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6.0

Numerical groundwater flow modelling – GEN3

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#	Department Condition		Description	Completion date	Status
	Pre-Dec 2012	Post-Dec 2012			
6	**49b**		Completion and reporting on GEN3 model build	April 2013	🟢
9	**49b**	**53B a**	Submission of consolidated Surat Basin Hydrogeological Model and recalibration of GEN3 model. Commitment to ongoing model recalibration and reporting with annual report. Reporting of connectivity studies.	October 2014	🔴
50	**49i**		Submission of Annual Report including (from October 2013) reporting results of ongoing GEN3 model recalibration	October 2013 and annually thereafter	△

🟢	Commitments completed	△	Evergreen Commitments
○	Commitments work in progress	🔴	Firm deliverables for that month

6.1 INTRODUCTION

Design, implementation and initial testing of the new GEN3 numerical groundwater flow model is underway. The key objective is to accurately explain the underlying dual-phase flow process in CSG systems. The GEN3 model has been built, initial testing is complete and calibration has begun. The model will simulate various scenarios to test the hypotheses contained in the Stage 3 WMMP and other Surat Basin studies.

This chapter summarises the design, implementation and initial testing of the GEN3 model. It explains the underlying process of dual-phase flow in CSG systems, which is central to the model objectives. Appendix H contains a full description of the model construction and testing. The GEN3 Surat Basin Regional Groundwater Flow Model is the third numerical groundwater flow model to be generated for the QCLNG project. It integrates a robust and regionally-consistent stratigraphic framework of the major geological units with the latest hydrogeological conceptualisation of the Surat Basin.

The key enhancements compared with previous simulations are the detailed characterisation of the Walloon Subgroup and the dual-phase gas and water modelling capability. This is the first (to our knowledge) regional flow model of this scale built for groundwater impact assessment incorporating dual-phase processes. The model was built in the ECLIPSE 100 environment which, with its dual-phase, dual porosity and single permeability functionality, aims to more accurately quantify the drawdown associated with coal seam depressurisation.

The model build includes two key data streams:

- High quality subsurface data from QGC's ongoing development, hydrogeological and exploration drilling programs; and
- Wide-ranging and varied information from water supply development in the Surat Basin aquifers.

These data streams have been integrated into the conceptual model described in Chapter 5 and which is the basis of the numerical model build.

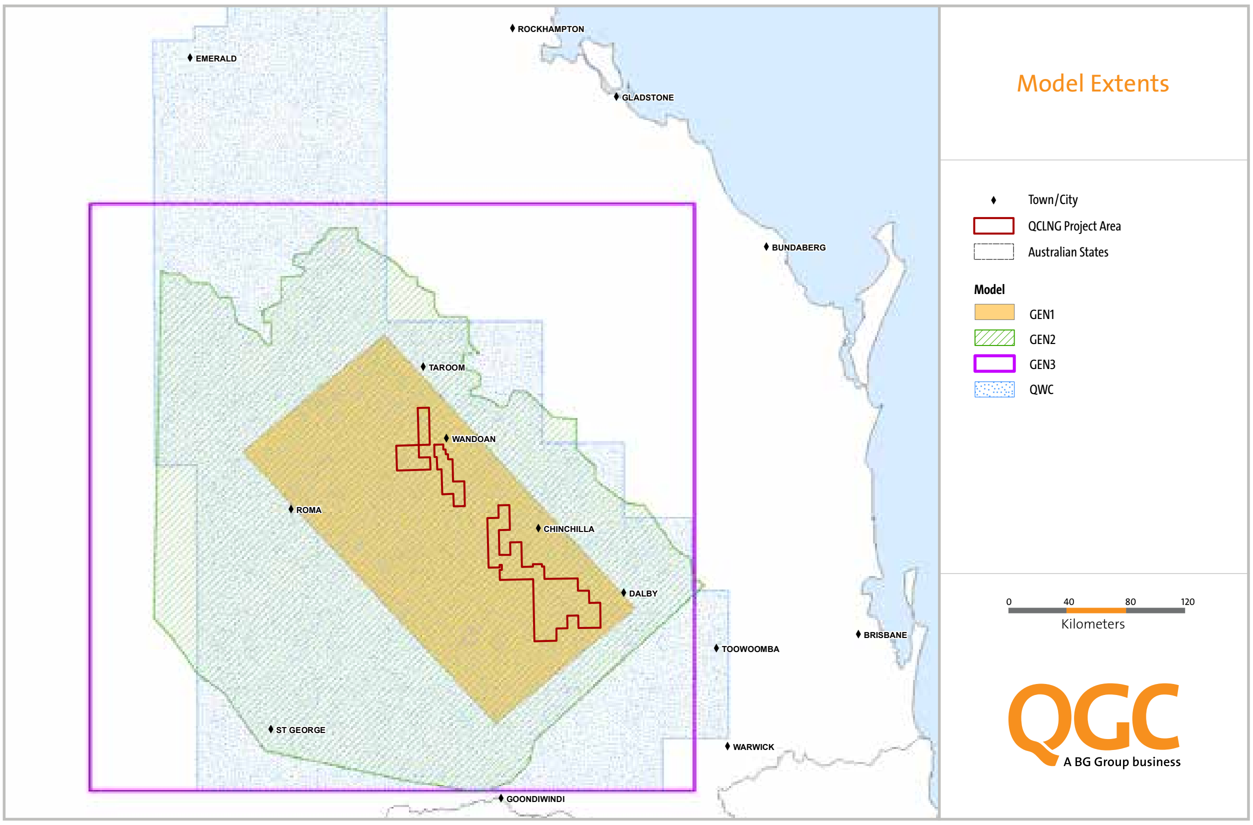

Figure 6-1 – Comparison of model extents of different regional groundwater flow models in the Surat Basin

