Modelling of climate and groundwater development

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

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21 December 2012
Great Artesian Basin Water Resource Assessment acknowledgments

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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).

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Cover photograph: Google image showing geographical extents of the GABtran model (red), the Queensland Water Commission model (Layer 3 is green, Layer 5 is blue and Layer 7 is yellow), and the Cape York model (pink) as well as the boundary of the Great Artesian Basin (black).
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.

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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/>.
## Units of measurement

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<th>Measurement unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>kL</td>
<td>kilolitres, 1,000 litres or 1 square metre</td>
</tr>
<tr>
<td>ML</td>
<td>megalitres, 1,000,000 litres</td>
</tr>
<tr>
<td>GL</td>
<td>gigalitres, 1,000,000,000 litres</td>
</tr>
<tr>
<td>TL</td>
<td>teralitres, 1,000,000,000,000 litres</td>
</tr>
<tr>
<td>cumecs</td>
<td>cubic metres per second; m³/sec; equivalent to 1,000 litres per second</td>
</tr>
<tr>
<td>mAHD</td>
<td>metres above Australian Height Datum</td>
</tr>
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### Acronyms and initialisms

<table>
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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AHD</td>
<td>Australian Height Datum</td>
</tr>
<tr>
<td>CSG</td>
<td>coal seam gas</td>
</tr>
<tr>
<td>EVT</td>
<td>the MODFLOW evapotranspiration package</td>
</tr>
<tr>
<td>GAB</td>
<td>Great Artesian Basin</td>
</tr>
<tr>
<td>GABSI</td>
<td>Great Artesian Basin Sustainability Initiative</td>
</tr>
<tr>
<td>GABtran</td>
<td>Great Artesian Basin transient groundwater flow model</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
</tr>
<tr>
<td>Kh</td>
<td>horizontal hydraulic conductivity</td>
</tr>
<tr>
<td>Kz</td>
<td>vertical hydraulic conductivity</td>
</tr>
<tr>
<td>MODFLOW</td>
<td>modular three-dimensional finite-difference groundwater flow model</td>
</tr>
<tr>
<td>MSR</td>
<td>mean sum of residuals</td>
</tr>
<tr>
<td>MSSQ</td>
<td>mean sum of squares</td>
</tr>
<tr>
<td>PEST</td>
<td>parameter estimation software (Doherty, 2010)</td>
</tr>
<tr>
<td>QWC</td>
<td>Queensland Water Commission</td>
</tr>
<tr>
<td>QWC model</td>
<td>Queensland Water Commission coal seam gas regional groundwater flow model</td>
</tr>
<tr>
<td>R</td>
<td>correlation coefficient</td>
</tr>
<tr>
<td>R²</td>
<td>coefficient of determination</td>
</tr>
<tr>
<td>RMS</td>
<td>root mean square</td>
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<tr>
<td>SMSR</td>
<td>scaled mean sum of residuals</td>
</tr>
<tr>
<td>SRES</td>
<td>the IPCC Special Report on Emission Scenarios</td>
</tr>
<tr>
<td>SR</td>
<td>sum of residuals</td>
</tr>
<tr>
<td>SRMS</td>
<td>scaled root mean square</td>
</tr>
<tr>
<td>SSQ</td>
<td>sum of squares</td>
</tr>
<tr>
<td>SVDA</td>
<td>Singular Value Decomposition Assist tool within PEST</td>
</tr>
<tr>
<td>TDS</td>
<td>total dissolved solids</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WCM</td>
<td>Walloon Coal Measures</td>
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</table>
Executive summary

About the Assessment

Since 2007, CSIRO has been undertaking groundbreaking 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.

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.

This report presents technical details regarding groundwater modelling that was undertaken in the Assessment. Groundwater modelling investigated the potential impacts of climate change and groundwater development regimes on groundwater resources, under different scenarios. Development scenarios included current and projected future groundwater demands from pastoral, petroleum, mining and other extractive industries. The groundwater modelling estimated the impacts of climate and groundwater development as changes in long-term groundwater level.

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 groundwater development on those water resources.
The groundwater models

Three groundwater models were used to estimate the impact of climate and groundwater development on groundwater levels in the GAB:

1. GABtran is an existing large-scale, transient groundwater model that simulates groundwater levels in the Cadna-owie – Hooray aquifer as a single layer spanning the GAB. GABtran uses the Habermehl (1980) conceptualisation of the GAB. GABtran covers most of the GAB, except Cape York Peninsula, and was originally developed for the Great Artesian Basin Sustainability Initiative (GABSI) in 2006. It is suitable for estimating the effects of future climate and groundwater development across the GAB, but cannot simulate the groundwater level impacts of coal seam gas (CSG) activities because the CSG is extracted from geological layers that lay beneath the aquifer modelled by GABtran.

2. The Cape York model is a large-scale, transient groundwater model limited by a steady state calibration that simulates groundwater levels in the Cadna-owie – Hooray aquifer as a single layer. It has a common boundary with GABtran near the Gilbert River. It uses the Habermehl (1980) conceptualisation of the GAB, and was developed for the Assessment in parallel with the re-conceptualisation of the GAB. There were insufficient data for a more complex model or for a transient calibration. Transient simulations use storativities based on three estimates of average aquifer thickness: 100, 150 and 200 m.

3. The Queensland Water Commission (QWC) model lies entirely within the Surat reporting region. It is a complex model with 19 layers representing the different aquifers and aquitards. The Cadna-owie – Hooray aquifer is represented by three aquifer layers in this model. The groundwater extraction for CSG occurs in the Walloon Coal Measures. Impacts on other layers from CSG-related development are likely to occur by vertical leakage, which will cause changes in groundwater levels in layers above and below. Results from the QWC model were provided to the Assessment by the QWC.

The model scenarios

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 during 2010 to 2070. 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 66 percent lower under the dry extreme climate and 83 percent higher under the wet extreme climate. In addition to the future climate with current (2010) groundwater development, consideration was given to a scenario of future climate with future development – created by changing rates of groundwater extraction.

Key findings

Figure 2.4(b) (GABtran, all regions) and Figure 4.16(b) (Cape York, Carpentaria region) show the change in groundwater level from 2010 to 2070 under the median future climate scenario and continuing the current level of groundwater extraction (Scenario Cmid). It is estimated that groundwater extraction will exceed replenishment in most of the south and west of the Eromanga Basin, in a wide arc through Roma and Charleville to Longreach, and near Weipa in the north of the Cape York Peninsula. Near areas of higher recharge in New South Wales and Queensland, groundwater levels are estimated to increase due to recharge exceeding groundwater use. The pattern is generally similar under the wet and dry extreme climates. Exceptions are increases in groundwater level near Marla in the west of the Western Eromanga region and in the north of the Cape York Peninsula under the wet extreme climate, and decreases in groundwater level...
over most of the intake beds under the dry extreme climate. These basin-margin areas that are most sensitive to changes in groundwater recharge have a lower capacity to transmit water down gradient (i.e. a lower transmissivity).

Figure 2.6(b) (GABtran, all regions) and Figure 4.23(b) (Cape York, Carpentaria region) show the change in groundwater levels from 2010 to 2070 under the median future climate scenario and future groundwater development (Scenario Dmid). It is estimated that groundwater extraction will exceed replenishment except where bore densities are high, such as around the Euroka Arch and the Nebine Ridge, driven by the rehabilitation of free-flowing stock and domestic water bores. The pattern is almost identical under the wet extreme climate. Under the dry extreme climate the intake beds in the south-east and south-west of the GAB are the most affected, with greater recharge deficits than under the median climate.

The impact of bore rehabilitation is greater than the impact of CSG development on the Cadna-owie – Hooray aquifer in the Surat region (comparing GABtran in Figure 2.6(d) with the QWC model in Figure 3.5(b)).

Uncertainty analyses are used to describe the predictive confidence for the average impact of the GABtran model scenarios, and to assess how best to improve the reliability of the average model results through improved aquifer parameter knowledge and additional data collection. The uncertainty in GABtran model results (Table 5.2) is highest for Scenario D, which includes the impact of time, climate and groundwater development, and lowest for Scenario C relative to Scenario A, which only includes the impact of climate. The analyses quantify the reduction in uncertainty from model calibration and the contribution to post-calibration prediction uncertainty (Figure 5.4 to Figure 5.9). The greatest contribution to post-calibration prediction uncertainty is from storage properties; the least contribution is from inter-aquifer leakage. Data worth analysis (Figure 5.10 to Figure 5.16) shows that extending the groundwater level monitoring network in the Western Eromanga region, and between Julia Creek and Longreach in the Central Eromanga region would provide the greatest improvements in prediction reliability for a future upgrade of GABtran. More data would be needed to develop a more complex model.

The implications of including any of the additional complexities determined in the Assessment in an updated version of the GABtran model are unknown. It can be reasonably assumed that in order to maintain a calibrated model, significant revision of the parameters of the models would be required. A difference in model layer thickness, hydraulic properties, or leakage from other layers would lead to different modelling outcomes.

Should a new groundwater model be developed for the GAB, the geological features outlined by the Assessment in the companion reports (as listed in Appendix A) 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.
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1 Introduction

1.1 The Great Artesian Basin Water Resource Assessment

The Great Artesian Basin (GAB) is Australia’s largest groundwater basin. It underlies arid and semi-arid regions and extends across one-fifth of Australia, including extensive areas of Queensland, South Australia, New South Wales and the Northern Territory. CSIRO and partners have been commissioned to conduct the Great Artesian Basin Water Resource Assessment (the Assessment) by building on the approach taken by CSIRO and partners in the Murray-Darling Basin, South-West Western Australia, Northern Australia, and Tasmania Sustainable Yields projects.

1.2 The Assessment area

For the purposes of the Assessment, the GAB (Figure 1.1) is defined as:

1. aquifers of the Jurassic and Cretaceous periods within the geographic extent of the GAB, including parts of those aquifers that are in a sub-artesian condition
2. relevant shallow, overlying aquifers and surface water, to the extent of their connection with the aquifers referred to in 1 above.

The geographic extent of the GAB is considered to mark the contiguous extent of the unconformity beneath the base unit of the Jurassic geological sequence, or, where the base unit is absent, that unit most immediately above it. See Figure 1.3 for stratigraphic sequences across the basins within the GAB. Consideration is given to underlying sequences where these are considered to be in hydraulic contact with the Jurassic (or Cretaceous) aquifers. The underlying Triassic beds are not considered, except where they impact on the waters within the Jurassic and Cretaceous beds.

1.3 The Assessment reporting regions

The GAB consists of a number of depositional basins that are variously separated by, but (at least in part) hydraulically connected across, intracratonic highs and zones of divergent groundwater flow. Each depositional basin has been the focus of exploration efforts and can be used to define discrete regions that might be described individually. The regions for which the Assessment was undertaken and reported on do not strictly adhere to the boundaries of these depositional basins. These region boundaries have been selected so they will not intersect areas of interest that will have focused investigation. Four reporting regions, each containing one of the major basins of the GAB, have been defined (Figure 1.2):

- Surat
- Central Eromanga
- Western Eromanga
- Carpentaria.
Figure 1.1 Geographic extent of the Great Artesian Basin and selected overlying surface water drainage divisions
Figure 1.2 The reporting regions used in the Great Artesian Basin Water Resource Assessment
Figure 1.3 Stratigraphic sequences across the basins of the Great Artesian Basin: the Eromanga and Carpentaria basins (adapted from Habermehl and Lau, 1997)
Chapter 1 Introduction

1.4 Review of groundwater models and modelling methodologies

The purpose of the groundwater modelling component of the Assessment is to estimate the impact of climate and groundwater development on long-term groundwater levels in 2070.

The first step in the groundwater modelling component was a review of groundwater models and modelling methodologies (Smith and Welsh, 2011). This review compiled a list of contemporary groundwater models within the Assessment area with the aim of identifying those models that are potentially suitable for the purposes of the Assessment. Generally, a groundwater model is designed for a unique purpose, and as such, it is developed in a specific manner to achieve specific goals. Models identified in the review were developed as water resource assessment tools or as predictive tools for environmental impact assessments. The specific choices made during conceptualisation of the
groundwater system and model design (e.g. areal extent, layering, boundary conditions) often constrain the application of a particular model for an alternative purpose.

For the purposes of the Assessment, a groundwater model must be capable of simulating impacts on water availability (expressed as groundwater level) of future climate, represented as future groundwater recharge, and groundwater development, represented as future groundwater extraction. A key finding of the review is that the Great Artesian Basin transient groundwater flow model (GABtran (Welsh, 2006; 2007)) is the most suitable model, noting the key limitation that the model is a single layer model. GABtran was originally developed for the GAB Sustainability Initiative in 2006. It was designed to simulate the water balance and changes in groundwater level in the confined parts of the Cadna-owie – Hooray aquifer under bore rehabilitation scenarios, but it has important shortcomings for some reporting regions. The Assessment has insufficient time and resources to extend the single-layer GABtran model to a multilayered groundwater flow model that would be more suitable for the Assessment. Any future redevelopment of GABtran should be based on the reconceptualisation of the GAB that will be a product of the Assessment. By reporting region, the review found the following.

For the Surat region:
- GABtran is capable of simulating the effects of future climate.
- GABtran is not capable of simulating all of the effects of groundwater development because extraction for CSG production will originate from formations underlying the aquifers represented in GABtran.
- An agreement was established between CSIRO and QWC to use the QWC groundwater model to assess CSG impacts in the Surat region.

For the Central Eromanga region:
- GABtran is capable of simulating the effects of future climate.
- GABtran is capable of simulating the effects of groundwater development from the Cannington-Osborne and Olympic Dam borefields.

For the Western Eromanga region:
- GABtran is capable of simulating the effects of future climate.
- GABtran is capable of simulating the effects of groundwater development from the Olympic Dam borefield.
- GABtran is not capable of simulating the effects of groundwater development at the Prominent Hill mine because extraction will originate from formations underlying the aquifers represented in GABtran.
- Simulated groundwater conditions at the Prominent Hill mine suggest interaction with GAB aquifers; however, cooperation with the Prominent Hill mine model developers is required to fully assess the potential for inter-aquifer leakage and an approach for replicating leakage in GABtran.

For the Carpentaria region:
- GABtran is capable of simulating the effects of future climate.
- GABtran is capable of simulating the effects of groundwater development at the Ernest Henry and Mount Margaret mines, following a comparison of parameterisation used in the fine-scale mine models and larger-scale GABtran model.

### 1.5 Future climate and groundwater development scenarios

The list below summarises the scenarios used in the Assessment.
- Base run – historical climate and development from 1 January 1965 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’. In addition, Scenario C is reported relative to Scenario A, and Scenario D is reported relative to Scenario C. Scenario A uses historical climate while scenarios C and D use future climate. Scenarios A and C use current development while scenario D uses future development. Results are not reported just under the base run.

To represent climate change, recharge scaling factors (Section 1.6) 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; 2009d) – a short recent climate scenario (past 10 or 11 years) used to evaluate the consequences of recent climate variations on surface water resources. The Assessment does not consider the consequences to surface water supplies (except those generated through discharge of GAB groundwater), and 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 pressure or for watertable 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.

1.6 Recharge scaling for future scenarios

Changes in climate conditions will result in changes to rainfall and potential evapotranspiration, which in turn will cause changes in groundwater recharge rates. Under scenarios C and D, groundwater recharge is altered compared to the baseline (historical) recharge. As in previous Sustainable Yields projects, the coupled soil, vegetation and atmosphere WAVES model (Zhang and Dawes, 1998) is used to develop relationships between the future climate scenario and groundwater recharge (Crosbie et al., 2010a). WAVES includes physiological feedbacks in response to increased CO₂ of future climate scenarios and recharge fluxes. The WAVES modelling assumes:

• a 4 m soil profile with a free-draining lower boundary
• drainage through the bottom of the model is equivalent to groundwater recharge
• diffuse recharge in dryland areas is independent of the depth of groundwater below ground surface.

The WAVES model is run for a set of control points that represent a range of soil types and land uses. The results of this point-scale modelling are then upscaled based on gridded climate, soil and vegetation data to create a recharge raster across the entire study region. 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 uses the results from a National Water Commission (NWC) funded project titled ‘Investigating the Impact of Climate Change on Groundwater Resources’ (Crosbie et al., 2012; 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 (2050) climates, and soil and vegetation types 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 (Table 1.1) 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 is expected to be minimal.

In this Assessment the range of future scenarios is represented using a weighted probability distribution. Smith and Chiew (2009) reviewed 16 global climate models, each of which simulated three future climate scenarios (i.e. wet, mid and dry). The 48 future climate recharge scaling factor rasters produced using these models represent the uncertainty in the projection of recharge under a future climate from the different global climate models and projections for global warming. These 48 variants were fitted to a weighted Pearson Type III distribution for each global warming scenario. The method for fitting the probability distribution is given in Crosbie et al. (2010a). The weights used in this modelling (Table 1.1) are derived from the analysis of Smith and Chiew (2009), which was updated by Smith and Chandler (2010).

