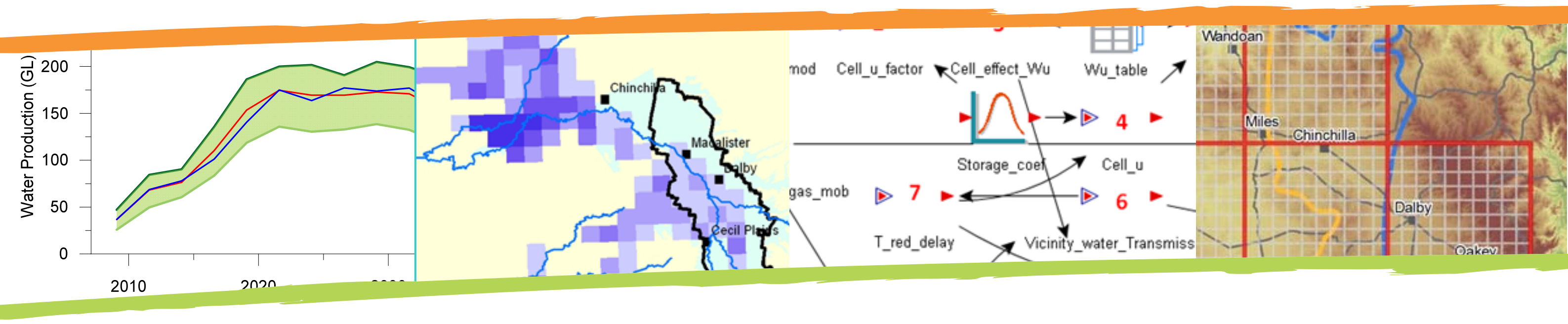
Forecasting coal seam gas water production in Queensland's Surat and southern Bowen basins

Technical report



Klohn Crippen Berger

Prepared for the Department of Natural Resources and Mines

September 2012

This document presents the outcomes of Activity 2 of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study.

The Healthy HeadWaters Coal Seam Gas Water Feasibility Study is analysing the opportunities for, and the risks and practicability of, using coal seam gas water to address water sustainability and adjustment issues in the Queensland section of the Murray-Darling Basin.

The study is being funded with $5 million from the Commonwealth Government, with support from the Queensland Government, as part of the Healthy HeadWaters Program, which is Queensland's priority project funded through the Commonwealth Government's Water for the Future initiative. The study is being managed by the Queensland Department of Natural Resources and Mines (DNRM), and is due to finish in 2012.

This report was prepared by Klohn Crippen Berger for the State of Queensland (Department of Natural Resources and Mines).

Klohn Crippen Berger acknowledges assistance from Angus Veitch of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study project team (DNRM) and from Econnect Communication in finalising this report.

The work described in this report was undertaken during the period October 2010 to March 2012, and thus reflects the state of knowledge and information available at that time.

Disclaimers

SUMMARY

Coal seam gas (CSG) is produced by extracting water from coal seams to release the pressure that holds the gas in place. This results in water coming to the surface. The water is known as ‘produced water’, ‘associated water’ or ‘CSG water’.

A major challenge in managing CSG water is predicting how much water will be produced, and when and where, as the industry develops.

The (then) Queensland Department of Environment and Resource Management (DERM)[1] commissioned Klohn Crippen Berger Ltd (KCB) to develop a tool to forecast where, when and how much CSG water will be produced in the Surat and southern Bowen basins.

This report describes how the tool was developed, how the tool works and the produced water estimates based on three industry-expansion scenarios for the period 2010–2060.

Development of the Water Production Tool

Work on this project has been completed in sequential phases. KCB had numerous meetings with DERM, CSG companies and external reviewers to collect baseline data and to seek third party review (formal and informal) of the adopted approach to estimating water production. The main steps in the development of the water production tool are summarised as follows:

- collect data and develop the conceptual design of the tool
- construct the tool using the GoldSim software platform
- upscale the tool to the basin-wide scale
- run initial simulations and assess the output
- develop and integrate unique CSG industry factors
- verify and validate the tool using historically reported water production and statistical analysis of the validation results
- assess and refine calibration factors
- finalise the tool and develop a user interface
- construct scenarios and use them to assess the functionality of the tool and its ability to estimate water production spatially and temporally.

The Water Production Tool (WPT) required a robust software platform to accommodate both quantitative inputs and inferred relationships. The platform needed to be flexible, transparent and represent the processes inherent in the system with appropriate recognition of uncertainty in all of the variables. The platform selected for the WPT was

[1] Following the change of government in March 2012, the Department of Environment and Resource Management was dissolved and its functions transferred to other departments. Responsibility for the current project was transferred to the newly created Department of Natural Resources and Mines.

GoldSim, which permitted construction of a multi-tiered, practical and modifiable tool, with the additional option of stochastic (Monte Carlo) modelling.

How the tool estimates CSG water production

A simple description of how the WPT estimates CSG water production is:

- Individual well pumping responses are assessed using the Theis equation, a non-equilibrium groundwater flow equation that accounts for the effect of pumping time on well yield in confined aquifers.
- Pumping effects are then projected spatially to assess the effect of each pumping well on nearby wells. Due to interference effects between wells, less pumping is needed at an individual well to achieve the same target drawdown performance.
- This water production is then upscaled to the basin-wide scale of the currently projected CSG industry. The geographic extent of the WPT is bounded by the lateral extent of the Queensland portion of the Surat Basin, and in the north includes southern areas of the Bowen Basin.
- Two modifications are then applied to address:
    - changes to water production rates as gas flow begins to dominate over water as production wells mature (dual-phase effects)
    - near-edge effects at the margins of the Surat Basin, where production zones are very shallow and local geological and hydrogeological conditions can have a greater influence on water production.

It is important to note that the WPT is not a groundwater flow model, and does not in any way predict effects other than the estimated water production amounts from CSG activities.

Verifying, validating and calibrating the WPT

The WPT was verified, validated and calibrated by:

- comparing a simplified version of the tool to equivalent Theis equations, and by visual comparisons of results against type curves provided by the CSG companies (verification)
- comparing historical (actual) values of water production for site-specific models with WPT outputs for periods of time consistent with the reported data (validation)
- running subsequent iterations of the Near-Edge Effects Factor (NEEF) and refining how it was applied (calibration).

Estimates of produced water from each of the three scenarios

Three primary scenarios were developed to provide a range of plausible estimates of future CSG water production and to test the functionality of the tool:

1. *Scenario 1*: company-supplied data (e.g. environmental impact statement) and inferred industry expansion
2. *Scenario 2*: simulated industry expansion using geology, infrastructure and current gas production areas as drivers for growth
3. *Scenario 3*: stochastically generated random industry expansion.

It is important to note that these scenarios represent only a small subset of all possible scenarios and should not be considered as exact representations of how the industry will evolve. The WPT has been constructed so that users can implement and simulate specific scenarios without significant effort.

The key results for these three scenarios are:

- *Scenario 1 (company-supplied data and inferred industry expansion)*. Data was sourced from company environmental impact statement (EIS) documents and information on well field development provided by the companies. Water production reaches a brief plateau of around 150 gigalitres per year (GL/year), before rising more gradually to reach an eventual peak of around 180 GL/year in 2030. Cumulative water production of about 4,500 GL is estimated to occur by around 2050.
- *Scenario 2 (expansion based on geology, infrastructure and current gas production)*. This scenario was based on thematic mapping of coal seam geology, current gas production areas (already developed/developing well fields) and proximity to regional infrastructure (roads and towns). This is similar to, but not a replication of, the approach of Evans & Peck's industry-wide assessment in that it considers broad drivers and constraints to industry development and uses a probabilistic approach. Under this scenario water production is more tempered, reaching a plateau of around 175 GL/year in about 2020. Cumulative water production is higher than Scenario 1, reaching about 5,100 GL by 2060.
- *Scenario 3 (random timing of well field initiation)*. This scenario is considered an unlikely development case as it assumes erratic and non-sequential well development. The scenario is run to observe the WPT response for a scenario considered to stress many of the input parameters. This is therefore an indicator of tool performance and not of expected water production. A peak of the order of 120 GL/year is noted early. For the remainder of operations to year 2040, water production averages around 130–140 GL/year. Cumulative water production is about 5,100 GL by 2060.

Comparison of estimated water production with previous estimates

Estimates of CSG water production have been developed by the Centre for Water in the Minerals Industry at The University of Queensland (CWiMI) in 2008, the CSG industry itself and by parties on behalf of the CSG industry (University of Southern Queensland, in 2011). A comparison of the available estimates is given in the table below.

Produced water estimates from the WPT and other studies

Assessment/source	Peak production (GL/year) [Mtpa: megatonnes per annum]	Cumulative production (GL)
CSG industry	140 (between 2018 and 2024)	2,500 (~Year 2040)
CWiMi (2008)	213 (28 Mtpa gas production) 300 (40 Mtpa gas production)	2,400 (Year 2025) (28 Mtpa gas production)
Aquaterra/UQS (2011)	200	4,100 (~Year 2040) 4,400 (~Year 2060)
WPT Scenario 1	180 (brief peak of 280 in raw output)	4,300 (~Year 2040) 4,500 (~Year 2060)
WPT Scenario 2	175	4,500 (~Year 2040) 5,100 (~Year 2060)
WPT Scenario 3	150 (varying 100–200 in raw output)	3,900 (~Year 2040) 5,100 (~Year 2060)

Up to about 2035, all of the estimates except for the CWiMI 40 megatonnes per annum scenario and the combined industry estimates are in fairly close agreement (although the CWiMI 28 mtpa scenario only lasts to 2025).

The differences among the various water production estimates are to be expected because the estimates have been derived using different methods, with access to different types and amounts of data, and with different assumptions about how the industry will develop.

Improving the tool

The tool has been designed to be readily updated and modified to incorporate new data and information about CSG water production and how the CSG industry expands. Four areas where improved knowledge will greatly assist in the estimation of water production are:

- *Regional geology*

  Improved knowledge of regional geology, and development of basin-scale mapping and datasets will develop with the evolution of the CSG industry. Maintaining regular period 'gates' when wholesale updates to the tool's primary database can occur is strongly recommended.

- *Dual-phase effects and consequential reduction in pumping demand*

  Due to the general uncertainty surrounding this variable, it is expected that more detailed assessment and representation will be needed. Further understanding of the effect of gas flow on water production should evolve with industry maturity. Important to this is its spatial representation, and quantifying the difference in dual-phase effects from deep basin sediments to basin-margin strata (if any).

- *Industry expansion knowledge*

  Significant uncertainty remains about the long-term evolution of the industry in terms of areas developed, well density, operational intensity and scheduling. This knowledge will improve WPT set-up and simulations.

- *Water quality*

  The tool is currently populated with a small subset of water qualities derived from the Queensland Government's Groundwater Database. Site-specific monitoring programs are underway, and populating the tool with a more representative set of water qualities across the domain would provide a far more accurate estimate of salinity and salt loads.

Regular re-verification is critical to the success of this tool. Verification of the tool every two years is recommended to take advantage of updated water production data and to provide time for new base data to be integrated. Once there is enough confidence in the ability of the tool to estimate produced water in response to industry factors, and if sufficient data is available, more formal calibration could be considered.

GLOSSARY

Aquifer	A sequence of permeable and transmissive strata that supplies groundwater.
Aquitard	A water-saturated sediment or rock whose permeability is so low it cannot transmit any useful amount of water. An aquitard allows some measure of leakage between the aquifer interval it separates.
Artesian	A condition which applies to aquifers which are confined by layers of low permeability, and where the hydraulic head in the aquifer is higher than the overlying ground surface. Wells penetrating such aquifers may result in groundwater flowing at the surface without pumping.
Cell	In the WPT, an area of 10 kilometres x 10 kilometres within a cell block.
Cell block	In the WPT, a collective of 100 cells in a uniform 10 x 10 configuration.
Confined aquifer	Exists where the groundwater is bounded between layers of impermeable substances such as clay or dense rock. When tapped by a well, water in confined aquifers is forced up, sometimes above the surface.
Confining layer/unit	Geologic material with little permeability or hydraulic conductivity.
Coal seam gas	A natural gas, consisting primarily of methane, that forms in underground coal seams. The gas is held within the coal by the pressure of water residing in and around the coal. When the water is extracted, the gas is released.
Dissolved solids	Minerals and organic matter dissolved in water.
Drawdown	A lowering of the groundwater level caused by pumping.
Dual-phase effects	The effective permeability of the aquifer or coal seam varies as a function of the relative amount of each phase (water and gas) present. When gas is produced in the CSG process, this competes with resident water in the aquifer or coal seam. The result is a change in the effective hydraulic conductivity of the rock as gas is produced and dual phase flow from the pumping zone occurs.
GoldSim	Software platform used to construct the WPT. GoldSim is a graphical program for carrying out dynamic, probabilistic simulation of systems.
Great Artesian Basin (GAB)	A confined groundwater basin which underlies 1.7 million square kilometres of Australia. The basin is a multi-layered aquifer system, with aquifers in Triassic, Jurassic and Cretaceous continental quartzose sandstones. Intervening confining beds consist of siltstone and mudstone; Cretaceous marine sediments form the main confining unit (Habermehl, 1998).
Groundwater	The water in the aquifer.
Groundwater flow model (numerical)	A numerical groundwater flow model is a mathematically constructed representation of a hydrogeological system that applies accepted theory of groundwater flow under various forms of groundwater stresses or boundaries. The model is used to predict the spatial representation of hydraulic heads, groundwater flow rates and regional hydrogeological gradients, under a variety of user initiated stress conditions.
Hydraulic conductivity	The ability of or ease with which water moves through pore spaces or fractures. It is measured as the volume of water that will move through a medium in a unit of time, under a unit hydraulic gradient, through a unit area measured perpendicular to the direction of flow.

Hydraulic gradient	The change in hydraulic head or water level over a distance.
Hydraulic head	The height above a datum (such as sea level) of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system.
Hydrochemical type	The definition of a chemical composition of groundwater based on the relative percentages of major cation and anion concentrations.
Hydrogeochemistry	The study of the chemical processes and reactions that govern the composition of water in relation to its interaction with rocks and the aquifer.
Hydrostratigraphic unit	Geological units that are not solely based on lithologic characteristics but also include characteristics related to water movement, occurrence and storage.
Impermeable layer	A layer of material (such as clay) in an aquifer through which water does not pass.
Isopach	A contour line of equal thickness.
Lithology	The systematic description of sediment and rocks, in terms of composition, texture and internal structure.
Near-Edge Effects Factor (NEEF)	A factor developed in the WPT to account for observed basin edge effects on hydraulic properties and hydrogeological response to pumping, which appear unique to shallower areas of CSG production. It was developed to provide a mechanism for alteration of hydraulic properties of the production zones, which translate to changes in predicted water production.
Potentiometric surface	A hypothetical surface representing the level to which groundwater would rise if not restricted in a confined aquifer. The potentiometric surface is to a confined aquifer what the water table is to an unconfined aquifer.
Salinity	The amounts of various types of salt present in water (see also *Total Dissolved Solids*).
Surat Basin	Basin located in south of Queensland and north of New South Wales. It contains up to 2500 metres of Jurassic to Lower Cretaceous sedimentary rocks. It merges eastward with the Clarence-Moreton Basin.
Stochastic	A stochastic model is a tool for estimating probability distributions of potential outcomes by allowing for random variation (usually within well constrained bounds) in one or more inputs over time
Storativity	The storage coefficient or storativity is a measure of the volume of water per volume of aquifer released as a result of a change in head. For confined aquifers, the storage coefficient is equal to the product of the specific storage and aquifer thickness.
Stratigraphy	A geological term commonly used in describing basinal or layered geology in terms of distribution, age and depositional environment. A stratigraphic column is a graphical depiction of stratigraphy commonly showing age of units, sequence of deposition, contact relationship and sometimes environment of deposition.
Theis equation	A commonly used equation to describe the transient flow of water a result of pumping in a confined aquifer. The equation was derived by CV Theis in 1935 and has been widely used to find average aquifer parameters such as T and S values near a pumping well, from drawdown data or to estimate drawdown using known aquifer parameters as a function of pumping rate.

Transmissivity	Transmissivity is the rate at which water is transmitted through a unit thickness of aquifer under a unit hydraulic gradient (Driscoll, 1986). It is the product of the hydraulic conductivity and the contributing thickness of the aquifer to flow.
Total Dissolved Solids (TDS)	Concentration of all substances dissolved in water (solids remaining after evaporation of a water sample).
Type curve	In the context of this report, these curves are water production curves for specific CSG extraction areas within the study region.
Walloon Coal Measures	Middle Jurassic coal measures of approximately 200 metres thick consisting of mudstone, siltstone, fine-grained clayey lithic sandstone and thin seams of coal. The unit rests conformably with the Hutton Sandstone and Marburg Formation.

ACRONYMS

CSG	Coal seam gas
CWiMI	Centre for Water in the Minerals Industry
DEEDI	Queensland Department of Employment, Economic Development and Innovation
DERM	Queensland Department of Environment and Resource Management
E&P	Evans & Peck (consultants)
EC	Electrical conductivity
EIS	Environmental impact statement
GAB	Great Artesian Basin
GWDB	Groundwater Database
LNG	liquefied natural gas
NEEF	Near-Edge Effects Factor
QPED	Queensland Petroleum Exploration Database
TDS	Total dissolved solids
TRF	Transmissivity Reduction Factor
WPT	Water Production Tool ('the tool')

TABLE OF CONTENTS

SUMMARY II

Development of the Water Production Tool ii

How the tool estimates CSG water production iii

Verifying, validating and calibrating the WPT iii

Estimates of produced water from each of the three scenarios iv

Comparison of estimated water production with previous estimates v

Improving the tool v

GLOSSARY VII

ACRONYMS IX

1. INTRODUCTION 1

1.1 Coal seam gas, produced water and the aim of the Water Production Tool 1

1.2 What this report covers 2

1.3 Scope of the project 2

1.4 Study approach 3

2. THEORY AND CONCEPTS BEHIND THE WATER PRODUCTION TOOL 4

2.1 How CSG water is produced 4

2.2 How the tool works 4

2.3 Using the Theis equation to estimate water produced by individual wells 5

2.4 Representing well placement and density 6

2.5 Simulating well interference effects 7

2.6 Accounting for basin-scale complexity 9

2.7 Addressing dual-phase and basin edge effects 10

2.7.1 Correcting for transmissivity 10

2.7.2 Factoring in basinal near-edge effects 11

2.8 Geographic scope of the tool 11

3. DATA USED BY THE TOOL 13

3.1 Collecting data 13

3.2 Data used to populate the tool 14

4. CONSTRUCTION AND FUNCTIONING OF THE TOOL 20

TABLE OF CONTENTS
(continued)

4.1 Software and simulation framework....20
4.2 The tool development process....21
4.3 Confidentiality considerations....22
4.4 Building the GoldSim model....22
4.4.1 Tiered tool and navigation structure....24
4.4.2 Methodology for water production calculations....26
4.4.3 GoldSim algorithm walk-through....27
4.4.4 Simulation factors to better simulate *in situ* conditions....35
4.4.5 Delays used in simulation....36
4.4.6 Water quality representation....37
4.5 Assumptions and limitations....39
5. VERIFYING AND VALIDATING THE TOOL....41
5.1 Verification....41
5.2 Validation....41
5.3 Calibration....45
6. INDUSTRY EXPANSION SCENARIOS....50
6.1 Industry scenario influences and the WPT....50
6.1.1 Using stochastic modelling to understand uncertainty....51
6.1.2 Timing and intensity of development....51
6.2 *Scenario 1*. Company-supplied and inferred industry expansion....52
6.2.1 Limitations of the data provided for Scenario 1....52
6.3 *Scenario 2*. Industry expansion considering geology, infrastructure and current gas production....53
6.3.1 Evans & Peck industry assessment and application to a geology- and infrastructure-driven scenario....53
6.3.2 Details of Scenario 2....54
6.4 *Scenario 3*. Stochastically generated expansion....59
6.5 Estimating the number of wells....59
6.5.1 Comparing WPT well-count estimates with estimates from Evans & Peck....60
7. ESTIMATED WATER VOLUMES AND QUALITY FOR THREE INDUSTRY EXPANSION SCENARIOS....62

TABLE OF CONTENTS
(continued)

7.1 Results from the WPT 62

7.1.1 Graphical and spatial presentation of results 62

7.1.2 Produced water peaks 63

7.2 Estimated water production 64

7.2.1 *Scenario 1*. Annual and cumulative water production 64

7.2.2 *Scenario 2*. Annual and cumulative water production 65

7.2.3 *Scenario 3*. Annual and cumulative water production 66

7.2.4 *Scenario 2*. Spatial water production estimates 68

7.3 Total estimated water production 73

7.3.1 Sensitivity Analysis 73

7.4 Estimated salt production 75

7.5 Previous water production estimates and comparisons with the WPT 76

7.5.1 Water production estimates produced by CSG companies 76

7.5.2 University of Southern Queensland/RPS Aquaterra (2011) 77

7.5.3 Centre for Water in the Minerals Industry (2008) 78

7.5.4 Comparing previous water production estimates with WPT estimates 80

8. IMPROVING THE TOOL 83

8.1 Incorporating new data 83

8.2 Re-verifying and re-calibrating the WPT 83

REFERENCES 84

APPENDIX I DETAILED DATA DISCUSSION 85

APPENDIX II DERIVATION OF THE WELL DENSITY FACTOR 89

APPENDIX III DETAILS OF NEEF VERIFICATION ASSESSMENT 93

APPENDIX IV HISTORICALLY REPORTED CSG WATER PRODUCTION VOLUMES 96

APPENDIX V RAW SIMULATED WATER PRODUCTION FOR THREE SCENARIOS 97

APPENDIX VI SPATIAL DISTRIBUTION OF P25, P50, P75 ESTIMATED WATER VOLUMES FOR SCENARIO 2 99

TABLE OF CONTENTS
(continued)

Tables

Table 3-1. Data types, sources and limitations used to populate the WPT (for 100 metre x 100 metre resolution) 14

Table 7-1. Each scenario's permutations and realisation numbers 62

Table 7-2. Water production by cell block for Scenario 2 (mean values) 68

Table 7-3. Sensitivity analysis variables 74

Table 7-4. Summary values for WPT and other water production estimates 81

Table AI-1. Summary of datasets, assumptions and interpolation methods 86

Table AIII-1. Sample population comparisons using ANOVA and descriptive statistics 93

Table AIV-1. Historic water production 96

Figures

Figure 2-1. How individual pumping rates cause interference with other wells in a well field (schematic representation) 8

Figure 2-2. Three scales of assessment—the cell, cell block and whole tool domain, shown with upscaling 10

Figure 2-3. The area covered by the WPT (each grey square is a cell, each red square a cell block) 12

Figure 3-1. A key spatial data layer—coal measure isopachs 17

Figure 3-2. A key spatial data layer—transmissivity 18

Figure 3-3. A key spatial data layer—well density 19

Figure 4-1. Calculations performed by the WPT in each time step 23

Figure 4-2. The spatial domain of the WPT showing the Surat and Bowen Basin coal measures (with cell block numbers overlaid). 25

Figure 4-3. The WPT calculations for cell block 12 as an example of the calculation sequence in GoldSim 28

Figure 4-4. Interpolated water-quality distribution over the WPT's domain 38

Figure 5-1. An example of a satisfactory validation (example shows Origin PL204 historical versus simulated results) 43

Figure 5-2. An example of an unsatisfactory validation (example shows Arrow Energy PL230 historical versus simulated results) 43

Figure 5-3. Correlation of historical and simulated cumulative production for an early attempted validation 44

TABLE OF CONTENTS
(continued)

Figure 5-4. Correlation of historical and simulated cumulative production with a proportional 15% NEEF applied 46

Figure 5-5. Correlation of historical and simulated cumulative production with variable NEEF applied to reflect varying coal seam depth 47

Figure 5-6. Final validation of PL198 using an updated and simplified NEEF (with certain criteria requirements met before the NEEF is applied) 48

Figure 5-7. Correlation of historical and simulated cumulative production with the final NEEF applied 49

Figure 6-1. Thematic maps used to develop Scenario 2, showing ratings for geology and proximity to towns and infrastructure. 55

Figure 6-2. Combined thematic map scores for Scenario 2, indicating priortised order of development. Red is highest priority (little or no delay to activation); green is lowest (longer delay to activation). 56

Figure 6-3. Number of month delays to activation in cells (in cell block 12) from the start of simulation 58

Figure 6-4. Variation in the properties of the coal seam across adjacent cells, and their effect on development priority (delays to cell activation) 59

Figure 6-5. Estimated number of wells in operation for each of the three scenarios in the WPT 60

Figure 6-6. Comparison between E&P and KCB estimated number of wells (until 2021). The percentile measures (P00 to P100) describe E&P's results. 61

Figure 7-1. Scenario 1 – cumulative and annual water production (smoothed) 64

Figure 7-2. Scenario 1 – cumulative and annual water production (raw simulated values) 65

Figure 7-3. Scenario 2 – cumulative and annual water production (smoothed) 66

Figure 7-4. Scenario 3 – cumulative and annual waters production (smoothed) 67

Figure 7-5. Simulated annual water production for each cell block 69

Figure 7-6. Time sequence of CSG water production for Scenario 2 (median values) 70

Figure 7-7. Comparison of median, 25th and 75th percentile CSG water production estimates for Scenario 2 in the period 2020–2025 71

Figure 7-8. Comparison of median, 25th and 75th percentile CSG water production estimates for Scenario 2 in the period 2035–2040 72

Figure 7-9. Results of sensitivity analysis for cumulative water production 75

Figure 7-10. Cumulative salt production for Scenario 2 76

TABLE OF CONTENTS
(continued)

Figure 7-11. Estimated water production as reported in EISs and related documents 77

Figure 7-12. Water production estimates based on 'low impact case' industry projections (University of Southern Queensland, 2011) 78

Figure 7-13. CWiMI model estimates of CSG water production 79

Figure 7-14. Comparison of projected CSG water production estimates 80

Figure 7-15. Comparison of projected cumulative CSG water production estimates 81

Figure AII-1. Normalised water production per well for varying well density 90

Figure AII-2. Interference effects resulting from varying well density (water production per well expressed as percentage of expected production from a single operating well) 91

Figure AII-3. Well density factor (the 200 well point extrapolated) 92

Figure AIII-1. No NEEF (mean = 132, SD = 678) 94

Figure AIII-2. Proportional 15% NEEF included (mean = 19, SD = 517) 94

Figure AIII-3. Variable NEEF included (mean = -6.1 SD = 539) 95

Figure AV-1. Scenario 1. Annual and cumulative water production 97

Figure AV-2. Scenario 2. Annual and cumulative water production 97

Figure AV-3. Scenario 3. Annual and cumulative water production 98

Figure AVI-1. Time sequence of CSG water production for Scenario 2 (P25 values) 100

Figure AVI-2. Time sequence of CSG water production for Scenario 2 (P50 values) 101

Figure AVI-3. Time sequence of CSG water production for Scenario 2 (P75 values) 102

1. INTRODUCTION

1.1 Coal seam gas, produced water and the aim of the Water Production Tool

Coal seam gas (CSG) is a natural gas, consisting primarily of methane, which is extracted from underground coal seams. The CSG industry in Queensland is rapidly expanding as CSG companies develop projects to export the gas as liquefied natural gas (LNG). CSG extraction in Queensland occurs mostly in the Surat and southern Bowen basins.

CSG is produced by extracting water from coal seams to release the pressure that holds the gas in place. This process results in water being brought to the surface. The water is known as ‘produced water’, ‘associated water’ or ‘CSG water’. It is generally saline and CSG companies need to manage it in accordance with the hierarchy of disposal and beneficial-use options set out in Queensland’s CSG Water Management Policy (DERM, 2010).

A major challenge in managing CSG water is predicting how much water will be produced, and when and where, as the industry develops. While CSG companies are required to include CSG water forecasts in their environmental impact statements (EISs) and coal seam water management plans, these forecasts are for individual projects only, and do not provide a consistent and transparent picture of water production by the industry as a whole.

The (then) Queensland Department of Environment and Resource Management (DERM)[2] commissioned Klohn Crippen Berger Ltd (KCB) to develop a tool capable of forecasting where, when and how much CSG water will be produced in the Surat and southern Bowen basins under various industry expansion scenarios. This is Activity 2 (Modelling and Forecasting of CSG Water Production) of the Healthy HeadWaters Coal Seam Gas Water Feasibility Study. The feasibility study is a $5 million, three-year project funded by the Commonwealth Government which is assessing opportunities to use CSG water to help achieve water sustainability outcomes in the Queensland Murray-Darling Basin (QMDB). The tool developed in Activity 2 is crucial for identifying the volumes of water that may be available for this purpose.

The tool will also assist in the management of CSG water more broadly; for example, by helping to identify when and where efforts to manage CSG water may need to be focused, and by indicating how alternative industry expansion paths may affect CSG water production. It will also indicate where and when CSG water may be available for beneficial use or injection into aquifers.

[2] Following the change of government in March 2012, the Department of Environment and Resource Management was dissolved and its functions transferred to other departments. Responsibility for the current project was transferred to the newly created Department of Natural Resources and Mines.

1.2 What this report covers

This report documents the development, construction and verification of the CSG Water Production Tool (WPT or 'the tool'). It also describes three broad scenarios that were run using the WPT and presents the estimates of produced water for each scenario.

The report covers:

- the theory and background of the WPT
- the data used to populate the tool
- how data and theory were applied to build a functional forecasting tool
- the process of validating and verifying the estimates and refining the tool based on these results
- the three CSG industry expansion scenarios used to assess the functionality of the tool and to provide plausible water production estimates
- the estimates of water produced under each scenario, and how they compare with other estimates
- how the tool can be improved in the future.

1.3 Scope of the project

This project aimed to construct a readily modifiable tool that:

- permits spatial appreciation of where and how much water may be produced as a result of CSG activities, based on a systematic and common approach to predicting water production where CSG extraction is being undertaken
- represents anticipated bulk water quality at these locations and times, based primarily on source water total dissolved solids (TDS)
- represents the system at a sufficient timescale to consider evolving site operations, and identify peak and long term rates of water availability.

This project applied an approach developed and founded on fundamental groundwater flow theory, adapted to the nuances of CSG production. Although the tool is comprehensive and complex, it has been developed in a manner to avoid the time-consuming complexity of updating input files typical of more traditional predictive groundwater modelling techniques. **Importantly, the WPT is not a groundwater flow model, and does not in any way predict effects other than the estimated water production amounts from CSG activities**. Separate studies focused specifically on impact assessment, groundwater modelling of CSG expansion and other issues should be consulted for this information.

The spatial domain of the tool is the Surat and southern Bowen basins, shown in Figure 2-3 in Section 2.8. This area covers the majority of currently planned CSG production in Queensland, although CSG companies are exploring regions outside the current domain

of the WPT. Temporally, the scenarios assessed in this investigation cover a nominal 50-year period from 2010–2060, which is expected to capture the duration of CSG activity. However, this is likely to change as the industry develops and matures.

1.4 Study approach

Work on this project has been completed in sequential phases. KCB had numerous meetings with DERM, CSG companies and external reviewers to collect baseline data and to seek third party review (formal and informal) of the adopted approach to estimating water production. The main steps in the development of the WPT are summarised as follows:

- collect data and develop the conceptual design of the tool
- construct the tool using the GoldSim software platform
- upscale the tool to the basin-wide scale
- run initial simulations and critique the output
- develop and integrate unique CSG industry factors
- verify and validate the tool using historically reported water production and statistical analysis of the validation results
- assess and refine calibration factors
- finalise the tool and develop a user interface
- construct scenarios and use them to assess the functionality of the tool and its ability to estimate water production spatially and temporally.

Because of confidentiality restrictions, presentation of some key information and spatial construction of the WPT has in some cases been constrained, or specific details have been excluded from this report. Confidential data that has been included in model development and simulations but that is not explicitly shown is listed in Appendix I.

Where such data constraint or exclusion occurred, this information has been conveyed to the reviewers for completeness. In populating the WPT, KCB has made no spatial or temporal distinction between company-supplied data and assumed or interpolated data. Nor has a distinction been made between data from different companies. As a result, certain factors such as tenement boundaries and potential conflicting interests of neighbouring CSG companies have not been taken into account.

2. THEORY AND CONCEPTS BEHIND THE WATER PRODUCTION TOOL

2.1 How CSG water is produced

Generating coal seam gas (CSG) and its associated 'produced water' is a complex process. A summary of the process is provided:

- Gas production wells are drilled and constructed to target producing zones within Surat Basin or southern Bowen Basin strata (e.g. the Walloon Coal Measures).
- These wells are equipped and groundwater is pumped to lower the hydrostratigraphic head within producing coal seams (the target producing zones).
- Water pumping is maintained at an intensity that depressurises the coal seam(s) to a design elevation or head above the target producing zone.
- This process of head reduction reduces the pressure and liberates the gas, which is collected at the surface. Through this process the coal seams are depressurised, not fully dewatered, so water needs to be continually pumped to maintain gas flow.
- With time, the amount of water that needs to be pumped to maintain this flow declines. This is because:
  - Yields naturally decline because of pumping (and the resulting distributed pumping stress across the aquifer or producing zone). This is consistent with accepted groundwater pumping theory.
  - Increased gas flow competes with, and replaces, water as it is pumped. This is called the 'dual-phase effect', and is unique to CSG production.

2.2 How the tool works

The WPT estimates produced water by following these steps:

- Individual well pumping responses are assessed using the Theis equation, a non-equilibrium groundwater flow equation that accounts for the effect of pumping time on well yield in confined aquifers. The Theis equation is traditionally used to predict drawdown at any time after pumping begins (Driscoll 1986). For the WPT, the equation was rearranged to solve for the pumping rate instead of drawdown.
- Pumping effects are then projected spatially to assess the effect of each pumping well on nearby wells. Due to interference effects between wells, less pumping is needed at an individual well to achieve the same target drawdown performance. Interference effects need to be calculated iteratively, and this is achieved within the Goldsim platform.

- Water production is then upscaled to the basin-wide scale of the currently projected CSG industry. Upscaling is not a simple matter of adding more wells in more regions, because of the numerical demands to solve the iterative equations and the exponential increase in equation complexity with increasing well count. The approach applied replicates the basin-wide scale of potential CSG operations while streamlining (and simplifying) the numerical intensity of the iterating equations.
- Two modifications are then applied to address:
  - changes to water production rates as gas flow begins to dominate over water as wells mature (dual-phase effects)
  - near-edge effects at the margins of the Surat Basin. At the edge of the basin, production zones are very shallow, and local geological and hydrogeological conditions are of more influence on water production than in deeper producing zones.

It is important to note that the WPT does not simulate groundwater flows and also assumes no recharge or vertical leakage.

These steps are discussed further in the following sections.

2.3 Using the Theis equation to estimate water produced by individual wells

The Theis equation[3] is given by:

$$s = \frac{Q}{4\pi T} W(u)$$

Where:

- s is drawdown, which is the amount of decline in groundwater level caused by pumping water from the well.
- Q is well production, or pumping rate applied to achieve the target drawdown.
- T is transmissivity, which is a hydrogeological measure of the ability of an aquifer to transmit water. It is simply derived as the hydraulic conductivity of an aquifer multiplied by its saturated thickness.
- W (u) is the well function, which is an indicator of steady state groundwater cone of depression for the dimensionless time parameter u, ($u = \frac{rS}{4\,Tt}$), where
  - S is storativity of the aquifer, which measures the amount of water available to pumping that is held in storage

[3] The Theis equation assumes the aquifer is confined, homogenous, isotropic and of infinite extent. The confined conditions assumption is important and is supported by the operational approach to depressurise and not dewater, thus a remnant head on the producing coal seams is maintained, which in turn maintains the confined nature of the producing zone.

- t is elapsed time since pumping began
- r is the distance from the pumping well the drawdown was observed.

All of these factors are incorporated in the tool and can be varied spatially according to available information. Further details of this groundwater theory can be found in recognised hydrogeological texts such as Driscoll (1986), Freeze and Cherry (1979), Fetter (1999), and Domenico and Schwartz (1998).

By rearranging the Theis equation, changes in pumping rate to maintain a static pumping water level can be derived from the following:

$$Q = \frac{4\pi Ts}{W(u)}$$

The equation is implemented in the tool to solve for pumping rate instead of drawdown. Using this approach, a pumping curve which decays with time to achieve a constant desired drawdown for a specific hydrogeological setting, and at any given well location and time, can be developed.

This scenario matches the premise of CSG operation, where pumping rate is stabilised to maintain a depressurised condition for gas flow. However, it is important to stress several aspects which this version of the WPT does not take into account. These include:

- For this version it has been assumed that non-CSG water abstraction from the coal seams is negligible compared to the water extracted for CSG production.
- Based on CSG industry assessments and more recent studies such as USQ (2011), vertical leakage into the coal seams is assumed to be negligible.
- Although the Theis equation is used, the assumptions of isotropy and homogeneity are only applied at the most local scale (i.e. at the cell scale). Aquifer parameters are variable at this scale and the most representative values for each cell are used. However, values of T and S do vary from one cell to the next.
- The tool currently does not consider the effects of fracking on aquifer parameters or on the amount of water produced.