The GEN3 model presents the following modelling enhancements:

- Capability to progress to a dual-phase simulation environment, post steady-state calibration;
- Implicit dual-porosity modelling of the Walloon Subgroup;
- Capture of the current mapping of coal property variability in the Walloon Subgroup from the QGC field development plan; and
- The areal extent of the GEN3 static model is defined by: the QCLNG project area, the northern limit of the Surat Basin, a majority portion of the Mimosa Syncline, and the distribution of external petroleum wells to constrain the stratigraphy and structure. It covers an area of 197,000 km^2. The comparative lateral extents of the different regional groundwater flow models over the Surat Basin are shown below in Figure 6-1.

The model has been built in accordance with Commitment 6 in the Stage 2 WMMP and is undergoing calibration. Dual-phase flow processes have been benchmarked in an accompanying research exercise with CSIRO. Resultant flow and water balances are consistent with the conceptualisation in Chapter 5.

Moving forward, the calibrated model will be used to run a number of simulations and test hypotheses developed during complementary technical studies, including:

- The change in pressure, drawdown and flow characteristics under single and dual-phase conditions;
- Assessment of vertical hydraulic connectivity;
- Potential impacts on EPBC listed springs;
- Potential impacts on water users and the resulting 'make good' obligations; and
- The need for and the effect of injection on aquifer repressurisation.

The GEN3 model is limited by the data available for its construction. Unlike the OGIA/QWC model which utilised data from all Surat Basin CSG operators, the GEN3 model is currently limited to public listed and QGC data only.

The 2012 Australian Groundwater Modelling Guidelines (Natural Water Commission, 2012) recommend a dual-phase flow approach to CSG-related groundwater flow modelling. Accordingly, QGC is assisting OGIA with data and expertise to implement this testing.

6.2 GEN3 PROJECT OBJECTIVES

To understand the objectives of this project, some of the higher level QCLNG Water Management and Monitoring Plan (WMMP) objectives and requirements for the GEN3 model should be stated. These are:

- Re-evaluate the conceptual hydrogeological model of the Surat Basin;
- Develop a consistent regional groundwater model that is compliant with the 2012 Australian Groundwater Modelling Guidelines;
- Create a model that is capable of:
  - Predicting drawdown to protect EPBC springs;
  - Modelling impacts for existing users;
  - Predicting the effectiveness of response actions; and
  - Monitoring uncertainty reduction.

Within that context, the detailed model objectives are:

- To advance the modelling of CSG depressurisation for the Surat Basin hydrogeological system;
- To account for the impact of dual-phase phenomenon on the drawdown associated with CSG production (as prescribed by the 2012 Australian Groundwater Modelling Guidelines);
- To incorporate the latest subsurface data from QGC's operations;
- To develop procedures that allow the modelling team to:
  - Improve the permeability model of the Walloon Subgroup coals;
  - Integrate a robust regionally consistent stratigraphic framework of the major geological units in the Surat;
  - Account for heterogeneity in the Walloon Coal Measures and Springbok formations and thus improve upscaling for regional models;
  - Refine the assumptions for model boundary conditions to reflect the latest understanding;
  - Qualify and quantify the uncertainty associated with the model and how that translates into a range of outcomes;
- Align QGC's geology and hydrogeological data into one model;
- Create a 3D visual and numerical representation of the Surat hydrogeological system which is of a Class 2 (2012 Australian Groundwater Modelling Guidelines) confidence level; and
- Create a tool to predict potential impacts and changes in water level spatially over time due to predicted QGC CSG production.

6.3 THE PHYSICS OF COAL SEAM GAS PRODUCTION AND DUAL-PHASE FLOW

As dual-phase flow simulation is an important part of the model objectives, it is useful to describe how dual-phase flow occurs in CSG systems and its potential influence on water pressures and flows.

CSG reservoirs are characterised by two distinct coal porosity systems: the primary porosity system and the secondary porosity system. The former is composed of extremely low permeability, isolated micropores with a very large internal surface area onto which gas is adsorbed and must migrate by diffusion. The latter is composed of macropores that are composed of the natural fracture network of cleats and fissures where gas in a free state is found. As fluid pressure in the coal declines, adsorbed gas within the primary porosity system is desorbed and becomes free phase gas that diffuses through the coal to the secondary porosity system where it flows. The mechanism of CSG production can be described by the 3D theory of desorption-diffusion-Darcy flow (Seidle 2011).

Permeability in coal is controlled by the magnitude of net stress in the reservoir. This can vary across the field, in different coal seams, and also change over time with production. Production influences permeability in two distinct and opposing ways:

- A decline in permeability due to cleat compaction; and
- An increase in permeability due to coal matrix shrinkage as gas desorbs.