The range of future scenarios 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. Figure 1.5 shows the recharge scaling factors for the wet extreme, mid and dry extreme future climates. The definition of recharge areas is taken from Habermehl and Lau (1997).

### Table 1.1 Global climate models and their weightings in the probability distributions (Source: Crosbie et al., 2012)

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Name</th>
<th>Country</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Department of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory</td>
<td>GFDL-CM2.1</td>
<td>USA</td>
<td>0.87</td>
</tr>
<tr>
<td>US Department of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory</td>
<td>GFDL-CM2.0</td>
<td>USA</td>
<td>0.8</td>
</tr>
<tr>
<td>Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)</td>
<td>MIROC3.2 (medres)</td>
<td>Japan</td>
<td>0.75</td>
</tr>
<tr>
<td>Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group</td>
<td>ECHO-G</td>
<td>Germany/Korea</td>
<td>0.67</td>
</tr>
<tr>
<td>Max Planck Institute for Meteorology</td>
<td>ECHAM5/MPI-OM</td>
<td>Germany</td>
<td>0.62</td>
</tr>
<tr>
<td>Meteorological Research Institute</td>
<td>MRI-CGCM2.3.2</td>
<td>Japan</td>
<td>0.6</td>
</tr>
<tr>
<td>Canadian Centre for Climate Modelling &amp; Analysis</td>
<td>CGCM3.1(T63)</td>
<td>Canada</td>
<td>0.5</td>
</tr>
<tr>
<td>CSIRO Atmospheric Research</td>
<td>CSIRO-Mk3.5</td>
<td>Australia</td>
<td>0.5*</td>
</tr>
<tr>
<td>Instituto Nazionale di Geofisica e Vulcanologia</td>
<td>INGV-SXG</td>
<td>Italy</td>
<td>0.5*</td>
</tr>
<tr>
<td>Institute for Numerical Mathematics</td>
<td>INM-CM3.0</td>
<td>Russia</td>
<td>0.41</td>
</tr>
<tr>
<td>CSIRO Atmospheric Research</td>
<td>CSIRO-Mk3.0</td>
<td>Australia</td>
<td>0.27</td>
</tr>
<tr>
<td>Météo-France / Centre National de Recherches Météorologiques</td>
<td>CNRM-CM3</td>
<td>France</td>
<td>0.25</td>
</tr>
<tr>
<td>Institut Pierre Simon Laplace</td>
<td>IPSL-CM4</td>
<td>France</td>
<td>0.25</td>
</tr>
<tr>
<td>Bjerknes Centre for Climate Research</td>
<td>BCCR-BCM2.0</td>
<td>Norway</td>
<td>0.12</td>
</tr>
<tr>
<td>NASA/Goddard Institute for Space Studies</td>
<td>GISS-ER</td>
<td>USA</td>
<td>0.12</td>
</tr>
<tr>
<td>National Center for Atmospheric Research</td>
<td>PCM</td>
<td>USA</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* these models were not included in the comparison by Smith and Chiew (2012; 2009) so were given the average weight
Figure 1.5 Spatial distribution of WAVES recharge scaling factors under scenarios C and D
1.7 Structure of this report

This report contains technical material to support the numerical groundwater flow modelling results presented in the four individual region reports and the whole-of-basin report. The key groundwater modelling components of the Assessment are the review of groundwater models and modelling methodologies (Smith and Welsh, 2011), the WAVES (Zhang and Dawes, 1998) recharge modelling (Crosbie et al., 2010a) used in the climate scenarios, the development of the Cape York model, the use of GABtran (Welsh, 2006; 2007), the QWC model (GHD, 2011) and the Cape York model (Chapter 4) for the climate and groundwater development scenarios, and the uncertainty analyses.

The structure of this report is as follows:

- 1 Introduction: introduces the Assessment and describes the review of groundwater models and modelling methodologies, the WAVES recharge modelling, the climate and groundwater development scenarios and the structure of the report
- 2 GABtran model: describes the existing model and its application for the climate and groundwater development scenarios
- 3 Cape York model: describes the development of the Cape York model and its application for the climate and groundwater development scenarios
- 4 Queensland Water Commission model: describes the existing QWC model and its development scenario results
- 5 Uncertainty analyses: describes the approach and processes used to quantify uncertainty in the groundwater modelling
2 GABtran model

2.1 Introduction

Free-flowing artesian bores are being progressively controlled under Great Artesian Basin Sustainability Initiative (GABSI) programs. Under these programs, existing bores are plugged and replaced with new bores fitted with controlled headworks that supply water tanks and cooling ponds that feed stock watering equipment like float-valve controlled troughs. The GABtran model was developed to estimate water level recoveries under different bore rehabilitation scenarios. It underwent peer review by members of the GAB Technical Working Group and three anonymous national/international reviewers.

2.2 Conceptualisation

In the conceptual framework used for GABtran, water enters the sandstone formations either directly as rainfall recharge or through saturated alluvium overlying the intake beds around the elevated basin margin where the modelled aquifer is not overlain by an aquitard. The area of greatest recharge is in the east, along the Great Dividing Range, where both the rainfall and ground elevation are highest. The sandstone aquifers outcrop and subcrop mainly on the western side of the Great Dividing Range. Successively deeper aquifers outcrop successively higher on the range, so deeper aquifers are more pressurised than shallower aquifers, producing upward hydraulic gradients in the basin under unstressed conditions. Lesser amounts of recharge enter along the elevated western and south-western marginal sandstones. Lateral pressure gradients drive groundwater flow through the sandstone aquifers to the discharge areas. Vertical pressure gradients drive inter-aquifer flow toward lower-pressure layers. The natural discharge areas are the lower-elevation parts of the basin margin and natural springs. Since groundwater development of the basin, discharge is also via abstractions from water bores, petroleum wells, mine dewatering, etc. A cross-section of this conceptual framework is shown in Figure 2.1.

![Figure 2.1 Cross-section of the Great Artesian Basin. The GABtran modelled aquifer is shaded blue; other aquifers are shaded grey (adapted from Habermehl and Lau, 1997)](image)

2.3 Original model

This section summarises aspects of the original GABtran model. GABtran was developed to run with standard USGS MODFLOW 2000 software (Harbaugh et al., 2000). Under the groundwater modelling guideline of Middlemis et al. (2000), GABtran has the level of complexity of an ‘Aquifer Simulator’ model. Under the more recent guideline of Barnett et al. (2012), GABtran has a confidence level classification of ‘Class 2.’ Further details are available in Welsh (2006; 2007).
Chapter 2 GABtran model

2.3.1 Boundary conditions

The spatial extent of the active model cells in GABtran is the onshore extent of the shallowest artesian aquifer sequence (Cadna-owie – Hooray and equivalents), truncated in the north approximately 15 km off the Gulf of Carpentaria shoreline and along the Gilbert River in Queensland. The Cape York Peninsula was not included due to data paucity and a lack of bores in that area that could be considered for the GABSI cap and pipe program. The entire model boundary is a no-flow boundary, except for a line of constant head cells off the Gulf of Carpentaria shoreline. The no-flow boundary coincides with the extent of the geological horizons, except along the Gilbert River, which is parallel to the groundwater flow direction in that region.

The Cadna-owie – Hooray Aquifer and equivalents are represented by a single model layer. Recharge enters where the Cadna-owie – Hooray and equivalents layer is not overlain by the Rolling Downs Group aquitard. Every other cell has some vertical leakage. These spatially variable inflows/outflows were estimated during model calibration and represent the net vertical leakage at those locations. The actual vertical leakage is not known, so an objective during model calibration was to minimise the net vertical leakage to prevent it from dominating the water balance. The water balance is presented in Section 2.3.10.

2.3.2 Discretisation

GABtran has annual stress periods and was developed in an Albers (equal area) projection centred over the GAB. The Albers parameters used are listed in Table 2.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>meters</td>
</tr>
<tr>
<td>Spheroid</td>
<td>Australian</td>
</tr>
<tr>
<td>Datum</td>
<td>WGS84</td>
</tr>
<tr>
<td>Quadrant</td>
<td>NE</td>
</tr>
<tr>
<td>1st standard parallel (degrees)</td>
<td>−21° 00’ 00”</td>
</tr>
<tr>
<td>2nd standard parallel (degrees)</td>
<td>−29° 00’ 00”</td>
</tr>
<tr>
<td>Central meridian (degrees)</td>
<td>143° 00’ 00”</td>
</tr>
<tr>
<td>Latitude of projection’s origin (degrees)</td>
<td>−25° 00’ 00”</td>
</tr>
<tr>
<td>False easting (metres)</td>
<td>0.0</td>
</tr>
<tr>
<td>False northing (metres)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The model grid is aligned north-south and east-west. The cells’ dimensions are all 5 km x 5 km, and so each cell has an area of 25 km². The grid information as represented in the ArcInfo Geographic Information System (GIS) is listed in Table 2.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of columns</td>
<td>376</td>
</tr>
<tr>
<td>Number of rows</td>
<td>359</td>
</tr>
<tr>
<td>X lower left corner</td>
<td>−1,045,000</td>
</tr>
<tr>
<td>Y lower left corner</td>
<td>−830,000</td>
</tr>
<tr>
<td>Cell size</td>
<td>5,000</td>
</tr>
</tbody>
</table>
2.3.3 Aquifer thickness

Aquifer thickness was initially determined from bore logs and seismic studies. A spatially variable scaling parameter (varying from 0.5 to 2.0) was subsequently estimated during model calibration, which allowed for cell-by-cell adjustment of aquifer thickness. The calibrated model layer thickness varies from 1.5 to 1409 m and averages 202 m. The greatest estimated aquifer thickness is in the north-east of the Surat Basin.

Since the compressibility factor was fixed during calibration (see next section), any variation in the compressibility is accounted for in the optimised aquifer thickness.

2.3.4 Aquifer hydraulic properties

Transmissivity was derived from the product of aquifer thickness with horizontal hydraulic conductivity. Storativity was derived from the product of aquifer thickness with the compressibility of water (set at $5 \times 10^{-6}$ per m (Hazel, 1975)) in the confined parts of the aquifer. Specific yield in the unconfined parts of the aquifer, which was assigned as those parts receiving recharge, was able to vary during calibration.

Values of horizontal hydraulic conductivity range from 0.1 to 20 m/day. It is lowest over the deepest parts of the Basin and over the Coonamble Embayment, in general agreement with Radke et al. (2000). Transmissivity values reach a maximum of 22,629 m²/day, but have a median of 326 m²/day over the whole model and are less than 5,000 m²/day over 92 percent of cells.

Calibrated storage coefficients range from $7 \times 10^{-6}$ to $7 \times 10^{-3}$ in the non-recharge parts of the model. Specific yield in the recharge areas ranges from $8 \times 10^{-6}$ to 0.155. The lowest values suggest that some areas designated for recharge might not be intake beds. The maximum specific yield occurs in the Queensland intake beds. The median storage values are $6.5 \times 10^{-4}$ and $3.3 \times 10^{-4}$ for the confined and unconfined parts of the basin respectively.

2.3.5 Natural recharge

Modelled recharge varies spatially from 0 m/day up to $9.0 \times 10^{-5}$ m/day (33 mm/year) but averages $6.5 \times 10^{-6}$ m/day (2.4 mm/year). The highest rate of recharge (about 7 percent of rainfall) occurs where the intake beds are at their maximum elevation on the Great Dividing Range. The lowest rates of recharge are in South Australia.

A recharge study by Kellett et al. (2003) found that, over most of the GAB intake beds they studied in Queensland, the time taken for recharge to enter the water table is thousands of years, so recharge is time-invariant and not calculated as a function of rainfall in the model.

2.3.6 Inter-aquifer leakage

Net vertical leakage rates range from $-2.6 \times 10^{-6}$ to $3.5 \times 10^{-6}$ m/day, i.e. from 0.94 mm/year out of the model aquifer to 1.3 mm/year into the model aquifer. The mean overall leakage rate at non-recharge model cells is $3.6 \times 10^{-8}$ m/day (about 0.01 mm/year) into the model aquifer. Inter-aquifer leakage is time-invariant in the model.

2.3.7 Water, oil and gas extraction

Water, oil and gas extraction rates are time-variant in the model. The locations of the extraction points are shown in Figure 2.2. Water, oil and gas extraction data obtained from the relevant state agencies were processed to produce average yearly extraction rates for each water bore and petroleum well. Spring discharges were estimated based on the available information. For many bores, extraction records were not available for every year; so discharge rates were kept constant at the last measured rate until the next available measurement. Bores with no recorded extraction rate, except those known to be for monitoring only, were assigned a rate of 0.2 L/second. This rate was based on an estimate of the average flow rate of bores in the unconfined parts of the Basin. Where available, the recorded flow-on-arrival rate was used as the modelled extraction rate. Flows from bores listed as tapping multiple aquifers were reduced proportionately.
For example, the extraction rate of a bore tapping both the Hooray Sandstone (part of the modelled aquifer) and the Hutton Sandstone (a deeper aquifer) would be halved.

Petroleum well extractions (oil, gas and water) were well documented. Averages over each year were used.

The total modelled extraction rate (Table 2.3) increases from 604 GL/year in 1965 to a maximum of 663 GL/year in 1995, and drops slightly to 660 GL/year in 1999.
Table 2.3 Selected annual modelled extraction rates (GL/year)

<table>
<thead>
<tr>
<th>Extraction component</th>
<th>1965</th>
<th>1995</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bores</td>
<td>554</td>
<td>607</td>
<td>604</td>
</tr>
<tr>
<td>Springs</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Petroleum wells</td>
<td>0</td>
<td>5.6</td>
<td>5.7</td>
</tr>
</tbody>
</table>

2.3.8 Natural springs

Spring flow rates were estimated from descriptions that accompanied the spring data, and were kept constant over the 1965–1999 calibration period. Springs are modelled as well file discharges. The locations of the springs are shown in Figure 2.2.

2.3.9 Calibration process

Model calibration was achieved using a combination of manual and automated parameter value adjustments. The most obvious data errors were identified and rectified during early manual calibration runs. Automated calibration was then undertaken using PEST (Doherty, 2010; WNC, 2004), which included use of parameter regularisation and manual adjustments to calibration data and/or parameter value limits between runs.

For the final calibration run, the number of calibration bores was reduced to 254 based on the work of Merrick (1999), who found that an exclusion radius of 20 km gave the smallest network that would be sufficient to describe the observed groundwater level distribution without undue deterioration of the resolution of the spatial groundwater level variations. Spatially distributed pilot point values were adjusted for two parameters (horizontal hydraulic conductivity and vertical leakage) and three multipliers (recharge, aquifer thickness and storage). Multipliers were used rather than parameters in order to constrain estimated values using the observed thickness and recharge data. The number of pilot points used and their respective parameter bound are listed in Table 2.4.

Table 2.4 Parameters modified by PEST during GABtran calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Permitted variation</th>
<th>Number of pilot points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal hydraulic conductivity</td>
<td>0.1–20 m/d</td>
<td>466</td>
</tr>
<tr>
<td>Vertical leakage</td>
<td>set individually</td>
<td>306</td>
</tr>
<tr>
<td>Recharge multiplier</td>
<td>0.5–2.0 times</td>
<td>465</td>
</tr>
<tr>
<td>Thickness multiplier</td>
<td>0.5–2.0 times</td>
<td>466</td>
</tr>
<tr>
<td>Storage multiplier – confined</td>
<td>set at 5 x 10^-6</td>
<td>1</td>
</tr>
<tr>
<td>Storage multiplier – unconfined</td>
<td>0–0.3</td>
<td>44</td>
</tr>
</tbody>
</table>

During each automated calibration run, estimated parameter values were substituted into a warm-up model (1960–1965), which produced an initial groundwater level distribution for the historical (1965–2000) model. The groundwater level distribution produced by the historical model was then interpolated to the observation bore locations and times and then corrected for local pumping effects. These corrections reduced the modelled hydraulic heads to resemble production bore observed hydraulic heads.

Automated calibration of the GABtran model sought to minimise three objectives:

1. the difference between modelled and observed temporal groundwater level gradients over 1-year intervals
2. the difference between modelled and observed groundwater level values at the end of each 1-year stress period
3. vertical leakage at each pilot point, for which an initial (i.e. preferred) value of zero was specified.
Observations were weighted so that the total objective function was most sensitive to changes in the groundwater level gradient (objective 1), less sensitive to changes in the absolute groundwater level (objective 2), and least sensitive to changes in the vertical leakage preferred value (objective 3). This reflects the relative importance of the model’s intended uses, these being respectively: to simulate the impact of changing bore flows, to more generally inform water management plans and to provide an estimate of the water balance. Leakage flux was minimised to prevent it dominating the water balance.

The statistical performance measures of the calibration were found to be well within acceptable levels, as defined by Barnett et al. (2012). For both objectives 1 and 2 above, the scaled mean sum of residuals (SMSR) is less than 2 percent and the scaled root mean square (SRMS) is less than 3 percent.

