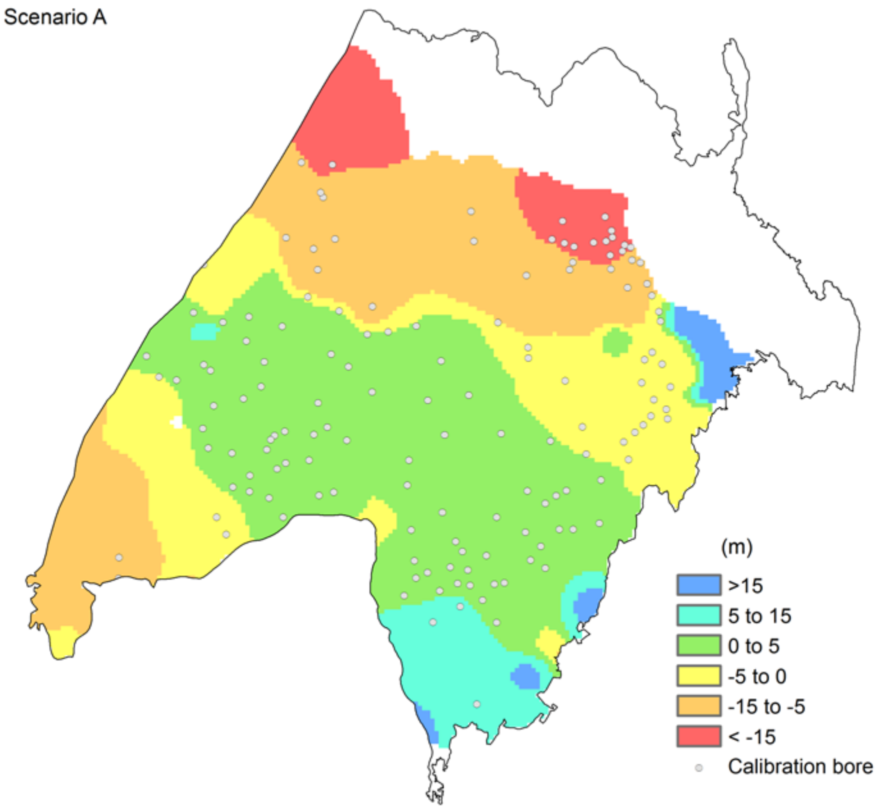


Figure 3.3 Change in GABtran groundwater level (m) under Scenario A
Note: legend shows change in groundwater level (m)

The modelling shows that about half of the region has impacts within a 5 m decrease and a 5 m increase in groundwater level. The apparent increases in groundwater level in excess of 15 m along the eastern margin are not supported by calibration bores and are likely to be an artefact of the modelling process. Generally groundwater level decreases in the north and west, and increases in the south and east of the region. Groundwater recharge exceeds groundwater extraction along the recharge area in the south and east, but groundwater is being extracted at a faster rate than it is replenished elsewhere in the region.

3.3 Scenario C: future climate and current development

3.3.1 GABtran

Under scenarios Cwet, Cmid and Cdry the recharge scaling factors (Figure 3.1) were linearly increased from a nil impact in 2010 to their full impact in 2070.

Figure 3.4 shows the change in groundwater level under scenarios Cwet, Cmid and Cdry at 2070. The results show the impact of projecting future climate to 2070 and continuing current development to 2070 assuming that GABSI had concluded in 2010 at approximately 75 percent of the total expected groundwater savings for the GAB. Under all three scenarios groundwater level decreases in the north and south-west. Recharge along the south-eastern margin exceeds extraction, leading to increasing groundwater level under scenarios Cwet and Cmid. Under Scenario Cdry, groundwater extraction exceeds groundwater recharge along the margin except over the southern part of the Coonamble Embayment. The apparent increases in groundwater level in excess of 15 m in the east under all three scenarios are not supported by calibration bores.

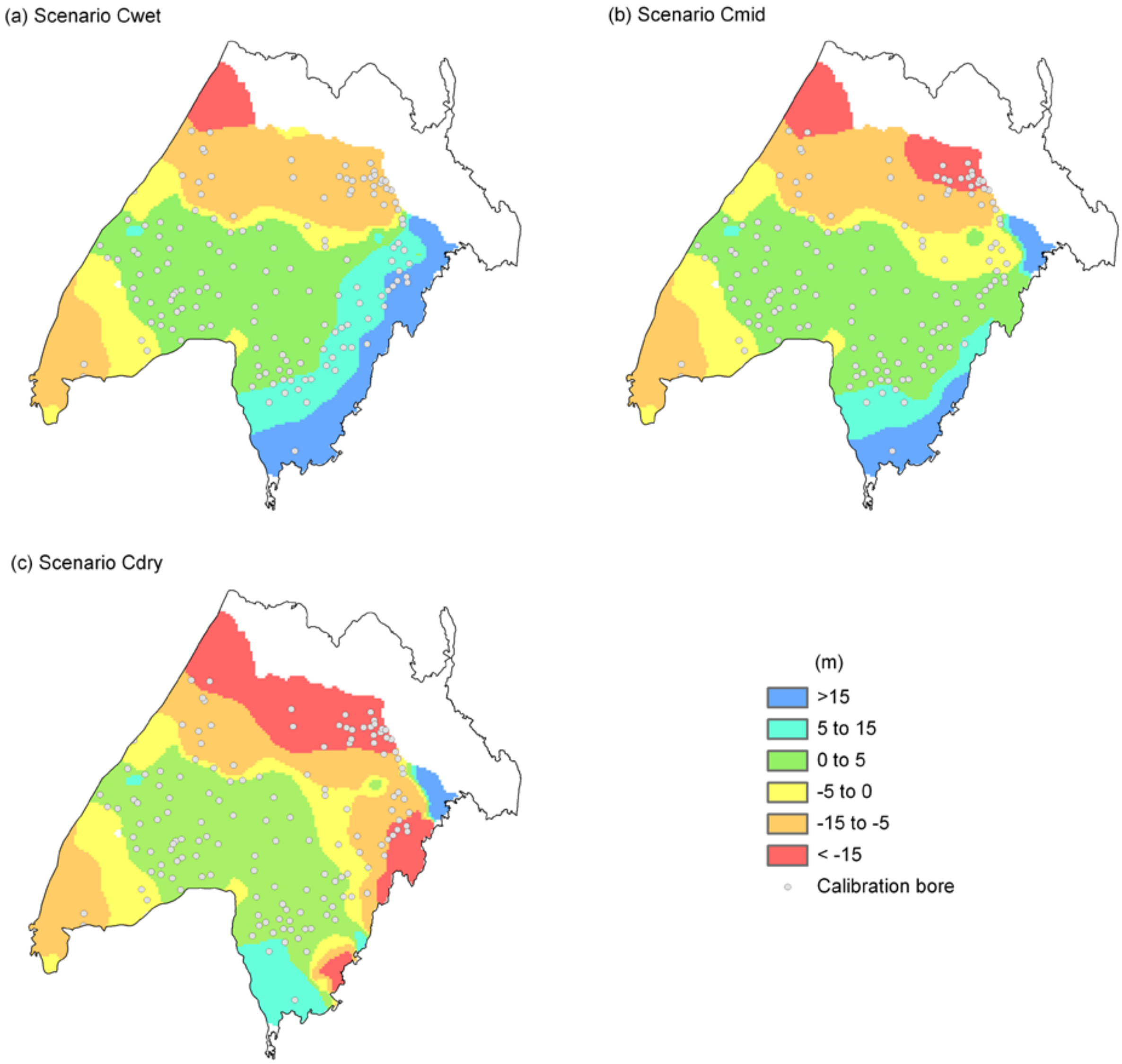


Figure 3.4 Change in GABtran groundwater level (m) under Scenario C
Note: legend shows change in groundwater level (m)

Figure 3.5 shows change in groundwater level under scenarios Cwet, Cmid and Cdry relative to Scenario A at 2070. These differences remove temporal effects and thereby identify impacts of climate alone. Since the recharge scaling factors are all less than 1 under Scenario Cdry, and all more than 1 under Scenario Cwet (Table 3.2), groundwater level decreases under Scenario Cdry relative to Scenario A and increases under Scenario Cwet relative to Scenario A. Under Scenario Cmid relative to Scenario A most groundwater level change is limited to ±5 m.

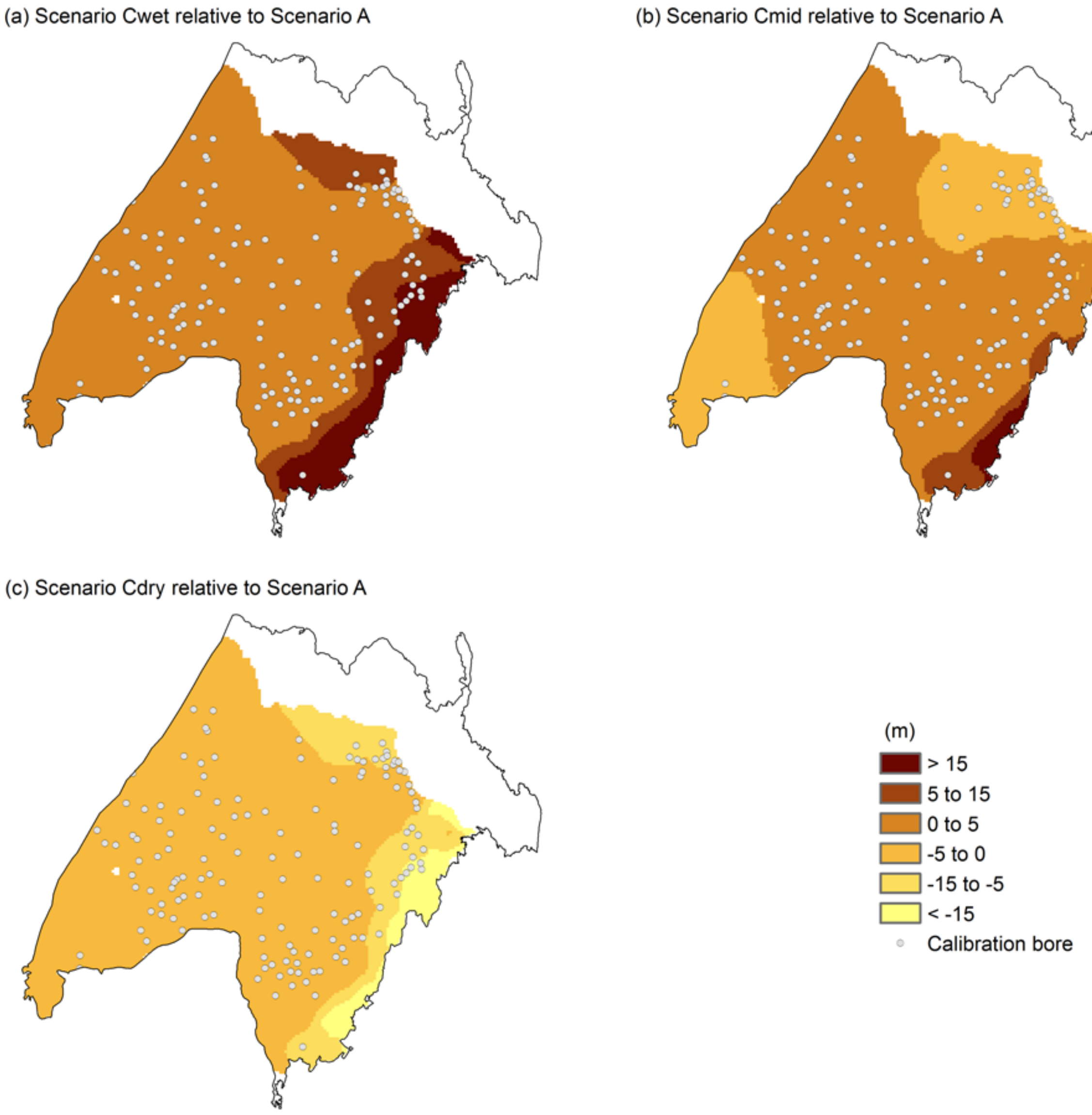


Figure 3.5 Change in GABtran groundwater level (m) under Scenario C relative to Scenario A
Note: legend shows change in groundwater level

3.4 Scenario D: future climate and future development

3.4.1 GABtran

Under scenarios Dwet, Dmid and Ddry the recharge scaling factors (Figure 3.1) were linearly increased from nil impact in 2010 to their full impact in 2070, the same as under scenarios Cwet, Cmid and Cdry.

The assumptions for estimating future development are listed in Table 3.3 and were developed in consultation with the relevant state agencies. Stock and domestic water bores will continue to be rehabilitated until the GABSI has run to full completion. The median post-rehabilitation flow rate (1.27 L/second), for all bores rehabilitated to date under the GAB Sustainability Initiative, was used. Allocations for town water supplies and other licensed bores continue unchanged, except for New South Wales supplementary licences that are being wound down. There are very little data on sub-artesian bores that do not have volumetric allocations; these are assumed to flow at 0.2 L/second, which does not change over time. There are insufficient data to estimate a future change in spring flows, so no change is assumed. There are no petroleum production wells in the GABtran aquifer layer in the Surat region. It is planned to allocate 30 percent of water saved through bore rehabilitations in New South Wales. In Queensland, the *Water Resource (Great Artesian Basin) Plan 2006* details the amounts of water that will be allocated by management zone. The planned amounts of allocation have been used in this modelling.

Table 3.3 Future development assumptions for GABtran under Scenario D

Development type	New South Wales	Queensland
Water bores with allocations	Flows are set to their licensed levels for 2011 to 2070.	Flows are set to their licensed levels for 2011 to 2070.
Artesian stock and domestic bores without water allocations	Bores not yet rehabilitated but flowing >1.27 L/second are rehabilitated at a rate of 20 bores per year (over the whole GABtran area) starting with the highest-flowing bores.	Bores not yet rehabilitated and flowing >1.27 L/second are rehabilitated at a rate of 27 bores per year (over the whole GABtran area) starting with the highest-flowing bores.
Sub-artesian bores without allocations	Flows remain at their 2010 levels to 2070.	Flows remain at their 2010 levels to 2070.
Allocation of water saved	30% of water savings are added back to the rehabilitated bore flow rates.	The full General Reserve amounts are spread across the existing water bores in each management zone from 1 January 2014. The State Reserve is not allocated in this region.
Petroleum wells	N/A	N/A
Springs	Flows remain at their 2010 levels to 2070.	Flows remain at their 2010 levels to 2070.

Figure 3.6(a), Figure 3.6(b) and Figure 3.6(c) show change in groundwater level under scenarios Dwet, Dmid and Ddry at 2070. The results show that the impact of projecting both future climate and future development from 2010 to 2070 is similar under all three scenarios. Although climate impacts appear to be greatest in the south-eastern Coonamble Embayment, this contention is not well-supported by calibration bores. Under all scenarios it is estimated that one half or more of the region will have a gradual recovery of groundwater level, as the impact of bore rehabilitation is greater than the impact of future climate.

Figure 3.6(d) shows the changes in groundwater level under Scenario D relative to Scenario C at 2070. Calculating this difference removes temporal and climatic effects and thereby identifies impacts of future development alone. The impact of future development alone is also estimated to be a gradual recovery of groundwater level over much of the Surat region due to ongoing capping and piping of stock and domestic water bores.

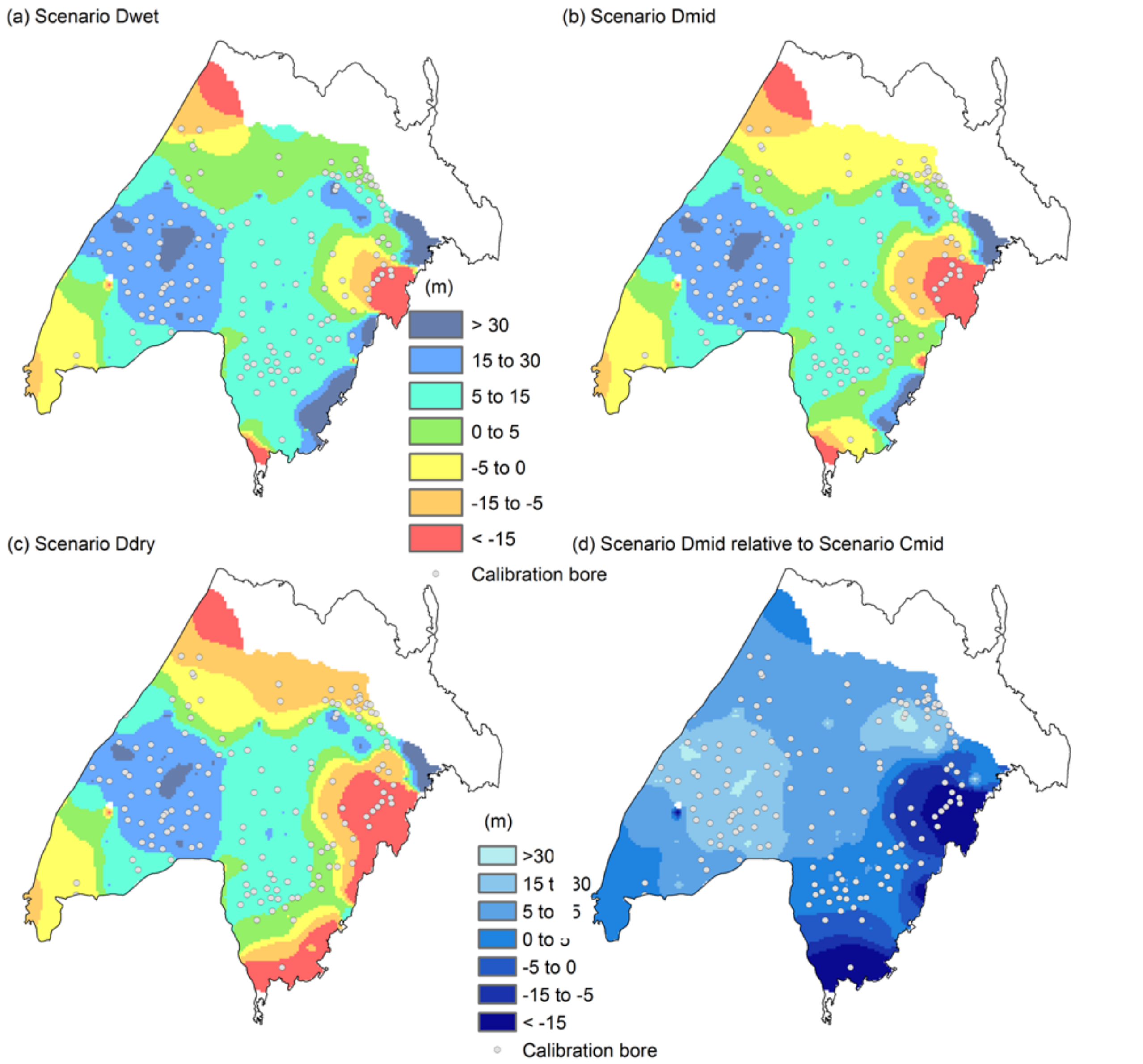


Figure 3.6 Change in GABtran groundwater level (m) under scenario D, and under Scenario D relative to Scenario C
Note: legend shows change in groundwater level (m)

3.4.2 Queensland Water Commission model

Figure 3.7 shows the median, and the upper and lower 95th percentile changes in groundwater level under Scenario D relative to Scenario C at 2075 for coal seam gas impacts on the Gubberamunda Sandstone estimated by the QWC model. This shows the impact of future development alone with temporal and climatic effects removed. Under the median and lower 95th percentile estimates the impact of CSG development alone in the Gubberamunda Sandstone and equivalents at 2075 is less than 0.2 m over more than three quarters of the model area. Under the upper 95th percentile estimate the impact is less than 1 m over most of the area.

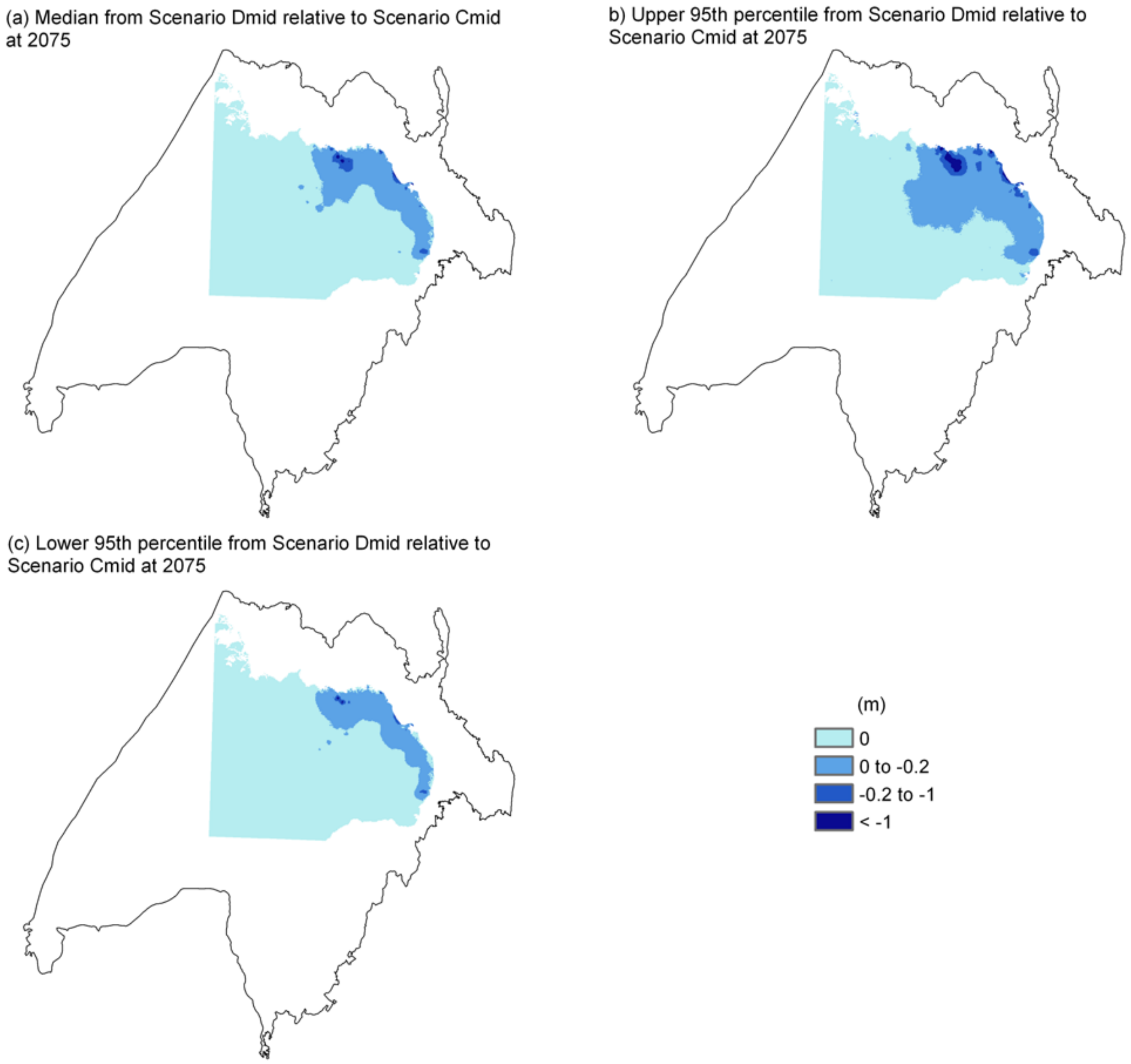


Figure 3.7 Change in the groundwater level (m) at 2075 under Scenario D relative to Scenario C for the QWC model
Note: legend shows change in groundwater level (m)

Figure 3.8 shows the combined impacts of all extractions including CSG under Scenario D relative to Scenario C. The result is very similar to Figure 3.6(d) because the estimated CSG impacts are small relative to the estimated impacts from stock and domestic bore rehabilitations. Compared to the increase in groundwater levels resulting from the GABSI program being run to full completion, whereby all eligible uncontrolled artesian bores are controlled, the estimated decrease in groundwater levels from CSG development is relatively small.

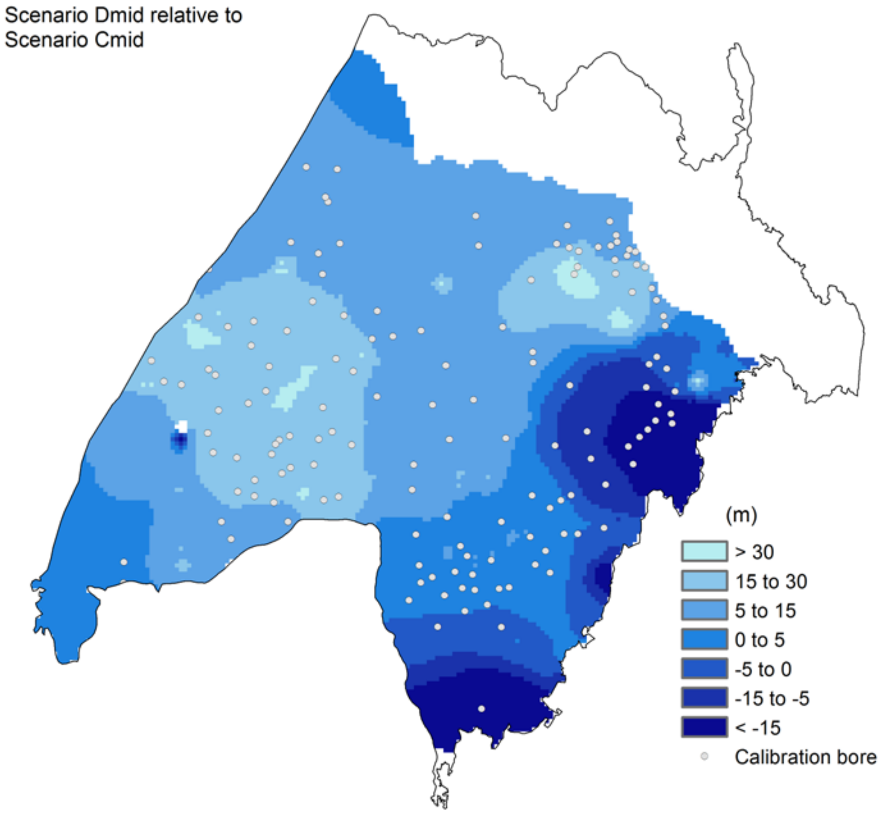


Figure 3.8 Change in groundwater level (m) for the combined impacts of water bores, springs and CSG under Scenario D relative to Scenario C at approximately 2070 from the GABtran and QWC models
Note: legend shows change in groundwater level (m)

3.5 Uncertainty, gaps and limitations

All model simulations are challenged to varying extents by data insufficiencies (e.g. lack of data, inaccurate data and data of the wrong type), and by the model's computational necessity to represent the complex real world in a relatively simple form. The more complex the real world is relative to its model representation, the greater are the impacts of these challenges. As a result of these challenges, model simulations cannot be made with perfect certainty; instead some uncertainty always accompanies a predictive model simulation.

GABtran, with its very large spatial extent and limited vertical extent, features both significant data insufficiency and significant real world simplification. Although it is more complex, the QWC model faces similar uncertainty challenges. Uncertainty analyses are used to describe the predictive confidence for model scenarios, to identify which knowledge and data gaps contribute most to the uncertainty, and which data and methods improve model predictive reliability the most. The uncertainty analyses convey the reliability of the scenario results, assess how best to improve this reliability through additional data collection, and inform risk assessments based on these scenarios.

3.5.1 Uncertainty and error analysis

Uncertainty and predictive error analyses provide a measure of the reliability of a model simulation. They quantify the lack of knowledge and provide a foundation on which to base decisions, to assess data worth and to inform future model development.

The uncertainty of estimated impacts on groundwater due to climate and development changes varies across an aquifer. This variation is governed by the aquifer heterogeneity, the magnitude of stresses, and the number of calibration observations that occur at any location. To simplify the uncertainty analysis reporting, a lumped description of the uncertainty of the overall changes occurring within the aquifer system was adopted. This analysis therefore emphasises the uncertainty of aquifer-wide trends occurring from climate and development changes, rather than at specific points within the aquifer. Uncertainty and predictive error analyses were applied to predictions of average change in groundwater level in the GABtran and QWC models arising under scenarios A, C, D, C relative to A, D relative to C.

GABtran model – uncertainty of the average groundwater level changes

For GABtran the uncertainty of the average change in groundwater level under each scenario was assessed using an error propagation analysis. This method also led to the identification of knowledge and data gaps in the following sections.

Scenario results in sections 3.2, 3.3 and 3.4 report groundwater level change for a particular scenario relative to another scenario to minimise uncertainty in the results (Section 3.1.1). The average groundwater level difference for each scenario was calculated and statistics were derived from the individual cell values (Table 3.4). The standard deviation quantifies the spread of the scenario results, noting that there is uncertainty in the parameters within the calibrated model. The standard deviation is highest for Scenario D, which includes the impact of time, climate and development, and lowest for Scenario C relative to Scenario A, which only includes the impact of climate.

Table 3.4 Statistics of the average groundwater level change in the GABtran model

Scenario	Median (m)	Standard deviation (m)	Lower 95% confidence limit (assuming Gaussian error) (m)	Upper 95% confidence limit (assuming Gaussian error) (m)
A	–1.37	0.71	–2.75	0.011
Cwet	2.80	0.85	1.14	4.47
Cmid	–0.63	0.73	–2.05	0.79
Cdry	–3.80	0.69	–5.16	–2.44
Dwet	7.76	0.95	5.89	9.63
Dmid	4.33	0.86	2.64	6.02
Ddry	1.16	0.85	–0.51	2.83
Cwet relative to A	4.17	0.35	3.48	4.87
Cmid relative to A	0.74	0.09	0.56	0.92
Cdry relative to A	–2.43	0.19	–2.06	–2.79
Dmid relative to Cmid	–4.96	0.49	–5.93	–3.99

Queensland Water Commission model – uncertainty of the average groundwater level changes

For its transient simulations, the QWC model uses 200 realisations of model parameters and boundary conditions that are all valid for the calibration of the steady state model. These realisations, and the associated calculated model drawdown outputs for 2075, were provided by QWC for the Assessment.

The average change in groundwater level from each of the realisations was calculated and collated into a probability distribution (Table 3.5, based on the probability density functions in Figure 3.9). The standard deviations and confidence limits give an indication of the spread of the scenario predictions. All lower and upper 95th percentile confidence limits are negative, confirming that groundwater levels are estimated to decrease under CSG development.

Table 3.5 Statistics of the average groundwater level change due to CSG in layer 5 of the Queensland Water Commission model

Scenario	Median (m)	Standard deviation (m)	Lower 95% confidence limit (m)	Upper 95% confidence limit (m)
Dmid relative to Cmid	–0.0410	0.00733	–0.0299	–0.0571

Figure 3.9 shows the probability density functions for the average groundwater level change in Scenario D relative to Scenario C for CSG development. The uncertainty distributions indicate that from the available knowledge, this is a reasonably robust prediction of impacts from CSG development in the region. However, this result does not exclude the possibility that more extreme CSG-derived impacts could occur before or after 2070. Nor does it exclude the possibility that more extreme localised impacts might be obscured in the averaging process.

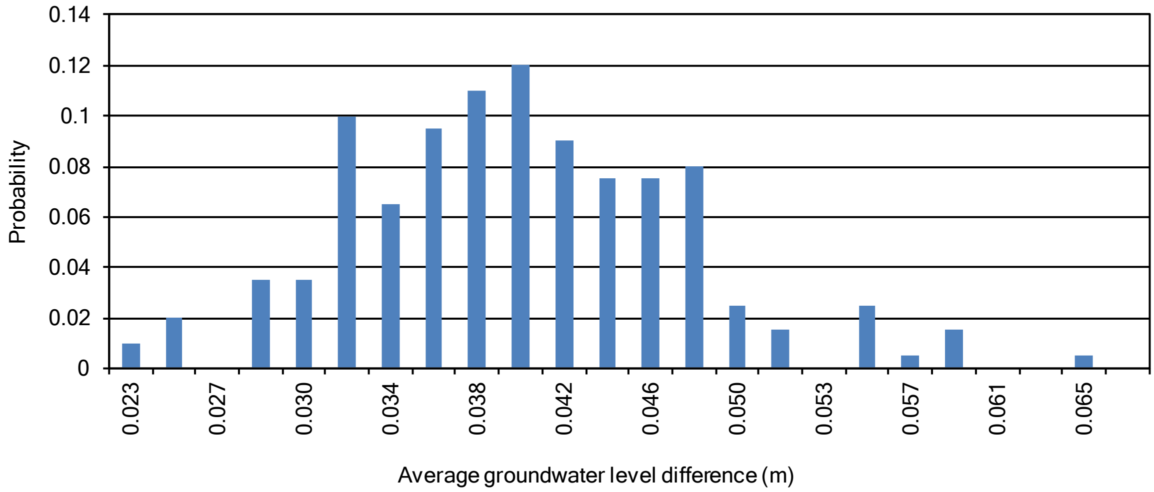


Figure 3.9 Probability density function for the average groundwater level change under Scenario D relative to Scenario C for the Queensland Water Commission model

3.5.2 Knowledge gaps

The worth of improved knowledge from new data is assessed by the potential of the new data to reduce the uncertainty in scenario predictions, through reducing the uncertainty in model parameter values.

The contribution to predictive reliability from various GABtran model inputs was examined using the calibration dataset, the 'a priori' parameter distributions in the calibrated model, and calculated parameter sensitivities. The analysis was applied to the model both with and without calibration constraints. This is possible because the analysis requires only the sensitivities of model outputs with respect to the model parameters, and not the values of these model outputs or of the parameters themselves. Although the results for each scenario differ, the contribution of each parameter value to this uncertainty is consistent within each scenario for dry, mid and wet climates, so this analysis gives the same results for the dry, mid and wet future climates.

The results (Figure 3.10) show the contribution of various key model parameters to the uncertainty of the predictions of average water level changes over the Surat region for both the calibrated and uncalibrated GABtran model. GABtran was not re-calibrated for this analysis.

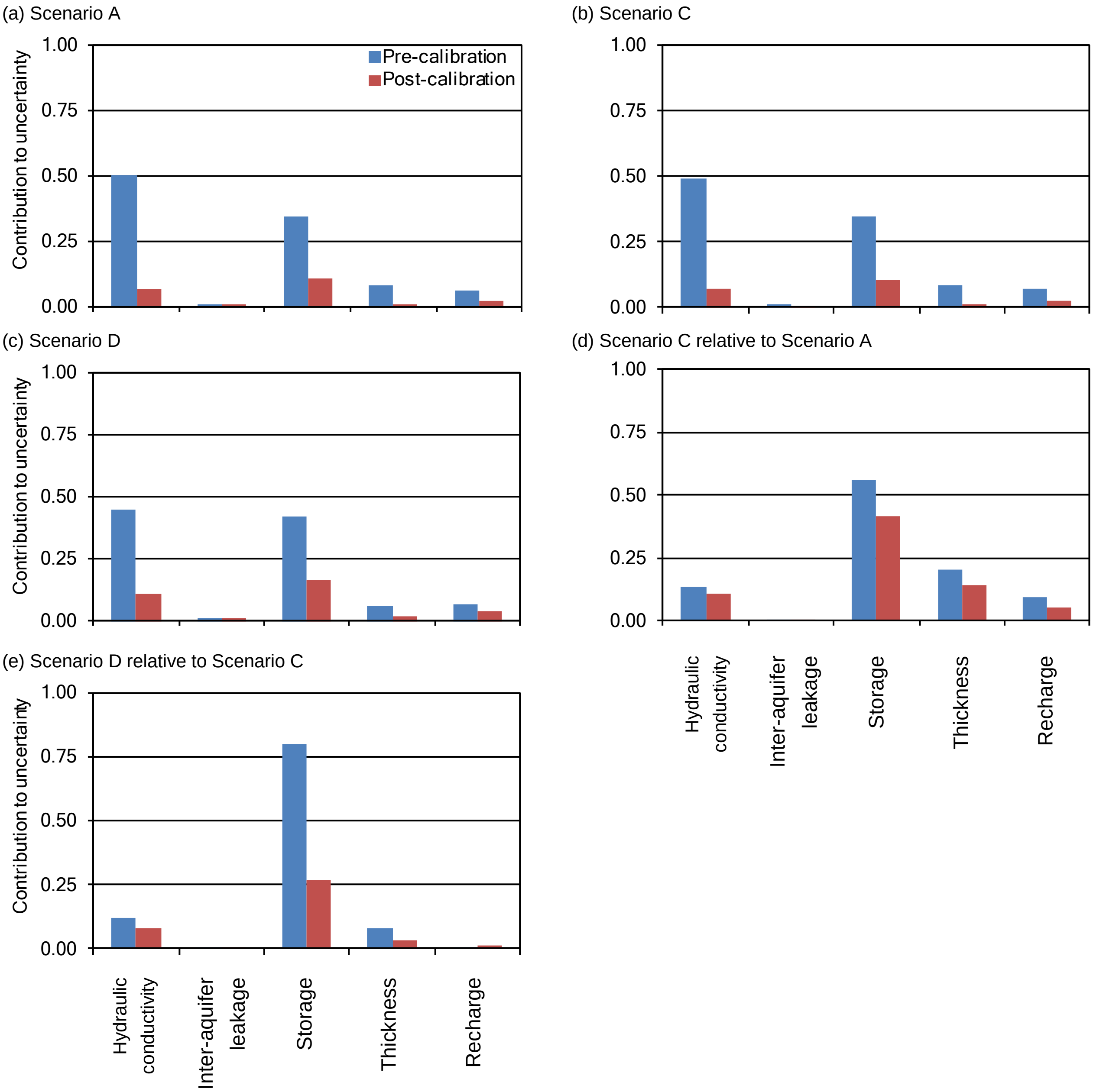


Figure 3.10 Relative increase in prediction reliability of long-term groundwater level changes that would be possible in GABtran with enhanced knowledge of parameters and model inputs

An overall reduction in the uncertainty from the imposition of calibration constraints is evident when comparing the pre- and post-calibration contributions. For all cases, the greatest contribution to post-calibration prediction uncertainty is from hydraulic conductivity and storage properties. Inter-aquifer leakage, rainfall recharge and aquifer thickness contribute smaller amounts of uncertainty.

Future data collection efforts could be prioritised in accordance with these results. Assessing the impact of the uncertainty of future development and climate scenarios would be a useful extension of this analysis in future projects. Related analyses could explore the interdependencies between these parameter groups. Future work could also explore the impact of alternative GAB system conceptualisations on these results.

3.5.3 Data gaps

Uncertainty analysis can also be used to inform more specific monitoring and measurement optimisation decisions. It can answer such questions as: where, when and which data type has the most worth, where data worth is defined in terms of the reduction of scenario prediction uncertainty. Data worth can be assessed for existing monitoring networks, and for potential future data acquisitions, by identifying where data collection will have greatest impact on improving predictive reliability for model-based environmental management.

This uncertainty analysis assessed the information content of the locations of the GABtran calibration bores in terms of how well they inform estimates of average change in groundwater level over the whole region under scenarios A, C and D. It did not assess the temporal spread or number of observations at each point. Where the data worth analysis indicates that there are sufficient measurement points to estimate the average groundwater level change over the whole region, there can be insufficient measurement points to estimate groundwater level change at specific locations away from the calibration bores. A future analysis could assess the information content of the existing monitoring network for particular model cells.

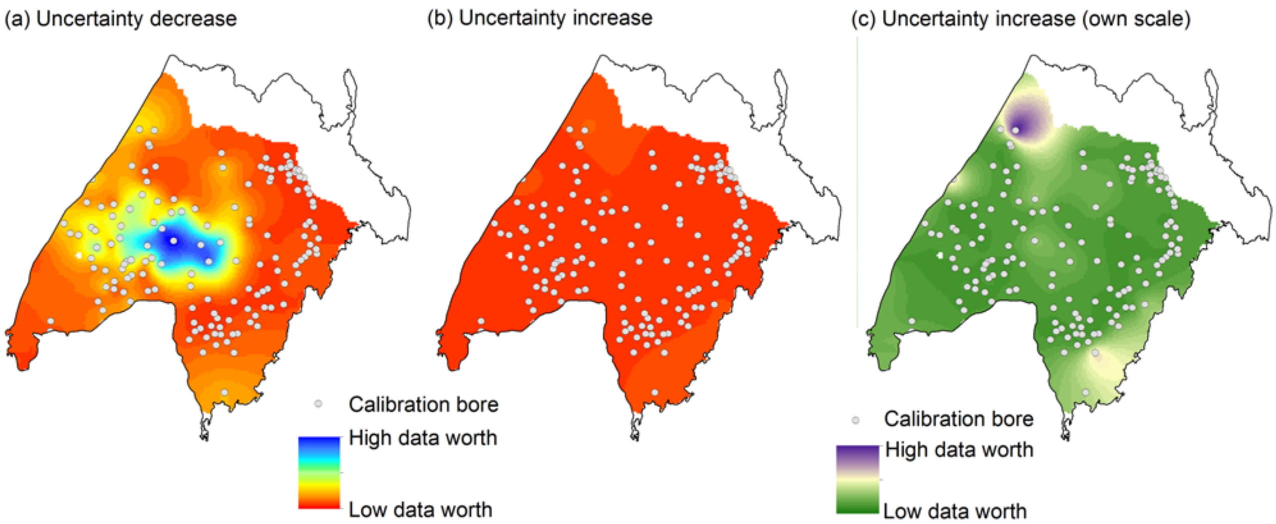


Figure 3.11 Spatial distribution of data worth of monitored groundwater level for GABtran
Note: data worth is shown by a coloured spectrum ranging from blue which indicates higher data worth (e.g. a larger decrease in the prediction uncertainty) to red which indicates a lower data worth (e.g. a smaller decrease in the prediction uncertainty). Uncertainty decrease: data worth determined by beginning with no observations and adding an observation one at a time. Uncertainty increase: data worth determined by beginning with a set of observations and removing an observation one at a time. Uncertainty increase plotted to its own scale is shown by a coloured spectrum ranging from purple to green.