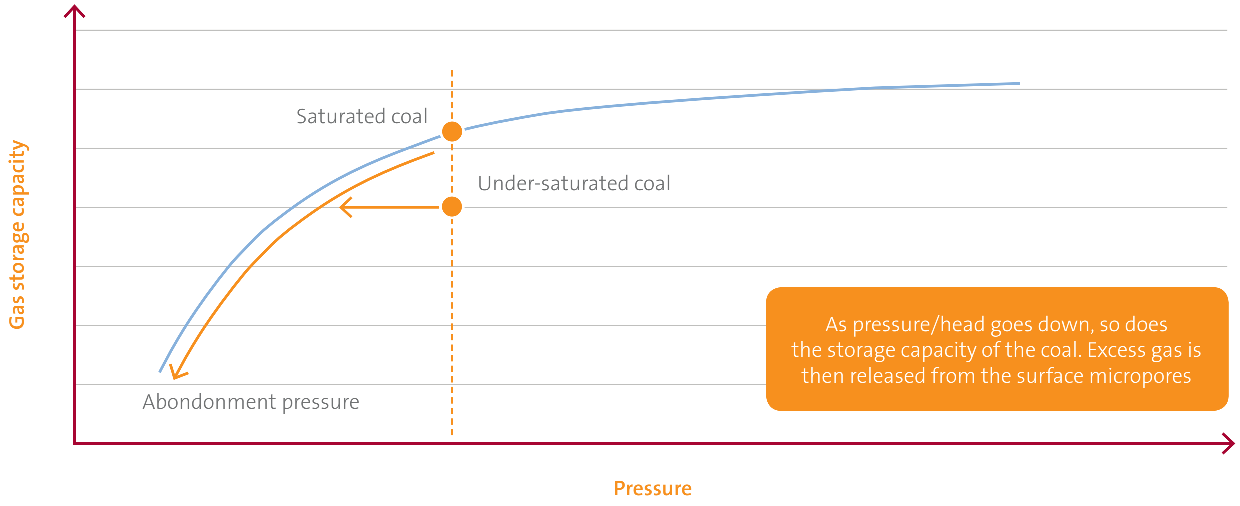

Figure 6-2 – Langmuir sorption isotherm curve

The pressure controlled desorption of gas from the surface micropores of the coal matrix was demonstrated empirically by Langmuir in 1916. CSG simulators apply a Langmuir sorption isotherm curve to correlate the rate of gas release with the depressurisation of the coal. The concept is illustrated in Figure 6-2. As water is extracted from the cleat system, the pressure drops and the system moves down the Langmuir isotherm until gas is liberated from the surface of the surrounding coal matrix. If the coal is saturated, gas will be liberated immediately as pressure is reduced with conditions reflecting the move down the Langmuir curve. Once gas is liberated to freely move within the fracture pore space, it will travel like the water phase towards the localised region of lowest pressure (most likely the nearest pumping bore). The two phases will compete and thus the ease of their passage as quantified by permeability will decrease. At the same time, the total fluid compressibility of the system will change dramatically as it will be dominated by the highly compressible gas. This will delay the reduction in pressure/head.

A simple way of visualising the difference is that, in a single-phase system, a unit of water is removed from the coal, the pressure difference between the coal and the bounding aquifer will need to be high enough to replace that unit of water. In a dual-phase system the removal of a unit of water is partly compensated by the generation of a volume of gas. Therefore, there is less need for the system to replace that unit of water and the pressure differential is lower. To demonstrate the difference between simulating in single and dual-phase, CSIRO (co-funded by QGC) (Moore and Doherty, in prep.) has recently completed a comparison of MODFLOW with ECLIPSE. This study has highlighted the variation in modelled drawdown based on the exact same model and pumping rates in both models. Figure 6-3 compares the difference in drawdown between single-phase MODFLOW and dual-phase ECLIPSE after 20 years of pumping through a fine-scale sector model with identical grid properties.

In the ECLIPSE example, pumping-related drawdown initiates gas desorption which in turn increases the system compressibility, relative to the single-phase example. This explains the difference in drawdown between the two plots. The significance of this is that there is less drawdown propagated into underlying and overlying aquifers when a dual-phase modelling approach is used. Accordingly, predicted impacts are lower.

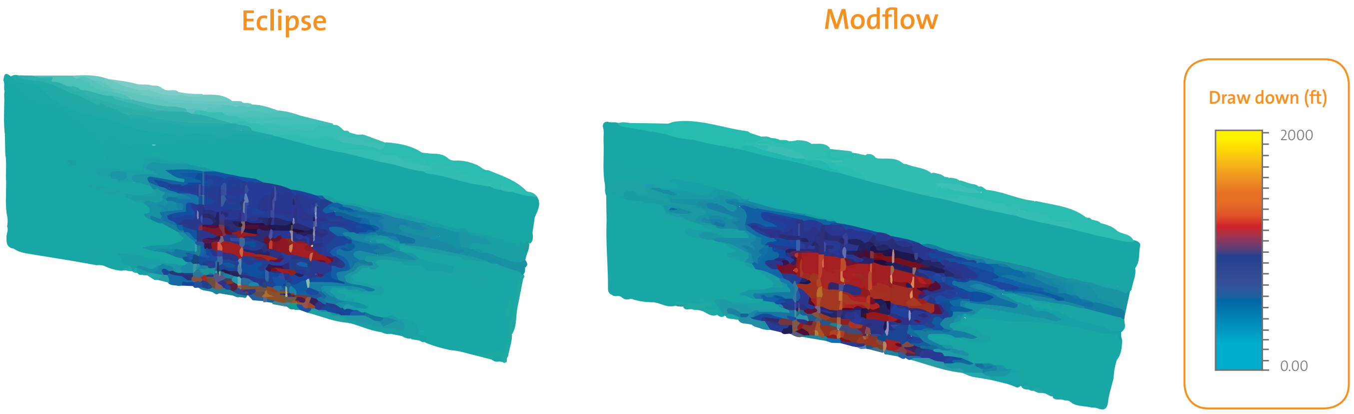

Figure 6-3 – Comparison in vertical cross-section of MODFLOW and ECLIPSE Drawdown in Walloon Subgroup and Springbok Sandstone sector model (modified from Moore and Doherty, in prep.)