### 2.3.10 Water balance

The GABtran water balance is shown in Table 2.5. Water bore extractions form the largest component of the water balance and are approximately double the recharge rate to intake beds. Water savings from GABSI phase 1 were estimated to be 96 GL/year, or nearly 30 percent of the shortfall between inflows and outflows in GABtran.

The net rate of vertical leakage out of the model is eight times the net rate of vertical leakage into the model. Leakage fluxes represent only 12 percent of the total outflows from the model, and only 2 percent of the total inflows. Actual leakage rates are likely to be higher because the reported values are the residual (net) flows. As a comparison, the Assessment estimated diffuse leakage at 294 GL/year from the Cadna-owie – Hooray Aquifer and equivalents for the combined Central Eromanga, Western Eromanga and Surat regions; no estimate was able to be made for the Carpentaria region (see Chapter 7 in the companion region reports as listed in Appendix A). Vertical leakage could be through the top or the bottom of the modelled aquifer.

<table>
<thead>
<tr>
<th>Flow direction</th>
<th>Water balance component</th>
<th>Range of values (GL/y)</th>
<th>Average value (GL/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In Recharge</td>
<td></td>
<td>323</td>
<td>323</td>
</tr>
<tr>
<td>In Vertical leakage</td>
<td></td>
<td>106</td>
<td>106</td>
</tr>
<tr>
<td>In Sea water</td>
<td></td>
<td>0.7 to 1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>In Total inflow</td>
<td></td>
<td>430 to 431</td>
<td>430</td>
</tr>
<tr>
<td>Out Water bores</td>
<td></td>
<td>554 to 607</td>
<td>591</td>
</tr>
<tr>
<td>Out Springs</td>
<td></td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Out Petroleum wells</td>
<td></td>
<td>0 to 5.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Out Vertical leakage</td>
<td></td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>Out Coastal discharge</td>
<td></td>
<td>9.6 to 15.0</td>
<td>11.5</td>
</tr>
<tr>
<td>Out Total outflow</td>
<td></td>
<td>707 to 760</td>
<td>742</td>
</tr>
<tr>
<td>Change in storage</td>
<td></td>
<td>–330 to –277</td>
<td>–312</td>
</tr>
</tbody>
</table>

### 2.3.11 Sensitivity analysis

The following order of increasing model sensitivity of the average groundwater level change to parameter perturbations was determined by changing one parameter per model run:

- sensitivity to storage < sensitivity to leakage < sensitivity to transmissivity < sensitivity to recharge < sensitivity to extractions

The area with the steepest hydraulic gradient, which is adjacent to the recharge area at the highest ground surface elevation on the Great Dividing Range, was the most sensitive to changes in recharge rate.
2.3.12 Limitations of GABtran

The review of groundwater models and modelling methodologies (Smith and Welsh, 2011) recommended that the GABtran model should be adopted as the most suitable existing groundwater model for the purposes of the Assessment, noting that key limitations with respect to the Assessment need to be addressed. Since the Assessment is unable to extend GABtran to a multi-layered model, the technical report further recommended that the inherent limitations of using GABtran should be accepted by the Assessment. This section discusses those limitations.

Model purpose

Every groundwater model is developed with an end use in mind. GABtran was developed to inform the GABSI and designed to answer questions such as: ‘what is the likely regional water level recovery if the flow from artesian bore X is reduced through bore rehabilitation from Y L/second to Z L/second?’. That objective differs slightly from the objective of the Assessment, which is to estimate the impact of the climate and groundwater development scenarios across the GAB in 2070.

Model conceptualisation

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.

Spatial extent

GABtran has 84 percent ground coverage of the GAB (Smith and Welsh, 2011). The main areas not covered are: (i) Cape York Peninsula north of the Gilbert River, (ii) the Laura Basin, and (iii) intake beds of the deeper artesian aquifers.

Since GABtran covers only 46 percent of the Carpentaria region, a new numerical groundwater flow model for Cape York has been developed (Chapter 4).

The spatial distribution of water bore data in the GAB is quite uneven. Model results in areas located away from calibration bores are less reliable. In particular, the emphasis for GABtran calibration was the confined/artesian areas of the basin, so model results in the unconfined recharge areas are less reliable. Model reliability is emphasised in the Assessment by including the locations of the calibration bores in maps of model results.

Climate scenarios

Climate change impacts are implemented in GABtran as recharge scaling factors, which are applied over areas of rain-derived recharge. Consequently, the ability to run the climate scenarios is contingent on having those recharge areas represented in the model.

GABtran models only the shallowest artesian aquifer, so the impacts of climate change on this layer can be estimated. Historically, most GAB water extractions have been from this layer. The impacts of climate change on other GAB aquifers cannot be estimated using GABtran because those layers are not included in the model.

Groundwater development scenarios

Future development is represented as water, oil and gas extraction or injection rates that vary over time. The ability to simulate development scenarios is contingent on having time-varying extraction/injection fluxes represented in the model.

GABtran can include these time-varying fluxes, but only if they come from or go into the shallowest artesian aquifer. As described above, deeper and shallower GAB units are not represented. Consequently, GABtran is able to estimate the impact of mine site developments at Olympic Dam, Cannington-Osborne, Ernest Henry and Mount Margaret, but not from the coal seam gas industry in the Surat region or from Prominent Hill mine in the Western Eromanga region. A collaboration and data transfer agreement were established between CSIRO and the QWC for the Assessment’s modelling of CSG impacts (Chapter 0).
Feedback loops

Ideally, when bore flows are reduced after rehabilitation works, the flow from nearby springs and uncontrolled bores should increase. These feedback loops are not implemented in GABtran, so these water level recoveries are expected to be overestimated. Similarly, when more water is extracted from the basin, spring flow rates in the vicinity should decrease, but these feedback loops are not in GABtran, so water level reductions under these circumstances are expected to be overestimated. Vertical inter-aquifer leakage should respond to changes in hydraulic head in adjacent layers, but this is not implemented in GABtran either.

Scenario durations

The generally-accepted rule of thumb is that simulations that extend a model for more than 100 percent of the calibration period provide increasingly uncertain results. The scenarios under this Assessment extend the GABtran calibration period by 200 percent.

2.4 Modifications to original model

GABtran was not modified from its original parameterisation, except as required to run the climate and groundwater development scenarios.

2.5 Model application: scenarios

The spatially variable long-term average vertical leakage parameters were extended unchanged under all the following scenarios.

2.5.1 Base run

The base run simulates the effects of:

- historical climate from 1 January 1965 to 31 December 2010
- historical development from 1 January 1965 to 31 December 2010.

GABtran has a single, spatially variable long-term average recharge parameter set for the period 1965–1999. For the base run, this was extended unchanged to 2010.

GABtran’s historical extractions for the period 1965–1999 were based upon analyses of production data provided by state agencies. Similar analyses were used to extend the well file 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. In the absence of new data, spring flows were held at their 1999 rates.

2.5.2 Scenario A: historical climate and current development

Scenario A extends 31 December 2010 climate and groundwater development unchanged to 2070. Figure 2.3 shows the change in groundwater level under Scenario A at 2070.

Scenario A estimates that groundwater extraction exceeds replenishment in South Australia; in Queensland the greatest impacts are along the eastern boundary; and in New South Wales most impacts are within a 5 m increase and a 5 m decrease in groundwater level. The apparent increase in groundwater level in excess of 5 m in the Central Eromanga region is not supported by calibration bores and is likely to be an artefact of the modelling process. Similarly, confidence in the model results is lower in other areas without calibration bore coverage. Boundary conditions at the Gulf of Carpentaria and at the Cape York Peninsula divide might be affecting results in the north.
Figure 2.3 Change in GABtran groundwater level (m) under Scenario A
Note: legend shows change in groundwater level (m)
2.5.3 Scenario C: future climate and current development

Under scenarios Cwet, Cmid and Cdry the recharge scaling factors (Figure 1.5) were linearly increased from nil impact in 2010 to their full impact in 2070. Scenario C extends 31 December 2010 development unchanged to 2070.

Statistics of the recharge scaling factors and their impact on model recharge over all GABtran recharge cells and in the four regions are shown in Table 2.6. Note that the average impact of these, as shown by the change in recharge compared 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 in the Carpentaria region, average groundwater recharge in 2070 is an increase of 34 percent compared to recharge in 2010.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Recharge scaling factor range</th>
<th>Recharge scaling factor mean</th>
<th>Recharge scaling factor median</th>
<th>Mean change in recharge in 2070 relative to Scenario A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GABtran</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cwet and Dwet</td>
<td>1.01–2.39</td>
<td>1.43</td>
<td>1.41</td>
<td>1.55</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>0.72–1.80</td>
<td>0.96</td>
<td>0.90</td>
<td>1.08</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.13–1.30</td>
<td>0.55</td>
<td>0.50</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Carpentaria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cwet and Dwet</td>
<td>1.48–2.39</td>
<td>1.84</td>
<td>1.81</td>
<td>1.83</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>1.18–1.80</td>
<td>1.40</td>
<td>1.36</td>
<td>1.34</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.70–1.30</td>
<td>1.01</td>
<td>1.00</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>Central Eromanga</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cwet and Dwet</td>
<td>1.04–1.90</td>
<td>1.45</td>
<td>1.44</td>
<td>1.55</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>0.80–1.42</td>
<td>0.99</td>
<td>0.97</td>
<td>1.12</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.29–0.93</td>
<td>0.60</td>
<td>0.60</td>
<td>0.72</td>
</tr>
<tr>
<td><strong>Surat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cwet and Dwet</td>
<td>1.01–2.05</td>
<td>1.59</td>
<td>1.61</td>
<td>1.54</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>0.74–1.31</td>
<td>1.10</td>
<td>1.11</td>
<td>1.06</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.13–0.90</td>
<td>0.66</td>
<td>0.68</td>
<td>0.62</td>
</tr>
<tr>
<td><strong>Western Eromanga</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cwet and Dwet</td>
<td>1.04–1.54</td>
<td>1.25</td>
<td>1.23</td>
<td>1.32</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>0.72–1.26</td>
<td>0.79</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.25–0.90</td>
<td>0.39</td>
<td>0.41</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Figure 2.4 shows the change in groundwater level under scenarios Cwet, Cmid and Cdry. It is estimated that groundwater extraction will exceed replenishment in most of the south and west of the Eromanga Basin and in a wide arc through Roma and Charleville to Longreach, while near areas of higher recharge in New South Wales and Queensland, groundwater levels are estimated to increase due to recharge exceeding groundwater use. The pattern is generally similar under the wet and dry extreme climates. Exceptions are increases in groundwater level near Marla in the west of the Western Eromanga region under the wet extreme climate, and decreases in groundwater level over most of the intake beds under the dry extreme climate. These basin-margin areas that are most sensitive to changes in groundwater recharge have a lower capacity to transmit water down gradient (i.e. a lower transmissivity).
Figure 2.4 Change in GABtran groundwater level (m) under Scenario C

Note: legend shows change in groundwater level (m)

Figure 2.5 shows the change in groundwater level under scenarios Cwet, Cmid and Cdry relative to Scenario A. These differences remove temporal effects and thereby identify impacts of climate alone. Since the recharge scaling factors are all more than 1 under Scenario Cwet, and mostly less than or equal to 1 under Scenario Cdry (Figure 1.5), groundwater level increases under Scenario Cwet and mostly decreases under Scenario Cdry.
Figure 2.5 Change in GABtran groundwater level (m) under Scenario C relative to Scenario A

Note: legend shows change in groundwater level (m)
2.5.4 Scenario D: future climate and future development

Under scenarios Dwet, Dmid and Ddry the recharge scaling factors (Figure 1.5) 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 made when estimating future development are listed in Table 2.7. Stock and domestic water bores will continue to be rehabilitated. 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 a constant 0.2 L/second. There are insufficient data to estimate a future change in spring flows, so no change is assumed. Petroleum extractions overall have been stable over recent years, so no change is assumed for these too. New South Wales plans to allocate 30 percent of their water saved through bore rehabilitations. In Queensland, the Water Resource (Great Artesian Basin) Plan 2006 details the amounts of water that will be allocated to each groundwater management zone. South Australia has no plan to reallocate water saved through their bore rehabilitations. Although Queensland and New South Wales reallocations to date have been less than planned, the planned amounts have been used in this modelling.

Table 2.7 Future development assumptions under Scenario D for the GABtran model

<table>
<thead>
<tr>
<th>Development type</th>
<th>New South Wales</th>
<th>Queensland</th>
<th>South Australia</th>
<th>Northern Territory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bores with allocations</td>
<td>Flows are set to their licensed levels for 2011 to 2070</td>
<td>Flows are set to their licensed levels for 2011 to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
</tr>
<tr>
<td>Artesian stock and domestic bores</td>
<td>Bores not yet rehabilitated but flowing &gt;1.27 L/s are reha</td>
<td>Bores not yet rehabilitated and flowing &gt;1.27 L/s are reha</td>
<td>Bores not yet rehabilitated and flowing &gt;1.27 L/s are reha</td>
<td>Flows remain at their 2010 levels to 2070</td>
</tr>
<tr>
<td>domestic bores without water allocations</td>
<td>bilitated at a rate of 20 bores per year (over whole GABtran area) starting with the highest-flowing bores.</td>
<td>bilitated at a rate of 27 bores per year (over whole GABtran area) starting with the highest-flowing bores.</td>
<td>bilitated over 10 years starting with the highest-flowing bores.</td>
<td>Flows remain at their 2010 levels to 2070</td>
</tr>
<tr>
<td>Sub-artesian bores without allocations</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
</tr>
<tr>
<td>Allocation of water saved</td>
<td>30 percent of water savings are added back to the rehabilitated bore flow rates.</td>
<td>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.</td>
<td>No reallocation</td>
<td>No reallocation</td>
</tr>
<tr>
<td>Petroleum wells</td>
<td>N/A</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>No petroleum wells</td>
</tr>
<tr>
<td>Springs</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
<td>Flows remain at their 2010 levels to 2070</td>
</tr>
</tbody>
</table>

Table 2.8 compares Scenario D development in 2070 with scenario A and C development for the whole of GABtran and the four regions. Under Scenario D, total discharge is estimated to decrease by about 40 percent (from 532 GL/year to 322 GL/year) due to ongoing capping and piping of stock and domestic water bores.
### Table 2.8 Summary of current and future development discharge estimates used in GABtran scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Water bores</th>
<th>Petroleum wells</th>
<th>Springs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ML/y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GABtran</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A and C</td>
<td>2070</td>
<td>481,557</td>
<td>3,450</td>
<td>47,139</td>
<td>532,146</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>271,721</td>
<td>3,450</td>
<td>47,139</td>
<td>322,310</td>
</tr>
<tr>
<td>Carpentaria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A and C</td>
<td>2070</td>
<td>37,846</td>
<td>0</td>
<td>694</td>
<td>38,540</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>9,707</td>
<td>0</td>
<td>694</td>
<td>10,401</td>
</tr>
<tr>
<td>Central Eromanga</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A and C</td>
<td>2070</td>
<td>152,120</td>
<td>3,450</td>
<td>5,775</td>
<td>161,345</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>62,485</td>
<td>3,450</td>
<td>5,775</td>
<td>71,710</td>
</tr>
<tr>
<td>Surat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A and C</td>
<td>2070</td>
<td>231,532</td>
<td>0</td>
<td>2,644</td>
<td>234,176</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>140,747</td>
<td>0</td>
<td>2,644</td>
<td>143,391</td>
</tr>
<tr>
<td>Western Eromanga</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A and C</td>
<td>2070</td>
<td>60,058</td>
<td>0</td>
<td>38,025</td>
<td>98,083</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>58,782</td>
<td>0</td>
<td>38,025</td>
<td>96,807</td>
</tr>
</tbody>
</table>

Figure 2.6(a), Figure 2.6(b) and Figure 2.6(c) show changes in groundwater level under scenarios Dwet, Dmid and Ddry. The results show the impact of projecting both future climate and future development from 2010 to 2070. It is estimated that groundwater extraction will exceed replenishment over most of the GAB except where bore densities are high around the Euroka Arch and the Nebine Ridge, driven by the rehabilitation of free-flowing stock and domestic water bores. The pattern is very similar under the wet and dry extreme climates, except in the south-eastern and south-western intake beds, which are the most sensitive to changes in recharge.

Figure 2.6(d) shows changes in groundwater level under Scenario D relative to Scenario C. Calculating this difference removes both temporal and climatic effects and thereby identifies impacts of future development alone. The impact of future development alone is estimated to be a gradual recovery of groundwater level, except in some parts of the east of the Surat Basin where some groundwater level decline is estimated. Note that the high estimated groundwater level declines in the south of the Surat Basin are not well-supported by calibration bores.
Figure 2.6 Change in GABtran groundwater level (m) under Scenario D
Note: legend shows change in groundwater level (m)
3 Queensland Water Commission model

3.1 Introduction

The Queensland Water Commission (QWC) model was developed to provide information to meet the QWC’s cumulative management area reporting requirements under Section 376 of the Queensland Water Act 2000. In particular, the QWC model synthesises knowledge of the aquifers, water bores, hydrological processes and quantities of water being extracted and forecasts impacts from coal seam gas (CSG) activities on groundwater levels and natural springs in the Surat area. The model underwent peer review by members of a Technical Advisory Panel appointed by the QWC.