2.4 Representing well placement and density

Closer to a pumped bore, there are greater impacts on local groundwater conditions because of drawdown effects. As a single bore or well is pumped, a cone of depression develops which (in an ideal aquifer) propagates away from the pumping bore as a conical depression in the potentiometric surface of the aquifer being pumped.

This concept is fundamental to the design of groundwater supply or dewatering bore fields, where design requires measured placement of pumping bores to minimise or maximise pumping impacts of one bore on another (interference).

In the CSG industry, well placement will not be determined as a function of idealised water production. Wells will be placed based on the gas production potential of the target zone, which will probably also be affected by access and economic factors (e.g. drill depth, maturity of field). Regardless, well fields are expected to have a well density sufficient for wells to impose pumping effects on each other during operation.

For this reason the design of the WPT needs to consider interference effects between CSG wells, from a water production perspective, and also needs to account for the large scale and development area expected of the industry.

2.5 Simulating well interference effects

One producing well in isolation will need to pump sufficient water to achieve the target operational drawdown. If there are two wells in close proximity, then the cone of depression from pumping from each well will extend across and affect the other well.

As a theoretical example, if these two wells need to achieve 50 metres of drawdown each, and the cone of depression of each extends and imposes the equivalent of one metre of drawdown at the other well, then the required pumping rate can lower slightly as the target drawdown is marginally reduced to 49 metres.

In a well field situation, there may be numerous pumping wells affecting each other—the collective result can be a significant reduction in individual pumping rates needed to achieve the same target drawdown (shown in Figure 2-1).

Figure 2-1 is not a literal representation of what occurs in the field. In reality, and in the WPT, pumping reduces the water *pressure* (represented by the potentiometric surface) within the coal seam rather than physically lowering the level of the water above the coal seam.

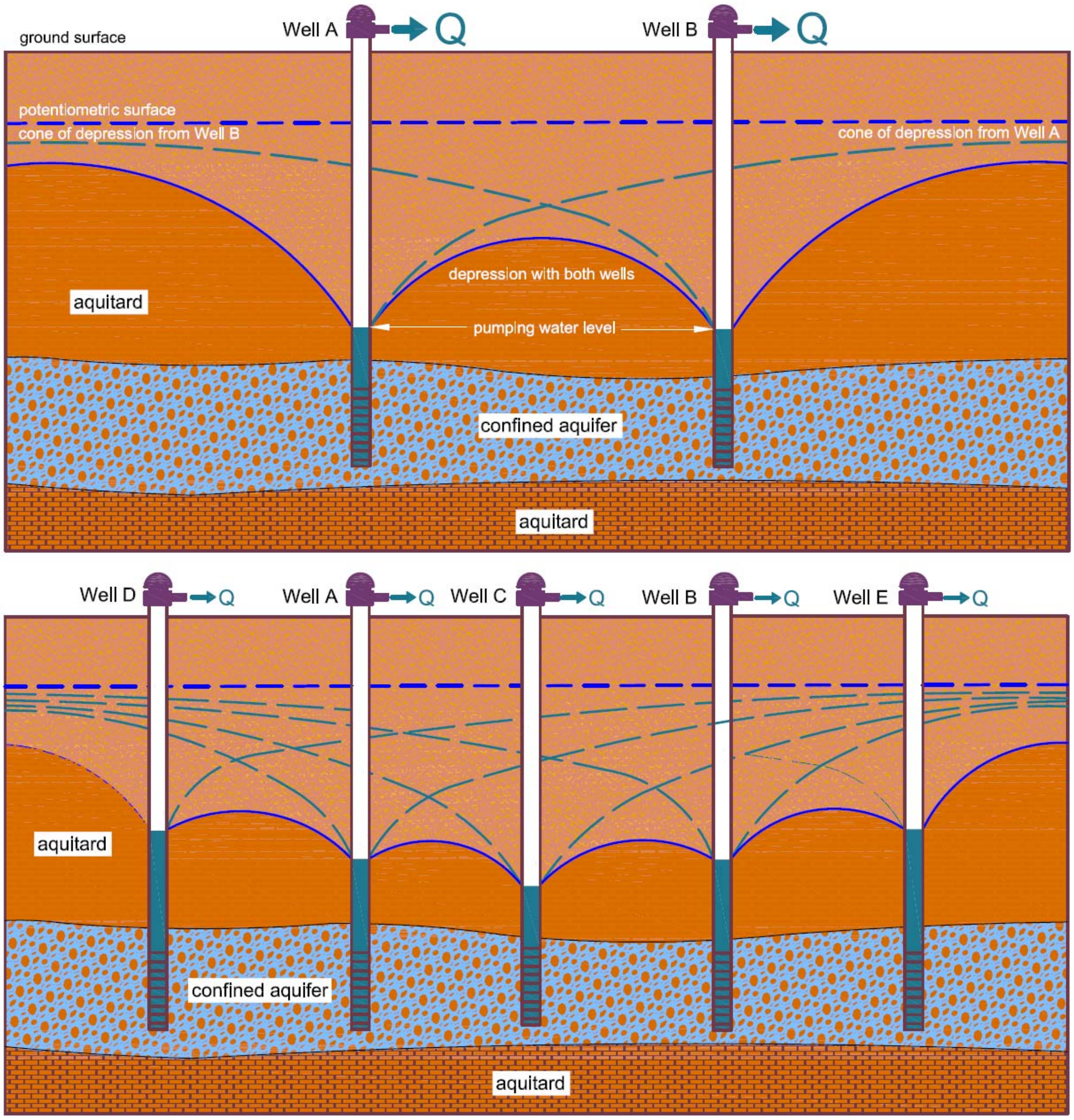


Figure 2-1. How individual pumping rates cause interference with other wells in a well field (schematic representation)

The Theis equation is rearranged to simulate the effect of interference in the WPT. This permits the prediction of drawdown at distances away from the pumping well. These distances need only align with the distance to nearby wells to evaluate the effect they have on each other. (The reader is reminded the intent of this tool is not to predict drawdown—in this case the drawdown effect away from the pumping well is used to adjust the desired target drawdown so pumping rates can be determined.)

Logically, a greater density of wells for a given aquifer condition will individually need to pump less than a more distributed field as each of the wells are ‘closer’ to each other and ‘deeper’ within the neighbouring cones of depression.

2.6 Accounting for basin-scale complexity

The concept of well interference is relatively straightforward. However, the scale of the CSG industry and the large number of wells expected complicates the process of assessing well interference. For example, calculating the effect of 10 wells on each other requires 100 calculations for a single time step. This might at face value seem numerically achievable, but the calculations become further complicated with varying well-to-well distances, residual effects from previous pumping from other wells, wells switching on and off, forward-looking pumping stress calculations, and variability in aquifer conditions. Accounting for these complexities for thousands of wells is impractical because the tool would lose flexibility and speed.

Some numerically intensive elements of the calculation process have therefore been simplified in order to achieve the project objectives without impractical model complexity and excessive run times. These are discussed further in Section 4, but in brief:

- Well density (and therefore distances between wells) is derived from a suite of matrices (based on information provided by each of the CSG companies) rather than individually calculated well to well distances. Drawing on matrix-derived density reduces the millions of calculations that would otherwise be required to assess inter-well distances on an industry-wide scale. Any lost accuracy in well densities using this technique is probably offset by the uncertainty in industry expansion scenarios, and by locations and densities of ultimate operational well configurations.
- The study area is parcelled into three tiers of assessment, because attempting to calculate water production at the well-field scale for the whole of the basin in one step would introduce impractical calculations. The three tiers used in the assessment process are depicted in Figure 2-2 and explained further in Section 4.4.1. The tiers are as follows:
    - A well-field scale (or cell) is the smallest parcel of study area. Each cell is 10 kilometres x 10 kilometres, and permits the most detailed assessment.
    - The well fields are then upscaled to a cell-block scale of 100 kilometres x 100 kilometres. This scale retains the interference effect calculations. There are 100 cells to a cell block.
    - Each cell block is then regionally upscaled to the whole basin. The current model has 15 cell blocks, each with 100 ten-kilometre x ten-kilometre cells.
- Interference effects are represented similarly to well density. Aquifer conditions, anticipated pumping requirements and well density were used to develop a series of matrices to replicate inter-well interference for a suite of generic conditions. Again, attempting this at the well-to-well scale over the extent of the operating basins would introduce extreme and unworkable numerical complexity.

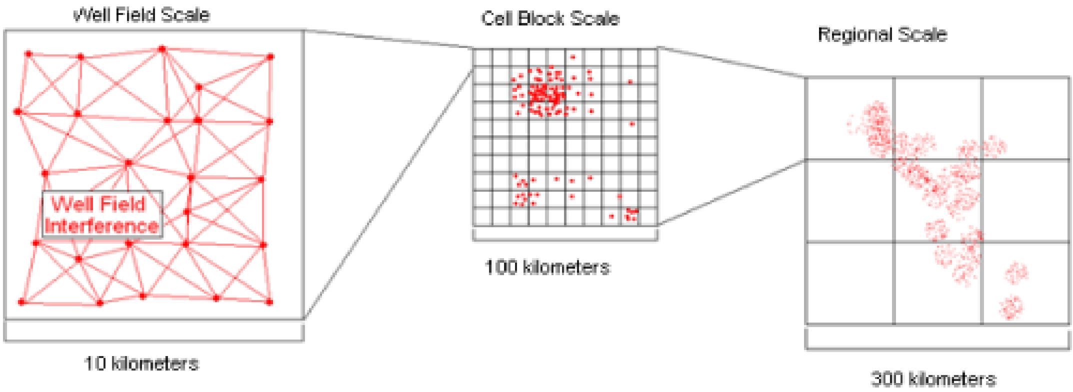


Figure 2-2. Three scales of assessment—the cell, cell block and whole tool domain, shown with upscaling

2.7 Addressing dual-phase and basin edge effects

Until this point in the description of the WPT, the theory used has largely been consistent with that applied for a typical saturated flow hydrogeological problem of large scale and moderate complexity.

However, CSG operations are complicated by the dual-phase effects of gas flow and variability of the Surat and Bowen Basin gas extraction targets. These issues have been addressed by making two modifications to the WPT:

- Introducing a transmissivity reduction factor (TRF) to address how dual-phase effects reduce water flow (or pumping demand).
- Introducing a Near-Edge Effects Factor (NEEF) for the Surat Basin margins at the easternmost edge, where geologically the basin-edge sediments are expected to react differently to deeper unweathered and less structurally deformed sections of the stratigraphy.

2.7.1 Correcting for transmissivity

The effect of gas flow (or dual-phase conditions) on water production is generally observed as a reduction in water yield as gas becomes the dominant product during pumping.

It is not possible to modify the Theis equation to replicate dual-phase flow. However, a two stage approach has been applied to represent the end effect of gas flow on the rate of water production:

- A transmissivity reduction factor (TRF) has been included. This lowers the effective transmissivity of the producing zone as the wells mature, and reduces

the amount of water produced to maintain the same target drawdown as the expected gas-to-water ratio increases.

- The TRF has been used as one of the verification criteria for comparisons with historical production data from the four CSG companies. In doing this, the use of the TRF as a surrogate to true dual-phase flow equations is verified against actual field data.

2.7.2 Factoring in basinal near-edge effects

Higher historic comparative water production has also been noted along the eastern edge of the Surat Basin, particularly where target zones appear to be relatively shallow. This observation was significant enough to have disrupted earlier attempts to validate the tool.

It is thought that the higher production may be because of higher local transmissivity of the producing zone. Basin-edge factors that may contribute to this include the shallower producing zone; possible structural influences being more prominent on basin edges (such as opening of coal cleats and secondary porosity); and reduced overburden influences in areas where cover thickness is typically less than 500 metres, and as indicated in Section 4.4.4, particularly where depths are between 240 and 400 metres.

A factor to account for these near-edge effects (the NEEF) was consequently developed to provide a mechanism for alteration of hydraulic properties of the production zones along the shallowest and easternmost margins of the study area. The effect of NEEF on water production is to increase estimated water production rates in areas of shallowest gas production. As with the TRF, the NEEF was used to assess the validity of representing a complex and diverse range of shallow factors with the potential to affect water production.

2.8 Geographic scope of the tool

The geographic extent of the WPT is shown in Figure 2-3. The domain is bounded by the lateral extent of the Surat Basin, and includes southern areas of the Bowen Basin in the north.

The WPT is spatially discretised into fifteen ‘cell blocks’ of 100 kilometres x 100 kilometres. Its total area is about 600 kilometres from north to south, and 400 kilometres west to east. This structure provides improvement in WPT run time, permits areas of no CSG activity to be ignored (for the present time), and gives flexibility for geographic tool expansion later.

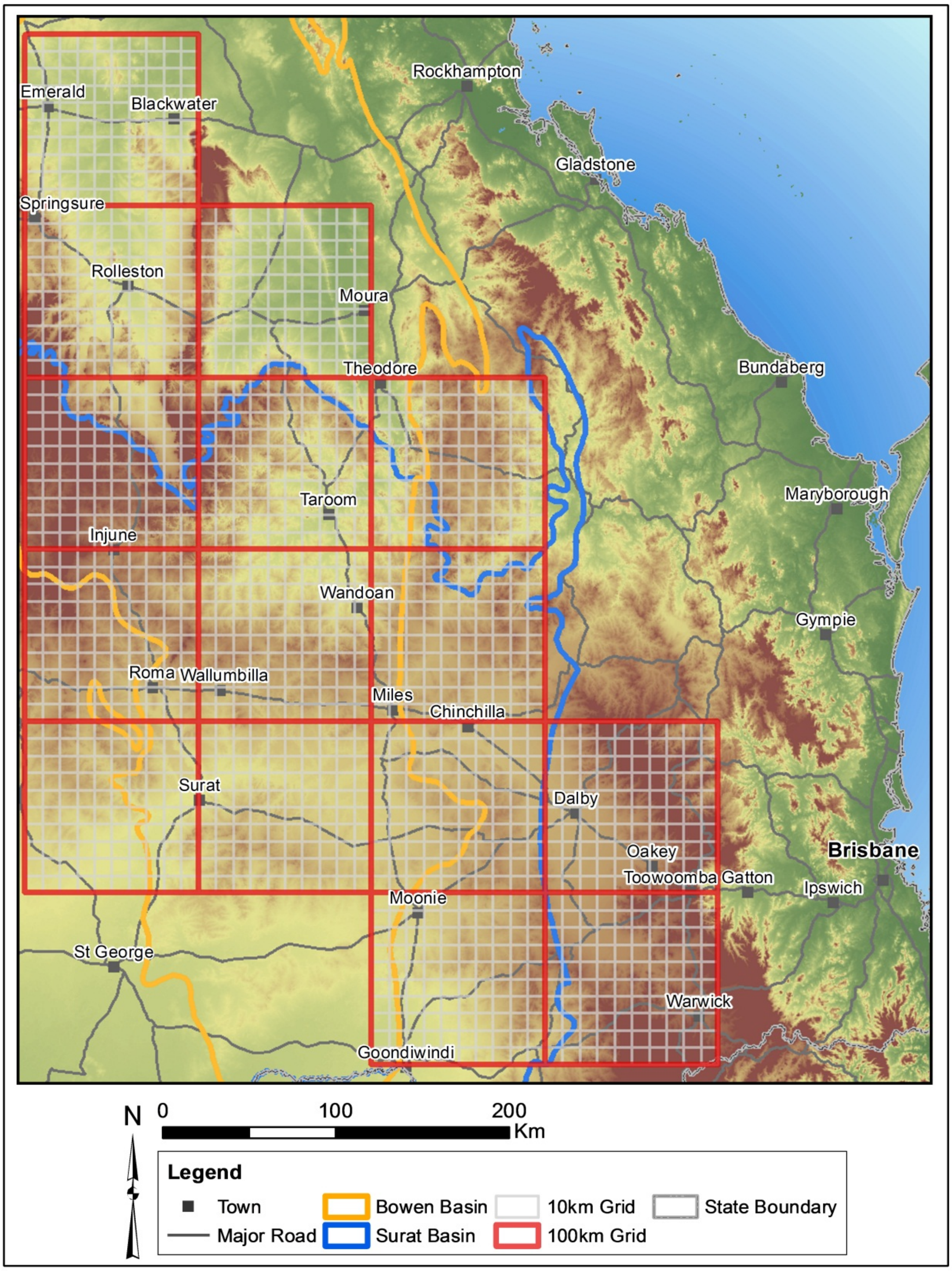


Figure 2-3. The area covered by the WPT (each grey square is a cell, each red square a cell block)

3. DATA USED BY THE TOOL

3.1 Collecting data

Two significant factors have resulted in the data collection exercise being undertaken incrementally:

- This project was the first groundwater-related activity to be commissioned under the Healthy HeadWaters CSG Water Feasibility Study. The context of the overall study, the role that this project is expected to play and the expected interaction between the government and CSG companies had to be communicated to various parties.
- The commercial sensitivity of the data to be provided was such that agreements on confidentiality terms had to be resolved with each CSG company.

With support from DERM, KCB took an approach that included a combination of industry-wide meetings, company-specific meetings, and information documents and data requests to each CSG company. Specifically:

- KCB presented the proposed approach and expected outcomes of the project to the APPEA Groundwater subgroup meeting (10 September 2010).
- KCB provided each of the attendant companies with a data request for information.
- KCB held individual meetings with Origin, Arrow Energy, QGC and Santos between 20 September 2010 and 1 October 2010. DERM was present at several of these meetings to provide a broader perspective on the context of the project.
- Several companies requested additional information, and raised concerns about confidentiality and the content of KCB's data request, especially in terms of readily available data from each company.
- KCB obtained 'in principle' agreement to the approach, and received anecdotal data about the approach to gas production, factors affecting water production, considerations to include in the tool and approaches to dealing with future development scenarios.
- DERM provided follow-up information on the Healthy HeadWaters study, then KCB distributed a summary of the approach to be followed and a draft confidentiality agreement to each CSG company.
- KCB updated the data request to each CSG company to clarify uncertainties and to refine the data request such that no potential commercially sensitive information was included in this request.
- KCB held follow-up discussions with all the CSG companies to further facilitate data collection.
- KCB presented the approach to developing the tool and its underlying principles to CSG companies, DERM and other interested parties.

- KCB had further discussions with CSG companies to obtain clarification about the context of provided data.
- Meetings with other parties such as the (then) Department of Employment, Economic Development and Innovation (DEEDI) and Evans & Peck to establish a base-case of expected CSG industry expansion.
- KCB presented results from the study to an open forum with delegates from regulators and the CSG industry in December 2011.

3.2 Data used to populate the tool

The data required to populate the tool is summarised in Table 3-1. To be incorporated into the tool, this data needed to be distributed at a resolution of 100 metres x 100 metres. In many cases, the data was not available at this resolution, in which case data was then interpolated/extrapolated to populate the full extent of the WPT domain. Details about how the data was interpolated can be found in Appendix I.

Table 3-1. Data types, sources and limitations used to populate the WPT (for 100 metre x 100 metre resolution)

Data	Source	Purpose	Limitations
Topography	CGIAR CIAT 3 Second SRTM Dataset, original source NASA, post processed by CGIAR http://srtm.csi.cgiar.org/	Required to define water production calculations	Relatively good dataset. Value per cell is interpreted as the centre-point for each 10 kilometre x10 kilometre unit.
Basinal-scale coal seam geometry, with focus on depth of seam	Bowen and Surat Basins Regional Structural Framework Study (DEEDI, 2010)	Dimension of producing zones for assessment of drawdown requirements and for water production calculations	Relatively intact dataset of regional scale consistent across the study area.
Coal seam properties such as (bulk) thickness, porosity and permeability	Bowen and Surat Basins Regional Structural Framework Study (DEEDI, 2010)	Definition of production zone properties for inclusion in water production calculations	Transmissivity/permeability data was incomplete. Spatial interpolation was required.
Gas/water production profiles for individual and multiple wells (including possible derivation of field trends at the basin to sub-basin scale)	Supplied by CSG companies (multiple wells were supplied, individual wells were not)	For tool verification to compare estimated water production with actual field data where available	Limitations to type curves through confidentiality of information resulted in assumptions for timing and well densities.
Transmissivity	Interpolated from data from CSG companies and DERM Groundwater Database	Required for water production calculations	Transmissivity/permeability data was incomplete. Spatial interpolation was required.

Data	Source	Purpose	Limitations
Water quality and hydrochemistry data	Some data available from company EISs; data interpolated over study area	Required for estimation of produced water TDS across the study area	Water quality data was patchy at best and required interpolation and extrapolation to populate the tool.
Data for in-situ dual-phase interactions and impacts these may have on produced water yield as gas replaces displaced water	Not available—inferred from other company-supplied and historical data	Assumptions based on multiphase flow diagrams and curves from contaminant hydrogeology (e.g. Fetter, 1999)	Limited, although some verification application was used. Further assessment needed.
Well density (population of wells per cell)	Company-supplied, also interpreted from Petroleum Lease maps (QPED database)	Required for water production calculations	Company-supplied data is relatively complete; Petroleum Lease maps data is projected.

Further information about these data types and their role in the WPT is provided below. For additional detail, see the explanatory notes in Appendix I.

- **Coal seam elevation** is entered as an elevation above mean sea-level in metres. This value is entered at the cell level[4], and each value is assumed to be representative of the coal seam depth in the centre of that cell.
- **Original water level** is entered as an elevation above mean sea-level in metres. This value is entered at the cell level and represents the pre-drawdown value for the hydraulic head within the coal seam. This data has been obtained from the DERM database or site-specific data where provided by CSG companies.
- **Water pressure required for gas production** in metres is entered at the cell level. In the absence of site-specific data provided by CSG companies, an assumed value of 35 metres (of head above the producing seam/s) is applied, which represents a pressure of 50 psi (pound per square inch); reducing pressure to this level is generally required for gas production to occur. Adjustments to this value may be dependent on transmissivity (or another parameter), and should be calculated before populating the tool.
- **Transmissivity** is populated at the cell level.
- **Storativity** is assumed to be 0.00025 where data is not available. This value is assumed to vary minimally between cells and therefore is only required for each cell block (100 kilometre x 100 kilometre) area.
- **Well density** is a count of the number of wells which populate each of the cells. The well density is entered as the maximum density of wells within the cell. Well density may change, depending on plans to increase or abate production from a tenement, but generally CSG companies so far have indicated that they

[4] The discretisation between wells, cells and cell blocks is discussed in Section 4.4.1.

use 160 acre/well or 320 acre/well spacing, which is then converted to a density of wells per cell.

- **Cell start month** is a time period and is entered as the delay from the start date of the calculation run before a cell becomes active. This is necessarily imprecise because of confidentiality constraints, so spatially and temporally there remains uncertainty as to when a cell is likely to become active. This value is entered as the number of months until that zone starts production (from an assumed model start date of January 2010).
- **Water quality distribution** is entered as the representative water quality of total dissolved solids (TDS) for that cell. The water quality data available for each area is sporadic, and the data that is available has been interpolated between the different data sources to provide a map of water quality over the region. The tool only considers TDS until more representative water quality data becomes available. This data is limited in extent and temporal duration, and in many cases the average value for a cell block may be based on very few data points.

Key layers used in the WPT are shown in Figure 3-1, 3-2 and 3-3. The following key data were provided by CSG companies subject to confidentiality agreements, and therefore are not reproduced in this report[5].

- Site-specific aquifer parameter distributions of hydraulic conductivity, transmissivity and porosity where they were provided by the CSG companies.
- Site-specific type curves (of water production) for individual areas. This information was provided at scales ranging from tenement to well field.
- Specific timing associated with the installation and operation of depressurisation wells. These were provided to KCB as schedules or were inferred through a secondary process from provided water production estimates.
- Specific number and density of proposed well distributions for each area. Where this data was not explicitly provided, a general well-spacing for each tenement was applied.

[5] Confidentiality agreements were required with each of the companies before information was provided to KCB. These agreements relate to the data provided, its storage and security, and how the data is used and presented in the WPT. Because of the legal implications of these clauses, and the commercial sensitivity of the information provided, much of the baseline data is not explicitly presented in this document. Data of greatest concern to the companies generally focused on the development scenarios, and the timing and density of ultimate well fields.

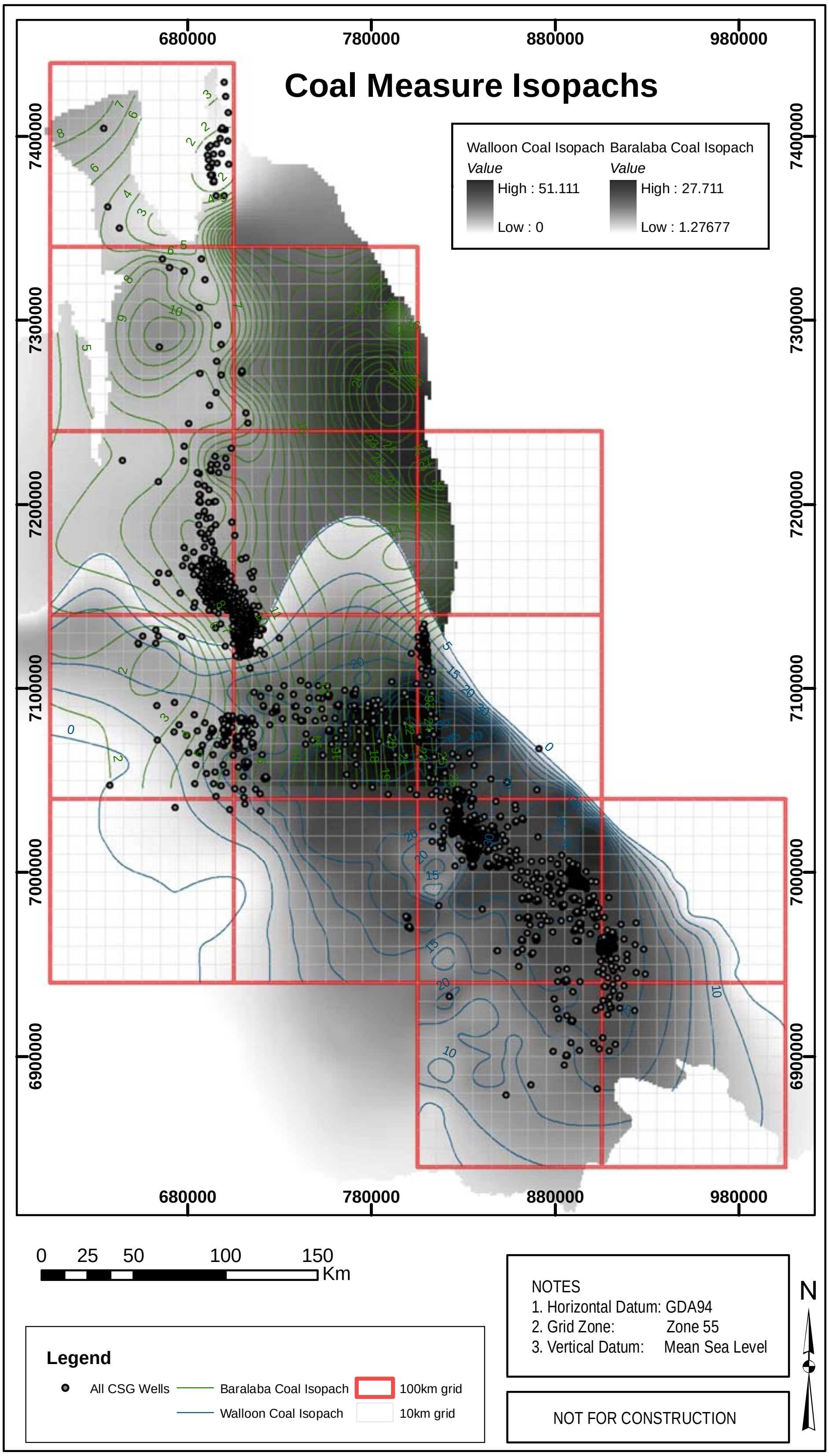


Figure 3-1. A key spatial data layer—coal measure isopachs

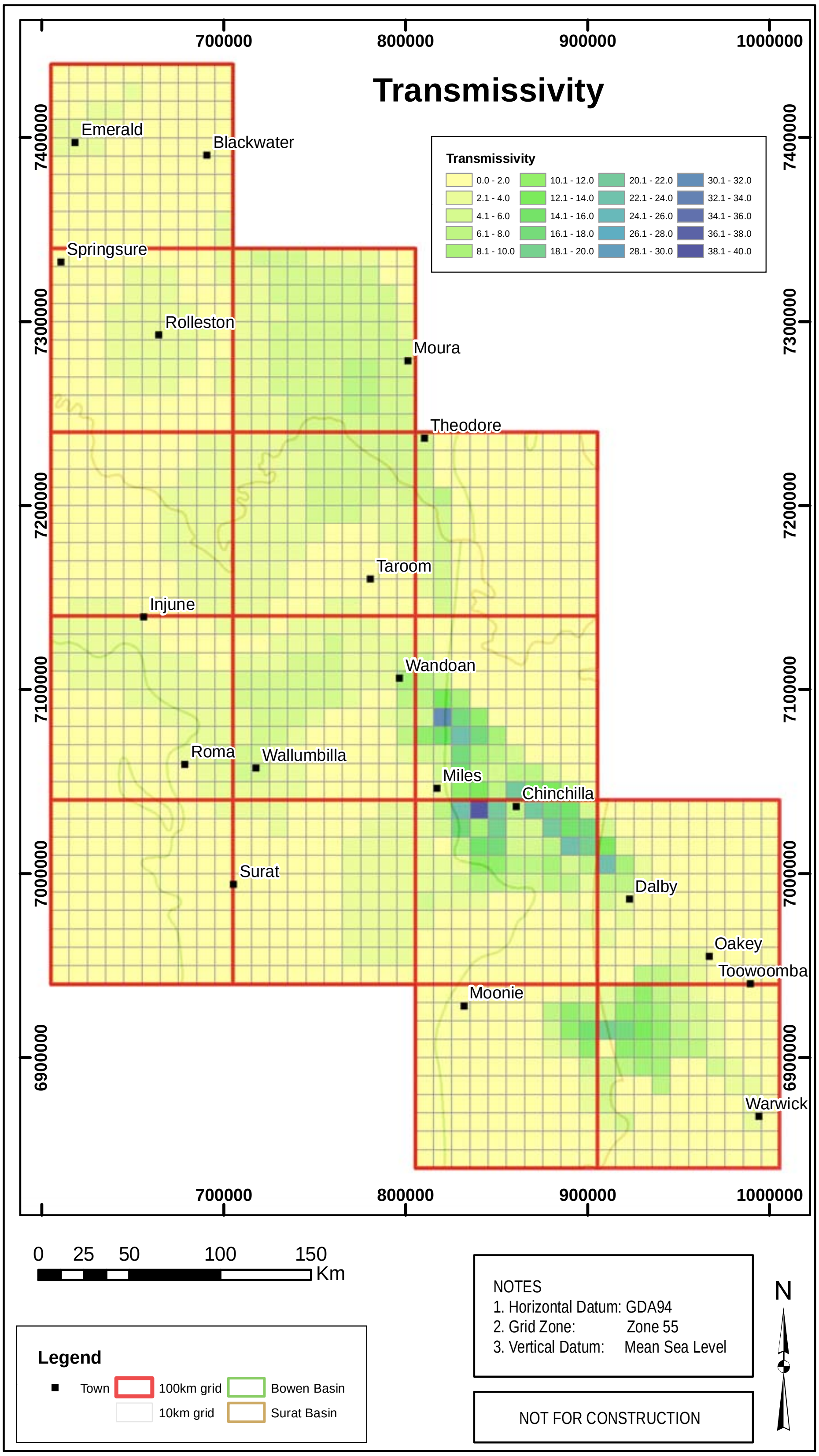


Figure 3-2. A key spatial data layer—transmissivity

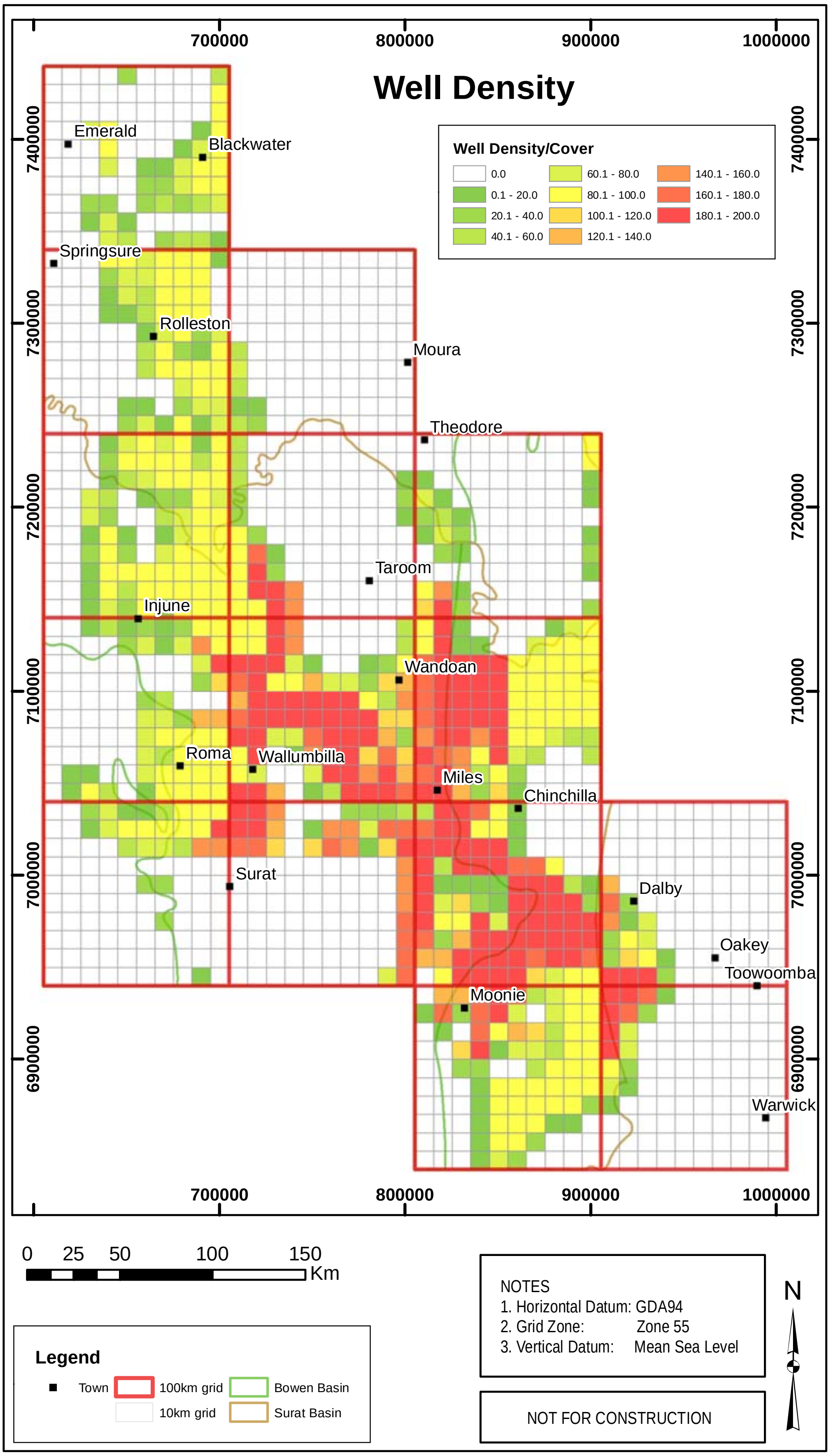


Figure 3-3. A key spatial data layer—well density

4. CONSTRUCTION AND FUNCTIONING OF THE TOOL

4.1 Software and simulation framework

The tool required a robust software platform to accommodate both quantitative inputs and inferred relationships. Furthermore, the platform needed to be:

- flexible, to represent system nuances and changing information, to incorporate different demand scenarios for CSG industry expansion, and to relate a variety of variables
- transparent, so it can be explained to stakeholders and peer-reviewed by DERM and others, and such that relative complexity reflects the accuracy and quality of the data it is based on
- representative of the processes inherent in the system with appropriate recognition of uncertainty in parameters and schedules.

The platform selected for the WPT was GoldSim, which permitted construction of a multi-tiered, practical and modifiable tool, with the additional option of stochastic (Monte Carlo) modelling. The tiers of assessment and reporting are directly integrated from the individual well scale through to the regional scale (basin-wide). The WPT is capable of simulating discrete events (such as wells or well fields turning on and off) and continuous processes (such as the water pressure response to these events).