6.4 MODELLING APPROACH

The GEN3 modelling approach and associated reporting are significantly different from the previous regional groundwater flow modelling performed within the Surat Basin. These changes in approach have been driven by the selection of software and a mandate to use as much of the available data as possible. With the selection of petroleum industry software the workflows required to use this software have had to mimic industry practices. Equally, the available data for this regional groundwater flow model is significantly different in type and quantity compared with many previous equivalent studies.

As the data has been collected under petroleum industry standards, the team has implemented petroleum industry modelling practices. However, the project objectives and model user community are hydrogeologically focused. Therefore, every effort has been made to be consistent with the 2012 Australian Groundwater Modelling Guidelines and amalgamate hydrogeological modelling best practices with the inherent modelling best practices inherited from the software and data available. As a result, Figure 6-4 shows the overall procedure for the GEN3 model. This model build (Appendix H) covers only the initial third of the modelling workflow illustrated.

In accordance with the Commitment, the model has been built and is undergoing calibration. Dual-phase flow processes have been benchmarked in an accompanying research exercise. Resultant flow and water balances are consistent with the conceptualisation. Considering the regional nature of the model and the resultant coarse scaling adopted, the simulation is deemed a suitable starting point for commencement of computer assisted steady state calibration.

QGC is using a petroleum industry standard software tool called MEPO that allows computer assisted (automated) optimisation for the steady state calibration. This process includes an uncertainty workflow which optimises the calibration target match. The model is being run via full simulation means over a period of time deemed to be long enough to satisfy the performance measures stipulated within the Australian Groundwater Modelling 2012 Guidelines.

The transient calibration includes the following actions:

- Single-phase single porosity calibration between 1912 and 1995 accounting for historical water extraction in the Surat Basin prior to CSG extraction; and
- Dual-phase, dual porosity calibration between 1995 and the end of 2012 accounting for historical water extraction associated with traditional use as well as QGC CSG gas and water extraction from 2005.
- Successful calibration of the model will be confirmed by internal review processes and an independent external reviewer. The calibrated model will then be used to run a number of simulations and test hypotheses developed during complementary technical studies, including:
    - The propagation of drawdown under single and dual-phase conditions;
    - The change in pressure, drawdown and flow characteristics under single and dual-phase conditions;
    - Conclusion on aquifer interaction arising out of the connectivity study;
    - Potential impacts on Matter of National Environmental Significance (MNES);
    - Potential impacts on water users and ‘Make Good’ obligations; and
    - The effect of injection on aquifer repressurisation.

Overall the model will be used as a tool to enhance QGC’s understanding of the groundwater flow system.