The QWC model area straddles the Great Dividing Range, and encompasses the Queensland portion of the Surat Basin and the western part of the Clarence-Morton Basin, and the southern part of the Bowen Basin. The Bowen Basin is the oldest basin and runs north-south through the centre of the region. Overlying this is the Surat Basin. The Clarence-Moreton Basin interfingerls with the Surat Basin across the Kumbarilla Ridge to the east. Overlying these Basins are extensive areas of unconsolidated Cainozoic alluvial sediments and volcanics.

3.2 Conceptualisation of Great Artesian Basin components

The GAB comprises a sequence of alternating layers of water-bearing (permeable) sandstone aquifers and non-water-bearing (low permeability) siltstone or mudstone aquitards, which generally dip in a south-westerly direction in this region. Regionally the main aquifers and aquitards in the GAB approximate the stratigraphic units or geological formations. However locally, most aquifers contain minor interbedded siltstone and mudstone, and several aquitards contain minor aquifers of permeable sandstones and siltstones. Permeability, and therefore hydraulic conductivity, declines with depth within the deeper units.

Recharge mostly occurs along the outcrop areas in the north, north-west, north-east and east along the Great Dividing Range. Groundwater movement is dominated by sub-horizontal flow in the aquifers, with upwards vertical leakage from the aquifers through the aquitards occurring at a much slower rate.

Natural discharge occurs through springs, rivers, vertical leakage, and subsurface flow into adjoining areas. Groundwater extraction for agriculture and urban uses is variable across the basin. Shallower artesian aquifers are more heavily utilised than deeper aquifers. CSG extraction in the Surat Basin commenced in 2002, later than the Bowen Basin. The Surat Basin wellfields extract gas from Walloon Coal Measures (WCM). The major CSG fields in the Surat Basin are:

- Talinga Field, located approximately 25 km south-west of Chinchilla – operated by Origin Energy since 2005
- Argyle-Kenya and Berwyndale South fields – operated by Queensland Gas Company in its Central Development Area near Chinchilla since mid-2005
- Kogan North, Tipton, Daandine, and Stratheeden fields – operated by Arrow Energy since 2006
- Roma field – operated by Santos since mid 2007.

Water quality in the aquifers is generally fresh to brackish and suitable for stock, with salinity averaging 1,200 mg/L total dissolved solids (TDS). The WCM generally have a higher salinity, varying from approximately 1,000 mg/L to over 20,000 mg/L TDS. Water quality is spatially variable due to the lateral and vertical heterogeneity of the WCM lithology. Generally, low permeability siltstones and mudstones at the top and bottom of the WCM act as aquitards separating the productive coal seams from the overlying Springbok Sandstone aquifer and the underlying Hutton and Marburg Sandstone aquifers.

The system conceptualisation for the QWC model is consistent with that for the GABtran model.
3.3 Model construction

This section summarises aspects of the Queensland Water Commission coal seam gas regional groundwater flow model (the ‘QWC model’). Under the groundwater modelling guideline of Middlemis et al. (2000), the QWC model has the level of complexity of an ‘Aquifer Simulator’ model. Under the more recent guideline of Barnett et al. (2012), the QWC model has a confidence level classification of ‘Class 2’. Further details on the QWC model are available in GHD (2011).

3.3.1 Modelling approach

The QWC model is run using MODFLOW 2005 (Harbaugh, 2005). A calibrated steady state model for the period prior to 1995 was developed to estimate aquifer properties and initial hydraulic conditions. A full transient model was not calibrated due to insufficient groundwater level time series data for calibration, and practical considerations related to long model run times. Instead, a transient sub-model of an existing CSG production field (Kogan North / Daandine, operational since 2005) was developed and calibrated over the period of January 1995 to December 2010. This sub-model is nested within, and took initial boundary conditions from the steady state model. Calibrated parameters from the nested sub-model were imported into the larger steady state model, which was then re-calibrated with these parameters fixed. The transient regional model was used for the predictive scenarios.

Calibration of both the steady state regional model and the transient sub-model was undertaken using pilot point parameterisation and using the Singular Value Decomposition Assist (SVDA) capability included in PEST (Doherty, 2010). SVDA allows for parameters to be grouped according to their sensitivity. These linear combinations of base parameters are then adjusted during the optimisation process rather than adjusting parameters individually. This approach greatly improves efficiency when calibrating a complex transient model while preserving a highly parameterised approach.

The regional steady state model was calibrated to average groundwater levels from 1541 production bores. Overall, there was no general long-term trend in pre-1995 groundwater levels. To maximise use of the available data, some post-1995 water levels were included based on individual assessments of suitability. The data included some nested piezometer readings to help constrain rates of vertical leakage. Due to erroneous observations, 136 calibration boreholes were discarded during calibration. The SRMS error of the steady state calibration across all targets is 3.7 percent, which is within the guideline recommendation (Barnett et al., 2012).

3.3.2 Discretisation and boundaries

The model area of 661.5 km (north-south) x 547.5 km (east-west) is discretised into 441 rows and 365 columns, so that each model layer contains up to 160,965 model cells. Individual model cell dimensions are 1500 m x 1500 m. The active model area is 278,883 km². There are 19 model layers, from the Cainozoic Main Range Volcanics down to pre-Bandanna Formation Permian units of the Bowen Basin. The GAB sequence within this (i.e. Rolling Downs Group to Precipice Sandstone) is represented with 13 layers.

No-flow boundaries are used to the north of the Surat Basin units, and to the east and west of the Bowen Basin units because there is no evidence of groundwater connectivity across these geological boundaries. There is no anticipated connectivity between the northern and southern halves of the Bowen Basin, so the northern model boundary is a no-flow boundary. The western model boundary is a no-flow boundary because little or no interaction is thought to occur across the Nebine Ridge. A general head boundary is used along the eastern margin of the model in the CSG-producing layers to simulate interaction with the Clarence-Moreton Basin across the Kumbarilla Ridge. A general head boundary is also used along the southern margin of the model (which coincides with the State border) in the productive coal and aquifer units to allow flow to continue to the south into New South Wales.

All model layers are simulated as fully confined units. Consequently, transmissivity remains constant as water level varies. Storativity values are based on specific yield (i.e. unconfined storage) in areas where layers are present at outcrop and specific storage (i.e. confined storage) in non-outcrop areas.

The predictive model simulates a 3,000 year period from the commencement of CSG extraction in early 1995, through the main extraction period to 2050, and a subsequent 2,944 year recovery period.
A total of 259 stress periods are distributed as:

- 1 initial steady state stress period (pre-1995)
- 64 quarterly stress periods (January 1995 to December 2010)
- 84 annual stress periods (January 2011 to December 2014)
- 90 decadal stress periods (January 2015 to December 2044)
- 20 century-length stress periods (January 2045 to December 2094).

During model development, one time step was specified per stress period, but extra time steps were added to improve model convergence:

- 14 time steps were added to 5 stress periods between 2011 and 2015
- Two time steps were added to 9 stress periods between 2016 and 2033.

The scenarios under this Assessment extend the QWC calibration period by about 400 percent. Generally, simulations that extend a model for more than 100 percent of the calibration period provide increasingly uncertain results.

### 3.3.3 Hydraulic conductivity

Horizontal flow dominates in the aquifers and vertical leakage dominates in the aquitards. Horizontal hydraulic conductivity ($K_h$) was calibrated for all productive coal and aquifer units; vertical hydraulic conductivity ($K_z$) was calibrated for all aquifers. $K_h$ was allowed to vary during calibration between about $1 \times 10^{-4}$ and 5 m/day. $K_z$ was allowed to vary during calibration between about $1 \times 10^{-7}$ and $1 \times 10^{-3}$ m/day.

Vertical anisotropy (i.e. $K_h/K_z$) factors, which are used to calculate $K_z$ for aquifers and $K_h$ for aquitards, were calibrated. Upper bounds for most layers were set to 1,000; most lower bounds were set to 1 for aquifers and 10 for aquitards. Calibrated anisotropy factors for the sandstones layers varied from 6 to 18. Anisotropy factors for the aquifers were much more variable (6 to 5000) suggesting significant grainsize coarsening in some units, and showing the impact of coal stratification in the WCM.

Initial values of hydraulic conductivity were calibrated within permissible limits. Existing data suggested a statistically significant depth relationship with hydraulic conductivities for coal formations and deeper GAB formations. Therefore for deeper formations the initial values of hydraulic conductivities were based on depth relationships.

### 3.3.4 Recharge

Recharge was applied to the uppermost active layer (aquifer or aquitard) in each model cell. During calibration, recharge was allowed to vary on a zonal basis between 1 mm/year and 30 mm/year, with the following exceptions:

- zero recharge was assumed where Condamine Alluvium was present,
- a lower limit of 20 mm/year was applied where Main Range Volcanics were present.

Recharge rates for the 278,883 km$^2$ area of active model cells were informed by a study of bore RN 4222061, which monitors groundwater level in the Mooga Sandstone west of Roma. The study also considered results produced by the PERFECT model (Littleboy et al., 1989) based on climate information from the Roma airport weather station as well as the recharge estimation work of Kellett et al. (2003). The study found that the long-term average recharge rate at RN 4222061 is 25.4 mm/year comprising 21.0 mm/year of bypass recharge and 4.4 mm/year of diffuse rainfall recharge.

The steady state (pre-1995) regional model estimates a long-term average recharge rate of 6.8 mm/year, which represents 1.2 percent of mean annual rainfall at Roma airport.

For the transient regional model, multipliers for each of the 21 recharge zones were calculated as the ratio of the calibrated recharge for that zone from the steady state model to the long-term average recharge estimate from the PERFECT model for monitoring bore RN 4222061. For the period from January 1995 to December 2010, these multipliers were used to adjust the PERFECT model recharge time series using observed climate data for each of the
21 recharge zones. For the post-2010 period, these multipliers were used to adjust the long-term average PERFECT model recharge time series for each of the recharge zones.

3.3.5 Surface water – groundwater interactions

Surface water – groundwater interactions have been simulated using the MODFLOW Drain and River packages. Consistent with Hillier (2010), it was assumed that GAB aquifers discharge through the overlying Condamine Alluvial sediments (where present), which thereby act as a drain for the underlying GAB strata.

Calibrated groundwater levels from the more detailed transient Condamine Water Resource Planning model (Berger, 2011) were used to define the river cell elevations within the modelled Condamine Alluvium area. River stages in other areas are set at ground level, consistent with the relatively minor extractions beyond the Condamine Alluvium. Otherwise the uppermost active layer cells were specified as drains whose elevations were set at ground level. This enforced topographic control on groundwater levels.

The modelled water balance results suggest that 93 percent of recharge exits the model locally via surface water systems, i.e. as discharge via modelled drain and river cells.

Flows into and out of the model are small:

- The rate of inflow from the Clarence-Moreton Basin to the east is 0.6 percent of the modelled recharge rate.
- The rate of outflow to the remainder of the GAB to the south is 0.9 percent of the modelled recharge rate.

3.3.6 Storage

Storage coefficients were estimated via calibration of the Kogan North / Daandine sub-model. This CSG development area has been operational since 2005 and has a good observation bore network, including time series of groundwater levels from six monitoring bores screened in the productive coal units of the WCM. The sub-model represents an area of 24 km (north-south) x 25.5 km (east-west) that is discretised into 96 rows x 102 columns, giving up to 9,792 model cells in each layer. The cells are 250 m x 250 m and use the same 19 layer vertical discretisation as the regional model. Quarterly stress periods were used, with one time step per stress period. The sub-model was calibrated to groundwater levels over the period January 1995 to December 2010 (16 years). During model calibration, specific storage was allowed to vary from $5 \times 10^{-6}$ to $1 \times 10^{-1}$ per metre for aquifers and $1 \times 10^{-2}$ per metre for aquitards. The average specific storage for the productive WCM layer was estimated as $1.9 \times 10^{-5}$ per metre.

Specific storage values for the Bandanna Formation were taken from the Bowen Basin groundwater model developed by Santos (2010).

For the transient regional model, specific storage was allowed to vary spatially within each model layer. For the WCM and the Bandanna Formation, distributions were estimated using depth relationships that honoured the calibrated values. For other model layers, specific storage was assumed to be $5 \times 10^{-5}$ per metre. Storativity values of generally $5 \times 10^{-3}$ were used in outcrop areas, based on appropriate specific yield values (i.e. unconfined storage).

3.3.7 Extractions

All known pre-1995 borehole extractions from the 19 Cainozoic to Permian layers (totalling approximately 19,000 locations) were included in the calibrated steady state regional model. These include licensed entitlements, stock and domestic bores and conventional gas and oil extractions. Past observations (January 1995 to December 2010) and future estimates of abstractions from the CSG fields were added for the transient regional model.

Optimal conditions for gas flow are usually achieved when the groundwater level is about 40 m above the top of a productive coal seam. Each CSG field is operated to gradually reduce groundwater levels to this target over a 5 year period. CSG extractions were simulated using the MODFLOW Evapotranspiration (EVT) package, which simulates outflow from a model cell as a function of hydraulic head above a specified elevation, below which outflows remain constant. EVT parameters were adjusted according to known historical flow rates to ensure that modelled rates were
consistent with measured rates. Use of the EVT package to simulate CSG pumping enabled these modelled extraction rates to follow a realistic pattern of pumping until production is scheduled to stop.

Due to various issues with estimates of future water production from the CSG companies (see GHD (2011) for details), QWC developed independent estimates of water production for each CSG field for the future scenarios.

### 3.4 Uncertainty analysis

To account for model uncertainty, the transient QWC model uses 200 realisations of model parameters and boundary conditions that all result in an acceptable calibration of the steady state model. The realisations vary recharge rates, hydraulic conductivity, vertical anisotropy factors that relate vertical to horizontal hydraulic conductivity, and the general head boundary conductances on the eastern and southern model boundaries. The associated calculated model drawdown outputs from the 200 realisations were provided by QWC for the Assessment. Because QWC provided results for 2075 but not for 2070, the 2075 results are presented here.

Independently of this, 45 percent of the 200 realisations of model parameters and boundary conditions were run for 2070 by CSIRO for the Assessment. The CSIRO results were very similar to the QWC results, but are not presented here because the QWC results are superior, being based on the larger set of 200 realisations.

### 3.5 Model application: scenarios

The QWC model lies entirely within the Surat reporting region and was used to simulate the impacts on the GAB from CSG activities alone. 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.

Modelling results from three of the aquifers in the QWC model that represent or immediately underlie the most-exploited GAB aquifer (Cadna-owie – Hooray Sandstone and equivalents) are presented here. The three aquifers are:

- **Layer 3** – Mooga Sandstone, Bungil Formation
- **Layer 5** – Gubberamunda Sandstone
- **Layer 7** – Springbok Sandstone.

The active extents of layers 3, 5 and 7 are shown in Figure 3.2. The three QWC layers extend further than GABtran in the north-east because the GABtran model boundary follows a local groundwater divide in this area. 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 transient predictions, the QWC model uses 200 realisations of model parameters and boundary conditions that all result in an acceptable calibration of the steady state model.

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. 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: Layers 3, 5 and 7 described above. QWC provided the results from simulating the impacts on the GAB from CSG activities under Scenario D relative to Scenario C at 2075.
3.5.1 Scenario D relative to Scenario C

Figure 3.2, Figure 3.3 and Figure 3.4 show the median, and the upper and lower 95th percentile changes in groundwater level under Scenario D relative to Scenario C at 2075 for CSG impacts on the Mooga, Gubberamunda and Springbok sandstones respectively. The figures show the impact of future CSG development alone with temporal, climatic and other effects removed. Of the three layers, CSG development is estimated to have the greatest impact on the Springbok Sandstone, particularly in the north-east of the Surat Basin, and the least impact on the Mooga Sandstone. In the Mooga Sandstone the impacts are estimated to be mostly less than 1 m. In the Gubberamunda Sandstone under the median and lower 95th percentile estimates, the impact of CSG development alone 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. In the Springbok Sandstone the impacts are estimated to be less than 0.2 m over more than three-quarters of the area.