The relative worth of the spatial distribution of the existing GABtran calibration bores is shown in Figure 3.11. Figure 3.11(a) shows data worth calculated on the basis that there are initially no observations to constrain the Surat region average groundwater level change prediction. The data from each observation bore are then systematically added and the relative reduction in uncertainty is assessed. The greatest uncertainty reduction (i.e. highest data worth) is shown by shading at the blue end of the coloured spectrum and the least uncertainty reduction is indicated by shading towards the red end of the spectrum. The analysis suggests that the groundwater level monitoring occurring within the blue shaded area near the centre of the region contains the greatest information for predicting the average groundwater level changes.

Figure 3.11(b) shows data worth calculated on the basis that all currently available observations have been used to constrain the average groundwater level change prediction. The data from each observation bore are then systematically removed and the relative increase in uncertainty is assessed. The results are displayed using the same scale as Figure 3.11(a). There is almost no variation in data worth across the existing monitoring network, indicating there are currently sufficient groundwater level data for the assessment of the Surat region average groundwater level change. This discrepancy in data worth between the two calculation methods indicates there are currently more than sufficient groundwater level data for the assessment of average groundwater level change in the Surat region. However if the network were to be significantly reduced, retaining monitoring locations within the areas of Figure 3.11(a) shaded towards the blue end of the spectrum would allow more reliable predictions than retaining alternative existing monitoring locations.

Figure 3.11(c) is the same as Figure 3.11(b), but plotted over its own range of values. T he highest data worth generally occurs for observations located in areas where groundwater abstractions and spring discharges are dense and there is a low measurement density.

This analysis relates to the GABtran model in its current form. If a more complex model is developed, more monitoring data would be needed. This analysis alone is not sufficient to determine where additional monitoring effort will have the most impact. Instead, all of the predictions the data are used to inform must be considered in combination. The combined data worth analyses will suggest optimum locations for future monitoring data acquisition using the existing monitoring network. Although data worth is a function of the modelling scenarios, these analyses can provide valuable information even before a numerical model is constructed because the broad patterns of data worth seem to be robust.

The same method could be extended to future data acquisition strategies for a range of disparate data types (e.g. groundwater levels, isotope data, bore flow data, etc.). Strategies that provide the greatest return for future investment could then be identified.

To continue this analysis in future studies would require an extension based on the knowledge gaps identified in the hydrodynamics component of the Assessment (Section 6.6). Such extensions might include additional abstraction records, groundwater recharge sources and age information furnished from isotope measurements, hydrochemical patterns, and more dense measurements of the distributions of groundwater level changes in space and time.

3.5.4 Limitations

The GABtran model was built on the Habermehl (1980) conceptualisation of how the whole groundwater system operates – in which the Cadna-owie – Hooray Aquifer and equivalents are approximated with a single layer spanning the GAB. An implicit assumption with the single layer approach is that only the groundwater conditions of the shallowest artesian aquifer are simulated. In the Assessment, the impacts of climate change on this layer and groundwater extraction from this layer were able to be estimated. However, the impacts on the deeper aquifers could not be estimated using GABtran, because these layers are not included in the model. Similarly, the shallower non-artesian GAB aquifers were not included in GABtran. Likewise, calibration and evaluation of the GABtran model relied on time-series observations for bores completed in the shallowest artesian aquifer. These observations are unevenly distributed across the GAB.

Based on the single layer approach and having calibrated to sparse data, GABtran is a simplified representation of the groundwater conditions of the Cadna-owie – Hooray Aquifer and equivalents. The Assessment has shown that the GAB is a groundwater basin, with uncertain groundwater exchanges occurring between overlying and underlying geological formations. Furthermore, the categorisation of GAB hydrostratigraphy into aquifers and aquitards has been updated based on variability of formation properties, to include distinctions of aquifer, partial aquifer, leaky aquitard, tight aquitard and aquiclude. The Assessment has also shown that faulting is pervasive in many parts of the GAB, which creates an offset for layers, where an aquifer may terminate abruptly against a different layer that has been moved because of faulting. These geological complexities represent the reality of the GAB as it has been reconceptualised in the Assessment (Chapter 5). When structural features – such as faulting – are incorporated into mapping a potentiometric surface, a more complex representation of the groundwater conditions emerges.

Groundwater modelling provides a rigorous numerical approach to evaluate the conceptual understanding of a groundwater system. The large-scale GABtran model – and its predecessors – was aligned with the Habermehl (1980) conceptualisation. The results generated by the GABtran model are also aligned with the Habermehl (1980) conceptualisation. Inclusion of multiple layers, connectivity with overlying and underlying geological formations, and the presence of faults in a new regional-scale groundwater could potentially improve the predictive ability under future scenarios of climate change and groundwater development. However, such an advanced and complex model would require sufficient data to achieve a representative groundwater condition.

Notwithstanding advancement of the GAB conceptualisation, the GABtran model appears to represent the broad trends of groundwater levels across the GAB. Inclusion of any complexity in a new groundwater model will lead to a different result than simulated in the Assessment. The consequence of using GABtran in the Assessment is that vertical leakage rates are not represented with any physical reality and the changes in groundwater levels are not impacted by faults. The net result is that predicted changes in groundwater levels under future scenarios is uncertain in areas where multiple layers and faults are prevalent. In turn, estimation of the risk to groundwater-dependent ecosystems is also uncertain.

3.6 References

Crosbie RS, McCallum JM, Walker GR and Chiew FHS (2010a) Modelling climate-change impacts on groundwater recharge in the Murray-Darling Basin, Australia. Hydrogeology Journal 18(7), 1639–1656.

Crosbie RS, Pickett T, Mpelasoka FS, Hodgson GA, Charles SP and Barron O (2010b) Diffuse recharge across Australia under a 2050 climate: Modelling results. CSIRO Water for a Healthy Country Flagship.

CSIRO (2008) Water availability in the Murray-Darling Basin. A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

CSIRO (2009a) Water availability for Tasmania. Report one of seven to the Australian Government from the CSIRO Tasmania Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

CSIRO (2009b) Water in northern Australia. Summary of reports to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO, Australia.

CSIRO (2009c) Water yields and demands in south-West Western Australia. A report to the Australian Government from the CSIRO South-West Western Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Australia.

GHD (2011) Report for QWC17–10 Stage 2 Surat cumulative management area groundwater model report (Draft), December 2011. Queensland Water Commission, Brisbane, Australia.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Habermehl MA and Lau JE (1997) Hydrogeology of the Great Artesian Basin Australia (Map at scale 1:2,500,000). Australian Geological Survey Organisation, Canberra.

IPCC (2000) Emissions scenarios. A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Smith AJ and Welsh WD (2011) Review of groundwater models and modelling methodologies for the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

Welsh WD (2006) Great Artesian Basin transient groundwater model. Bureau of Rural Sciences, Canberra. Viewed 15 October 2012, <http://adl.brs.gov.au/brsShop/data/gabtransient1.pdf>.

Welsh WD (2007) Groundwater balance modelling with Darcy's Law. PhD Thesis, Fenner School of Environment and Society, The Australian National University, Canberra. <https://digitalcollections.anu.edu.au/bitstream/1885/48015/6/02whole.pdf>.

Wigley TML and Raper SCB (2001) Interpretations of high projections for global-mean warming. Science 293, 451–454.

Zhang L and Dawes W (1998) WAVES – An integrated energy and water balance model. Technical Report No. 31/98. CSIRO Land and Water.

4 Potential impacts on groundwater-dependent ecosystems

Authors: Miles C, White M and Scholz G

4.1 Purpose and approach

This chapter firstly identifies the different types of groundwater-dependent ecosystems (GDEs) found in the Great Artesian Basin (GAB) and their ecological values. A high-level assessment of the risks to and opportunities for these GDEs that may arise from changes in hydrology resulting from changes in groundwater levels as reported in Chapter 3 is then presented.

The approach used in this assessment was developed in conjunction with the project 'Allocating water and maintaining springs in the Great Artesian Basin' (Green et al., 2013) and draws on its risk assessment process for evaluating water use impacts in the GAB. The Assessment's risk assessment process differs from that of Green et al. (2013) in three key areas:

1. it looks at changes in groundwater levels across the entire GAB based on the results of the GABtran modelling reported in Chapter 3
2. it incorporates an assessment of opportunities for recovery in flow
3. it has a lower level of resolution and greater levels of uncertainty resulting from using datasets available at the whole-of-GAB scale.

To consistently report across all four Assessment regions, the level of impact which informs risk and opportunity has been assessed at the spring complex scale. Assessing impact at a smaller scale (e.g. individual springs) requires ecological and hydrological data which are not uniformly available across the GAB. A process for assessing impact at the supergroup scale is reported in this report. A more detailed evaluation, using more comprehensive methods and focusing on two case studies within data-rich areas of the GAB, is presented in the companion technical report (see listing in Appendix A).

4.2 Types of groundwater-dependent ecosystems

Many ecosystems, including wetlands and terrestrial vegetation that relies on the availability of shallow groundwater, depend on groundwater from the GAB aquifers. The Assessment focussed on GAB springs, which are points of natural discharge of groundwater at the ground surface that originate from GAB aquifers. They vary in biological function and composition and exist at a range of scales from small vents to large mounds or spring mound deposits and may be surrounded by wetlands, the area of which is dependent on the discharge (White and Lewis, 2013).

Jurisdictions use different terms when describing GAB springs at a variety of scales, the main national difference is that Queensland uses the terms provided in Table 4.1 with the addition of distances determining spring group and spring complex (see Fensham and Fairfax (2003) for details). This Assessment used the terms in Table 4.1 as they reflect the common ground in spring terminology between Queensland and South Australia. Clusters of springs that share similar water chemistry and are related to common geological features are known as 'spring groups'; clusters of spring groups that share similar geomorphological settings and are referred to as 'spring complexes'; clusters of spring complexes are referred to as 'supergroups' (Green et al., 2013). There are 13 supergroups found in the GAB, four of which are located in the Surat region (Fensham and Fairfax, 2003; Fensham et al., 2010; Habermehl and Lau, 1997).

The GAB is an inter-jurisdictional groundwater resource for which there is a need to be able to compare and manage GDEs at a basin-wide scale. A first step is to identify the range of different underground geological and hydrological processes that drive the formation and maintenance of GAB springs. The ability to differentiate between formation processes forms the basis of understanding the impact to a spring supergroup or individual spring from hydrological changes such as drawdown.

Table 4.1 Definition of springs at a variety of spatial scales adapted from Fensham and Fairfax (2003)

Term	Definition
Vent	Point of natural groundwater discharge at the ground surface
Spring	A vent or vents where the natural groundwater outflow forms a (single) spring wetland and/or stream(s)
Spring group	Multiple springs all related to the same hydrogeological structure and probably the same aquifer (or groundwater source) and hydrochemistry (at the present time)
Spring complex	Collection of springs all related to a particular location and hydrogeological feature(s)
Supergroup	Major regional clusters of spring complexes with some consistent hydrogeological characteristics as defined in Fensham and Fairfax (2003).

4.2.1 Spring classification

An Australian National Aquatic Ecosystem (ANAE) framework has been developed for jurisdictions to classify their aquatic ecosystems (Aurichit, 2011). Using the ANAE classification scheme, springs are classified as palustrine wetlands (primarily vegetated, non-channel environments of less than 8 ha). A further four tiers of classification have been developed by Green et al. (2013) to differentiate types of GAB springs (Figure 4.1).

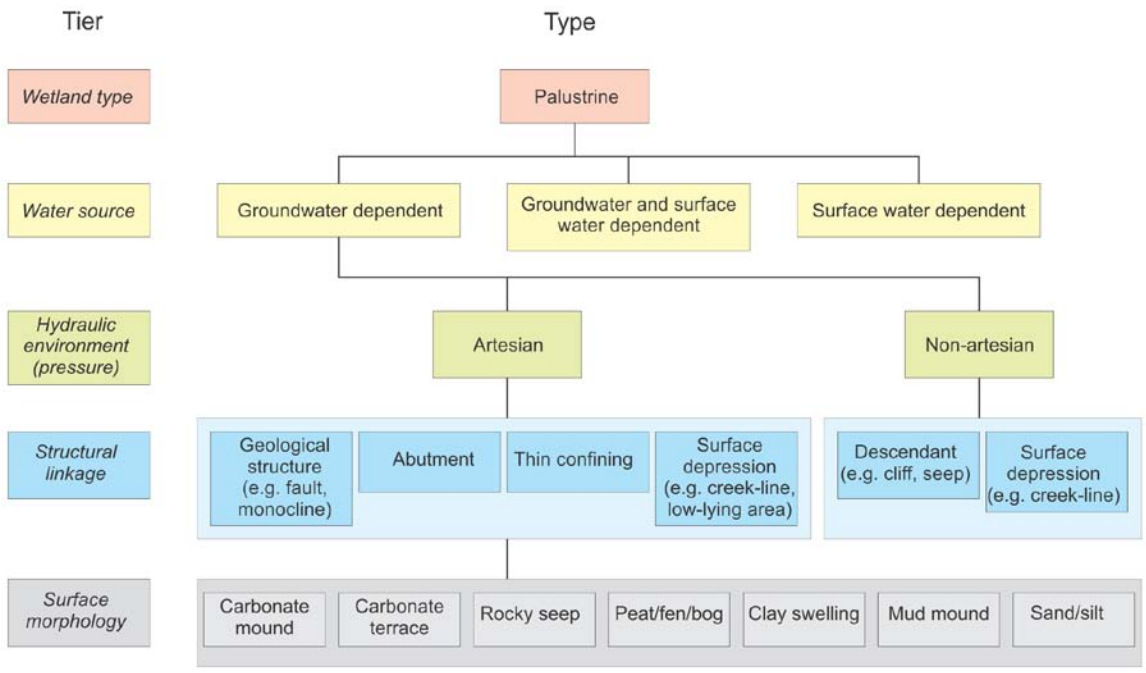


Figure 4.1 Classification of springs within the Great Artesian Basin (Green et al., 2013).
Springs within the artesian hydraulic environment are commonly called 'discharge springs' and those in the non-artesian hydraulic environment are commonly called 'recharge springs'

Water source

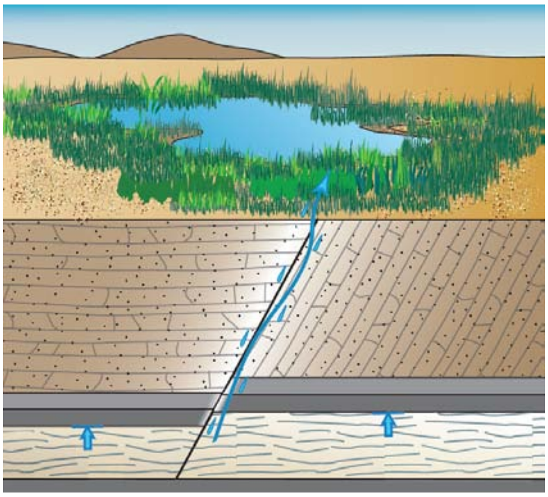
The focus of this report is on the ecosystems dependent on groundwater from the GAB. However, wetlands dependent on surface water and shallower aquifers also exist within the Assessment area (Figure 4.1 – Water source tier).

Hydraulic environment

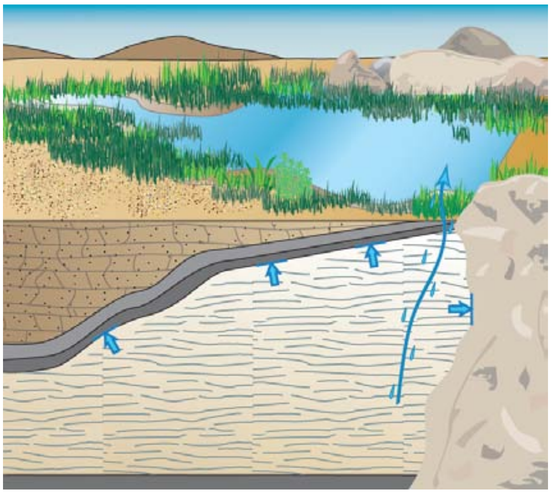
GAB springs are often referred to as either recharge or discharge springs (e.g.Fensham and Fairfax, 2003; Fensham et al., 2012). Recharge springs have been defined by their occurrence in the outcropping sandstone formations on the eastern margin of the GAB where the groundwater level of the source aquifers of the GAB is generally lower than the local ground topography except at the immediate location of the spring (non-artesian). Discharge springs are sourced from aquifers of the GAB with a groundwater level that is historically higher than the ground topography at the location of the spring (artesian). An alternative terminology to recharge and discharge springs has been developed in South Australia, where artesian replaces discharge and non-artesian replaces recharge (Green et al., 2013). Recharge and discharge were used in this Assessment for consistency with existing legislation and plans such as the EPBC Act (Figure 4.1 – Hydraulic environment tier).

Structural linkage

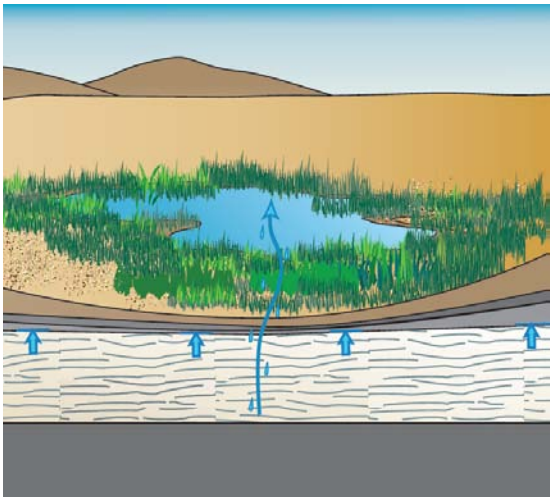
The structural linkage tier (Figure 4.1) relates to understanding the different geological and hydrological processes that form discharge springs in the GAB, as illustrated in Figure 4.2.



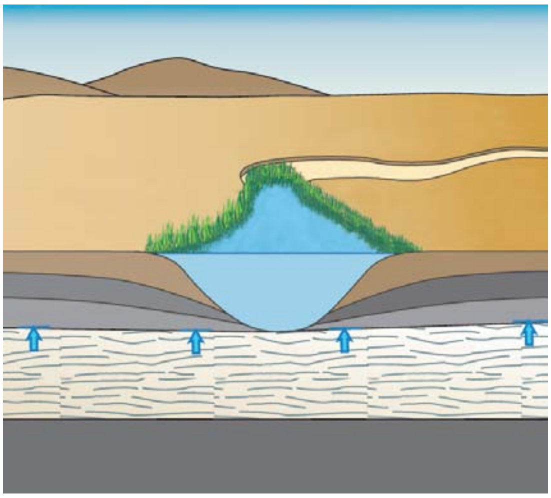
(a) Geological structure type, where water flows upward through a fault



(b) Abutment type, where aquifers abut against an impermeable outcrop



(c) Thin confining type, where groundwater breaks through to the surface



(d) Surface depression type, where a creek line comes into contact with Great Artesian Basin aquifers

Figure 4.2 Conceptualisation of the structural linkage processes that form springs in the Great Artesian Basin
(a) to (c) developed by Queensland Department of Environment and Resource Management (DERM, 2011); (d) adapted from DERM (2011). Updated conceptual models are available online at
<http://wetlandinfo.derm.qld.gov.au/wetlands/ScienceAndResearch/ConceptualModels.html>

Surface Morphology

The surface morphology types are described in Green et al. (2013) as follows for artesian GAB springs:

- Carbonate mound – characterised by rocky travertine positioned above the surrounding terrain, typically forming a raised vent area that may or may not be accompanied by a travertine tail feature.
- Carbonate terrace – lateral flow of groundwater deposits travertine terraces can be raised above the surrounding landscape but does not form the distinctive mound.
- Rocky seep – groundwater seeps from rocky cracks and fissures, significant deposits of travertine are not associated with this morphological type.
- Peat/Fen/Bog – spring substrate is largely organic in origin and can form large mounds.
- Clay swelling – groundwater emerging just below the surface creates a swelling mound of mud/clay with little or no water discharge. The mound is quite plastic and will deform under pressure often releasing more water.
- Mud mound – formed as groundwater emerges below the surface into unconsolidated soil. A mound is formed as mud is forced upwards under pressure of the discharging groundwater.
- Sand/silt – forms when wind-blown sand is deposited around wet vegetation and then is expanded as more vegetation grows on the substrate. The resulting wetland vegetation may deposit large amounts of organic matter and form a peat/fen bog at the vent.

4.2.2 Types within the Surat region

Within a supergroup, springs of more than one structural linkage type and surface morphology may occur. Although a comprehensive classification of springs by their type has not been undertaken for the entire the Surat region, a search of the literature (DERM, 2011; Fensham and Fairfax, 2003; Habermehl, 1982; 1998; Ponder, 1986) shows spring supergroups throughout the region in which the various structural linkage types occur (Table 4.2).

Table 4.2 A literature summary of spring types in the Surat region

Spring supergroup	Dominant hydraulic environment	Structural linkage types present*
Springsure	Recharge and discharge	**Surface depression** (creek-line); Geological structure (fault); Thin confining
Eulo	Discharge	**Abutment structures and processes;** Thin confining; Geological structure (fault)
Bourke	Discharge	**Geological structure** (fault); Thin confining beds; Abutment
Bogan River	Discharge**	**Thin confining and abutment**

* Dominant structural linkage types are shown in bold type
** Two spring complexes in the Bogan River supergroup have been classified as non-GAB dependent (NSW Government, 2011)

Artesian GAB springs with mud mound surface morphology commonly occur in the Eulo supergroup (DERM, 2011), peat mounds commonly occur in the Springsure supergroup (Fensham et al., 2012). Mounded springs are described for the Bourke and Bogan River supergroups (Habermehl, 1982).

4.3 Ecological values of groundwater-dependent ecosystems

GDEs are distinctive features in the arid areas of the GAB. They provide a permanent source of water and hence have great cultural (Hercus and Sutton, 1985) and biological significance (Fensham et al., 2010). The persistence of the springs over tens of thousands to hundreds of thousands of years (Prescott and Habermehl, 2008) has allowed the development of distinct species within certain groups of aquatic plants and animals that are sometimes confined to one or a few springs.

The identification and assignment of ecological values to GDEs (and other wetlands) depends on the purpose of the assessment, the scale at which it is being undertaken and the availability of information about the ecosystems in question (Hale, 2010). In the context of assessments of risks and opportunities from changes in groundwater level, it is necessary to understand the ecological values of springs that may be degraded or restored. The following discussion presents a range of systems that have been used to classify the ecological values of GAB springs.

Within the Surat region there are five sites listed under the Ramsar Convention on Wetlands of International Importance (Ramsar Convention Secretariat, 2005) and of these, two include GAB springs as key features: springs from the Eulo supergroup in the Currawinya Lakes Ramsar site and springs from the Bourke supergroup within the Paroo River Wetlands Ramsar site (Table 4.3).

Table 4.3 Significant groundwater-dependent ecosystems and wetlands within the Surat region

Spring supergroup	Number of individual springs*	Percentage of EPBC-listed spring complexes*	Ramsar sites	Directory of Important wetlands
Springsure	206	59	0	1
Eulo	216	100	1	1
Bourke	216	100	1	1
Bogan River	6**	100	0	0

* Fensham et al. (2010)
** Two spring complexes in the Bogan River supergroup have been classified as non-GAB dependent (NSW Government, 2011)

Nationally, ‘the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin’ is listed as endangered under the Commonwealth’s *Environmental Protection and Biodiversity Conservation Act 1999* (the EPBC Act). Within the Surat region there are 192 EPBC-listed springs (Figure 4.3) and 162 springs that have either endemic or threatened species associated with them. Three wetlands are listed in the Directory of Important wetlands (Environment Australia, 2001): Boggomoss Springs in the Springsure supergroup, the Eulo supergroup and the Bourke supergroup (Table 4.3).

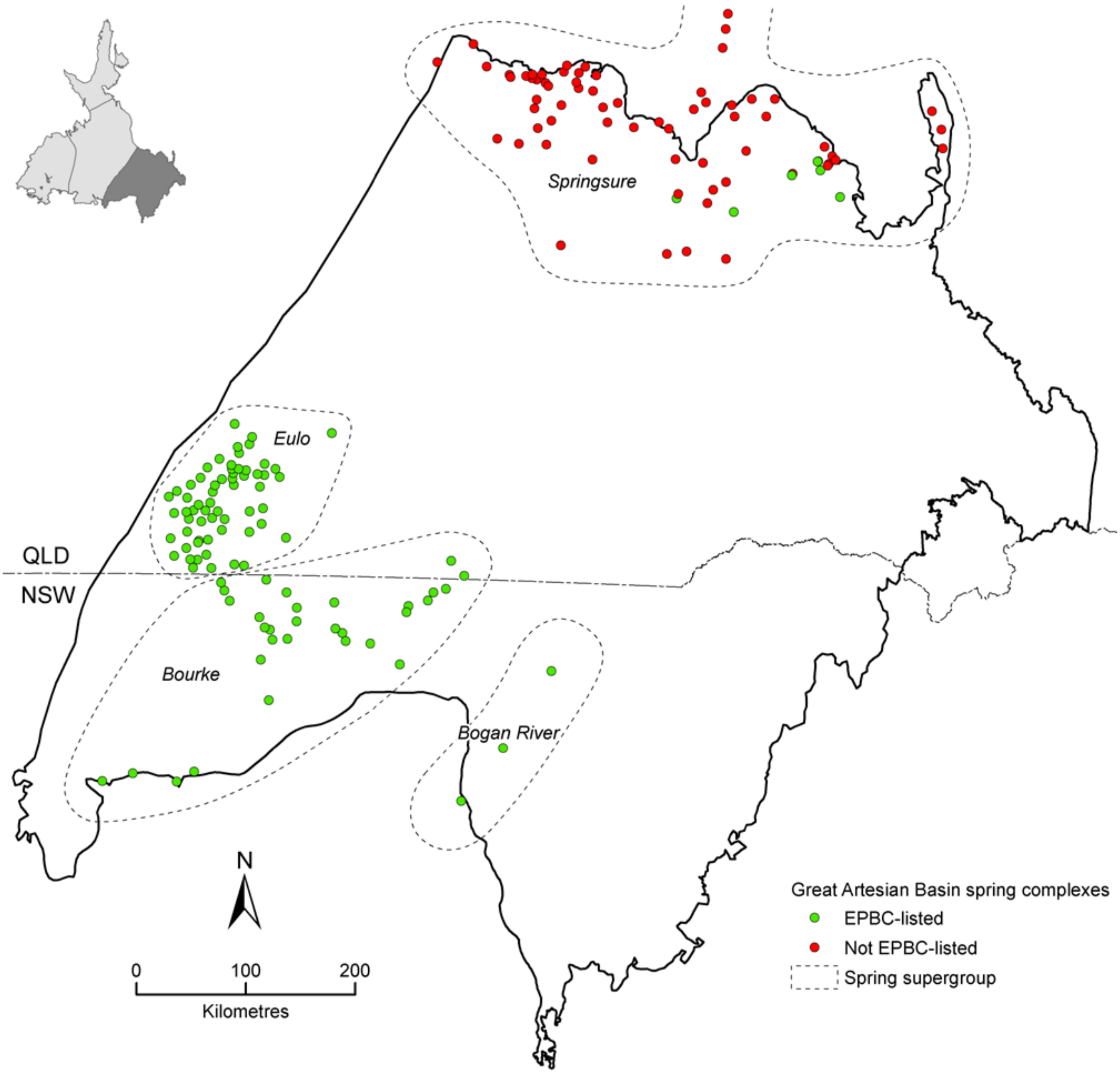


Figure 4.3 Spring complexes of the Surat region
Note: map shows listing status of springs under the *Environmental Protection and Biodiversity Conservation Act 1999* (the EPBC Act)

The National Water Initiative requires governments to ‘identify and acknowledge surface and groundwater systems of high conservation value, and manage these systems to protect and enhance those values’ (NWI, 2004).The need for a national systematic approach to identify and manage all types of aquatic ecosystems resulted in the development of a High Ecological Value Aquatic Ecosystems (HEVAE) framework (Aquatic Ecosystem Task Group, 2009). This approach uses measurable criteria to identify HEVAEs in a consistent and transparent manner. The framework has been trialled within the Lake Eyre Basin (LEB) including those GAB springs occurring within the LEB (Hale, 2010). To undertake a HEVAE assessment on GDEs across the GAB is beyond the scope of this Assessment but results from the Lake Eyre Basin trial can be used to inform the Assessment about the ecological value of discharge springs across the GAB. Results from the trial, which compared surface water and groundwater aquatic ecosystems, found that GAB-dependent springs are highly valued ecosystems in the Lake Eyre Basin with specific attributes determining their value (Table 4.4).

Table 4.4 Specific attributes that determined Great Artesian Basin artesian groundwater springs as valued aquatic ecosystems in the Lake Eyre Basin

Criteria	Attribute
1. Diversity	1A: diversity of aquatic ecosystem type
	1B: diversity of native aquatic ecosystem dependent species
	1C: diversity of aquatic ecosystem vegetation types
2. Distinctiveness	2A: threatened species
	2E: threatened aquatic ecological community
3. Vital habitat	3C: refugia
4. Evolutionary history	4A: endemic species

Source: (Hale, 2010)

Another two approaches which can further build upon the HEVAE approach but are beyond the scope of this Assessment are (i) the systematic conservation planning approach, which identifies the minimal area required to conserve maximum values using large data input and detailed modelling; and (ii) the science and socio-economic consultation process which balances socio-economic costs with different conservation management actions, (for example site acquisition, site tradeoffs, buffer zones, threat mitigation, rehabilitation, restoration and conservation). A systematic conservation planning approach would overcome issues of complementarily and irreplaceability and could be undertaken using existing data and expert knowledge. The science and socio-economic consultation process can be resource intensive as it links research and assessment to planning and policy outcomes. Each of these approaches would require cross-juridictional collaboration.

At the whole-of-GAB scale, the only systematic classification of GAB springs has been based on the criteria of endemic species, threatened species and naturalness (Fensham et al., 2010) (Table 4.5). Under this system, spring complexes are ranked based on the highest value spring within the complex, regardless of the condition of other springs within the complex.

Table 4.5 Summary of conservation rankings for spring complexes within the Surat region (Fensham et al., 2010)

Category	Criteria (from Fensham et al., 2010)	Springsure supergroup	Eulo supergroup	Bourke supergroup	Bogan River supergroup
1a	Contains at least one endemic species not known from any other location	3	4	0	0
1b	Contains endemic species known from more than one spring complex; or have populations of threatened species listed under State or Commonwealth legislation that do not conform to Category 1a	7	4	1	0
2	Provides habitat for isolated populations of plant and/or animal species; populations of species not known from habitat other than spring wetlands within 250km	14	3	1	0
3	Contains intact springs without identified biological values but includes springs that are not highly degraded and may have important ecological values with further study	35	15	10	1
4	All springs are highly degraded	1	4	1	0
5	All springs are inactive	2	31	18	1

4.4 Current status of groundwater-dependent ecosystems

Before the development of artesian water began in the 1880s, the groundwater level of GAB aquifers was above the ground level, causing surface discharge of groundwater (i.e. springs) to occur where there were weaknesses in the confining layers (see Section 4.2.1). When Europeans discovered springs in the arid landscape in the late 1800s, they reasoned that artesian water could be accessed to support pastoral development. The first flowing bores were subsequently drilled near discharge springs in the southern areas of the GAB in New South Wales and South Australia (Habermehl, 1980; 1982; Habermehl, 2001). Since then the groundwater level has decreased in some regions resulting in many artesian springs across the GAB becoming inactive (flowing discharge at the surface ceased). The Eulo supergroup within the Surat region has been the most impacted area within the GAB and has experienced an average decrease in groundwater level of 39 m resulting in a cease-to-flow of a high proportion of flowing discharge springs and bores (DERM, 2011).

The development of the pastoral industry in the GAB has meant that permanent water which was once sparse is now accessible almost every 6 km due to the thousands of dams, bores and bore drains. This increased accessibility of permanent water and the associated formation of artificial wetlands has had mixed consequences for native animals with some being displaced while others have opportunistically moved in – though the greatest beneficiary has been for feral animals and weeds. Some of these artificial wetlands have social, economic or ecological values connected with them which has led to a consultative process to determine their value. Consequently some have been decommissioned while others have been capped to minimise their flow. This Assessment only focuses on natural environments. It also acknowledges the Great Artesian Basin Bore Rehabilitation Program (1989 to 1999) and the GAB Sustainability Initiative (GABSI) which from 1999 to 2010 has rehabilitated and controlled 517 free-flowing artesian bores and has removed 16,437 km of bore drains across the GAB.

Within the Surat region, 643 springs have been identified, 52 percent of which remain active (Figure 4.3). The variability in spring activity differs across the region with 98 percent of springs active within the Springsure supergroup down to 17 percent of springs active within the Bogan River supergroup (Table 4.6).

Table 4.6 Status of individual springs within the Surat region

Spring supergroup	Number of springs	Percentage of active springs
Springsure	206	98
Eulo	216	40
Bourke	216	22
Bogan River	6	17

In this region, 77 percent of springs are listed as endangered under the EPBC Act. Listing of GAB springs for protection under the EPBC Act requires that they are identified as springs dependent on natural discharge from the GAB. Along the eastern margin of the GAB, some of which is shared by the Surat region, there are numerous springs that are identified as ‘recharge springs’ or non-artesian (Fensham and Fairfax, 2003) and not EPBC-listed.

4.5 Future risks to and opportunities for groundwater dependent ecosystems

4.5.1 Conceptual framework for assessing risks and opportunities

This chapter reports the broad-scale evaluation of the impact of changes to groundwater levels at artesian GAB springs as modelled by GABtran (see Chapter 3 for a detailed description of the modelling process). Likely changes in groundwater levels under different climate and groundwater development scenarios (as defined in Chapter 3) are presented. In this Assessment, the range of future scenarios is represented using a weighted probability distribution – the range includes the wet extreme, median and dry extreme future climates (i.e. scenarios Cwet, Cmid and Cdry). As the mid-range is the most likely, that is what is reported in this chapter under the future scenarios.

The GABtran modelling estimates both increases and decreases in groundwater levels occurring in different parts of the region under the scenarios. The greater the decline, the greater the likelihood that flow will be reduced and the greater the risk that the ecological values of artesian GAB springs will decline. Conversely, the greater the rise in groundwater level, the greater the likelihood that flow to artesian GAB springs will be increased and the greater the opportunity that ecological values of the artesian GAB springs will be recovered. However, because of uncertainties and potential errors in the modelling and data sources, and that the approach does not address all threats to artesian GAB springs, nor capture the current risks to springs, where there is a rise in groundwater level, there is still some likelihood, albeit lower, that the groundwater level may actually fall. The closer the change is to zero, the greater the uncertainty about the direction of change in groundwater level. Therefore, separate assessments are presented for

1. The risk of decline in the ecological values of artesian GAB springs resulting from decline in flow.
2. The opportunity for recovery in ecological values of artesian GAB springs resulting from increase in flow.

The opportunity assessment assumes that an increase in flows – being a return to natural flow conditions – will only have a positive impact.

The broad-scale approach used cannot determine if a given change in groundwater level would result in a 10 percent reduction in flow or a 100 percent reduction in flow at a given spring. Whilst a high risk of complete cessation in flow at a spring will clearly lead to a decline in the ecological values of artesian GAB springs, a reduction in flow without cease-to-flow may still cause a change in ecological character by reducing the range of wetland habitats, connectivity and ecological conditions. The magnitude of change is therefore classified in relative terms from greatest likelihood of a decline or rise to least likelihood of a decline or rise.

The conservation ranking of spring complexes (Fensham et al., 2010) is used to assess the consequence of a change in spring flow (Table 4.7). Fensham et al. (2010) classify all springs within a complex by the highest conservation ranked spring within the complex, regardless of the condition of all other springs. The spring complex is recommended as the most appropriate scale for management to preserve genetic diversity and maintain metapopulation dynamics (Fensham et al., 2012). This classification is also the only spring classification that has been applied across the entire GAB. All results are presented for spring complexes rather than individual springs or spring vents.

Table 4.7 Risk ranking matrix

		Least consequence				Greatest consequence
		Conservation ranking				
		5	4	3	2	1a & 1b
Greatest likelihood	Highest drawdown	Moderate	Moderate	High	Highest	Highest
	Moderate drawdown	Lowest	Moderate	High	High	Highest
	Least drawdown	Lowest	Moderate	Moderate	High	High
	Least rise	Lowest	Lowest	Moderate	Moderate	Moderate
Least likelihood	Moderate to Highest rise	Lowest	Lowest	Lowest	Lowest	Lowest

The risk assessment framework draws on two other risk assessment methodologies developed for GAB springs: the South Australian Risk Assessment Framework (Green et al., 2013) and Queensland's risk assessment for the Surat Cumulative Management Area (QWC, 2012). Other components of a risk assessment could include an assessment of the vulnerability of GAB springs to changes in groundwater level. Green et al. (2013) recommend assessing spring surface environment vulnerability (morphology, salinity, wetland extent and acid sulphate conditions) and ecosystem connectivity vulnerability (ecological focal zones and vulnerability to fragmentation). the ecological, hydrogeological and hydrological data needed to undertake this kind of detailed classification are not uniformly available across the GAB.

A comparative risk and opportunity assessment approach has been used as the most appropriate tool given the paucity of data. Table 4.7 presents the risk ranking matrix and the opportunity ranking matrix is presented in Table 4.8. A more detailed discussion about the risk and opportunity, including the drawdown categories, is given in the companion technical report as listed in Appendix A.

Table 4.8 Opportunity ranking matrix

		Least consequence				Greatest consequence
		Conservation ranking				
		5	4	3	2	1a & 1b
Greatest likelihood	Highest rise	Moderate	Moderate	High	Highest	Highest
	Moderate rise	Lowest	Moderate	High	High	Highest
	Least rise	Lowest	Moderate	Moderate	High	High
	Least drawdown	Lowest	Lowest	Moderate	Moderate	Moderate
Least likelihood	Moderate to Highest drawdown	Lowest	Lowest	Lowest	Lowest	Lowest

4.5.2 Status of groundwater-dependent ecosystems under Scenario A: historical climate and current development to 2070

Under Scenario A, groundwater levels are likely to increase from their current (circa 2010) levels for 75 percent of springs within the GABtran model boundaries (Figure 4.4). Two spring complexes are ranked at highest level of risk, these are Peery Springs in the Bourke supergroup and Spring Ridge in the Springsure supergroup. The majority of springs are ranked at moderate (35) and low (58) risk under Scenario A.

Under Scenario A there is likely to be a very high opportunity for recovery for three springs and low to moderate opportunity for most flowing springs.

Because the GABtran model is a single aquifer model, the effects of future developments that impact aquifers other than the modelled aquifer are not incorporated into the impact assessment. Coal seam gas developments in particular are not able to be modelled using GABtran and therefore the results of the assessment presented here do not account for coal seam gas impacts.

An analysis of the risks to springs from CSG in the Surat Cumulative Management Area (SCMA), which covers springs in the Springsure supergroup, has been undertaken by the Queensland Water Commission (QWC, 2012). In this analysis, the risk assessment was applied to springs that overlie GAB aquifers where a drawdown of more than 0.2 m has been predicted (59 of a total 330 springs within the SCMA). Under the QWC (2012) framework, the highest likelihood of impact category for predicted drawdown was >0.5 m which is significantly less than the smallest predicted drawdown category in the Assessment (0 to 5 m). The QWC analysis found 25 and 18 springs at the high and highest level of risk respectively from CSG. The greatest magnitude of projected drawdown from CSG in the source aquifer at any spring in the SCMA is 1.3 m (QWC 2012). For more information about the QWC springs assessment see <www.qwc.qld.gov.au/csg>.

The results of the assessment are summarised in Table 4.9.