The stochastic modelling capability of GoldSim is able to provide an envelope of results from multiple realisations where predictive uncertainties exist. The magnitude of these envelopes and the deviation from the average value time-series is subject to the numerical range assigned to constrain the uncertainties.

In most situations, including CSG water production, the hydrological system is driven by stochastic variables and involves uncertain processes, parameters and events. The uncertainty and variability associated with CSG water production is touched on by CWiMI (2008). In addition to allowing for stochastic variation of the key hydrogeological parameters, the WPT was constructed to allow representation of uncertainty in:

- operational duration and timing of well fields
- consequences and effects of carrying out various activities (such as varying operational schedules through delayed or accelerated production by prioritising target areas or changing well densities in a target area)
- occurrence of outside events or new developments which would affect the rate or intensity of development (such as regulatory enforcement effects, a change in gas demand, changes in legal framework or changes in economic conditions).

All of these parameters are included as stochastic or sequentially changing multipliers. The distribution and range of each change was based on values obtained from previous studies (e.g. CWiMI 2008), consultation with stakeholders and the ranges of values in

the provided datasets. Many of these variables have been included in the WPT as user-definable inputs. Sections 4.4.3 and 5 give more detail on the implementation and ranges of these parameters.

A top-down modelling system in conjunction with spatial analysis was applied to capture interactions affecting water production. Specifically:

- Spatial representation in the WPT is achieved by creating a base grid at the local scale, and assigning operational wells to respective cells within the cell block. There are three scales of spatial representation:
    - Individual well representation at the conceptual level that provides a means of identifying water–gas production relationships, and linking these to the geology of differing areas of the study area. Assessment of yield with time is equation based. No assessment of drawdown in adjacent strata, in any manner, is made.
    - Local well field representation using a regular mosaic or tile overlay to assess potential well interference effects and the resultant effect on produced water yields. Again, this does not address drawdown or regional impacts other than the estimated rate of water production.
    - Regional-scale (lease and basin) assessment aggregates the local-scale well field representations to identify consolidated areas of peak water production and estimate yields after considering interference effects.
- Timing of well-field development is on an annual scale to reduce computational intensity and also to recognise the coarseness of the base data and consequent tool outputs. This means the resultant water production forecast may have sharper increases than would occur in reality, as switching wells on/off is not tempered over several months.
- On the scale of the WPT, water quality data is spatially and temporally sparse. Mapping of water quality (from coal measures) was spatially extrapolated to the local and regional grid. Data was obtained from the DERM Groundwater Database and provided for a selected number of currently producing tenements; this data was interpolated and the centroid value was assigned an average to each cell block as a grid. This mapped water quality grid, paired with water production, provides an indication of how the average water quality changes in each regional area as peak water production shifts across the basin.

4.2 The tool development process

The WPT was developed through the following steps:

- requesting and receiving CSG companies' data
- constructing the GoldSim structure and developing internal algorithms and equations that included appropriate references

- numerically verifying (using standard Theis drawdown curves, theoretical effects of dual-phase interaction and applicable factors) and calibrating the analytical approach based on operational data from CSG companies
- having an external review of the verification process and re-calibrating the tool, focusing on specific areas of tool uncertainty
- including industry scenarios as outlined by DERM, and through discussions with peer reviewers
- including Monte Carlo stochastic modelling and statistical components
- including hydrochemistry data
- developing a user interface and operational manual.

The peer review and discussions with industry, DERM and other stakeholders resulted in additional considerations in developing the tool, such as model verification/calibration factors and timing of well-field activation.

4.3 Confidentiality considerations

The development of the WPT required the provision of confidential and commercially sensitive data from each of the CSG companies. KCB was required to sign confidentiality agreements before data was released for use. These clauses prevent disclosure of some of the information needed to construct the WPT, although general description of this information is provided throughout this report.

Data provided by the CSG companies was analysed and deconstructed to provide a consistent suite of base data which maintained confidentiality agreements. The results of the deconstruction provided (for example) estimates of the timing and distribution of well densities, but not exact numbers for a particular area. For example, we may know that there will be approximately 200 wells in a given cell area, but we don’t know the exact number, nor do we know the order or sequence within the cell that they would be installed, or their specific timing.

The tool was populated using the best data available. Where no data were available or where data resolution was too poor to discern detail, assumptions were required to coarsely adapt input for the WPT while preserving confidentiality of the CSG companies’ data. It is expected that with time—with publication of increasingly detailed and better quality operational data—greater accuracy in the WPT construction can be achieved and therefore predictive capacity can be improved. Further detail is provided in Appendix I.

4.4 Building the GoldSim model

The GoldSim software platform was used to manage and integrate the equations and algorithms describing the hydrogeological processes in the WPT. These equations were checked for correctness using comparisons with standard Theis curves to assess interference effects for uniform environments (all Theis criteria fulfilled), and overall

tool functioning was verified using historical CSG water production data. Figure 4-1 is a flow diagram of the calculations performed in each time step. These calculations are discussed in more detail in Section 4.4.3.

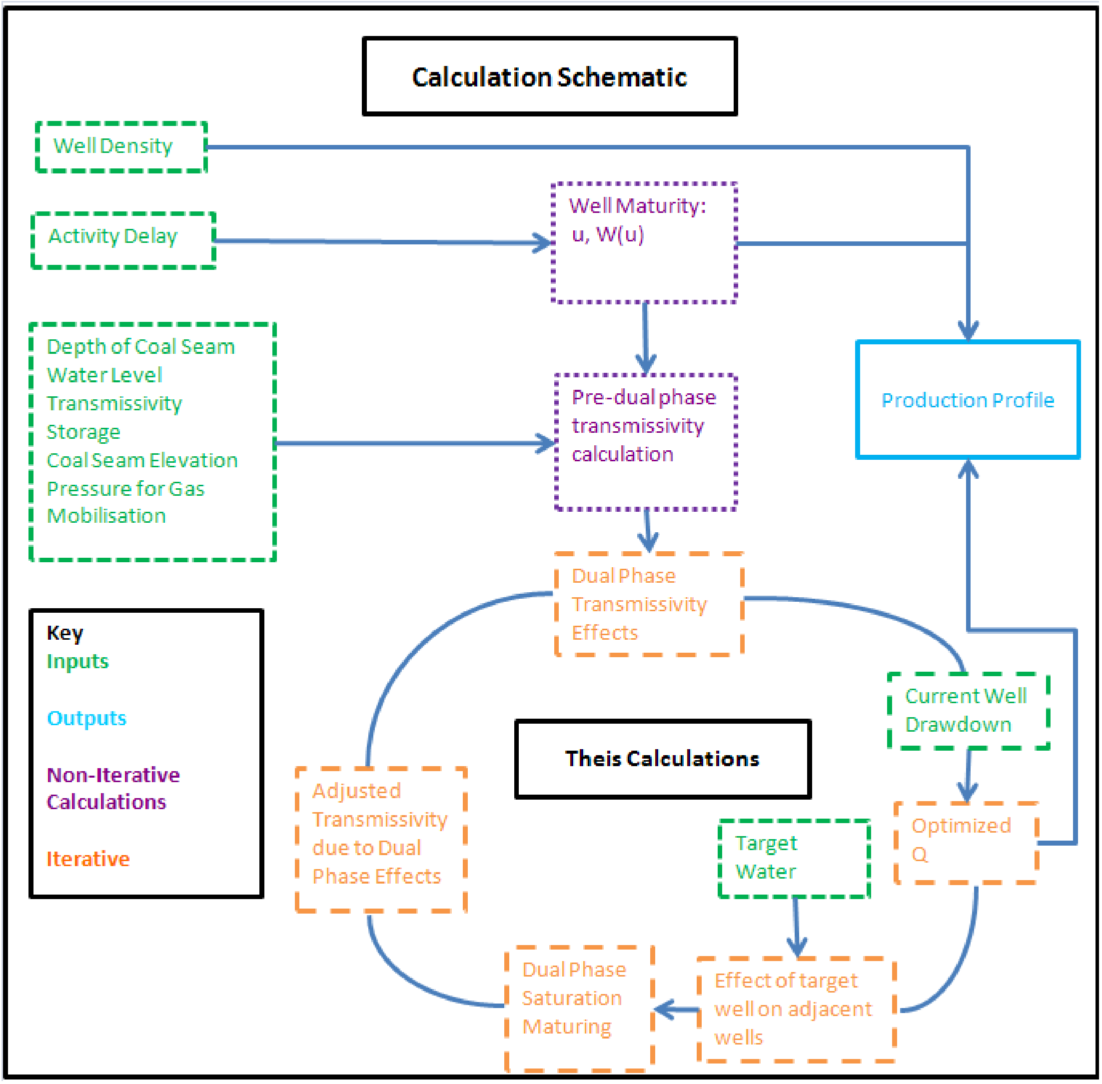


Figure 4-1. Calculations performed by the WPT in each time step

Simply put, the WPT works by:

- reviewing the inputs and checking elapsed time since run started
- finding the maturity of the pumped cells based on the elapsed time for which the cell has been active. It checks a variety of physical inputs (e.g. depth of coal seam, storativity and transmissivity) then applies the coal measure transmissivity (a user entry, currently based on CSG company-supplied data across the Basins) if the first dual-phase transmissivity lag-time has not been exceeded (i.e. if gas is not yet produced as the overlying water pressure still limits gas mobilisation).

- beginning the iterative calculations, which are as follows:
    - Water production is calculated based on original transmissivity and the required drawdown to start gas production.
    - This water production induces a pressure reduction in adjacent wells. This pressure reduction is then summed, and this total pressure reduction is checked against the water pressure for which gas mobilisation occurs.
    - If that pressure is reached, the tool assumes that gas mobilisation is initiated (the WPT does not calculate gas production but considers the impact of gas production on target zone transmissivity).
- when the gas mobilisation check is positive, additional calculations are activated for transmissivity reductions as a function of elapsed time since gas production commenced. The next calculation adjusts the transmissivity in the vicinity of the target well, and when the transmissivity is adjusted, the induced pressure as a result of pumping relationship changes. This change is calculated, and affects the water production (and therefore the dual-phase corrected or 'optimized Q'). This closes the iterative calculation loop.

4.4.1 Tiered tool and navigation structure

The WPT is tiered both in navigation and in concept.

The navigable aspect allows drill-down from the top tiers which characterise the conceptual representation of the CSG basins and the framework of the overall WPT, down to the calculations which represent the body of technical elements maintaining the conceptual design.

Similarly, the scale of the tool is tiered, as shown in Figure 2-2 (Section 2.6) which portrays the three tiers of physical scale applied. At the regional scale, the WPT is a series of 15 containers, representing 150,000 square kilometres of active domain (Figure 4-2). Each of these containers represents one cell block, which comprises 100 cells in a 10 x 10 configuration, 100 kilometres x 100 kilometres in dimension. The individual cells which make up the cell block are 10 kilometres x 10 kilometres in dimension, and are at a scale that permits representation of local uniqueness of well fields (well density, production zone parameters and interference effects).

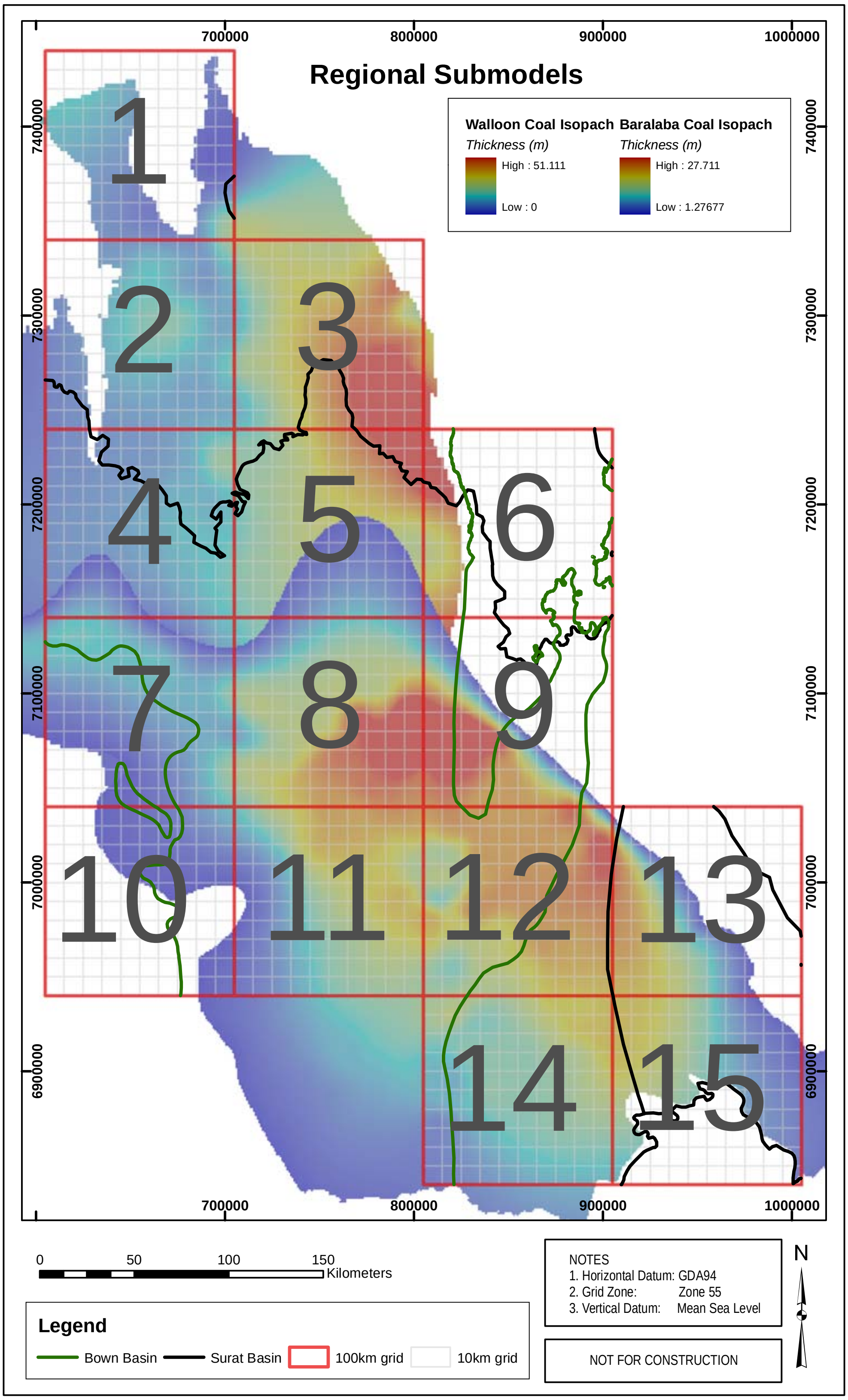


Figure 4-2. The spatial domain of the WPT showing the Surat and Bowen Basin coal measures (with cell block numbers overlaid).

Water production and interference calculations extend across and between all cells in a cell block, and from one cell block to an adjacent cell block. This upscaling permits the evaluation of interference effects on pumping yield across a very large study area without generating unmanageable complexity.

The upscaling of interference effects was achieved through the development of a well density factor. This factor adjusts the water production of a cell based on well field interference (and lowered production) of multiple wells within a cell. Well field interference effects were first modelled with a prototype version of the WPT. This prototype modelled the effects of neighbouring wells, with a 'well block' capable of housing up to 100 wells in a 10 x 10 matrix (similar to the cell block for the WPT). By running different scenarios with increasing numbers of neighbouring wells (1, 2, 5, 10 and so on up to 100), the interference effects on produced water could be plotted against the number of interacting wells. This relationship is the basis for the well density factor. The ratio of water production to well density was calculated before building the WPT and is implemented as a matrix which allows the range of well densities to be represented in the WPT. Detail of this process is provided in Appendix II.

4.4.2 Methodology for water production calculations

The fundamental groundwater theory used to calculate water production is based on application of the Theis solution (Section 2). The equations are *not* used to predict drawdown; the target drawdown is a user-defined input of the calculations. The tool uses the Theis equation as follows:

- The target operational groundwater level and the pre-operational water levels are used to determine the yield (pumping rate) needed to achieve the required drawdown.
- The hydraulic properties at the point of calculation are used by the Theis equation to determine the required water production (or pumping) rate.
- Interference effects are represented in a well field scale to account for the effect of multiple wells pumping (on each other), and compute total yield required to achieve the same drawdown target within the well field.
- The interference effects within a cell are a function of aquifer parameters, the well density and the number of adjacent wells considered in the calculation.
- The well density factor is an externally derived scaling factor based on the normalised water production for varying densities of wells in a uniform cell.

The hydraulic properties and the evolving water production rates at various scales form the basis of the overall water production calculation. The drawdown effects from all nearby cells are summed, in accordance with basic well interference effects theory, to produce a net drawdown effect and a time-variant Q. The tool does not predict the drawdown spatially or as a function of interference effects in adjacent aquifers.

4.4.3 GoldSim algorithm walk-through

GoldSim software platform equations are intuitive but unconventional in the way they are laid out. The equations that make up the bulk of the technical algorithms for each sub-model are replicated in each cell block. Therefore, the calculations shown in Figure 4-3 occur 15 times in each time step (once for each cell block) in the WPT.

A walk-through of the calculations in Figure 4-3 is provided below, along with secondary references in calculation chains. This is not only useful in presenting the extent and nature of the equations' interrelationships, but also describes some of the triggers or delays that have been included in the WPT. The walk-through and the following sections are crucial to understanding the details of the approach and uncertainties in the WPT.

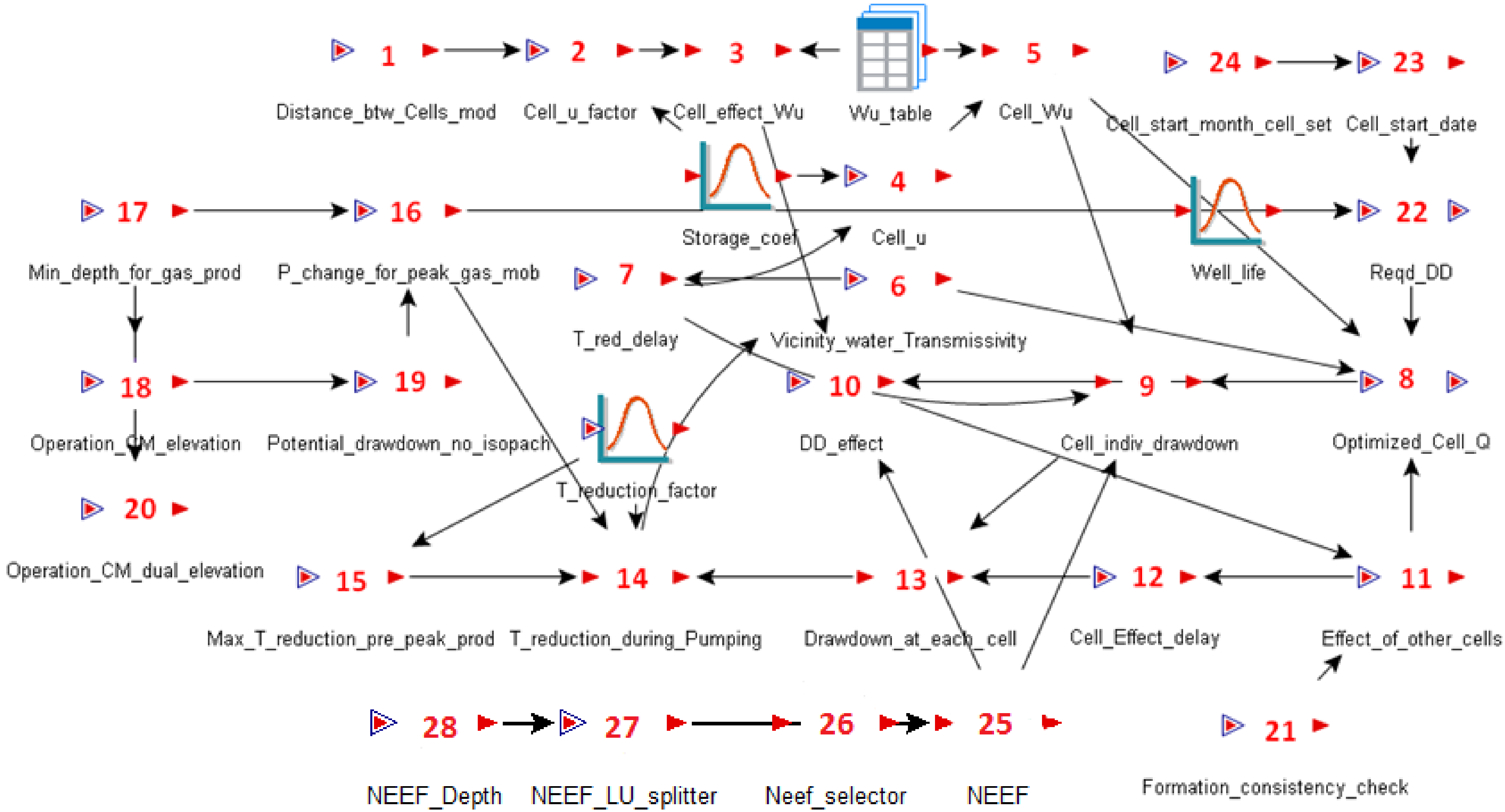


Figure 4-3. The WPT calculations for cell block 12 as an example of the calculation sequence in GoldSim

The calculations in Figure 4-3 are described below:

1. Distance_between_cells_mod – This element references the output from a calculation in which two 100 x 100 matrices are used to find the hypotenuse distance between any two cells in the cell block.
    - Equation: sqrt(Cell_row_distance + Cell_column_distance)+Cell_diameter.
    - Cell row distance reference: (Distance_Matrix_Rows * Cell_spacing)^2.
    - Cell column distance reference: (Distance_matrix_Columns * Cell_spacing)^2.
    - Distance matrix column and row are matrices which look up the number of cells between interacting cells along a vertical (row) path, and along a horizontal (column) path.
2. Cell_u_factor – In this calculation, the Theis µ time factor is calculated for abstraction of water beyond where the dual-phase effects are considered:
    - Equation: (Distance_btw_cells_mod^2) * Storage_coef / (4 * Transmissivity *max(Elapsed_time_matrix ,matrix(Cell_set,Cell_set,1day))).
    - The formula calculates µ with a one-day delay included to eliminate the 'divide by zero' error at start-up.
3. Cell_effect_ W(u) – The µ factor is the Theis variable located in a lookup table for which the value of the W(µ) function is returned (outside the dual-phase affected area):
    - Equation: Wu_table(Cell_u_factor).
4. Cell_u – In this calculation, the Theis µ time factor is calculated for well pressure reduction, which is affected by dual-phase effects.
    - Equation: (Vector(Cell_set,0.1m)^2) * Storage_coef / (4*Vicinity_water_Transmissivity * Elapsed_time_since_cell_on).
5. Cell_Wu (dual-phase affected) – The cell µ is looked up for the corresponding W(u) function.
    - Equation: Wu_table(Cell_u).
6. Vicinity_water_transmissivity – In this calculation, the tool calculates the transmissivity in the immediate vicinity of the well as a function of original transmissivity, and the reduction of transmissivity due to pressure change and gas mobilisation.
    - Equation: Transmissivity-T_reduction_during_Pumping.
7. T_reduction_Delay – This calculation applies a time lag between when mobilisation of gas mobilisation occurs and when the corresponding reduction in transmissivity occurs. The delay is subject to Erlang dispersion to reduce

feedback effects. (Erlang is a probability distribution for describing queuing systems, but has wider applicability as a method of describing variability in a delayed system; this dispersion does not affect the calculation but serves to stabilise the calculations so that the iterations can converge.)

This factor is included to reduce feedback loops to allow the solution to the algorithms to converge.

- Equation: Vicinity_water_Transmissivity applied after T_reduction delay.

8. Optimised_Cell_Q – The 'optimised' water production at each cell is calculated as a function of the required drawdown (or effort needed to reach production pressure) at the cell minus the drawdown as a result of interference effects (inter-cell), vicinity water transmissivity and the cell W (u) calculated in the previous step using the Theis equation.

   The 'optimised' production is the converged Q as a function of all the preceding factors. Water production for the populated cell is Optimised_Cell_Q multiplied by the number of wells in the cell and the well density factor.

   - Equation: max(Vector(Cell_set,0m3/d),(Reqd_DD-Effect_of_other_cells)*4*pi*Vicinity_water_Transmissivity/Cell_Wu).

9. Cell_Individual_Drawdown – This element recalculates the drawdown in the coal seam (target zone) of the target cell, as a function of the optimised water production, the cell W(u) and the vicinity water transmissivity.

   - Equation: Optimized_Cell_Q*Cell_Wu/(4 * pi * Vicinity_water_Transmissivity).

10. DD_Effect (drawdown effect) – The drawdown effect is the total drawdown effect of all cells at the target cell using the general transmissivity value. (Use of this value alone underestimates the drawdown at the target cell; the effect at the target cell is amended by the dual-phase effects as shown in the next calculation).

    - Equation: vvmatrix(Optimized_Cell_Q,Online_cells) * (Cell_effect_Wu / (4 * pi * vvmatrix(Transmissivity,vector (Cell_set,1)))).

11. Effect_of_other_cells – This calculation determines the interference effects from all other cells in the 10 x 10 matrix, subject to user limitations on effective distance (the default is one cell-length [10 kilometres]). This calculation is an input for the water production calculation.

    - Equation: sumc(Combined_effects_matrix*DD_effect*(Matrix(Cell_set,Cell_set,1)-Matrix_1)).

    - Combined_effects_matrix – This calculation removes the effects from inactive cells. It looks up if a cell is active and if it is active it will record a '1' in that location; if it is not active it records '0'. The result is that any matrix which is multiplied by this value will record a zero if a cell is not

yet active. This is included to eliminate calculations in inactive cells to minimise computing run times.

- Equation: vvmatrix(Online_cells,Online_cells).

- Matrix_1 – This is a support matrix that separates a cell's effect on itself from the cell's effect on any other cell. The matrix value for a well is '1' when it is looking at itself, and '0' when looking at any other. This matrix is used only in this calculation to separate a target cell from the other cells.

  The reason these need to be separated is because the solved-for drawdown of the non-target cells uses a non-dual-phase effect transmissivity and the target cells' solved-for drawdown needs to be re-solved for current drawdown using the dual-phase affected transmissivity.

  The result is that the total interference-effects matrix and the individual drawdown-effects matrix can be disassembled and rebuilt for every iterative step of the algorithm to find the total interference and drawdown effects for the coal seam (target zone) in each cell.

12. Cell_Effect_Delay – This delay is required so that the calculation affecting the optimised cell Q is not circular (iterative calculations are by definition repetitive, but there must be offsets in time or references to previous values in order to advance the iteration without a circular reference occurring). It has no overall impact on the estimated volumes.

    - Equation: Effect_of_other_cells.

13. Drawdown_at_each_cell – This calculation maintains the defined drawdown at each cell using the interference effects and dual-phase effects at the target cell.

    - Equation: Cell_Effect_delay+Cell_indiv_drawdown.

14. T_reduction_during_pumping – This calculates the reduction in transmissivity before peak gas mobilisation has occurred. It is a factorised transmissivity reduction based on the pressure as a fraction of peak mobilisation pressure. It includes the assumption that gas mobilisation starts prior to achieving peak production pressure.

    - Equation: min ((Vector(Cell_set,T_reduction_factor),(Drawdown_at_each_well/max(Vector(Cell_set,1m) ,P_change_for_peak_gas_mob))^0.5)* Transmissivity.

15. T_redn_as_result_of_gas_Prod – This calculation determines the maximum reduction in transmissivity due to the defined transmissivity reduction factor.

    - Equation: Transmissivity * T_reduction_factor.

    - T_reduction_factor – This is a stochastic variable, and samples normally between 0.95 and 0.999, with a mean of 0.99 and standard deviation of

0.003. This factor is based on matching of the company-provided type curves and manually calibrating the transmissivity reduction to match the real data. Although dual-phase flow would impact on both T and S, this has been simplified in the Theis formulation as a T-reduction factor only, with the uncertainty in S accounted for by stochastic sampling of this parameter.

16. P_change_for_peak_gas_mobilisation – This calculation is an extension of the minimum depth for gas production, but this includes information about the isopach. Where thickness (isopach) data was available, it was included.

    This is of most importance on the edges of the basin where, if the thickness of the coal seam (target zone) is not included in the calculation, there is a chance that the tool calculates that gas production depth is reached without pumping—resulting in no abstraction. Calculations 17, 18 and 19 are supporting equations which account for the isopach where available.

    The reason it is not included in all calculations is that at greater depths, it is more likely that ground surface, groundwater pressure and coal seam depth errors will not occur in magnitude great enough to cause non-abstraction.

    However, near the basin edge where the coal seam approaches the surface, it may be below ground level on one edge of the cell, and above ground on the adjacent cell, the tool may interpret average depths and elevations improperly, thus causing the tool's logic to determine that no production will/can occur in that cell.

    - Equation: if(Potential_drawdown_no_isopach<Min_depth_for_gas_prod,Potential_drawdown_no_isopach+Isopach_conversion,Potential_drawdown_no_isopach).

17. Min_depth_for_gas_production – This calculation determines the pressure change of water (in metres of head) at each location in the grid required to get to peak production (target pressure as defined by each CSG company).

    - Equation: GS_Elevation_CS -Water_pressure_surface_WCM +1.1*vector(Cell_set,mhead).
    - Mhead is the pressure in metres of water above the coal seam target depth at which mobilisation of the second phase will occur.

18. Operation_CM_elevation – This calculates the elevation of the coal seam (target zone), or the maximum elevation possible of the coal seam if the depth of the coal seam is at a depth that is less than the minimum water pressure needed to retain gas. If the depth is greater than the minimum pressure needed, the elevation of the coal seam is returned; if the depth is less than the minimum pressure needed, the elevation of that minimum depth is returned.

    - Equation: GS_Elevation_CS-if(Walloon_Coal_M_Depth_CS<Min_depth_for_gas_prod,Min_depth_for_gas_prod,Walloon_Coal_M_Depth_CS).

19. Potential_drawdown_no_isopach – This calculation is a supporting equation for the Min_depth_for_gas_production, and it calculates the drawdown needed in order to reach peak production when no coal measure isopach data is present.

    - Equation: (Water_pressure_surface_WCM-Operation_CM_elevation-vector(Cell_set,Pressure_m_reqd_for_Gas_Prod)).

20. Operation_CM_dual_elevation – This calculation is a precursor (in cell blocks where both the Baralaba Coal Measures and the Walloon Coal Measures have a data value greater than zero) to the Formation_consistency_check calculation. The purpose of this calculation is to determine the elevation of the coal seam in operation, similar to calculation 18; however, in this case, the requirement is to identify which coal seam is likely to be the one from which gas extraction will occur—by checking if the Walloon Coal Measures meets the minimum depth criteria or not. If the Walloon Coal Measures does not meet the minimum depth criteria, then the Baralaba Coal Measures is selected instead, resulting in (usually) a deeper coal seam.

    - Equation: GS_Elevation_CS-if(Walloon_Coal_M_Depth_CS<Min_depth_for_gas_prod,max(Bandanna_Coal_M_Depth,Min_depth_for_gas_prod),Walloon_Coal_M_Depth_CS).

21. Formation_consistency_check – This calculation looks at two datasets and establishes whether or not two strata are connected. The logic requires that the producing coal seam surface is below the Pressure_m_reqd_for_Gas_Prod at which gas will be kept immobile by water pressure. If the top of the producing coal seam is above this critical depth, the toggle changes to false for that cell and cell effects from water production in neighbouring cells will not be considered in the cell in question.

    - Equation: if(VVMatrix(Formation_cell_set,Formation_cell_set)=Matrix(Cell_set,Cell_set,1) or VVMatrix(Formation_cell_set,Formation_cell_set)=Matrix(Cell_set,Cell_set,4) or VVMatrix(Formation_cell_set,Formation_cell_set)=Matrix(Cell_set,Cell_set,9), Matrix(Cell_set,Cell_set,1), Matrix(Cell_set,Cell_set,0)).

    - Formation_cell_set – This matrix converts the formation_sub_set cell-block format to the cell set format.

    - Formation_sub_set – This calculation assigns a matrix of different values depending on whether the Walloon Coal Measures depth plus the Walloon Coal Measures thickness is greater than zero metres. The reason for this is that if the value is greater than zero, there is a possibility that pumping may occur in the cell, however, if it is zero or less than zero, no pumping will take place. This calculation is a precursor for the Formation_cell_set and Formation_consistency_check.

    - Equation:if(Walloons_depth+Walloons_isopach>Matrix(sub_set,sub_set,0m),matrix(sub_set,sub_set,1),Matrix(sub_set,sub_set,2)).

22. Reqd_drawdown – This calculation provides a trigger to pump. The trigger is delayed by the cell start date, but once that date is realised, an automatic switch turns on and the effect of pumping as a result of required drawdown begins. The element references pressure change for peak gas mobilisation which is the drawdown which must be met in order to mobilise gas.
    - Equation: if(Vector(Cell_set,ETime)>Cell_start_date,P_change_for_peak_gas_mob,Vector(Cell_set,0m)).

23. Cell_start_date – This is required to initiate a cell within the calculations. A cell is not included in the calculations until the cell start date is reached. The cell is active for the duration of the cell life (function of mean well life, which varies stochastically within bounds provided by the CSG companies).
    - Equation: Cell_start_month_cell_set+vector(Cell_set,Start_Time).

24. Cell_start_month_cell_set – The cell start month cell set equation incorporates the timing variable factor. The timing variable is the factor which is affected by potential delayed industry starts.
    - Equation: start_month*Timing_variable.

25. NEEF (Near-Edge Effects Factor) – This element is a switch that toggles between the adjusted transmissivity (if a cell meets the depth criteria), or the regular transmissivity. This function looks up the depth to the coal seam and applies a stochastic factor to the efficiency. Anything below the cut-off NEEF_Depth is ignored. If the NEEF cut off is triggered, the NEEF adjusts the aquifer parameters for the shallowest coal seams only, based on information provided to us by CSG companies in these areas.
    - Equation: if(NEEF_Depth<Vector(Cell_set,Cutoff_Depth),NEEF_Factor,Vector(Cell_set,1).

26. NEEF Selector – This is the criterion for the element in the previous step. The selector can be turned on or off from the control panel.
27. NEEF_LU_Splitter – This element performs a switch based on the pressure of water above the target seam. Based on the cut-off depth (adjustable on the control panel of the tool), this switch provides a transmissivity multiplier.
    - Equation: if(NEEF_Depth<Vector(Cell_set,NEEF_Cutoff_Depth),NEEF_Factor,Vector(Cell_set,1))

28. NEEF_Depth – This element calculates the water pressure above the target seam based on the water pressure above datum, the ground surface and the depth of the target seam.
    - Equation: Water_pressure_surface_WCM-(GS_Elevation_CS-Walloon_Coal_M_Depth_CS).

Following these calculations are a relatively simple set of calculations for water quality. Each cell in a cell block has a representative water quality (at this stage limited to TDS) which is either known at a site-specific scale from company data or interpolated from regional data. The water quality is multiplied by the respective water production in each cell to find the salt production. Salt production for all cells in the cell block can then be divided by the total water production to find the average water quality for that time step in that cell block.

4.4.4 Simulation factors to better simulate *in situ* conditions

To better explain or simulate *in situ* conditions, simulation factors were added to account for dual-phase effects, near-edge effects and well/coal seam lifetimes. These three factors are described below.

4.4.4.1 Transmissivity reduction factor (TRF)

Gas production in the coal seams results in a reduction of the water permeability (or water transmissivity) of the coal seams. This is a function of pressure reduction liberating the gas, which then competes with water for the available pore space. Dual-phase effects are not represented in the Theis equation; however, the impact on production of water as a surrogate to true dual-phase calculations is described in the WPT by the inclusion of the TRF:

$$T' = T * \min(T_{rf}\,,\, (D_{Ww} / \delta P_{mob})^{1/2})$$

Where:

T' = the adjusted transmissivity

T = original transmissivity

T_{rf} = maximum transmissivity reduction factor (user input, and stochastically sampled with a standard deviation of TRF/60, a minimum value of 0.85*TRF, and a maximum value of 0.9999)

D_{Dw} = drawdown in water pressure at each well

δP_{mob} = the change in pressure head required to mobilise gas (specific to each cell, depending on ground-surface elevation, water pressure in coal seam, depth to coal seam, and target pressure required for peak gas mobilisation [35 metres head]).

The reduction in transmissivity is directly proportional to the square root of the ratio between the current drawdown and the peak mobilisation pressure, and is capped at the maximum transmissivity reduction. This means that as the water pressure gets closer to the peak mobilisation pressure, the effect of the transmissivity reduction decelerates to the minimum transmissivity as the pressure difference reaches the target pressure. The minimum transmissivity (maximum transmissivity reduction) occurs at peak gas production which is varied stochastically due to inherent uncertainties.

The TRF was implemented during the WPT's validation. Variation of the TRF allowed improved matches between company-supplied type curves and preliminary production results (Section 5.1).