Figure 3.2 Change in Queensland Water Commission model groundwater level (m) for the Mooga Sandstone (Layer 3) under Scenario D relative to Scenario C

Note: legend shows change in groundwater level (m)
Figure 3.3 Change in Queensland Water Commission model groundwater level (m) for the Gubberamunda Sandstone (Layer 5) under Scenario D relative to Scenario C

Note: legend shows change in groundwater level (m)
The GABtran and QWC model simulations are mutually exclusive because the QWC model was used to assess the impact from future CSG developments alone and no CSG impacts were included in the GABtran model simulations. Figure 3.5 shows the combined impacts of all extractions including CSG under Scenario D relative to Scenario C for the Mooga, Gubberamunda and Springbok sandstone layers (i.e. GABtran estimates plus QWC model estimates). All three results are very similar to Figure 2.6(d) because the estimated CSG impacts are small compared to the estimated impacts from stock and domestic bore rehabilitations.
Figure 3.5 Change in groundwater level (m) for the combined impacts of water bores, springs and coal seam gas under Scenario D relative to Scenario C at approximately 2070 for the (a) Mooga Sandstone, (b) Gubberamunda Sandstone and (c) Springbok Sandstone

Note: legend shows change in groundwater level (m)
4 Cape York model

4.1 Introduction

A numerical groundwater model was developed for the Assessment to simulate the impacts over Cape York under the climate and groundwater development scenarios. This model lies within the Carpentaria reporting region and extends under the Gulf of Carpentaria to include the mapped extent of the aquifer (Figure 4.3). It has a common onshore boundary with GABtran (Figure 4.1). Under the groundwater modelling guideline of Middlemis et al. (2000), the Cape York model has the level of complexity of an ‘Impact Assessment’ model. Under the more recent guideline of Barnett et al. (2012), the Cape York model has a confidence level classification between ‘Class 1’ and ‘Class 2’. The model does not include the Laura Basin due to a lack of data in that area. There is no hydraulic connection between the Laura Basin and the rest of the GAB due to a groundwater divide where the Laura Basin joins the rest of the GAB on the Great Dividing Range.

Figure 4.1 Extent of the Cape York active model cells
4.2 System conceptualisation

Conceptually, rainfall recharge enters the confined aquifer (the Gilbert River Formation (Figure 1.3), which is equivalent to the artesian aquifer that is modelled by GABtran) through the eastern intake beds (Figure 1.5) on the Great Dividing Range and flows generally westward. Springs in and adjacent to the intake beds provide baseflow for streams.

There is insufficient information to estimate vertical leakage from deeper artesian aquifers or to shallower aquifers, so groundwater is conceptualised as exiting in the Gulf of Carpentaria through a north-south line of constant head model cells (Figure 4.1) just beyond the known extent of the aquifer (Figure 4.2, Figure 4.3). Water is conceptualised as not leaving or entering across the other lateral model boundaries, which are either parallel to the groundwater flow direction or represent the lateral extent of the aquifer.

There are some low-flowing discharge springs and soaks in the Holroyd River catchment south of the Holroyd River, but their locations are not mapped. There are no petroleum extractions in the region. No stock and domestic water bores are free-flowing. The only water bores with volumetric entitlements are near Weipa.

4.3 Data

4.3.1 Stratigraphic data

From available seismic cross-sections (Figure 4.2) the thickness of the Jurassic aquifer appears to be relatively uniform and to pinch out below the Gulf of Carpentaria. Offshore, the top and bottom elevation information is predominantly from Seismic information with stratigraphy from one well (Duyken 1). Onshore, there is more stratigraphic information from boreholes, and this was used in combination with aeromagnetic modelling to map the bottom elevation. There is very little seismic information on the Cape York Peninsula, so the onshore top elevation is based on stratigraphic information from boreholes. The stratigraphic surfaces developed for the Assessment (Figure 4.3) suggest that much of the aquifer is between 50 m and 200 m thick, and that the elevation of the aquifer under the Gulf of Carpentaria is about 1 km below sea level. The aquifer thickness is unknown over about three-quarters of the Cape York Peninsula. The aquifer is predominantly the Gilbert River Formation, but could include some of the Eulo Queen Group (Figure 1.3).
Figure 4.2 Regional seismic cross-sections (McConachie et al., 1997)
4.3.2 Transmissivity, hydraulic conductivity, storage

Model reports for mine sites near Weipa (Golder Associates, 2005; 2006; 2008) contain hydraulic property values estimated from pumping tests that are summarised in Table 4.1. There is considerable variability in estimated values, even though these measurements are representative of only a small part of the Cape York Peninsula.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Units</th>
<th>n</th>
<th>Mean value</th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer thickness</td>
<td>b</td>
<td>m</td>
<td>34</td>
<td>153</td>
<td>108</td>
<td>185</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>K</td>
<td>m/d</td>
<td>37</td>
<td>3.9</td>
<td>0.6</td>
<td>10.2</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>T</td>
<td>m²/d</td>
<td>38</td>
<td>555</td>
<td>70</td>
<td>1490</td>
</tr>
<tr>
<td>Storativity</td>
<td>S</td>
<td>1/m</td>
<td>9</td>
<td>1.8 x 10⁻⁴</td>
<td>1.0 x 10⁻⁴</td>
<td>3.3 x 10⁻⁴</td>
</tr>
<tr>
<td>Specific storage</td>
<td>Ss</td>
<td>1/m</td>
<td>8</td>
<td>2.3 x 10⁻⁶</td>
<td>6.9 x 10⁻⁷</td>
<td>7.6 x 10⁻⁶</td>
</tr>
</tbody>
</table>
4.3.3 Recharge

Rainfall on the Cape York Peninsula is seasonal and consistent with a tropical climate. The wet season is from November to April, and the dry season is from May to October. Rainfall ranges from over 2000 mm/year in the north to about 700 mm/year in the south. Figure 4.4 shows annual rainfall at Moreton Telegraph rainfall station located near Weipa.

Springs in the intake beds are associated with ‘overflow’ and ‘rejection’ of recharge, or from the interaction between topography and aquifers (CSIRO, 2009c).

Habermehl and Lau (1997) defined the extent of the recharge area shown in Figure 1.5.

![Figure 4.4 Annual rainfall at Moreton Telegraph rainfall station near Weipa](image)

4.3.4 Water bores

Figure 4.5 shows the locations of bores with groundwater level observations and bores with recorded water extraction measurements. Most of the bores are located toward the northern end of the Cape York Peninsula. Bramwell Station bore (RN 109815) is not included because, although it has previously been considered to be tapping a Gilbert River Sandstone equivalent formation (Golder Associates, 2011), it is now considered to be tapping the Rolling Downs Group.

Through a quality control process, inconsistent groundwater level records were removed and the groundwater level measurements were density corrected to 25 °C. Only four bores have multiple groundwater level measurements (Figure 4.6) and these bores are clustered in the north (Figure 4.5). However, 14 bores have at least one reasonable groundwater level record (Table 4.2, Figure 4.5).

Figure 4.7 shows the total annual extraction for the 18 bores located in the north of the Cape York Peninsula. Comparing this with Figure 4.6 suggests that it took about three years for the drawdown caused by water extractions near Weipa to be observed at the eastern bores, and not all of the eastern bores were equally affected. The bores that were least affected (72374, 92500006) are closest to the recharge area. In addition, there seems to be no significant correlation between annual rainfall (Figure 4.4) and groundwater level (Figure 4.6).
Figure 4.5 Locations of water bores used in the Cape York modelling
Figure 4.6 Average annual Great Artesian Basin groundwater levels at monitored Cape York Peninsula water bores with multiple readings

Note: all bores are east of Weipa

Table 4.2 Earliest observed Great Artesian Basin groundwater levels in the Cape York Peninsula

<table>
<thead>
<tr>
<th>Bore name</th>
<th>Registered number</th>
<th>Year</th>
<th>Density-corrected groundwater level (mAHD at 25 °C)</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Art 1</td>
<td>35609</td>
<td>1971</td>
<td>44.2</td>
<td>1</td>
</tr>
<tr>
<td>Art 3</td>
<td>35611</td>
<td>1971</td>
<td>42.8</td>
<td>1</td>
</tr>
<tr>
<td>Sudley Station</td>
<td>72262</td>
<td>1988</td>
<td>50.3</td>
<td>1</td>
</tr>
<tr>
<td>Rocky Creek / Bahrs</td>
<td>72374</td>
<td>2008</td>
<td>77.4</td>
<td>1</td>
</tr>
<tr>
<td>Bramwell Junction</td>
<td>72421</td>
<td>1989</td>
<td>44.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Wrotham Park Station</td>
<td>78714</td>
<td>1993</td>
<td>151.9</td>
<td>1</td>
</tr>
<tr>
<td>Art 7</td>
<td>109347</td>
<td>2003</td>
<td>38.6</td>
<td>1</td>
</tr>
<tr>
<td>Art 6</td>
<td>109348</td>
<td>2003</td>
<td>37</td>
<td>1</td>
</tr>
<tr>
<td>Art 11</td>
<td>109748</td>
<td>2005</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Art 9</td>
<td>109750</td>
<td>2005</td>
<td>36.4</td>
<td>1</td>
</tr>
<tr>
<td>Art 8</td>
<td>109770</td>
<td>2005</td>
<td>30.8</td>
<td>1</td>
</tr>
<tr>
<td>Wolverton Homestead</td>
<td>92300002</td>
<td>1992</td>
<td>95.9</td>
<td>1</td>
</tr>
<tr>
<td>Batavia Downs</td>
<td>92500002</td>
<td>1992</td>
<td>59.8</td>
<td>1</td>
</tr>
<tr>
<td>Weipa Crossroads</td>
<td>92500006</td>
<td>2004</td>
<td>101.2</td>
<td>1</td>
</tr>
</tbody>
</table>
4.4 Previous modelling

Previous modelling in the Cape York Peninsula is limited to the Rio Tinto Alcan groundwater model and its predecessors (Golder Associates, 2005; 2009; 2011). A MODFLOW model was commissioned in 2003 to assist with management of the artesian aquifer for compliance with statutory licensing requirements and to support Comalco’s commitment to sustainable water use. This was revised in 2005 and 2006, then replaced with a FEFLOW (Diersch, 2009) model in 2008. The FEFLOW model is updated annually. Its extent is shown in Figure 4.1.

The Rio Tinto Alcan model has one aquifer layer representing the GAB stratigraphy (Gilbert River Formation) whose elevation and dimensions were determined from bore log information. Aquifer hydraulic properties are informed by pumping test results. Conceptually, the system is confined with recharge along the eastern margin along the Great Dividing Range. The model simulates unconfined to confined conditions. Recharge includes rainfall, and potential seepage loss from the Wenlock River as a head-dependent flow boundary condition. There is a constant head boundary condition of 10 m AHD along the western boundary. The northern and southern margins of the model are no flow boundaries, being parallel to the estimated groundwater flow direction. The model was calibrated in steady state mode to estimated pre-1970 groundwater levels, then calibrated in transient mode using monitored pumping rates and groundwater levels. Further details are available in Golder Associates (2009).

4.5 Modelling scope and scale

As the available temporal series of groundwater level monitoring information is concentrated in a small area (Figure 4.5, Figure 4.6) there is insufficient information on which to base the development of a regional transient groundwater model of the whole Cape York area. However, there is a greater spread of observations when water bores with one or more groundwater level measurements are considered (Figure 4.6). The earliest groundwater level observation from each bore was considered to be locally representative of pre-development conditions for a steady state model. To enable transient simulations, each scenario was run with three different storage coefficients applied to the calibrated steady state model.

The model was developed using MODFLOW 2000 (Harbaugh et al., 2000).

4.6 Model definition

The limited spatial complexity of the model is commensurate with the sparseness of the available observed data. The Jurassic aquifer (Gilbert River Formation) is represented as a single confined layer. Model cell dimensions are 5 km x 5 km, which is consistent with the discretisation used in the GABtran model.
Chapter 4 Cape York model

The steady state model simulates pre-development conditions, so no water extraction bores are included. No springs are included because they are either closely associated with recharge processes, or have low flows and their locations are not available. There are no petroleum wells in the Cape York Peninsula.

4.6.1 Boundary conditions

There is no flow into or out of the model across the model boundary except for the line of constant head cells along the western boundary (Figure 4.1). In the east the boundary represents the edge of the aquifer. In the north and south the boundary is approximately parallel with the direction of groundwater flow.

Recharge occurs along the eastern edge of the area (Figure 1.5).

Although it is likely that there is some vertical leakage both into and out of the modelled aquifer, its magnitude is unknown, and no vertical leakage is simulated. Instead, groundwater exits via the constant head boundary under the Gulf of Carpentaria (Figure 4.1). The effect of this conceptualisation decision on modelled groundwater levels is likely to be very minor. However, the transmissivity parameter values are likely to be overestimated, as groundwater that might in reality exit the aquifer vertically, can only exit the model along the western boundary.

4.6.2 Aquifer properties

Aquifer transmissivity was estimated during calibration. Figure 4.8(a) shows the transmissivity distribution from the calibrated steady state model. Interpolation artefacts visible in the offshore part of the model are due to a scarcity of pilot points in that region. The median transmissivity is 1558 m²/day over the whole model area, but only 198 m²/day over just the onshore part of the model. If it is assumed that the average aquifer thickness over the entire modelled area is 150 m, this equates to hydraulic conductivities of about 10 m/day and 1.3 m/day respectively. These values are in the range of measured values (Table 4.1).

Figure 4.8(a) also shows the locations of the pilot points from which the transmissivity surface was interpolated. Interpolation to any given cell was undertaken using the values of the two nearest pilot points, which were weighted according to distance. Pilot points were located over bores with observations used in the calibration process, and are less densely distributed elsewhere.

Figure 4.8(b) shows hydraulic conductivity that was back-calculated from the estimated transmissivity distribution (Figure 4.8a) and the thickness distribution shown in Figure 4.3(c). About half of the values are between 1 m/day and 20 m/day. Hydraulic conductivity is lower in the north and east than in the south and west.
4.6.3 Recharge

The recharge process is conceptualised as the intake beds over-filling during each wet season, with excess recharge discharging through springs in the intake beds that provide year-round stream baseflow. Recharge is implemented as a spatially variable recharge rate through the MODFLOW RCH package. In the absence of available recharge rate estimates, elevations of topographic lows (spill points) in the intake beds were used during model calibration to constrain groundwater levels in the recharge area. Figure 4.9 shows the ground surface elevations that were used to constrain the recharge rates, and the recharge rates in the calibrated steady state model. The average recharge over the area is about $2 \times 10^{-6}$ m/day.

![Figure 4.9 Cape York model recharge rates (m/day) and ground surface elevations at spill points (mAHD) used to constrain the calibration](image)

4.6.4 Matrix solver

The finite-difference method used by MODFLOW to solve the groundwater flow equation calculates the groundwater level at the centre of each model cell as a function of the groundwater level in adjacent cells. This requires that the equations for the entire grid be solved simultaneously. The Preconditioned Conjugate-Gradient 2 solver (Hill, 1990) was used to achieve this by iteration. The maximum number of outer iterations was set at 50, and the maximum number of inner iterations at 30. The Modified Incomplete Cholesky matrix preconditioning method was chosen. The maximum groundwater level change criterion and residual criterion for convergence were both set at $1 \times 10^{-4}$ m.

4.6.5 Water budget

Table 4.8 lists the water budget for the calibrated Cape York model. Total inflows must equal total outflows under steady state flow conditions. Since the steady state model represents pre-development conditions, the only inflows are from rain-derived recharge on the eastern margin. The only outflows are through the constant head model cells under the Gulf
of Carpentaria. There are no inflows through the constant head model cells. There are no independent recharge or discharge measurements with which to compare these results.

Table 4.3 Water budget for pre-development conditions from the steady state Cape York model

<table>
<thead>
<tr>
<th>Flow direction</th>
<th>Water balance component</th>
<th>Flow (m$^3$/d)</th>
<th>Flow (ML/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In</td>
<td>Recharge</td>
<td>65,122</td>
<td>23,786</td>
</tr>
<tr>
<td>Out</td>
<td>Discharge into overlying layers and the Gulf of Carpentaria</td>
<td>65,122</td>
<td>23,786</td>
</tr>
</tbody>
</table>

4.6.6 Sensitivity analysis

The sensitivity of modelled groundwater levels to changes in transmissivity and recharge parameter values at the pilot point locations was calculated using PEST (Doherty, 2010). Although some locations are more sensitive than others (Figure 4.10, Figure 4.11), on average the sensitivity of modelled groundwater levels to small changes in transmissivity is about the same as the sensitivity to small changes in recharge.

The model is most sensitive to recharge changes at some locations south-east of Weipa, and least sensitive to both transmissivity and recharge changes in the north (Figure 4.11).

Figure 4.10 Normalised model sensitivity to changes in transmissivity and recharge at the pilot point locations

Figure 4.11 Spatial distribution of normalised model sensitivity to changes in transmissivity and recharge at the pilot point locations

Note: Labels relate to pilot point names in Figure 4.10
4.6.7 Conditions for transient simulations

To run transient simulations the steady state model was modified to include:

- storage coefficients consistent with average aquifer thicknesses of 100, 150 and 200 m
- annual stress periods starting from 1965
- an initial groundwater level distribution produced by the calibrated steady state model.