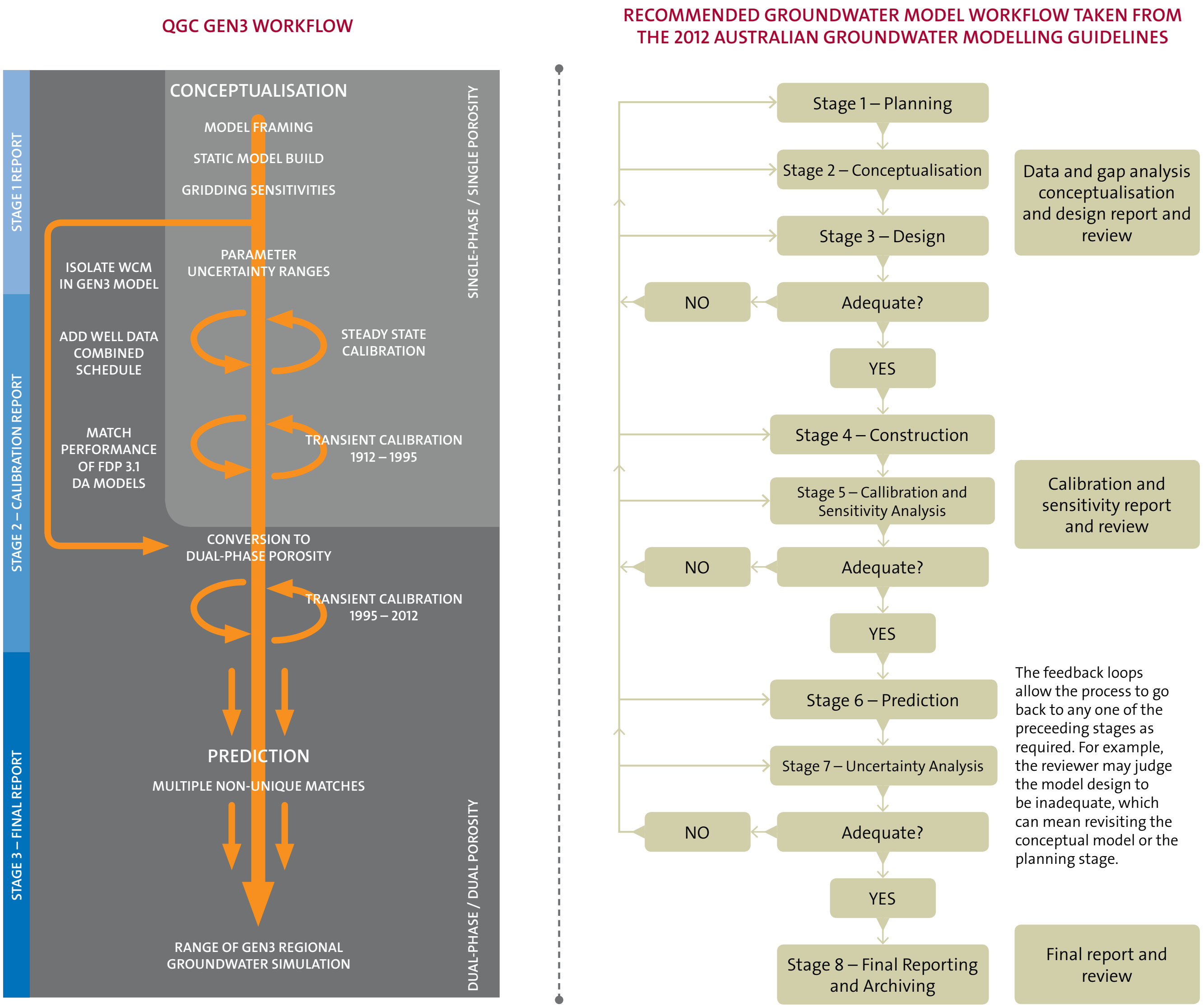

Figure 6-4 – Workflow chart of GEN3 model

6.4.1 MODEL HORIZONS

The first step in model construction was generating a three horizon model equivalent to surface elevation, the base of the Surat Basin sequence, and an arbitrary model base (made at 3,000 m below Australian Height Datum (AHD). This allowed for the succession to be populated with zones between the base of the Surat Basin and surface elevation. The generation of the Base Jurassic surface was the foundation on which the rest of the zones were developed. This was a four-step process designed to generate a surface that best represented the structural surface of the Base Jurassic Unconformity.

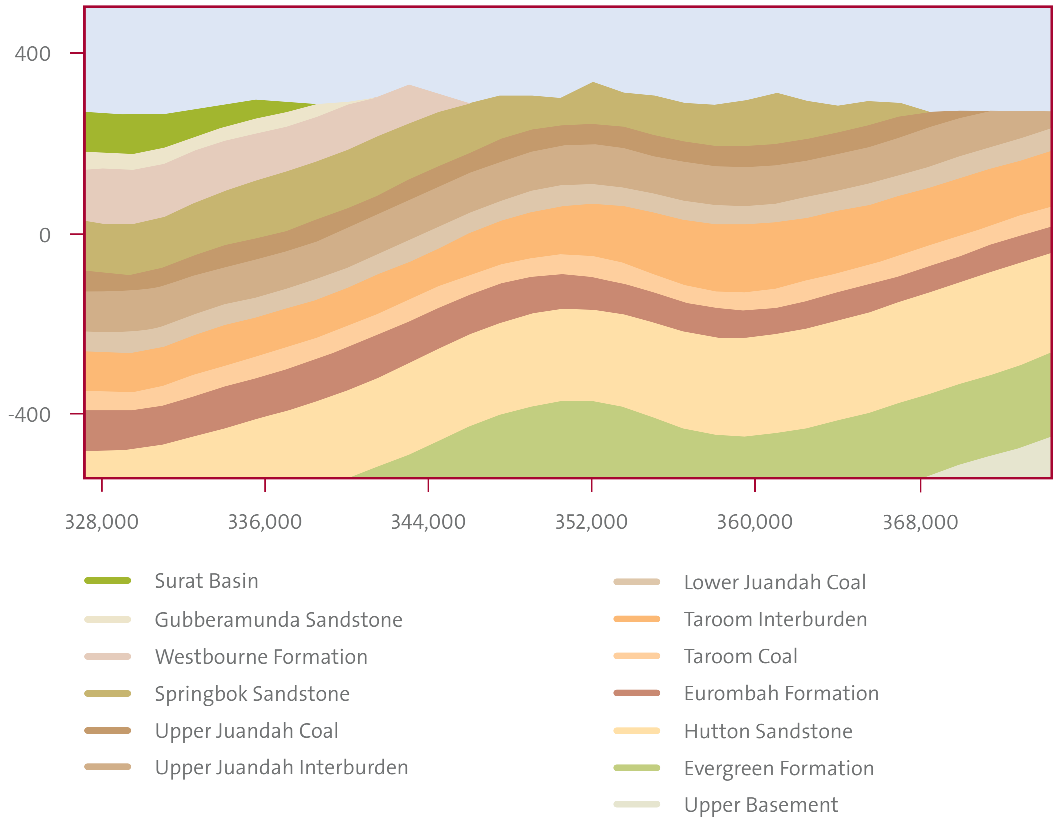

Figure 6-5 – Illustration of the five-layer Walloon model

The steps were:

1. Generate composite Base Jurassic surface from Sedimentary Basins of Eastern Australia (SBEA) mapping grids;
2. Tie Base Jurassic surface to Top Walloon Subgroup (as this was the unit with highest number of well tops);
3. Tie corrected surface back to Base Jurassic well tops (so that structural variability observed from the Walloon Subgroup well tops is retained) and outcrop edge; and
4. Clip Base Jurassic surface to outcrop edge and make 1,000 m high beyond outcrop edge (this ensures that a simple outcrop edge equivalent to base of the Surat Basin sequence is generated during the 'Make Horizons' process).