4.4.4.2 Near-edge effects factor (NEEF)

During initial verification the WPT was found to under predict water production along the easternmost margins of the Surat Basin. Closer review of the historic data and further discussion with CSG companies identified that higher water production records in these areas were real, and that the application of the TRF appeared to have too great an impact in these eastern areas.

Unique to these areas, key attributes are noted:

- The gas producing zones are typically shallower, consistent with the regional trend of the Walloon Coal Measures. Their shallow nature means a thinner overburden cover and a reduced wedge of water to be depressurised for gas production.
- The coals in the edge of the basin may have observed greater structural influences associated with basin margins, and possible deeper structural elements such as the Kumbarilla Rise (Exon 1976). Such features might open cleats in coal seams and introduce some degree of secondary permeability not common elsewhere across the basin.

To address these features, the NEEF was developed to address the potential of higher local water producing conditions along the very edge and shallowest sequences of the Surat Basin.

4.4.4.3 Well lifetime factor

The well lifetime factor was included to account for the gradual depletion of the resource from the coal seam. This factor is included to provide a time limit in mature production phase. It is a stochastic factor because it is currently unknown.
The stochastic factor is sampled each sequential run, so each run it may be different. This is set at a 15-year mean by default and is sampled from a normal distribution with a standard deviation of one year. The well/coal seam lifetime factor is based on CSG companies' supplied production curves. It is acknowledged that this element of the tool will require further refinement once greater understanding of well operational time lines is understood.

4.4.5 Delays used in simulation

Three delays were included to reduce feedback in modelling results. Because the tool relies on iterative solutions to solve the algorithms, the final step and the first step of the iteration must be offset so as not to have a circular reference. In early versions of the tool only a small delay was necessary, but when more complexity was added by

increasing the number of cells interacting, larger delays were necessary to stop this numerical feedback from occurring.

The first delay affects the initiation of the transmissivity reduction due to replication of dual-phase effects, and represents the time taken for peak gas production to be achieved from start of pumping. This delay has a default value of 120 days but can be varied by the user. It is included to prevent sudden and extreme reduction in transmissivity, which results in tool instability. Because of the time-step lengths, sudden reductions in transmissivity may artificially (and erroneously) constrain the amount of water produced by reducing the period of peak water production. The sensitivity of this delay is ultimately linked to the time steps of the WPT. Shortening time-step durations may support a reduction in this delay period without consequent effect; however, doing so would result in significant run-time increases and may reduce tool stability.

The second delay is applied so that the appropriate water production rate to achieve target drawdown, taking into account all the factors impacting on Q, can be solved. To improve the stability of estimated water production and prevent feedback loops on calculations (i.e. to allow convergence of the solutions) a feedback delay of at least three time steps is needed.

The final factor—the cell effect delay—is included to slightly delay the response of the well drawdown on neighbouring wells. This delay is usually less than one-third of a time step.

4.4.6 Water quality representation

Water quality data was sourced from the Queensland Petroleum Exploration Database (QPED) and from the CSG companies. The water quality data was limited in areal coverage, so interpolation of the data was required prior to population of the tool. The result provided coverage of the basin (Figure 4-4).

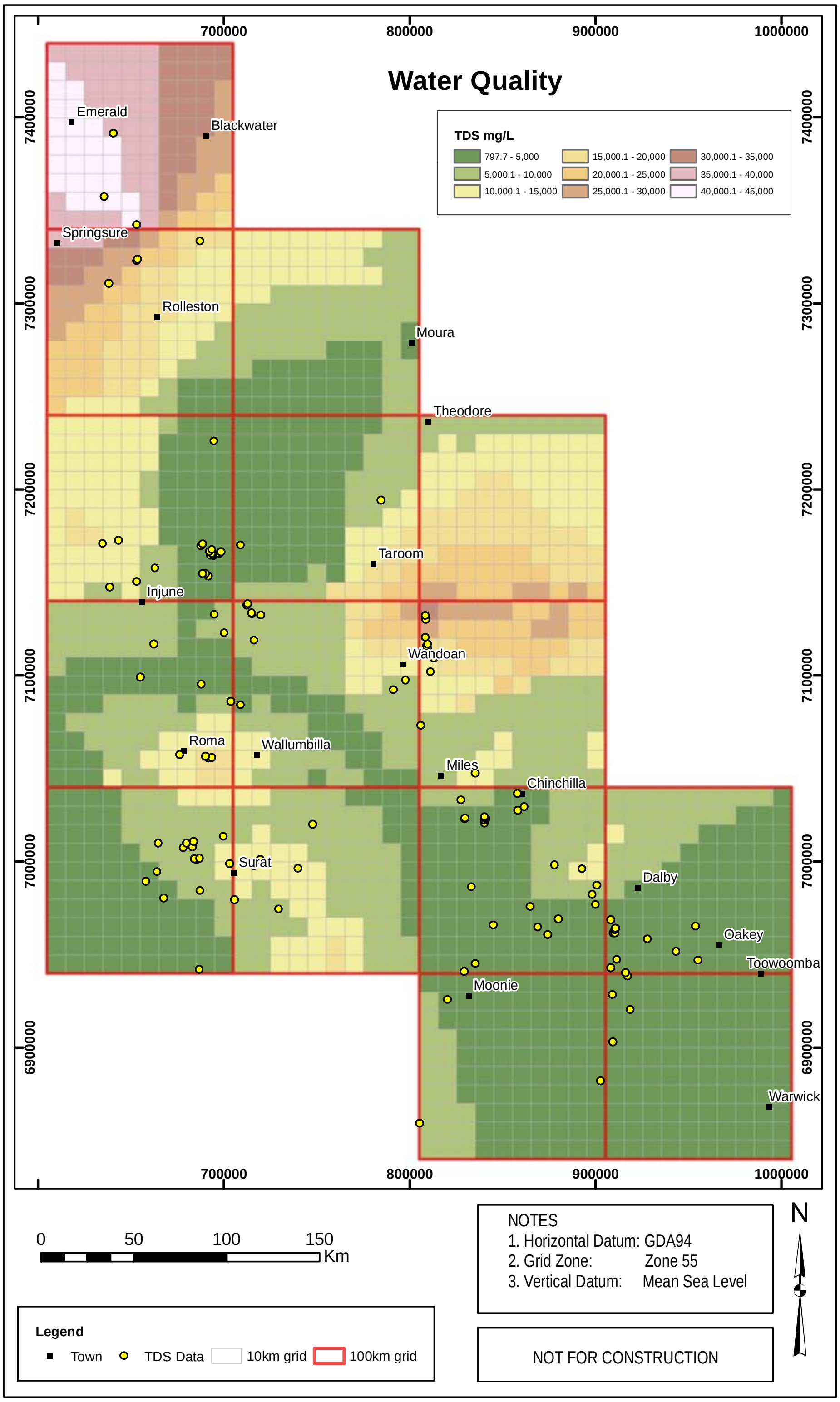


Figure 4-4. Interpolated water-quality distribution over the WPT's domain

4.5 Assumptions and limitations

There are numerous uncertainties associated with the WPT, largely a result of:

- limitations in base data
- uncertainty regarding how and at what scale the industry will evolve
- how gas production on an operational scale will affect water production.

It is not practical to attempt to capture all areas of uncertainty; however, it is important to document areas where assumptions have been made to either fill a data gap or to extrapolate knowledge to permit the WPT to operate.

Key technical assumptions associated with the fundamental hydrogeological equations (Theis) which are required for this approach include:

- The water bearing formation is uniform in character and the hydraulic conductivity is the same in all directions across each 10 kilometre x 10 kilometre cell. The formation is uniform in thickness and equal in areal extent.
- Storativity (S) is assumed to be consistent across each 10 kilometre x 10 kilometre cell. This is not the same as the total storage, which would vary according to coal seam thickness and porosity, but this factor defines the volume of water released from storage per unit surface area of the aquifer per unit of decline in the hydraulic head (i.e. the volume released as a function of change in water pressure in the coal seam).
- The simulation assumes that the formation receives no recharge. The WPT assumes that vertical leakage from other units is zero.
- The zone of water production fully penetrates the target producing zone. Water removed from storage is discharged continuously when the head is lowered, and only from the production zone being modelled.
- The pumping well (system) is assumed to be 100 per cent efficient.

Tools such as this are often built in order to simplify and replicate an intricate process. To do so, assumptions must be made to distil these processes so that simple algorithms can be used to describe them. Any assumption reduces overall accuracy, but the trade-off is that computationally complex processes become simple enough that they can be repeated. The result is that ranges of results rather than single values are produced; distributions of these ranges ultimately result in confidence bounds.

Assumptions used to simplify complex relationships in the WPT are:

- Each cell block (100 kilometres x 100 kilometres) is isolated with respect to pressure interactions (there is no water movement between them).

- There is no inclusion of regional groundwater flows. Water ‘movement’ is an assumed condition of shifting drawdown pressure between cells.
- Factors and delays applied in the WPT adequately replicate the conditions in the system that they are designed to represent. Some error bound is expected, although effort has been made to prevent undue impacts to total water production forecast results.
- Limitations inherent in the application of the Theis solution for this model result in inaccurate solutions near the boundaries of the basin. Due to the assumption of ‘infinite areal extent’, the Theis solution criteria are not met, and at the edge of the WPT area, the search radius for near-edge cells results in a limited radius of influence (i.e. the domain ends as there is not data populated beyond the edge of the basins). The application of NEEF has been included in an attempt to address this (Section 4.4.4.2).

The following assumptions were made to help account for nuances which are apparent *in situ*, but difficult or impractical to account for in a tool of this scale:

- Distances between wells within a cell are assumed to be equidistant and to show interference effects in a similar fashion to the same number of wells in an environment where all Theis criteria are met.
- Interference effects are not considered to occur at the cell block scale because of the large distances involved (100 kilometres between centre of one cell block to the centre of the adjacent cell block). However, interference does occur between cells.

5. VERIFYING AND VALIDATING THE TOOL

Once the initial tool construction was completed, a process of verification, validation and—where possible—calibration was followed. Each of these steps in outlined in more detail below, serve to show the sequential steps undertaken to produce the initial simulation results.

5.1 Verification

Verification is the process of assessing that the outputs of the tool adequately describe the system being simulated.

Verification of the WPT was achieved by comparing a simplified tool to equivalent Theis equations, and by visual comparisons against type curves provided by the CSG companies.

The comparisons against Theis equations showed that the computer code correctly calculates the mathematics as intended. However, while preliminary comparisons to theoretical curves indicated that the Theis mechanisms represented water flow (and interference) adequately, evidence of deviations from the production type curves provided by the CSG companies suggested that gas production may require a subtle shift in the mechanisms that govern production of associated water.

After consideration of dual-phase flow, the TRF was introduced to mimic the effect of competing phases in the seams (Section 4.4.4.1). Once the TRF was implemented, the capability of the model to match water production curves in gas producing environments was significantly improved. Comparisons were again made against company-supplied type curves for future scenarios. The objective of this step was not to be able to replicate production, but to be able to recreate the lead-up, peak and tail of the production curves.

With the primary mathematics of the model properly representing Theis flow, and the effect of dual-phase flow represented by simplified functions, the tool was considered ready for the next phase of testing.

5.2 Validation

The validation process assesses the predictive ability of the tool.

The WPT was validated using historical values of water production as input for site-specific models run for periods consistent with the reported data. The resultant WPT output was compared to actual field water production. The historic water production data is included in Appendix IV.

The validation process was deemed either satisfactory or unsatisfactory based on how closely estimated production matched with historical production. The basis of accuracy

was visual comparison, but a component of statistical analysis was included to provide a numerical summary of the visual observations.

The process for validation of the tool is outlined below:

- Sub-models were populated with historical known well density and estimated hydrogeological data, and were run to estimate water production for the same period of record for which historic data were available (from DEEDI data and provided in the appendixes).
- If the results of the comparison were satisfactory, then the sub-model was considered verified. Sub-models with unsatisfactory results were analysed to assess magnitude of discrepancy and seek commonality in areas of over- or underestimation of produced water.
- Statistical analyses were performed on the residuals to assess distribution and error and to support factor modifications which were relied on heavily to achieve a verified sub-model.
- The residual distribution and the accuracy of the estimations were again reviewed. Comment was provided on the quality of the verification for each of the areas assessed. By necessity, an iterative approach was developed for the validation process, since each subsequent factor adjustment from one company (or tenement) could potentially alter the earlier 'satisfactory' production from another, or at least the neighbouring cell.

Visual comparison was again used to identify a satisfactory match between historical and simulated production, which was followed by cumulative (total) tenement production, company production, and all company production analysis. Partial results of comparisons are provided in Figure 5-1, Figure 5-2 and Figure 5-3.

Once a satisfactory visual match was identified between historical and simulated production, the difference between these two results (the residual) was analysed. Figure 5-1 presents an example of a satisfactory validation, while Figure 5-2 displays an unsatisfactory validation.

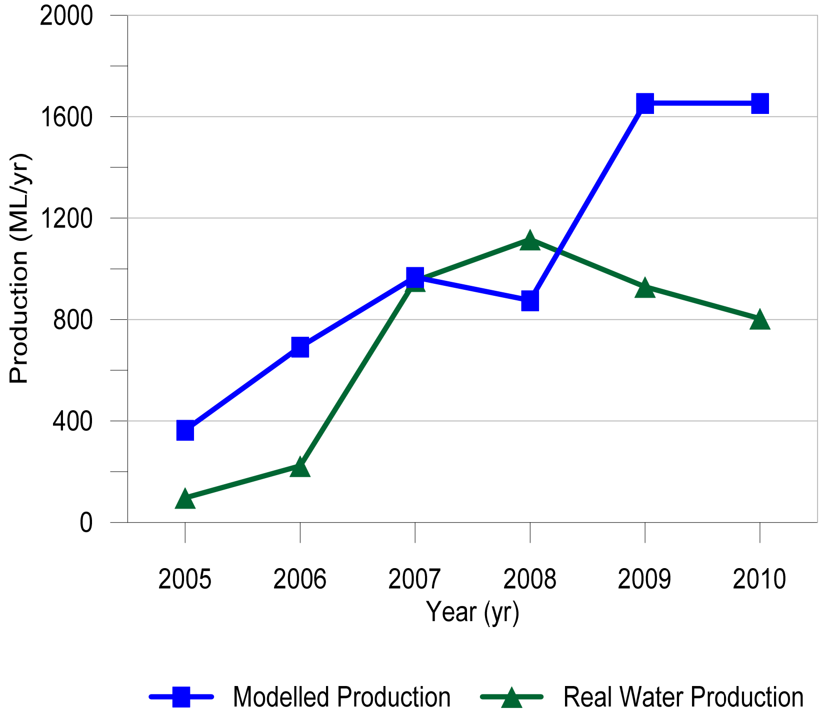


Figure 5-1. An example of a satisfactory validation (example shows Origin PL204 historical versus simulated results)

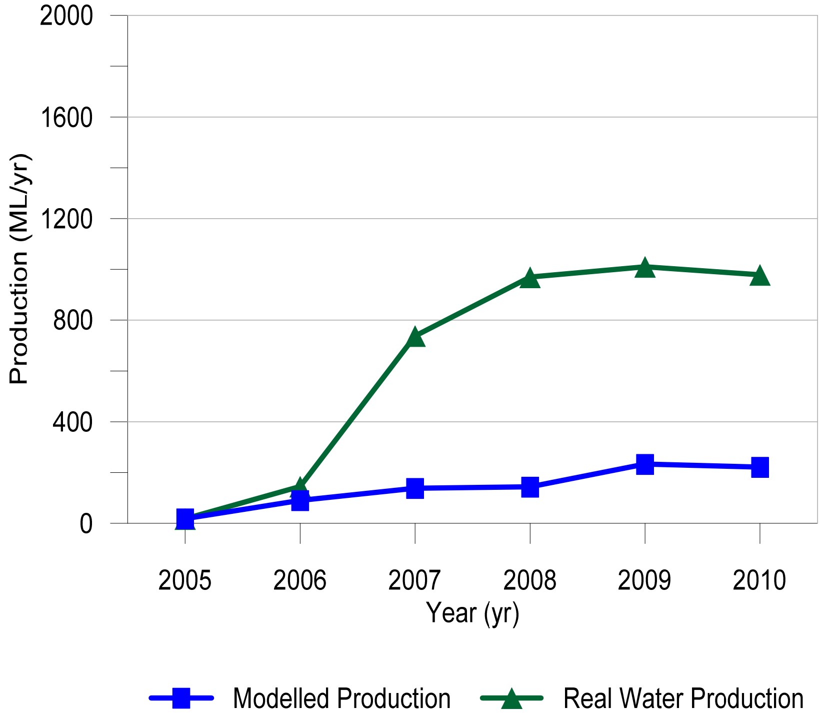


Figure 5-2. An example of an unsatisfactory validation (example shows Arrow Energy PL230 historical versus simulated results)

Figure 5-3 presents the historical cumulative production versus simulated production for an early attempted validation. Results that display a y = x trend indicate a satisfactory match between simulated and historical production. However, where these do not match, a discrepancy exists. The discrepancy can be measured through simple linear analysis.

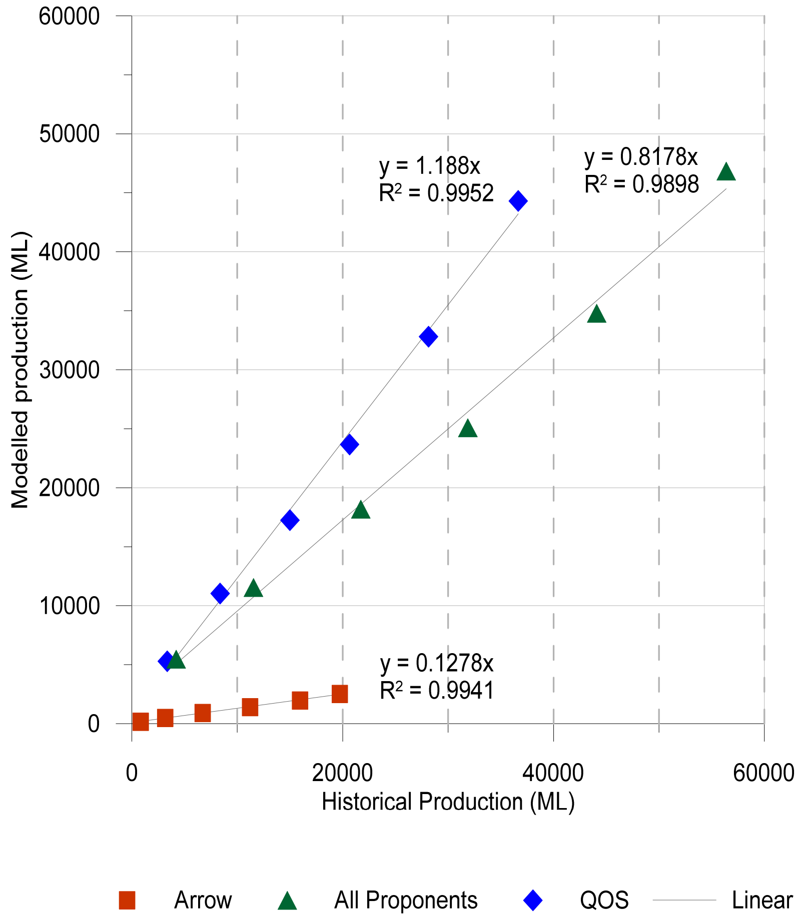


Figure 5-3. Correlation of historical and simulated cumulative production for an early attempted validation

The blue diamonds in Figure 5-3 are representative of cumulative production data from three CSG companies (QGC, Origin and Santos – QOS) which have tenements located over deep coal measures (>250 metres from the surface). Red squares represent cumulative production from Arrow Energy, which has tenements located over near-surface coal measures (<200 metres from the surface). Green triangles represent cumulative production data from a combination of all CSG companies, with tenements located over coal measures at variable depths.

The CSG companies excluding Arrow Energy (blue diamonds), have slightly higher than a one-to-one ratio (y = x). All the CSG companies' data points (green triangles) are

slightly lower than the one-to-one ratio, while the Arrow Energy data points (red squares) are significantly lower than one-to-one, indicating underestimation of water production on these tenements.

Based on these initial validation results, it was identified that the simulated production rates significantly differed from the historical production rates for tenements located along the eastern edge of the Surat Basin.

5.3 Calibration

Calibration is the process of fitting and/or constraining parameters to improve the fit between simulated results and historical or measured results.

The initial approach to resolving the verification inconsistency was the introduction of the NEEF. Calibration of the tool was achieved through subsequent iterations of the NEEF mechanism and refining how it was applied.

The method in which the NEEF was iteratively applied is as follows.

A practical explanation of how this factor works is provided. For example, if a well pumping at one litre per second normally produced 20 metres of drawdown, with a NEEF of 10 per cent applied the same well would only produce two metres of drawdown—requiring the well to pump harder to achieve the target drawdown established without the NEEF.

Figure 5-3 (red squares) shows the simulated cumulative production of basin edge tenements to be approximately 10–15 per cent of historical cumulative production. This was used as the preliminary NEEF to adjust estimated production. Cumulative production for simulated and historical scenarios with inclusion of the first iteration of the NEEF is provided in Figure 5-4.

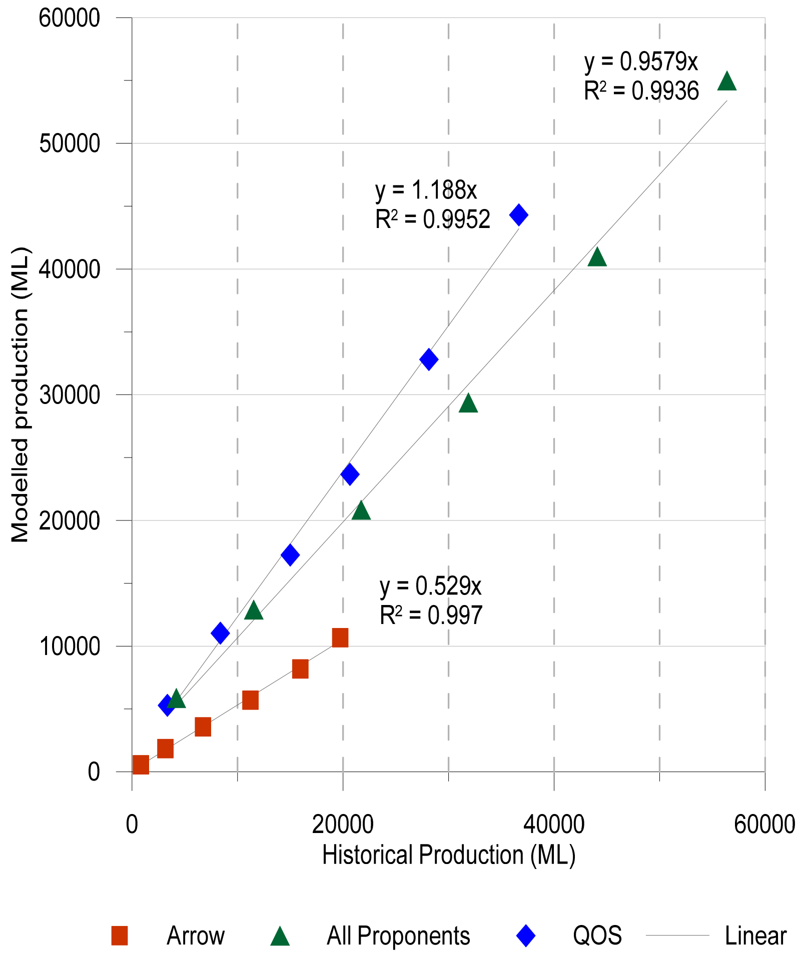


Figure 5-4. Correlation of historical and simulated cumulative production with a proportional 15% NEEF applied

This provided a better match, albeit still not ideal, with estimation of edge of basin water production still below historic records. A second iteration of the NEEF is seen in Figure 5-5. For this iteration, the NEEF was linked to the depth of the Walloon Coal Measures with a trigger and extinction depth (representing the depth to coal where gas has already naturally left the system) applied. At 250 metres depth, the factor was simulated at 100 per cent; at 200 metres depth, the factor diminishes to 20 per cent; at 100 metres depth it is 12 per cent. At depths shallower than 100 metres, the NEEF gradually declines to only five per cent effectiveness.

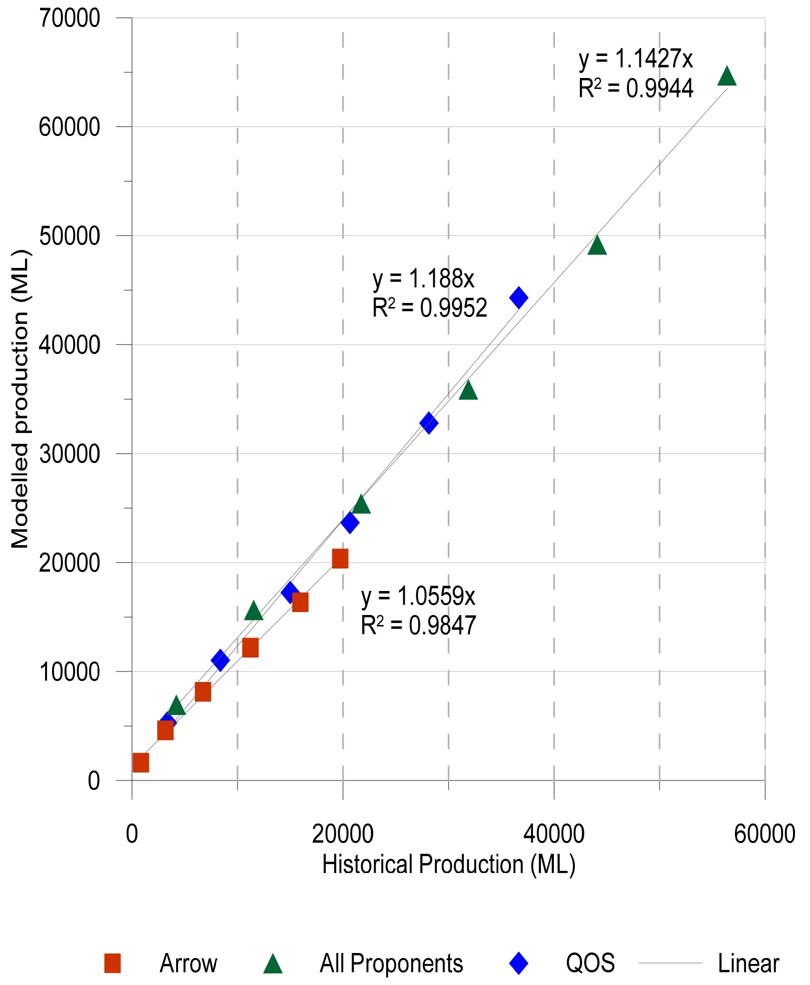


Figure 5-5. Correlation of historical and simulated cumulative production with variable NEEF applied to reflect varying coal seam depth

This provided a further improved match of the historical data and appears to have some physical basis for discrimination of these eastern tenements. Application of the depth-specific NEEF (variable or linear) in the basin-wide WPT also resulted in the NEEF having a disproportionate influence on water production forecasts. Because of this, matches were still not considered ideal, and further effort was required in understanding the required mechanism of the NEEF and the effect this has on other (deeper) tenements. To address this uncertainty, the following steps were taken:

- Water production profiles including and excluding the NEEF for a range of scenarios were generated and reported to DERM. This showed the potential effect that inclusion of an incorrect (although consistently applied) factor would have on projected basin-wide water production rates.
- A further series of meetings were requested with Arrow Energy to assist with understanding the data and the basin edge effects that were not readily matched with earlier validation attempts.

- Arrow Energy provided additional data and further assisted with understanding their historic production. This additional knowledge was then re-applied in the development of the NEEF, through:
    - confirmation that the historically reported data from DEEDI were consistent with Arrow Energy's internal records for these tenements
    - an indication that the higher water production rates are likely a result of the shallower coal seams where hydraulic conductivity and porosity may be more variable and higher than in adjacent areas
    - hydraulic conductivity and porosity values, and an indication of multipliers used to match these to historic data (for individual coal seams within coal measures for three Arrow Energy tenements used in the validation process). This data supported assumptions KCB had made about basin edge effects.

Using this knowledge, the NEEF was simplified to vary transmissivity by a factor of 2.5 and storativity by an order of magnitude; for simplicity, this was applied to only impact on bulk transmissivity of shallow coal seams where a set of criteria indicative of the shallower tenements is met. These criteria set a minimum depth of water above the coal seam before the NEEF is applied. Figure 5-6 shows an example of the final validation on an earlier problematic tenement (PL198).

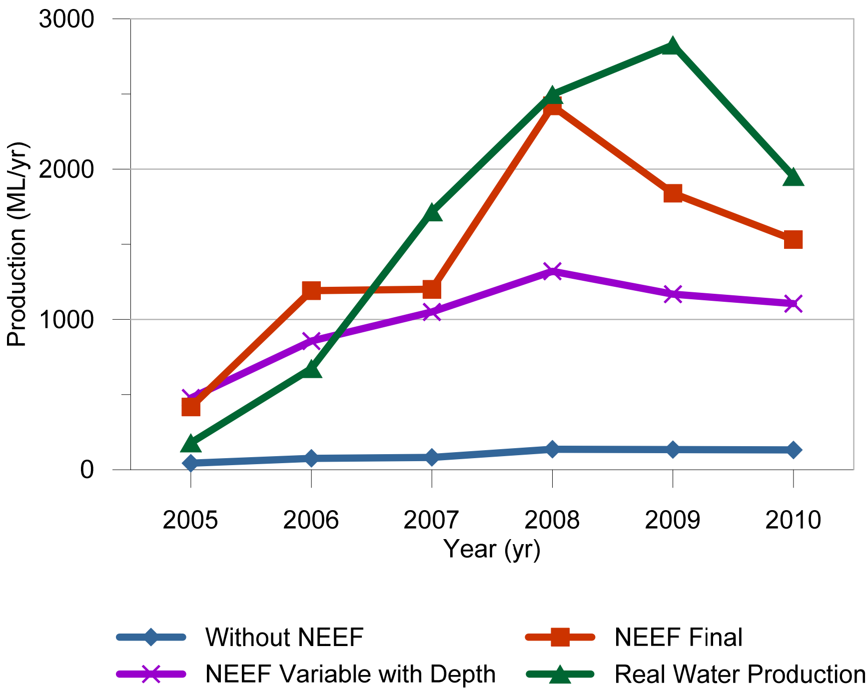


Figure 5-6. Final validation of PL198 using an updated and simplified NEEF (with certain criteria requirements met before the NEEF is applied)

The overall impact of this new validation is further observed (for example, in Figure 5-6) in results that showed a strong linear correlation (Figure 5-7) between historic and estimated water production for all tenements used in the validation process. At this point, calibration was considered adequate based on the currently available data.

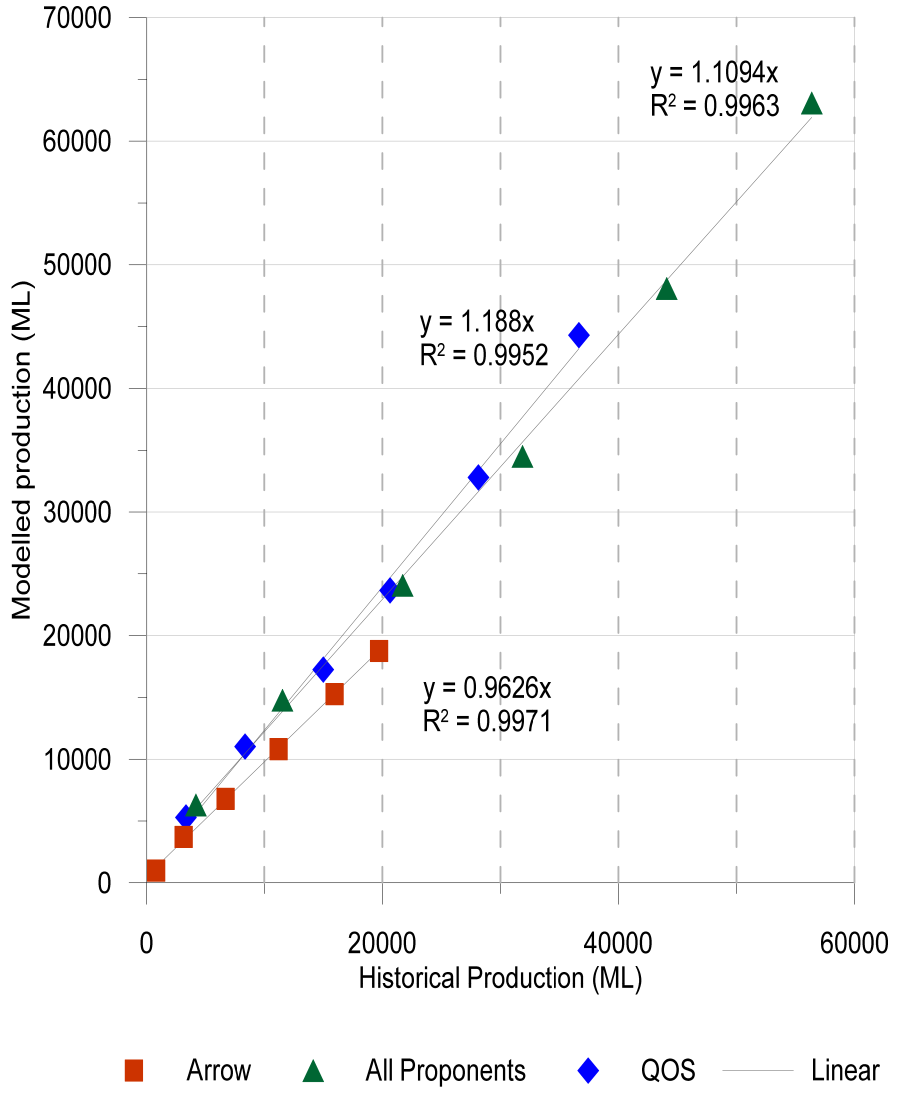


Figure 5-7. Correlation of historical and simulated cumulative production with the final NEEF applied

Further details of the verification process are included in Appendix III.

6. INDUSTRY EXPANSION SCENARIOS

6.1 Industry scenario influences and the WPT

Although it is preferable to have a single, universally-agreed base case describing how the CSG industry will expand, development of such a scenario is constrained by uncertainties arising through:

- individual company data confidentiality
- the reality that not all CSG companies will develop tenure in exact accordance with their current plans (therefore affecting WPT scheduling assumptions)
- effects of industry demographic factors which are outside of the control of CSG companies.

Recognising these uncertainties, three industry expansion scenarios were developed. These scenarios were designed both to provide a range of plausible estimates of future CSG water production and to test the functionality of the tool—particularly its ability to simulate changing spatial water production patterns as gas fields are decommissioned and new fields are brought online. It is important to note that these scenarios represent only a small subset of all possible scenarios and should not be considered as exact representations of how the industry will evolve. The WPT has been constructed so that users can implement and simulate specific scenarios without significant effort. It is intended that future users of the tool will be able to construct and modify scenarios to match and assess variations in industry direction and development.

The three scenarios are as follows, and are discussed more fully in subsequent sections:

Scenario 1. Company-supplied and inferred industry expansion

Scenario 2. Simulated industry expansion considering geology, infrastructure and current production drivers

Scenario 3. Stochastically generated, random industry expansion.

The total cumulative gas production from each of these scenarios may eventually be very similar, provided the demand for gas remains at a high enough level. Importantly though, gas production does not translate to equivalent cumulative water production volumes from each scenario due to factors such as:

- inter-well interference impacts on water production
- impact of start-up and shut-down of well fields
- cumulative pressure reduction in higher development scenarios
- dual-phase effects significantly diminishing long-term production of water
- longevity of production wells.

These aspects are discussed in more detail in Sections 6.1.1, 6.1.2, 6.3 and 8.

6.1.1 Using stochastic modelling to understand uncertainty

Given the inherent uncertainties and those highlighted in the preceding section, a single outcome or single water production profile would not be the most useful way to assess the likely water volumes.

For each scenario multiple realisations can be run where several parameters are varied within a range of plausible values. This results in a distribution of water production values over time which can be reported in terms of probabilities of occurrence or distributions of values for each scenario. In many of the graphs which follow, these distributions show average (arithmetic mean), median values and a lower and upper percentile value (25th and 75th percentile). This presents a plausible range of values that each scenario is likely to produce, with an associated probability of occurrence. For example, if we consider the distribution of predicted volumes from multiple simulations, there is a 75% probability of the predicted volume being less than or equal to the 75^{th} percentile value. The 50^{th} percentile value or median represents the value that lies at the mid-point of all the values.

To allow for the inclusion of uncertainty, the WPT has also included Monte Carlo stochastic variation of the following key parameters:

- well life (length of time that a well is in operation)
- storage coefficient (varies normally around a mean of 0.000025, with a standard deviation of 0.000001)
- the NEEF (discussed earlier)
- the TRF (discussed earlier).