Storativity for the confined part of the aquifer was calculated as the product of the compressibility of water ($5 \times 10^{-6}$ per metre) and aquifer thickness (Hazel, 1975). Storage coefficients corresponding to aquifer thicknesses of 100, 150 and 200 m were calculated as $5.0 \times 10^{-4}$, $7.5 \times 10^{-4}$ and $1.0 \times 10^{-3}$ respectively. These storativity values and aquifer thicknesses are similar to the values calculated from pumping tests (Table 4.1).

Storativity in the recharge beds was assumed to be two orders of magnitude greater, i.e. 0.050, 0.075 and 0.10 for aquifer thicknesses of 100, 150 and 200 m respectively.

Modelling the climate and groundwater development scenarios using these storage coefficients provided an indication of uncertainty in the modelling results. Table 4.4 shows the water budgets for the base run with the three storativity estimates averaged over the 1965 to 2010 simulation period.

<table>
<thead>
<tr>
<th>Water balance component</th>
<th>100 m</th>
<th>150 m</th>
<th>200 m</th>
<th>100 m</th>
<th>150 m</th>
<th>200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean flow (m³/d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>11,067</td>
<td>11,285</td>
<td>11,388</td>
<td>4,042</td>
<td>4,122</td>
<td>4,159</td>
</tr>
<tr>
<td>Recharge</td>
<td>65,123</td>
<td>65,123</td>
<td>65,123</td>
<td>23,786</td>
<td>23,786</td>
<td>23,786</td>
</tr>
<tr>
<td>Total in</td>
<td>76,191</td>
<td>76,409</td>
<td>76,511</td>
<td>27,828</td>
<td>27,908</td>
<td>27,945</td>
</tr>
<tr>
<td>Mean flow (ML/y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>134</td>
<td>149</td>
<td>166</td>
<td>49</td>
<td>54</td>
<td>61</td>
</tr>
<tr>
<td>Discharge into overlying layers and the Gulf of Carpentaria</td>
<td>64,790</td>
<td>65,005</td>
<td>65,078</td>
<td>23,664</td>
<td>23,743</td>
<td>23,769</td>
</tr>
<tr>
<td>Water bores</td>
<td>11,260</td>
<td>11,260</td>
<td>11,260</td>
<td>4,113</td>
<td>4,113</td>
<td>4,113</td>
</tr>
<tr>
<td>Total out</td>
<td>76,184</td>
<td>76,414</td>
<td>76,504</td>
<td>27,826</td>
<td>27,910</td>
<td>27,942</td>
</tr>
</tbody>
</table>

4.7 Calibration process

The aim of the calibration was to estimate parameter sets that:

- were realistic
- replicated the observed groundwater levels as accurately as possible
- for transient modelled scenarios, produced temporal changes in groundwater levels that were consistent with the magnitudes of observed responses.

The observed groundwater levels (Table 4.2) were temperature corrected to 25 ºC. The estimated groundwater levels in the recharge area that were based on ground surface elevations are shown in Figure 4.9. The observed groundwater responses to groundwater extractions at water bores are shown in Figure 4.6.

Both manual and automated methods were used during model calibration. Pilot points were used to produce spatially varying parameter distributions. Pilot points were located over observations and scattered more sparsely over other parts of the model area (Figure 4.8, Figure 4.9) to define transmissivity and recharge parameters. The single value assigned to constant head cells in the Gulf of Carpentaria (Figure 4.1) of 0 mAHD was fixed during model calibration. All groundwater
level observations were assigned a unit weighting except: (1) observations from bore 72421 that were inconsistent with nearby observations and (2) the ground surface elevations in the intake beds, which were all assigned a weighting of 0.1.

### 4.8 Evaluating the calibration

Statistical measures of the calibration that are independent of sample size, range in measured values and choice of datum are shown in Table 4.5. The scaled mean sum of residuals (SMSR) and the scaled root mean square (SRMS) should both be less than 5 percent (Barnett et al., 2012; Middlemis et al., 2000). These measures were both less than 2 percent for estimated groundwater levels calibrated to observations from bores, and less than 1 percent for estimated groundwater levels calibrated to ground surface elevations. The formulae for calculating these statistical measures are provided in Appendix B.

In transient mode, the temporal changes in groundwater level at the locations with multiple groundwater level measurements are reasonably consistent with the hydrographs in Figure 4.6.

#### Table 4.5 Statistical performance measures for the calibration of the steady state Cape York model

<table>
<thead>
<tr>
<th>Type of observation</th>
<th>n</th>
<th>Scaled mean sum of residuals (SMSR, percent)</th>
<th>Scaled root mean square (SRMS, percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed groundwater levels</td>
<td>14</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Estimated recharge area groundwater levels</td>
<td>24</td>
<td>0.72</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Figure 4.12 compares modelled and observed groundwater levels. The coefficient of determination ($R^2$) is high for both sets of observations, but is slightly better for the water bores than for the recharge elevations. For a perfect calibration $R^2$ would be unity.

![Figure 4.12 Modelled versus observed groundwater levels for the Cape York model calibration](image)

### 4.9 Modelled flow regime

The steady state model provides an estimate of pre-development groundwater levels and flow directions, which are perpendicular to the groundwater level contours shown by the colour breaks in Figure 4.13. Groundwater flows from east to west in the north, and from south-east to north-west in the south. Flow directions adjacent to the boundaries are influenced by the placement of the boundaries: flow is perpendicular adjacent to constant head cells, and parallel adjacent to no-flow boundaries, except in the recharge area where the combined impacts of recharge rate and transmissivity determine the groundwater flow direction.
4.10 Model application: scenarios

To simulate the climate and groundwater development scenarios, historical development conditions from 1 January 1965 to 31 December 2011 were compiled from the available water bore discharge measurements, including Rio Tinto Alcan groundwater extractions near Weipa. Future climate was simulated by the use of recharge scaling factors (Section 1.6). Future development was simulated through changes to water bore extraction rates.

4.10.1 Scenario A

Figure 4.14 shows the change in groundwater level under Scenario A at 2070 with the three different storativity assumptions for aquifer thicknesses of 100, 150 and 200 m. The results show the impact of continuing historical climate and current development from 2010 to 2070.

The modelling estimates that groundwater level will decrease over the whole area due to groundwater being extracted at a faster rate than it is replenished. The estimated response is very similar under Scenario A for all three storativity assumptions, and is mostly between 0 and 5 m.
4.10.2 Scenario C

Under scenarios C and D the recharge scaling factors were applied to all model cells representing rain-derived recharge. Statistics of the recharge scaling factors and their impact on model recharge are shown in Table 4.6. Note that the average impact of these, as shown in the change in recharge compared 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 in 2070 increases by 17 percent.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Recharge scaling factor range</th>
<th>Recharge scaling factor mean</th>
<th>Mean change in recharge in 2070 relative to Scenario A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cwet and Dwet</td>
<td>1.26–2.41</td>
<td>1.60</td>
<td>1.46</td>
</tr>
<tr>
<td>Cmid and Dmid</td>
<td>0.85–1.79</td>
<td>1.23</td>
<td>1.17</td>
</tr>
<tr>
<td>Cdry and Ddry</td>
<td>0.56–1.29</td>
<td>0.91</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Under scenarios Cwet, Cmid and Cdry the recharge scaling factors (Figure 1.5) were linearly increased from a nil impact in 2010 to their full impact in 2070.

Figure 4.15, Figure 4.16 and Figure 4.17 show the change in groundwater level under scenarios Cwet, Cmid and Cdry at 2070 with the three different storativity assumptions for aquifer thicknesses of 100, 150 and 200 m. The results show the impact of projecting future climate to 2070 and continuing current development to 2070. Figure 4.15, Figure 4.16 and Figure 4.17 are very similar, suggesting that the impact of future climate is greater than the uncertainty in modelled aquifer response expressed through the three storativity estimates. Under all three scenarios for all three storativity assumptions there is some groundwater level increase in the south, and in the east near the Laura Basin, due to increased recharge in these areas (Figure 1.5), even under the dry extreme future climate.

Figure 4.15 Change in Cape York groundwater level (m) under Scenario C with storativity corresponding to an aquifer thickness of 100 m

Note: legend shows change in groundwater level (m)

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change
Figure 4.16 Change in Cape York groundwater level (m) under Scenario C with storativity corresponding to an aquifer thickness of 150 m.

Note: legend shows change in groundwater level (m)

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.
Figure 4.17 Change in Cape York groundwater level (m) under Scenario C with storativity corresponding to an aquifer thickness of 200 m

Note: legend shows change in groundwater level (m)

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.

Figure 4.18, Figure 4.19 and Figure 4.20 show the change in groundwater level under scenarios Cwet, Cmid and Cdry relative to Scenario A at 2070 with the three different storativity assumptions consistent with aquifer thicknesses of 100, 150 and 200 m. These differences remove temporal effects and thereby identify impacts of climate alone. Under all scenarios with all storativity assumptions the estimated impacts are mostly between ±1 m. Since the recharge scaling factors are all more than 1 under Scenario Cwet (Table 4.6), groundwater level increases everywhere under Scenario Cwet. The recharge scaling factors are all more than 1 except in the northern area (Figure 1.5) under Scenario Cmid, resulting in some reduced groundwater levels in the north. Under Scenario Cdry the recharge scaling factors are mostly less than 1 in the north and mostly more than 1 in the south, so groundwater level decreases in the north and increases in the south. Some of the estimated groundwater level increases over the eastern recharge areas will probably result in more water available for stream baseflow.
Figure 4.18 Change in Cape York groundwater level (m) under Scenario C relative to Scenario A with storativity corresponding to an aquifer thickness of 100 m

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.
Figure 4.19 Change in Cape York groundwater level (m) under Scenario C relative to Scenario A with storativity corresponding to an aquifer thickness of 150 m

Note: legend shows change in groundwater level (m)

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.
Figure 4.20 Change in Cape York groundwater level (m) under Scenario C relative to Scenario A with storativity corresponding to an aquifer thickness of 200 m

Note: legend shows change in groundwater level

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.

4.10.3 Scenario D

The assumptions used when estimating future development are listed in Table 4.7. Extraction rates for mine-related activities are estimated for individual sites. All known mining is expected to cease by 2050, so mining extractions reduce to zero before 2070. There are no other water bores with volumetric allocations in the modelled aquifer. Springs are not included (Section 4.2). There are no petroleum wells. There are very little data on sub-artesian bores; these are assumed to flow at a rate of 0.2 L/second, which remains constant over time. There are no uncontrolled stock and domestic bores. The Queensland Water Resource (Great Artesian Basin) Plan 2006 details the amounts of water that will be reallocated to each groundwater management zone. Although the reallocations to date have been less than planned, the planned amounts have been used in this modelling.
Table 4.7 Future development assumptions for the Cape York model under Scenario D

<table>
<thead>
<tr>
<th>Development type</th>
<th>Queensland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bores (mining)</td>
<td>Rio Tinto Alcan: 6 GL/y across Art6-Art12 from 2012 to 2026, then zero to 2070.</td>
</tr>
<tr>
<td></td>
<td>South of Embley: 6 GL/y across 6 bores from 2012 to 2026, then 15 GL/y across 12 bores from 2027 to 2050, then zero to 2070.</td>
</tr>
<tr>
<td></td>
<td>Aurukun: 3 GL/y across 3 bores from 2027 to 2050, then zero to 2070.</td>
</tr>
<tr>
<td></td>
<td>Gulf Alumina: 1.83 GL/y from 1 bore from 2014 to 2016, then 1.3 GL/y from 2017 to 2034, then zero to 2070.</td>
</tr>
<tr>
<td>Water bores with volumetric allocations (non-mining)</td>
<td>No non-mining water bores with volumetric allocations</td>
</tr>
<tr>
<td>Artesian stock and domestic water bores</td>
<td>No bore rehabilitation</td>
</tr>
<tr>
<td>Sub-artesian bores</td>
<td>Flows remain at their 2010 levels to 2070.</td>
</tr>
<tr>
<td>Allocation of water saved</td>
<td>The full General Reserve amounts are spread across the existing non-coastal water bores in each management zone from 1 January 2014.</td>
</tr>
<tr>
<td>Petroleum wells</td>
<td>No petroleum wells</td>
</tr>
<tr>
<td>Springs</td>
<td>No springs</td>
</tr>
</tbody>
</table>

Figure 4.21 shows the total modelled extraction per year for the period 1965 to 2070. The steep reduction estimated after 2050 is due to the cessation of South of Embley and Aurukun mine operations. Table 4.8 summarises 2070 development under the different scenarios. Under Scenario D, total discharge is estimated to decrease by about 80 percent mostly due to all current and anticipated mines in the model area ceasing operation before 2070.

![Figure 4.21 Total groundwater extraction rates (kL/day) for the Cape York model under Scenario D](image)

Table 4.8 Current and future development discharge estimates for the Cape York model

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Year</th>
<th>Water bores</th>
<th>Petroleum wells</th>
<th>Springs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A and C</td>
<td>2070</td>
<td>25,541</td>
<td>0</td>
<td>0</td>
<td>25,541</td>
</tr>
<tr>
<td>D</td>
<td>2070</td>
<td>5,454</td>
<td>0</td>
<td>0</td>
<td>5,454</td>
</tr>
</tbody>
</table>

Under scenarios Dwet, Dmid and Ddry, recharge scaling factors (Figure 1.5) were linearly increased from nil impact in 2010 to their full impact in 2070, the same as under scenarios Cwet, Cmid and Cdry.
Figure 4.22 Change in Cape York groundwater level (m) under Scenario D, and under Scenario D relative to Scenario C with storativity corresponding to an aquifer thickness of 100 m

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.

Figure 4.22, Figure 4.23 and Figure 4.24 show change in groundwater level under scenarios Dwet, Dmid and Ddry at 2070 using the three different storativity assumptions consistent with aquifer thicknesses of 100, 150 and 200 m. The results show the impact of projecting both future climate and future development from 2010 to 2070. The estimated impact under all three future climates for all three storativity assumptions is similar, suggesting that the impact of future climate with future development is greater than the uncertainty in modelled aquifer response expressed through the three storativity estimates. Even though groundwater use is expected to increase in the medium term (Table 4.7, Figure 4.21), groundwater extraction for mining is expected to cease before 2070, greatly reducing 2070 groundwater use relative to 2010 groundwater use. Groundwater level increases near Weipa, where Rio Tinto Alcan will have ceased operations, and in or near the recharge beds. The greatest groundwater level decrease is south of Weipa. Groundwater level decreases in the recharge beds might result in diminished stream baseflows.
Figure 4.23 Change in Cape York groundwater level (m) under Scenario D, and under Scenario D relative to Scenario C with storativity corresponding to an aquifer thickness of 150 m

Note: legend shows change in groundwater level (m)

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.

Figure 4.22(d), Figure 4.23(d) and Figure 4.24(d) show the change in groundwater level under Scenario D relative to Scenario C at 2070 using the three different storativity assumptions consistent with aquifer thicknesses of 100, 150 and 200 m. Calculating this difference removes temporal and climatic effects and thereby identifies impacts of future development alone. Impacts on groundwater level over most of the model area are within ±5 m. The increase at Weipa is due to the current mining extractions ceasing before 2070.
Figure 4.24 Change in Cape York groundwater level (m) under Scenario D, and under Scenario D relative to Scenario C with storativity corresponding to an aquifer thickness of 200 m

Note: legend shows change in groundwater level

Note: The Cape York model has only been calibrated to steady-state conditions using sparse groundwater observation data. In the absence of data, the modelled groundwater response is based on qualitative knowledge of the region. Results for future scenarios are uncertain and only represent an indicative change.
5 Uncertainty analyses

5.1 Introduction

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 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 some uncertainty always accompanies a predictive model simulation.

GABtran and the Cape York model, with their large spatial extents and limited vertical extents, feature 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 the average impact under the GABtran and QWC model scenarios. The GABtran uncertainty analyses are also used to assess how best to improve the reliability of the average model results through improved aquifer parameter knowledge and additional data collection. Identifiability indices that show how well the model parameter values were constrained by the observation data were calculated for the Cape York model.

5.2 Uncertainty and error analysis

Uncertainty analysis provides a measure of the reliability of a model simulation. The results of such analyses can be communicated using either a probability density function or by assigning confidence limits. Such analyses 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 changes in climate and groundwater development varies across an aquifer. This variation is governed by aquifer heterogeneity, the magnitude of stresses, and the number of calibration observations that occur at any location. To simplify the reporting of the uncertainty analysis, 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 groundwater development changes, rather than at specific locations within the aquifer. In the future this analysis could be extended to assess the uncertainty of estimated changes to groundwater levels at each model grid cell. Uncertainty analyses were applied to estimations of average change in groundwater level in the groundwater models arising under scenarios A, C, D, C relative to A, D relative to C; and at Granite Springs in the Surat region and Dalhousie springs in the Western Eromanga region. The spring sites were selected on the basis that they are the subject of case studies in the companion Environment technical report as listed in Appendix A.