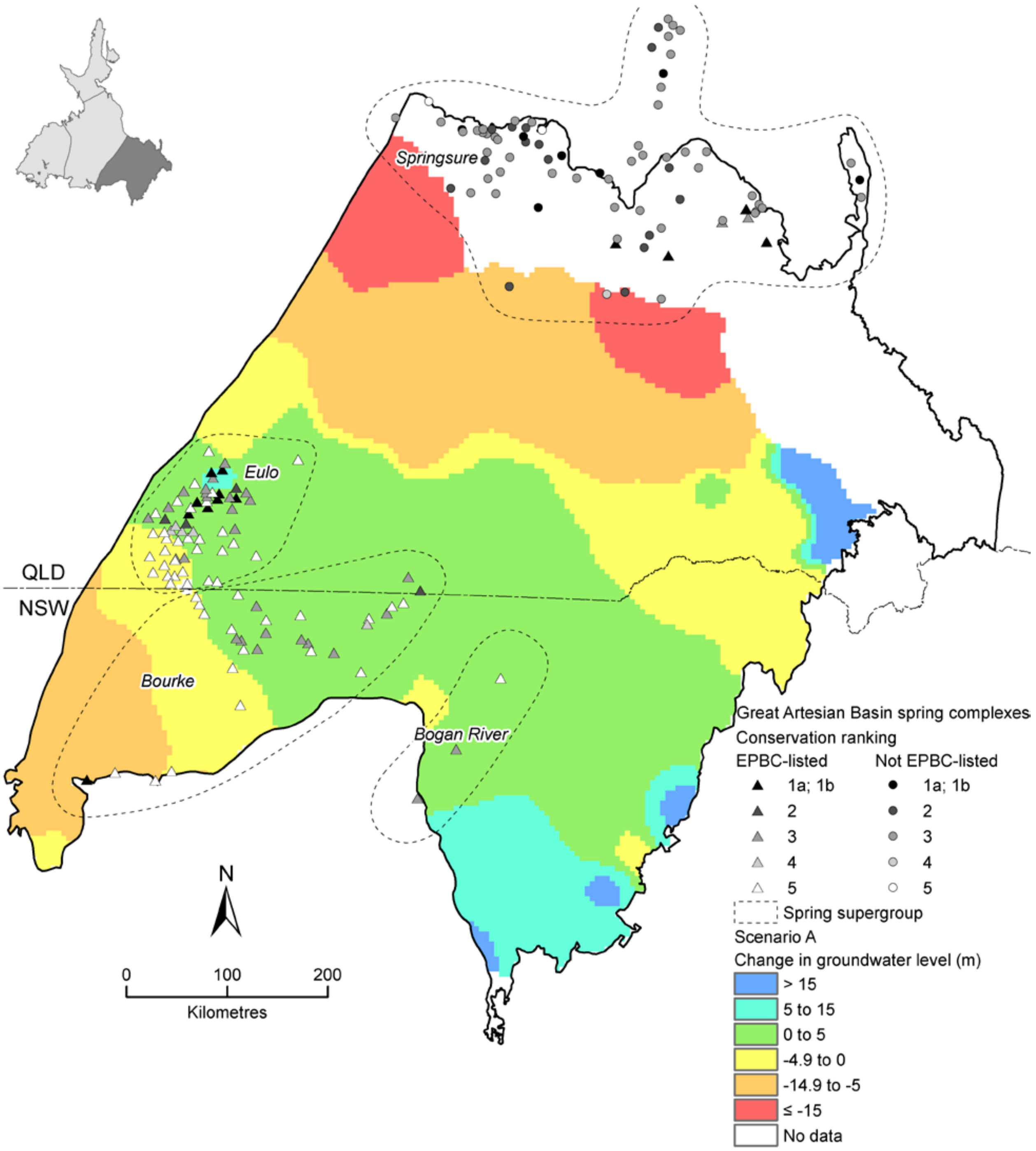


Figure 4.4 Spring complex conservation ranking and change in groundwater levels for the Surat region under Scenario A (Note that a negative change indicates a decline in groundwater level)

Table 4.9 Ranking of risk and opportunity for spring complexes under scenarios A and Cmid

Ranking	Risk (number of spring complexes)	Opportunity (number of spring complexes)
Highest	2	3
High	1	6
Moderate	35	30
Lowest	58	51
Unknown	60	60

4.5.3 Groundwater-dependent ecosystems at risk from hydrological change under Scenario C: future climate and current development 2070

Under Scenario Cmid, the risks to GAB springs from changes in groundwater levels are predominantly low – and the same as under Scenario A. (see Chapter 3). This indicates that by 2070, the effects of climate change on aquifer groundwater levels will not be felt at artesian GAB springs. There may, however, be other effects of climate change on the surface environments of the springs, such as changed evaporation rates impacting hydrology and water chemistry.

4.5.4 Groundwater-dependent ecosystems at risk from hydrological change under Scenario D: future climate and future development

Under Scenario Dmid, none of the modelled springs are likely to be at the highest level of risk from a decline in groundwater level.Three sites are ranked at high level of risk and the majority are at the lowest level of risk. Under Scenario Dmid, 94 percent of spring complexes are in areas where the groundwater level is likely to increase. There is the highest opportunity for recovery of 11 spring complexes and high opportunity for recovery of 27 (Figure 4.5).

Many of the spring complexes where an increase is likely, are currently inactive and the groundwater level is likely to increase significantly (by more than 15 m). However, with the current level of data and knowledge, it is not possible to assess whether this will be sufficient to return flow to any of these springs. For those springs that are currently active, an increase in groundwater level of this magnitude should be sufficient to generate an increase in flow.

The results of the assessments are summarised in Table 4.10 .

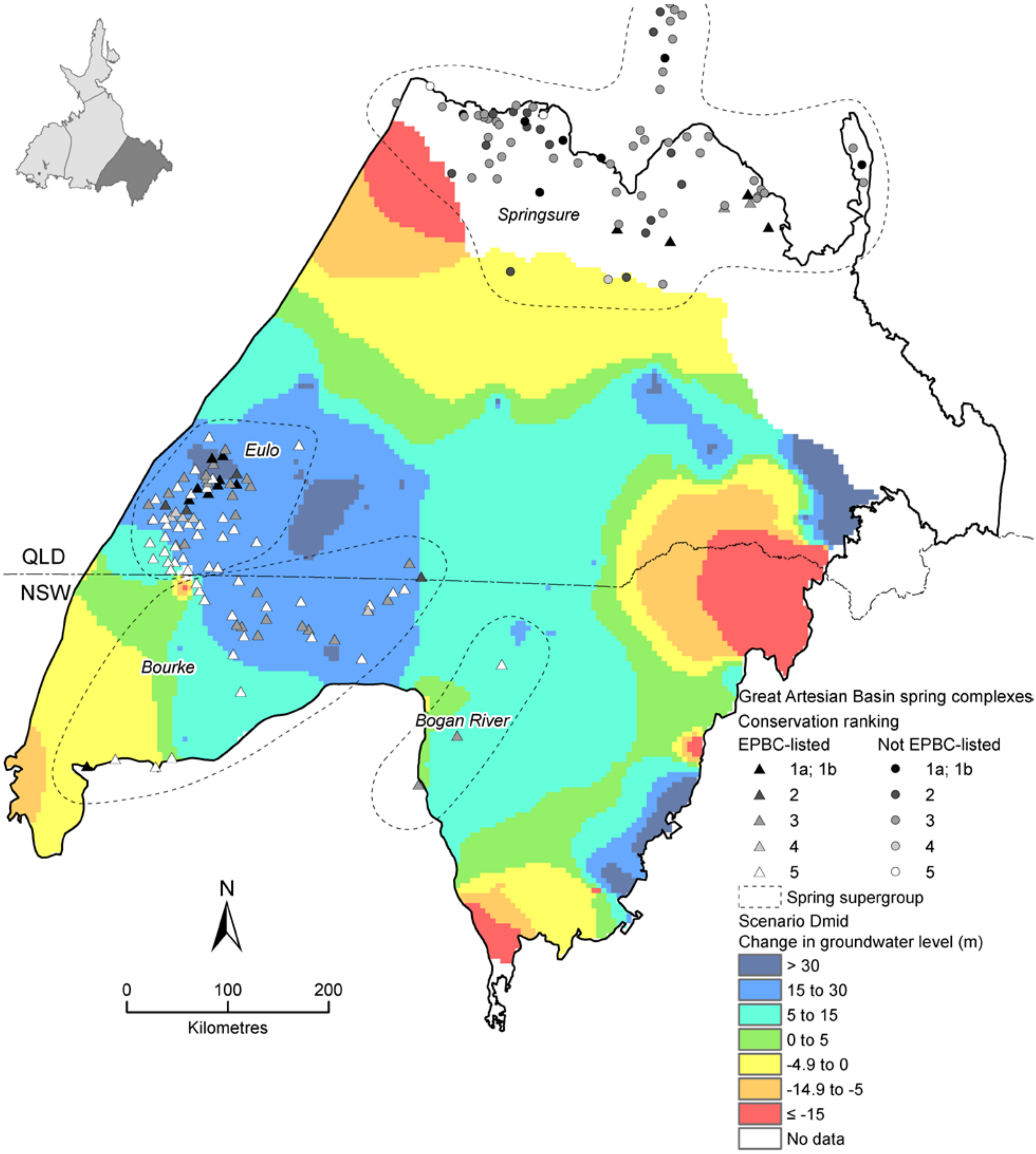


Figure 4.5 Spring complex conservation ranking and change in groundwater levels for the Surat region under Scenario Dmid (Note that a negative change indicates a decline in groundwater level)

Table 4.10 Ranking of risk and opportunity for spring complexes under scenarios Dmid

Ranking	Risk (number of spring complexes)	Opportunity (number of spring complexes)
Highest	0	11
High	3	27
Moderate	1	10
Lowest	92	48
Unknown	60	60

4.5.5 Gaps, uncertainty and risks

Knowledge gaps

Knowledge gaps are listed below and discussed in more detail in the companion technical report (see listing in Appendix A):

- Springs sourced from different aquifers than modelled by GABtran will be subject to different groundwater levels under future scenarios.
- The vulnerability of different spring types (structural linkages and surface morphology) to changes in groundwater levels.
- The difference between the vent elevation and groundwater level (the excess head) for springs.
- Whether the conductivity of spring vents decreases if the vent ceases to flow.
- How springs in different situations and different levels of condition respond to changes increases in groundwater level with and without management interventions .
- Potential for negative impacts from increasing flow to springs such as from invasive species and acid sulphate conditions.
- Impact to other types of GDEs, such as terrestrial vegetation that relies on the availability of shallow groundwater.

Data gaps

Data gaps can be grouped into two themes: spring data and model extent.

Spring data

Ecological and hydrological (including water quality) data are not uniformly available across the GAB. These data are required to prioritise conservation and management or to undertake a more comprehensive assessment of the vulnerability of springs to drawdown.

For the risk analysis, the whole-of-GAB dataset was used (from Fensham et al., 2010). This dataset has multiple springs listed against each spring ID which caused a number of problems in the analysis. For example, in order to determine the excess head above a spring, all springs associated with a spring complex can only be assigned a single elevation based on the spring ID location. Calculating the excess head at springs did not deliver reliable results using the GAB-wide dataset and therefore only the magnitude of the change in groundwater level could be used in this analysis.

The whole-of-GAB dataset has a limited range of fields that are desirable in assessing the impacts of drawdown on springs – for example, it does not contain water quality information or information about the spring types (structural linkages and surface morphology) at a suitable scale for assessment.

Within the Surat reporting region, a comprehensive survey of springs within the Surat Cumulative Management Area has recently been completed that includes all spring locations and elevation of springs to +/-1.5m accuracy (Fensham et al., 2012). However, as most of these springs are classified as non-artesian, the data could not be used in the Assessment. An earlier dataset has also been collated for Queensland that includes information on the location of all surveyed springs in the Queensland portion of the GAB (Fensham pers. com.). This data has been used in the uncertainty analysis and case study (see companion technical report listed in Appendix A).

Spring type information is only available at a very broad level for the GAB, very few sites have been characterised for their structural linkage processes or surface morphology.

Model extent

A major gap in assessing the risks to GAB springs from climate change and development is that GABtran does not model the entire GAB and therefore springs outside the modelled aquifer could not be assessed. In particular, almost all of the springs in the Springsure supergroup were not able to be assessed. Whilst the QWC model does cover the Springsure supergroup in parts of the Surat region outside the GABtran model area, it only covers a small proportion of the entire GAB. Additionally, springs outside the Assessment boundaries, such as Cuddie springs in the Bogan River supergroup could not be assessed.

Uncertainty and error analysis

Most non-EPBC-listed springs are located outside of the GABtran model area (see Chapter 3) and the impacts of climate change and future development could not be assessed for these springs.

Each of the source datasets have elements of uncertainty and error (Table 4.11), a more detailed uncertainty and error analysis is presented in the companion technical report (as listed in Appendix A). By far the largest source of uncertainty and error in the impact assessment arises from the use of GABtran for modelling the likelihood of increased or decreased groundwater levels at springs. Of particular relevance to the Surat region is that GABtran results do not include impacts from CSG activities.

Table 4.11 Error in risk assessment

Data source	Error	Impacts on Risk Assessment
Spring location	Springs may occur up to 14 km from the spring location	Calculation of spring elevation and drawdown
GABtran modelling	Model uncertainty is greatest where no calibration bores were available and also near edges and in recharge zones (see Chapter 3); pixel size 5 x 5 km	Calculation of drawdown under scenarios (significant impact) Modelling change in groundwater level for recharge springs and springs near the edge of the model
Spring source	Spring may not be uniquely sourced from the aquifer that is being modelled	Inaccurate results

4.5.6 Current controls

There is different legislation for ‘protection’ of springs in water plans across the four state jurisdictions and at the National level. This section summarises the key points from those plans around the protection of GAB springs in the Surat region:

- *Environment Protection and Biodiversity Conservation (EPBC) Act:*
    - The EPBC Act lists the ‘community of native species dependent on natural discharge of groundwater from the Great Artesian Basin’ as an endangered ecological community and recognises listed ecological communities as a matter of national environmental significance.
    - Any action that is likely to have a significant impact on listed threatened species and ecological communities must be referred to the Minister and undergo an environmental assessment which is subject to an approval process.
- *Queensland Water Resource (Great Artesian Basin) Plan 2006:*
    - Section 39 allows approval of stock bores more than 5 km from a spring.
    - A water licence may be issued if, in combination with all other approvals made under the plan, it will not result in any spring having a cumulative spring factor of more than 400. This is equivalent to a pressure reduction of 400 mm head of water.
- *Queensland Water Act 2000:*
    - Chapter 3 provides for the management of impacts on underground water caused by the exercise of underground water rights by petroleum tenure holders. This includes requirements to prepare underground water impact reports that establish underground water obligations, including obligations to

monitor and manage impacts on aquifers and springs and manage the effects of cumulative impacts caused by more than one petroleum tenure holder exercising their right to groundwater.

- As described in the Draft Underground Water Impact Report 2012 (Surat Cumulative Management Area), the Spring Impact Mitigation Strategy proposes that, where a water level of greater than 0.2m is predicted at the location of a spring, petroleum tenure holders be required to evaluate potential mitigation options.

- *Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources 2008 Order:*
    - Clause 29(2) – water utility or town water supply bore cannot be located within (a) 5 km of high priority GDE in the Eastern Recharge and Southern Recharge groundwater sources and (b) 50 km of high priority GDE in the Surat, Warrego and Central groundwater sources.
    - Clause 29(3) – water supply bore cannot be located within (a) 50 km of high priority GDE in the Surat, Warrego and Central groundwater sources, (b) 5 km of high priority GDE in the Eastern recharge and Southern Recharge groundwater sources for a bore which may extract more than 20 ML/year and (c) 1 km of high priority GDE in the Eastern or Southern Recharge groundwater sources for a water bore which may not extract more than 20 ML/year.
    - Clause 29(11) – water bore access licence will not be granted where the taking of water would result in a predicted cumulative drawdown in excess of 10 percent of the potentiometric surface at the commencement of this plan at the state border with Queensland or South Australia.

4.5.7 Risk and opportunity evaluation

The evaluation of risk takes into consideration the risk assessment (likelihood and consequence of reduction in flow) to springs dependent on artesian groundwater based on modelled change in groundwater levels (sections 4.5.2 to 4.5.4). The risk assessment needs to be considered in light of the knowledge and data gaps and uncertainties (Section 4.5.5), in particular, the potential errors in the GABtran modelling (Section 3.5). Finally, the evaluation of risk needs to consider if the risk requires treatment or is acceptable given the current controls in place (Section 0).

Under all scenarios, the highest level of risk is attributed to Peery Springs complex in the Bourke supergroup. Two recharge springs in the Springsure supergroup are also categorised as high to highest risk, however there is a low level of confidence that these springs are sourced from the modelled aquifers. Under Scenario D (future climate and future development) a decline in risk and increase in opportunity for recovery is more likely for more springs. This is largely due to the likely recovery in groundwater levels in the vicinity of the Eulo, Bourke and Bogan River supergroups as a result of estimated future bore rehabilitations that improve water use efficiency, such as are currently supported by the GABSI program.

For an assessment at which scale this was undertaken, the knowledge and data gaps and uncertainties are sufficient that the risk assessment should only be seen as indicative. Further investigations are required to determine a more precise level of risk and the Peery Springs complex (being the highest risk site) should be a priority for such an investigation. Sites ranked as high likelihood of opportunity for recovery should be high priority sites to monitor and invest in on-ground threat abatement.

A detailed evaluation is included in the companion technical report listed in Appendix A.

4.6 References

Aquatic Ecosystem Task Group (2009) Draft guidelines for applying the criteria for the HCVAE assessment process. Report to the Australian Government Department of Environment, Water, Heritage and the Arts from the Aquatic Ecosystems Task Group, Canberra.

Auricht CM (ed.) (2011) Towards an Australian national aquatic ecosystem classification (ANAE). Prepared by Auricht Projects for the Aquatic Ecosystem Task Group and the Department of Sustainability, Environment, Water, Population and Communities, Canberra.

DERM (2011) Conceptual model case study series: Eulo springs super-group. Queensland Department of Environment and Resource Management. Viewed 23 August 2011, <http://www.epa.qld.gov.au/wetlandinfo/resources/static/pdf/conceptual-model-case-studies/Eulo_springs_supergroup.pdf>.

Environment Australia (2001) A directory of important wetlands in Australia, third edition. Environment Australia, Canberra. Viewed 19 December 2012, <http://www.environment.gov.au/water/publications/environmental/wetlands/directory.html>.

Fensham RJ and Fairfax RJ (2003) Spring wetlands of the Great Artesian Basin, Queensland, Australia. Wetlands Ecology and Management 11, 343–362.

Fensham RJ, Pennay C and Drimer J (2012) Ecological and botanical survey of springs in the Surat Cumulative Management Area. Department of Environment and Resource Management, Queensland.

Fensham RJ, Ponder WF and Fairfax RJ (2010) Recovery plan for the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin. Department of Environment and Resource Management, Brisbane.

Green G, White M, Gotch T and Scholz G (eds) (2013) Allocating water and maintaining springs in the Great Artesian Basin, Volume VI: Risk assessment process for evaluating water use impacts on Great Artesian Basin springs. National Water Commission, Canberra.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Habermehl MA (1982) Springs in the Great Artesian Basin, Australia – their origin and nature. Bureau of Mineral Resources, Canberra.

Habermehl MA (1998) Section 1.7: Hydrogeology. In: Cox R and Barron A (eds) Great Artesian Basin resource study. Great Artesian Basin Consultative Council, Brisbane, 44–59.

Habermehl MA (2001) Chapter 11: Hydrogeology and environmental geology of the Great Artesian Basin, Australia. In: Gostin VA (ed.) Gondwana to greenhouse – Australian environmental geoscience. Special Publication 21. Geological Society of Australia, Sydney, 127–143, 344–346.

Habermehl MA and Lau JE (1997) Hydrogeology of the Great Artesian Basin Australia (Map at scale 1:2,500,000). Australian Geological Survey Organisation, Canberra.

Hale J (2010) Lake Eyre Basin high conservation value aquatic ecosystem pilot project. Report to the Australian Government Department of Environment, Water, Heritage and the Arts from the Aquatic Ecosystems Task Group, Canberra.

Hercus LA and Sutton P (1985) The assessment of Aboriginal cultural significance of mound springs in South Australia. Kinhill Steams, Adelaide.

NSW Government (2011) Water sharing plan for the NSW Great Artesian Basin Groundwater Sources Amendment Order 2011. Viewed 19 December 2012, <http://www.legislation.nsw.gov.au/sessionalview/sessional/SRTITLE/Water%20Management%20Act%202000%20-%20Water%20Sharing%20Plan%20for%20the%20NSW%20Great%20Artesian%20Basin%20Groundwater%20Sources%20Amendment%20Order%202011%20(2011-422)%20LW%2012%20August%202011.pdf>.

NWI (2004) Intergovernmental agreement on a National Water Initiative. An agreement between the Commonwealth of Australia and the Governments of the States and the Australian Capital Territory and the Northern Territory. National Water Commission, Australia. Viewed 23 October 2012, <http://nwc.gov.au/__data/assets/pdf_file/0008/24749/Intergovernmental-Agreement-on-a-national-water-initiative.pdf>.

Ponder WF (1986) Mound springs of the Great Artesian Basin. In: De Deckker P and Williams WD (eds) Limnology in Australia. CSIRO, Melbourne and Dr. W. Junk Publishers, Dordrecht, Netherlands, 403–420.

Prescott JR and Habermehl MA (2008) Luminescence dating of spring mound deposits in the southwestern Great Artesian Basin, northern South Australia. Australian Journal of Earth Sciences 55(2), 167–181.

QWC (2012) Assessment of the risks and potential consequences to springs in the Surat Cumulative Management area. Queensland Water Commission, Brisbane.

Ramsar Convention Secretariat (2005) The Ramsar Convention on Wetlands. Ramsar Convention Secretariat, Ramsar Convention Bureau, Gland, Switzerland.

White D and Lewis M (2013) Associating wetland extent and spring flow rates. In: Lewis M, White D and Gotch T (eds) Allocating water and maintaining springs in the Great Artesian Basin, Volume IV: Spatial survey and remote sensing of artesian springs of the western Great Artesian Basin. National Water Commission, Canberra.

Part III Assessments drawing on the reconceptualisation of the Great Artesian Basin

5 Hydrogeological framework

Authors: Kellett JR, Radke BM, Ransley TR, Bell JG and Stewart GA

This chapter summarises the updated understanding of the hydrogeological framework and hydrostratigraphy as well as the boundaries and physical properties of aquifers and aquitards in the Great Artesian Basin (GAB).

5.1 Geological framework

5.1.1 The Great Artesian Basin

The GAB is a variably confined groundwater basin comprising a multi-layered complex of aquifers of variable character within predominantly continental sandstones. These aquifers are separated and centrally confined by aquitards of both fluvial and marine mudstone and siltstone of Jurassic and Cretaceous age.

The GAB was defined as a hydrogeological basin by Habermehl (1980) comprising the geological Eromanga, Surat and Carpentaria basins as well as the underlying Triassic sequences in the Bowen and Galilee basins.

For the purpose of the Great Artesian Basin Water Resource Assessment (the Assessment), the hydrogeological basin is taken to exclude the Triassic sequences, restricting the focus to the laterally extensive hydrogeological units of Jurassic and Cretaceous of the Eromanga, Carpentaria, Surat and Clarence-Moreton basins and overlying Tertiary sequences in the Lake Eyre, Billa Kalina and Karumba sedimentary basins, and overlying unconsolidated cover (Figure 5.1). This Assessment confirms that the western part of the Clarence-Moreton Basin is the eastern hydrogeological extension to the Surat Basin.

The GAB is stratigraphically bounded above and below by major unconformities (periods of erosion and no deposition). A Late Triassic unconformity defines the base of the host sedimentary basins that cover many underlying Triassic and Paleozoic basins as well as crystalline and metamorphic basement (Figure 5.1 and Figure 5.2). The Middle to Late Cretaceous unconformity generally demarcates the top of the GAB sequence except where additionally covered by Tertiary deposits. Elsewhere the upper surface has been lateritised by several Cenozoic weathering events at approximately 60, 30 and 7 Ma, and subsequently eroded or covered by alluvium.

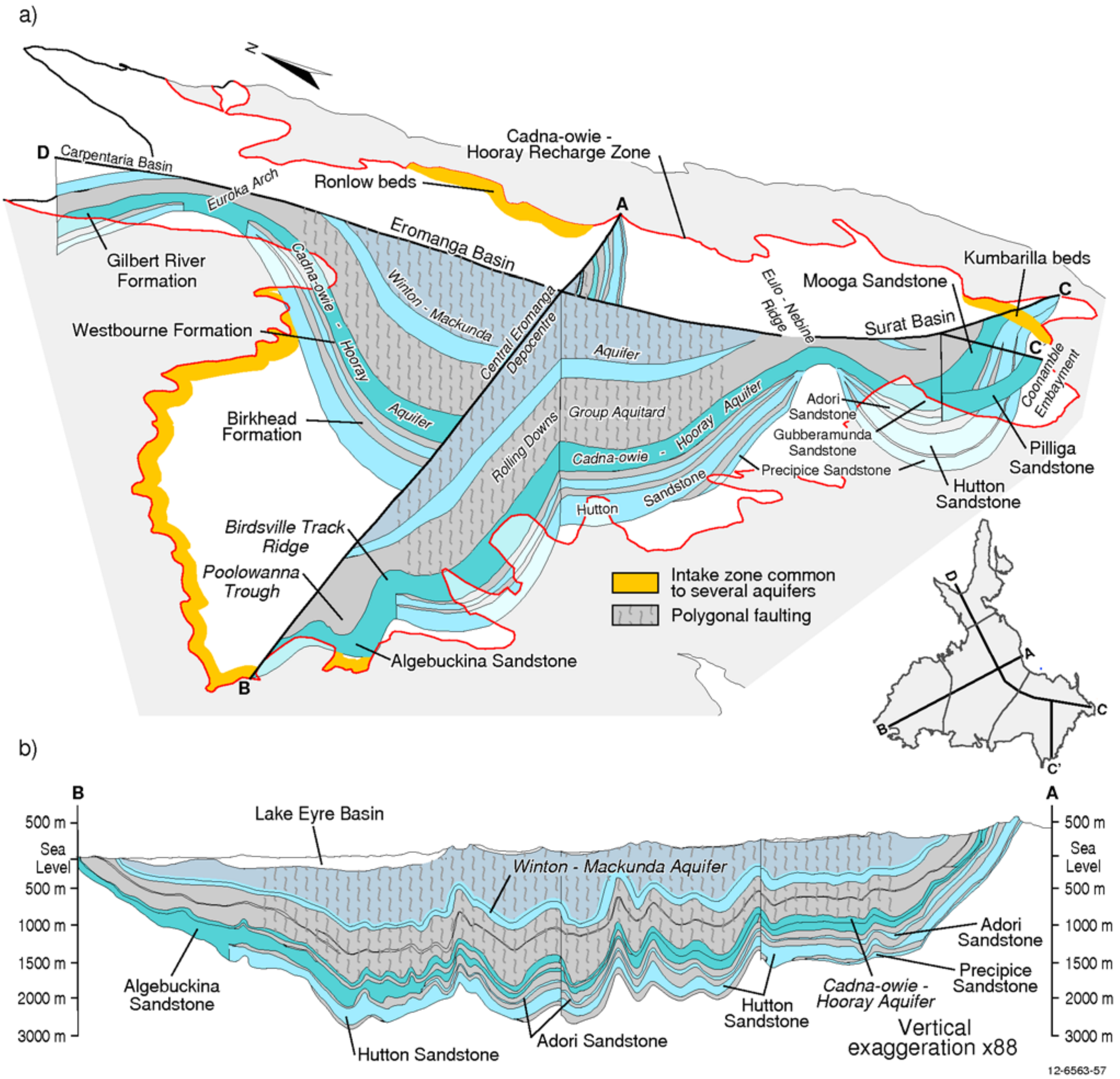


Figure 5.1 Three-dimensional conceptualisation of the Great Artesian Basin (updated from (Radke et al., 2000)

5.1.2 Reporting region boundary

For the purpose of the Assessment, the Surat region boundary in the west is arbitrarily taken to be the western extent of the broad high comprising the Eulo and Nebine ridges (Figure 5.2). The northern boundary is coincident with that of the Surat geological basin. Eastward it extends across the Kumbarilla Ridge into the Clarence-Moreton Basin to the West Ipswich Fault, east of Toowoomba (Figure 5.2) so as to include the Cecil Plains sub-basin. This western part of the Clarence-Moreton Basin is hydrogeologically continuous with the Surat Basin. In the south the Surat region boundary includes the Coonamble Embayment.

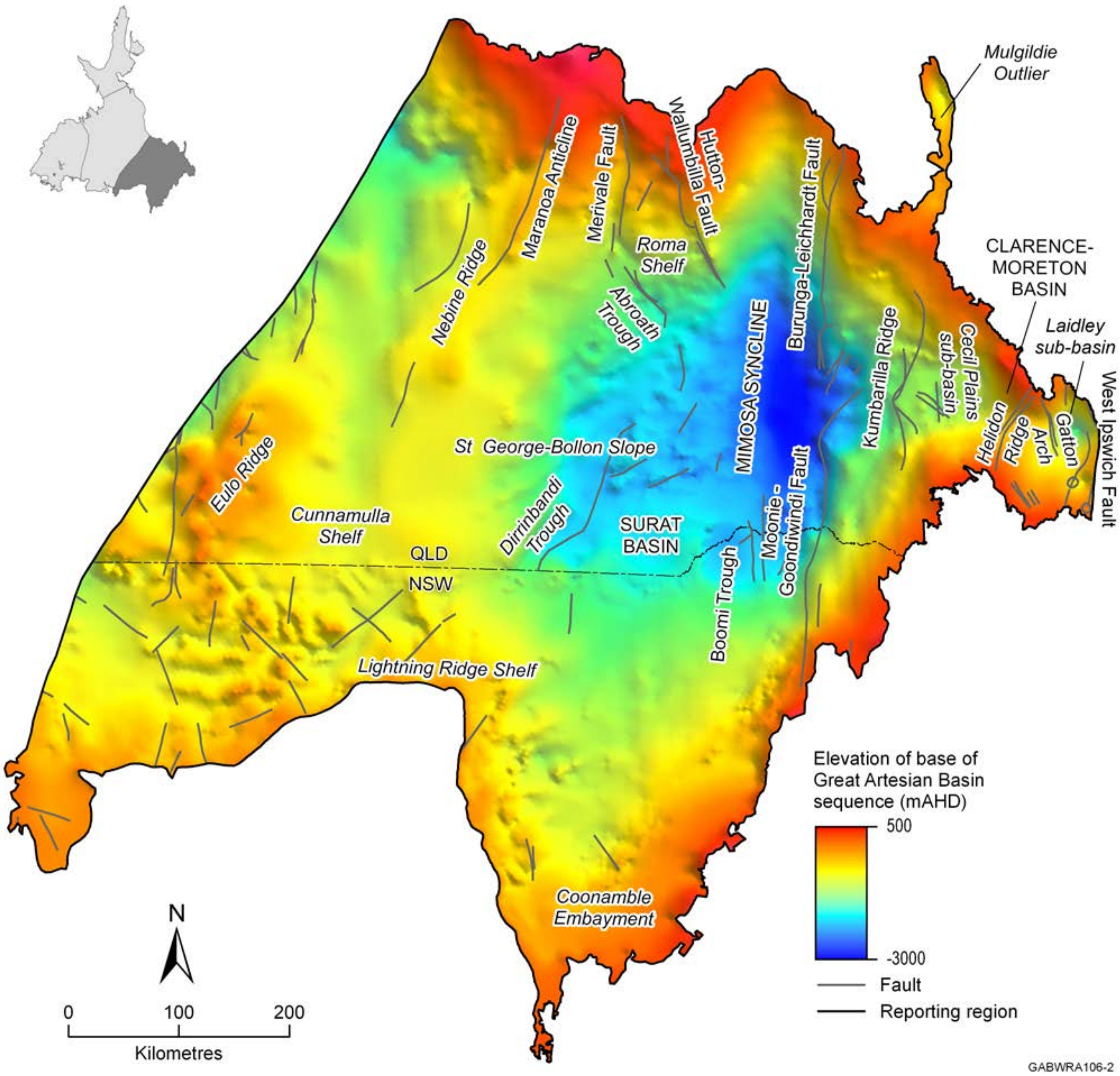


Figure 5.2 Structural elements of the Surat and Clarence-Moreton basins at the base of the Surat sequence

5.1.3 Modifications to the boundary of the Great Artesian Basin

Groundwater divide in the Clarence-Moreton Basin

The easternmost extent of the GAB has previously been loosely defined as a groundwater divide on the Kumbarilla Ridge (Habermehl, 1980; Habermehl and Lau, 1997). In contrast, the state of Queensland manages water resources within the Queensland portion of the Clarence-Moreton Basin as part of the GAB.

The Kumbarilla Ridge separates the boundary between the Surat Basin and Cecil Plains sub-basin of the Clarence-Moreton Basin, with the Kumbarilla beds forming a transitional facies with much of the Jurassic sequence. This suggests continuity of the sequence across the ridge.

As part of this assessment a detailed examination of stratigraphic and petroleum wells in this region indicates that there is a clear lithostratigraphic correlation between the Jurassic sequences in the Surat and Clarence-Moreton basins (Figure 5.9) and that Precipice Sandstone equivalents interconnect around the northern end of the Kumbarilla Ridge. In the Clarence-Moreton Basin, the upper Woogaroo Subgroup is equivalent to the Precipice Sandstone, while the upper Koukandowie Formation, of the Marburg Subgroup, is an equivalent of the Hutton Sandstone (Figure 5.9).

The Helidon Ridge (proposed informal name) is a subtle north-northeast to south-southwest trending basement structure that separates the Laidley sub-Basin and the Cecil Plains sub-Basin, and merges northward into the Gatton Arch (Figure 5.3). With drape of the sequence over this ridge, there is a regional change in dip that likely also controls groundwater flow in much of the lower Jurassic sequence. Structurally, the ridge affects every horizon from basement up to the Walloon Coal Measures.

The Assessment confirms the emerging understanding that a complex groundwater divide lies within the Clarence-Moreton Basin. The position of this divide differs between the deeper and shallower formations. Basement structure influences the deeper aquifers but the dramatic surface topography has a dominating influence on the shallower aquifers.

The groundwater divide in both the Hutton Sandstone and equivalents, and the overlying Walloon Coal Measures aligns generally with the edge of the escarpment of the Great Dividing Range. Groundwater levels associated with the topography of this escarpment are sufficient to override the effect of the Helidon Ridge in these shallower formations. In contrast, the Helidon Ridge is the most probable groundwater divide for deeper formations, including the Evergreen Formation and Precipice Sandstone (Figure 5.3).

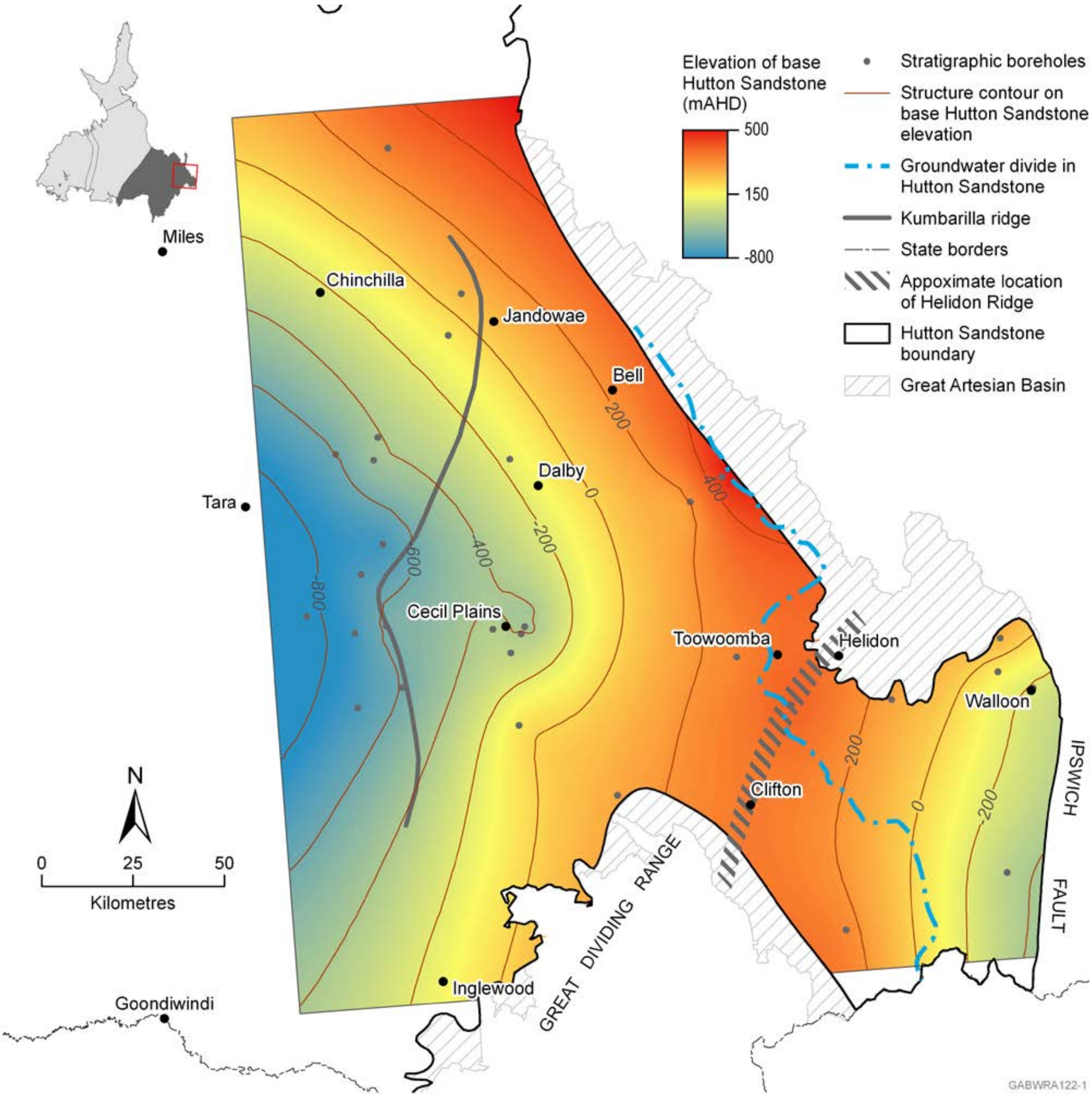


Figure 5.3 Location of Helidon Ridge

Coonamble Embayment

The GAB boundary on the north eastern side of the Coonamble Embayment is an erosional one, delineated by the limit of Pilliga Sandstone. In the south-east, the Pilliga Sandstone and underlying Purlawaugh Formation extend east beyond the boundary of the GAB. In this area a groundwater divide demarcates the boundary between the GAB and the adjacent Oxley Basin. The western GAB margin is concealed beneath Cainozoic sediments where the GAB sediments abut deeply weathered schists and phyllites of the Ordovician Girilambone Group. The Lower Macquarie River Valley airborne electromagnetic (AEM) survey (Macaulay and Kellett, 2009) in conjunction with revised geological mapping of the Narromine, Nyngan and Walgett 1:250,000 sheets, offers better delineation of the concealed boundary in some places (Figure 5.4). This is due to a marked conductivity contrast between the top of the Rolling Downs Group saprolite and overlying Cainozoic sediments, as well as highly conductive saprolite of the older Ordovician Girilambone Group (Figure 5.4). The revised western extent of the GAB in the Coonamble Embayment has been shifted between 10 and 30 km eastward (Figure 5.5).

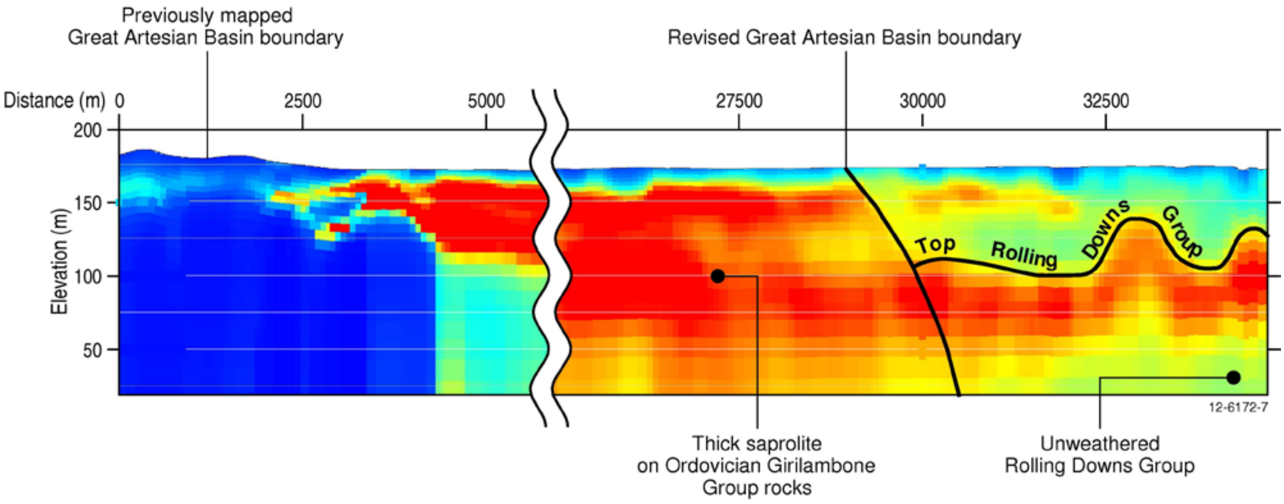


Figure 5.4 Airborne electromagnetic properties of flight line 24010 (shown in Figure 5.5) indicate the margin of the Great Artesian Basin sequence, western Coonamble Embayment

Note: the image displays apparent conductivity, with red showing high apparent conductivity, and blue low apparent conductivity. In this case, changes in conductivity indicate changes in geology

The southern extent of the Coonamble Embayment is revised, based on recent geological mapping that shows undifferentiated Jurassic GAB sediments extending along the axis of the Tullamore Syncline, approximately 60 km further south than previously mapped (Figure 5.5).