6.1.2 Timing and intensity of development

As well as each development scenario, the WPT has two drivers which act as surrogate indicators of industry change:

- Delays to implementation or commissioning are represented by a series of timing factors. These timing factors represent a specific well field’s time lag to production. This is applied at the cell scale (10 kilometres x 10 kilometres).
- Industry demand is represented in the WPT as a function of intensity of development. This is applied to each cell as a function of the well density. More intense gas production is simulated by increasing well density.

The delay factor allows a user to shift time lines in the WPT, which may occur because of events such as operational approval delays, or labour and materials shortages, for example. The timing factor factorises the delay-to-start date by one (no lag), 1.1 (10 per

cent delay) or 1.4 (40 per cent delay), resulting in an 'on-time' case scenario, a 'moderate delay' case scenario and a 'delayed' scenario.

The industry demand factor was included to describe possible changes within the industry—for example, periods of heightened gas production for commercial or operational reasons. This factor effectively changes the well density within the cell.

6.2 *Scenario 1*. Company-supplied and inferred industry expansion

For the first scenario, KCB populated the WPT based on information:

- given by the CSG companies on proposed development time lines (which may extend beyond current environmental impact statement [EIS] documents)
- given by CSG companies about well density
- inferred information from historical data that has been publicly reported and from EIS documents.

A limitation of the current data is the life of each field, which is not explicitly available from provided or public domain information. However, using analysis of the provided field development data and type curves for wells and well fields, a mean lifetime of well fields has been estimated. This varies across the basin according to inferred information and is stochastically sampled to account for the uncertainty in this estimate.

Because this scenario assumes that all CSG companies will succeed in advancing their projects within their intended time frames, this is the most optimistic scenario considered from a gas production perspective. This scenario is not expected to produce the highest water production profiles, because although gas production is high, there is also good opportunity for inter-well pumping effects to lower total water produced at a given time.

This scenario was selected to permit comparison of the tool results with those of the currently predicted industry development (largely by the CSG companies themselves). It is not considered a plausible development case because it is highly unlikely that all companies will develop their tenements based on currently established schedules and yields.

6.2.1 Limitations of the data provided for Scenario 1

The quality and extent of the data provided to KCB has been discussed in previous sections. For scenario development, it is important to stress that although the project data has been provided by CSG companies or derived from company EISs and other public documents, this information reflects the intended future development from each CSG company's individual perspective. This is likely to change as the industry develops (and as projects are potentially cancelled/absorbed). Such changes may be due to technical advancements or challenges, market and financial conditions, or may be in response to policy or regulatory changes.

The consistency of data provided to KCB is variable between different CSG companies. Because of this, it has not always been possible to manage data in consistent formats, or as complete datasets. In many cases, data has been inferred rather than directly provided. See Appendix I for a more complete discussion.

It is also important to consider the timescale of likely changes. Public domain information such as EIS documents generally only provide projected development over a 30-year period. However, to populate the WPT use was made of each company's provided data which reflects longer term expected implementation. Information on the longevity of the individual gas fields is not yet proven and it has been necessary to include assumptions regarding future development of well fields based on company data and also on the likely operational life of well fields (beyond which water production from CSG operations is considered negligible).

6.3 *Scenario 2*. Industry expansion considering geology, infrastructure and current gas production

6.3.1 Evans & Peck industry assessment and application to a geology- and infrastructure-driven scenario

DEEDI commissioned Evans and Peck (E&P) to undertake an assessment of likely future development of major mining and resource projects within the Surat Basin (Evans & Peck, 2010). The version of their work used in this study provides the likely development scenarios based on information up to the end of 2010. The E&P work is far broader than that of the WPT and is not specifically focused on the CSG industry. Their work applied a number of industry drivers to predict resource development influenced by economic (and other) factors that may not have been explicitly represented by company EISs.

E&P have based their 'most probable case' on the most likely case of eight liquid natural gas trains in existence by 2020, and from this have determined different probabilities of gas export volumes. The approach employed applies a series of factors such as project information, company market and development appetite, approvals requirements and a range of other factors limited by a series of constraints such as likely market growth, infrastructure, labour availability and so on. Of additional interest to the WPT is their consideration of development clusters, which suggest preferential development in areas of current or existing infrastructure—such as regional town centres and transport corridors.

Development clusters, or external factors which may positively or negatively influence the development of well fields (outside of company plans), are not represented in Scenario 1 of the WPT. The work of E&P presents a plausible approach to introducing such factors to the WPT.

Scenario 2 was therefore developed to permit the WPT to simulate an industry development scenario constrained and led by external factors not directly linked to the CSG company plans. This is considered a more credible development case than

Scenario 1 because it applies constraint to development representative of potential external industry factors. For this reason, Scenario 2 is presented and analysed in greater detail.

Furthermore, the use of Monte Carlo probabilistic modelling by E&P to express the likely industry expansion is aligned with the approach in the WPT, which expresses water production as probabilities of occurrence.

6.3.2 Details of Scenario 2

Scenario 2 was produced based on geological and coal seam variability, the current and likely development of infrastructure (regional centres and lineal corridors) and the status of current gas production. This has been achieved by applying a series of thematic maps which represent:

- Geological and coal seam information (e.g. depth to coal seam as shown on Figure 6-1), assuming that generally, shallower targets will be preferentially developed ahead of deeper targets.
- Current gas production areas (already developed/developing well fields) and proximity to infrastructure (towns and linear corridors for transport of product and equipment, shown in Figure 6-1). This accounts for industry growth in areas of initial development and close to centres where project servicing and housing facilities are established. The total score rating (Figure 6-2) has been used to populate the WPT for Scenario 2.

The geological scoring used the depth to the target coal seam at each point across the study area and normalised these values on a scale of zero (shallowest) to 10 (deepest). Areas with no seam present were given a value of ten. In a similar way, the radial distance from the nearest town and the linear distance to the linear transport corridors was calculated and each score was again normalised on a scale of one (closest) to 10 (furthest away). These three themes were weighted equally and summed to give an overall score.

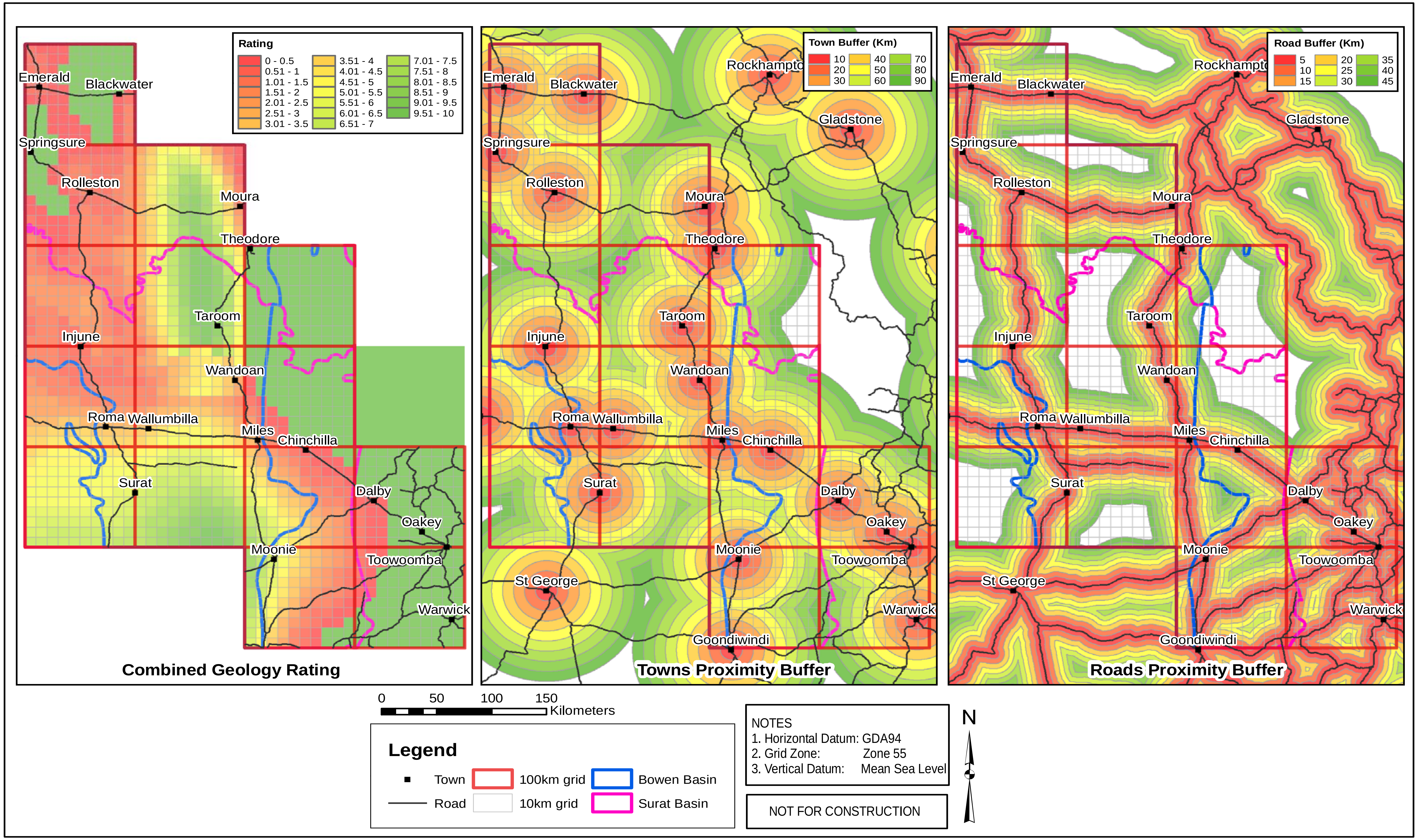


Figure 6-1. Thematic maps used to develop Scenario 2, showing ratings for geology and proximity to towns and infrastructure.

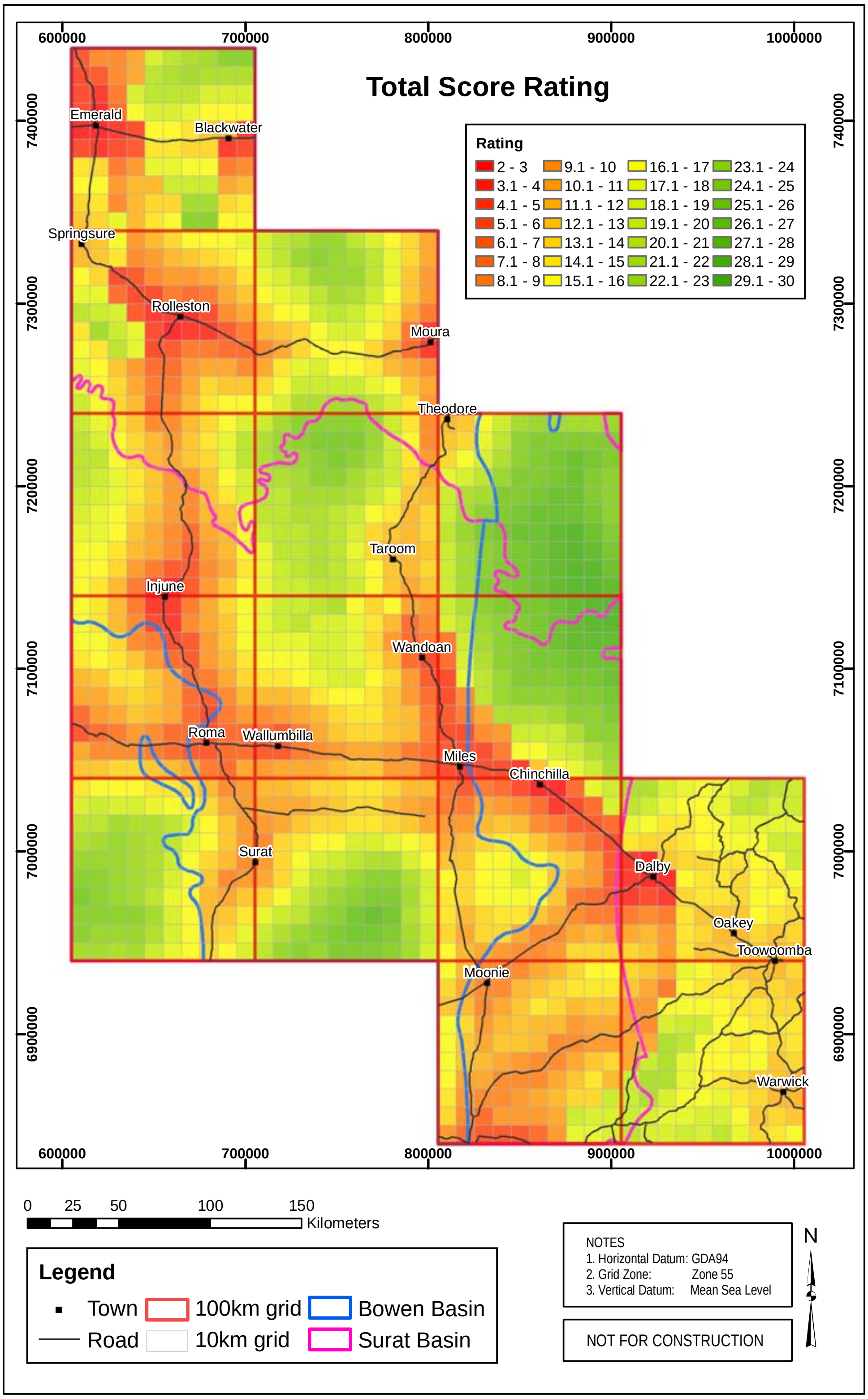


Figure 6-2. Combined thematic map scores for Scenario 2, indicating priortised order of development. Red is highest priority (little or no delay to activation); green is lowest (longer delay to activation).

The overall thematic mapping score was used to simulate the order in which cells would be activated (i.e. when pumping commences). The scores were converted into a magnitude of months of delay, accounting for the time span of the simulation, which was chosen to reflect an assumed industry life span. As explained previously (Section 4.4) a delay is a length of time that a cell is inactive (no pumping takes place). Cells with a lower score were assigned a smaller delay to activation; cells with a higher score were assigned a larger delay. The process for calculating the delays is as follows:

1. Calculate the total score from thematic mapping. Compile the score with no weighting (meaning each theme has equal weight) giving a maximum score of 30 and a minimum score of two.
2. Normalise the scores to distribute the delays over the projected life of the CSG operations (in this case an industry life of 60 years was assumed).
3. Assign all currently producing cells a value of zero, indicating no delay to pumping.

The ‘delay to start’ values were then populated in the WPT, which simulates the spatial growth of a developing field through preferential activation of the nearest adjacent cell with the least delay to production. The resultant spatial growth time line of industry expansion was paired with expected well densities in each cell to provide a time line of operational wells in each cell block.

This approach differs to that used in Scenario 1, where the delay for a cell was measured from the beginning of the simulation to the time when the majority of wells in a cell become active, based on information provided by the CSG companies (Section 4.4).

The spatial distribution of expected well densities places a constraint on where water production will be simulated in Scenario 2. The scoring system described above will assign the maximum geology score to cells with no underlying coal seam. These cells will therefore have a moderate to large delay value, but will still be activated within the time frame of the simulation. However, because these cells will also generally have an expected well density of zero, no water production will be simulated by the WPT.

The scoring method described above results in the formation of clusters of development around current well fields, propagating outwards along lineal corridors, near regional centres, and most importantly, in areas overlying shallow- to mid-depth coal seams. The way in which this development occurs can best be explained by considering a single cell block. Figure 6-3 shows the distribution and magnitude of delays for cell block 12 as an example.

95	62	0	73	47	5	4	74	288	324
105	108	0	0	108	83	26	42	76	306
132	136	176	182	171	126	102	63	62	74
161	165	205	229	217	189	162	0	0	44
190	195	235	240	282	234	206	180	0	0
238	206	247	269	292	244	198	153	128	68
231	199	239	261	265	235	188	107	81	56
224	173	211	232	217	186	158	114	105	97
213	161	199	200	148	117	125	153	180	153
236	164	147	129	114	118	143	206	215	205

Figure 6-3. Number of month delays to activation in cells (in cell block 12) from the start of simulation

The numbers in each cell in Figure 6-3 represent the delay to activation, measured in months from the start of the simulation. The cells are coloured: green cells correspond to short delays to activation; red cells correspond to longer delays to activation. For the cell block shown, the minimum time to becoming active is zero months (i.e. already under development), as seen in the seven darkest green cells, and the maximum time to becoming active is 324 months (27 years), as seen in the single cell in the upper right-hand corner.

In general, the delays in Scenario 2 allow for smooth transitioning across the basin with adjacent cells being turned on one after the other, because the delays between adjacent cells are usually small. However, sharp distinctions occur between cells where there is a sudden change in the underlying geology, such as at the shallow edge of a coal seam, as illustrated in Figure 6-4.

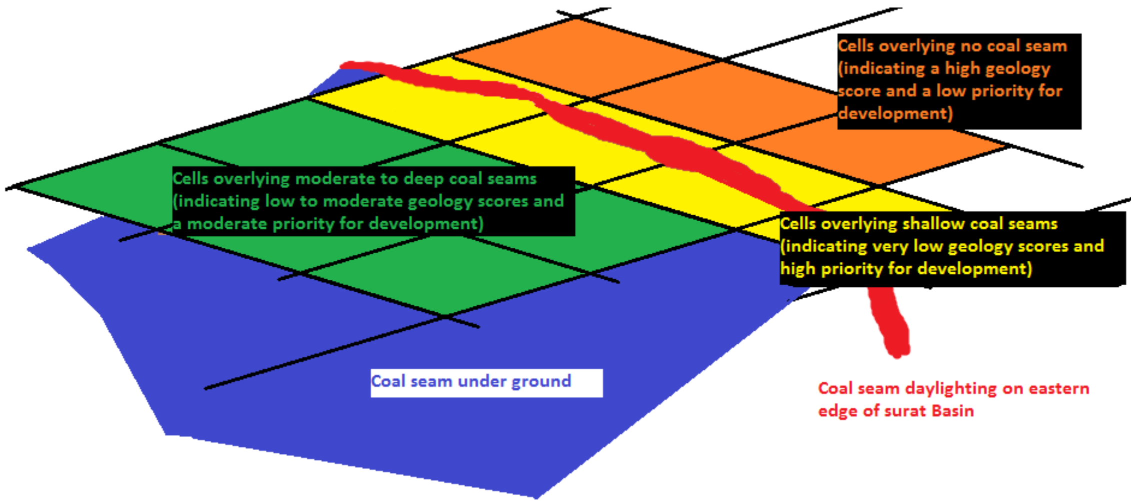


Figure 6-4. Variation in the properties of the coal seam across adjacent cells, and their effect on development priority (delays to cell activation)

This approach enabled the development of an alternative WPT scenario which is derived independently to the company-supplied time lines to allow assessment of possible water production profiles.

6.4 *Scenario 3*. Stochastically generated expansion

Random timing of well field initiation represents an unlikely water production case because the concept requires random installation and commissioning of gas production wells. This has been incorporated by introducing a factor which resets the cell start date to a random number. This results in a different water production profile from the production curves supplied by the CSG companies. The result of non-sequential well field development is a greater need to reduce hydrostratigraphic pressure in new areas, and consequently higher cumulative water production.

Therefore this scenario, although unlikely, presents a potential upper bound of cumulative water production because it assumes minimal pumping advantage from interference effects from nearby operations. This is considered an unlikely development case but is presented as it is completely disconnected from confidential data or from external industry development factors. This is a useful comparison scenario to Scenarios 1 and 2, but it is not a likely industry case and should be considered as a tool functionality assessment scenario only.

6.5 Estimating the number of wells

Figure 6-5 summarises estimated number of wells in operation (not CSG water production) over time for each of the three scenarios in the WPT. The differences in well numbers are a reflection of timing of start dates and/or inferred intensity of development. The values represent the deterministic results of the simulation and provide a relative comparison of well counts for each scenario.

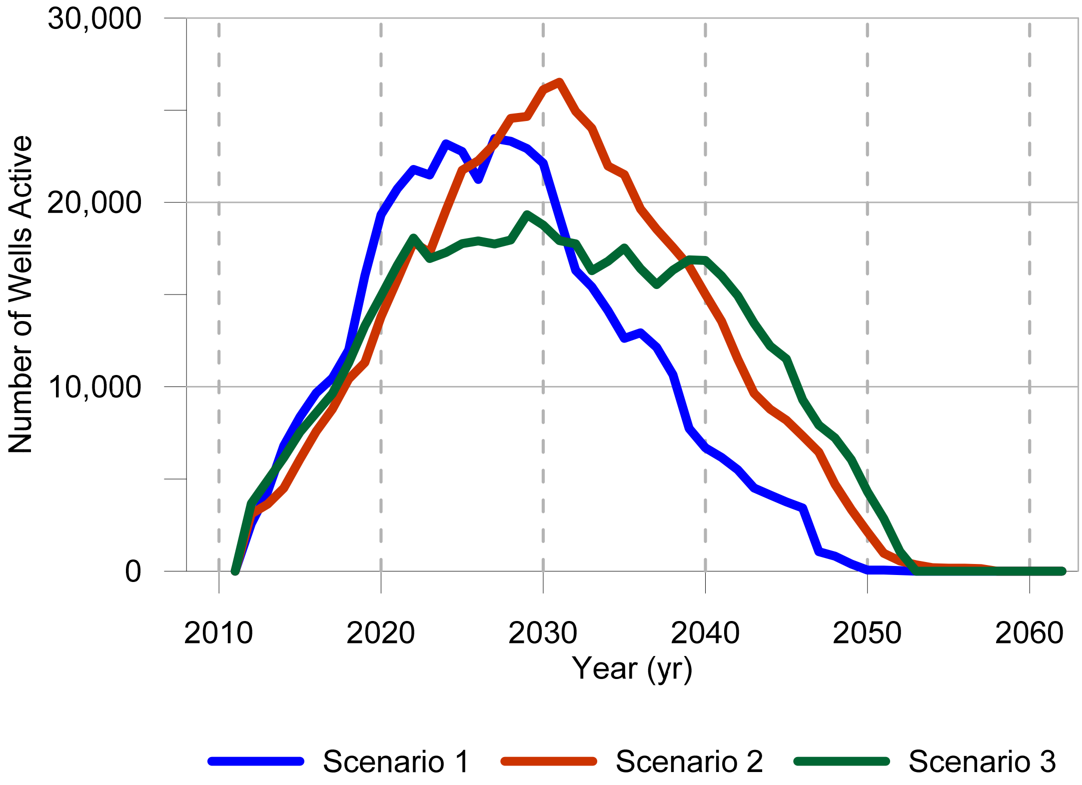


Figure 6-5. Estimated number of wells in operation for each of the three scenarios in the WPT

For Scenario 1, the well profile for 2011–2060 shows a peak of production in about 2027; Scenario 2 peaks later and higher in well numbers, and Scenario 3 plateaus between 2020 and 2040, with well count relatively static at between 15,000 and 20,000.

All scenarios observe similar escalation in well count from start-up to about year 2020, with Scenario 1 showing a more rapid development profile than the other two scenarios. This is not unexpected considering this scenario represents a more optimistic industry expansion condition with all CSG companies achieving their development objectives within their target time frames.

6.5.1 Comparing WPT well-count estimates with estimates from Evans & Peck

E&P (2010) provided an estimate of total CSG well count for each of their development probability curves (equivalent to just the first 10 years of the period shown in Figure 6-5). These values are used as a secondary form of comparison for the different WPT scenarios. The WPT has not employed the E&P well counts as a specific input or to force field development in the tool. Instead, the WPT has been allowed to simulate industry development with a similar set of industry drivers and constraints, and the resulting well count has been compared with the work of E&P.

A comparison of the E&P well count with the three WPT scenarios shows that the estimated number of active wells from the WPT scenarios compares favourably with the E&P estimates for the period up to 2020 (Figure 6-6). At December 2011, no other publically available estimates are available for the period after 2025.

Like the WPT, the E&P work employs Monte Carlo stochastic modelling, whereby a scenario is simulated multiple times to account for possible variations in one or more parameters. The results are presented through the use of percentiles, which describe the proportion of simulated outcomes (or estimates) that fall below a certain value (or series of values over time). In Figure 6-6, the P80 line depicts the 80th percentile estimate of well counts forecasted by E&P, meaning that 80 per cent of E&P's well-count estimates fall below this line. The P50, or 50th percentile line corresponds with what is commonly called the median.

By taking the range from P20 to P80 (the middle 60 per cent of all estimates), a reasonable range of probable outcomes can be obtained. Figure 6-6 shows that the estimated numbers of wells for each of the three WPT scenarios up to 2020 generally fall within the P20 to P80 range of the E&P forecasts.

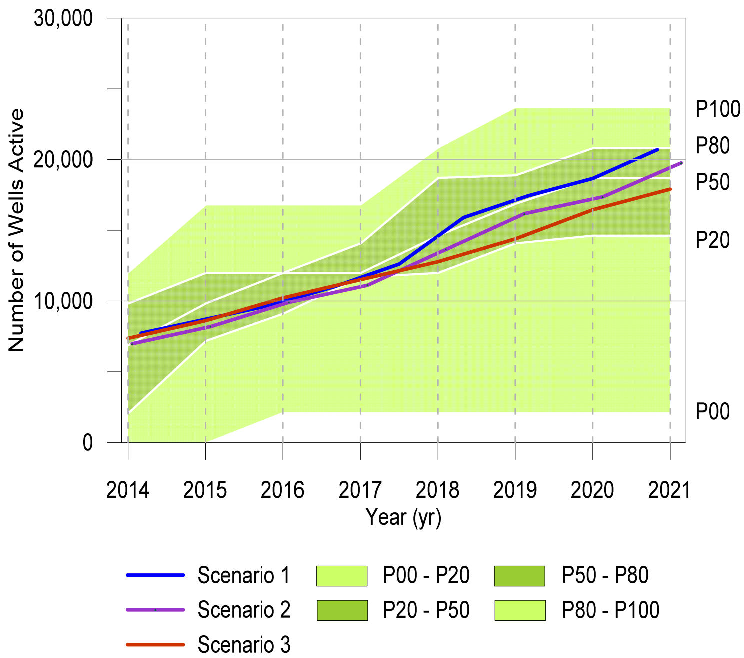


Figure 6-6. Comparison between E&P and KCB estimated number of wells (until 2021). The percentile measures (P00 to P100) describe E&P's results.

WPT well counts are comparable for 2014-2021 and generally fall within the P20 to P80 range for the E&P results. This should not be interpreted to mean that one study is driving the results of the other—the comparison was done to show that two independent approaches to water production generate a roughly comparable well count result.

7. ESTIMATED WATER VOLUMES AND QUALITY FOR THREE INDUSTRY EXPANSION SCENARIOS

7.1 Results from the WPT

Implementation of the three industry scenarios was achieved by constructing the scenarios as pre-set options in the WPT, establishing well field development intensity and timing factors, and running multiple realisations of each scenario (as a default 99 realisations are run for each simulation) to permit probabilistic reporting of the water production and water quality results.

For each scenario, runs have been completed representing variability in well densities (low, default and high) and variability in production delays (lesser, default and greater). This approach permits nine permutations in total of the three scenarios (Table 7-1). Users can vary the delays and well densities in the tool with the default values provided in Table 7-1.

Table 7-1. Each scenario's permutations and realisation numbers

	Delay to Start		
Well Density	100%	110%	140%
130%	1	2	3
100%	4	5	6
70%	7	8	9

The results are presented as:

- annual and cumulative water production for the entire WPT coverage for all three scenarios
- rolling average water production at the cell-block scale and five-year-snapshot water production for Scenario 2 at the cell scale (10 kilometres x 10 kilometres) for the mean, median and the P25 (25th percentile) and P75 (75th percentile) cases.

Focus is placed on Scenario 2 because it represents a realistic industry expansion scenario that is not constrained to specific CSG company plans that may be overly optimistic and/or cover a shorter time period than the expected life of the industry.

7.1.1 Graphical and spatial presentation of results

Simulated water production results are visible on the cell block level and entire region basis. Two types of results—time series of the entire WPT area and spatial tile mosaics of specific time intervals—are presented.

For the time series of the entire WPT area (Figure 7-1 to Figure 7-4), the following points are worth highlighting:

- The time series represents the results of multiple realisations of each scenario. The stochastic capabilities of the GoldSim software are used to vary several of the input parameters. Typically, 99 realisations of each scenario are represented by each plot.
- Both the median value and mean value for the multiple realisations are shown, within an envelope of uncertainty or probability. The result is an envelope of likely water production values over time. The band between 25th and 75th percentile values is shown on these graphs.
- As discussed in Section 7.1.2 below, the raw simulated water production values show transient peaks in the results as new production areas are brought online. As the actual water production is not expected to be 'peaky', a five-year moving average has been implemented in the WPT. Raw and smoothed values are displayed and are discussed for Scenario 1 in Section 7.2.1. For Scenarios 2 and 3, only the smoothed value is shown in the body of the text with the unsmoothed, peaky data included for comparative purposes in Appendix V.

For the spatial representations (Section 7.2.4), the mean, median, 25th percentile and 75th percentile values are shown as cumulative water production values from each cell. This provides an indication of the spatial evolution of water production in five-year increments across the region.

7.1.2 Produced water peaks

Some of the results presented in the following sections exhibit brief periods of extreme water production. However, these are not necessarily an indication of sudden intensified industry expansion.

Because of the simulated erratic nature of development under these scenarios (in particular, Scenarios 1 and 3), water production peaks occur, and are largely attributed to new areas of development opening up (as shown in Figure 7-2). Under such conditions, and because of the coarse nature of the time steps, sudden periods of increased water production are predicted by the WPT, and are not able to be readily 'absorbed' in the overall simulation time frame. This also occurs in the first year of the WPT; however this data is able to be excluded as it is known to be a function of the WPT calculation process and the sudden initiation of CSG activity over coarse scale time steps.

This is a drawback of the coarse time steps of the data supplied and applied to the WPT. Although it possible to smooth these peaks with smaller time steps, it is considered more reasonable to adjust such peaks with simple averaging rather than to shorten time steps and increase WPT run times and numeric complexity. The results shown have applied a five-year moving average to the data.

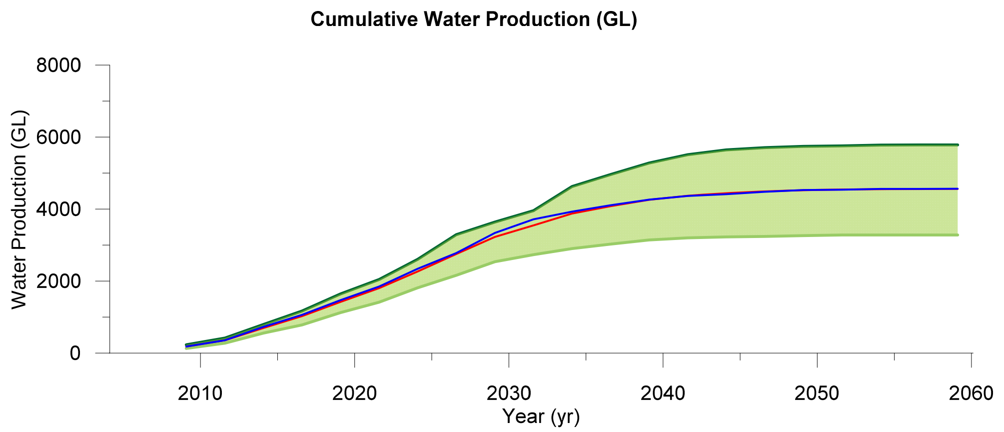
7.2 Estimated water production

7.2.1 *Scenario 1*. Annual and cumulative water production

The smoothed annual water production (Figure 7-1) increases rapidly at first, reaching around 150 gigalitres per year (GL/year) in 2017, before rising more gradually to reach an eventual peak of around 180 GL/year in 2030. Water production then decreases, reaching relatively low levels by 2050.

By comparison, the raw simulated values () are more erratic. This is partly a reflection of proposed operational schedules from different CSG companies overlapping, resulting in a less coherent spatial progression of the industry. New areas coming online do not always have adjacent areas already developed, thus they may require a greater initial pumping effort (and therefore produce more water) to achieve the operational targets. In addition, the extreme spikes are thought to be artefacts from the tool (as discussed in Section 7.2.1) and are not considered likely to reflect actual industry development.

Cumulative water production for Scenario 1 is about 4,500 GL, predicted by around year 2050.



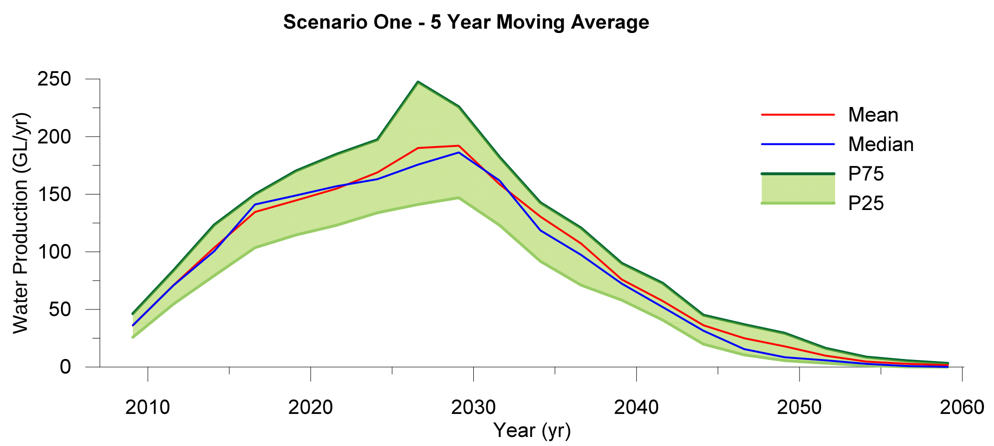


Figure 7-1. Scenario 1 – cumulative and annual water production (smoothed)

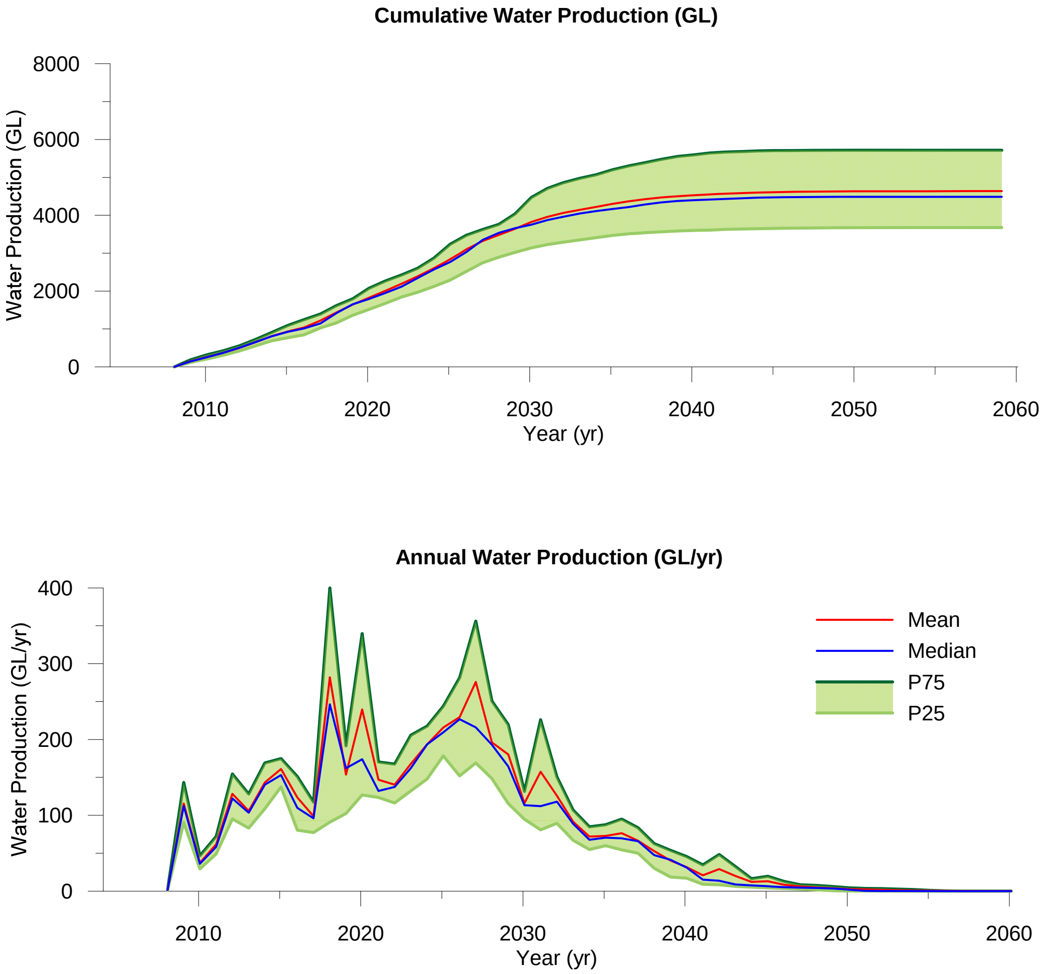


Figure 7-2. Scenario 1 – cumulative and annual water production (raw simulated values)

7.2.2 *Scenario 2*. Annual and cumulative water production

Scenario 2 water production (Figure 7-3) is more tempered than Scenario 1, reaching a plateau of around 175 GL/year after 2022. Water production starts to decline gradually after 2032.