5.2.1 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 a linear error propagation analysis that describes the effect of model parameter uncertainty on the uncertainty of model simulation results. The method assumes that the simulation results can be linearly related to model parameters, so the variance in simulation results can be described as a function of the parameter covariance matrix, and the sensitivity of the simulation results to those parameters. Because the linearity assumption is often not strictly correct, the uncertainty description must usually be considered as approximate. The method also led to the identification of knowledge and data gaps in the following sections. It is described in Moore and Doherty (2005; 2006) and Doherty (2012).

Scenario results in Section 2.5 report groundwater level change for a particular scenario relative to another scenario to minimise uncertainty in the results (Section 1.5). For the whole GABtran area and for the individual regions the average groundwater level difference for each scenario was calculated and statistics were derived from the individual cell values. At the case study spring locations that fall within the GABtran model area (Granite Springs and Dalhousie Springs) the error propagation analysis used point estimates of drawdown at the spring locations. The standard deviation of the
change in groundwater level quantifies the spread of the scenario results, created by the uncertainty in the parameters within the calibrated model.

Over the entire GABtran model area the standard deviation is highest for Scenario D, which includes the impact of time, climate and groundwater development, and lowest for Scenario C relative to Scenario A, which only includes the impact of climate. Since confidence limits are calculated from standard deviations, the upper and lower confidence limits have the largest range for Scenario D and smallest range for Scenario C relative to Scenario A.

The standard deviations and confidence limits for the Carpentaria, Central Eromanga and Surat regions follow a similar pattern to the GABtran area as a whole with standard deviations highest for Scenario D and lowest for Scenario C relative to Scenario A. In contrast, standard deviations at the location of Granite Springs in the Surat region are highest for Scenario C relative to Scenario A and lowest for Scenario D. The standard deviations of drawdown estimates at the Granite Springs location are larger than those for the whole region (Table 5.1). This is consistent with mathematical theory that the uncertainty of an averaged estimate is always less than the uncertainty of a point estimate. Both extremes of the 95 percent confidence intervals for Scenario C relative to Scenario A at Granite Springs are positive, indicating that irrespective of which climate is considered, the impact of climate is likely to increase groundwater levels relative to Scenario A. Since both extremes of the 95 percent confidence intervals for Scenario D relative to Scenario C at Granite Springs are negative, the impact of future development is likely to decrease groundwater levels. Regardless of which climate and groundwater development scenario is considered, their combined impact over time is likely to result in little change to the average groundwater level, as indicated by the positive and negative 95 percent confidence limits.

In the Western Eromanga region and at the location of Dalhousie Springs the standard deviation is highest for scenarios A, C and D, all of which include the impact of time, and lowest for Scenario D relative to Scenario C, which only includes the impact of groundwater development. Similarly to Granite Springs, the standard deviations of drawdown estimates at the Dalhousie Springs location are larger than those for the whole region (Table 5.1). Both extremes of the 95 percent confidence intervals for scenarios A, C and D at Dalhousie Springs are negative, indicating that irrespective of which climate or groundwater development scenario is considered, groundwater levels are likely to fall. Table 5.1 is represented graphically in Figure 5.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Median</th>
<th>Standard deviation</th>
<th>Lower 95 percent confidence limit (assuming Gaussian error)</th>
<th>Upper 95 percent confidence limit (assuming Gaussian error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GABtran</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>−2.83</td>
<td>0.66</td>
<td>−4.13</td>
<td>−1.53</td>
</tr>
<tr>
<td>Cwet</td>
<td>2.82</td>
<td>0.75</td>
<td>1.35</td>
<td>4.28</td>
</tr>
<tr>
<td>Cmid</td>
<td>−2.08</td>
<td>0.68</td>
<td>−3.40</td>
<td>−0.75</td>
</tr>
<tr>
<td>Cdry</td>
<td>−6.52</td>
<td>0.70</td>
<td>−7.88</td>
<td>−5.16</td>
</tr>
<tr>
<td>Dwet</td>
<td>12.69</td>
<td>1.11</td>
<td>10.51</td>
<td>14.88</td>
</tr>
<tr>
<td>Dmid</td>
<td>7.80</td>
<td>0.98</td>
<td>5.87</td>
<td>9.73</td>
</tr>
<tr>
<td>Ddry</td>
<td>3.36</td>
<td>0.92</td>
<td>1.56</td>
<td>5.15</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>5.64</td>
<td>0.32</td>
<td>5.02</td>
<td>6.27</td>
</tr>
<tr>
<td>Cmid relative to A</td>
<td>0.75</td>
<td>0.12</td>
<td>0.53</td>
<td>0.98</td>
</tr>
<tr>
<td>Cdry relative to A</td>
<td>−3.69</td>
<td>0.24</td>
<td>−4.16</td>
<td>−3.23</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>−9.88</td>
<td>0.63</td>
<td>−11.11</td>
<td>−8.64</td>
</tr>
</tbody>
</table>
Table 5.1 Statistics of the average groundwater level change in the GABtran model (continued)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Median</th>
<th>Standard deviation</th>
<th>Lower 95 percent confidence limit (assuming Gaussian error)</th>
<th>Upper 95 percent confidence limit (assuming Gaussian error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carpentaria region</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2.46</td>
<td>1.14</td>
<td>0.23</td>
<td>4.69</td>
</tr>
<tr>
<td>Cwet</td>
<td>18.10</td>
<td>2.25</td>
<td>13.69</td>
<td>22.50</td>
</tr>
<tr>
<td>Cm</td>
<td>8.65</td>
<td>1.47</td>
<td>5.77</td>
<td>11.53</td>
</tr>
<tr>
<td>Cd</td>
<td>−0.33</td>
<td>1.12</td>
<td>−2.53</td>
<td>1.86</td>
</tr>
<tr>
<td>Dwet</td>
<td>49.89</td>
<td>5.65</td>
<td>38.82</td>
<td>60.97</td>
</tr>
<tr>
<td>Dmid</td>
<td>40.44</td>
<td>4.84</td>
<td>30.95</td>
<td>49.94</td>
</tr>
<tr>
<td>Ddry</td>
<td>31.46</td>
<td>4.16</td>
<td>23.30</td>
<td>39.62</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>15.64</td>
<td>1.66</td>
<td>12.39</td>
<td>18.88</td>
</tr>
<tr>
<td>Cm relative to A</td>
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<td>0.67</td>
<td>4.88</td>
<td>7.49</td>
</tr>
<tr>
<td>Cd relative to A</td>
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<td>−3.47</td>
<td>−2.12</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>−31.80</td>
<td>3.86</td>
<td>−39.35</td>
<td>−24.24</td>
</tr>
<tr>
<td>Central Eromanga region</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>−1.36</td>
<td>0.91</td>
<td>−3.13</td>
<td>0.42</td>
</tr>
<tr>
<td>Cwet</td>
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<td>2.01</td>
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<tr>
<td>Cm relative to A</td>
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<td>1.44</td>
</tr>
<tr>
<td>Cd relative to A</td>
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<td>0.94</td>
<td>−6.13</td>
<td>−2.46</td>
</tr>
<tr>
<td>Dwet</td>
<td>16.33</td>
<td>1.63</td>
<td>13.15</td>
<td>19.52</td>
</tr>
<tr>
<td>Dmid</td>
<td>12.00</td>
<td>1.41</td>
<td>9.24</td>
<td>14.76</td>
</tr>
<tr>
<td>Ddry</td>
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<td>1.25</td>
<td>5.59</td>
<td>10.49</td>
</tr>
<tr>
<td>Cwet relative to A</td>
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<td>0.48</td>
<td>4.42</td>
<td>6.28</td>
</tr>
<tr>
<td>Cm relative to A</td>
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<td>0.76</td>
<td>1.28</td>
</tr>
<tr>
<td>Cd relative to A</td>
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<td>−2.40</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>−12.34</td>
<td>0.95</td>
<td>−10.47</td>
<td>−14.20</td>
</tr>
<tr>
<td>Surat region</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
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<tr>
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<td>1.14</td>
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</tr>
<tr>
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<td>0.73</td>
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<td>0.79</td>
</tr>
<tr>
<td>Cd relative to A</td>
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<td>−5.16</td>
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</tr>
<tr>
<td>Dwet</td>
<td>7.76</td>
<td>0.95</td>
<td>5.89</td>
<td>9.63</td>
</tr>
<tr>
<td>Dmid</td>
<td>4.33</td>
<td>0.86</td>
<td>2.64</td>
<td>6.02</td>
</tr>
<tr>
<td>Ddry</td>
<td>1.16</td>
<td>0.85</td>
<td>−0.51</td>
<td>2.83</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>4.17</td>
<td>0.35</td>
<td>3.48</td>
<td>4.87</td>
</tr>
<tr>
<td>Cm relative to A</td>
<td>0.74</td>
<td>0.09</td>
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<td>0.92</td>
</tr>
<tr>
<td>Cd relative to A</td>
<td>−2.43</td>
<td>0.19</td>
<td>−2.06</td>
<td>−2.79</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>−4.96</td>
<td>0.49</td>
<td>−5.93</td>
<td>−3.99</td>
</tr>
</tbody>
</table>
### Table 5.1: Statistics of the average groundwater level change in the GABtran model (continued)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Median (m)</th>
<th>Standard deviation (m)</th>
<th>Lower 95 percent confidence limit (assuming Gaussian error) (m)</th>
<th>Upper 95 percent confidence limit (assuming Gaussian error) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Western Eromanga region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>–8.37</td>
<td>1.50</td>
<td>–11.32</td>
<td>–5.42</td>
</tr>
<tr>
<td>Cwet</td>
<td>–5.49</td>
<td>1.60</td>
<td>–8.62</td>
<td>–2.36</td>
</tr>
<tr>
<td>Cmid</td>
<td>–10.20</td>
<td>1.52</td>
<td>–13.17</td>
<td>–7.22</td>
</tr>
<tr>
<td>Dwet</td>
<td>–4.56</td>
<td>1.59</td>
<td>–7.67</td>
<td>–1.46</td>
</tr>
<tr>
<td>Dmid</td>
<td>–9.27</td>
<td>1.50</td>
<td>–12.22</td>
<td>–6.32</td>
</tr>
<tr>
<td>Ddry</td>
<td>–13.30</td>
<td>1.64</td>
<td>–16.52</td>
<td>–10.09</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>2.88</td>
<td>0.42</td>
<td>2.07</td>
<td>3.70</td>
</tr>
<tr>
<td>Cmid relative to A</td>
<td>–1.82</td>
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<td>–2.29</td>
<td>–1.36</td>
</tr>
<tr>
<td>Cdry relative to A</td>
<td>–5.86</td>
<td>0.79</td>
<td>–7.42</td>
<td>–4.30</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>–0.93</td>
<td>0.25</td>
<td>–1.42</td>
<td>–0.44</td>
</tr>
<tr>
<td><strong>Dalhousie Springs in the Western Eromanga region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>–11.51</td>
<td>3.81</td>
<td>–18.98</td>
<td>–4.04</td>
</tr>
<tr>
<td>Cwet</td>
<td>–10.64</td>
<td>3.40</td>
<td>–17.30</td>
<td>–3.98</td>
</tr>
<tr>
<td>Cmid</td>
<td>–12.06</td>
<td>4.07</td>
<td>–20.04</td>
<td>–4.08</td>
</tr>
<tr>
<td>Cdry</td>
<td>–13.24</td>
<td>4.68</td>
<td>–22.41</td>
<td>–4.07</td>
</tr>
<tr>
<td>Dwet</td>
<td>–10.64</td>
<td>3.40</td>
<td>–17.30</td>
<td>–3.97</td>
</tr>
<tr>
<td>Dmid</td>
<td>–12.05</td>
<td>4.08</td>
<td>–20.06</td>
<td>–4.05</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>0.87</td>
<td>0.53</td>
<td>–0.17</td>
<td>1.91</td>
</tr>
<tr>
<td>Cmid relative to A</td>
<td>–0.55</td>
<td>0.32</td>
<td>–1.17</td>
<td>0.08</td>
</tr>
<tr>
<td>Cdry relative to A</td>
<td>–1.73</td>
<td>1.02</td>
<td>–3.72</td>
<td>0.27</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>–1.0 x 10^-3</td>
<td>0.13</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>Granite Springs in the Surat region</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.49</td>
<td>2.06</td>
<td>–3.55</td>
<td>4.538</td>
</tr>
<tr>
<td>Cwet</td>
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<td>2.08</td>
<td>–3.56</td>
<td>4.59</td>
</tr>
<tr>
<td>Cmid</td>
<td>0.49</td>
<td>2.074</td>
<td>–3.57</td>
<td>4.56</td>
</tr>
<tr>
<td>Cdry</td>
<td>0.47</td>
<td>2.06</td>
<td>–3.57</td>
<td>4.51</td>
</tr>
<tr>
<td>Dwet</td>
<td>0.0264</td>
<td>0.12</td>
<td>–0.21</td>
<td>0.26</td>
</tr>
<tr>
<td>Dmid</td>
<td>0.0006</td>
<td>0.126</td>
<td>–0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Ddry</td>
<td>–0.022</td>
<td>0.109</td>
<td>–0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>Cwet relative to A</td>
<td>19.83</td>
<td>3.88</td>
<td>12.22</td>
<td>27.43</td>
</tr>
<tr>
<td>Cmid relative to A</td>
<td>19.80</td>
<td>3.87</td>
<td>12.22</td>
<td>27.39</td>
</tr>
<tr>
<td>Cdry relative to A</td>
<td>19.78</td>
<td>3.86</td>
<td>12.21</td>
<td>27.34</td>
</tr>
<tr>
<td>Dmid relative to Cmid</td>
<td>–19.31</td>
<td>2.42</td>
<td>–24.05</td>
<td>–14.57</td>
</tr>
</tbody>
</table>
Figure 5.1 Statistics of the average groundwater level change in the GABtran model
5.2.2 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 all result in an acceptable calibration of the steady state model. These realisations, and the associated calculated model drawdown outputs for 2075, were provided by QWC for the Assessment. Independently of this, 45 percent of the 200 realisations of model parameters and boundary conditions were run by CSIRO for 2070. The CSIRO results were very similar to the QWC results, but are not presented here because the QWC results are superior, being based on the larger set of 200 realisations.

The average change in groundwater level from each of the realisations was calculated and collated into a probability distribution (Table 5.2, based on the probability density functions in Figure 5.2). The standard deviations and confidence limits give an indication of the statistical spread of the scenario predictions. Confidence in the results is highest for the Mooga Sandstone (lowest standard deviation) and lowest for the Springbok Sandstone (highest standard deviation). All lower and upper 95th percentile confidence limits are negative, confirming that groundwater levels are estimated to decrease under CSG development.

### Table 5.2 Statistics of the average groundwater level change in the Queensland Water Commission model under Scenario Dmid relative to Scenario Cmid for model layers 3, 5 and 7

<table>
<thead>
<tr>
<th>Model layer</th>
<th>Median (m)</th>
<th>Standard deviation (m)</th>
<th>Lower 95th percentile confidence limit (m)</th>
<th>Upper 95th percentile confidence limit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 3 – Mooga Sandstone</td>
<td>–0.021</td>
<td>–0.0043</td>
<td>–0.015</td>
<td>–0.030</td>
</tr>
<tr>
<td>Layer 5 – Gubberamunda Sandstone</td>
<td>–0.041</td>
<td>–0.0073</td>
<td>–0.030</td>
<td>–0.057</td>
</tr>
<tr>
<td>Layer 7 – Springbok Sandstone</td>
<td>–0.73</td>
<td>–0.086</td>
<td>–0.58</td>
<td>–0.90</td>
</tr>
</tbody>
</table>

Figure 5.2 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 by the averaging process.
5.2.3 Cape York model – uncertainty of the model parameters

The relative confidence in estimated parameters can be evaluated by their identifiability indices (Doherty, 2010), which are real numbers between 0.0 and 1.0 that show how well the model parameter values are constrained by the observation data. As identifiability indices of estimated parameters approach 1.0, the parameters are able to be estimated with greater precision than when they are near 0.0. However, parameters with an identifiability of 1.0 may still be in error if the model conceptualisation and parameter discretisation are not correct. Other factors, such as uncertainties in the observation data, can generate additional errors.

The identifiability analysis indicates that the transmissivity parameters were estimated with a high precision: for the 26 pilot points, 15 have identifiability indices above 0.9 and three have indices below 0.6. The three low indices are in the central part of the model (Figure 5.3(a)). In contrast, the recharge parameters were estimated with a lower precision: for the 21 pilot points, nine have identifiability indices above 0.9 and nine have indices below 0.6. The greatest recharge parameter uncertainty is in the north of the Cape York Peninsula (Figure 5.3(b)).
5.3 Knowledge gaps

The worth of improved knowledge of aquifer system components is assessed by its potential to reduce the uncertainty in scenario estimations by reducing the uncertainty in model parameter values. The method of linear error propagation analysis described in Section 5.2.1 was used for the following prediction reliability analysis.