5.1.4 Basins

There is a common genesis and consequently a similar history of sediment accumulation within the component geological basins, closely linked to the tectonic evolution of the Eastern Plate boundary of Australia throughout the Mesozoic era. However, each geological basin differs slightly in timing of subsidence and deposition, partly a result of structural fabrics (i.e. the texture, arrangement and orientation of structures) which are inherited from older underlying basins.

Surat Basin

The main depocentre in the Surat Basin lies within the north-south aligned Mimosa Syncline – Boomi Trough that directly overlies the Taroom Trough of the underlying Bowen Basin. Other areas are the Nebine Ridge, Eulo Ridge, Roma Shelf, St George-Bollon Slope, Coonamble Embayment, Kumbarilla Ridge, Mulgildie Basin to the north, and the subdued Cecil Plains sub-basin to the east (Figure 5.2 and Figure 5.6).

The axis of the Mimosa Syncline follows that of the Taroom Trough but the syncline is much broader and shallower than the underlying trough.

During deposition, the depocentre in the Mimosa Syncline migrated south in relation to that of the underlying Taroom Trough. The base of the thickest sequence in the Surat Basin is now near Meandarra and lies at about –1800 mAHD.

The topography at the base of the Surat sequence is reflected in the overlying structure of sedimentary layers of the Surat Basin. This structure becomes progressively subdued up sequence. For example, at the top surface of the Evergreen Formation, basement topography is still evident but is significantly subdued. At this surface, displacement on the Moonie-Goondiwindi Fault seldom exceeds 100 m.

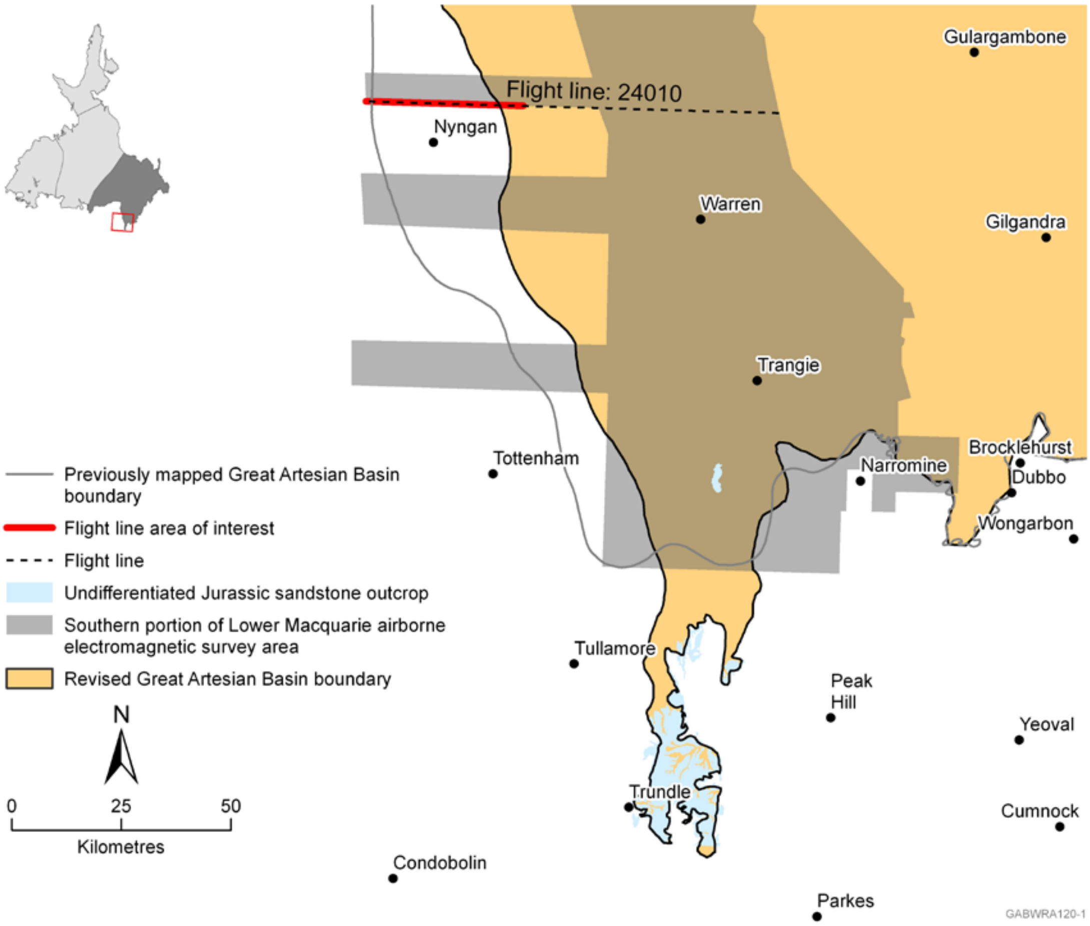


Figure 5.5 The revised Great Artesian Basin boundary, airborne electromagnetic flight lines and revised geological mapping within the Coonamble Embayment
Note: flight line area of interest shown in Figure 5.4

The Surat Basin overlies a number of major faults that in some cases disrupt the Surat Basin sequence (Figure 5.2). Fault movement occurred prior to deposition of the Surat Basin sequence (Exon, 1976). In basement to the Surat Basin, two major fault systems delimit the Roma Shelf. Its eastern margin is demarcated by the north-northwest trending Hutton-Wallumbilla Fault which has a westerly downthrow of up to 800 m in the north. The Merivale and Abroath faults, which form the western limit of the shelf, may be separate structures within the Surat sequence but are on the same underlying structure in basement. The maximum westerly downthrow exceeds 1000 m on the northerly-trending Merivale Fault which is a probable thrust feature. The Abroath Fault (north-east of Abroath Trough) has a downthrow of about 1200 m. However, displacements within the Surat sequence are significantly less and rarely exceed 100 m

The Moonie – Goondiwindi fault is a prominent basement fault over which the Surat sequence has been draped. Reactivation of this fault has resulted in minor dislocation of the Surat sequence by up to 100 m along the northern portion of the fault.

The Eulo and Nebine ridges area is a broad complex high separating the Eromanga and Surat basins. The Nebine Ridge is an anticlinal feature that plunges south-westward from the intake bed area, and diminishes into the Cunnamulla Shelf. The Eulo Ridge parallels the Nebine Ridge but lies to the west-southwest, beyond the recognisable limit of the Nebine Ridge. The GAB sequence does not fully cover basement in the crest of the Eulo Ridge which is a broad dome of faulted granitic basement. Between and around these ridges is the Cunnamulla Shelf (Figure 5.2).

Clarence-Moreton Basin

The Clarence-Moreton Basin is separated from the Surat Basin by the north-south aligned Kumbarilla Ridge. This ridge is a very broad basement high that separates the depocentre of the Woogaroo subgroup (Figure 5.9) in the Cecil Plains sub-basin from those in the Surat Basin (Day et al., 1974). However, the GAB sequence is continuous with that of the Clarence-Moreton Basin across and around the northern side of the Kumbarilla Ridge.

Eastward from the Kumbarilla Ridge, the Horrane Trough (see Figure 5.6) is basement to the Cecil Plains sub-basin which is partly differentiated from the Laidley sub-basin by the Gatton Arch on the northern margin of the Clarence-Moreton Basin (Figure 5.2). This arch is a broad ridge in basement over which the Clarence-Moreton sequence thins slightly and is gently folded (Gray, 1975).

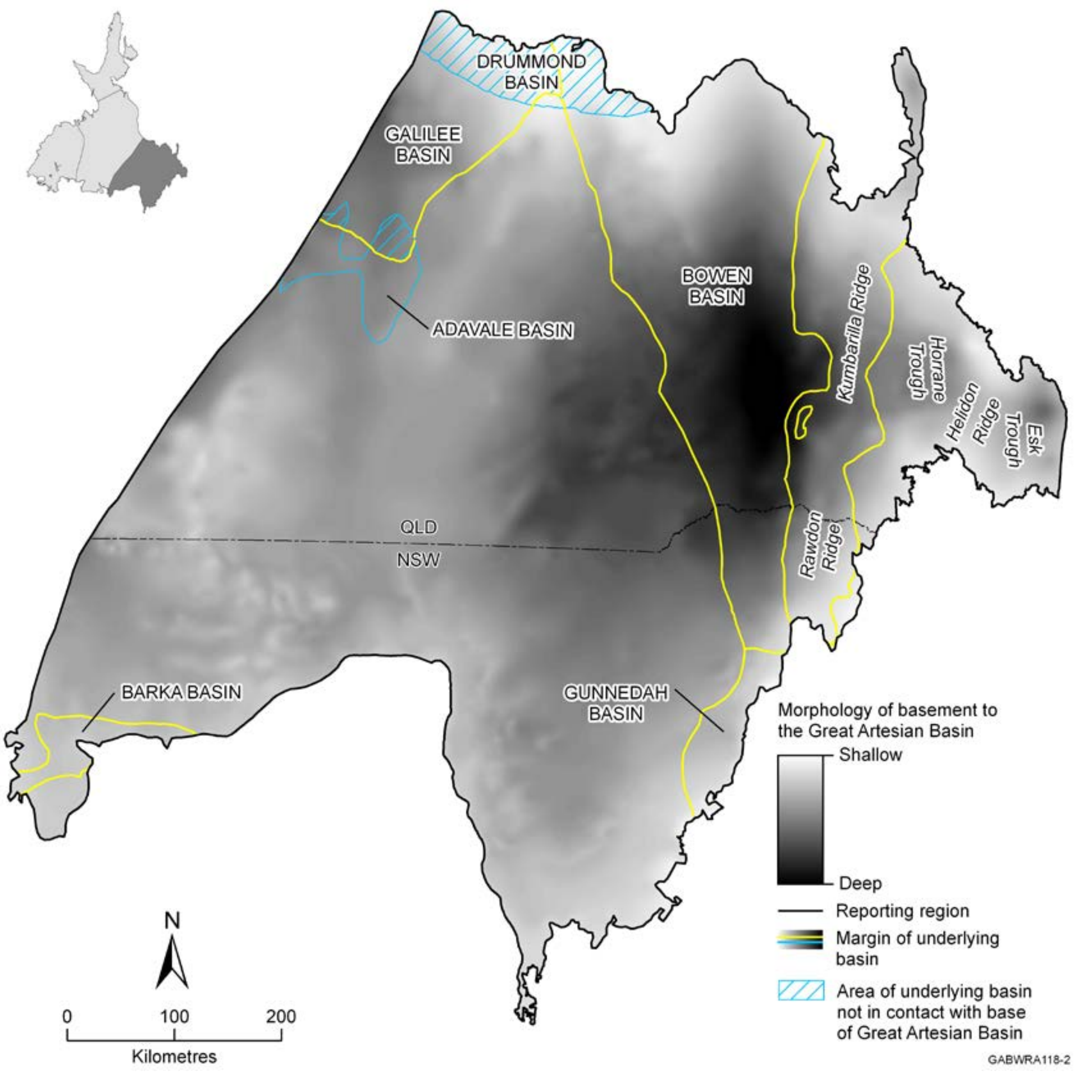


Figure 5.6 Basement of Surat and Clarence-Moreton basins with underlying geological basins

The Helidon Ridge is a subtle north-north-east trending basement structure that lies just east of Toowoomba below the foot of the main escarpment, and converges northwards with the Gatton Arch near the northern margin of the Clarence-Moreton Basin (Figure 5.2).

East of the Gatton Arch, the Esk Trough in basement extends southward to underlie the depocentre of the Laidley sub-basin.

There is a complex groundwater divide within the Clarence-Moreton Basin that varies in position with the level of the aquifer in the sequence. In the deeper aquifers, this groundwater divide is considered to be the Helidon Ridge (Figure 5.3) while for upper aquifers, the groundwater divide is influenced by topography and extends from the Cecil Plains Sub-basin in the north into the Laidley Sub-basin to the south-east.

The uppermost Triassic sequence of the Bowen and Galilee basins, namely the Moolayember Formation, Clematis Sandstone and Rewan Formation, are normally considered to be part of the hydrogeological basin that is the GAB. Because these formations underlie the widespread Jurassic-Cretaceous sequence of the GAB and are more confined in their extent (Figure 5.6), they have been treated in this Assessment as hydraulically-connected basement to the Surat Basin sequence.

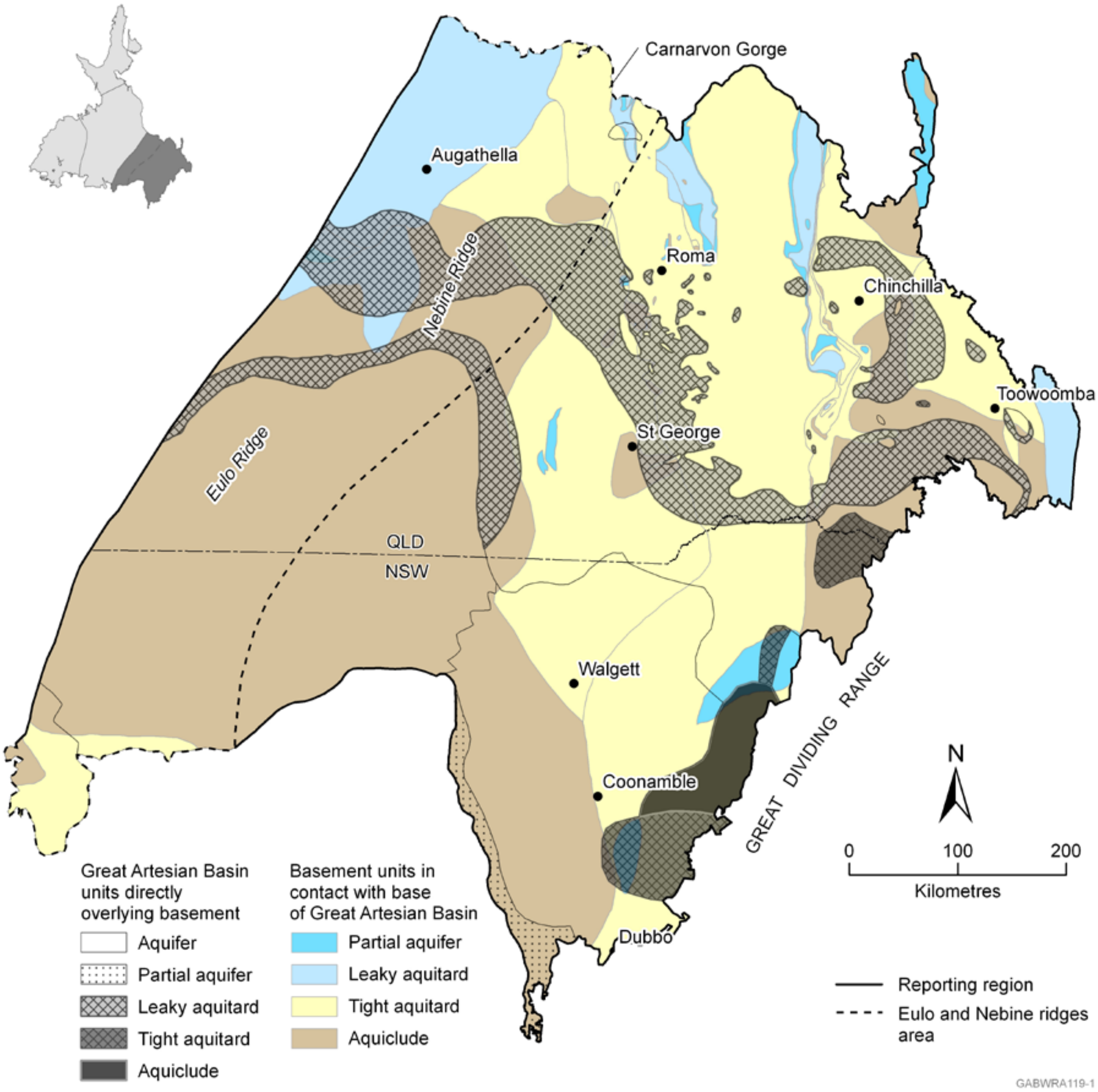


Figure 5.7 Potential areas of hydraulic interconnection between the base of the Great Artesian Basin and underlying basement units in the Surat and Clarence-Moreton basins

Most structural features manifested in the Surat Basin are inherited from underlying basins and basement. Below the Mimosa Syncline of the Surat Basin, the Permian-Triassic Bowen Basin sequence is contained predominantly within the north-south aligned Taroom Trough and extends southward to the Gunnedah Basin (Figure 5.2 and Figure 5.6). In the northern region of the Surat Basin, this underlying sequence spreads north-westward over the Nebine Ridge into the Galilee Basin.

Based on a regional hydrostratigraphic classification of GAB units, potential hydraulic connectivity of the GAB with underlying basins exists through the juxtaposition of aquifers and leaky aquitards, above and below the basal unconformity of the GAB (Figure 5.9).

In contrast to the Central Eromanga Basin where the area of potential connectivity approaches 50 percent, potential hydraulic connectivity with basement in this region is much more limited, only approaching 10 percent of the area (Figure 5.7). However, notable potential aquifer interconnection across the basal unconformity of the Surat Basin exist:

- On the mid flanks of the Mimosa Syncline at its northern end where a synclinal Bowen sequence in the underlying Taroom Trough exposes some leaky aquitards and partial aquifers.
- Below the St George Bollon Slope, small isolated flat-lying remnants of Reids Dome Beds of the Bowen Basin lie at the basal unconformity.
- In the Mulgildie Outlier, aquifers of the Bowen sequence are in direct contact with the Precipice Sandstone.
- Less definitively, below the Laidley sub-basin of the Clarence-Moreton Basin, Triassic coal measures below the base are seen as leaky aquitards.
- Below the eastern side of the Coonamble Embayment, patches of some upper aquifers of the Gunnedah Basin sequence offer connection.

5.2 Depositional and tectonic history

5.2.1 The Great Artesian Basin

Many earlier attempts to explain the formation of the geological basins that host the GAB, proposed single mechanisms, but such reductions in conceptualisation fall short of explaining the complexity. It now appears that at least four overlapping mechanisms may be necessary to explain the major features of the GAB:

- continental scale tilting of the Australian plate as a response to subduction on its eastern margin
- intracratonic subsidence
- sea-level changes (Waschbush et al., 2009)
- increased loading on the eastern plate margin from abnormal amounts of volcanogenic sediment deposition and subsequent subsidence (Gallagher and Lambeck, 1989).

A more comprehensive discussion of the tectonic history of the GAB can be found in the companion technical report about the lithostratigraphic units of the GAB as listed in Appendix A.

5.2.2 Surat Basin evolution

The Surat Basin evolved over a long period from about 200 to 100 Ma as part of the larger subsidence-depositional system that included the Eromanga, Carpentaria, Maryborough and Clarence-Moreton basins – a system as broad as it was long, that enabled accumulation of up to 2.5 km of sediment during the Late Triassic, Jurassic and Cretaceous periods (Exon, 1976).

Subduction and associated volcanism was occurring concurrently on the eastern margin of the Australian Plate. Consequently sediment was contributed from two sides of the Surat Basin (Figure 5.8). A low-lying cratonic source contributed mature and cleaner quartzose sands from the south-west while volcanogenic sediment came from the volcanic province adjoining a subduction zone on the eastern plate margin. The resultant Jurassic sandstones (later to become the Jurassic aquifers) accumulated mainly from the quartzose cratonic source, and the intervening siltstones and mudstones (later to act as aquitards) from predominantly volcanic sources.

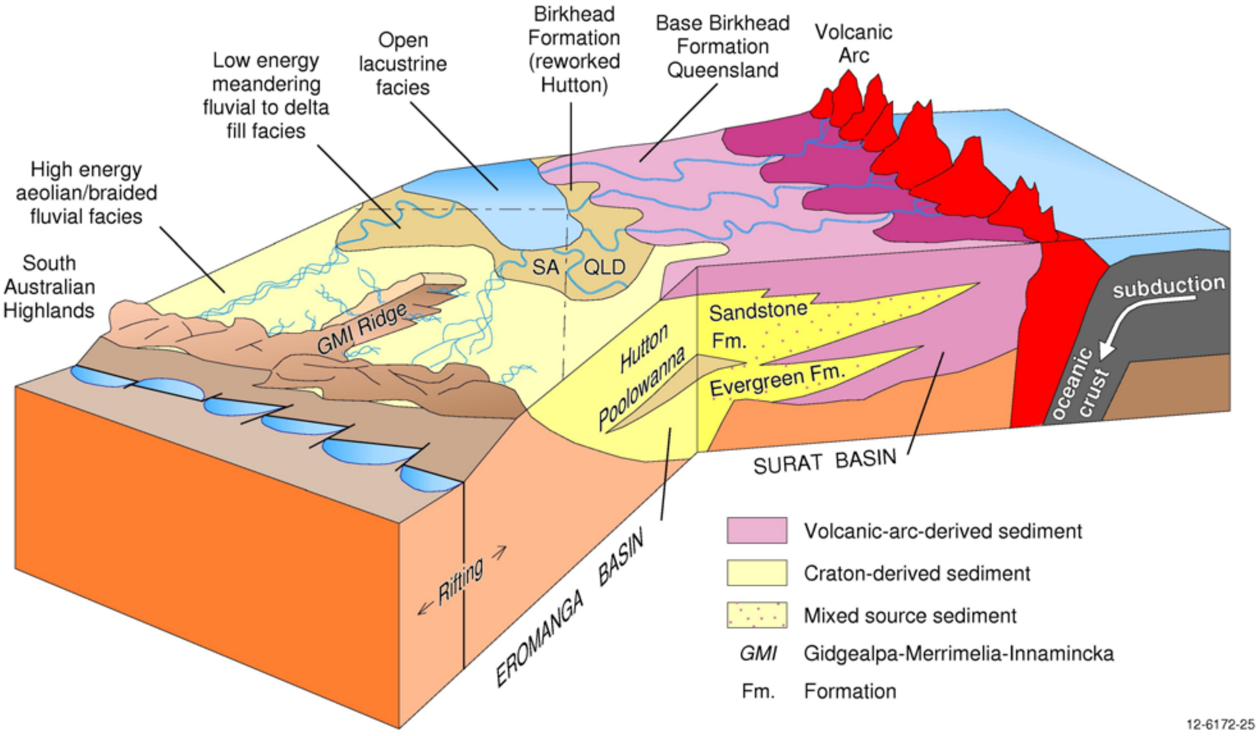


Figure 5.8 Deposition from dual provenance sediment sources in the context of the Australian plate dynamics (after Boult et al., 1997)

5.2.3 Clarence-Moreton Basin evolution

The Basement rocks of the New England and Yarrol Orogens that surround and underlie the Clarence-Moreton Basin were cut by major, long-lived strike-slip faults. This faulting continued into the Mesozoic and exerted a major influence on the formation and deformation of the sediments in the overlying Clarence-Moreton Basin.

Accumulation of the Mesozoic sediments was initiated by extension in basement, followed by extended subsidence from crustal cooling. The Clarence-Moreton sequence accumulated under smaller and diminishing subsidence rates, with sediment thicknesses up to 1650 m and 1300 m being deposited in the Laidley and Cecil-Plains Sub-basins respectively (O'Brien et al., 1994).

Within the Clarence-Moreton Basin sequence, the lower Bundamba Group comprises predominantly fluvial sediments that do not contain coal. The composition of sediments within the group was determined by cyclic nature and rate of tectonic uplift and subsidence. The overlying Walloon Coal Measures accumulated in low-gradient fluvial environments and coal-swamps.

5.2.4 Uplift: creation of the artesian basin

Maximum marine inundation of Australia occurred 120 to 110 Ma (Struckmeyer and Brown, 1990). This marine transgression eventuated in both extensive fine grained marine and terrestrial floodplain sedimentation during the later part of the Early Cretaceous – the accumulated sequence effectively sealing the GAB. Areas that are now the eastern highlands would have at that time been at or below sea level. At about 90 Ma, the first phase of uplift and creation of the eastern highlands caused widespread erosion on the eastern margin of the GAB. Eroded sediment contributed to further infill of the GAB that terminated marine conditions and created the fluvial Griman Creek Formation. Compression and uplift around the GAB in the Eocene (~50 Ma), initiated inversion and folding of the sequence. After repeated denudation and weathering cycles (occurring at about 60, 30 and 7 Ma), a final uplift of the eastern highlands at about 5 Ma elevated the eastern intake beds of the GAB, creating an asymmetric westward tilt to the GAB, initiating artesian conditions and westward throughflow of groundwater within the GAB.

5.3 Hydrogeology

Only within the central thicker part of the sub-basin, can the GAB be considered to be a series of stacked aquifers of variable quality separated by aquitards. Over highs connecting laterally to adjacent sub-basins, the aquitards are thinner, and the separate aquifers coalesce (Figure 5.1). In some cases, these aquitards are leaky. Dual permeability, flow through both intergranular pores and through fractures, is inferred as the regional characteristic for the main artesian aquifers.

The basin-wide categorisation of aquifers and aquitards (confining beds) (Figure 5.1) is an oversimplification as there is much more variability in the properties of hydrostratigraphic units. A more realistic but qualitative approximation (as applied in Figure 5.9) proposes the distinction of good aquifer, partial aquifer, leaky aquitard, tight aquitard and aquiclude. This is the best summation at present and is applied across the Surat and Clarence-Moreton basins. Furthermore with closer scrutiny, the hydrogeological properties of a unit may vary in different parts of a basin and between basins.

This variation in properties may be due to one or a combination of: sediment source, rate of basin subsidence during deposition, and alteration since the time of deposition.

5.3.1 Lithostratigraphic framework

The GAB covers three states and the Northern Territory, and its regional-scale understanding has steadily evolved over the last century through the comparison and correlation of many separate and geographically-isolated studies. As a result, there are now understood to be some 47 formations and 20 members that make up the lithostratigraphic framework of the Eromanga, Surat and Clarence-Moreton, Carpentaria geological basins that host the hydrogeological GAB.

With extensive seismic survey coverage over deeper parts of the basins, the continuity and correlation of rock units has been directly confirmed. Certain distinctive seismic reflectors such as the seismic ‘C’ reflector at the top boundary of the Cadna-owie – Hooray Aquifer have enabled basin-wide mapping of individual units.

Figure 5.9 summaries the lithostratigraphic sequence in individual basins and provinces of the Surat and Clarence-Moreton basins. The comparison and correlation of many formations in this figure between the Surat and Clarence-Moreton basins provide the basis for a hydrogeological framework. However, the correlation between the age and hydrogeological properties of these basin sequences can vary depending on palaeogeography and depositional history between the Surat basin and Clarence-Moreton basins. For example, an individual hydrostratigraphic unit can vary in age and lithology laterally.

A systematic summary of individual lithostratigraphic units was developed in conjunction with the companion technical report about the lithostratigraphic units of the GAB as listed in Appendix A. Their context in the basinal sequence is summarised in the lithostratigraphic correlation.

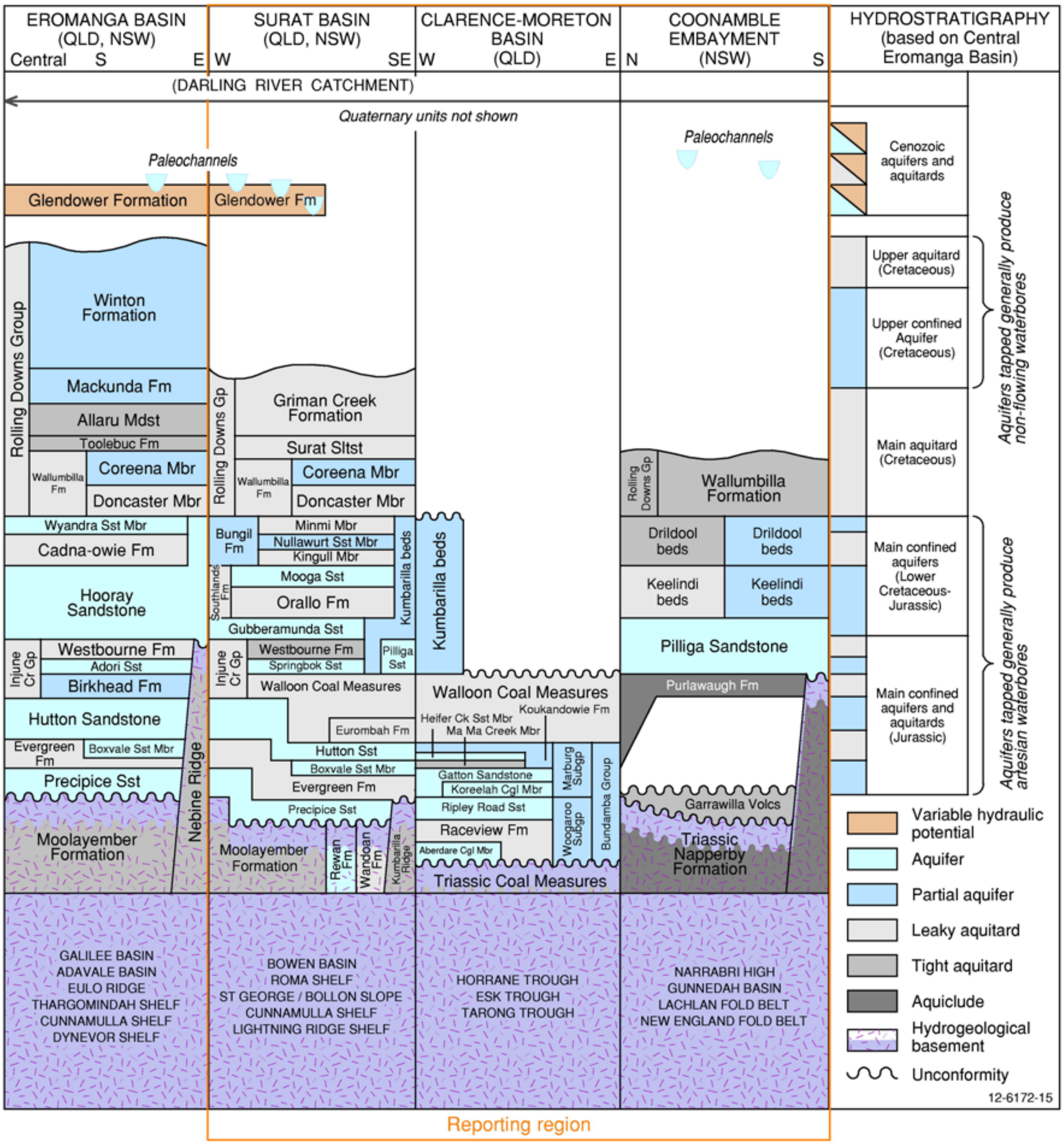


Figure 5.9 Stratigraphic sequence of the Surat and Clarence-Moreton basins with context of an adjoining basin Jurassic – Lower Cretaceous hydrogeological system

5.3.2 Jurassic – Early Cretaceous hydrogeological system

The Surat Region hydrogeological system comprises the main artesian aquifers and their equivalents, the Precipice, Hutton, Adori and Gubberamunda-Mooga sandstone aquifers, with interspersed aquitards (Figure 5.10). There is apparent hydrological connection across the Kumbarilla Ridge (Figure 5.9). The Precipice and Evergreen formations interconnect around the northern part of this structure. The Hutton Sandstone Aquifer appears hydrologically continuous with both the Marburg sub-group aquifers and most probably the underlying Woogaroo Subgroup aquifers that lithostraigraphically correlate with the Precipice Sandstone.

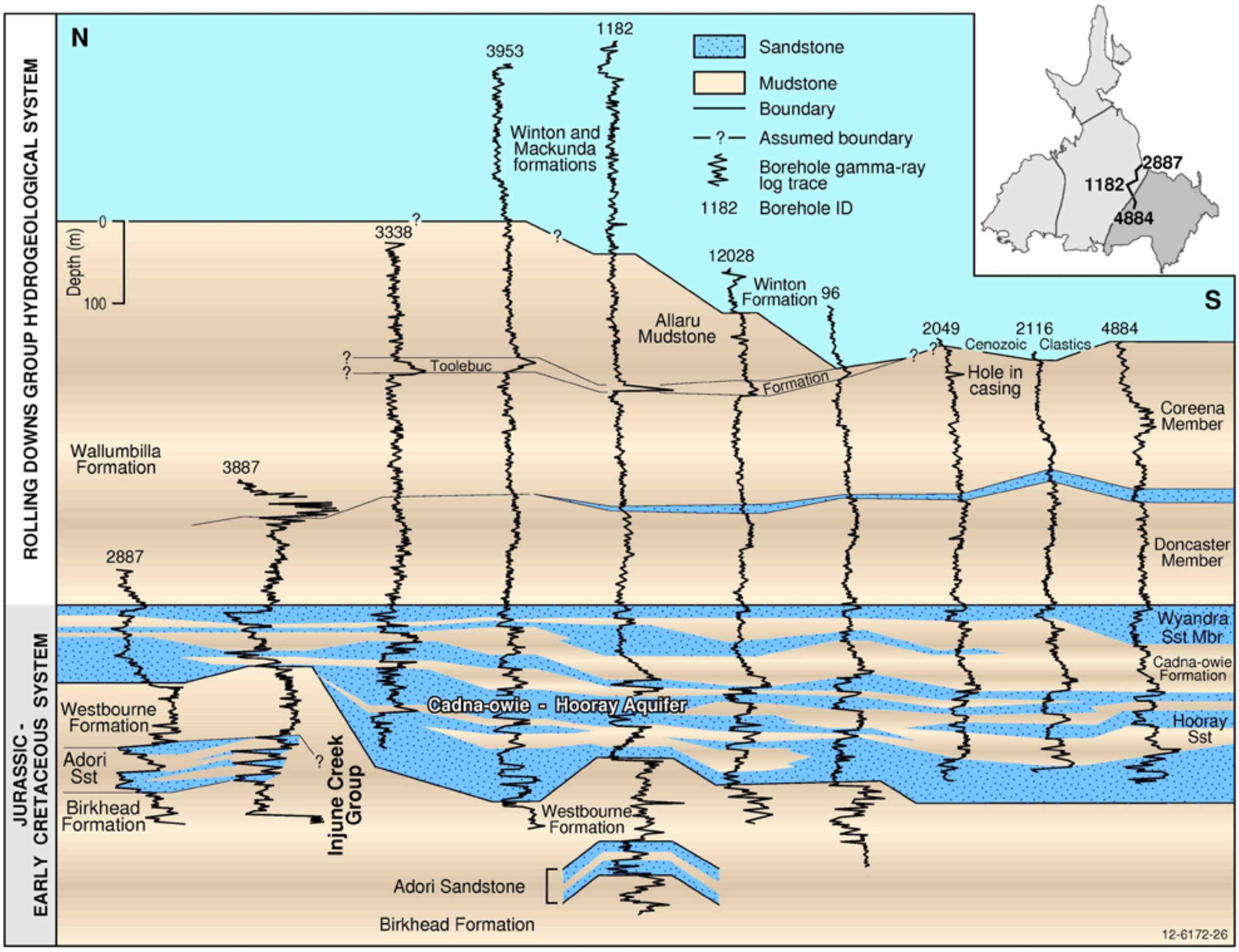


Figure 5.10 Distribution of aquifers in the Jurassic – Early Cretaceous and Rolling Downs Group hydrogeological systems
Note: the gamma ray log trace was used to define formation boundaries

Rolling Downs Group hydrogeological system

The predominantly marine sequence in the Rolling Downs Group, comprising the Wallumbilla Formation and Surat Siltstone, has been considered the main confining sequence to the underlying Jurassic to Early Cretaceous artesian aquifers. This system lies entirely within the Rolling Downs Group (Figure 5.9 and Figure 5.10). It comprises a very thick leaky aquitard and an upper semi-confined partial aquifer. This partial aquifer exists within the Coreena Member (Wallumbilla Formation) and the uppermost Griman Creek Formation.

Hydrogeological properties

An analysis of porosity and permeability data contained within the Queensland Petroleum Exploration Database (QPED) has been undertaken for the Surat region (Table 5.1). This analysis allows comparison, between units, of physical rock properties that influence the ability to store water (porosity) and to conduct water (permeability).

Measured mean horizontal permeability values have been converted to horizontal hydraulic conductivity to allow comparison with model derived, calibrated values of horizontal hydraulic conductivity reported for the Queensland Water Commission – Surat Cumulative Management Area Groundwater model (GHD, 2012) (Table 5.1). This comparison highlights the skewed distribution toward higher permeability values in aquitards (particularly the Westbourne Formation). In contrast, calculated hydraulic conductivity values for aquifers are in general agreement with the reported QWC values. This is because the reported permeability values in QPED are predominantly those of sandy units in these formations and are likely to be skewed toward higher values within a particular formation. Therefore skewed distribution toward higher permeability values is more apparent in aquitards that contain sandy units. It should also be noted that the reported permeability values were measured in a laboratory using a rapid assessment technique performed at ambient conditions for temperature and pressure.

Generally, an order of magnitude difference in mean horizontal permeability is exhibited between aquifers and aquitards, with the highest mean permeability (1051 mD) present within the Gubberamunda Sandstone (Table 5.1). An exception is the Westbourne Formation aquitard, which exhibits a relatively high mean permeability of 630 mD. However it is uncertain if this value is representative due to the low number of measurements (24) within this particular formation.

Table 5.1 Measured mean porosity and permeability and calculated and modelled horizontal hydraulic of formations

Formation	Porosity measurements	Mean porosity	Permeability measurements	Mean horizontal permeability	Calculated mean horizontal hydraulic conductivity**	QWC mean horizontal hydraulic conductivity ***	Hydrogeological classification
	number	percent	number	mD	m/day		
Wallumbilla and equivalents****	33	30	17	71	0.0593	N/A	Leaky aquitard/Partial aquifer
Mooga Sandstone	35	28	29	728	0.6076	1.5	Aquifer
Gubberamunda Sandstone	38	28	23	1051	0.8772	0.69	Aquifer
Westbourne Formation	24	26	21	630*	0.5258*	0.0014	Tight/Leaky aquitard
Walloon Coal Measures	118	18	95	67	0.0559	0.031	Leaky aquitard
Hutton Sandstone	333	22	301	426	0.3555	0.52	Aquifer
Evergreen Formation	766	15	624	87*	0.0726*	0.00013	Leaky aquitard
Precipice Sandstone	3172	16	2799	320	0.2671	0.34	Aquifer

* Unlikely to be representative of formation due to sampling bias toward sandy units

** Calculated from Mean horizontal permeability using $Kh = (kh/1000)\times 9.66\times 10^{-6}\times 86400$

*** Calibrated model values from Queensland Water Commission (GHD, 2012)

**** Includes hydrostratigraphic equivalents of the Wallumbilla formation and its component Doncaster and Coreena members

Figure 5.11 and Figure 5.12 show frequency plots of porosity and permeability for the major formations in the Surat region. Note that porosity is plotted at a linear scale and permeability is at a log scale.

The aquifer plots (Figure 5.11(a)) indicate the porosities of all four formations approach uniform distributions but their means are significantly different. Figure 5.12(a) indicates higher porosities in the Mooga (28 ±5 percent) and Gubberamunda (28 ±4 percent) sandstones than in the Hutton (22 ±6 percent) and Precipice (16 ±5 percent) sandstones. However, caution needs to be exercised in interpreting these results because of the small number of samples in the former aquifers. The distribution of points in the Hutton Sandstone is incipiently bimodal, the Precipice Sandstone distribution is slightly right skewed and both Mooga and Gubberamunda sandstones are left skewed.

When compared to equivalent aquifers in the Eromanga Basin, the porosities of the Mooga and Gubberamunda sandstones are significantly higher than the equivalent Hooray Sandstone, but again attention is drawn to the small sample of the former formations. Likewise mean porosity in the Hutton Sandstone is significantly higher in the Surat than in the Eromanga Basin. In this case the sample numbers are sufficiently large to provide confidence in the statistics, but there are almost ten times more samples in the Eromanga Basin (n = 2928) than in the Surat Basin (n = 333).

Porosity distributions for the aquitards show a far greater spread than for equivalent aquitard formations in the Eromanga Basin. In increasing order, the mean porosities are – Evergreen Formation (15 ±6 percent – excluding the Boxvale

Sandstone Member), Walloon Coal Measures (18 ±5 percent), Westbourne Formation (26 ±6 percent) and Wallumbilla Formation (30 ±8 percent), but sample numbers for the latter two formations are very small.