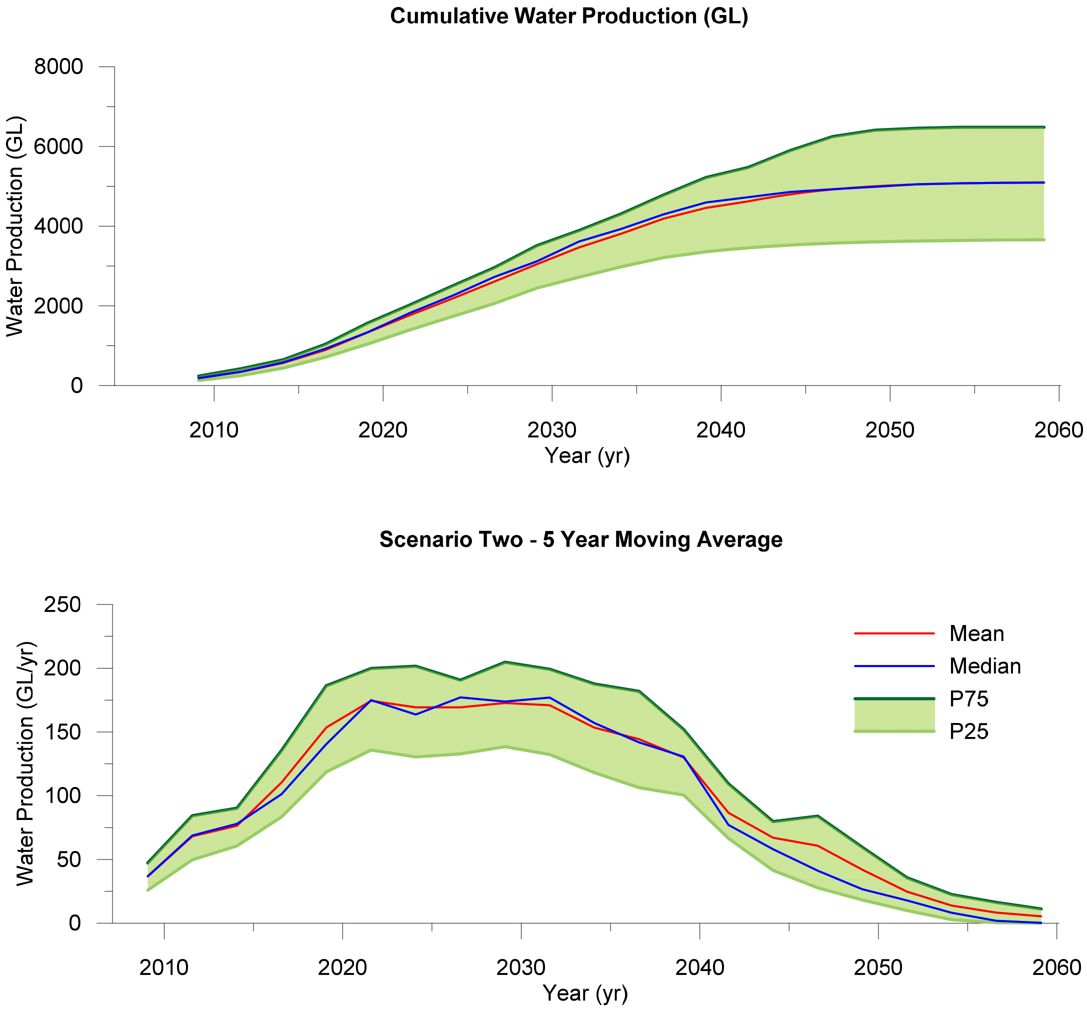


Figure 7-3. Scenario 2 – cumulative and annual water production (smoothed)

Annual water production profiles for Scenario 2 are more balanced and represent a more coherent industry expansion with increased influence from adjacent development areas in advance of new developments. In the raw annual outputs (Appendix V), peak production amounts are significantly less than for Scenario 1, and the peakiness of the WPT output is more balanced. This is a function of the industry expansion approach applied constraining CSG growth to logical and progressive development, rather than less coordinated development which will require more intensive start-up pumping.

Scenario 2 cumulative water production is about 600 GL higher than Scenario 1, at about 5,100 GL by 2060.

7.2.3 *Scenario 3*. Annual and cumulative water production

Simulated water production for Scenario 3 (Figure 7-4) starts with a peak of the order of 120 GL/year. This is a reflection of the WPT needing to start the process of water production and therefore (initially) pumping hard to achieve desired depressurisation

targets in new areas of development. This is far more pronounced in the Scenario 3 output as this represents random sequencing and therefore minimal interference effects from adjacent pumping cells.

For the remainder of operations to year 2040, water production averages around 130–140 GL/year, although in the raw annual output (Appendix V), there is an erratic cycle of peaks and troughs between 100 GL/year and 200 GL/year. This erratic production is to be expected, given the constant restarting of depressurisation effects that is needed.

Scenario 3 cumulative water production is about 5,100 GL by 2060. Not surprisingly, despite lower peaks, this scenario predicts similar or greater volumes of water produced compared with previous scenarios.

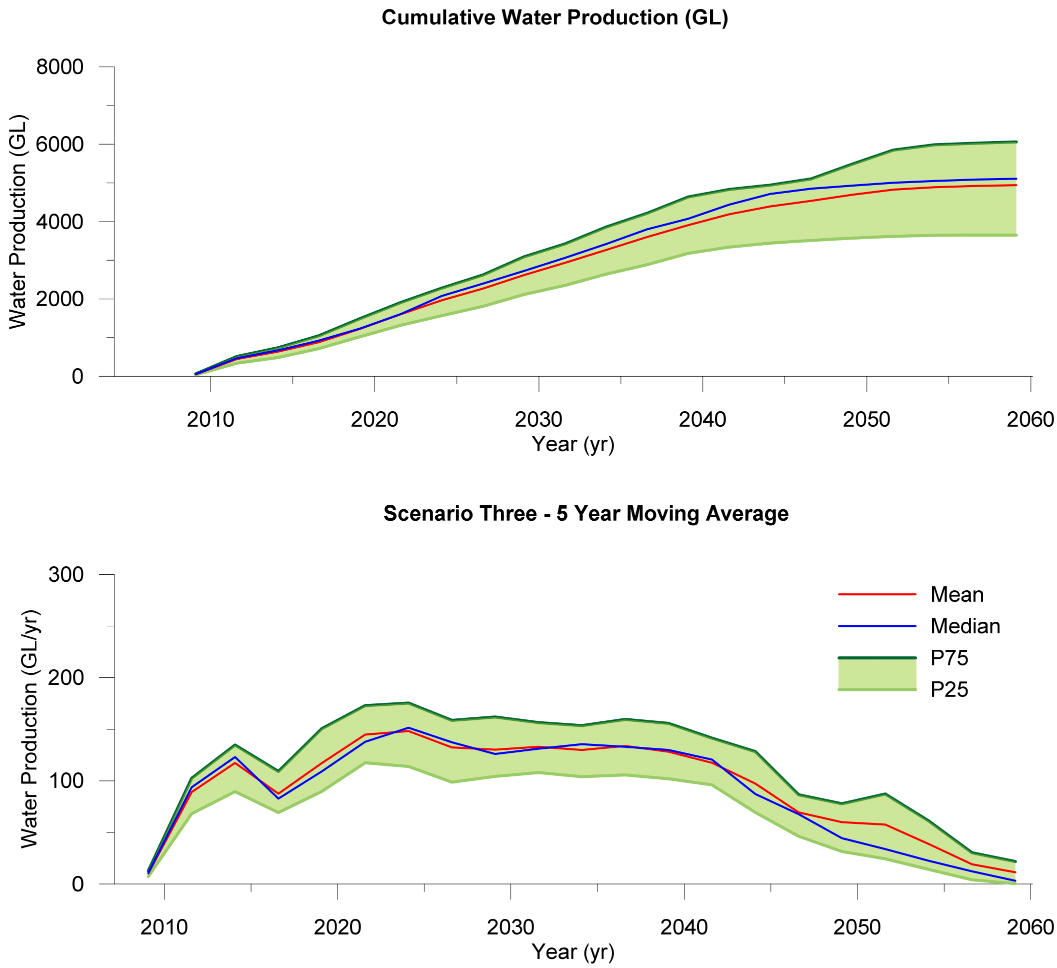


Figure 7-4. Scenario 3 – cumulative and annual waters production (smoothed)

7.2.4 *Scenario 2*. Spatial water production estimates

A coarse depiction of spatial water production over time is provided for Scenario 2 based on production by five-year period for each of the 15 cell blocks. These results are tabulated (Table 7-2) at the cell block level; the locations of the cell blocks are shown in Figure 4-2.

Table 7-2. Water production by cell block for Scenario 2 (mean values)

Cell block	**Period**								
	2010–2015	**2015–2020**	**2020–2025**	**2025–2030**	**2030–2035**	**2035–2040**	**2040–2045**	**2045–2050**	**2010–2050**
CB1	4	5	5	5	5	3	1	1	*29*
CB2	12	31	31	32	25	9	3	0	*143*
CB3	0	10	24	14	7	3	1	0	*59*
CB4	46	68	73	72	70	82	50	22	*483*
CB5	0	2	11	6	31	119	112	69	*350*
CB6	0	0	0	1	1	2	4	2	*10*
CB7	53	76	67	63	83	48	16	3	*409*
CB8	62	308	197	170	127	100	61	22	*1047*
CB9	82	49	34	10	3	2	2	2	*184*
CB10	0	0	0	0	0	0	0	0	*0*
CB11	0	0	93	82	132	163	115	38	*623*
CB12	85	175	222	351	268	125	37	6	*1269*
CB13	18	11	13	8	5	2	1	0	*58*
CB14	1	7	49	50	31	12	3	0	*153*
CB15	0	1	26	9	5	1	0	0	*42*
Total	*363*	*743*	*845*	*873*	*793*	*671*	*406*	*165*	*4589*

Note: Orange cells represent water production per 5 years of >200 GL (or 40 GL/year)
Yellow cells represent water production per 5 years of 100–200 GL (or 20–40 GL/year)

The volumes in Table 7-2 and the graph in Figure 7-5 illustrate several notable patterns concerning the spatial variability of CSG water production. Although these are specific to Scenario 2, the general information that can be drawn (for any later simulations of water production made with the WPT) include:

- Water production can be expected to be concentrated in certain regions throughout the period of industry development.
    - For example, cell blocks 8 and 12 have sustained average production of more than 20 GL/year for the 25-year period between 2015 and 2040. These two cell blocks also produce more than 1,000 GL of water in total over the whole 40-year period, which is a significantly greater volume than any other cell blocks.

- Different areas can be expected to peak at different times.
  - For example, the highest five-year total for cell block 8 (308 GL) occurs in 2015–2025, whereas cell block 5 ‘ramps up’ much later and does not peak until 2035–2040. (However, it should be noted that these five-year totals are not necessarily representative of when peaks over smaller time frames may occur.)
- Some areas may not exhibit strong water production profiles at all.
  - For example, cell blocks 1 and 3, which produce low water volumes for the full duration of the simulation.

A more detailed spatial depiction of the Scenario 2 results is presented in Figure 7-6 to Figure 7-8, which show the amount of water produced in five-year periods for the 10km cells. Figure 7-6 shows these the median results for the period 2010–2050, while Figure 7-7 and Figure 7-8 compare the median, P25 and P75 results for two 5-year periods. Results for 2010–2050 for the P25, mean and P75 outputs are in Appendix VI.

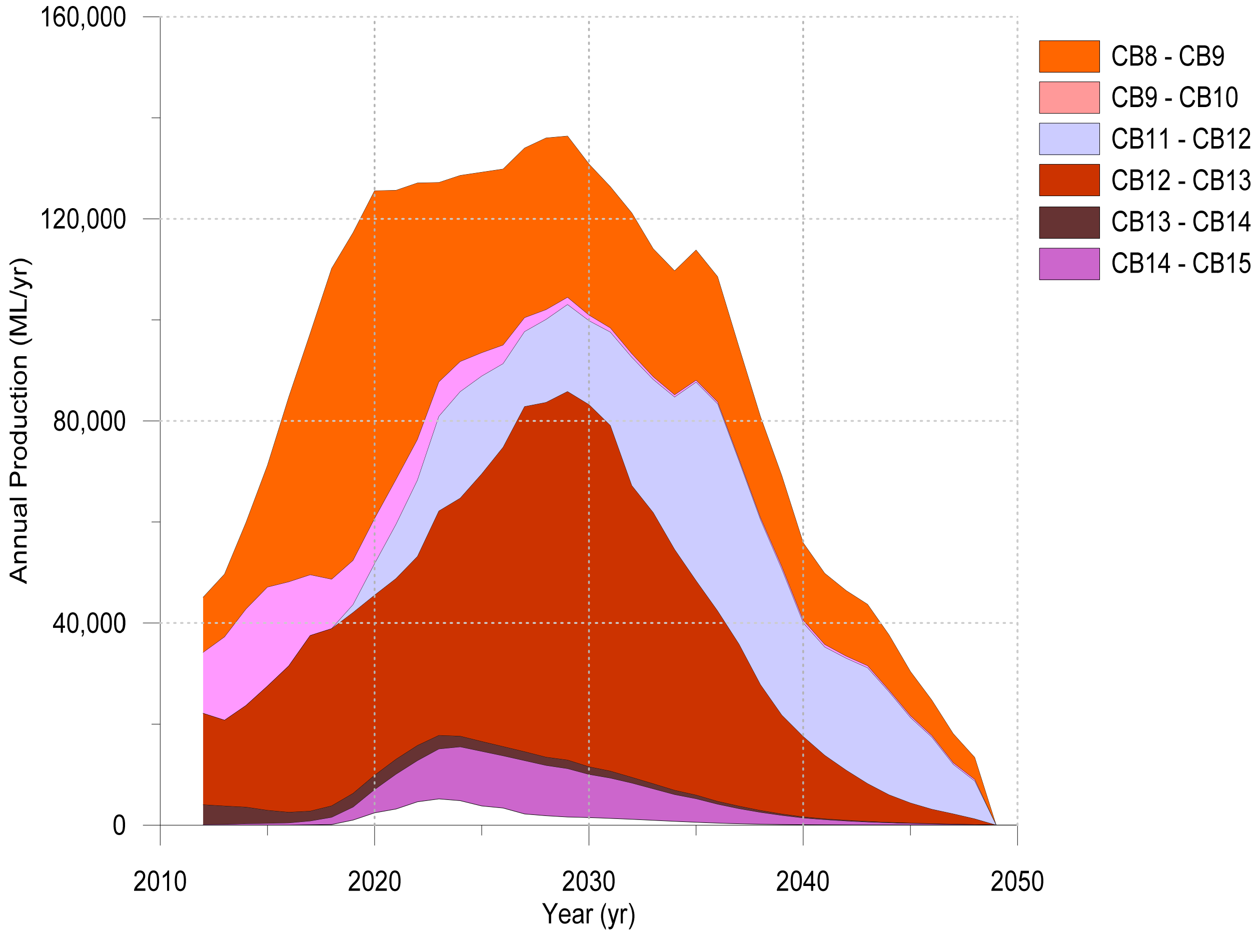


Figure 7-5. Simulated annual water production for each cell block

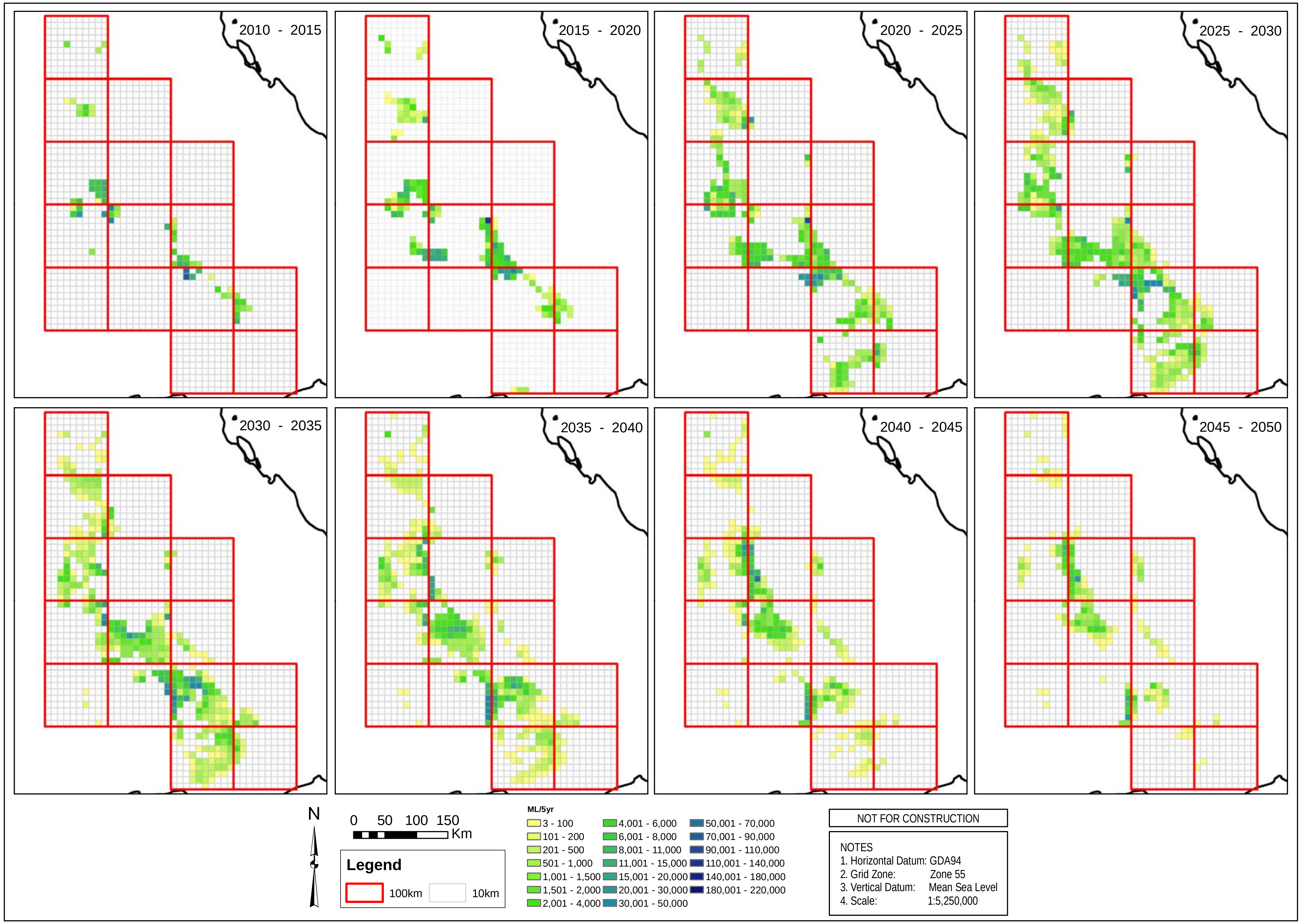


Figure 7-6. Time sequence of CSG water production for Scenario 2 (median values)

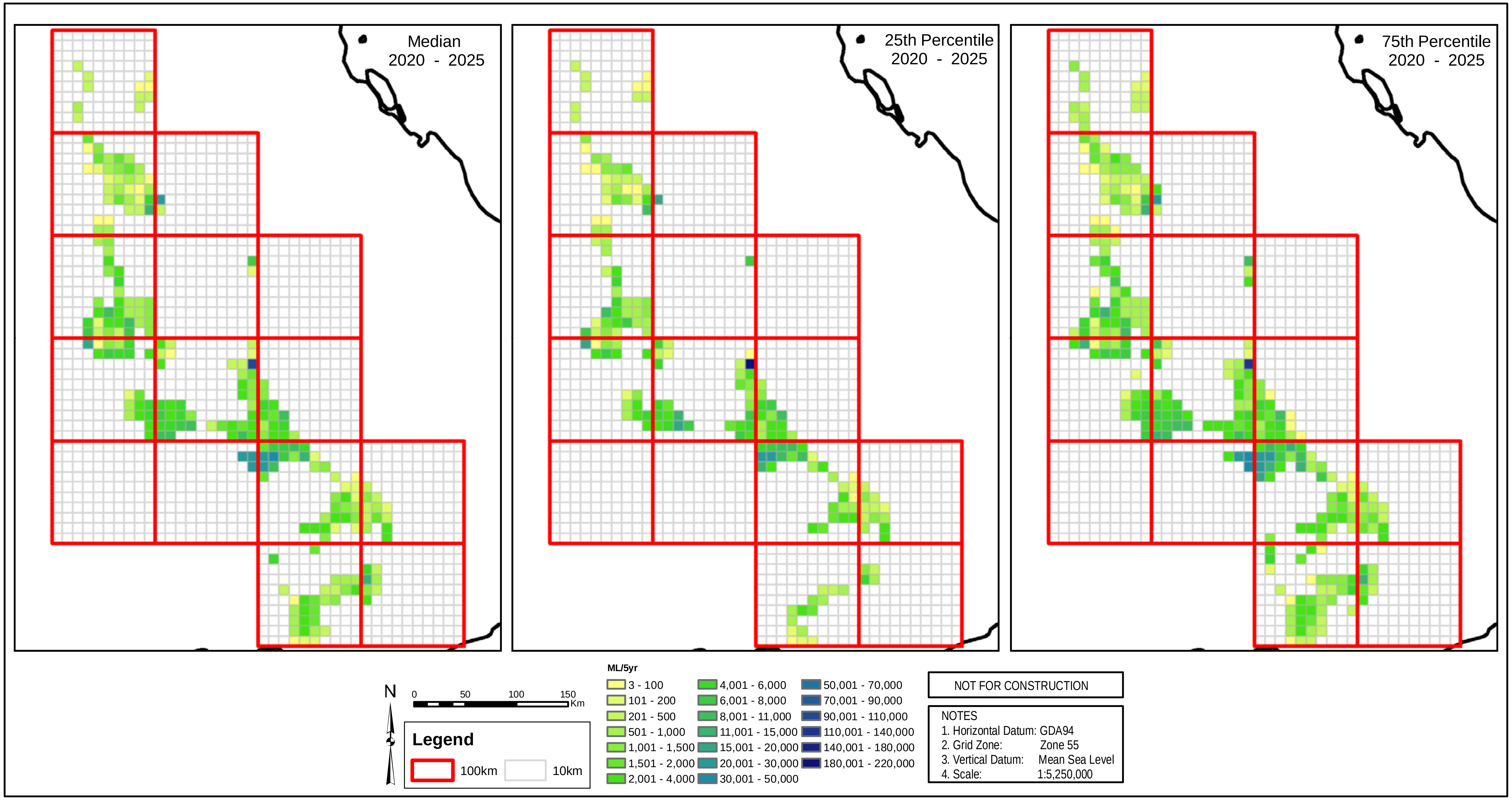


Figure 7-7. Comparison of median, 25th and 75th percentile CSG water production estimates for Scenario 2 in the period 2020–2025

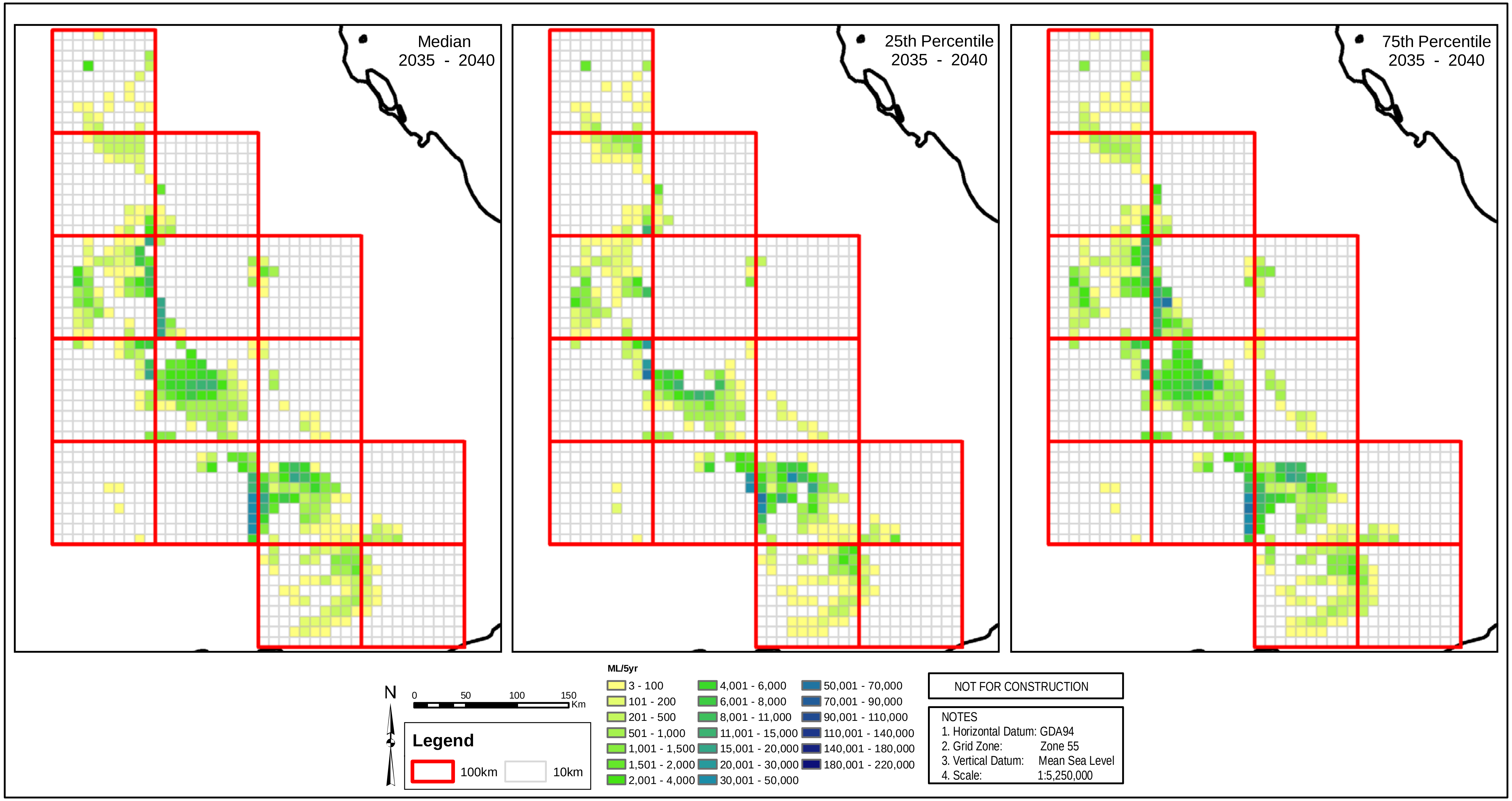


Figure 7-8. Comparison of median, 25th and 75th percentile CSG water production estimates for Scenario 2 in the period 2035–2040

7.3 Total estimated water production

The mean cumulative water production volumes estimated by the WPT for the three scenarios vary from about 4,500 to about 5,000 GL. To put this amount of produced water into a regional and temporal context:

- For an area of 150,000 square kilometres, over a period of 40 years, this equates to approximately 3,600 litres per second to 4,000 litres per second across the entire WPT domain.
- Peak production for any five-year period at the cell block level is 351 GL (shown in Table 7-2). Applying the same calculation as above, this converts to about 0.22 litres per second per square kilometre.
- For an average producing aquifer (coal seam) calculated from the available coal measure isopachs across the entire WPT domain, with an assumed five per cent porosity, the total volume of produced water (upper bound at 5,000 GL) is less than 10 per cent of total potential water in storage. This may vary locally but indicates that the entire sequence will not be completely dewatered over the 50-year period considered in the WPT.

The magnitude of the simulated volumes suggests that estimates of produced water are not in excess of water potentially available in storage, when considering the thickness of the units pumped and the reported aquifer parameters for the coal seams.

7.3.1 Sensitivity Analysis

As an initial consideration of the variability in the water volume forecasts, the variables presented in Table 7-3 were used to assess the likely sensitivity of cumulative water production.

GoldSim's internal sensitivity calculator was used to generate a tornado graph (Figure 7-9). It displays the variables tested, arranged from most sensitive to least sensitive. The sensitivity is assessed by independently varying a single parameter and assessing the net impact on the cumulative water volume produced.

A central value is entered for all variables (which represents the default value used in the tool for a single run or realisation) with an associated range of values for each variable; the lower bound and upper bound representing the range used in the tool are assessed for each variable. The Goldsim platform allows the tool to run a single simulation to find the 'default' cumulative production, then each upper- and lower-bound variable is varied independently. The result for each run is a higher or lower cumulative production than the average case (in this case, approximately 5,000 GL over the period of simulation). When put together, the results provide a listing of the variables in descending order, indicating the most to least sensitive parameter. The absolute values of the upper and lower estimates are of less importance than the relative magnitude of the variance from the average cumulative production.

Table 7-3. Sensitivity analysis variables

Parameters	Units	Lower bound	Central value	Upper bound	Description of parameter
Industry intensity		0.8	1	1.3	This parameter is an indication of intensity of industry and is expressed in terms of a well density multiplier (from the company-proposed case).
NEEF		1	3	5	NEEF roughly equates to a 2.5x multiplier on transmissivity and a 10x multiplier on storage, which is thought to represent the change in the hydraulic parameters in the shallow coal seams where NEEF applies.
TRF		0.98	0.99	0.999	TRF or the Transmissivity reduction factor is the maximum reduction in transmissivity possible under peak gas production.
Mean well field life	yr	10	15	20	Length of time that a well field pumps for before gas is no longer produced
Storativity		1×10^{-5}	2.5×10^{-5}	5×10^{-5}	Storativity of the coal seam
NEEF cut-off depth	m	75	125	175	The cutoff depth is the depth at which NEEF applies
Delay to start variable		1	1.1	1.3	The timing variable is a multiplier on the delay to start. For any value greater than 1 there is an extra delay to the start date as planned in the company proposed case.

The resultant tornado graph illustrates which variables are the most sensitive (have the greatest impact on the cumulative water production volumes) and which are least sensitive (have the least impact on the outcome).

The tornado graph created for the WPT is provided in Figure 7-9. The horizontal axis of the graph shows the variance from the average cumulative production for each independent variable. For example, industry intensity has the greatest potential effect on water production—higher intensity could increase cumulative production from an average of 5,000 GL to as high as 6,400 GL or as low as 4,000 GL when less intense development is simulated. This plot shows which variables create the greatest uncertainty and resulting impact on estimates made by the WPT. The effect of industry development and expected operational life of each producing well play an important role in defining the estimated water production. The NEEF factor and TRF have been adjusted and calibrated using currently available data but results are fairly sensitive to these parameters. Further effort in improving the tool or the base data which it accesses should therefore focus on the variables with the greatest uncertainty.

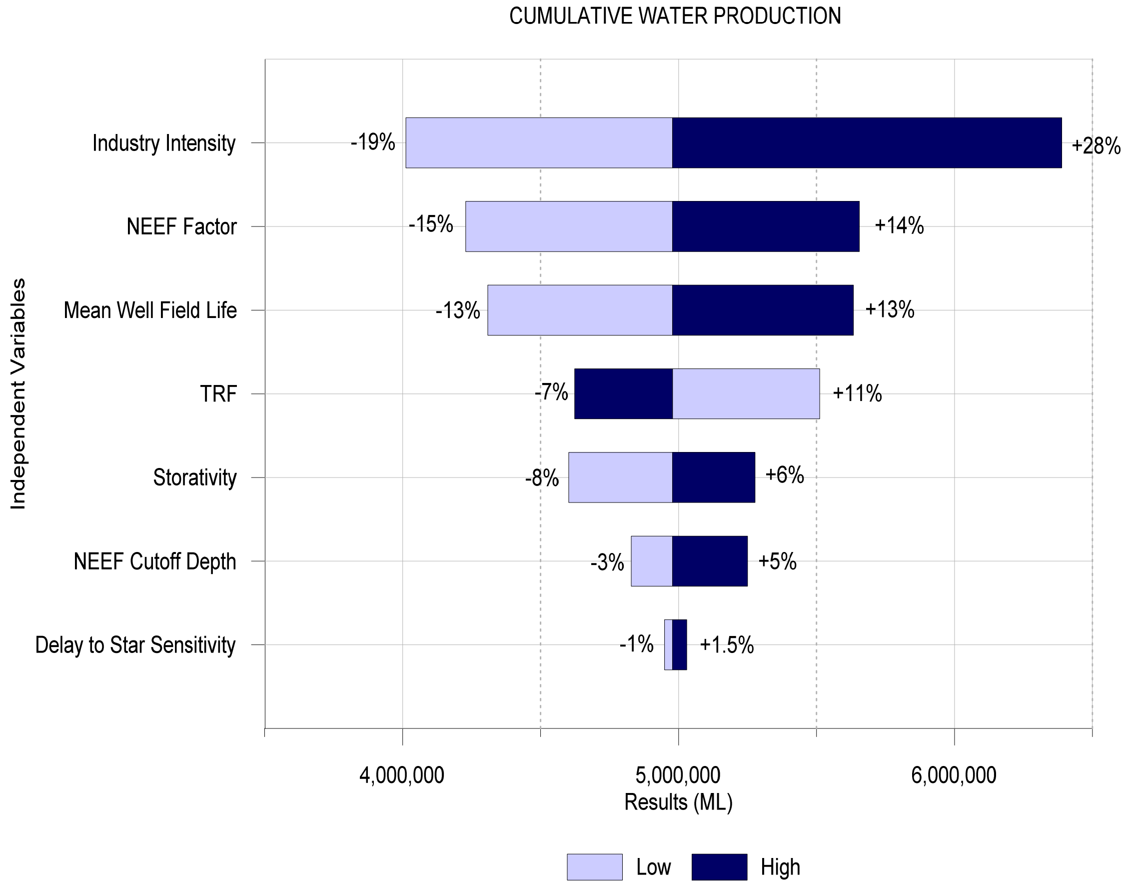


Figure 7-9. Results of sensitivity analysis for cumulative water production

7.4 Estimated salt production

The water quality forecasts have been based on the limited amount of water quality data for the coal measures available to date. These have been input as static water qualities, indicative of the groundwater data for the coal measures. It is likely that as further data becomes available, as new fields are initiated, that information about the spatial variation of water quality will improve significantly.

At this time, it should be noted that the values provided are based on a very small subset of available data, and it is likely that as more representative data is obtained and populated in the tool, that the profiles will look significantly different. This intent of this section is to show the capacity of the tool to estimate water quality and salt loads, rather than to provide a current quantitative indication of projected salt loads.

On this basis, salt production as a function of water production and water quality is provided in Figure 7-10. Salt production is a product of the flow rate in each cell and the representative water quality (TDS) associated with that cell. Total production estimated by the WPT is simply the sum of all cells. The figures show the expected salt production across the total tool domain over time; users can view water-quality distribution in each area separately in the WPT. This is a rudimentary estimate of

produced salt volumes based on basic mass balance calculations from the estimated *in situ* water quality and the estimated water production estimates. The WPT also provides the opportunity to assess total salt loads across the basin and for each specific area.