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 5.4, Figure 5.5, Figure 5.6, Figure 5.7 and Figure 5.8) show the contribution of the key model parameters to the uncertainty (expressed as normalised sensitivity coefficients) of the estimations of average groundwater level changes over the GABtran model, its extent in the four regions, and at Dalhousie and Granite Springs for the GABtran model, both before and after it was calibrated. The results for Granite Springs under all scenarios were very similar, so only Scenario C is shown. Note that GABtran was not re-calibrated for this analysis.
Figure 5.4 Relative increase in prediction reliability of long-term groundwater level changes in GABtran that would be possible with enhanced knowledge of parameters and model inputs.
Figure 5.5 Relative increase in prediction reliability of long-term groundwater level changes in the Carpentaria region of GABtran that would be possible with enhanced knowledge of parameters and model inputs.
Figure 5.6 Relative increase in prediction reliability of long-term groundwater level changes in the Central Eromanga region of GABtran that would be possible with enhanced knowledge of parameters and model inputs.
Figure 5.7 Relative increase in prediction reliability of long-term groundwater level changes in the Surat region of GABtran and at Granite Springs that would be possible with enhanced knowledge of parameters and model inputs.
Figure 5.8 Relative increase in prediction reliability of long-term groundwater level changes in the Western Eromanga region of GABtran that would be possible with enhanced knowledge of parameters and model inputs.
Figure 5.9 Relative increase in prediction reliability of long-term groundwater level changes in GABtran at Dalhousie Springs that would be possible with enhanced knowledge of parameters and model inputs.
An overall reduction in uncertainty from the imposition of calibration constraints is evident when comparing the pre- and post-calibration contributions. Overall, the greatest contribution to post-calibration prediction uncertainty is from storage properties, and then from hydraulic conductivity. The least contribution to post-calibration prediction uncertainty is from inter-aquifer leakage, then aquifer thickness and recharge.

Over the whole GABtran model area (Figure 5.4) and in the Surat region and at Granite Springs (Figure 5.7), aquifer thickness and recharge uncertainty contribute more under the influence of climate alone (Scenario C relative to Scenario A) than under the other scenarios. In the Central Eromanga region (Figure 5.6) aquifer thickness uncertainty contributes more under the influence of future development alone (Scenario D relative to Scenario C) than under the other scenarios. At Dalhousie Springs (Figure 5.9) recharge uncertainty contributes more under the influence of future development alone than under the other scenarios. The imposition of calibration constraints increased the uncertainty in hydraulic conductivity parameter values under most scenarios in the Western Eromanga region (Figure 5.8), under the influence of future development alone over the whole GABtran model area (Figure 5.4), and under the influence of future climate alone at Dalhousie Springs (Figure 5.9).

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, in which enhanced knowledge of one parameter could result in a reduction of contributions to uncertainty from other parameter groups. The contribution of the key model parameters to the uncertainty of the predictions of groundwater level changes in each individual model cell could be calculated. The analysis could be extended to examine the impact of specific knowledge gaps, such as groundwater discharge 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. Future work could also explore the impact of alternative GAB system conceptualisations on these results.

### 5.4 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 prediction uncertainty (e.g. Dausman et al., 2010; Fienen et al., 2010; Merrick, 1999; Moore, 2005; Turnadge, 2010). 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.

The assessment of data worth can be undertaken both in terms of:

1. the increase in uncertainty resulting from the removal of an observation from an existing dataset (i.e. starting conditions assume that all observations are available)

2. the reduction in uncertainty resulting from the addition of an observation to the dataset (i.e. starting conditions assume that no observations are available).

In both of these cases the observations can be existing or nominal future observations, as the actual value of the observation is not used in the uncertainty calculation.

The results presented here follow from the earlier work of Merrick (1999) and Sinclair et al. (2000) who found that an exclusion radius of 20 km gave the smallest network that would be sufficient to describe the observed groundwater level distribution without undue deterioration of the resolution of the spatial groundwater level variations, and ranked monitoring bores in order of their significance to estimation of the average change in groundwater level for monitoring network observations.

This uncertainty analysis assessed the information content of the locations of the GABtran calibration bores in terms of how well the network informs estimates of average change in groundwater level over the whole region under the scenarios for the whole GABtran model area, for each region and at the Dalhousie Springs (Western Eromanga region) and Granite Springs (Surat region) locations. 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. The patterns shown derive from the interpolation of the results of the uncertainty analysis. A different interpolation method would produce slightly different patterns. A future analysis could assess the information content of the existing monitoring network for particular model cells.

Figure 5.10(a) shows data worth calculated on the basis that there are initially no observations to constrain the average groundwater level change prediction over the whole GABtran model area. The data from each observation bore are then systematically added and the associated 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 monitoring undertaken within the blue shaded area straddling the south of the Carpentaria region and the north of the Central Eromanga region contains significant groundwater level information. In addition, monitoring locations toward the southern part of the common boundary between the Western Eromanga and Central Eromanga regions, and in the north-eastern part of the Surat region also contain high amounts of information. Conversely, the monitoring occurring within areas of the GAB with red shading in Figure 5.10(a) have less information content to inform the average groundwater level change predictions within the whole GABtran model area.

Figure 5.10(b) shows data worth calculated on the basis that all currently available observations have been used to constrain the average groundwater level change predictions under the scenarios. The data from each observation well are then systematically removed and the resulting increase in uncertainty is assessed. In contrast, this figure, which is plotted to the same scale as Figure 5.10(a) indicates almost no variation in data worth across the existing monitoring network. This discrepancy in data worth between the two calculation methods is informative. Low data worth (red shading) in Figure 5.10(b), but high data worth (blue shading) in Figure 5.10(a) indicates that removing an observation from the existing data set in this area would have little impact on predictive uncertainty, but if there were no existing data, observations from the area would most significantly reduce prediction uncertainty. This means that, for areas with this discrepancy in data worth, there are currently sufficient groundwater level data for the assessment of the average groundwater level change under the scenarios. However, if the network was significantly reduced, retaining monitoring locations within the blue shaded areas of Figure 5.10(a), would allow more reliable predictions than retaining alternative existing monitoring locations.

Figure 5.10(c) is the same as Figure 5.10(b), but plotted over its own range of values. This shows that observations within the less dense monitoring areas where there are many bores and springs generally have the highest data worth.

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.
Chapter 5 Uncertainty analyses

Figure 5.11 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration in the Carpentaria region

Figure 5.12 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration in the Central Eromanga region

Figure 5.13 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration in the Surat region
Figure 5.14 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration at Granite Springs in the Surat region

Figure 5.15 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration in the Western Eromanga region

Figure 5.16 Spatial distribution of data worth of monitored groundwater levels used in GABtran calibration at Dalhousie Springs in the Western Eromanga region
Chapter 5 Uncertainty analyses

Figure 5.11, Figure 5.12, Figure 5.13, Figure 5.14, Figure 5.15 and Figure 5.16 show data worth results for the Carpentaria regions, Central Eromanga region, Surat region, Granite Springs location, Western Eromanga region and Dalhousie Springs location respectively. Within each figure, uncertainty increase is plotted to the same blue to red scale as uncertainty decrease, with uncertainty increase also plotted to its own purple to green scale.

For data worth calculated on the basis that there are initially no observations to constrain the average groundwater level change prediction (i.e. uncertainty decreases as observations are added), the analysis estimates that the groundwater level monitoring occurring within the blue shaded areas contains the greatest information for predicting the average groundwater level changes.

For data worth calculated on the basis that all currently available observations have been used to constrain the average groundwater level change predictions under the scenarios (i.e. uncertainty increases as observations are removed), all figures except Dalhousie Springs show almost no variation in data worth across the existing monitoring network. For these cases there are currently sufficient groundwater level data for the assessment of the average change in groundwater level. However, if the network was significantly reduced in size then retaining monitoring locations within the blue shaded areas shown in the uncertainty decrease results would allow more reliable predictions than retaining alternative existing monitoring locations.

Overall, when uncertainty increase results are plotted over their own value ranges, the highest data worth generally occurs for observations located in areas where groundwater extractions and spring discharges are dense, and where there is a low measurement density.

For Dalhousie Springs, the analysis indicates that monitoring occurring in the areas in Figure 5.16(a) and Figure 5.16(b) shaded at the blue end of the coloured spectrum contains the greatest information for making a prediction of groundwater level change at the Dalhousie Springs location. This consistency between the two analyses suggests that more groundwater level measurements would assist in the making of more reliable predictions of average groundwater level change at Dalhousie Springs.

For Granite Springs, the analysis indicates that the monitoring occurring in the area shaded at the blue end of the spectrum in the vicinity of the springs (Figure 5.14(a)) contains the greatest information for making a prediction of groundwater level change at the Granite Springs location. There are currently sufficient groundwater level data for the assessment of the water level change at the springs (Figure 5.14(b)). However, if the size of the network was significantly reduced, retaining monitoring locations within the areas of Figure 5.14(a) shaded at the blue end of the coloured spectrum would allow more reliable predictions at Granite Springs than retaining alternative existing monitoring locations. The highest data worth from the uncertainty increase results (Figure 5.14(c)) is for observations in the vicinity of the Granite Springs location.

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 appear 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, groundwater ages and flow rates derived from isotope data, or bore flow data). 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. Such extensions might include additional extraction 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.
6 Summary and conclusions

Three groundwater models were used to estimate the impact of climate and groundwater development on groundwater levels in the Great Artesian Basin (GAB):

- **GABtran:** an existing large-scale, transient groundwater model that simulates groundwater levels in the Cadna-owie – Hooray aquifer as a single layer spanning the GAB. GABtran uses the Habermehl (1980) conceptualisation of the GAB. It covers most of the GAB, except Cape York Peninsula, and was originally developed for the Great Artesian Basin Sustainability Initiative (GABSI) in 2006. It is suitable for estimating the effects of future climate and groundwater development across the GAB, but cannot simulate the groundwater level impacts of coal seam gas (CSG) activities because the CSG is extracted from geological layers that lay beneath the aquifer modelled by GABtran.

- **Cape York model:** a large-scale, transient groundwater model limited by a steady state calibration that simulates groundwater levels in the Cadna-owie – Hooray aquifer as a single layer. It has a common boundary with GABtran near the Gilbert River and also uses the Habermehl (1980) conceptualisation of the GAB. It was developed for the Assessment in parallel with the re-conceptualisation of the GAB. There were insufficient data for a more complex model or for a transient calibration. Transient simulations use storativities based on three estimates of average aquifer thickness: 100, 150 and 200 m.

- **Queensland Water Commission (QWC) model:** an existing regional-scale transient groundwater model that lies entirely within the Surat reporting region. It is a complex model with 19 layers representing the different aquifers and aquitards. The Cadna-owie – Hooray aquifer is represented by three aquifer layers in this model. The groundwater extraction for CSG occurs in the Walloon Coal Measures. Impacts on other layers from CSG-related development are likely to occur by vertical leakage, which will cause changes in groundwater levels in layers above and below. Results from the QWC model were provided to the Assessment by the QWC.

The modelling considered different scenarios of climate and groundwater development. The modelling scenarios include:

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

The future climate scenario included a change in rainfall and evaporation that would produce different groundwater recharge rates occurring at the intake beds during 2010 to 2070. These were simulated as 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 66 percent lower under the dry extreme climate and 83 percent higher under the wet extreme climate. In addition to the future climate with current (2010) groundwater development, consideration was given to a scenario of future climate with future development – created by changing rates of groundwater extraction.

6.1 Key findings

Figure 2.4(b) (GABtran, all regions) and Figure 4.16(b) (Cape York, Carpentaria region) show the change in groundwater level from 2010 to 2070 under the median future climate scenario and continuing the current level of groundwater extraction (Scenario Cmid). It is estimated that groundwater extraction will exceed replenishment in most of the south and west of the Eromanga Basin, in a wide arc through Roma and Charleville to Longreach, and near Weipa in the north of the Cape York Peninsula. Near areas of higher recharge in New South Wales and Queensland, groundwater levels are estimated to increase due to recharge exceeding groundwater use. The pattern is generally similar under the wet and dry extreme climates. Exceptions are increases in groundwater level near Marla in the west of the Western Eromanga region and in the north of the Cape York Peninsula under the wet extreme climate, and decreases in groundwater level over most of the intake beds under the dry extreme climate. These basin-margin areas that are most sensitive to changes in groundwater recharge have a lower capacity to transmit water down gradient (i.e. a lower transmissivity).
Figure 2.6(b) (GABtran, all regions) and Figure 4.23(b) (Cape York, Carpentaria region) show the change in groundwater levels from 2010 to 2070 under the median future climate scenario and future groundwater development (Scenario Dmid). It is estimated that groundwater extraction will exceed replenishment except where bore densities are high, such as around the Euroka Arch and the Nebine Ridge, driven by the rehabilitation of free-flowing stock and domestic water bores. The pattern is almost identical under the wet extreme climate. Under the dry extreme climate the intake beds in the south-east and south-west of the GAB are the most affected, with greater recharge deficits than under the median climate.

The impact of bore rehabilitation is greater than the impact of CSG development on the Cadna-owie – Hooray aquifer in the Surat region (comparing GABtran in Figure 2.6(d) with the QWC model in Figure 3.5(b)). Uncertainty analyses were used to describe the predictive confidence for the average impact of the GABtran model scenarios, and to assess how best to improve the reliability of the average model results through improved aquifer parameter knowledge and additional data collection. The uncertainty in GABtran model results (Table 5.2) is highest for Scenario D, which includes the impact of time, climate and groundwater development, and lowest for Scenario C relative to Scenario A, which only includes the impact of climate. The analyses quantify the reduction in uncertainty from model calibration and the contribution to post-calibration prediction uncertainty (Figure 5.4 to Figure 5.9). The greatest contribution to post-calibration prediction uncertainty is from storage properties; the least contribution is from inter-aquifer leakage. Data worth analysis (Figure 5.10 to Figure 5.16) shows that extending the groundwater level monitoring network in the Western Eromanga region, and between Julia Creek and Longreach in the Central Eromanga region would provide the greatest improvements in prediction reliability for a future upgrade of GABtran. More data would be needed to develop a more complex model. An analysis of the information content of the existing monitoring network for particular model cells would indicate if the existing monitoring network is adequate at locations distant from the bores used for GABtran calibration.

The implications of including any of the additional hydrogeological complexities determined in the Assessment in a more complex version of the GABtran model are unknown. It can be reasonably assumed that in order to maintain a calibrated model, significant revision of the parameters of the current models would be required. A difference in model layer thickness, hydraulic properties, or leakage from other layers would lead to different modelling outcomes.

Should a new groundwater model be developed for the GAB, the geological features outlined by the Assessment in the companion reports (as listed in Appendix A) 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.
References


CSIRO (2009d) 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.


Chapter 7 References


Appendix A Reports published by the Assessment


Data reports


Region reports


Summary reports


Technical reports


Appendix A Reports published by the Assessment


Three-dimensional visualisation report


Whole-of-GAB reports


Appendix B  Statistical measures for evaluating model calibration

The statistical measures in Apx Table B.1 were used in the quantitative assessment of the calibration of the Cape York steady state groundwater model.

<table>
<thead>
<tr>
<th>Description</th>
<th>Definition or equation</th>
<th>Units</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size</td>
<td>$n$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Measured head</td>
<td>$H_i$</td>
<td>m</td>
<td>Head measured at point i</td>
</tr>
<tr>
<td>Modelled head</td>
<td>$h_i$</td>
<td>m</td>
<td>Modelled head at approximate location of point i</td>
</tr>
<tr>
<td>Residual</td>
<td>$R_i = h_i - H_i$</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Range of measured values</td>
<td>$\Delta H$</td>
<td>m</td>
<td>Range of measured heads across model domain</td>
</tr>
<tr>
<td>Sum of residuals</td>
<td>$SR = \sum_{i=1}^n W_i</td>
<td>R_i</td>
<td></td>
</tr>
<tr>
<td>Mean sum of residuals</td>
<td>$MSR = SR/n$</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Scaled mean sum of residuals</td>
<td>$SMSR = \frac{100MSR}{\Delta H}$</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Sum of squares</td>
<td>$SSQ = \sum_{i=1}^n (W_i R_i)^2$</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>Mean sum of squares</td>
<td>$MSSQ = SSQ/n$</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>Root mean square</td>
<td>$RMS = \sqrt{MSSQ}$</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Scaled RMS</td>
<td>$SRMS = \frac{100RMS}{\Delta H}$</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Correlation coefficient</td>
<td>$R = \frac{\sum_{i=1}^n (h_i - \bar{h})(H_i - \bar{H})}{\sqrt{\sum_{i=1}^n (h_i - \bar{h})^2} \sqrt{\sum_{i=1}^n (H_i - \bar{H})^2}}$</td>
<td>-</td>
<td>$\bar{h}$ is the mean of the modelled head values $\bar{H}$ is the mean of measured head values</td>
</tr>
<tr>
<td>Coefficient of determination</td>
<td>$R^2 = (R)^2$</td>
<td>-</td>
<td>$R^2$ is one for a perfect calibration</td>
</tr>
</tbody>
</table>

Apx Table B.1 Statistical measures (Middlemis et al., 2000)