6.4.2 MODEL ZONATION

Generating the zones throughout the model so that the stratigraphic interpretation, isopach mapping and surface outcrop were honoured required significant trial and error. One of the main zonation aims was to ensure a simple set of outcropping zones occurred along the flank of the basin such that appropriate boundary conditions could be modelled with minimal stratigraphic complexity (cells of younger and older stratigraphic zones overlying the outcrop areas).

The two major inputs zonation was carried out using the PETREL Geomodelling Package:

- Isopach maps; and
- A combined set of well tops and a simplified set of points to represent the outcrop edge.

6.4.3 WALLOON ZONATION

The coal-bearing intervals of the Walloon Subgroup comprise a highly-interbedded sequence of thin, discontinuous coal seams interbedded with low-permeability sediments (Ryan et al, 2012). The coal seams typically comprise 10% of the gross Walloon Subgroup thickness and include up to 45 seams, with 75% of the coal seams less than 30 cm thick (Ryan et al, 2012).

Capturing this level of stratigraphic heterogeneity in a regional model is not possible. After internal discussions about upscaling and facies aggregation, it was decided to sum and average the properties of the coal-bearing intervals into three zones equivalent to the Upper Juandah, Lower Juandah and a combined Tangalooma/Taroom coal seam. The zones and associated interburden units were generated by dividing the gross Walloon Subgroup thickness (excluding the Eurombah Formation) by seven and then assigning the coal measure units as 1/7th the thickness and the interburden units as 2/7th the total thickness. This resulted in a five-layer Walloon model as pictured in Figure 6-5. The three coal seams each represent 1/7th of the Walloon Subgroup and each of the interburden layers represent 2/7th.

6.4.4 LAYERING

The layering philosophy is driven by the modelling project objectives and by the zone of interest (focus on Walloon Subgroup with overlying and underlying aquifers and aquitards). Additional layering where more than one layer exists within a zone was performed on the Eurombah Formation, Springbok Sandstone, Bowen/Basement zone and the Cretaceous Sediments. Table 6-1 demonstrates the layering approach used which is fully aligned with the hydrostratigraphy. The objectives and parameters of additional layering for each zone are:

- Cretaceous Sediments: Divide the thick zone into thinner layers to avoid simulation convergence problems that are common when small cells are next to very large cells (i.e. between these layers and the thinner Gubberamunda Sandstone);
- Springbok Sandstone: There is a higher resolution dataset in the Springbok Sandstone as every CSG well first intersects the Springbok Sandstone. Additional petrophysical resolution is provided throughout this unit given the stratigraphic and lateral heterogeneity of hydraulic properties. A low-permeability Springbok Sandstone unit is identified throughout the Southern Development Area;
- Eurombah Formation: Layered to allow sensitivity studies of layering and vertical connectivity between the coal-bearing units and the Hutton Sandstone; and
- Bowen/Basement: This zone is a generic stratigraphic unit that captures everything below the Precipice Sandstone to a fixed depth of 3,000 m below AHD for ease and for future expandability if required. This zone is not within the zone of interest but, in line with groundwater 'best practice', it was determined there should not be a no-flow boundary at the base of the Precipice Sandstone.

	Previous QGC model – GEN2 (Golder)		GEN3 – Dynamic	Single porosity layering	Additional layers in dual porosity model
	Model layer name	Layer #	1500 m model zone		
				Matrix	Fracture
	Griman/Surat/Coreena/Doncaster	1	Cretaceous sediments	1	22
	Bungil/Mooga Formation	2		2	23
	Oralio Formation	3		3	24
	Gubberamunda Formation	4	Gubberamunda Sandstone	4	25
	Westbourne Formation	5	Westbourne Formation	5	26
Springbok	Springbok Sandstone	6	Springbok Sandstone	6	27
				7	28
				8	29
				9	30
Walloon Subgroup	Confining Layer of Juandah	7	Upper Juandah Coal	10	31
	Juandah Coal Seam(s)	8	Interburden	11	32
	Confining layer of Juandah	9	Lower Juandah Coal	12	33
	Tangalooma	10	Interburden	13	34
	Confining Layer of Taroom	11			
	Coal Seam of Taroom	12			
	Confining Layer of Taroom	13	Taroom and Tangalooma	14	35
	Durabilla Formation	14	Eurombah Formation	15	36
				16	37
	Hutton Sandstone	15	Hutton Sandstone	17	38
	Evergreen Formation	16	Evergreen Formation	18	39
	Precipice Sandstone	17	Precipice Sandstone	19	40
			Bowen	20	41
				21	42

Table 6-1 – Summary and comparison of GEN2 and GEN3 layering

6.4.5 STATIC PROPERTIES

A key component of the GEN3 geological model build is to calculate and populate static hydrogeological properties (porosity, horizontal permeability and vertical permeability) throughout the model based on the best-available datasets.

Where insufficient field data exists to generate estimates for dynamic properties, the inputs for the model build have been conceptualised using the Darcy (saturated) fluid flow equation. That is, they have been assigned based on the hydraulic conductivity of the formation within which they are to be assigned (e.g. recharge has been calculated based on the hydraulic gradient of the aquifer, outcrop and formation thickness). This approach has the following benefits:

- It enables an estimate of model input parameters when limited direct field measurements are available (e.g. recharge and river conductance parameters);
- It reduces model instabilities by ensuring input parameters are consistent with one another (e.g. by not trying to assign large recharge volumes into a tight aquitard sequence);
- Is conceptually consistent with groundwater flow principles; and
- Is consistent with the regional scale nature of the GEN3 model.