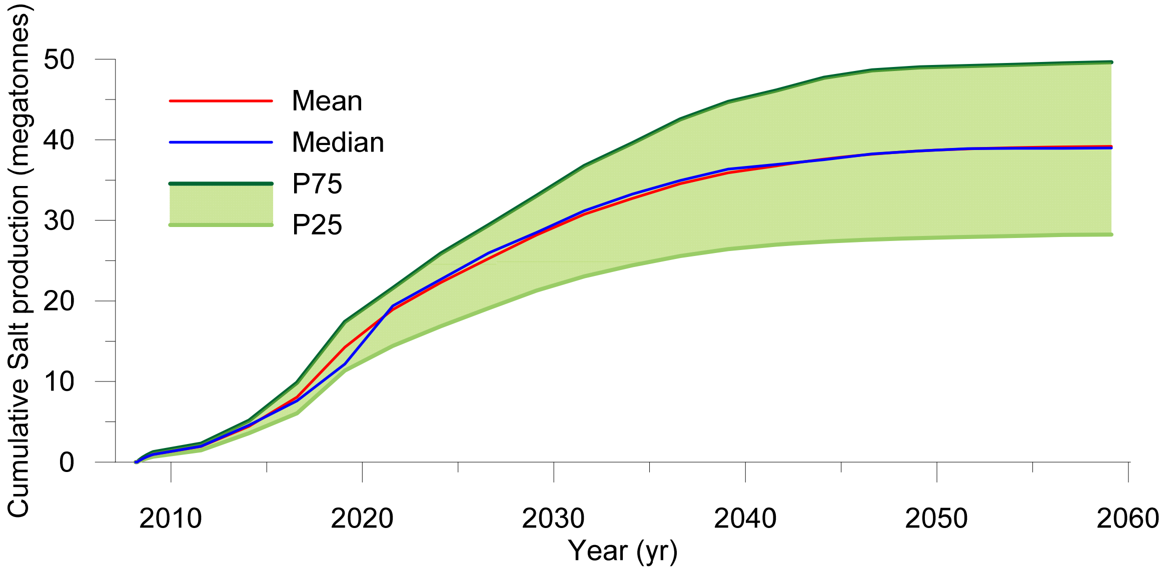


Figure 7-10. Cumulative salt production for Scenario 2

7.5 Previous water production estimates and comparisons with the WPT

This section reviews CSG water production estimates produced by previous studies and by the CSG industry, and discusses these in the context of the WPT outputs. The intent of the discussion is to examine and explain the broad similarities and differences among the various estimates.

7.5.1 Water production estimates produced by CSG companies

CSG companies are required to include estimates of future water production in their EISs and related project documents (e.g. CSG water management plans). To date, the CSG industry has not published a combined whole-of-industry forecast of CSG water production. However, a summation of estimates for individual companies and projects can provide a basis for comparison against the WPT outputs. At March 2012, the most recently available estimates that could be summed in this way were produced between March 2010 and April 2011[6]. These are presented in Figure 7-11. It should be noted that these estimates do not necessarily cover the full extent of expected development for all companies, and that CSG companies are revising their estimates constantly, and that future estimates are likely to differ to those presented here.

[6] The estimates were sourced from those listed below. While more recent estimates have been submitted, they covered only a subset of the area covered by earlier estimates. Arrow Energy (May 2010), Australia Pacific LNG (March 2010), Santos Ltd (April 2011), Santos Ltd (November 2010), Santos Ltd (November 2010), Queensland Gas Corporation (September 2010)—see References for full publication titles.

The combined industry estimates suggest that water production will reach 120 GL/year by about 2016, and remain near that level until about 2026, when there is a peak approaching 140 GL/year followed by a steady decline. Cumulative production amounts to about 2,500 GL by 2040.

Water production estimates from the industry generally do not extend past 2040, or suggest negligible volumes after this time. This is likely to reflect the nominal project lifespans of 25–30 years specified in the associated EIS documents. If the projects extend beyond this time frame, then gas and water production could be expected to remain at higher levels.

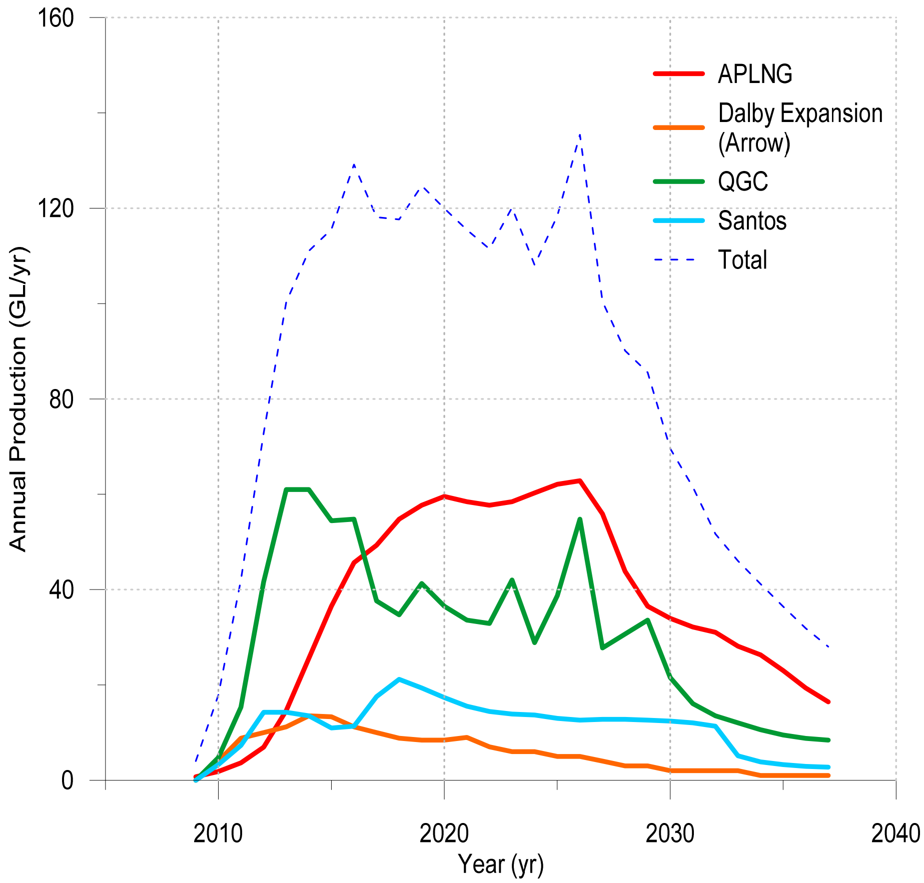


Figure 7-11. Estimated water production as reported in EISs and related documents

7.5.2 University of Southern Queensland/RPS Aquaterra (2011)

In late 2010, the four major CSG companies operating in Queensland engaged RPS Aquaterra to independently assess the cumulative impacts of CSG operations on groundwater drawdown in the Surat Basin, based on published impact-assessment reports and other information provided by the companies for the purpose of the study. The University of Southern Queensland was commissioned to manage the study.

This study did not undertake any new modelling of groundwater flows and impacts, but rather summed the impacts that had been modelled independently by each of the four companies. At least two of the assessments done by the CSG companies did not account for interactions with water extraction activities associated with other companies' operations.

Figure 7-12 shows the annual water production volumes associated with the 'low impact case' assessed by Aquaterra. Peak production is about 200 GL/year, lasting from 2020 to 2025.

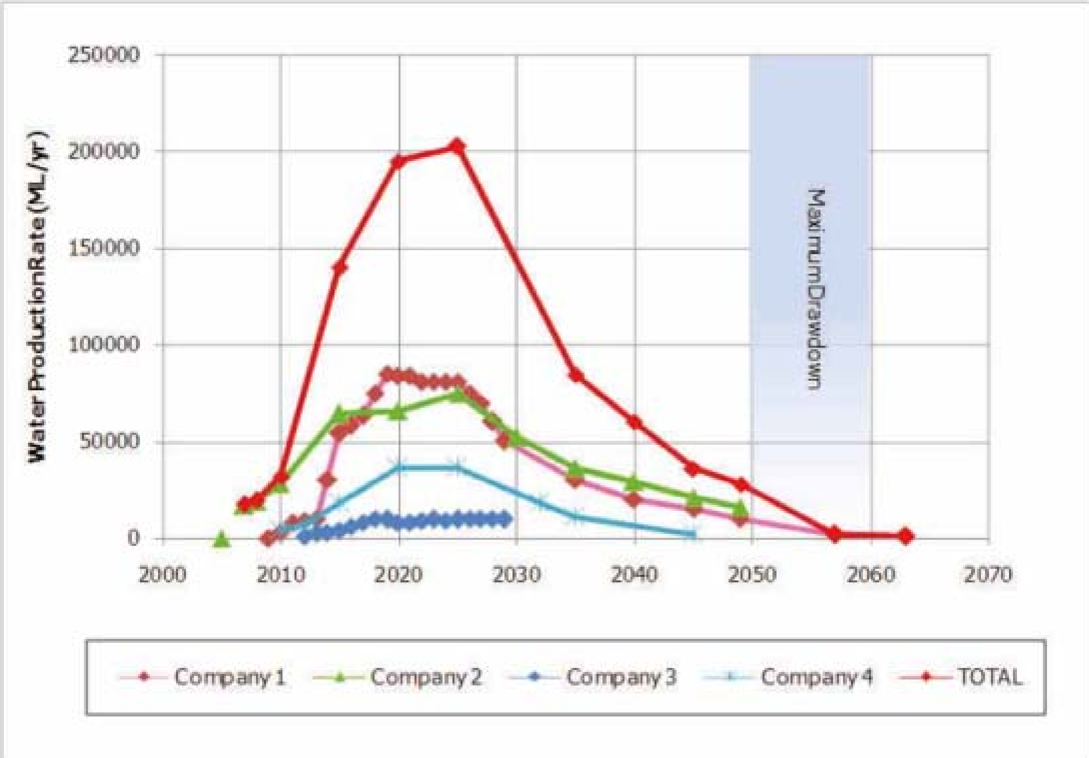


Figure 7-12. Water production estimates based on 'low impact case' industry projections (University of Southern Queensland, 2011)

Cumulative production is about 4,100 GL by 2040 and 4,500 GL by 2060.

7.5.3 Centre for Water in the Minerals Industry (2008)

In late 2008, the Centre for Water in the Minerals Industry (CWiMI) produced a scoping study on the groundwater impacts of CSG development for the Queensland Department of Infrastructure and Planning (CWiMI 2008). The study used a simple conceptual water- and gas-accounting model to produce broad estimates of CSG water production under three potential 20-year liquid natural gas industry development scenarios with production targets of 10, 28 and 40 megatonnes per annum (Mtpa), in addition to concomitant growth in the existing domestic market.

These estimates were produced by making simplifying assumptions about gas and water production per well (on the basis of available well data from coal measures in the Surat and Bowen basins), and about where and when new wells and tenements would be developed in order to meet gas production targets over a 20-year time horizon.

The overall volumes of CSG water estimated are shown below in Figure 7-13. In 2020, the estimated volumes are 126, 196 and 281 GL/year respectively for the proposed 10, 28 and 40.8 Mtpa gas production scenarios.

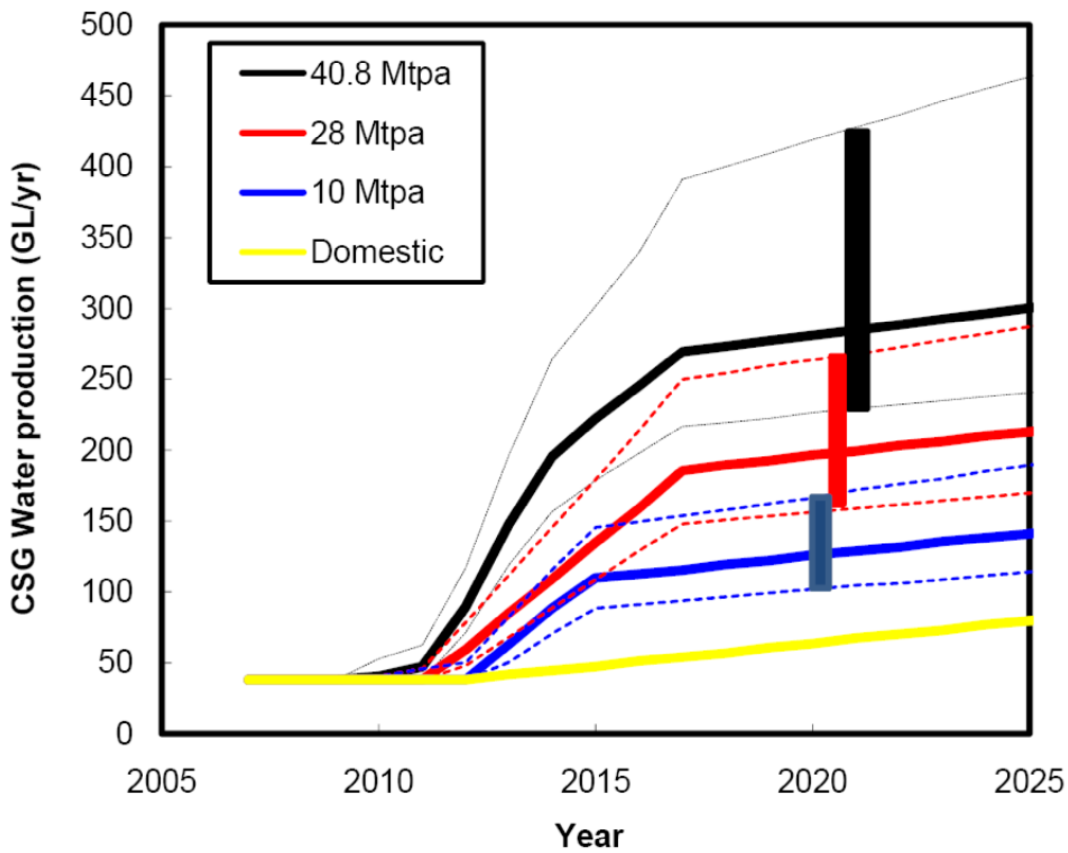


Figure 7-13. CWiMI model estimates of CSG water production. Dotted black, red and blue lines show sensitivity of water production based on +/-25% uncertainty in average gas production rates per well. Vertical bars indicate the range in sensitivity of water production estimates for 2020. (CWiMI 2008)

Cumulative water production for the 28 Mtpa scenario is just over 2,400 GL in 2025.

The level of uncertainty in these estimates is high due to the data limitations and the many simplifying assumptions that underlie the model. In particular, no data was available on individual well production rates and their spatial variability. A further limitation of the CWiMI estimates is that they extend only until 2025, which may be earlier than when peak gas and water production will occur.

7.5.4 Comparing previous water production estimates with WPT estimates

A comparison of the peak and cumulative water production estimated by previous authors and the WPT is provided in Figure 7-14 and Figure 7-15, and with numerical values in Table 7-4.

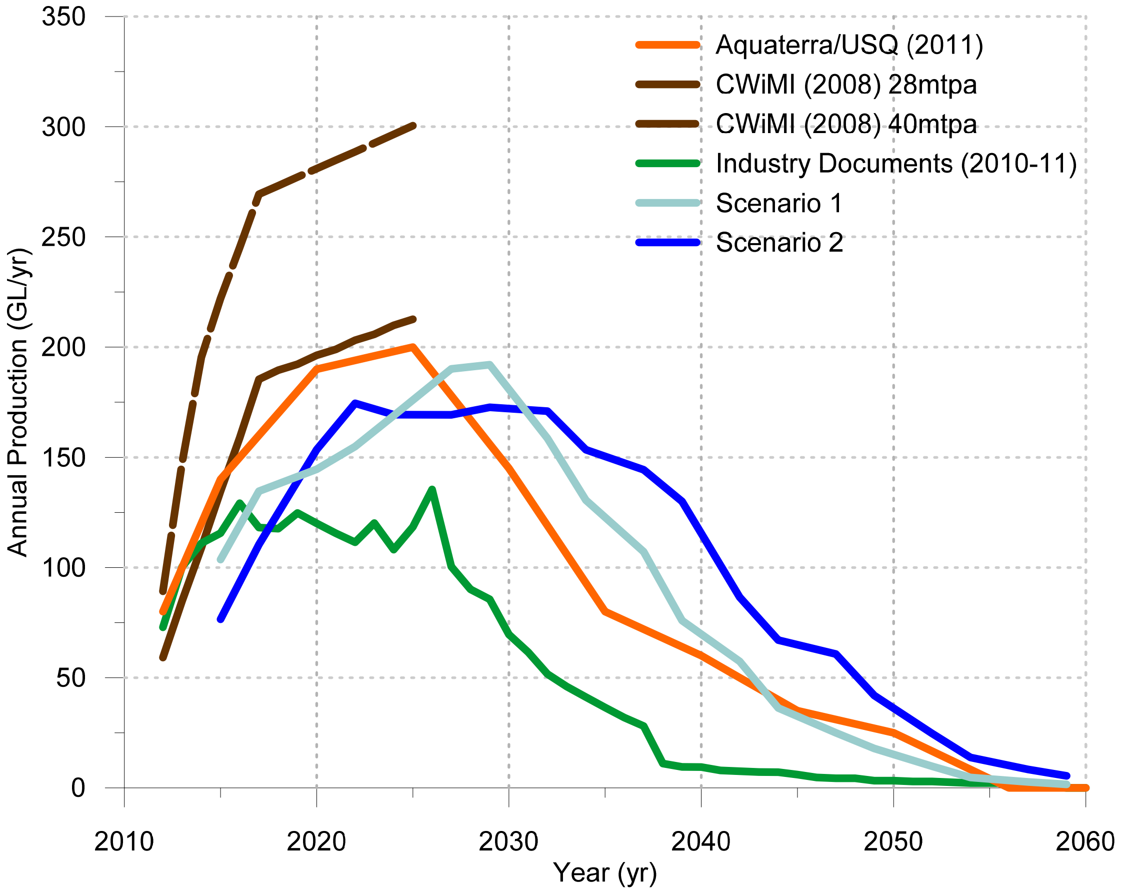


Figure 7-14. Comparison of projected CSG water production estimates

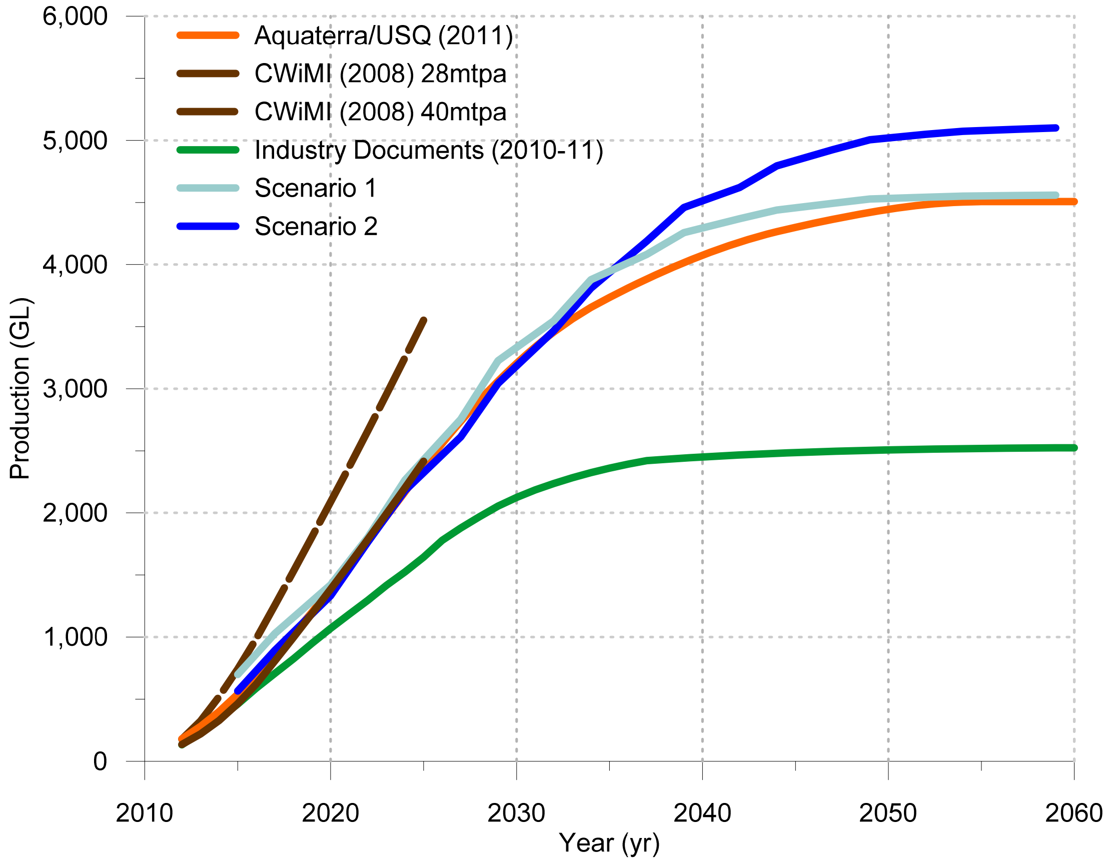


Figure 7-15. Comparison of projected cumulative CSG water production estimates

Table 7-4. Summary values for WPT and other water production estimates

Assessment/source	**Peak production (GL/year)** [Mtpa: megatonnes per annum]	**Cumulative production (GL)**
CSG industry	140 (between 2018 and 2024)	2,500 (~Year 2040)
CWiMi (2008)	213 (28 Mtpa gas production) 300 (40 Mtpa gas production)	2,400 (Year 2025) (28 Mtpa gas production)
Aquaterra/USQ (2011)[7]	200	4,100 (~Year 2040) 4,400 (~Year 2060)
WPT Scenario 1	180 (brief peak of 280 in raw output)	4,300 (~Year 2040) 4,500 (~Year 2060)
WPT Scenario 2	175	4,500 (~Year 2040) 5,100 (~Year 2060)
WPT Scenario 3	150 (varying 100–200 in raw output)	3,900 (~Year 2040) 5,100 (~Year 2060)

[7] Aquaterra undertook the analysis as part of the assessment that was managed by the University of Southern Queensland (2011).

Peak water production rates range from around 140 GL/year for the combined industry estimates to 300 GL/year for CWiMI's 40 Mtpa scenario, while cumulative production in 2050 ranges from 2,500 GL (industry estimates) to 5,100 GL (WPT Scenarios 2 and 3).

Until about 2035, all of the estimates except CWiMI's 40 Mtpa scenario and the combined industry estimates are in fairly close agreement (though it should be noted that CWiMI's 28 Mtpa scenario only lasts to 2025). After 2035, Scenario 2 predicts a higher level of water production, while the Scenario 1 and Aquaterra estimates remain similar. The differences among the water various production estimates are to be expected, as the estimates have been derived using different methods, with access to different types and amounts of data, and with different assumptions about how the industry will develop.

The CSG company estimates are likely to have been produced with consistent quality data about coal seam properties, water production profiles and expected development patterns, because this data is typically generated and held by the companies themselves. However, the methods used to generate these estimates have not been published. In addition, the time frame modelled by the companies is generally shorter than that considered by the WPT. More fundamentally, the industry estimates presented here are likely to be incomplete, because documentation was not available at the time of writing for all expected gas developments projects—most notably those proposed by Arrow Energy. It is therefore difficult to assess the reliability of these estimates, or to make a meaningful comparison with the WPT results.

The similarity between the Aquaterra estimates and the WPT Scenario 1 results is notable. These are, in principle, the most directly comparable estimates available, given that they both represent whole-of-industry production and both are based on the industry's own development schedule. However, as before, making a direct comparison between these estimates is problematic, because many of the assumptions and methods underpinning the Aquaterra estimates are not known.

Until the WPT, the CWiMI results were the only CSG water production estimates available for which the underlying methodology was transparent and in the public domain. The CWiMI estimates were produced with many simplifying assumptions and with very limited data. They were only ever intended as a rough 'first cut' at assessing the potential scale of water production from the CSG industry. However, it is of note that water production estimated under the 28 Mtpa scenario up to 2025 is similar to the WTP scenarios and to Aquaterra's estimates.

Differing assumptions about the size and rate of industry development are likely to account for much of the variation observed between the different estimates, especially in the later part of the time frame considered. The increasing divergence among the estimates in later years is therefore to be expected, as more assumptions have to be made about industry development and hydraulic properties of coal seams where little or no exploration has yet occurred.

8. IMPROVING THE TOOL

8.1 Incorporating new data

The WPT has been designed to be readily updated and modified to incorporate new data and information about CSG water production and how the CSG industry expands. Four areas where improved knowledge will greatly assist in the accuracy of water production estimates are:

- Regional geology

  Improved knowledge of regional geology, and development of basin-scale mapping and datasets will develop with the evolution of the CSG industry. Maintaining regular period 'gates' when wholesale updates to the tool's primary database can occur is strongly recommended.

- Dual-phase effects and consequential reduction in pumping demand

  Due to the general uncertainty surrounding this variable, until further information on the nature of these interactions is available for the study area, it is expected that more detailed assessment and representation will be needed. Further understanding of the effect of gas flow on water production should evolve with industry maturity. Important to this is its spatial representation, and quantifying the difference in dual-phase effects from deep basinal sediments to basin margin strata (if any).

- Industry expansion

  Significant uncertainty remains about the long-term evolution of the industry in terms of areas developed, well density, operational intensity and time scheduling. This knowledge will improve WPT set-up and simulations.

- Water quality

  The tool is currently populated with a small subset of water qualities derived from the Queensland Government's Groundwater Database. Site-specific monitoring programs are underway, and populating the tool with a more representative set of water qualities across the domain and improved understanding of the depths and distributions of contributing zones would provide a far more accurate estimate of salinity and salt loads.

8.2 Re-verifying and re-calibrating the WPT

Regular re-verification is critical to the success of this tool. Verification of the tool every two years is recommended to take advantage of updated water production data and to provide time for new base data to be integrated.

Once there is enough confidence in its ability to estimate produced water in response to industry factors, and if sufficient data is available, a more formal calibration could be considered.

REFERENCES

Arrow Energy, May 2010, *CSG water management plan – South*.

Australia Pacific LNG, March 2010, *Australia Pacific LNG project environmental impact statement*, vol. 2, 12.

Centre for Water in the Minerals Industry, 2008, *Scoping study: groundwater impacts of coal seam gas development – assessment and monitoring*, report prepared by S Vink, N Kunz, D Barrett & C Moran, for LNG Projects, Infrastructure and Economic Development Group, Department of Infrastructure and Planning, <http://espace.library.uq.edu.au/view/UQ:186762>.

Department of Employment, Economic Development and Innovation, 2010, *Bowen and Surat Basins regional structural framework study*, The State of Queensland.

Domenico, PA & Schwartz, W, 1998, *Physical and chemical hydrogeology*, 2nd edn, Wiley and Sons Inc, New York.

Department of Employment, Economic Development and Innovation, Queensland, 2011, <http://www.dme.qld.gov.au/mines/production_and_reserves_statistics.cfm>

Driscoll, FG, 1986, *Groundwater and wells*, 2nd edn, Johnson Filtration Systems, Inc., St. Paul, Minnesota.

Freeze, RA & Cherry, JA, 1979, *Groundwater*, Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Fetter, CW, 1999, *Contaminant hydrogeology*, Prentice Hall, Upper Saddle River, New Jersey.

Queensland Gas Corporation, September 2010, *CSG water management plan*.

Evans & Peck, December 2010, *Major projects in the Surat Basin assessment model report*, report prepared for Queensland Government (Department of Employment, Economic Development and Innovation). Unpublished report.

Exon, N. F. (1976), *Geology of the Surat Basin, Queensland. Bureau of Mineral Resources, Geology and Geophysics, Bulletin 166.*

Santos Ltd, April 2011, *Upstream – Arcadia Valley CSG water management plan, Rev 0*.

Santos Ltd, November 2010, *Roma shallow gas project area coal seam gas water management plan, Rev 0*.

Santos Ltd, November 2010, *Fairview project area coal seam gas water management plan, Rev 0*.

University of Southern Queensland, 2011, *Preliminary assessment of drawdown impacts in the Surat Basin associated with the coal seam gas industry: Investigation of parameters and features for a regional model of Surat Basin coal seam gas developments*, <http://eprints.usq.edu.au/19462/>

APPENDIX I DETAILED DATA DISCUSSION

Data sources, assumptions, interpolation and applicable ranges used in the WPT

Table AI-1 describes the data used to populate the WPT, including data type, data source, assumptions and range of values. Further information about the assumptions and interpolation methods applied to data describing well start dates, well density, transmissivity and storativity is presented after the table.

Table AI-1. Summary of datasets, assumptions and interpolation methods

	Dataset	Resolution available	Interp/ assumed	Method of interpolation/ assumption	Resolution applied	Data source	Data range
1	Topography (ground surface elevation)	Cell level	no	Centrepoint (value at centre of cell used to represent whole cell)	cell level	Map of Queensland (Queensland Government)	80–900 (m)
2	WCM Structure Contours	cell level	no	Centrepoint	cell level	Bowen and Surat Basins regional structural framework study (DEEDI, 2010)	0–1500 (m)
3	Baralaba Coal Measures Structure Contours	Cell level	no	Centrepoint	cell level	Bowen and Surat Basins regional structural framework study (DEEDI, 2010)	500–1500 (m)
4	Piezometric condition	Regional/patches of data	yes	Kriging	cell level	Great Artesian Basin Groundwater Map	230–350 (m)
5	WCM Isopach	Cell level	no	Centrepoint	cell level	Bowen and Surat Basins regional structural framework study	1–50 (m)
6	CSG start date	multiple cell	yes	inferred from geological factors, company supplied data, distance to nearest infrastructure	cell level	Company supplied, Assumed	1/01/2010–1/1/2050
7	CSG well density	multiple cell	yes	visual inference	cell level	Company supplied, Assumed	0–200
8	Aquifer Transmissivity	Inconsistent; good detail in certain areas; regional averages only through much of the WPT area	yes	If data was available, the data was used, if not, interpolated	cell level	Transmissivity is product of conductivity and aquifer thickness . Conductivity obtained through various sources: EISs, some companies supplied data, some conductivity values available in publically available data.	1–38 (m^2/d)
9	Aquifer Storativity	Inconsistent; limited site specific data available	yes	representative value	uniform (re-sampled stochastically)	Primarily from EISs, some reported values were not used as they were considered outliers.	0.000025 +/- 0.000001
10	Gas mobilisation water pressure	industry standard	no	N/A	uniform	Company supplied	50psi/35m head
11	CSG Well density factor	Multiple to single cells	Assumed/ back – calculated	Sequential calculation of varying well density	Uniform in cell	N/A	1–200 wells per cell
12	WCM groundwater quality	Inconsistent; limited site-specific data, mostly obtained from GWDB	yes	Kriging	cell level	Publically available data from the Groundwater Database.	800–40000 (TDS in mg/L)

Well start date data for Scenario 1

The well start date data was supplied in different formats from each of the companies, with most data comprising broad, non-specific ranges of information.

Assumptions were required in allocating the position and timing of well field start dates. Where specific coordinates or locality was unknown (or not on the same scale as the WPT), the following logic chain was used to populate well start dates:

- If well start date is known for a cell, use the date for that cell.
- If maps of the well field at different dates are available for any particular cell, assign a start date which is representative of the majority of the wells in the proximity of the cell.
- If a well field map is not available, choose a start date which is representative of the majority of wells starting based on company-supplied anticipated water production curves, where these are available (these production curves were available for several of the larger tenements, but in several cases only included the production for the tenement as a whole).
- If the preceding methods did not provide an unambiguous well start date for a particular cell, then the following sub-process was used:
    - In each area, the number of wells and projected water production rates were used to define the likely wells required and the associated timing of the wells. Where this was not provided, the number of wells was estimated based on the projected water production rates and well spacing provided by the company for each area. This process provided relatively good chronological interpretation, but with no/poor spatial representation.
    - The spatial component was approximated based on other data available for each cell (e.g. maps or general production curves or localities of proposed well fields). Where such data was not available, approximations were used to populate the start dates in each cell.
    - If spatial definition could not be gleaned by a previously mentioned process, the assumption was that shallower coal seams are targeted first, moving toward the deeper seams.
    - In most cases, deriving the start dates as described above results in a relatively gradual increase of wells over time. If in a given cell a range of dates was applicable, the date corresponding to the majority of wells coming online was used as a start date for the cell.

Well density

The density of wells per cell, or the number of wells populating a cell, was supplied as well spacing data per tenement or as estimated well spacing by each region, from which the well density was derived from proposed production curves.

Calculating the number of wells in a tenement was accomplished in the same manner as the timing data was found using the average well production. The total number of wells in a cell is the maximum population of wells in the field (which may not all be activated on the same date in reality).

Transmissivity

Transmissivity distribution was the most inconsistent of any dataset. Several separate sources for transmissivity data were compiled and interpolation by kriging (a statistical technique) was performed in order to distribute the data across the WPT domain.

Transmissivity is the product of hydraulic conductivity and aquifer thickness. Conductivity data was made available by some companies on a tenement scale. This data was supplemented by publicly available sources such as company EIS documents and QDEX (Queensland Digital Exploration Reports system). The data was put into GIS and kriging was used to interpolate the hydraulic conductivity distribution across the WPT domain. Isopachs for the coal seam(s) were then used to calculate the transmissivity distribution.

Storativity

Storativity data is very limited. No specific data was received from companies and there was very little data available from EISs or through publically accessible sources.

The EIS data was limited to averages over a tenement or individual points, heavily biasing any methods to interpolate these spatially. Data was instead compiled and the median value was adopted as the value for the entire domain.

It is acknowledged that data scarcity is a drawback—in light of this, a stochastic modifier to the storativity was included in the model in order to provide some semblance of variability. The storativity value used is $2.5x10^{-5}$ and is varied normally with a standard deviation of $1.0x10^{-6}$.

APPENDIX II DERIVATION OF THE WELL DENSITY FACTOR

At the most detailed level of the model, each cell (10 kilometres by 10 kilometres) is populated with a specific number of wells. This population of wells is assumed to be distributed equally across the cell. The population of wells (well density) is subject to the same pumping effects (interference) as that applied across the rest of the WPT. This interference can be quantified, and the value of this interference is called the well density factor.

In order to quantify the well density factor, a simulation was set up to assess how additional wells in a system would impact the system. The simulation was similar to a single cell block in the full-scale model. The simulation contained 100 cells, in a 10km x10km grid, with each cell 1 kilometre x 1 kilometre in dimension. The simulation was, in effect, a cell block of higher resolution.

In this high resolution sub-model, all of the data layers were adjusted to be consistent across the simulation domain—the thickness of the aquifer, the required drawdown, the depth of the aquifer, the water pressure—and all other parameters (except well density) were kept constant across the simulation domain. This simulation then formed the template for tests of varying well density from one well to 100 wells. For each simulation, the production value and the number of wells were recorded. The production for each simulation was normalised to find the relative production of each well in an increasingly dense formation. The result is seen in Figure AII-1.

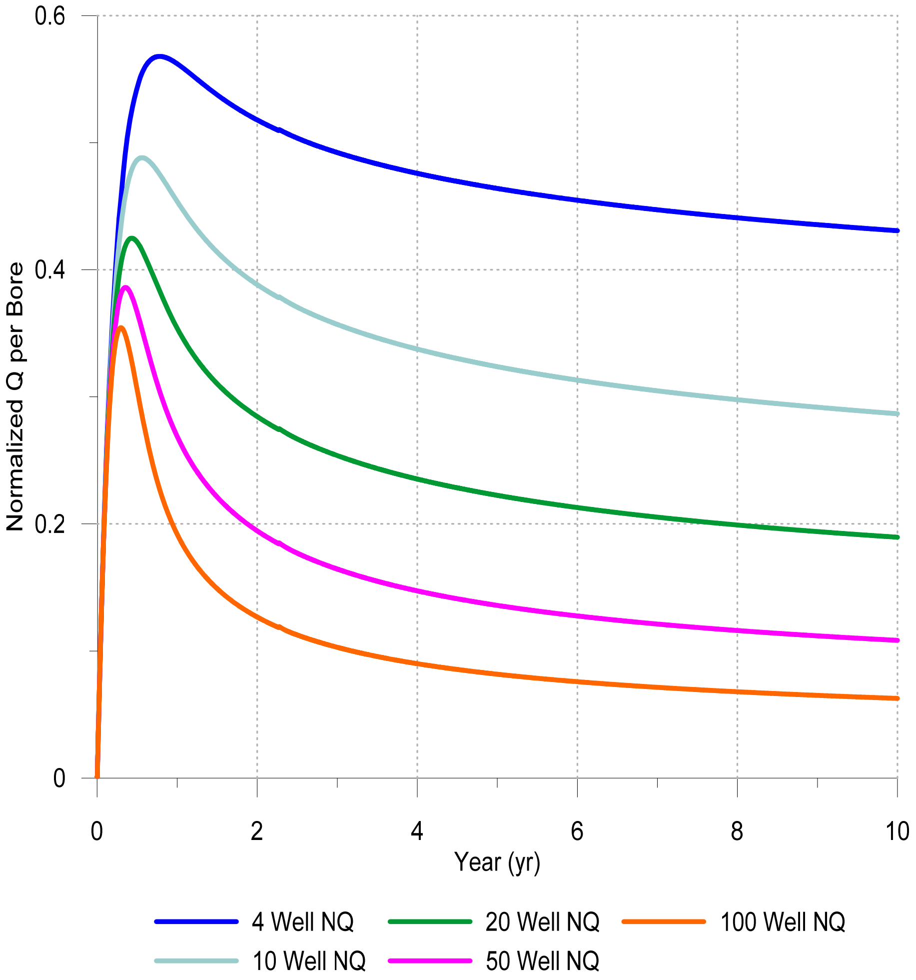


Figure AII-1. Normalised water production per well for varying well density

These results were then compared with the production expectation for a single well under the same conditions. The result is the percentage production per well that would be expected by adding more wells to a finite area. The result is intuitive—the more wells placed in a finite area, the less production per well would be expected—as seen in Figure AII-2.