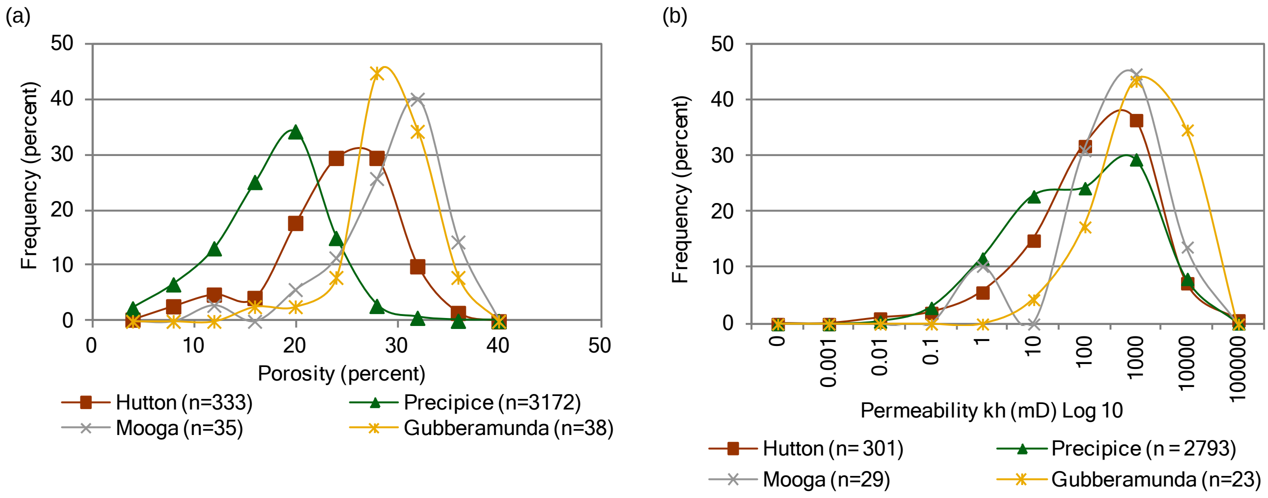


Figure 5.11 Frequency plots of (a) porosity and (b) permeability distribution for the major aquifers in the Surat region
Note: ‘n’ = number of samples

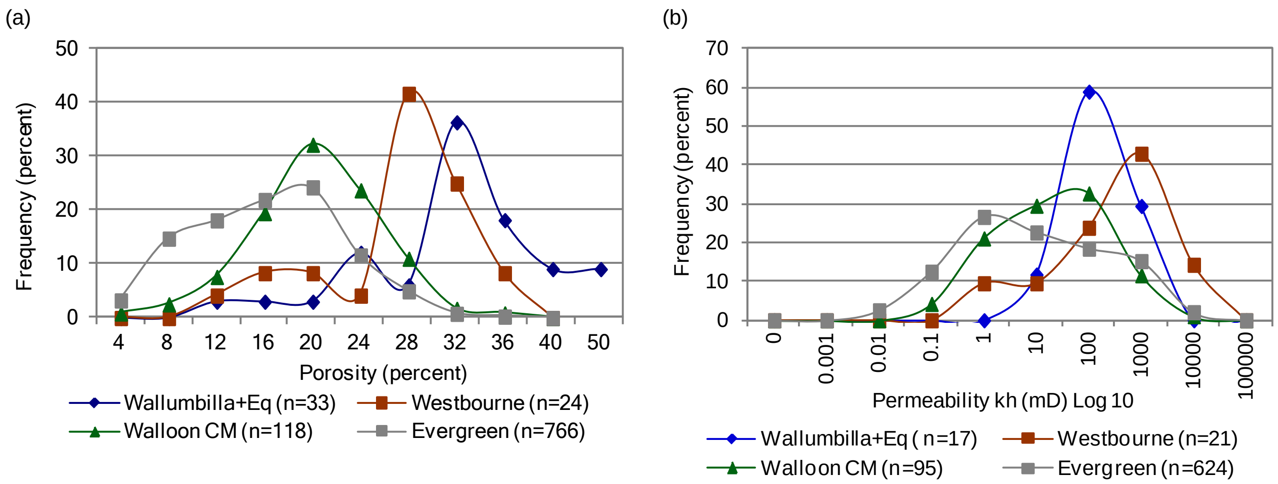


Figure 5.12 Frequency plots of (a) porosity and (b) permeability distribution for the major aquitards in the Surat region
Note: ‘n’ = number of samples

In the case of the Westbourne Formation, this anomalous difference between basins highlights a need for further investigation. The porosity distribution in the Surat Basin is left skewed with the suggestion of bimodality while the porosity distribution in the Eromanga Basin is distinctly unimodal and leptokurtic.

Figure 5.12(a) shows the distribution for the Evergreen Formation is strongly left skewed, the Walloon Coal Measures is slightly left skewed, and the Westbourne and Wallumbilla Formations are bimodal. In the particular case of the Wallumbilla Formation, the primary mode has a mean of about 32 percent which is close to the theoretical maximum for unweathered sediments.

The permeability characteristics for the Surat Basin aquifers (Figure 5.11(b)) do not appear to differ greatly, but the aquifer means are very different – Hutton Sandstone (426 ±1334 mD), Precipice Sandstone (320 ±905 mD), Mooga Sandstone (728 ±1463 mD) and Gubberamunda Sandstone (1051 ±1613 mD). The means do not appear to be significantly different in the plots because the Hutton and Precipice sandstones distributions are strongly left skewed. Interestingly, the mean permeability values for the Hutton Sandstone are almost identical in both the Surat and Eromanga basins.

The permeability characteristics for the four Surat Basin aquitards (Figure 5.12(b)) shows that only the Wallumbilla Formation approaches a uniform distribution and the other three are irregularly distributed. Mean permeability values are Evergreen Formation (87 ±245 mD), Walloon Coal Measures (67 ±234 mD), Westbourne Formation (630 ±1150 mD) and the Wallumbilla Formation (71 ±75 mD). However, only the first two of these have a sufficiently large number of samples to be statistically credible. It is important to note that the nature of the sampling biases the data towards more sandy permeable portions of these aquitards. The dominant fine grained sediment within these aquitards is the primary hydrogeoloical feature. Given the importance of the Westbourne Formation functioning as an effective aquitard, for exploitation of the Walloon Coal measures, the minimal available quantitative data and its high standard deviation in permeability, highlights a need for more detailed analysis of the hydrogeological properties of this unit.

Spatial distribution

Until isopach and sand-to-shale data are available for all hydrostratigraphic units, explanation of these patterns (shown in Figure 5.13) is speculative. All data presented are horizontal permeability. Vertical permeability determinations are too few in number to be representative for any unit.

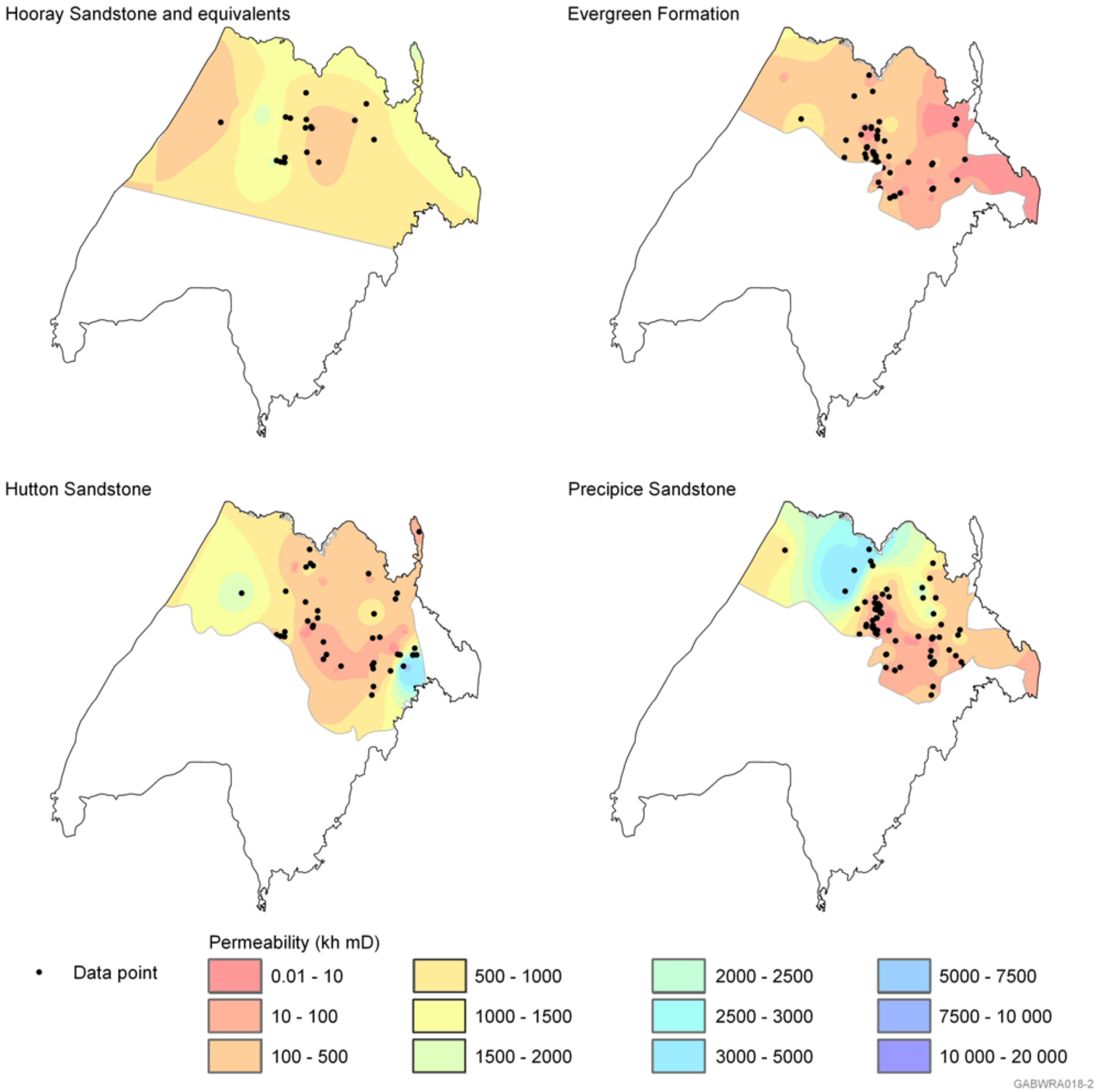


Figure 5.13 Spatial distribution of mean horizontal permeability and locations of data points
Note: coloured areas correspond to formation extents. Reliability of contours away from data points is low)

Precipice Sandstone

Highest permeabilities of sandstones within the Precipice Sandstone (5 to 7 D) appear restricted to the area of the eastern flank of the Nebine Ridge and eastwards over the St George-Bollon Slope to the western margin of the Roma Shelf. On the Roma Shelf as well as southward and south-eastward into the Mimosa Syncline mean permeability is greatly diminished. There is a north-west to south-eastward narrow trend on the flank of the main depocentre where permeability is again much higher (500 mD to 1 D) in the northern Mimosa Syncline, extending across to the Texas High.

High permeabilities on the eastern flank of the Nebine Ridge may be due to both mature sediment sources as well as lower accommodation rates, and hence cleaner permeable facies in this area. The lower permeabilities eastward and south-eastward may in contrast result from greater accommodation and less sorting of sediment during deposition. The north-west to south-east band of moderately higher permeability has a similar alignment with patterns in the Evergreen Formation and may relate to shallower depositional facies with lower accommodation rates around the margin of the main depocentre of the Mimosa Syncline immediately to the south (Figure 5.2).

Evergreen Formation

Sandstones of the Evergreen Formation are generally lower in permeability except locally on the Nebine Ridge and on the eastern margin of the Roma Shelf. Lowest permeabilities are within the Clarence-Moreton Basin, and north-east of the main depocentre to the east of the Burunga-Leichhardt Fault.

Diminishment of permeability relative to the Precipice Sandstone would be expected in the meandering floodplain depositional facies compared to Precipice braided stream deposition. The much lower permeabilities in the north-east may reflect lacustrine-dominant facies.

Hutton Sandstone

Over the Nebine Ridge onto its eastward flank and the Roma Shelf, permeability of sandstones in the Hutton Sandstone (500 to 1000 mD) appears to be twice, or up to an order of magnitude greater than eastward into the depocentre of the Mimosa Syncline. On the eastern side of the Goondiwindi Fault, lowest permeabilities are to the north while the southern part adjoining the Texas High has variably higher permeability.

Eastwards into the Clarence-Moreton Basin, the Hutton equivalents have permeabilities of 100 to 500 mD with locally higher values of 500 to 1000 mD centrally in the Cecil Plains sub-basin and decreasing permeability against the West Ipswich Fault.

In comparison to permeabilities of the Precipice Sandstone, sandstones of the Hutton Sandstone have lower permeability which progressively decreases into the depocentre of the Mimosa Syncline. This reduced permeability may be due to greater depositional accommodation rates, a burial diagenetic effect as observed in the Eromanga Basin across the Canaway fault by Green et al. (1989), or a combination of both. The patchy but higher permeability east of the Moonie-Goondiwindi Fault appears to extend over the Kumbarilla Ridge into the Clarence-Moreton Basin.

Hooray Sandstone

The distribution of available data precludes any comment on the Eulo Ridge and southern part where this aquifer is known to be present.

Over the eastern flank of the Nebine Ridge and the St George-Bollon Slope to the south, permeabilities are highest, exceeding 1 D and up to 2 D. In contrast, the Roma Shelf appears to be in a transition to lower permeability (100 to 500 mD) on the north-western slopes of the Mimosa Syncline depocentre. East of this area, permeabilities are higher.

The area of highest permeability, over the crest and on the eastern flank of the Nebine Ridge, is to be expected where the formation is thinner and has experienced lower accommodation rates with better sorting. The low permeability area to the east, as also seen in the Hutton Sandstone, may suggest subsidence was greater in this area, offset to the west of the main cumulative depocentre of the Surat Basin.

5.4 Regional watertable

The regional watertable of the Surat and western Clarence-Moreton basins is shown in Figure 5.14. In Queensland, the watertable slopes from the east and north-east to south-west, sympathetic with the topography, with the notable exceptions of the Dawson River valley and the Mulgildie Basin. Previously, Audibert (1976) and Habermehl (1980) noted the close affinity between the regional watertable and the topography throughout the GAB. In the Coonamble Embayment (New South Wales), the watertable slopes from east to west and north-west.

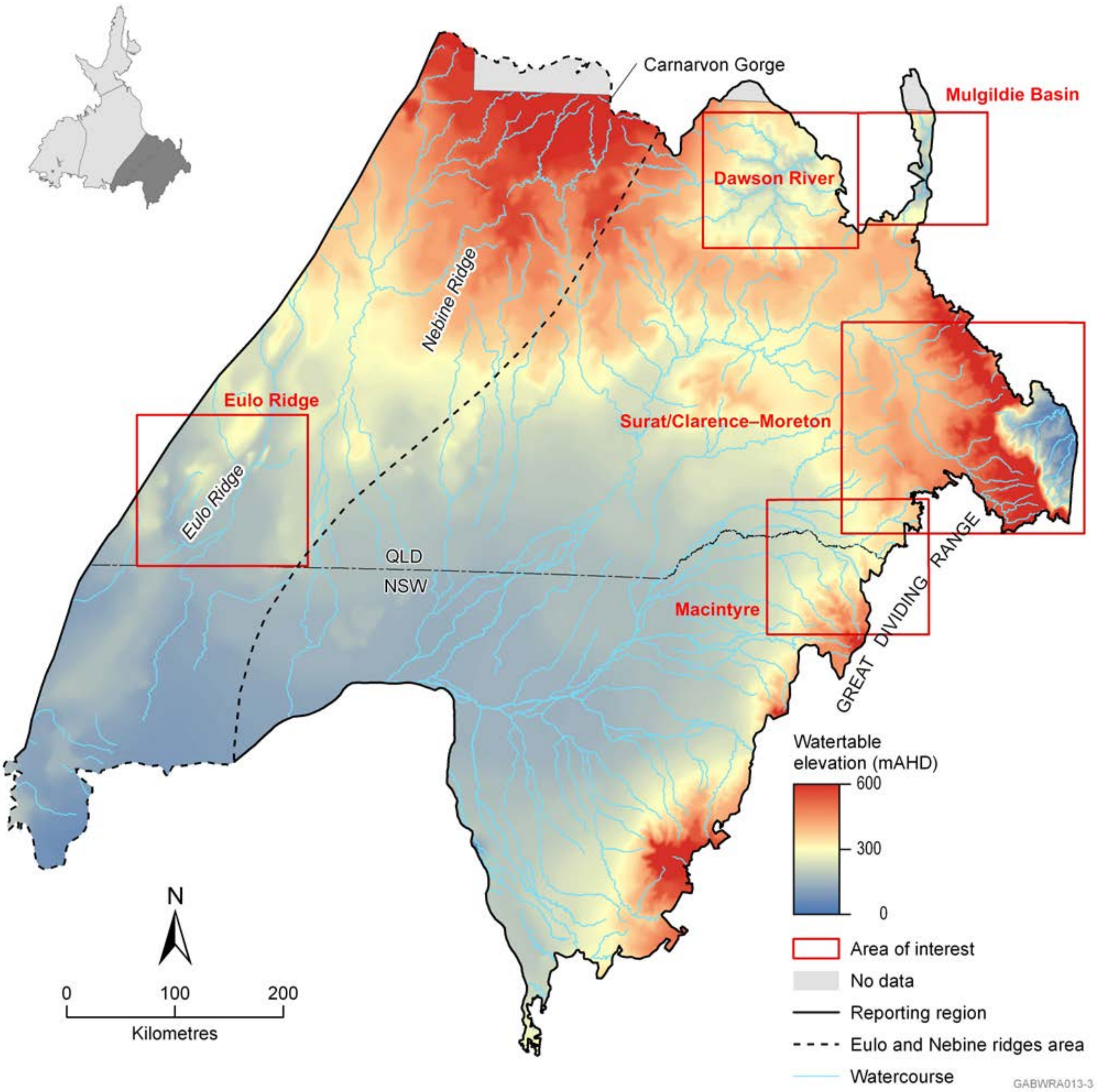


Figure 5.14 Great Artesian Basin watertable elevation

In Queensland, the watertable in the Surat Basin lies in the areas of outcrop of all the GAB aquifers (intake beds) and aquitards along the western slopes of the Great Dividing Range. It then passes into the Rolling Downs Group (Doncaster and Coreena members of the Wallumbilla Formation in the north and Griman Creek Formation in the south) which abut the intake beds and dip gently basinward, to the south-west. In the Clarence-Moreton Basin, the watertable lies in Jurassic sandstone of the Hutton Sandstone, Marburg Subgroup and Walloon Coal Measures (Figure 5.9).

In New South Wales, the watertable along the western slopes of the Great Dividing Range lies in the main GAB aquifer in New South Wales, the Pilliga Sandstone. It then passes into thin bands of Keelindi and Drildool Beds and then into undifferentiated Rolling Downs Group basinward. This latter unit is the major area of occurrence of the watertable and is most likely composed of Griman Creek Formation sediments (not recognised in New South Wales) overlying marine sediments of the Wallumbilla Formation. In the Coonamble Embayment, the watertable lies in the Drildool Beds from the southern boundary to Warren and thence in the Rolling Downs Group.

The majority of sub-artesian stock and domestic bores in the southern part of the Surat Basin in Queensland obtain their groundwater supplies from the Griman Creek Formation. This partial aquifer has very similar hydrogeological characteristics as its equivalent formation in the Eromanga Basin, the Winton Formation. Like the Winton Formation, most bores in the Griman Creek Formation in the Surat Basin obtain their groundwater supplies from the higher-yielding, more permeable basal sandstone beds. The water level in the basal sandstone rises to equilibrate with the first water cut, and can therefore be considered as equivalent to the regional watertable. In New South Wales, the Drildool Beds yield moderate quantities of fresh to brackish water and this formation appears to be hydraulically continuous with the Keelindi Beds. The marine sediments that are equivalent to the Wallumbilla Formation in New South Wales are low yielding and tend to produce poor quality water.

Extensive deposits of Cenozoic alluvium blanket the Surat Basin in both states. In Queensland, two fluvial formations are recognised. The lower alluvium occurs in paleochannels and is up to 150 m thick. In general the head in the lower (Tertiary) alluvial aquifer is lower than that of the upper (Quaternary) alluvial aquifer. The latter formation is known to be hydraulically connected to rivers in some places in eastern New South Wales and Queensland areas of the GAB. In most cases the watertable is in the alluvium. An exception is the Gwydir and Macintyre interfluve. Water levels in the upper alluvium are sensitive to changes in river stages and such sites may well be areas of GAB aquifer recharge via bed underflow leakage through the alluvium. Cenozoic paleochannels are known to exist in the Dirranbandi Paleovalley (Balonne/Culgoa rivers), the Border Rivers, and the valleys of the Gwydir, Namoi, Macquarie and Warrego rivers. Elsewhere the alluvium is thought to be shallow Quaternary sediments, however there have not been systematic investigations carried out on river systems west of the Warrego River to confirm this (i.e. there may be undiscovered paleochannels associated with these river systems

No water level data from any of the alluvial aquifers were used in the construction of Figure 5.14.

Areas of interest in the regional watertable

The area in Figure 5.15 comprises the Taroom 1:250,000 sheet which contains the Dawson River catchment. The Dawson River joins the Fitzroy River west of Rockhampton and then flows into the Pacific Ocean. Headward erosion of the Dawson River has produced a deeply dissected valley in the north-west of the Taroom sheet. Figure 5.15 shows the effect of this dissection on the regional watertable with flow from the watertable aquifer directed towards the Dawson River and its tributaries, notably Hutton Creek – a line sink with many baseflow springs. Exon (1971) estimated that the Dawson River system removed up to 1000 feet (~300 m) of Mesozoic sediments during its entrenchment, and in his opinion, this area is still a site of active erosion. The watertable converges to a choke in the Dawson River 45 km north-east of Taroom where it leaves the Great Divide (Figure 5.16). Thus the Dawson River valley is an area of flow loss from the GAB.

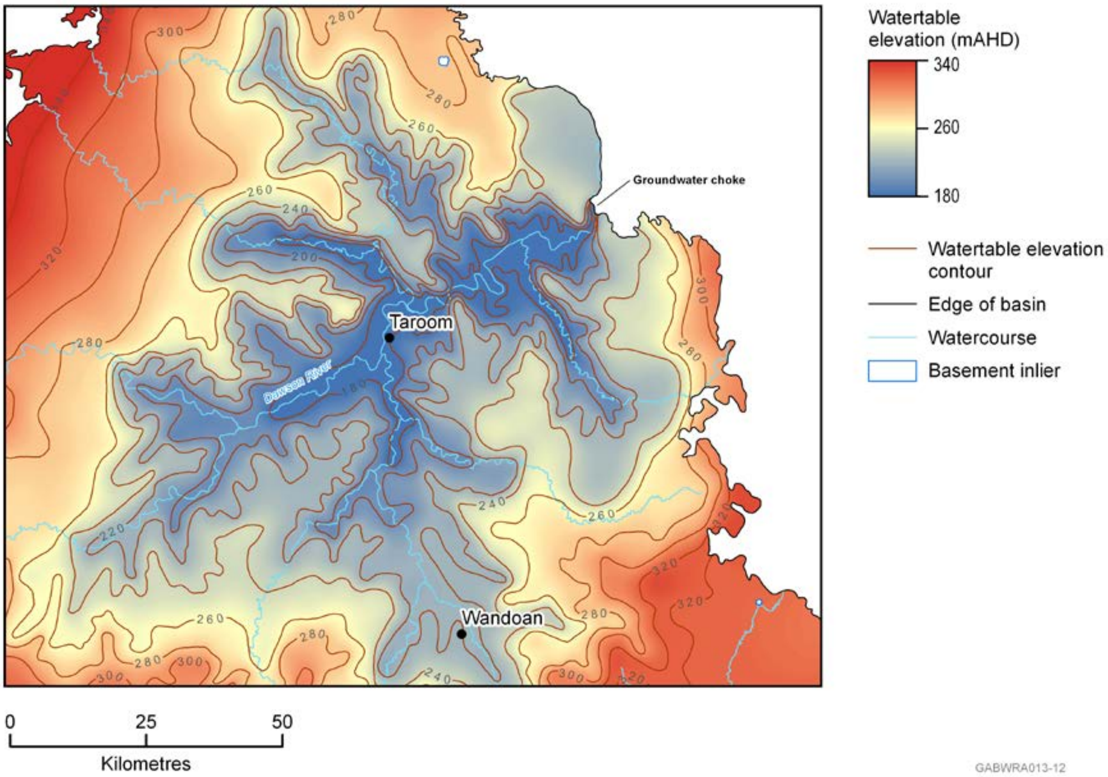


Figure 5.15 Watertable contours in the Dawson River valley on the Taroom 1:250,000 sheet

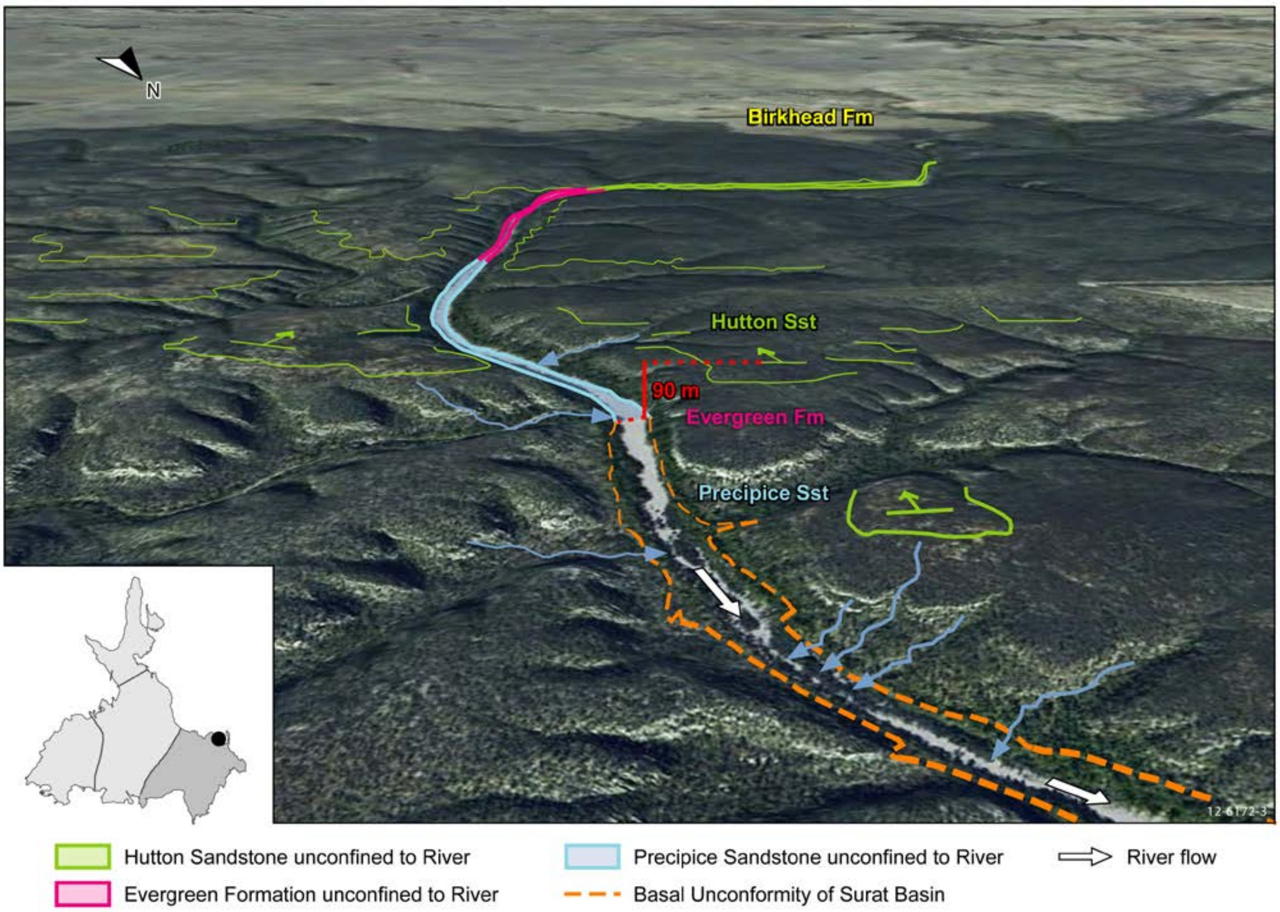


Figure 5.16 Satellite image looking south-west from the choke of the Dawson River Gorge
Note: bleached areas are Precipice Sandstone outcrop. Blue arrows represent groundwater seepage to the River (baseflow)

Figure 5.17 is the eastern half of the Mundubbera 1:250,000 sheet. The elongated lobe 10 km west of the town of Mundubbera is known informally as the Mulgildie Basin and is intersected at its narrowest point by the Burnett River which flows eastward towards Bundaberg and the Pacific Ocean. The watertable map clearly shows the neck of the Mulgildie Basin drains groundwater from the north and from the south – from GAB aquifers, the Precipice and Hutton Sandstones. The groundwater leaves the system as baseflow into the Burnett River (Figure 5.18). Therefore, like the Dawson River valley, the Mulgildie Basin is an area of flow loss from the GAB.

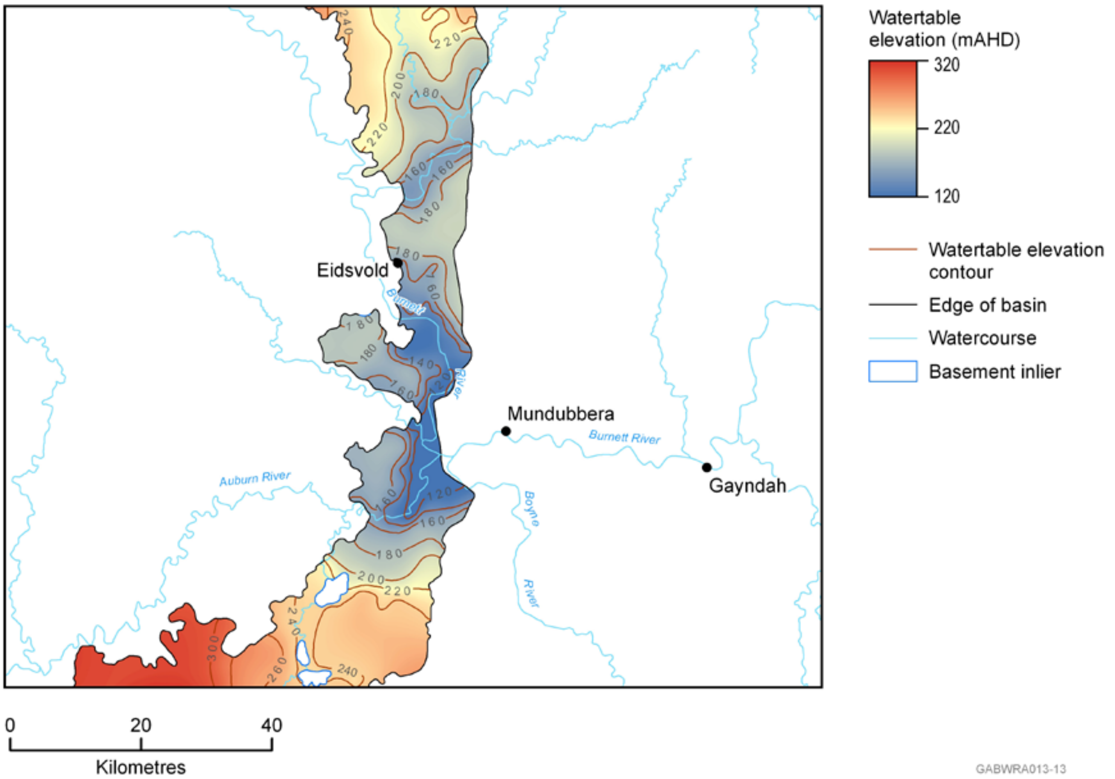


Figure 5.17 Watertable contours in the Mulgildie Basin on the Mundubbera 1:250,000 sheet

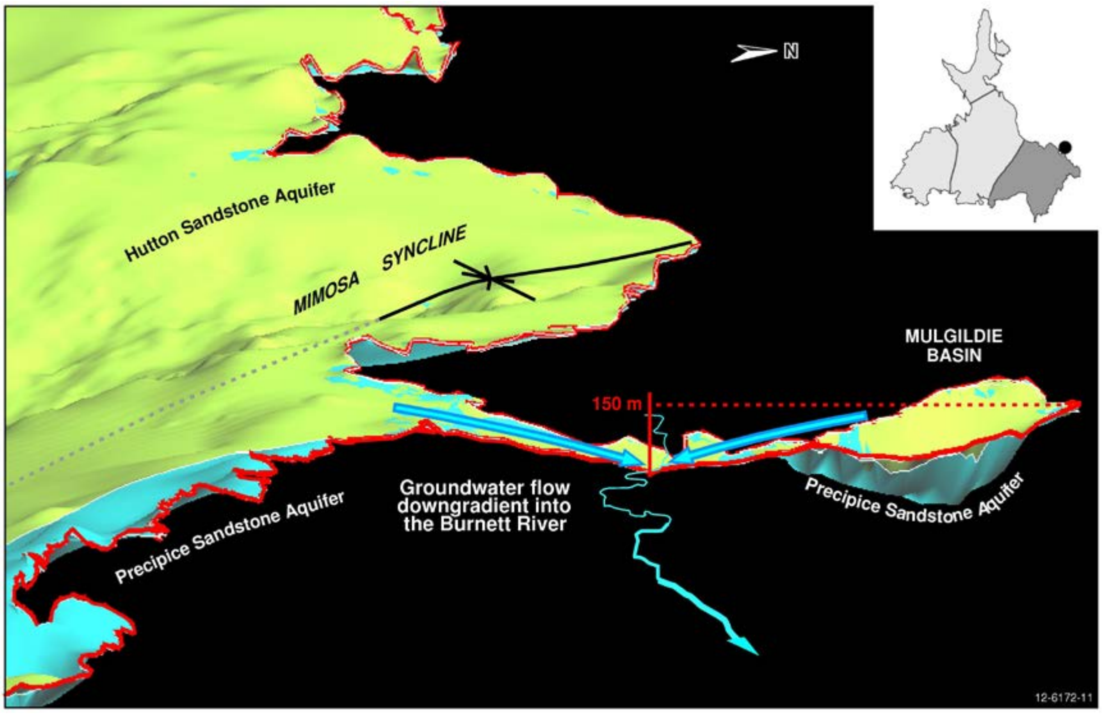


Figure 5.18 Three-dimensional model layer of the Mulgildie Basin showing baseflow into the Burnett River from the north and south

Figure 5.19 is part of the Border Rivers area – the Goondiwindi 1:250,000 sheet. The watertable is remarkable here because of the influence of the rivers on its configuration. East of Goondiwindi, the watertable aquifers are the Hutton Sandstone and sandstones of the Marburg Subgroup intake beds, which grade northward to the Kumbarilla Beds. On the New South Wales side the watertable aquifer is the Pilliga Sandstone in the intake beds, grading westwards to undifferentiated Rolling Downs Group (probably Griman Creek Formation equivalent). The flow directions in the watertable are noteworthy – in Queensland, groundwater flow is towards the south-west and in New South Wales it is to the north-west. The flowlines converge around the Macintyre River. Anecdotal reports of declining pressures in artesian bores in New South Wales had previously been attributed to excessive groundwater withdrawals on the Queensland side of the river, but at least as far as the watertable is concerned, the groundwater system in both states is virtually independent. This is a rare example of a state boundary coinciding with a hydrogeological one. East of Goondiwindi, the watertable is depressed about the Macintyre Brook, Dumaresq River and Macintyre River indicating that these may be gaining streams. However, the watertable shows a groundwater mound 10km west of Goondiwindi, possibly indicating the Macintyre River here is a losing stream recharging the Griman Creek Formation partial aquifer. The groundwater mound may in part be generated by hydraulic loading from the Goondiwindi Weir which lies 5 km downstream of the centre of the town. The bankfull water level of the weir is 217 mASL and the estimated watertable elevation beneath the weir is 202 mASL.

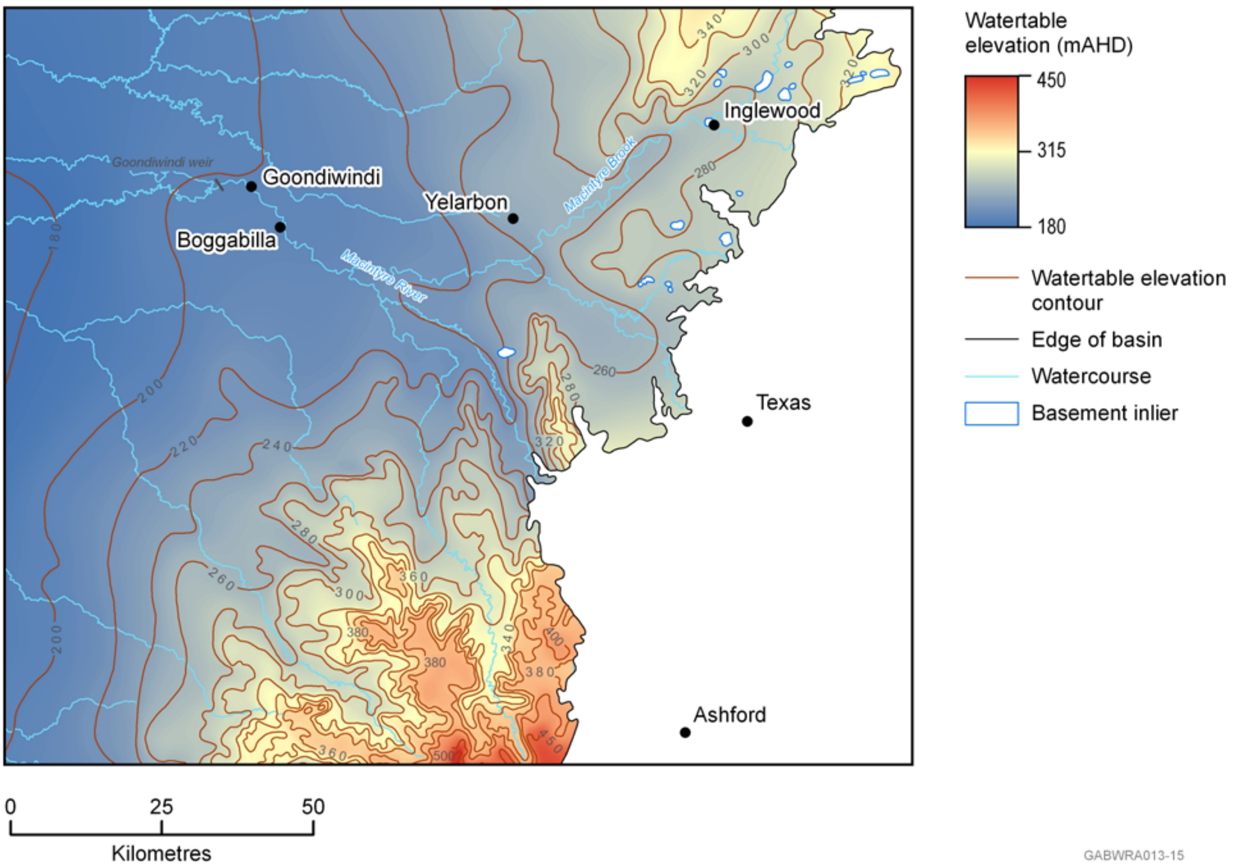


Figure 5.19 Watertable contours in the Border Rivers area on the Goondiwindi 1:250,000 sheet

Figure 5.20 shows the watertable on the Dalby and Ipswich 1:250,000 sheets. The western Clarence-Moreton Basin (Cecil Plains and Laidley sub-basins) was included in the Assessment to gain a better understanding of the complex groundwater divide between the Clarence-Moreton and Surat basins. Two structures and one groundwater divide are shown in Figure 5.20 – the Kumbarilla Ridge, Helidon Ridge and the watertable divide on the Great Divide. The watertable lies in the Kumbarilla Beds (specifically the Springbok Sandstone) on the Kumbarilla Ridge and in the Walloon Coal Measures in the Condamine River valley. The Condamine alluvium water level data were not included in the construction of the watertable map – generally the alluvial water levels are equal to or slightly lower than those in the Walloon Coal Measures (Hillier, 2010). Further east the watertable grades into the Hutton Sandstone, sandstones of the

Marburg Subgroup and Main Range Volcanics, and in some areas, the Walloon Coal Measures where this formation has not been significantly eroded.

The structure of the Kumbarilla Ridge comprises two slightly offset topographic highs trending north-northwest, coinciding with two slightly offset groundwater mounds. One could speculate that the offset could be a result of movement along an intervening north-east trending fault which could explain the displacement, but no such feature is shown on the 1:250,000 geological map. The name 'Helidon Ridge' is informally proposed for the basement high which separates the Cecil Plains and Laidley sub-basins of the Clarence-Moreton Basin. This structure creates a complex groundwater divide that varies according to the hydrostratigraphic level of each aquifer. For the Hutton Sandstone, Marburg Subgroup and Walloon Coal Measures, the watertable divide coincides with the topography (Figure 5.20). Finally, for the Evergreen Formation and basal Precipice Sandstone, the groundwater divide coincides with Helidon Ridge (Figure 5.3).