This approach differs from that used by QWC (2012) and in the QGC GEN2 model.

6.4.6 BOUNDARY CONDITIONS

Boundary conditions have been assigned within the model to represent regions of inflow, outflow and absence of flow within the groundwater system. Boundary conditions utilised in the model include:

- Recharge via rainfall and rivers;
- Discharge via model boundaries and rivers; and
- No flow along some model boundaries.

Boundary conditions are illustrated in Figure 6-7 and discussed in more detail above.

Constant head boundary

Constant head boundaries were assigned to the southern extent of the model. This is representative of the generally interpreted discharge out of the model to the south. A constant head induces discharge out of the model which is commensurate with the head difference and aquifer properties.

No flow boundary

No flow boundary conditions exist around the remainder of the model boundary not covered by constant head boundaries. No flow boundaries reflect regions where the conceptual interpretation suggests that groundwater movement into and out of the model is anticipated to be limited.

Aquifer recharge

Model recharge input values were limited to rates that the system could feasibly accept. The remainder of water would conceptually be rejected as surface water runoff and or lost to evaporation. The outcome is that estimated recharge values approximate 'net recharge' rates, and net recharge assumes evapotranspiration has already been deducted from the recharge rate prior to being applied.

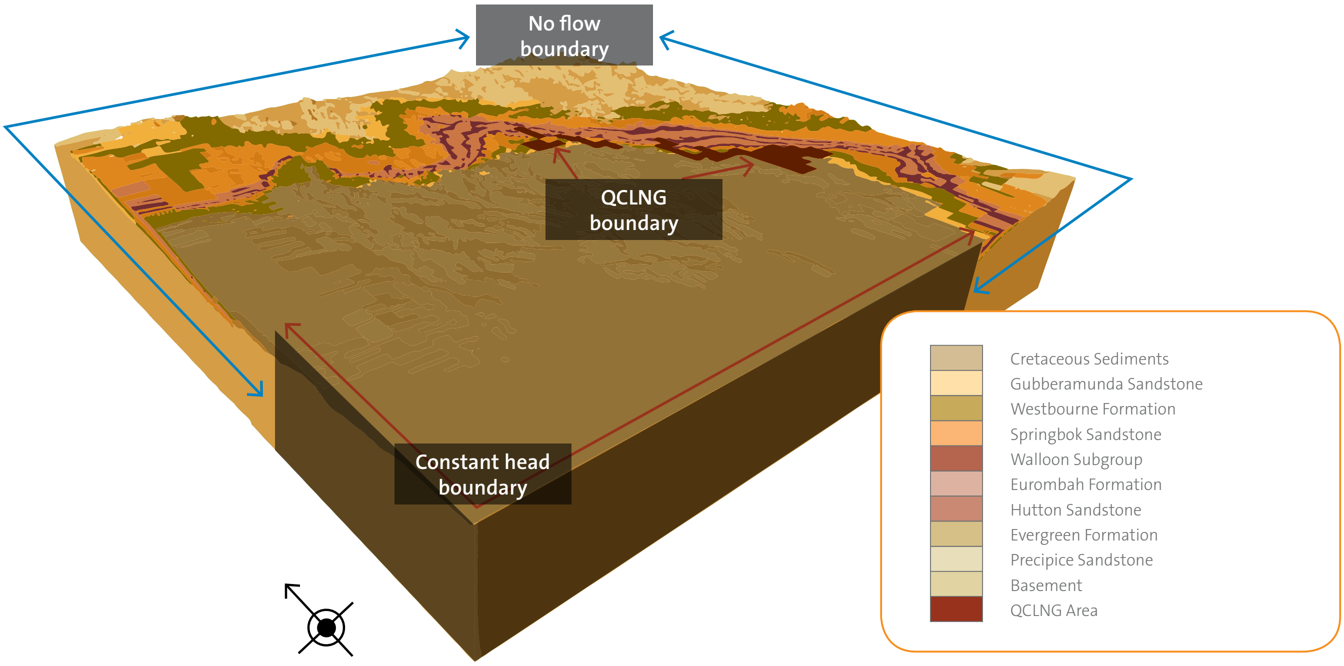

Figure 6-6– Location of boundary conditions

Outcrop

Aquifer recharge was assigned over regions of outcrop and subcrop for each formation as illustrated in Figure 6-8.

Field measurements of recharge were not available for the majority of formations within the basin. Consequently, an alternate method of calculating recharge to the system was used to provide a reasonable approximation based on the known hydrogeology. A suitable 'saturated zone technique using Darcy's Law' was identified within CSIRO publication 'Review of Recharge Mechanisms for the Great Artesian Basin, Nov 2007' and is detailed below.

In the absence of field testing and measurements, the saturated zone technique using Darcy's Law can be used to estimate groundwater recharge by relating the groundwater flow rate through a cross-sectional area of the aquifer to the surface area that contributes to recharge. Initial parameters and tolerances used within the model are illustrated in Table 6-2 (OGIA UWIR values are provided in the table for reference).

River zones

Additional recharge was assigned to major rivers within the model domain to reflect increased availability of water in these locations.