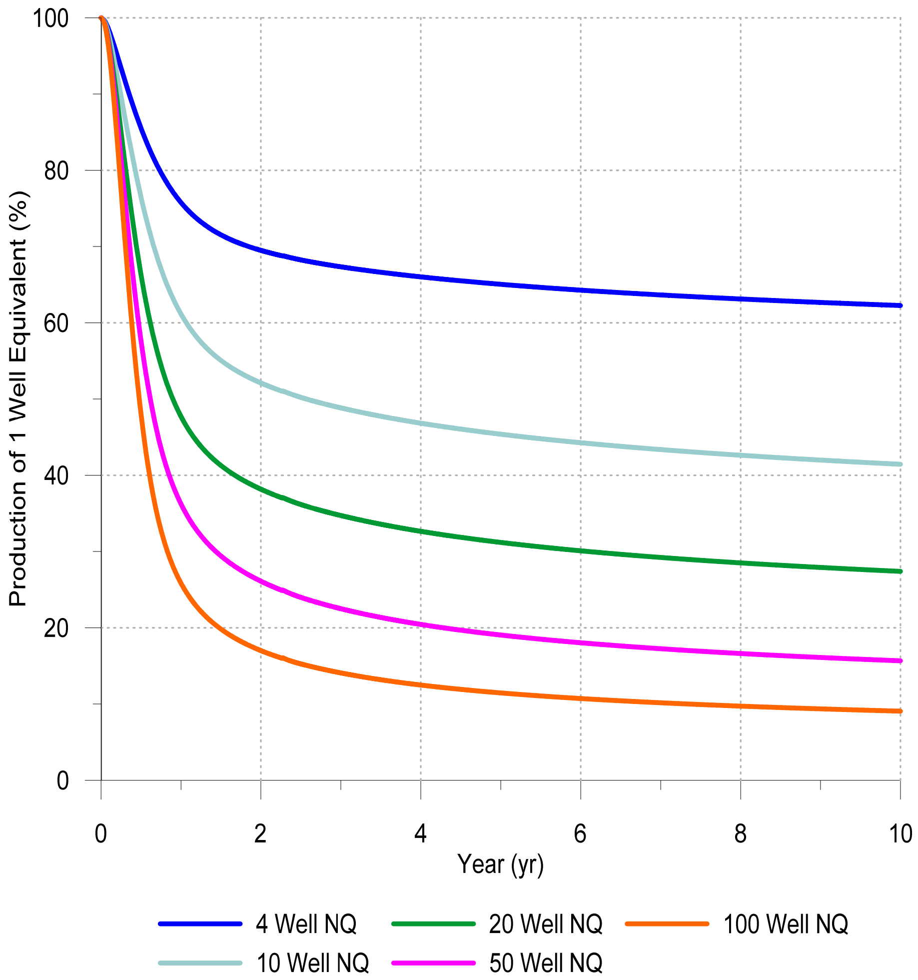


Figure AII-2. Interference effects resulting from varying well density (water production per well expressed as percentage of expected production from a single operating well)

Following from Figure AII-2, the near steady-state value of each production value is used as the relative production expected after interference effects are taken into account at the cell level, and at a time period roughly estimated to be close to a steady-state condition. The well density factor applied is therefore representative of the equivalent single well production expected after interference effects are taken into account, per number of wells in the cell, as seen in Figure AII-3.

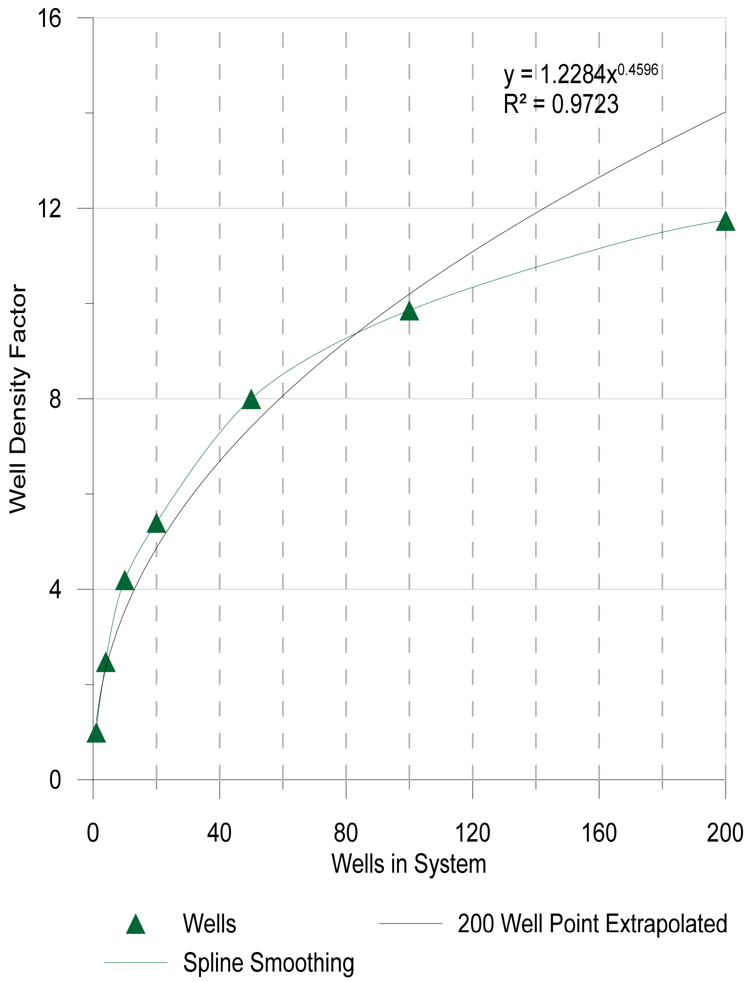


Figure AII-3. Well density factor (the 200 well point extrapolated)

APPENDIX III DETAILS OF NEEF VERIFICATION ASSESSMENT

Verification results assessment

The verifaction process is described in Section 5 of the main report. Further details of the statistical analysis are included here.

Statistical analysis of NEEF

ANOVA (ANalysis Of VAriance) is a set of statistical tests used to compare population datasets, and particularly, the means of these datasets. Other descriptive statistics such as skewness and standard deviation were also included to develop an understanding of the distribution of the residuals (the difference between the modelled production and the historical production rates). With the updated NEEF included, the distribution of residuals improves, as summarised in Table AIII-1. However, the subsequent iteration with variability with depth has mixed results.

Table AIII-1. Sample population comparisons using ANOVA and descriptive statistics

Statistical Function	With NEEF (Variable)	With NEEF (15%)	Without NEEF
Residuals mean	-6.1	19 (optimally 0)	132 (optimally 0)
Standard deviation	539	517	678
Range	3,210	2,907	3,718
Skewness	1.59	1.10	1.45
Sample variance	291,169	266,948	459,273

The figures below present the frequency of residuals in 100 ML/yr increments (blue diamonds), and the normal distribution for a population of samples with the same mean and standard deviation (red line). The blue diamonds are not required to correlate with the red line exactly, and given the relatively small sample size, any cluster of points around a mean of zero is indicative of some level of success.

The residuals for the verification process without NEEF are skewed slightly positive, as displayed in Figure AIII-1. The mean is shifted to the right, and there are four points in the far positive range indicating eight samples which appear to be near or above the 95th percentile.

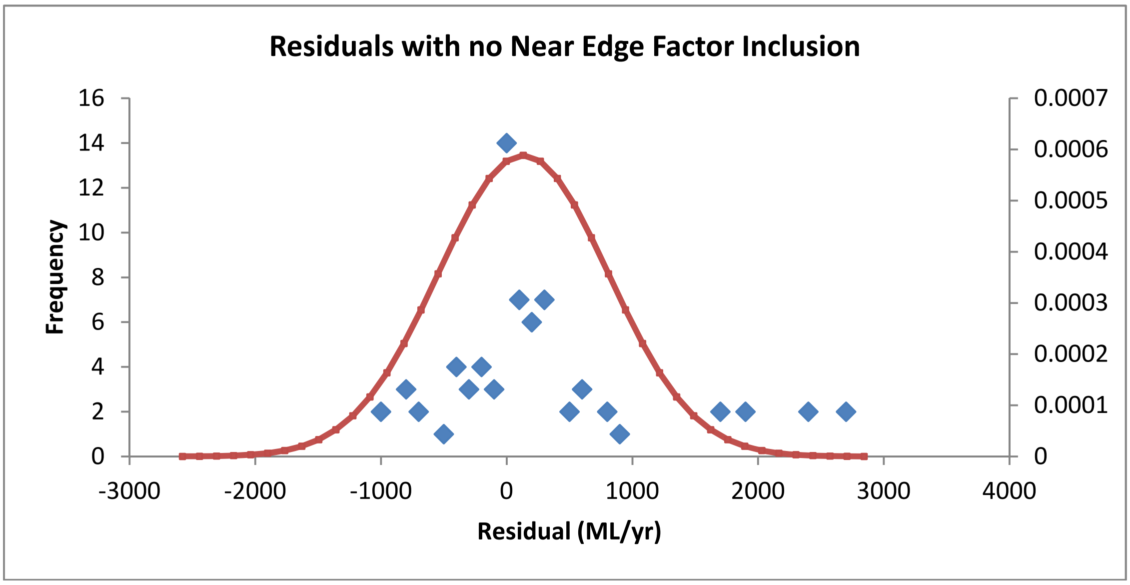


Figure AIII-1. No NEEF (mean = 132, SD = 678)

The residuals for the verification process including the NEEF are skewed only very slightly positively, and there is only one point to the far right, indicating two samples at this higher percentile. Overall, the skewness and the mean of the residuals with the NEEF fit a normal distribution significantly better than without NEEF.

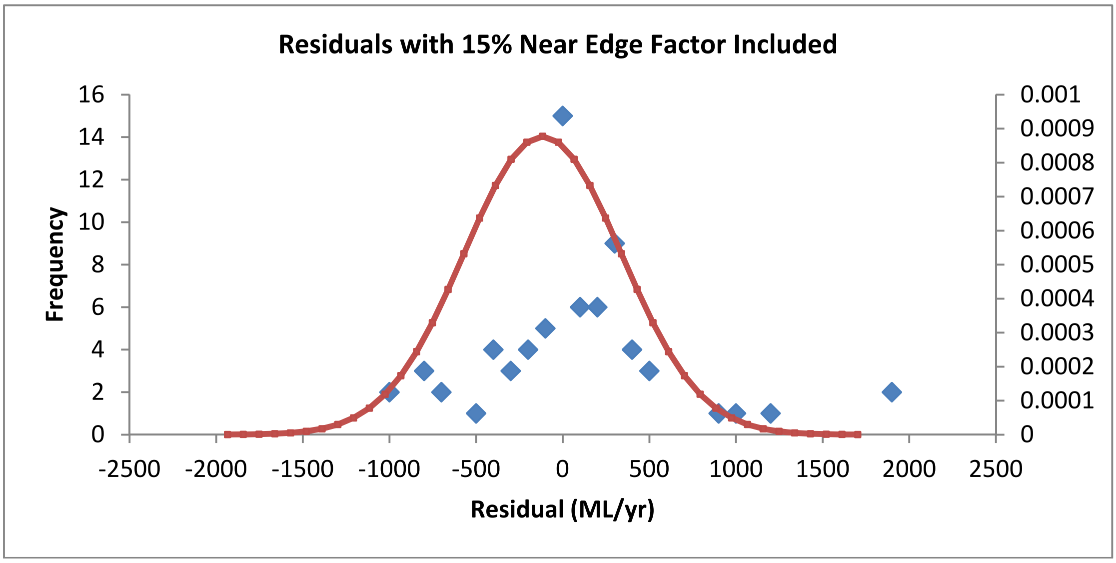


Figure AIII-2. Proportional 15% NEEF included (mean = 19, SD = 517)

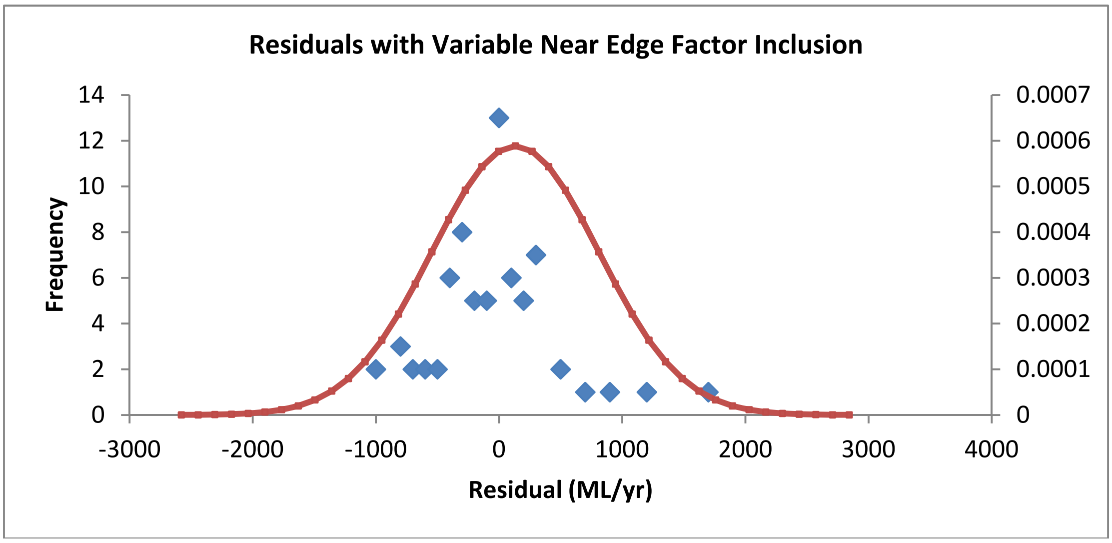


Figure AIII-3. Variable NEEF included (mean = -6.1 SD = 539)

Chi-squared test

To assess whether visual assessment was reasonable, the chi-squared goodness of fit test is used. To do this, test parameters should be described:

H_0 = Null hypothesis: the data follow a normal distribution.

H_a = Alternate hypothesis: the data do not follow a normal distribution.

Test statistic: For a chi-square goodness of fit test, the data are divided into k bins and the test statistic is defined as:

$$\chi^2 = \sum_{i=1}^{k} (O_i - E_i)^2 / E_i$$

Where:

O_i is the observed frequency in bin i.

E_i is the expected frequency in bin i.

E_i is calculated from the cumulative normal distribution multiplied by the sample size, N (72), $E_i = N(F(Yu) – F(Yi))$.

The null hypothesis is accepted if the chi-squared score is less than the critical value. The critical value for 40 degrees of freedom and 99.5 per cent confidence is 20.707. The chi-square value for this distribution is 11.24. The chi-square score is less than the critical value (11.24<20.707), meaning, with 99.5 per cent confidence we have accepted the null hypothesis. While the distribution of the residuals is approaching normal, the mean of the residuals is approximately -115 megalitres per year per tenement, which implies that the WPT is currently slightly overpredicting water production.

APPENDIX IV HISTORICALLY REPORTED CSG WATER PRODUCTION VOLUMES

Table AIV-1. Historic water production

Operator	Tenure No.	30/06/2005	31/12/2005	30/06/2006	31/12/2006	30/06/2007	31/12/2007	30/06/2008	31/12/2008	30/06/2009	31/12/2009	30/06/2010
		Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)	Water (ML)
	101	11.5	10.5	14.8	13.6	11.1	8.9	10.3	7.3	7.0	6.3	5.8
	195	470.6	523.3	514.1	541.8	499.7	524.1	497.7	450.4	495.8	523.6	549.9
	204	38.4	58.7	45.9	176.8	327.6	624.4	588.6	527.5	506.6	422.5	402.0
Origin	226	12.2	240.9	173.4	103.8	372.6	295.6	280.2	245.8	241.3	475.9	1,148.3
	90	130.5	94.3	69.5	49.2	71.7	60.3	66.6	86.5	93.2	24.0	24.0
	91	543.7	454.0	416.4	450.6	480.9	607.8	426.1	341.8	465.2	329.9	329.9
	92	294.7	188.5	221.3	219.3	234.1	263.5	194.5	242.9	600.1	528.0	528.0
	99	20.8	23.5	12.6	67.7	131.2	156.0	141.9	154.9	519.7	465.8	465.8
	100	0.0		0.0	0.0	0.4	1.2	22.6	38.0	113.1	134.9	138.1
	232							1.8	1.6	1.7	1.4	1.4
	234							35.9				
Santos Ltd	176		0.0	0.0		0.0				6.0	0.0	0.0
	230	0.0	17.6	33.3	111.9	241.5	496.5	525.5	444.1	334.0	676.4	489.4
	194	29.4	620.4	911.7	589.9	545.3	557.3	585.2	442.3	442.6	457.1	423.0
	198	58.9	119.6	130.1	543.0	854.5	861.1	1,088.6	1,407.9	1,385.9	1,439.8	975.5
Arrow Energy	252										128.8	0.0
	179	0.0	0.0	0.0	0.0	0.0	139.0	103.4	158.6	292.7	417.7	446.5
	229	0.0	0.0	0.0	0.0	0.0	0.0	0.0	125.8	210.0	188.1	149.3
	201	96.6	146.8	933.5	988.4	962.5	992.5	793.5	604.0	954.4	821.7	803.1
QGC	228	0.0	0.0	0.0	0.0	402.8	1,198.7	702.5	678.0	789.6	688.1	611.1

Historical production data was obtained from the DEEDI website, http://www.dme.qld.gov.au/mines/production_and_reserves_statistics.cfm.
The data is limited to the time period 30 June 2005 to 30 June 2010.

APPENDIX V RAW SIMULATED WATER PRODUCTION FOR THREE SCENARIOS

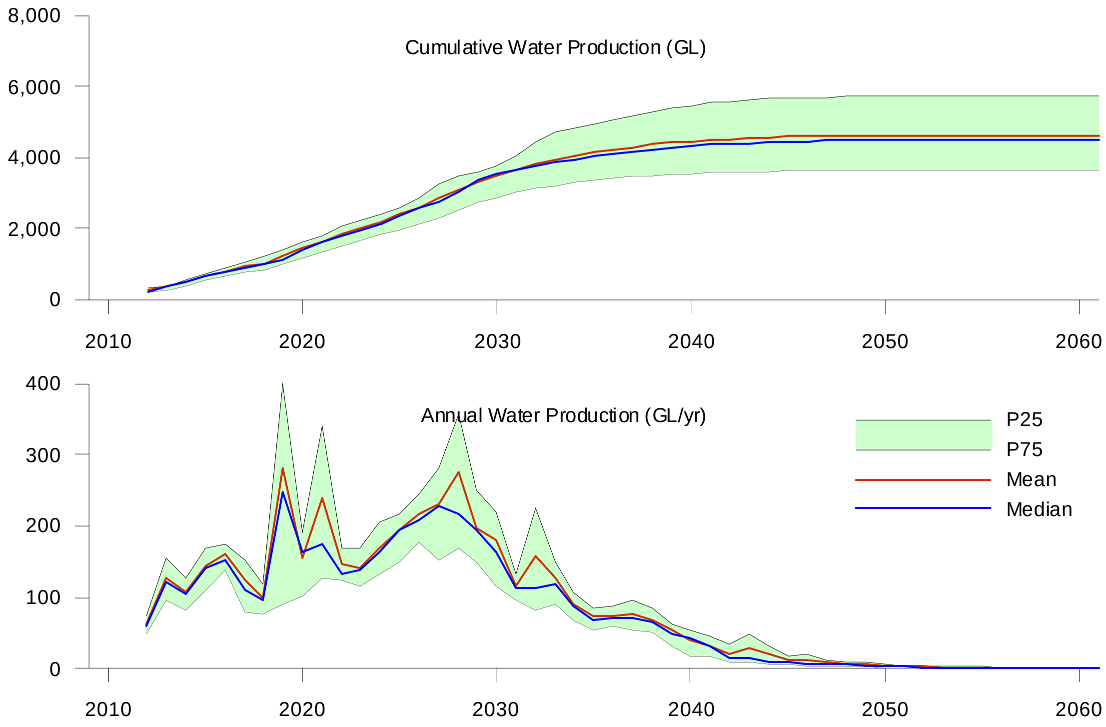


Figure AV-1. Scenario 1. Annual and cumulative water production

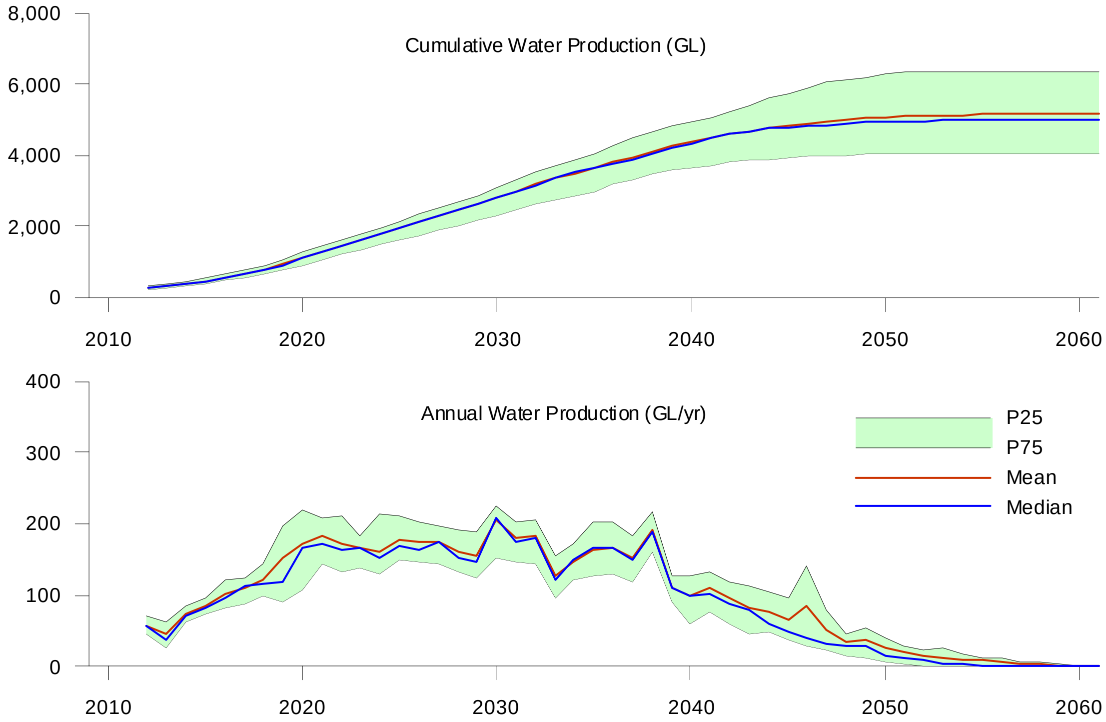


Figure AV-2. Scenario 2. Annual and cumulative water production

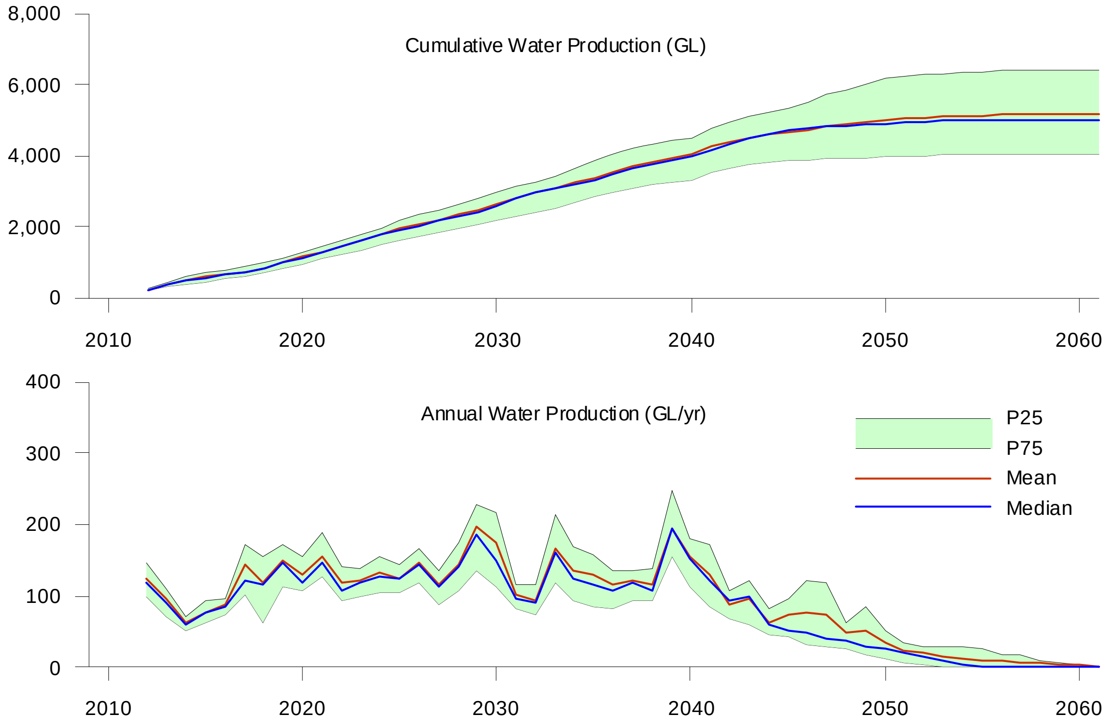


Figure AV-3. Scenario 3. Annual and cumulative water production

APPENDIX VI SPATIAL DISTRIBUTION OF P25, P50, P75 ESTIMATED WATER VOLUMES FOR SCENARIO 2

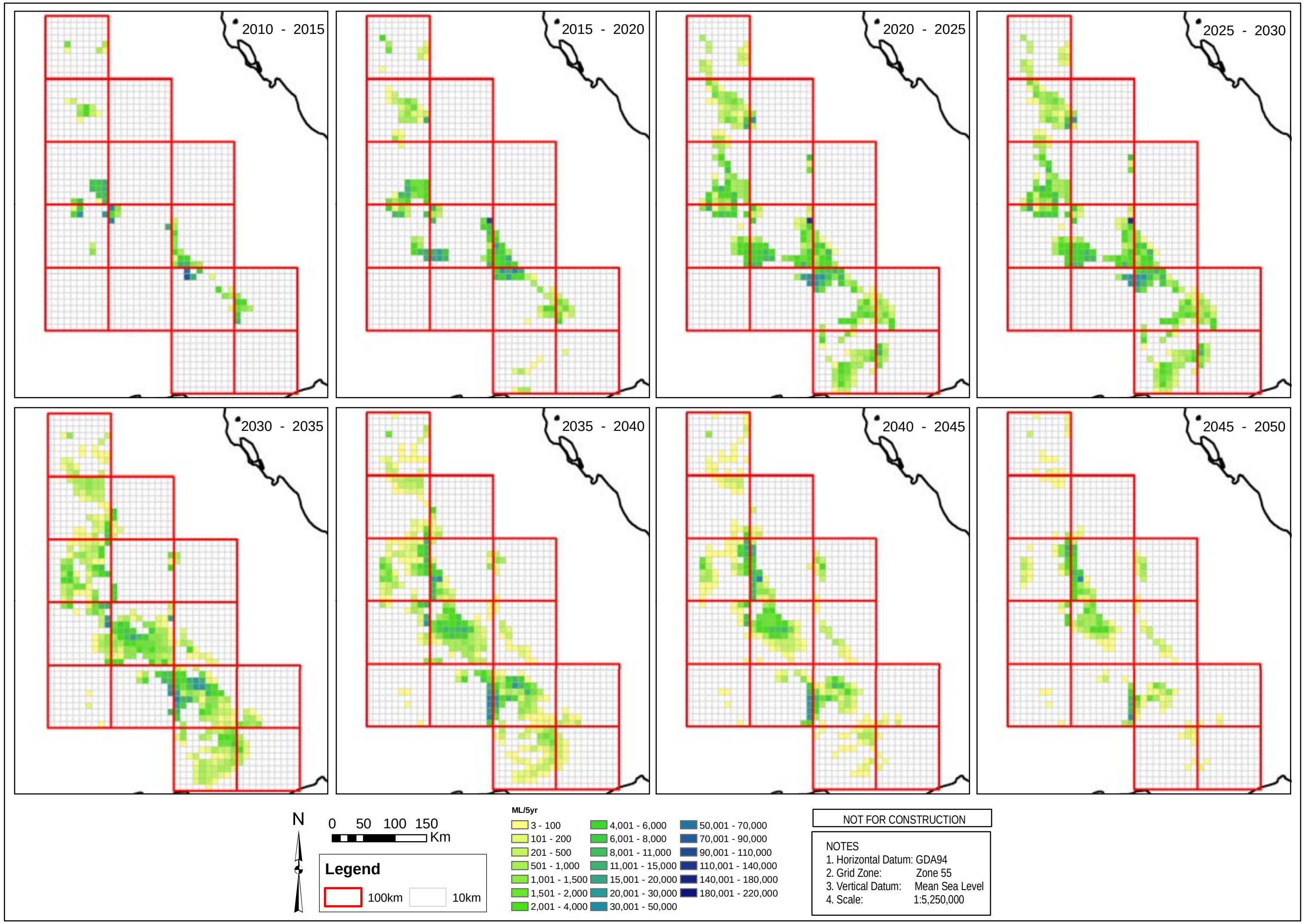


Figure AVI-1. Time sequence of CSG water production for Scenario 2 (P25 values)

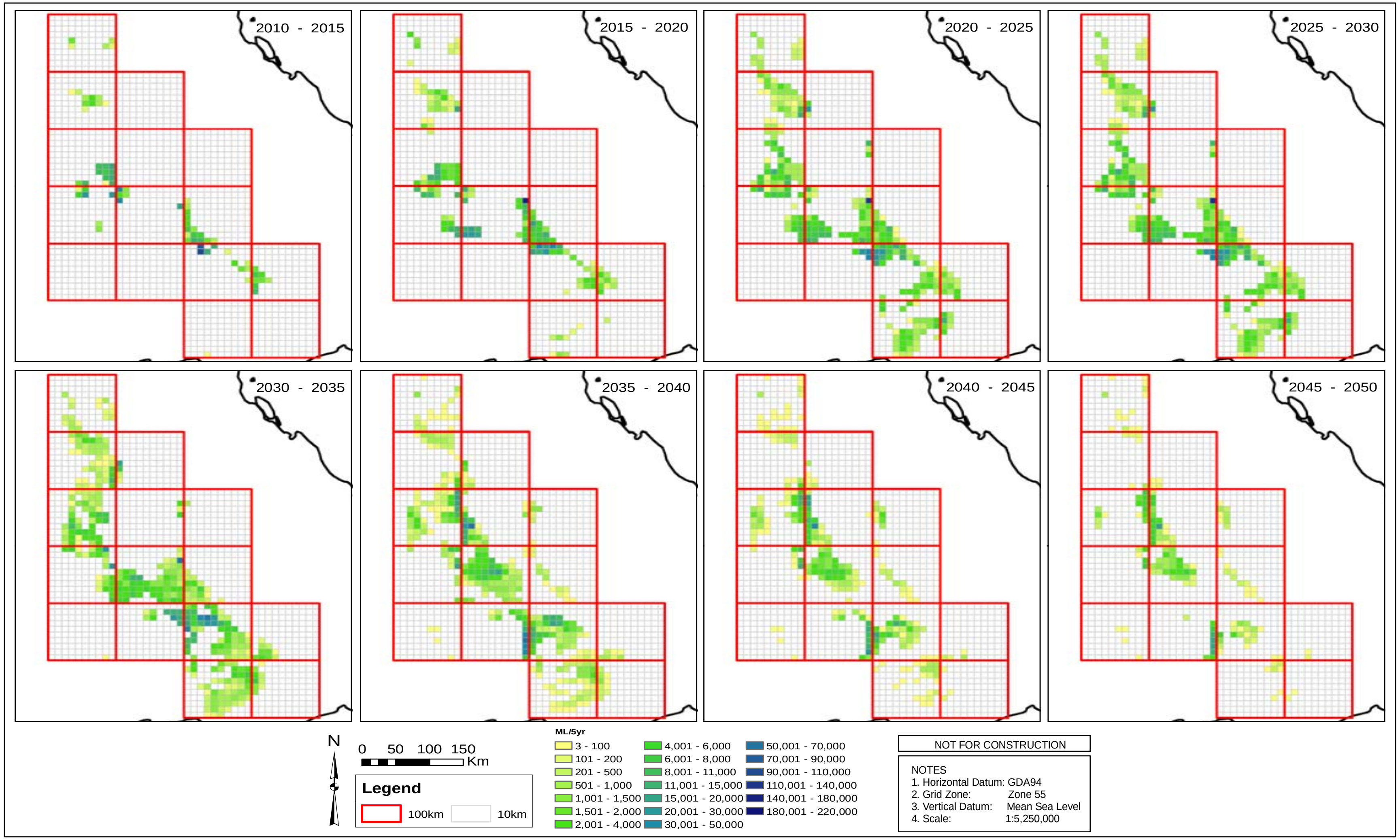


Figure AVI-2. Time sequence of CSG water production for Scenario 2 (P50 values)

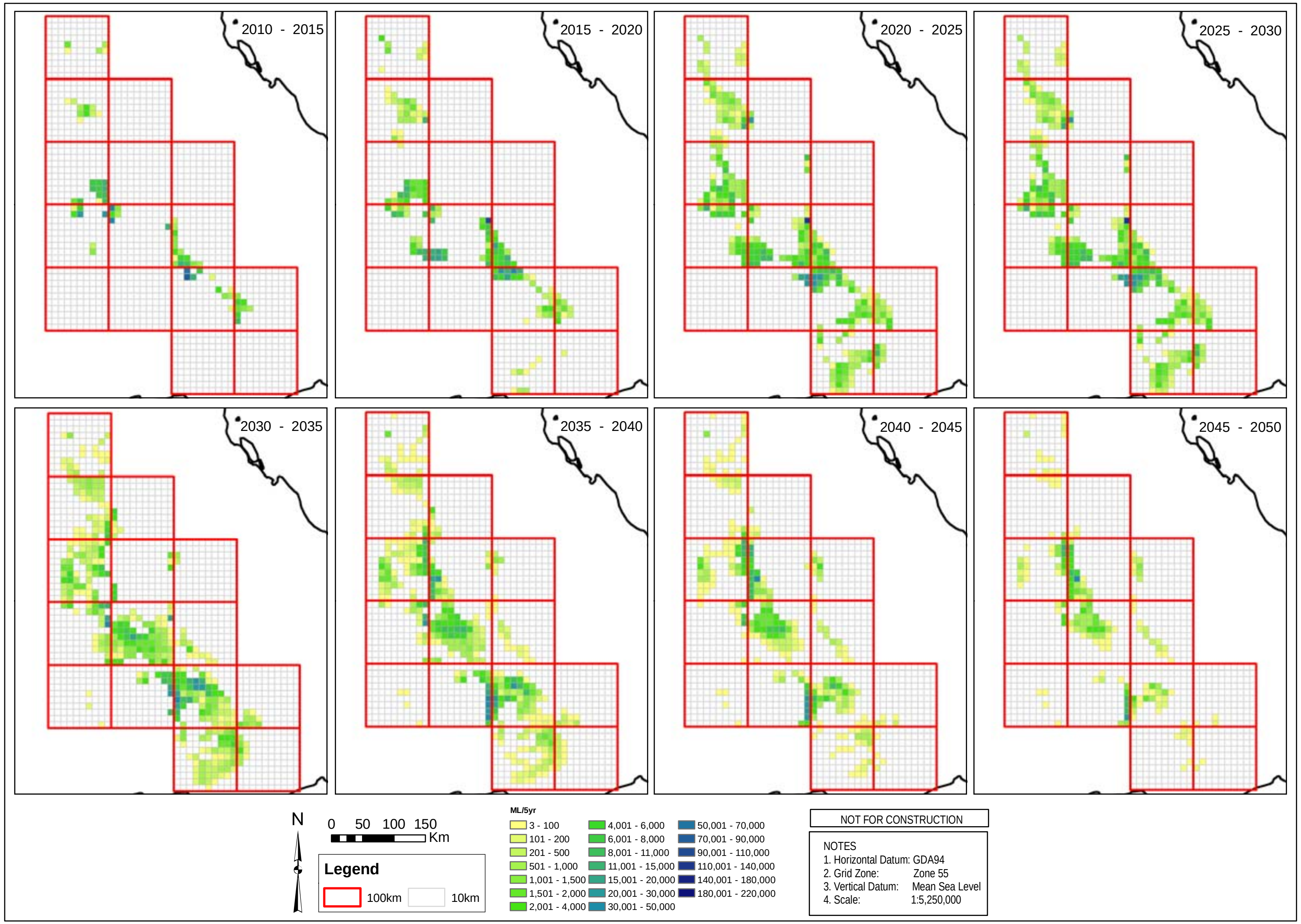


Figure AVI-3. Time sequence of CSG water production for Scenario 2 (P75 values)