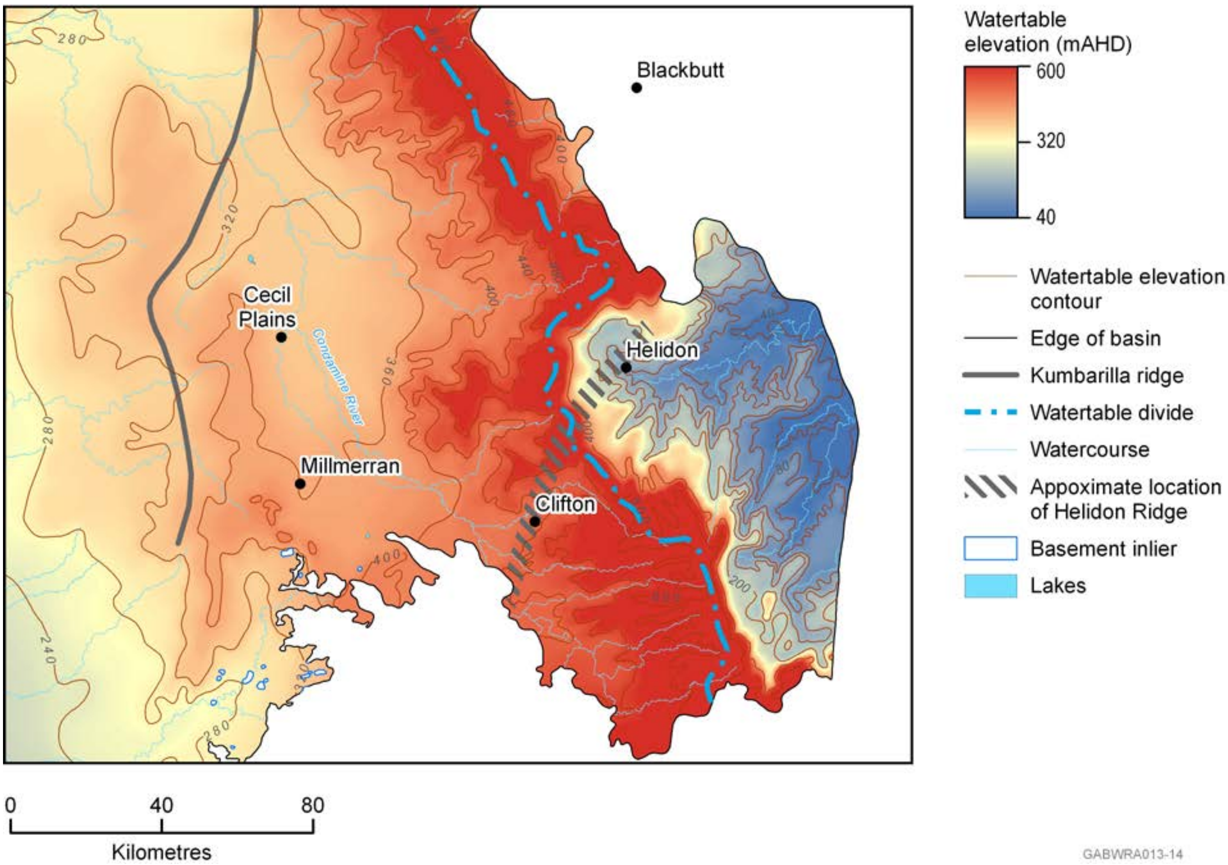


Figure 5.20 Watertable contours in the eastern Surat and western Clarence-Moreton Basins on the Dalby and Ipswich 1:250,000

Figure 5.21 is the potentiometric surface of the uppermost Early Cretaceous aquifers and leaky aquitards over the Eulo Ridge. The area shown in Figure 5.21 is from the Eulo and Toompine 1:250,000 sheets. The Eulo Ridge is the basement high separating the Surat and Eromanga Basins and is also a site of many springs, most of which have ceased to flow. The axis of the Eulo Ridge is shown in Figure 5.21, coincident with the watertable highs and passing through granite basement inliers. The potentiometric surface in Figure 5.21 was constructed from recent (post 2000) water level measurements in bores in the Winton Formation west of the Ridge, and from bores in the Wallumbilla Formation (mainly Doncaster Member) east of the Ridge where the Winton Formation is patchy, thin and generally unsaturated.

Remarkable features shown in Figure 5.21 are the local groundwater recharge and discharge zones in the watertable aquifer. Although the watertable is considered to be regional in nature, on the Eulo Ridge it exhibits characteristics of a local groundwater flow system. There are local recharge mounds along the Eulo Ridge and there are two mounds straddling the Paroo River and a small granite intrusive (too small to see in the figure). Bores in these mounds intersect the Doncaster Member and are flowing artesian wells.

A local groundwater discharge zone is indicated by the closed 120 m watertable contour around Lake Wyara. Lake Wyara is an episodically filled salt lake of area 50 km^2 and its mean floor elevation is 119 mASL. 'Wyara' means 'bitter water' in the local Budjari tongue, an acknowledgement of the fact that its waters reach extreme salinities (350 g/L).

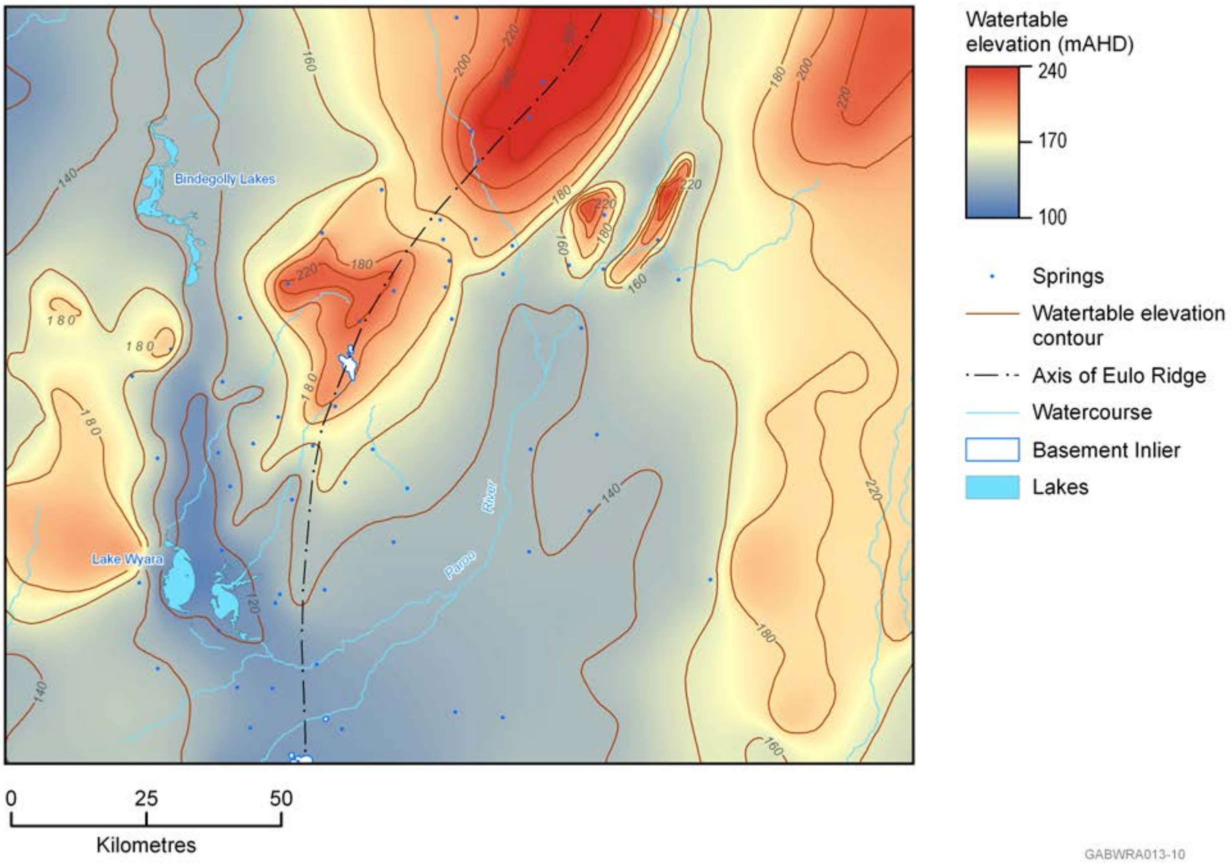


Figure 5.21 Potentiometric surface of groundwater in the uppermost Early Cretaceous partial aquifers and leaky aquitards over the Eulo Ridge sheets

5.5 References

Audibert M (1976) Progress report of the Great Artesian Basin hydrogeological study, 1972–1974. Record 1976/5. Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Boult PJ, Theologou PN and Foden J (1997) Capillary seals within the Eromanga Basin, Australia: implications for exploration and production. In: Surdam RC (ed.) Seals, Traps and the Petroleum System. American Association of Petroleum Geologists, Tulsa, Oklahoma, 143–167.

Day RW, Cranfield LC and Schwarzbock H (1974) Stratigraphy and structural setting of Mesozoic Basins in southeastern Queensland and northeastern New South Wales. In: Denmead AK, Tweedale GW and Wilson AF (eds) The Tasman Geosyncline – A symposium. Geological Society of Australia, Queensland Division, Brisbane, 319–363.

Exon NF (1971) Roma, Queensland. Explanatory notes. 1:250,000 geological series – sheet SG55/12. Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Exon NF (1976) Geology of the Surat Basin in Queensland. Bulletin 166. Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Gallagher K and Lambeck K (1989) Subsidence, sedimentation and sea level changes in the Eromanga Basin, Australia. Basin Research 2(2), 115–131.

GHD (2012) Report for QWC17–10 Stage 2 Surat Cumulative Management Area groundwater model report, May 2012. Queensland Water Commission, Brisbane.

Gray ARG (1975) Bundamba Group – stratigraphic relationships and petroleum prospects. Queensland Government Mining Journal 76, 310–324.

Green PM, Brain TJ, John BH and Almond CS (1989) Subsurface correlation of the Jurassic rocks of the southern Eromanga Basin, Queensland. Queensland Department of Mines, Record, 1989/1 and 2, Brisbane, Queensland.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Habermehl MA and Lau JE (1997) Hydrogeology of the Great Artesian Basin Australia (Map at scale 1:2,500,000). Australian Geological Survey Organisation, Canberra.

Hillier JR (2010) Groundwater connections between the Walloon Coal Measures and the Alluvium of the Condamine River. A Report for the Central Downs Irrigators Limited. Central Downs Irrigators Limited, Pittsworth, Queensland. <http://www.cdil.com.au/documents/JHillierfinaldoc.pdf>.

Macaulay S and Kellett JR (2009) Airborne electromagnetic survey of the Lower Macquarie River Valley, New South Wales - final report. Bureau of Rural Sciences, Canberra.

O'Brien PE, Korsch RJ, Wells AT, Sexton MJ and Wake-Dyster K (1994) Structure and tectonics of the Clarence-Moreton Basin. Bulletin 241. In: Wells AT and O'Brien PE (eds) Geology and petroleum potential of the Clarence-Moreton Basin, New South Wales and Queensland. Australian Geological Survey Organisation, 195–216.

Radke BM, Ferguson J, Cresswell RG, Ransley TR and Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra.

Struckmeyer HIM and Brown PJ (1990) Australian sealevel curves. Part 1, Australian inundation curves. Bureau of Mineral Resources, Australia.

Waschbush P, Korsch RJ and Beaumont C (2009) Geodynamic modelling of aspects of the Bowen, Gunnedah, Surat and Eromanga Basins from the perspective of convergent margin processes. Australian Journal of Earth Sciences 56, 309–334.

6 Hydrodynamics

Authors: Cresswell RG, Smerdon BD, Rousseau-Gueutin P, Simon S, Taylor AR, Davies PJ and Habermehl MA

This chapter describes the flow system dynamics, including collation of groundwater data to develop a historical overview of groundwater levels, analysis of hydrochemical and isotopic data for evaluating flow paths, and interaction of Great Artesian Basin (GAB) aquifers with adjacent aquifers and surface drainage basins.

6.1 Methodology

The assessment of the hydrodynamics of groundwater in the Surat region is based on the reconceptualisation of the hydrogeological framework (Chapter 5) and subsequent mapping of the groundwater flow from recharge through to discharge. The collated groundwater level and hydrochemical data were the basis for the following new maps:

- a pre- or early-development map of groundwater levels (circa 1900, i.e. based on pressure data from the first few years of groundwater exploration and development) to facilitate assessment of hydrochemical and isotopic data trends
- a recent map of groundwater levels (circa 2010, i.e. based on data from the most recently available pressure measurements)
- sufficient additional time intervals to establish the maximum drawdown period and the spatial relationships of groundwater extraction across the region
- a series of maps illustrating spatial trends in hydrochemical and isotopic data.

6.2 Data

6.2.1 Groundwater level

The distribution of groundwater level data is dependent on the distribution of the water bores and the number of water bores measured. Initially, most flowing artesian water bores in the northern Surat Basin in Queensland were located near the margins of the aquifers, where the latter are relatively shallow, as well as on and near the Nebine Ridge and Cunnamulla Shelf and Eulo Ridge. At present, however, most of the remaining flowing artesian bores are restricted to the deeper parts of the Surat Basin. Bores in the centre of the northern Surat Basin in Queensland are relatively evenly distributed and bores measured for pressures reflect that pattern. The flowing artesian water bores in the New South Wales part of the Surat Basin are similarly distributed, with a rather dense concentration on the Cunnamulla Shelf west of the Nebine Ridge and a patchy distribution in the Coonamble Embayment.

Digital records of groundwater monitoring data were obtained from the NSW Office of Water, NSW Department of Mineral Resources (DMR) and Queensland Department of Environment and Resource Management (DERM). Each groundwater database included artesian groundwater pressure and sub-artesian groundwater level measurements from the early 1900s to 2010. The artesian pressure values are dependent on the temperature and salinity of the groundwater. As these properties vary across the GAB, the pressure values must be converted to a common basis – referred to as a correction. From this common basis, maps of groundwater levels can be made across the GAB.

There are multiple steps for the pressure correction. Each groundwater monitoring location was georeferenced to the 1-second digital elevation model and the approximate temperature and salinity were derived from data in Radke et al. (2000). The artesian pressure measurements were converted to an equivalent groundwater level at 25 °C using a temperature and salinity correction (Post et al., 2007) that includes the density estimation algorithm of Batzle and Wang (1992). In addition to the steps required for correction, each state agency databases is unique, having different formats, levels of information and quality control. Moreover, the databases contain information that pre-dates the establishment of these agencies and may be either unreliable or incomplete.

To establish a common database for the Assessment, large text files of the original data were imported into a Microsoft Access database where the data could be sorted, queried and exported into one workable spreadsheet. After an extensive survey and query of both databases it became evident that there were a number of missing fields and sparsely populated fields. For example, information about depths of casing slots and bottom levels of open bores from the ground surface and aquifer association to a particular bore were not always available. The compiled data were then subject to a quality assurance (QA) process to validate different fields of the original data through cross referencing and spatial information tools, for example, high resolution digital elevation models to validate surveyed geographical data.

6.2.2 Groundwater temperature

Temperatures of artesian groundwater have been measured since the early days of development at the surface (ICAW, 1913; 1914; 1922; 1925; 1929) but downhole temperatures and temperatures in the aquifers have only been measured with downhole probes in later years. Continuous downhole temperature readings have been acquired with wire-line tools lowered into the boreholes together with other geophysical equipment since the 1960s. Surveys by the Bureau of Mineral Resources, Geology and Geophysics (BMR), (now Geoscience Australia) acquired geophysical logs from approximately 1250 water bores in Queensland, New South Wales and the Northern Territory parts of the GAB between 1960 and 1975 (Habermehl, 2001b). This includes temperature and differential temperature logs from water bores and these logs provide a record of temperature versus depth and the rate of change versus depth respectively. Groundwater temperature and geothermal gradient maps have been prepared from these data (Habermehl, 2001b).

In addition, temperature data was available from petroleum exploration and production wells and maps have been prepared for south-west Queensland and north-east South Australia (Pitt, 1986). State water and geological authorities applied geophysical logging of water bores to obtain more and better information, especially as part of the GAB Bore Rehabilitation Program (1989 to 1999) and the Great Artesian Basin Sustainability Initiative (GABSI) (1999 to 2014).

Other limited sources of geothermometry information include interpretation of chemistry analyses results (Pirlo, 2004).

6.2.3 Groundwater chemistry

Groundwater samples have been collected from water bores in the GAB since the early years of development and analysed for chemical constituents to determine the suitability of the artesian groundwater for use. State water authorities usually also collected samples during the testing of water bores for regular pressure and flow measurements, which were carried out at different times. As a result, for many bores multiple analyses of samples are available and these have been compared and reported in the interstate conferences on artesian water (ICAW, 1913; 1914; 1922; 1925; 1929). Water samples were also collected during surveys such as the wire-line logging program by BMR from 1960 to 1975 (Habermehl, 2001b) and the hydrogeological surveys by the Geological Survey of Queensland (Muller, 1989; Quarantotto, 1986; 1989) and Geological Survey of New South Wales.

Hydrochemistry and isotope samples have been collected, analysed and interpreted as part of specific hydrochemistry and isotope hydrology studies in recent decades, in particular by BMR/AGSO and the Bureau of Rural Sciences (BRS), with samples collected throughout the GAB between 1974 and 1996 (Habermehl, 2001a; Radke et al., 2000) and between 2002 and 2005 (Habermehl, 2003; 2004; 2005a; 2005b; Mahara et al., 2009).

Hydrochemistry and isotope sampling campaigns and investigations between 1974 and 2005 (Habermehl, 2001a; Habermehl, 2001b; 2004; 2005a; 2005b; Mahara et al., 2009; Radke et al., 2000) were primarily aimed at sampling the Cadna-owie – Hooray Aquifer in the Eromanga, Carpentaria and Surat basins recharge margin in Queensland and Surat Basin in northern New South Wales and in the Coonamble Embayment. Few samples were collected in the central part of the Surat Basin in Queensland except for the samples collected in the recharge areas of the GAB (Habermehl, 2001b; Kellett et al., 2003; Radke et al., 2000). GA collected hydrochemistry (and isotope) samples as part of Carbon Capture and Storage studies in recent years from bores in the eastern and central parts of the Surat Basin. The state water authorities of Queensland collected hydrochemistry samples from aquifers in the Winton Formation and Mackunda Formation in the southern parts of the Surat Basin and Eromanga Basin in Queensland, in addition to the studies by Muller (1989) and Quarantotto (1986; 1989). Sampling of bores in New South Wales for the Exploration 2000 initiative provided isotopic information for the region north of Bourke and recent sampling as part of GA's investigations under their Carbon Capture and Storage Programs, has provided substantial isotopic data for the eastern Surat region. These data are currently being evaluated and interpreted.

Stable and radio-active isotopes in the groundwater have been used to give an understanding of the source and origin of the groundwater and the ages and dynamics of the groundwater (Airey et al., 1983; Airey et al., 1979; Bentley et al., 1986; Bethke et al., 1999; Calf and Habermehl, 1984; Habermehl, 2000; Kellett et al., 2003; Love et al., 2000; Mahara et al., 2009; Torgersen et al., 1991). The results from isotopes allow the calculation of travel times of the artesian groundwater and a comparison with travel times determined from hydrogeological and hydraulic characteristics and the results from numerical groundwater modelling.

6.3 Groundwater level maps

6.3.1 Previous mapping

Audibert (1976) compiled a groundwater level map of the Cadna-owie – Hooray Aquifer in the Eromanga and Surat basins for 1900. This coverage was derived from initial bore data over the period 1880 to 1920, and as such was compiled from much fewer data points than subsequent mapping for 1960 (Welsh, 2000) and 1970 (Audibert, 1976; Habermehl, 1980).

Habermehl (1980) presented a groundwater level map of the same aquifer for 1880, the time when the first boreholes were sunk in the GAB. The Habermehl (1980) coverage was derived inversely by model simulation (GABHYD) and recorded pressure data. The Audibert (1976) map is generally lower (by about 20 m) than the equivalent surface of Habermehl (1980).

Welsh (2000) generated a groundwater level map for the same aquifer for 1960, and the Habermehl (1980) and Welsh (2000) maps are broadly similar.

Brownbill (2000) presented a discontinuous contour coverage of groundwater levels of the Pilliga Sandstone Aquifer (the New South Wales equivalent of the Cadna-owie – Hooray Aquifer) for 1986. The data were not temperature corrected. Groundwater flow directions in the Brownbill (2000) coverage are similar to the Habermehl (1980) and Welsh (2000) coverages, but, in general, the groundwater levels in Brownbill (2000) are lower than either Habermehl (1980) or Welsh (2000), particularly in the Coonamble Embayment. Analysis of groundwater levels to assess the effectiveness of GABSI (Macaulay et al., 2009) revealed a varying but generally increasing response across the region over the period 2000 to 2007. Bores with records from 1980 were assessed and most showed a reversing trend in groundwater level as the bore capping and piping program was carried out.

The Geological Survey of Queensland (GSQ) have also prepared maps of groundwater levels for Surat aquifers within Queensland as part of their assessment for carbon capture and storage (Hodgkinson et al., 2010).

6.3.2 Mapping the evolution of groundwater levels

As part of the Assessment, groundwater level data were collated for an analysis of historical groundwater conditions, grouped into 20-year increments (1900 to 1920, 1920 to 1940, 1940 to 1960, 1960 to 1980, and 1980 to 2000). The 20-year interval allowed a greater number of monitoring data to be used, especially where an individual bore may only be measured very infrequently. The groundwater level data were interpolated considering the presence of major faults (Chapter 5). Where a fault had caused a vertical offset in the Cadna-owie – Hooray Aquifer and equivalent formations, the fault was assumed to act as a barrier to groundwater flow. The resultant maps illustrate the spatial distribution of groundwater levels, from which groundwater flow directions can be inferred, and influence of faults on groundwater levels.

Groundwater levels in the Surat Basin are highest along the northern and eastern margins of the basin, in and near the aquifer exposures in the recharge areas (Figure 6.1). Groundwater levels diminish towards the south in the northern Surat Basin in Queensland and towards the west and north-west in the Surat Basin and Coonamble Embayment in New South Wales.

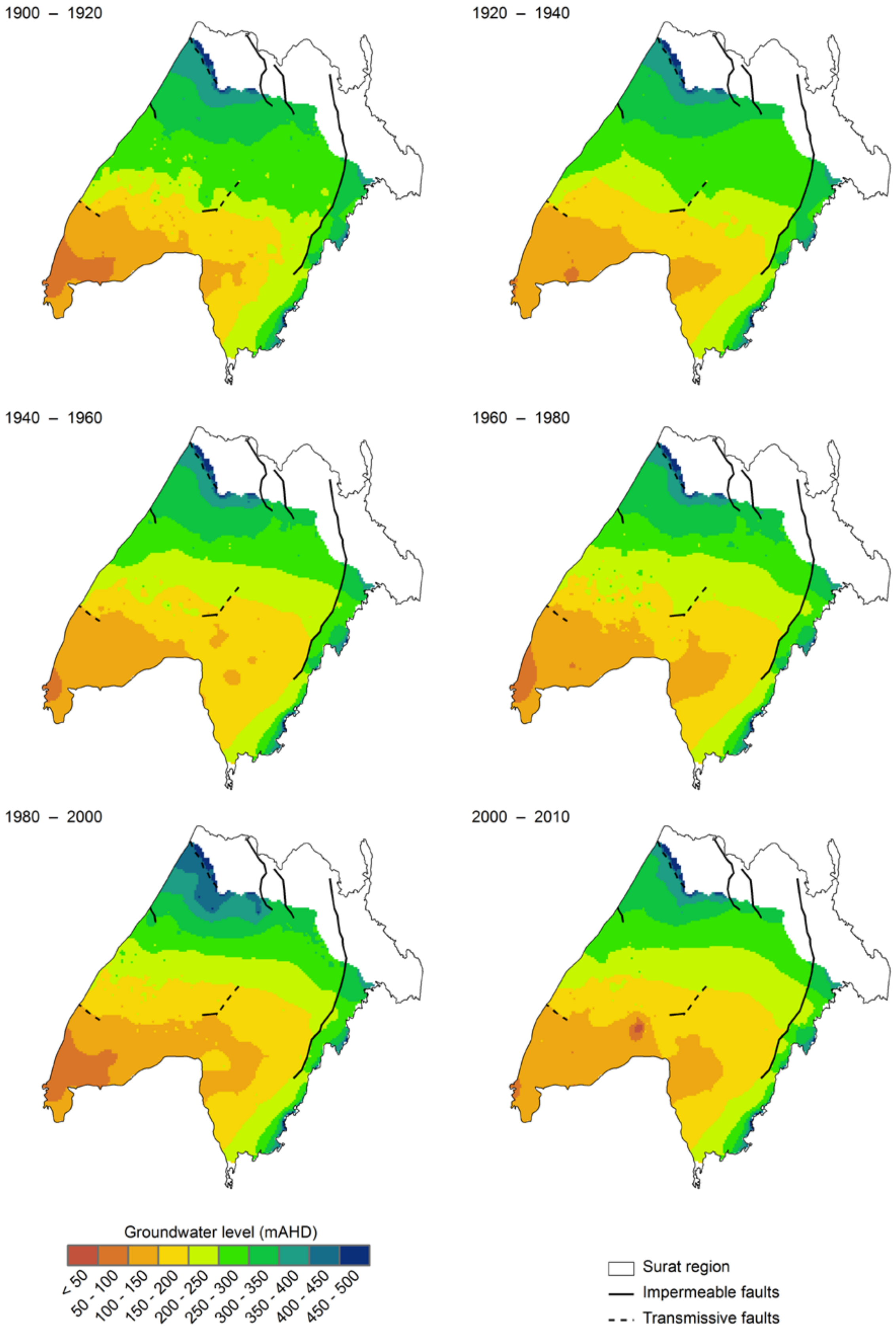


Figure 6.1 Time series of the regional groundwater levels for the Cadna-owie – Hooray Aquifer and equivalents
Note: the elevated groundwater levels in the north part of the region for the 1980 to 2000 increment are a result of additional data in this location that is not available in other time increments

In the Surat region, groundwater flow in the Cadna-owie – Hooray Aquifer is largely south and west from the recharge zones in the east. Flow from the Coonamble Embayment in the south-east is initially to the north, then to the west and south to join flow paths from the north. Within the Assessment, groundwater level mapping was completed for Cadna-owie – Hooray Aquifer and its equivalents, as groundwater data for the lower Jurassic and Triassic aquifers has been insufficient until recently to prepare these maps. Groundwater level mapping for other aquifers, including the Adori Sandstone, parts of the Birkhead Formation, Hutton Sandstone, Precipice Sandstone and Clematis Sandstone and their equivalents in the Surat Basin have recently been prepared by the Queensland Water Commission (QWC) as part of its coal seam gas investigations and GSQ as part of their CCS investigations. The latter indicate that flow in the lower formations, particularly the Hutton aquifer, may be towards the north in the northern part of the Surat Basin

Selected bores across the Surat region are illustrated in Figure 6.2, together with the difference in groundwater level between the first 20-year increment (1900 to 1920) and the most recent increment (2000 to 2010). Areas of large decline, ranging up to several tens of metres, correlate with areas of high bore densities in the western Surat Basin. The drilling of the bores and the subsequent discharge of artesian groundwater caused this decline. This is exacerbated by the accumulation of declining groundwater levels through the interference effects of neighbouring bores. During the early stages of development the large number of free flowing bores discharged large amounts of groundwater. Some of these bores are still present and free flowing today and many others leak from corroded bore casings and headworks (Habermehl, 2009). High initial discharge from individual bores (and from the GAB as a whole) during the early years of exploitation was mainly the result of the release at high pressure of groundwater from elastic storage of the confined aquifers.

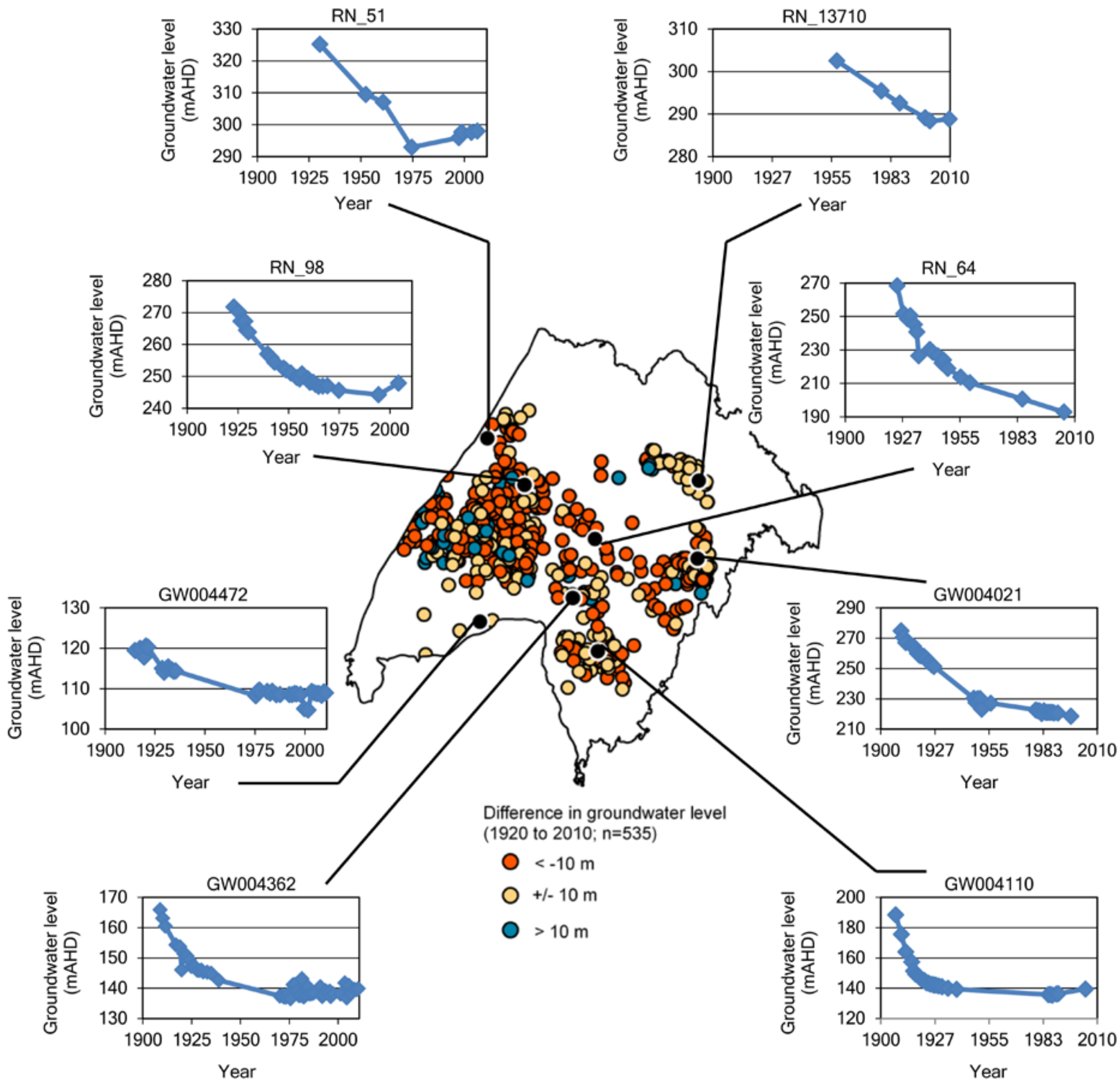


Figure 6.2 Difference in groundwater level between the first 20-year increment (1900 to 1920) and the most recent increment (2000 to 2010) with selected bores to illustrate the change over time

The lowering of the groundwater level of the Cadna-owie – Hooray Aquifer and equivalents caused it to fall below the ground surface in several areas and as a result flows from artesian water bores in those areas ceased or where the potentiometric surface is still above the ground surface, flows diminished. Deeper aquifers in the Surat Basin, that had previously not been heavily developed, have been tapped in recent times as alternatives. Aquifers in the overlying Cretaceous aquifers of the Winton Formation, Mackunda Formation and the Griman Creek Formation did not produce flowing artesian bores, as the groundwater level rises above the aquifer, but has always been below the ground surface and therefore resulted in non-flowing artesian or sub-artesian bores.

6.4 Temperature

The high temperatures of the artesian groundwater in the GAB (Figure 6.3) represents a potential geothermal resource, and some geothermal energy projects have been developed, for example, a geothermal power station at Birdsville (on the boundary between the Central Eromanga and Western Eromanga regions), where the groundwater temperature is 99 C at the ground surface (Habermehl and Pestov, 2002). The high temperatures from flowing artesian water bores require the cooling of the water for use, both for drinking water purposes within towns and homesteads, as well as for pastoral use.

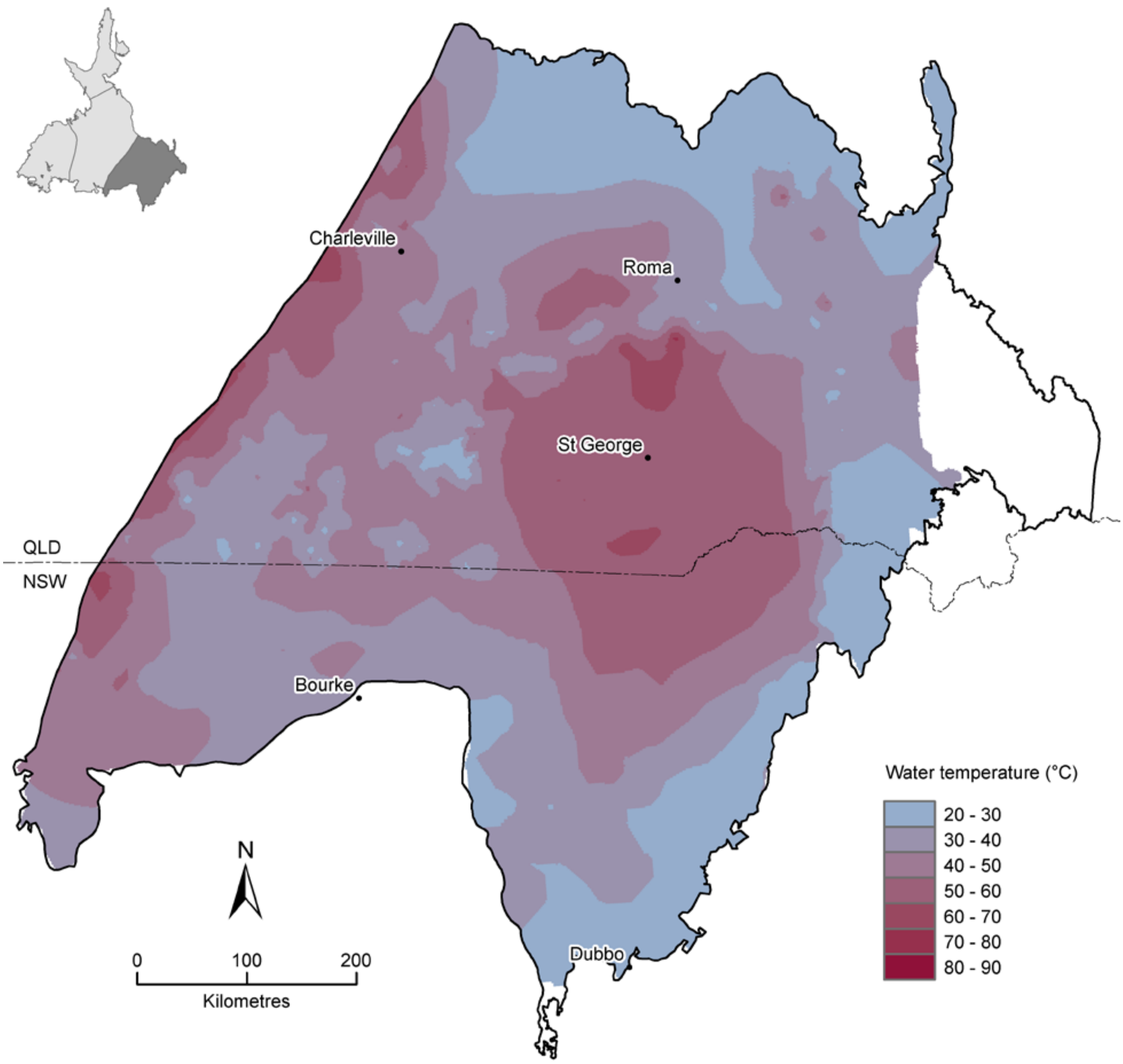


Figure 6.3 Regional groundwater temperature of the Cadna-owie – Hooray Aquifer and equivalents, derived from downhole, bottom of hole and surface (free-flowing) measurements

A correlation exists between the temperature of the groundwater in the aquifers and the depths of the aquifers. Shallow parts of the GAB, where aquifers are relatively close to the ground surface, such as near the recharge areas, contain relatively cool water, with temperatures only up to 40 °C. The regions of intermediate depths have temperatures between 40 and 60 °C and the deeper parts of the GAB show higher temperatures between 60 and 100 °C (Habermehl, 2001a).

The geothermal gradient, derived from the temperature log data from water bores in the region, indicates low geothermal gradients for most parts of the Surat region (Habermehl, 2001b).

6.5 Hydrochemistry

Groundwater chemistry within the recharge zones of aquifer sequences in the Surat Basin (and the GAB as a whole) is largely inhomogeneous. The diversity of geochemical signatures within the recharge zones results from the range of processes contributing to recharge, together with localised evapotranspiration, deposition of marine aerosols via rainfall, leaching of salts during recharge and the numerous water-rock interactions that occur initially as infiltrating water equilibrates with the subsurface materials (Radke et al., 2000).

In the transition to confined aquifer conditions, local homogenisation of the geochemical signature may occur, although regional heterogeneity remains significant throughout the GAB (Radke et al., 2000).

Following the infiltration of rainfall, the evolutionary path of groundwater generally begins through low salinity, slightly acidic groundwater, to Ca-Mg-HCO_3-Cl groundwater and finally to Na-HCO_3-Cl dominant groundwater.

Initially, carbon dioxide (CO_2) (up to three orders of magnitude above atmospheric levels) is acquired by waters near the recharge area, owing to plant respiration and oxidation of organic matter in the soil zone. In turn, silicate (i.e. plagioclase or orthoclase) and carbonate minerals may dissolve, contributing to elevated alkalinity levels and Na, Ca and Mg ion concentrations. As the groundwater progresses basin-wards, cation exchange of the Na present in aquifer materials for Ca and Mg in solution occurs. This may lead to the subsequent conversion of Na-smectite-rich clays to kaolinite-rich clays, releasing Na to solution (Herczeg et al., 1991). A consequence of this is to elevate the sodium levels relative to other cations resulting in waters that are too sodic for irrigation (sodium adsorption ratios (SAR) > 8 (Figure 6.4).

With the removal of Ca (and Mg) from the groundwater by exchange with Na in clay minerals within the aquifer framework, H^+ ions are released, further promoting carbonate dissolution (Radke et al., 2000). As a consequence of these processes the groundwater evolves towards elevated Na and HCO_3 concentrations (Figure 6.4). The geochemical signature may, however, be overprinted to some extent by the diffusion of Cl (and other soluble ions) from overlying or underlying aquitards with marginal marine depositional histories (i.e. Rolling Downs Group, Bungil Formation, Westbourne Formation and Evergreen Formation) (Radke et al., 2000). Leaching of soluble ions from these formations may be responsible for the elevated chloride concentrations in the groundwater geochemistry records and the general increase in salinity along the groundwater flow paths of aquifers in the GAB (Figure 6.5). The increasing salinity trend may also be a consequence of mixing of dilute recharge waters with saline waters present within deeper parts of the GAB and the dissolution or weathering of evaporates, carbonate minerals or incongruent dissolution of feldspars, micas or clay minerals along the flow path (Herczeg et al., 1991).

Groundwater in the most widely exploited confined aquifers in the Lower Cretaceous-Jurassic sedimentary sequence generally contains about 500 to 1500 mg/L total dissolved solids. Artesian groundwater has pH values which are almost always between 7.5 and 8.5.

Observed systematic variations in the salinity levels have been postulated to reflect variations in the rate of recharge and infiltration of recycled salt throughout the late Quaternary Period, with minima and maxima in chloride concentrations representing the last glacial and interglacial period, respectively (Airey et al., 1979). One such anomaly persists across the Eulo and Nebine ridges area and ^{36}Cl data (see below) substantiates the interglacial origins for these pulses (Radke et al., 2000).

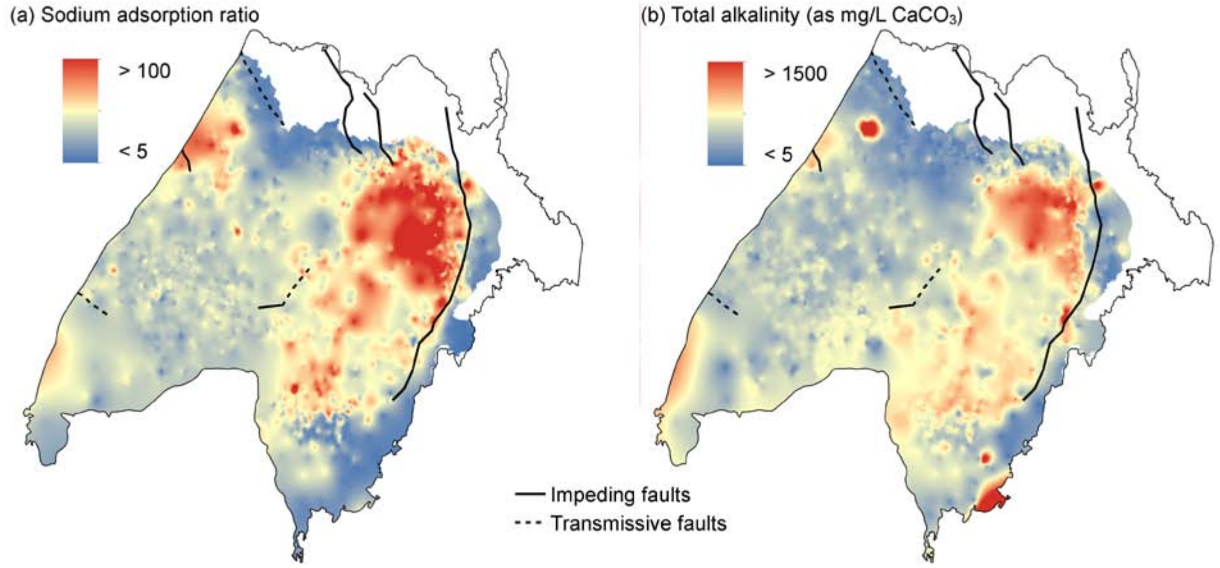


Figure 6.4 Spatial distribution of sodium adsorption ration (SAR) (left) and alkalinity (right) show evolutionary trends from fresher, slightly acidic recharge water along the eastern and north margins to more brackish, sodium-rich, alkali waters towards the discharge zones to the south and west

Salinity in recharge areas is variable, however, and locally high salinity zones occur in the intake beds. This is more prominent in the Upper Cretaceous aquifers where vertical, downwards infiltration is more prevalent and shallow interaction with more saline soils (Figure 6.5).

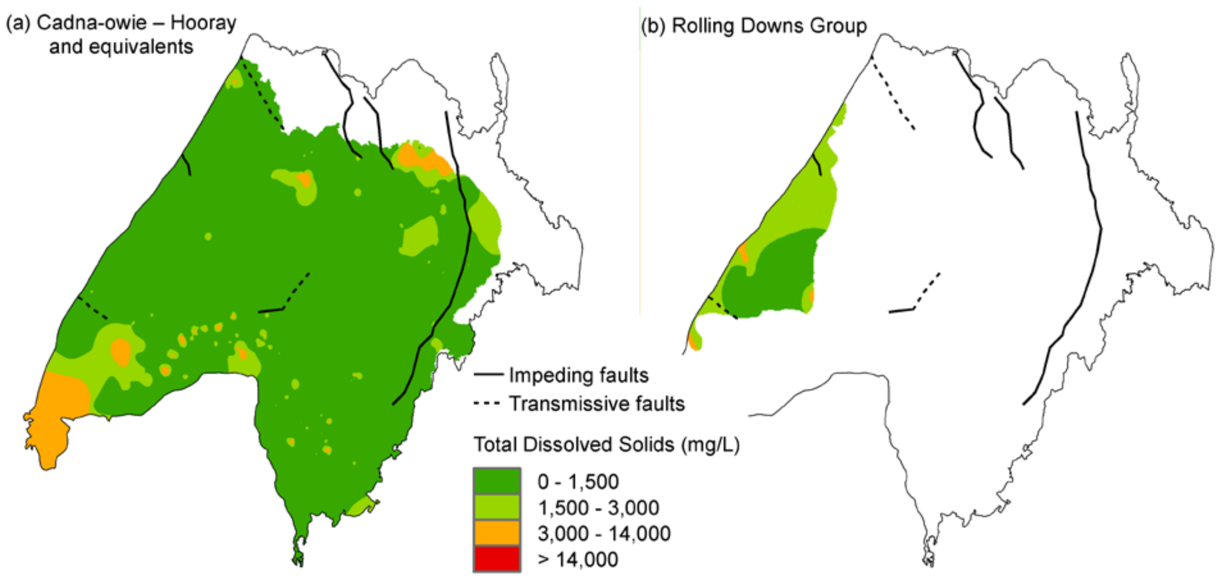


Figure 6.5 Total dissolved salts in the Lower Cretaceous-Jurassic (left) and Cretaceous (right) aquifers and their equivalents

Fluoride values in many parts of the GAB are high, with values up to 10 mg/L and more, which is a problem for domestic and stock water supplies (Figure 6.6). High fluoride concentrations in the artesian groundwater have been attributed to groundwater being in contact with igneous (hydrogeological basement) rocks (Evans, 1996; Habermehl and Lau, 1993; Habermehl et al., 1996). Contact of the artesian groundwater with igneous rocks has also been interpreted to be the reason for the occurrence of surprisingly unradiogenic $^{87}Sr/^{86}Sr$ ratios (Collerson et al., 1988).

Sulphate tends to be high in recharge areas (Figure 6.6), decreasing down flow paths as reactions with aquifer materials precipitates gypsum ($CaSO_4$)as calcium and sodium exchange on constituent clays.

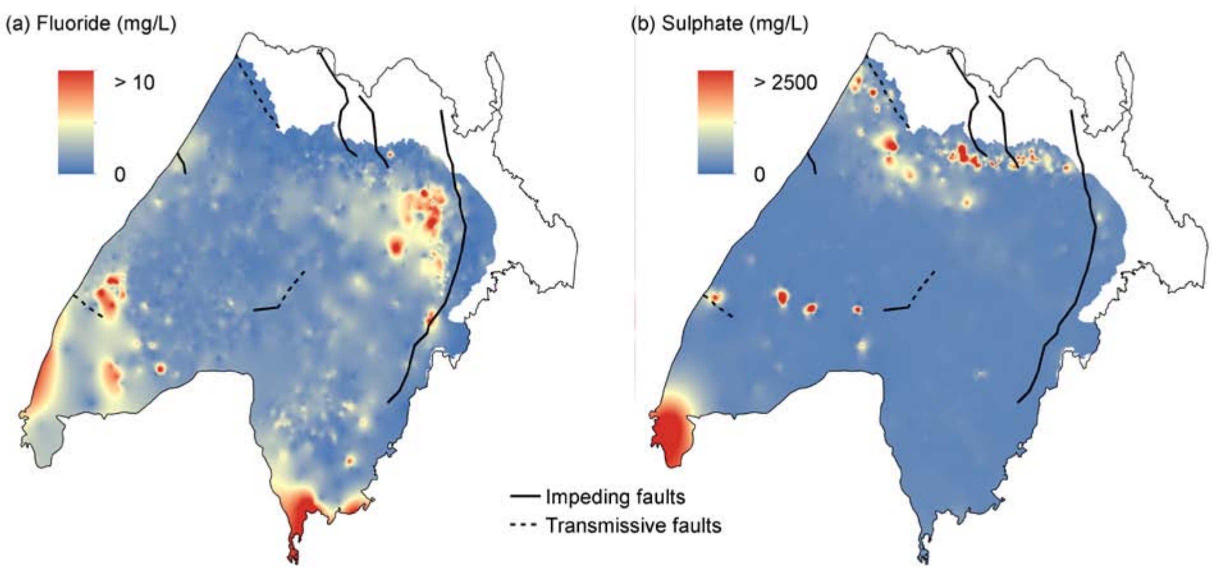


Figure 6.6 Spatial distribution of fluoride (left) and sulphate (right) in the main production (Lower Cretaceous) aquifers of the Surat region

Upper Cretaceous aquifers have higher salinities and chloride values than the Lower Cretaceous-Jurassic aquifers, and the high Na-Cl values of the Na-Cl and Na-Cl-HCO_3 type hydrochemistry of the artesian groundwater in the Cretaceous aquifers probably reflects the poorly-flushing characteristics of these mainly isolated and lenticular shaped aquifers.

The Lower Cretaceous-Jurassic aquifers can be distinguished from the Cretaceous aquifers based on their hydrochemical characteristics, as the former are characterised by Na-HCO_3-Cl type chemistry and the latter by Na-Cl type chemistry. The distinction between individual aquifers in the Lower Cretaceous-Jurassic sequence is less obvious (Muller, 1989; Quarantotto, 1986; 1989). Mixing of groundwater from the latter aquifers occurs where intervening confining beds pinch out and the aquifers are in contact, such as on the Cunnamulla Shelf – Eulo Ridge area. The chemistry of the groundwater in the upper parts of the Cadna-owie – Hooray Aquifers may be influenced by downward diffusion of ions from the marine mudstones of the Rolling Downs Group.

The effects of structural features can be distinguished in the chemical patterns. Notably, the Goondiwindi Fault along the east margin of the Surat region appears to have a control over the movement of groundwaters away from the intake beds, as can be seen in the chemistry plots for the Lower Cretaceous aquifers above. The impact of the fault is not apparent in the overlying Upper Cretaceous ionic distributions (Figure 6.6).

Most artesian groundwater from water bores produce varying amounts of gases. The main gases include N_2, CO_2, Ar and small amounts of H_2 and He. Hydrocarbons may also be produced; mainly CH_4 and lesser amounts of C_2H_6 to C_7H_{16} and liquid hydrocarbon fractions have also been detected (Habermehl, 1986; 1989). Hydrocarbon source and reservoir rocks are abundant in the sedimentary sequence of the region, and commercial and sub-commercial oil and gas discoveries have been made in several Jurassic and Cretaceous sandstones, and also the underlying Permian and Triassic sediments, contradicting earlier beliefs that GAB-wide groundwater flow had flushed hydrocarbons out of the system. Dissolved hydrocarbons in the artesian groundwater are generally dry gases and are useful petroleum exploration indicators.

Water quality improves with depth in the aquifers of the Lower Cretaceous-Jurassic sequence and groundwater from all of the aquifers in the Lower Cretaceous-Jurassic sequence is of good quality and suitable for domestic, town water supply and stock use, though it is generally unsuitable for irrigation because in much of the region it is chemically incompatible with the dominantly montmorillonitic swelling clay soils (due to high sodicity). Groundwater from the upper, Late Cretaceous, Griman Creek Formation in the Surat Basin has a higher salinity, though it is still acceptable for stockwater.

6.6 Isotopes

Studies of stable isotope ratios $\delta^{2}H$ and $\delta^{18}O$ show that a plot of all values from samples throughout the GAB plot parallel to the global meteoric water line (Habermehl, 2001a) or at a slight angle to the global meteoric water line (Mahara et al., 2009). Both sets of samples show isotopic lighter groundwater and these have probably undergone evaporation or other processes. Plots of samples from specific regions, such as the recharge areas, central parts and discharge areas of the GAB provide different patterns, including for their evaporation lines. All $\delta^{2}H$ and $\delta^{18}O$ plots indicate that the artesian groundwater is meteoric in origin (Airey et al., 1979).

The age and residence times of the artesian groundwater and the groundwater movement rates and flow patterns in the region have been investigated both with ^{14}C (useful for waters up to 30,000 years old) and ^{36}Cl (for waters up to 1 Ma) radioisotopes. Chloride has a relatively conservative behaviour in groundwater and has a simpler geochemistry than carbon; hence there are advantages in using ^{36}Cl as a dating tool for the very old groundwater in the GAB.

Groundwater ages from the GAB determined from the ^{14}C and ^{36}Cl results are in general in good agreement with hydraulic ages estimated using Darcy's Law. This suggests that, at the millennia scale, it is feasible that flow conditions have not significantly changed, potentially for the last million years (Bentley et al., 1986; Calf and Habermehl, 1984; Cresswell et al., 1996; Habermehl et al., 1993; Radke et al., 2000; Torgersen et al., 1991).

Dating using these radiogenic isotopes, however, cannot determine short timeframe variability and hence cannot easily distinguish the impacts of recent extractions, nor the changes in recharge induced by climate variability. Recent modelling of analogous basins (Rousseau-Gueutin et al., 2012) , has demonstrated that groundwater basins of similar dimensions to the GAB cannot be operating under equilibrium conditions as they cannot equilibrate within the timeframe of climate variability. The simple assumption that recharge should be matched by discharge, therefore cannot be true.

It should be noted, however, that background levels of the long-lived radio-isotope ^{36}Cl (half-life = 301,000 years) are achieved relatively close to the recharge area of the Surat Basin in New South Wales, with a distinct break in signature over a restricted area coinciding with the Goondiwindi Fault. Upstream of the fault a ^{36}Cl /Cl ratio of 163 x 10^{-15} is indicative of recharge waters in this region. Thirty kilometres down gradient, groundwaters have a ratio of 127 x 10^{-15}. This equates to groundwaters taking 110,000 years to flow 30 km, giving a flow-rate of 0.3 m/a.

6.7 Cross-formational flow

Cross-formational flow occurs where a vertical pressure gradient exists between two formations and there is sufficient permeability to permit flow between them. The rate of transfer between units is therefore a function of the connectivity in terms of permeability between the two units and the magnitude of the pressure gradient between them. Where aquitards form good seals, this means that the rate of transfer is extremely slow even if the pressure gradient is strong. Conversely, even where two permeable units are adjoining, there may be little cross-formational flow if the vertical gradient is small relative to the lateral gradient.

Assessment of cross-formational flow can be through theoretical estimation of the potential and through measurement of physical exchange.

Vertical leakage or cross-formational flow is generally thought to take place in the GAB from the lower, higher pressure aquifers in the Jurassic sedimentary sequence through the overlying aquitards and aquifers of the Injune Creek Group and subsequent overlying aquifers in the Cadna-owie Formation and Hooray Sandstone and their equivalents, through the aquitards of the Rolling Downs Group and into the Cretaceous aquifers of the Mackunda Formation and Winton Formation, and/or the regional watertable. This vertical cross-formational flow or vertical leakage is a natural phenomenon, in contrast to the induced vertical leakage flow within or outside poorly-constructed or corroding bore casing within drill-holes where flow from a higher pressure lower aquifer into a lower pressure higher aquifer might take place. Measured pressure differences between aquifers are an indication of the vertical leakage or flow, and hydrochemistry and isotope hydrology provide evidence for the phenomenon and estimate leakage rates. Airborne geophysics and remote sensing applications supply information about subsurface and surface expressions of vertical leakage or shallow watertables.

6.7.1 Pressure-elevation profiles

Pressure-elevation profiles are used to characterise the potential for vertical flux. Pressure-elevation profiles are plots of the pore pressure as a function of the screen elevation. Pressure-elevation profiles can only be plotted for areas of similar topography where the water pressure surface does not show significant variations. In a purely hydrostatic environment, groundwater flow is essentially horizontal, following the path of least resistance through an aquifer. However, if vertical pore pressure gradients are higher or lower than the vertical hydrostatic pressure gradient groundwater flow may be upward or downward respectively (Tóth, 2009). Connectivity between adjacent beds and the characteristics of the intervening beds becomes critical in determining whether there is actual flow between formations.

Pressure-elevation profiles have been compiled in areas with sufficient data and where topographic variations were minimal (Figure 6.7). Five profiles have been analysed (Figure 6.8).

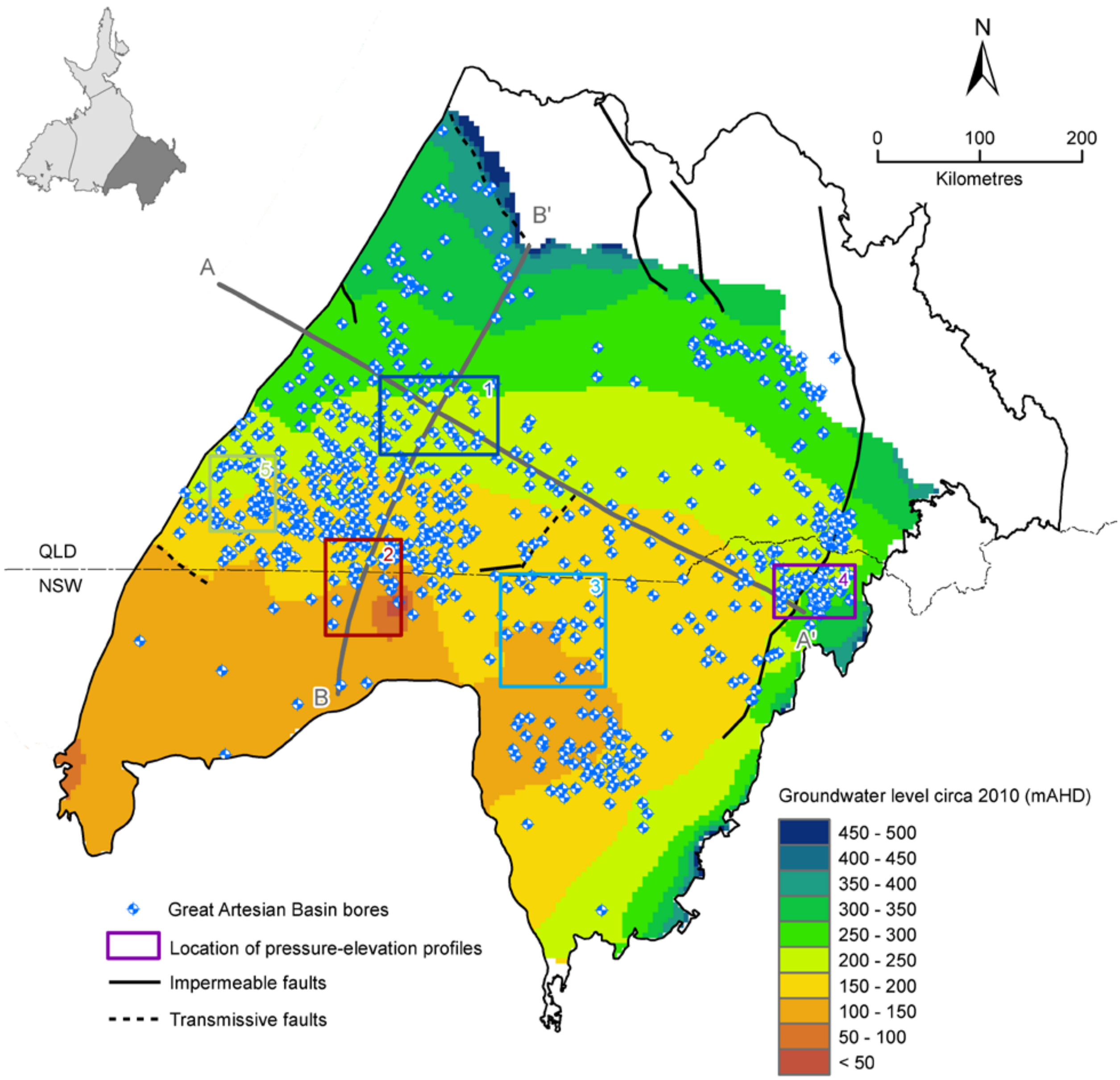


Figure 6.7 Map of groundwater level with cross-sections and pressure-elevation plot locations

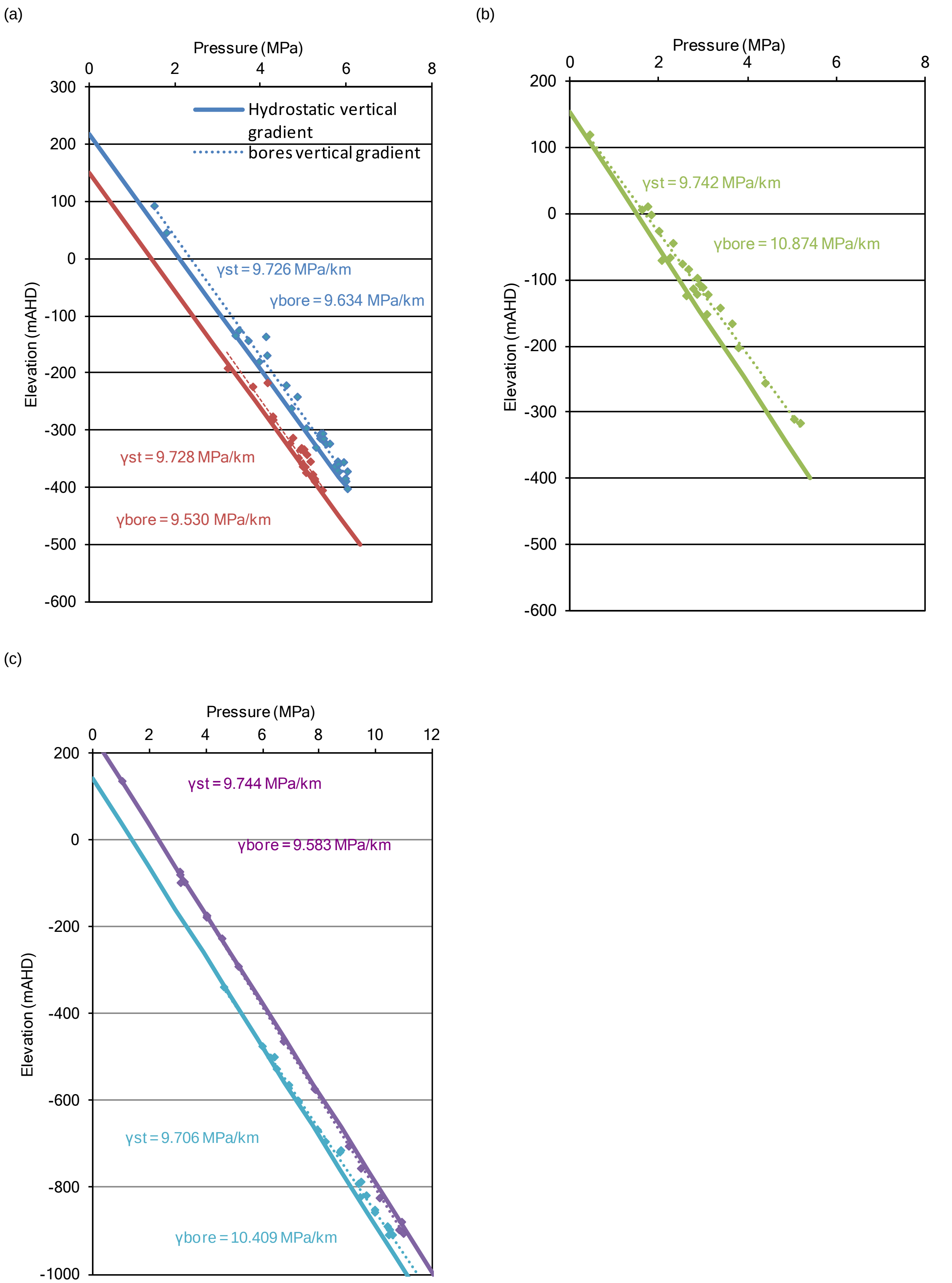


Figure 6.8 Trend in vertical flow compared with hydrostatic profile

Note: data is colour-coded to correspond to the located boxes in Figure 6.7. Left: bore areas 1, 2 and 4; right: bore areas 3 and 5, solid lines are the hydrostatic gradients

Profiles for areas 1, 2 and 4 indicate vertical gradients that are slightly lower than the local vertical hydrostatic gradient. This represents a small potential downward flow within a mainly through-flow condition. Profiles for areas 3 and 5 indicate potential upward flow conditions (pressure gradient higher than the hydrostatic pressure gradient) with potential for fluxes from depths ranging from 100 to 1000 m in the area of peak artesian pressures in the region, within the Cunnamulla Shelf.

Cross-formational flows may also be evaluated using transects of bores that sample different formations. Bores are rarely lined up on a straight transect, however, so bore information is generally projected from bores off the line to the line of the hydrogeological cross-section. Care must be taken with this approach as the hydrogeology can vary significantly even a short distance from the transect line. In order to minimise this concern, bores within a maximum of 10 km have been used to compile the hydrogeological cross-section.

Two cross-sections (Figure 6.9) can be compiled for the Surat region. Cross-section 1 runs from the east-south-east recharge area towards the west-north-west to the Eulo ridge area. Groundwater flow directions are directed towards the depocentre from the east-south-east recharge area as well as along the Eulo and Nebine ridges area. Cross-section 2 runs from the North-north-east recharge area to the south-south-west discharge area and represents a regional groundwater flow in that direction. Unfortunately, for both cross-sections, data are mainly from the Hooray and equivalent aquifers, making it difficult to state the true flux potential. Pressure in the Lower Cretaceous aquifers, however, appear to be slightly higher than surrounding formations, suggesting that the overlying Rolling Downs Group provides an effective seal and the Hooray equivalents in the Surat region are hydraulically separated from overlying and underlying formations.

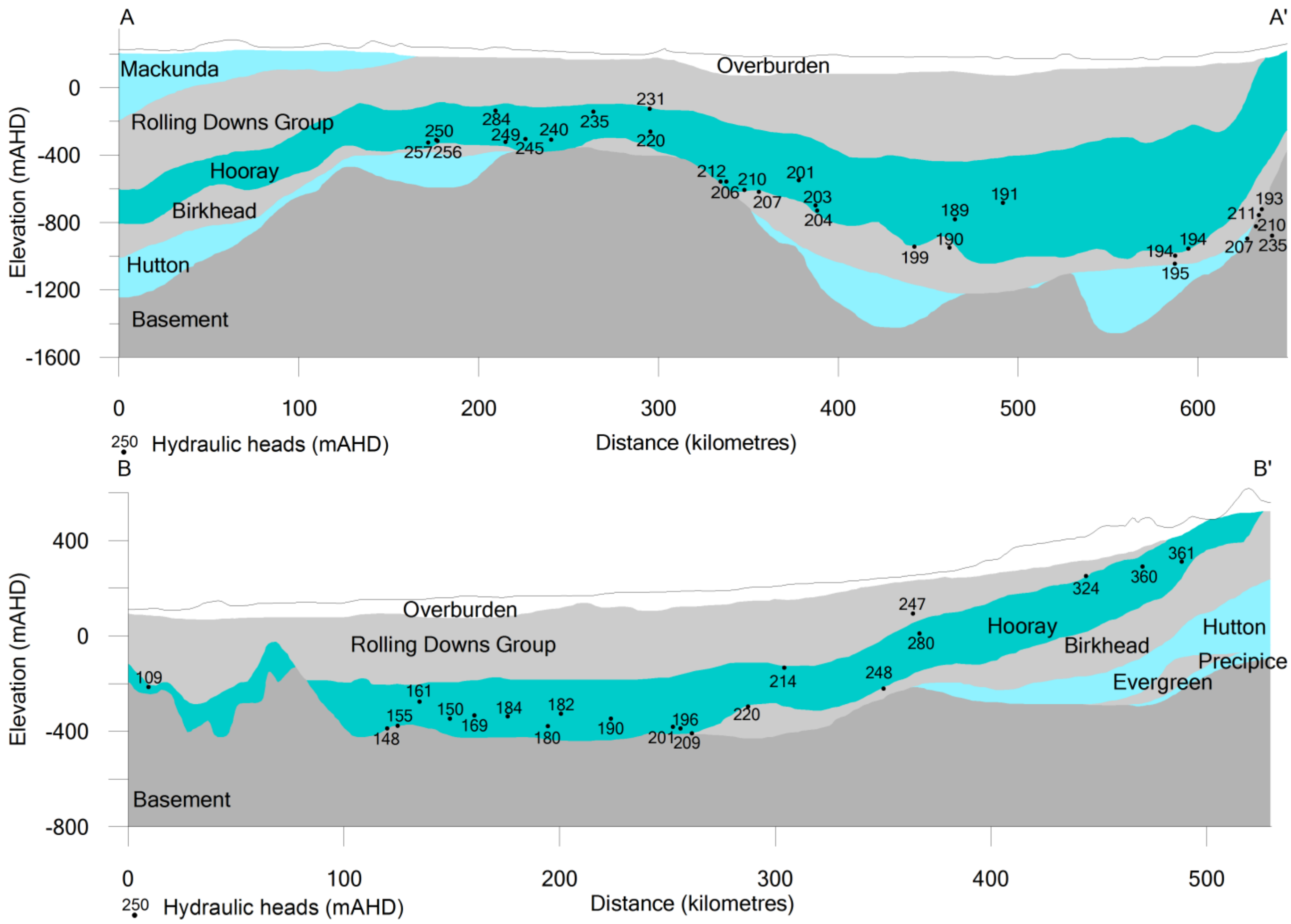


Figure 6.9 Groundwater levels on key cross-sections (cross sections 1 and 2: top to bottom)

6.7.2 Induced leakage

Induced leakage can result from drawdown due to extraction. These effects can reverse the direction of natural vertical leakage, whereby the reduced pressure of the drawdown cone causes artesian groundwater from overlying aquitards to leak downwards into the underlying, developed aquifer from which groundwater is extracted. In most cases this would be leakage from the aquitards of the Upper Cretaceous downwards into the underlying aquifers in the Lower Cretaceous, or into deeper aquifers in the Jurassic sequence. Similarly, downward leakage from overlying aquifers to underlying aquitards is also possible if extraction from the aquitards is enough to generate a sufficiently deep drawdown cone. This situation has the potential to occur in the vicinity of coal seam gas (CSG) extraction as the CSG industry ramps up production over the next five years. Modelling is currently being carried out by the QWC to assess this phenomenon which will not be observed for several years.

Another form of induced leakage is the vertical leakage flow of groundwater within or outside a poorly constructed, or corroding, bore casing. Interpretation of geophysical logs obtained specifically for these studies from a number of bores in Queensland and New South Wales showed the extent of this problem (Habermehl, 2009). Geophysical logs were acquired from 68 bores in Queensland and from 31 bores in New South Wales. In New South Wales 12 bores out of the 31 bores investigated show inter-aquifer leakage, 6 bores show possible inter-aquifer leakage and 13 bores do not leak. In Queensland 10 bores out of the 68 bores investigated show inter-aquifer leakage, 35 bores show possible inter-aquifer leakage and 23 bores do not leak.

6.7.3 Downward leakage

Surat-Bowen

As reported in the hydrogeological framework chapter, hydraulic connection is expected between the basal aquifers of the Surat Basin and the underlying formations of the Bowen Basin. The clay-rich Evergreen Formation immediately overlying the basal sandstones, however, is likely to act as a seal between the lowest (Precipice) formation and the overlying aquifers across most of the region (Hodgkinson et al., 2010).

Surat-Clarence Moreton

Hodgkinson et al. (2010) have re-analysed petroleum pressure test data in the Surat Basin in search of deep carbon storage aquifers. Resulting flow nets suggest substantial transfer of groundwater from the Surat Basin into the Clarence-Moreton Basin across the Kumbarilla Ridge in the lower aquifer units (Precipice and Evergreen Formations). For higher aquifers (e.g. Hutton Sandstone) the Surat Basin receives groundwater from the Clarence-Moreton as was suggested earlier by Habermehl (1980). Sub-surface, groundwater divides in this region are not coincident and result in a complex pattern of flow within largely isolated aquifer units.

6.8 Gaps and uncertainty

6.8.1 Knowledge gaps

The following knowledge gaps have been identified:

- vertical leakage and cross-formational leakage from Hooray Sandstone Aquifer up to Winton-Mackunda Formation Aquifer and equivalents
- effect of significant drawdown in southern Queensland and northern New South Wales on groundwater movement patterns
- effects of significant drawdown by CSG development in Surat Basin area on groundwater movement patterns
- better definition of regional groundwater flow lines and patterns using groundwater level maps, hydrochemistry and isotopes
- lateral and vertical differentiation of hydrochemistry and isotopes within aquifers, in particular Hooray Sandstone and the influence of the hydrochemistry of the groundwater in the Rolling Downs aquitards
- modelling of the detailed hydraulics and hydrochemistry of artesian groundwater discharge from water bores and study the interface of the Cadna-owie – Hooray Aquifer and overlying aquitards and their groundwater quality throughout the development of the Hooray Sandstone aquifer.

6.8.2 Data gaps

The following data gaps were identified:

- long-term pressure measurements at regular intervals of selected water bores, forming a representative measurement network across the whole of the GAB
- additional recharge and discharge studies
- additional hydrochemistry and isotope studies
- detailed studies in selected recharge and discharge areas, paleorecharge
- additional studies on spring deposits, their formation and ages
- vertical leakage/cross-formational flow characteristics
- hydraulic characteristics of Rolling Downs aquitards.

6.8.3 Uncertainty and error analysis

This report and earlier studies and publications reduce the uncertainty in the interpretation of the GAB hydrogeology and hydrodynamics, as well as hydrochemistry and isotope hydrology, but provide clear evidence of significant data gaps. It delivers a platform for designing a new program of data collection, analysis and interpretation to acquire an enhanced understanding of Australia's most important groundwater resource.

Significant limitations in the available data, associated with poor spatial and time coverage, variable data quality and a lack of detailed hydrogeological studies restrict the reliability of many interpretation results. A new program of data collection, analysis and interpretation designed to target basin-wide and detailed studies of past, present and future groundwater developments in the GAB will provide the understanding required for basin-wide strategic management.

6.9 References

Airey PL, Bentley H, Calf GE, Davis SN, Elmore D, Gove H, Habermehl MA, Phllips F, Smith J and Torgersen T (1983) Isotope hydrology of the Great Artesian Basin, Australia. Papers of the International Conference on Groundwater and Man, Sydney, 5-9 December 1983. Australian Water Resources Council Conference Series. Australian Government Publishing Service, Canberra, 1–11.

Airey PL, Calf GE, Campbell BL, Habermehl MA, Hartley PE and Roman D (1979) Aspects of the isotope hydrology of the Great Artesian Basin, Australia. International Symposium on Isotope Hydrology – International Atomic Energy Agency and United Nations Educational, Scientific and Cultural Organisation. International Atomic Energy Agency, Vienna, 205–219.

Audibert M (1976) Progress report of the Great Artesian Basin hydrogeological study, 1972–1974. Record 1976/5. Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Batzle M and Wang Z (1992) Seismic properties of pore fluids. Geophysics 57, 1396–1408.

Bentley HW, Phillips FM, Davis SN, Habermehl MA, Airey PL, Calf GE, Elmore D, Gove HE and Torgersen T (1986) Chlorine 36 dating of very old groundwater. The Great Artesian Basin, Australia. Water Resources Research 22(13), 1991–2001.

Bethke CM, Xiang Z and Torgersen T (1999) Groundwater flow and the ^{4}He distribution in the Great Artesian Basin of Australia. Journal of Geophysical Research 104(B6), 12,999–913,011.

Brownbill R (2000) New South Wales Great Artesian Basin status report – November 2000. NSW Department of Land and Water Conservation.

Calf GE and Habermehl MA (1984) Isotope hydrology and hydrochemistry of the Great Artesian Basin, Australia. Proceedings of the international symposium on isotope hydrology in water resources development,12-16 September 1983. International Atomic Energy Agency, and United Nations Educational, Scientific and Cultural Organisation, Vienna, Austria, 397–413.

Collerson KD, Ullman WJ and Torgersen T (1988) Ground waters with unradiogenic ^{87}Sr/^{86}Sr ratios in the Great Artesian Basin, Australia. Geology 16(1), 59–63.

Cresswell RG, Fifield LK, Keywood MD, Habermehl MA, Kellett JR, Jacobson G and Wischusen J (1996) Theory, rainfall and recharge: a Chlorine-36 story. American Geophysical Union, 1996 Western Pacific Geophysics Meeting, Brisbane, 23–27 July 1996. EOS Transactions, Supplement, American Geophysical Union, W44.

Evans PA (1996) Fluoride anomalies in aquifers of the Queensland section of the Great Artesian Basin and their significance. Mesozoic Geolgoy of the Eastern Australia Plate Conference. Geological Society Australia, Abstracts, Brisbane, 173–178.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Habermehl MA (1986) Regional groundwater movement, hydrochemistry and hydrocarbon migration in the Eromanga Basin. In: Gravestock DI, Moore PS and Pitt GM (eds) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. Geological Society of Australia Special Publication No. 12, 359–376.

Habermehl MA (1989) Groundwater movement, hydrochemistry and the potential migration of hydrocarbons in a part of the Eromanga Basin in South Australia. The Cooper and Eromanga basins Conference. The Petroleum Exploration Society of Australia, The Society of Petroleum Engineers and The Australian Society of Exploration Geophysicists, Adelaide.

Habermehl MA (2000) Main lithostratigraphic and hydrogeological units in the Great Artesian Basin. Hydrogeochemical baseline mapping of Great Artesian Basin groundwater. In: Radke BM, Ferguson J, Creswell RG, Ransley TR and Habermehl MA (eds) Hydrochemistry and implied hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra, 193–198.

Habermehl MA (2001a) Hydrogeology and environmental geology of the Great Artesian Basin, Australia (Chapter 11). In: Gostin VA (ed.) Gondwana to greenhouse – Australian environmental geoscience. Geological Society of Australia. Special Publication 21, Sydney, 127–143, 344–346.

Habermehl MA (2001b) Wire-line logged waterbores in the Great Artesian Basin, Australia – digital data of logs and waterbore data acquired by AGSO. Bureau of Rural Sciences, Canberra. <http://adl.brs.gov.au/brsShop/data/wire_lineloggedwaterbores_updated_2001.pdf>.

Habermehl MA (2003) Project – Verification of groundwater dating methods in the Great Artesian Basin, Australia. BRS – CRIEPI fieldwork 2002. Report on the field measurements and laboratory analyses results. Bureau of Rural Sciences – Water Sciences Program for Central Research Institute of Electric Power Industry, Japan. Bureau of Rural Sciences, Canberra.

Habermehl MA (2004) Project – Verification of groundwater dating methods in the Great Artesian Basin, Australia. BRS – CRIEPI fieldwork 2003. Report on the field measurements and laboratory analyses results. Bureau of Rural

Sciences - Integrated Water Sciences Program for Central Research Institute of Electric Power Industry, Japan. Bureau of Rural Sciences, Canberra.

Habermehl MA (2005a) Project – Verification of groundwater dating methods in the Great Artesian Basin, Australia. CRIEPI – BRS Mundowdna-1, fully cored drillhole near Marree SA, 2005. Well completion report by Bureau of Rural Sciences – Integrated Water Sciences Program for Central Research Institute of Electric Power Industry, Japan. Bureau of Rural Sciences, Canberra.

Habermehl MA (2005b) Project – Verification of groundwater dating methods in the Great Artesian Basin, Australia. CRIEPI – BRS Rolling Downs-1, fully cored drillhole near Richmond, Queensland 2004–2005. Well completion report by Bureau of Rural Sciences – Integrated Water Sciences Program for Central Research Institute of Electric Power Industry, Japan. Bureau of Rural Sciences, Canberra.

Habermehl MA (2009) Inter-aquifer leakage in the Queensland and New South Wales parts of the Great Artesian Basin. Final report for the Australian Government Department of Environment and Water Resources, Heritage and Arts. Bureau of Rural Sciences, Canberra.

Habermehl MA, Allan GL, Fifield LK and Davie RF (1993) Cl-36/Cl ratios in the Great Artesian Basin, Australia. In: 6th International Conference on Accelerator Mass Spectrometry, Abstract Volume. Canberra – Sydney, 64.

Habermehl MA and Lau JE (1993) Fluoride in groundwater of Cape York Peninsula. Aquifers at risk: towards a national groundwater quality perspective conference. Australian Geological Survey Organisation, Canberra, 316–317.

Habermehl MA, Lau JE, Mackenzie DE and Wellman P (1996) Sources of fluoride in groundwater in North Queensland, Australia. In: 13th Australian Geological Convention. Geological Society of Australia Abstracts No. 41, Canberra.

Habermehl MA and Pestov I (2002) Geothermal resources of the Great Artesian Basin, Australia. Geo-Heat Center Quarterly Bulletin 23(2), 20–26.

Herczeg AL, Torgersen T, Chivas AR and Habermehl MA (1991) Geochemistry of ground waters from the Great Artesian Basin, Australia. Journal of Hydrology 126(3–4), 225–245.

Hodgkinson J, Hortle A and McKillop M (2010) The application of hydrodynamic analysis of regional aquifers for carbon geostorage: preliminary results for the Surat Basin, Queensland. APPEA Journal 2010 50th Anniversary Issue, 445–462.

ICAW (1913) Report on the interstate conference on artesian water, Sydney, 1912. Interstate Conference on Artesian Water, Government Printer, Sydney.

ICAW (1914) Report on the second interstate conference on artesian water, Brisbane, 1914. Interstate Conference on Artesian Water, Government Printer, Brisbane.

ICAW (1922) Report on the third interstate conference on artesian water, Adelaide, 1921. Interstate Conference on Artesian Water, Government Printer, Adelaide.

ICAW (1925) Report on the fourth interstate conference on artesian water, Perth, 1924. Interstate Conference on Artesian Water, Government Printer, Sydney.

ICAW (1929) Report on the fifth interstate conference on artesian water, Sydney, 1928. Interstate Conference on Artesian Water, Government Printer, Sydney.

Kellett JR, Ransley TR, Coram J, Jaycock J, Barclay DF, McMahon GA, Foster LM and Hillier JR (2003) Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland. Final Report for the NHT Project #982713 Sustainable Groundwater Use in the GAB Intake Beds, Queensland. BRS, Natural Resources and Mines, Queensland Government, Brisbane, Queensland.

Love AJ, Herczeg AL, Sampson L, Cresswell RG and Fifield LK (2000) Sources of chloride and implications for ^{36}Cl dating of old groundwater, southwestern Great Artesian Basin, Australia. Water Resources Research 36(6), 1561–1574.

Macaulay S, Carey H and Habermehl MA (2009) Artesian pressure trends within the Great Artesian Basin. Selection of monitoring bores across the Great Artesian Basin to analyse and review the Great Artesian Basin Sustainability Initiative (GABSI) program for the Australian Government Department of Environment, Heritage and Water Resources. Bureau of Rural Sciences, Canberra.

Mahara Y, Habermehl MA, Hasegawa T, Nakata K, Ransley TR, Hatano T, Mizuochi Y, Kobayashi H, Ninomiya A, Senior BR, Yasuda H and Ohta T (2009) Groundwater dating by estimation of groundwater flow velocity and dissolved ^{4}He accumulation rate calibrated by ^{36}Cl in the Great Artesian Basin, Australia. Earth and Planetary Science Letters 287, 43–56.

Muller PJ (1989) Aspects of the hydrogeology of the southern Eromanga Basin, Queensland. In: O'Neill BJ (ed.) The Cooper and Eromanga Basins, Australia. Proceedings of the Cooper and Eromanga Basins Conference of Petroleum Exploration Society of Australia. Society of Petroleum Engineers, Australian Society of Exploration Geophysicists (SA Branches), 493–505.

Pirlo MC (2004) Hydrogeochemistry and geothermometry of thermal groundwaters form the Birdsville Track Ridge, Great Artesian Basin, South Australia. Geothermics 33, 743–774.

Pitt GM (1986) Geothermal gradients in the Eromanga-Cooper Basin region. In: Gravestock DI, Moore PS and Pitt GM (eds) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. Geological Society of Australia, Special Publication 12, 262–283.

Post V, Kooi H and Simmons C (2007) Using Hydraulic Head Measurements in Variable-Density Ground Water Flow Analyses. Ground Water 45(6), 664–671.

Quarantotto P (1986) Hydrogeology of the southeastern Eromanga Basin, Queensland. Record 1986/38. Geological Survey of Queensland, Brisbane.

Quarantotto P (1989) Hydrogeology of the Surat Basin, Queensland. Record 1989/26. Geological Survey of Queensland, Brisbane.

Radke BM, Ferguson J, Cresswell RG, Ransley TR and Habermehl MA (2000) Hydrochemistry and implied hydrodynamics of the Cadna-owie – Hooray Aquifer, Great Artesian Basin, Australia. Bureau of Rural Sciences, Canberra.

Rousseau-Gueutin P, Simon S, Love AJ, Post V, Doublet C, Simmons C, Wohling D and Fulton S (2012) Chapter 5: Groundwater flow and hydrodynamics. In: Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P and De Ritter S (eds) Allocating water and maintaining springs in the Great Artesian Basin, Volume II: Groundwater recharge, hydrodynamics and hydrochemistry of the western Great Artesian Basin. National Water Commission, Canberra.

Torgersen T, Habermehl MA, Phillips FM, Elmore D, Kubik P, Jones BG, Hemmick T and Gove HE (1991) Chlorine-36 dating of very old groundwater 3. Further studies in the Great Artesian Basin, Australia. Water Resources Research 27(12), 3201–3213.

Tóth J (2009) Gravitational systems of groundwater flow: theory, evolution, utilization. Cambridge University Press, New York.

Welsh WD (2000) GABFLOW: A steady state groundwater flow model of the Great Artesian Basin. Bureau of Rural Sciences, Canberra.

7 Regional water budget

Authors: Smerdon BD and Davies PJ

A regional groundwater budget provides an estimate of the total amount of groundwater inflow and outflow. For the Great Artesian Basin (GAB), inflow occurs as a combination of widespread diffuse recharge and direct (or localised) recharge, and outflows occur through springs, by diffuse discharge, and through water bores. For a complex groundwater system – such as the GAB – there could be several different components for inflow and outflow. There is a degree of uncertainty about each component of the water budget. This can lead to a range of values – that have either been determined from a single method (having a range of uncertainty) or from using the findings from different studies.

This chapter provides a summary of the region's water budget components and a brief comparison of some water components with previous estimates and groundwater modelling. A regional groundwater budget is often determined from the results of a groundwater model. However, considering that the primary aim of the Assessment is to update the conceptualisation of the GAB, the groundwater budget is estimated from the latest groundwater information (Chapters 5 and 6) rather than the existing groundwater model (Chapter 3). This groundwater information (e.g. groundwater chemistry, calculations by Darcy's Law) is independent of any groundwater model. The intention of this water budget is to provide an indication of the net inflow and outflow for the region.

The individual components of the water budget presented in this chapter are representative of the Cadna-owie – Hooray Aquifer and equivalents under present day conditions. Additional components, such as groundwater interaction with underlying basins (Chapter 5), are unknown and have not been considered.

7.1 Recharge

7.1.1 Recharge mechanisms

Recharge mechanisms in the Surat region are a combination of widespread diffuse recharge and direct (or localised) recharge. Recharge is thought to occur from direct infiltration to the soil into the outcropping regions of the Cadna-owie – Hooray Aquifer and equivalents, downward hydraulic movement through aquifers above the aquifer where the hydraulic conditions permit, direct recharge through ephemeral creeks and rivers, and recharge on mountain block alluvial fan systems, particularly within the Coonamble Embayment. The Coonamble Embayment is thought to be an isolated part of the GAB, with discharge and recharge occurring within the embayment and little if any connection to the remainder of the GAB outside of New South Wales. There have been widely disparate estimates of the water balance of the Pilliga Sandstone aquifer system, with estimates of recharge ranging over nearly two orders of magnitude (Habermehl et al., 2009; Wolfgang, 2000).

Unconsolidated Cainozoic alluvial aquifers generally allow leakage of water from the alluvial sediments into the underlying sandstone aquifers of the GAB, though the areal extent of alluvial sediments is limited to specific areas. Localised recharge takes place from rivers, creeks and alluvial groundwater systems overlying the intake beds. Localised recharge is relatively fast and effective as water infiltrates the underlying aquifers depending on the depth and configuration of the regional watertable and the hydraulic characteristics of the material overlying the aquifers. Prominent areas for localised recharge zones include stretches of the Macintyre, Gwydir, Namoi, Castlereagh, Macquarie and Bogan rivers where they cross the exposed Pilliga Sandstone aquifers.

7.1.2 Assessment method

The chloride-mass-balance method (CMB) was used to estimate recharge across the intake beds. The main advantage of using CMB is that recharge can be estimated over larger spatial scales. For this reason, it is the most widely used method for estimating recharge in Australia. The CMB method provides a smoothing effect that dampens the annual variations in rainfall and chloride and removes the sampling bias in mixed geological materials (i.e. heterogeneous deposits). At the spatial scale of the Assessment, the CMB method estimates total recharge for the area of the intake beds, which includes widespread diffuse recharge and direct (or localised) recharge.

The premise behind the CMB method is that, in low- to moderate-salinity environments the dissolved chloride ion is conservative (i.e. does not take part in any geochemical reactions). By comparing chloride concentrations in rainfall to those measured in groundwater, the recharge rate can be estimated. In the Assessment, chloride concentrations in rainfall were obtained from a recently constructed map of chloride deposition for Australia (Leaney et al., 2011) and chloride concentrations in groundwater were obtained from the recharge studies by Kellett et al. (2003) and Habermehl et al. (2009). This approach ensured that a consistent estimation of diffuse recharge for the GAB intake beds was used in the Assessment (Smerdon et al., 2012).

7.1.3 Recharge estimate

Figure 7.1 shows the recharge estimate for the Surat region for the Cadna-owie – Hooray Aquifer and equivalents. Across the majority of the intake beds, recharge is estimated to be less than 5 mm/year, with the exception of portions of the Hutton Sandstone, which have values greater than 20 mm/year in the north part of the region. Similarly, recharge values of up to 45 mm/year were estimated for a localised region on the east side of the Coonamble Embayment. Summed for the region, the total estimate recharge for the Cadna-owie – Hooray Aquifer and equivalents is 157 GL/year. Habermehl et al. (2009) estimated that recharge was 295 GL/year using the same method, but it should be noted that this higher value would also include recharge to the Hutton Sandstone. Including the Hutton Sandstone with the Cadna-owie – Hooray Aquifer and equivalents results in a total of 275 GL/year. The groundwater modelling (Chapter 3) had 185 GL/year of recharge for the Cadna-owie – Hooray Aquifer and equivalents.

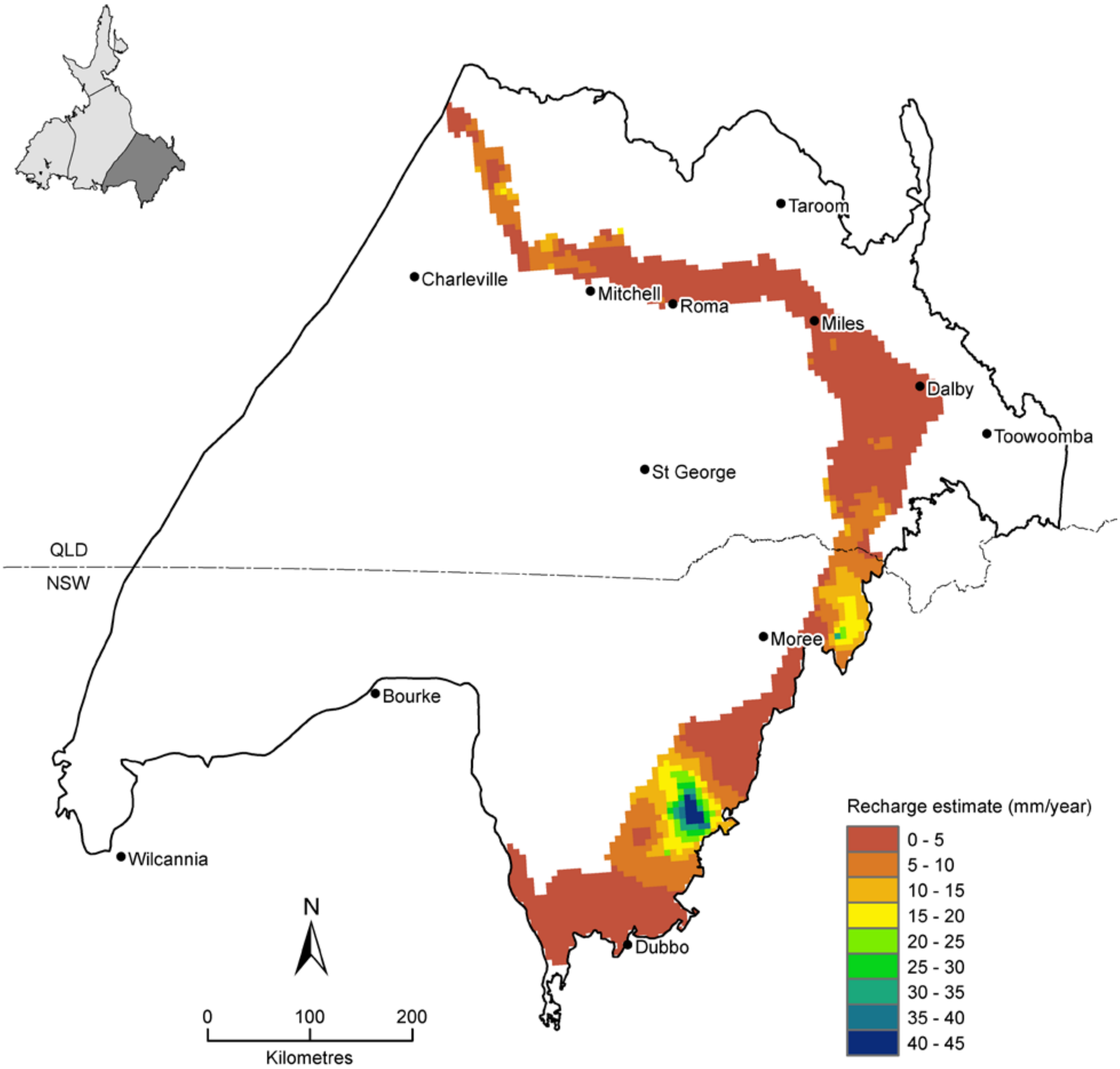


Figure 7.1 Recharge estimate by chloride-mass-balance of the Surat region for the Cadna-owie – Hooray Aquifer and equivalents

7.2 Discharge

Discharge from the GAB aquifers occurs naturally in the form of concentrated outflow from artesian springs, vertical diffuse leakage from the Lower Cretaceous-Jurassic aquifers towards the Cretaceous aquifers and upwards to the regional watertable and as artificial discharge by means of free or controlled artesian flow and pumped abstraction from water bores drilled into the aquifers.

7.2.1 Springs

Within the Surat region there are 643 springs that have varying activity (see Chapter 4), of which approximately 52 percent are active. The majority of these springs are associated with geological faults (see Chapter 4) with many springs in the recharge areas occurring as a result of ‘overflow’ or the ‘rejection’ of recharge into the aquifers, or result from the intersection of the local topography and aquifers. The Springsure supergroup has close to 100 percent of springs being active, with an estimated total of 2200 ML/year discharge (Fensham et al., 2012). The springs of the Eulo, Bourke, and Bogan supergroups have been impacted by decreased pressure level following the exploitation of GAB water. The total estimated spring discharge for the Surat region is 14000 ML/year (14 GL/year) (Habermehl, 1982).

7.2.2 Diffuse leakage

Diffuse groundwater discharge from the GAB occurs by a combination of very slow upward leakage through massive sections of aquitards and comparatively fast preferential flow along fractures and faults (Harrington et al., 2012). Both mechanisms discharge water upwards to the regional watertable. Diffuse discharge is a poorly constrained component of the GAB water balance and the proportion that may be very slow leakage to preferential flow is unknown. The rate of diffuse discharge is generally considered to be low; however, the process is also considered to occur across widespread areas.

To provide an indicative value in the water budget, a first-order approximation of the total diffuse groundwater discharge was made using the groundwater levels for the Cadna-owie – Hooray Aquifer and equivalents (Chapter 6) and the watertable (Chapter 5), combined with an estimate of the permeability following the method of Harrington et al. (2012). Using a Darcy's Law approach is not expected to generate robust discharge estimates – rather it provided a constraint to the estimated water budget.

The first-order approximation for diffuse discharge was completed for 10 km^2 areas across the region. For each 10 km^2 area the vertical hydraulic gradient was calculated between the groundwater level and watertable. A fraction (10 percent) of each area was assumed to be comprised of preferential pathways having a hydraulic conductivity of 1×10^{-9} m/second and the remainder of the area (90 percent) was assumed to have a hydraulic conductivity of 1×10^{-13} m/second. The fraction of the region that may contain preferential flow pathways is unknown, so additional fractions (5 and 15 percent) were also considered to create a range of potential estimates. There is also a great deal of uncertainty with the hydraulic conductivity values. However, this method provides a first-order estimate of diffuse discharge. Following this approach, diffuse discharge was estimated to be between 46 and 139 GL/year for the entire Surat region.

7.2.3 Bores

Groundwater discharge from GAB aquifers occurs through flowing artesian water bores, pumped water bores, and as part of petroleum extraction. The Assessment collated discharge rates for water bores and petroleum wells for the groundwater model (see Chapter 3) and found that the total groundwater discharge through bores and wells is 232 GL/year. For comparison, the Queensland Water Commission (QWC, 2012) reported a value of 23 GL/year for the Cadna-owie – Hooray Aquifer and equivalents in the Surat Cumulative Management Area, which is a smaller area than the Surat region. Considering the uncertainty in obtaining accurate groundwater extraction measurements, the Assessment has chosen 232 GL/year for the water budget estimate.

7.3 Water budget components

Estimates of the various components of the water budget are not known with great certainty. The values presented are representative of modern day values and do not reflect temporal variations in either recharge or discharge. The estimates of diffuse recharge and discharge are based on relatively simple relationships and the extrapolation of point measurements to a broad spatial scale. For recharge, this includes concentrations of chloride in precipitation and groundwater. For discharge, this includes the permeability (expressed as hydraulic conductivity) that is assumed to represent the entire thickness of a geological formation and the proportion of the region that may have preferential flow pathways. Considering these uncertainties, the regional water budget components presented should be considered indicative budget, rather than exact budget.

A summary of water budget components is provided in Table 7.1, which shows a range of values. Different values for each water budget component may represent the uncertainty of an estimation method (e.g. diffuse discharge) or the findings from different studies (e.g. recharge). The regional water budget components suggest that in the Surat region, the Cadna-owie – Hooray Aquifer and equivalents are not in equilibrium, having greater outflows than inflows.

Table 7.1 Water budget components for the Cadna-owie – Hooray Aquifer and equivalents in the region (values expressed in GL/year)

Groundwater recharge				Bore extraction
Chloride mass balance[1]	Chloride mass balance[2]	Assessment modelling[3]	Conceptual diagrams[4]	Assessment modelling[3]
157	295	185	237	232
Spring discharge	**Diffuse discharge[5]**			
Habermehl (1982)	5% preferential pathways	10% preferential pathways	15% preferential pathways	
14	46	92	139	

[1] Smerdon et al. (2012)

[2] Habermehl (2009)

[3] GABtran model (Welsh et al., 2012)

[4] Ransley et al. (2012)

[5] method described by Harrington et al. (2012)

7.4 References

Fensham RJ, Pennay C and Drimer J (2012) Ecological and botanical Survey of Springs in the Surat Cumulative Management Area. Department of Environment and Resource Management, Queensland Government, Queensland.

Habermehl MA (1982) Springs in the Great Artesian Basin, Australia – their origin and nature. Bureau of Mineral Resources, Canberra, Australia.

Habermehl MA (2009) Inter-aquifer leakage in the Queensland and New South Wales parts of the Great Artesian Basin. Final report for the Australian Government Department of Environment and Water Resources, Heritage and Arts. Bureau of Rural Sciences, Canberra.

Habermehl MA, Devonshire J and Magee J (2009) Sustainable groundwater allocations in the intake beds of the Great Artesian Basin in New South Wales (recharge to the New South Wales part of the Great Artesian Basin). Final report for the National Water Commission. Bureau of Rural Sciences, Canberra.

Harrington GA, Smerdon BD, Gardner PW, Taylor AR and Hendry J (2012) Chapter 8: Diffuse discharge. In: Love AJ, Shand P, Crossey LJ, Harrington GA and Rousseau-Gueutin P (eds) Allocating water and maintaining springs in the Great Artesian Basin, Volume III: Groundwater discharge of the western Great Artesian Basin. National Water Commission, Canberra.

Kellett JR, Ransley TR, Coram J, Jaycock J, Barclay DF, McMahon GA, Foster LM and Hillier JR (2003) Groundwater Recharge in the Great Artesian Basin Intake Beds, Queensland. Final Report for the NHT Project #982713 Sustainable Groundwater Use in the GAB Intake Beds, Queensland. BRS, Natural Resources and Mines, Queensland Government, Brisbane, Queensland.

Leaney F, Crosbie R, O'Grady A, Jolly I, Gow L, Davies PJ, Wilford J and Kilgour P (2011) Recharge and discharge estimation in data poor areas: Scientific reference guide. CSIRO Water for a Healthy Country Flagship, Australia.

QWC (2012) Draft underground water impact report for the Surat cumulative management area. State of Queensland (Queensland Water Commission), Brisbane. Viewed 20 August 2012, <http://www.qwc.qld.gov.au/csg/water-impact-report.html>.

Ransley TR, Smerdon BD and Radke BM (2012) Chapter 9: Advancing the understanding of the Great Artesian Basin. In: Ransley TR and Smerdon BD (eds) Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

Smerdon BD, Rousseau-Gueutin P, Love AJ, Taylor AR, Davies PJ and Habermehl MA (2012) Chapter 7: Regional hydrodynamics. In: Ransley TR and Smerdon BD (eds) Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

Welsh WD, Moore C, Turnadge C, Smith AJ and Barr TM (2012) Modelling of climate and development. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia.

Wolfgang C (2000) Hydrogeology of the Pilliga Sandstone Aquifer in the Coonamble Embayment and its implications for water resource management. PhD Thesis, Australian National University, Canberra.

8 Advancing the understanding of the Great Artesian Basin

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8.1 Updating the conceptual model

The Assessment has completed an integrated reappraisal of the latest geological and hydrogeological information for the Great Artesian Basin (GAB). This reappraisal has led to an update of the conceptualisation of how the groundwater system operates – an update of the conceptual model. The long-standing conceptualisation by Habermehl (1980) viewed the GAB as a single, large, contiguous groundwater flow system in which aquifers were considered to be laterally continuous across the extent of the entire GAB. Some findings of the Assessment reinforce concepts that have been known previously, whereas others present a new understanding. Knowledge of the GAB has gradually evolved since the late 1800s. The new findings of the Assessment make a contribution to this knowledge and are described here.

8.1.1 Hydrogeological framework

The cornerstone of a conceptual model for the GAB is the geology and how specific geological formations are perceived as hydrostratigraphic units (i.e. aquifers and aquitards). Assessment and interpretation of geological data has led to the new findings across three groups:

Boundary of the Great Artesian Basin

Interpretation of geophysical and geological data have led to a revised location of the western extent of the GAB in the Coonamble Embayment. The revised boundary has been shifted between 10 and 30 km to the east and approximately 60 km to the south.

The assessment of geological and hydrogeological data has also revealed that the hydrogeological boundary between the Surat and Clarence-Moreton basins is complex. For groundwater in Upper Cretaceous formations, the watertable divide delineates the boundary. However, a different boundary exists at depth. The presence of the Helidon Ridge is expected to influence groundwater flow in the Lower Cretaceous and Jurassic formations.

These findings reflect that the GAB is a groundwater basin that encompasses several geological basins. As new knowledge of the geology and hydrogeology is discovered, subsequent incorporation into groundwater resource management must also be assessed.

Influence of structural features

It was previously known that the GAB had interconnection with overlying, underlying, and adjacent geological basins. The Assessment has established a formal definition of underlying aquifers that are in contact with aquifers of the GAB. In addition to these direct connections, the Assessment has also identified locations where the structure of hydrostratigraphic units in the GAB has been inherited from deeper geological structures.

The Assessment has identified the importance of the influence of underlying geological basins on groundwater conditions in the GAB. Assessment of the potential for cross-formational flow found only a few locations where sufficient groundwater data existed to create pressure-elevation profiles. Thus, a quantitative link (i.e. rates of leakage) on the connection with underlying groundwater systems is unknown. The formal definition of interconnection areas provided by the Assessment will guide future work.

Hydrogeological properties

As part of the Assessment, a new categorisation for GAB hydrostratigraphy has been developed. This expands previously defined ‘aquifers and aquitards’ into gradations that better represent the variation in geological formations.

Combined with these refined categories, existing data for hydraulic properties (i.e. porosity and permeability) have been summarised for specific formations. The Assessment found that both data quantity and quality were highly variable. The Assessment also found that values reported for low permeability formations (leaky aquitard, tight aquitard, or aquiclude) are suspiciously high.

These findings have implications for the development of groundwater models and quantitative assessment of groundwater flow rates. The expanded categorisation for GAB hydrostratigraphy enables some consistency for model development by providing a common basis that represents geological variation. In contrast, uncertain or possibly erroneous hydraulic property data reduces constraints in model development.

8.1.2 Groundwater levels

Assessment of groundwater levels focused on the Cadna-owie – Hooray Aquifer and equivalents as well as the regional watertable. Groundwater data has been acquired in the GAB since the late 1800s, but the interpretations of groundwater levels provided by the Assessment are in the context of the new findings described for the geological framework in Section 8.1.1 above. Essentially this is a new look at old measurements, which has contributed to an updated conceptual model of the GAB.

Regional watertable mapping

The Assessment prepared the first ever maps of a regional watertable. The maps were interpreted from an understanding of the shallow hydrogeological conditions rather than a statistical contouring. This rudimentary approach allowed a mapping to be consistent across large areas that have a paucity of data. The resultant mapping provides a basis to evaluate relationships between groundwater recharge and discharge for non-artesian portions of the GAB, as well as a consistent data source to further investigate interaction between groundwater and surface water.

Geological faulting and groundwater flow

The Assessment also prepared the first ever maps of groundwater levels representing the Cadna-owie – Hooray Aquifer and equivalents that specifically included faults. The amount of vertical displacement from faulting is variable, but interpolation of groundwater levels where faults act as barriers to groundwater flow has led to a new perspective of groundwater conditions. In the Surat region, the presence of the Goondiwindi Fault results in elevated groundwater levels on the east side of the fault, compared with the west. In turn, the groundwater chemistry in Lower Cretaceous formations has been affected by the fault, compared with Upper Cretaceous formations that are shallower.

Inclusion of faulting when interpolating groundwater levels and interpreting groundwater chemistry poses a new challenge in the Surat region. The presence of such barriers to groundwater flow could caused unexpected changes where significant groundwater development occurs. These important geological structures are not considered in most groundwater models.

Monitoring changes

The maps of groundwater levels were prepared for 20-year intervals beginning in 1900. These ‘snapshots’ have not previously been created for the Cadna-owie – Hooray Aquifer and equivalents and clearly illustrate the decline in groundwater levels in the early part of the last century. However, the Assessment detected some increase (recovery) of groundwater levels that is assumed to be associated with capping and piping activities. In this regard, the efforts of the Great Artesian Basin Sustainability Initiative can be seen.

8.2 Implications for modelling

A groundwater model represents the complex real world in a relatively simple form. The process of conceptualisation is meant to capture available knowledge and information of a groundwater system and translate these into a representation to be used in subsequent analysis, such as a groundwater model. During this process real-world complexity is balanced against its certainty and requirement in the subsequent analysis. The new findings of the Assessment outlined in Section 8.1 are the basis for an update to the previous conceptualisation of the GAB. Instead of a single, large, contiguous groundwater flow system, the findings of the Assessment have shown that structural complexity, multiple-layers, and inclusion of barriers (faults) must also be part of the conceptualisation. None of these complexities have been included in the GABtran groundwater model (Welsh, 2006) used in the Assessment.

The implications of including any of the additional complexities in a groundwater model of the GAB is unknown. It can be reasonably assumed that in order to maintain a calibrated model, significant revision of the parameters of the model would be required. A difference in model layer thickness, hydraulic properties, or leakage from other layers would lead to a different modelling outcome. Should a new groundwater model be developed for the GAB, the geological features outlined in the Assessment should be considered explicitly. However, similar to the original intention of GABtran, a new model should only be developed for a specific purpose. While an all-encompassing advanced groundwater model of the GAB may fulfil an academic destiny, modelling groundwater conditions at a smaller scale may give results better fit for purpose.

An example of a new model that is fit for purpose is the model developed by the Queensland Water Commission (QWC) (GHD, 2011), which has been used in the Assessment, together with GABtran, for estimating the impact of coal seam gas (CSG) development under the climate and development scenarios. The groundwater model developed by QWC lies entirely within the Surat reporting region. Rather than simulating groundwater pressure in the Cadna-owie – Hooray Aquifer as a single layer, the QWC model has multiple layers to represent different rock layers in the Surat region – the aquifers and aquitards.

8.3 Knowledge gaps

The collation, analysis, and interpretation of geological and hydrogeological knowledge are ongoing in the GAB. Because the GAB is defined as a groundwater basin, it encompasses several geological basins and is also connected with other adjacent geological basins and formations. Comprehensively defining the connection of different geological basins and the role of large-scale geological structures on groundwater in the GAB requires closing these knowledge gaps:

- Quantifying the hydraulic connection between the GAB and underlying geological basins. The Assessment illustrated that potential ‘windows’ of connectivity with underlying basins exist. However, rates of groundwater exchange remain unknown. Where GAB aquifers are connected with underlying aquifers, there may be groundwater moving from one basin to another. Where development occurs near these critical connections, the impact could also move from one basin to another.
- Quantifying the hydraulic connection between the GAB aquifers and overlying, shallow groundwater systems. The Assessment has identified some areas where groundwater interacts with rivers. However, the broader exchange of groundwater between shallow systems (e.g. alluvial groundwater units) and the GAB aquifers is poorly known.
- The controlling mechanisms for vertical leakage (cross-formational flow) for the multiple layers of aquifers and aquitards present in the GAB. Understanding these mechanisms is critical for determining the effect of significant depressurization proposed for CSG development in the Surat region.
- The hydraulic properties of aquitards and response to changes in groundwater pressure within adjacent aquifers. Where several layers of aquifers and aquitards are present, pressure changes caused by groundwater extraction will propagate at various rates in various directions, depending on the physical properties unique to each aquifer and aquitard layer. The Assessment found that existing hydraulic property data are contained in the QPED and PIRSA databases are insufficient to characterise formations of low-permeability, such as aquitard.
- The relationship between groundwater conditions in GAB aquifers and the hydraulics of springs. Baseline spring information (local geology, hydrology) is often inadequate to assess the source aquifer for many springs, which reduces the accuracy of quantifying changes in spring flow. Nine spring complexes have been investigated in greater detail (EHA, 2009), which provides a method for completing more in-depth study of the source aquifers for springs. In addition to the baseline information, continued research of the hydraulics of springs will be required to establish cause-and-effect linkage between GAB aquifers and spring flow.

8.4 Data gaps

The GAB is a vast groundwater basin and detailed information is very sparse, often clustered in only a few areas. Sufficient data representing all geological formations that host the GAB are required for monitoring the water resource, and continuing to test and develop concepts of how it works. The Assessment identified the following information gaps:

- Groundwater level data is not currently measured for any vertical profiles across the thickness of the GAB. Groundwater level data within aquifers and aquitards at multiple depths will provide critical information for quantifying rates of vertical leakage. Specific areas of interest could be identified from maps of the regional watertable and potentiometric surface developed within the Assessment.
- There is a paucity of data about the physical properties aquitard layers. This missing information is critical for predicting the impact of groundwater extraction in areas where aquifer layers are separated by aquitard layers.
- Consistent interpretation of bore log data for calculation of the sand-to-shale ratio. The information to perform an estimation of sand-to-shale ratio is available from most geophysical logs; however, the calculations are incomplete for the GAB. Establishing a standard approach to determining the sand-to-shale ratio would help better define the hydrostratigraphy.
- Ecological and hydrological (including water quality) data are not uniformly available across the GAB. These data are required to prioritise conservation and management or to undertake a more comprehensive assessment of the vulnerability of springs to drawdown. Specifically, the location and elevation of spring vents would be required to accurately assess response to changes in groundwater pressure, combined with measurement of flow rates.

8.5 References

EHA (2009) Identification of source aquifers to significant springs dependent on groundwater flow from the Great Artesian Basin – Stage 1B Report – Volume 1 Overview Report. Environmental Hydrology Associates (EHA) Ltd., Brisbane.

GHD (2011) Report for QWC17–10 Stage 2 Surat cumulative management area groundwater model report (Draft), December 2011. Queensland Water Commission, Brisbane, Australia.

Habermehl MA (1980) The Great Artesian Basin, Australia. Bureau of Mineral Resources Journal of Australian Geology and Geophysics 5, 9–38.

Welsh WD (2006) Great Artesian Basin transient groundwater model. Bureau of Rural Sciences, Canberra. Viewed 15 October 2012, <http://adl.brs.gov.au/brsShop/data/gabtransient1.pdf>.

Appendix A Reports published by the Assessment

More information about the Great Artesian Basin Water Resource Assessment can be found at <http://www.csiro.au/science/Great-Artesian-Basin-Assessment.html>. This appendix lists all reports published by the Assessment.

Data reports

Hartcher MG, Davies PJ, Ransom GC, Turnadge CJ, Welsh WD, Taylor AR and Miles C (2012) Data acquisition and management. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~20 pp.

Ransom GC and Ransley TR (2012) Data delivery and custodianship. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~25 pp.

Region reports

Smerdon BD, Welsh WD and Ransley TR (eds) (2012) Water resource assessment for the Carpentaria region. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~120 pp.

Smerdon BD and Ransley TR (eds) (2012) Water resource assessment for the Central Eromanga region. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~120 pp.

Smerdon BD and Ransley TR (eds) (2012) Water resource assessment for the Surat region. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~125 pp.

Smerdon BD, Welsh WD and Ransley TR (eds) (2012) Water resource assessment for the Western Eromanga region. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~120 pp.

Summary reports

CSIRO (2011) The Great Artesian Basin Water Resource Assessment. Project overview. CSIRO Water for a Healthy Country Flagship, Australia. 2 pp.

CSIRO (2012) The Great Artesian Basin Water Resource Assessment: Update, January 2012. CSIRO Water for a Healthy Country Flagship, Australia. 4 pp.

CSIRO (2012) The Great Artesian Basin Water Resource Assessment: Update, September 2012. CSIRO Water for a Healthy Country Flagship, Australia. 2 pp.

Smerdon BD, Welsh WD, Marston FM and Ransley TR (2012) Water resource assessment for the Carpentaria region. Summary of a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~16 pp.

Smerdon BD, Marston FM and Ransley TR (2012) Water resource assessment for the Central Eromanga region. Summary of a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~16 pp.

Smerdon BD, Marston FM and Ransley TR (2012) Water resource assessment for the Surat region. Summary of a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~16 pp.

Smerdon BD, Welsh WD, Marston FM and Ransley TR (2012) Water resource assessment for the Western Eromanga region. Summary of a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~16 pp.

Technical reports

Smith AJ and Welsh WD (2011) Review of groundwater models and modelling methodologies. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~60 pp.

Miles C, White M and Scholz G (2012) Assessment of the impacts of future climate and groundwater development on Great Artesian Basin springs. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~50 pp.

Ransley TR and Smerdon BD (eds) (2012) Hydrostratigraphy, hydrogeology and system conceptualisation of the Great Artesian Basin. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~285 pp.

Radke BM, Kellett JR, Ransley TR and Bell JG (2012) Lexicon of the lithostratigraphic and hydrogeological units of the Great Artesian Basin and its Cenozoic cover. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~175 pp.

Welsh WD, Moore CR, Turnadge CJ, Smith AJ and Barr TM (2012) Modelling of climate and groundwater development. A technical report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~105 pp.

Three-dimensional visualisation report

Nelson GC, Carey H, Radke BM and Ransley TR (2012) The three-dimensional visualisation of the Great Artesian Basin. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~15 pp.

Whole-of-GAB reports

Smerdon BD, Ransley TR, Radke BM and Kellett JR (2012) Water resource assessment for the Great Artesian Basin. A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~50 pp.

Smerdon BD, Marston FM and Ransley TR (2012) Water resource assessment for the Great Artesian Basin. Synthesis of a report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment. CSIRO Water for a Healthy Country Flagship, Australia. ~12 pp.

Terms and concepts

The Great Artesian Basin (GAB) is a complex groundwater entity that is difficult to visualise and challenging to describe. To help describe the GAB and improve knowledge of groundwater resources, this report uses scientific and technical terms that may be unfamiliar to many readers. The definitions provided in this section are intended to assist readers understand most of the concepts covered by the report. However, it was beyond the scope of the Assessment to provide a full glossary – there are numerous other sources easily accessed online including:

> The National Water Commission's information about groundwater. Viewed 24 October 2012, <http://archive.nwc.gov.au/library/topic/groundwater/groundwater-essentials>.
>
> United States Geological Survey Water Science School groundwater basics. Viewed 30 October 2012, <http://ga.water.usgs.gov/edu/mearthgw.html>.
>
> United States Geological Survey Water Science School water science glossary of terms. Viewed 30 October 2012, <http://ga.water.usgs.gov/edu/dictionary.html>.
>
> United States Geological Survey Ground Water Glossary. Viewed 30 October 2012, <http://pubs.usgs.gov/gip/gw/glossary.html>.
>
> United States Geological Survey what is groundwater?, Viewed 30 October 2012, <http://pubs.usgs.gov/of/1993/ofr93-643/>.
>
> Oregon Water Science Centre glossary of hydrologic terms. Viewed 30 October 2012, <http://or.water.usgs.gov/projs_dir/willgw/glossary.html#A>.
>
> Houghton Mifflin (USA) website for teachers; includes glossary of geological terms. Viewed 30 October 2012, <http://college.hmco.com/geology/resources/geologylink/index.html>.

Anticline: an arch-shaped fold of originally flat lying sedimentary layers.

Aquiclude: a geological material that does not transmit water. Generally, this definition is meant to imply extremely limited movement of water even at the scale of geological time.

Aquifer: a permeable geological material that can transmit significant quantities of water to a bore, spring, or surface water body. Generally, 'significant' is defined based on human need, rather than on an absolute standard.

Aquitard (confining layers): a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

Artesian: a general term used when describing certain types of groundwater resources. **Artesian water** is underground water confined and pressurised within a porous and permeable geological formation. An **artesian aquifer** has enough natural pressure to allow water in a bore to rise to the ground surface. **Sub-artesian water** is water that occurs naturally in an aquifer, which if tapped by a bore, would not flow naturally to the surface. **Artesian conditions** refer to the characteristics of water under pressure.

Basement: the crust below the rocks of interest. In hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate 'bedrock' (i.e. underlying or encasing palaeovalley sediments).

Basin inversion: the relative uplift of a sedimentary basin to surrounding low lying areas from a variety of processes, with compressional folding being a dominant process referred to in this report.

Bolide: an extraterrestrial body which impacts the earth at high velocity. Generic term used to imply that the precise nature of the impacting body is unknown.

Craton: a large stable mass of rock that forms a major structural unit of the Earth's crust.

Depocentre: centre of deposition within a sedimentary basin. This is usually the deepest point within a sedimentary basin.

Diachronous: apparently similar features or events that vary in age at different locations. These features can be sedimentary rocks, erosional surface, or areas of uplifts.

Drainage division: the area of land where surface water drains to a common point. There are 12 major drainage divisions in Australia. At a smaller scale, surface water drainage areas are also referred to as river basins, catchments, or watersheds.

Drawdown: the lowering of groundwater level resulting from the extraction of water, oil or gas from an aquifer.

Elluviated: the lateral or downward movement of suspended material in by percolation of water.

Eustatic: global sea level change.

Facies: a distinctive rock unit that forms under certain conditions of sedimentation. In the context of this report, the term facies represents the change of depositional environment of sediments

Fluvial sediments: sediments deposited by rivers.

Geological basin: layers of rock that have been deformed by mega-scale geological forces to become bowl-shaped. Often these are round or oblong with a depression in the middle of the basin.

Geological formation: geological formations consist of rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time.

Groundwater (hydrogeology): water that occurs within the zone of saturation beneath the Earth's surface. The study of hydrogeology focuses on movement of fluids through geological materials (e.g. layers of rock).

Groundwater basin: a groundwater basin is a non-geological delineation for describing a region of groundwater flow. Within a groundwater basin, water enters through recharge areas and flows toward discharge areas.

Groundwater divide: a divide that is defined by groundwater flow directions that flow in opposite directions perpendicular to the location of the divide.

Groundwater flow (hydrodynamics): within a groundwater basin, the path from a recharge area to a discharge area is referred to as a groundwater flow system, where travel time may be as short as days or longer than centuries, depending on depth. The mechanics of groundwater flow – the hydrodynamics – are governed by the structure and nature of the sequence of aquifers.

Groundwater flow model: a computer simulation of groundwater conditions in an aquifer or entire groundwater basin. The simulations are representations based on the physical structure and nature of the sequence of aquifers and rates of inflow – from recharge areas – and outflow – through springs and bores.

Groundwater level: in this report refers to the elevation of equivalent freshwater hydraulic head at 25 °C

Groundwater recharge and discharge: recharge occurs where rainfall or surface water drains downward and is added to groundwater (the zone of saturation). Discharge occurs where groundwater emerges from the Earth, such as through springs or seepage into rivers.

Half-graben: a valley formed by movement on a fault.

Hydrodynamic divide: see *groundwater divide*.

Hydrostratigraphy (hydrogeological unit): geological formations that have similar hydraulic properties and are connected laterally. These are grouped as a single hydrogeological unit or hydrostratigraphic layer.

Inversion (basin): see *basin inversion*.

Intake beds: areas where the major aquifers of the GAB are exposed at the ground surface and become recharged. The GAB intake beds are generally located along the western slopes of the Great Dividing Range.

Lateritisation: a soil-forming process occurring in humid tropical and subtropical areas. The process involves the chemical weathering and deposition of metallic oxides (laterite) in and under the uppermost soil layer which contains organic matter.

Leaky aquitard: a semi-permeable geological material that can transmit groundwater. Although regionally non-productive, it may be classed as a very low yielding aquitard that is sometimes used to produced groundwater where no other source is available.

Lithology: the character of a rock; its composition, structure, texture, and hardness.

Lithostratigraphy: the classification by physical rock type of sedimentary layering or stratification. Changes in rock type resulting from changes in depositional environment are known as depositional facies change.

Orogeny, Orogenesis: the forces and events that lead to the deformation of the Earth's lithosphere (crust and upper mantle) resulting in the formation of mountains.

Palaeochannel: refers to the main channel of ancient rivers, sometimes called the 'thalweg', the lowest point of incision along the river bed where coarser sediments are commonly deposited. Former river channels that are recognised in the surface (from aerial or satellite images) or subsurface (typically in aerial electromagnetic surveys or drilling).

Palaeosol: former soil preserved by burial under lithified sediments or volcanic deposits.

Paludal: sediment accumulated in a marsh environment.

Partial aquifer: A permeable geological material with variable groundwater yields that are lower than in an aquifer and range from fair to very low yielding locally.

Permeability: a measurement describing the ability of any fluid (water, oil) to pass through a porous material. Values vary widely, with higher values corresponding to aquifers (i.e. highly permeable) and lower values corresponding to aquitards (i.e. less permeable).

Phyllite: a metamorphic rock similar to schist with coarser grains.

Saprolite: weathered or decomposed bedrock.

Schist: a metamorphic rock that has parallel bands of minerals.

Senescence: aging.

Seismics, seismic survey: the study of vibrations of the earth and their propagation through the ground. A seismic survey, is the acquisition of seismic data using artificial sources to induce vibrations in the earth. Provides information on the lateral extent and depth of rock layers.

Springs: result when water from a confined aquifer naturally reaches the surface, either because of faulting which fractures overlying aquitards, or because the aquifer is close to the surface at the margins of the basin.

Spring complex: clusters of springs that share similar water chemistry and are related to common geological features are known as '**spring groups**'; clusters of spring groups that share similar geomorphological settings and are referred to as 'spring complexes'; clusters of spring complexes are referred to as '**supergroups**'.

Subduction: the downward movement of a tectonic plate under another resulting from the convergence of the two plates. Considered a force in orogenies.

Subsidence: downward movements of the Earth's crust.

Syncline: a basin or 'U' shaped fold of originally flat lying sedimentary layers.

Tight aquitard: a semi-permeable geological material with very low to negligible transmission of water on a regional scale.

Unconformity: a boundary between two rock units that represents a significant period of time in which no sediment is deposited.

Volcanogenic sediment: sediments containing material that is derived from volcanic activity.

Watertable: the surface where the groundwater level is balanced against atmospheric pressure. Often, this is the shallowest water below the ground.

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