GEN3 Model Layer	Recharge value – Darcy equation modified for recharge (mm/yr)	Recharge value – diffuse rainfall and referential flow calculation (mm/yr)	QWC calibrated Water Table Recharge (mm/yr)	QWC Model OUTPUT – Net recharge (mm/yr)	GEN3 'Most Likely' recharge value (mm/yr)
Cretaceous Sandstones	0.033		1.0	0.0	0.033
Gubberamunda Sandstone	4.462	1.88	6.1	2.7	2 (Kellet)
Westbourne Formation	0.045	1.01	1.0	<0.05	0.05
Springbok Sandstone	0.485	0.86	2.1 (coal)	1.1	0.23
Upper Juandah Interburden	0.000	0.605 (interburden)	30.0 (interburden)	0.0	0.00
Lower Juandah Coal	0.620				0.62
Taroom Interburden	0.000				0.00
Taroom Coal	0.786				0.79
Eurombah (QWC WCM)	0.009	1.23	5.8	0.2	0.01
Hutton Sandstone	0.018	4.58	19.2	1.3	
Evergreen Formation	0.004	0.35	7.6	0.0	0.00
Precipice Sandstone	5.468	3.12	20.7	1.3	5.47
Basement 1	0.005		30.0	0.0	0.00

Table 6-2 – Range of calculated recharge rates for each hydrostratigraphic unit

6.4.7 AQUIFER DISCHARGE

River drains

Drain cells were assigned to all cells that were traversed by major rivers and streams within the region to represent potential discharge from the aquifer to the river. Drain cells were removed from the model's extremities to avoid overlap with constant head boundaries.

Evapotranspiration

There is sparse vegetation across much of the model domain. The vegetation that does exist is predominantly located in close proximity to rivers and tributaries and in elevated terrain and State Forests and National Park areas. While transpiration is not modelled specifically, the model construction includes drains along rivers (where the majority of trees are located). These drain cells can therefore also represent near surface interaction between groundwater and vegetation whose rooting depth is sufficient to reach the groundwater system in these locations.

Bores

For simplicity in the steady state model build and calibration, and due to the uncertainty surrounding their extraction history, groundwater extraction bores were not simulated within the steady state calibration process.

Springs

Discharge of groundwater via springs cannot be adequately simulated using a 1,500 m x 1,500 m cell size and will therefore not be simulated within the model. Instead, water levels at spring locations were observed using observation points and bores applied within each formation underlying the spring location (much like a conceptual nested piezometer installation). This will ensure the modelled pressure within individual aquifers underlying the spring locations is understood.

6.5 PRELIMINARY MODEL TESTING AND CALIBRATION OBJECTIVES

Steady-state calibration targets were identified and model testing has been implemented. Work has been undertaken to test model robustness and eliminate any model geometry and boundary condition-related issues before progressing to computer-assisted model calibration. The primary objective of the GEN3 regional groundwater flow model steady state calibration is to replicate average groundwater conditions prior to significant human impact on the groundwater system (i.e. the system in equilibrium – early 1900s). This calibrated model would then provide a starting point and initial conditions for transient model calibration runs between 1900 and 2005. The calibration dataset chosen as best reflecting this situation was between 1924 and 1945. This period reflected the earliest extended period of average rainfall conditions post 1900.

Calibration targets included:

- Water levels recorded within 269 bores between 1924 to 1945. This calibration target was to minimise the mean residual error between observed and modelled water-level per bore;
- Interpolated potentiometric surfaces for units above the Westbourne Formation. The calibration target was to achieve a broadly similar modelled potentiometric surface compared to the interpolated potentiometric surface for each formation.
- Interpolated potentiometric surfaces for units below the Westbourne. The calibration target was to achieve a broadly similar modelled potentiometric surface compared to the interpolated potentiometric surface for each formation.
- Model material balance error of less than 5% as recommended by the Australian Groundwater Modelling Guidelines; and
- Model water budget (inflow-outflow) error of less than 1% as recommended within the Australian Groundwater Modelling Guidelines.

6.5.1 APPROACH

To ensure that the model is suitable for computer assisted steady-state calibration a deterministic approach was applied to quality assure the model and test its stability. Model parameters were varied methodically in a series of steady state trial runs. The results of these trial runs were studied and a number of issues were identified. All of these construction issues were then rectified before the model was considered ready to start the calibration process. Parameters that were varied included:

- Horizontal permeability and vertical permeability;
- Recharge;
- Constant head boundaries; and
- River incision depth.

A summary of the issues identified is tabulated in Table 6-3.

Model run / sensitivity trialed	Modification to model	Result
Anomalous results near south/south west boundary indicates localised vertical connectivity is too high in this area	Assign area of low transmissivity to Westbourne and underlying units	Successfully confined artesian system
Lateral extent of formations is highly uncertain within south-west area. Pinch-out of formations inconsistent with conceptual model.	Deactivated 63,315 cells	Eliminated geometry issue
Water inflows along southern and south west constant head boundary	Reduced lateral extent of constant head boundary to southern model boundary	Halved water inflows - requires further refinement
Over pressuring of shallow regions of model	Reduced recharge within Cretaceous Sediments unit	Eliminated issue
Insufficient depiction of rivers within northern model domain	Increased river incision level from 1 m to 5 m	Rectified issue
Insufficient depiction of rivers within southern model domain	Increased creek inversion level from 1 m to 10 m	Rectified issue
Kv, Kh and anisotrophy sensitivity testing	Modified values slightly to determine sensitivity of model to each parameter	Confirmed range of values for computer assisted optimisation

Table 6-3 – GEN3 trial testing issues

6.5.2 MODEL TESTING OBSERVATIONS

Initial steady state model testing runs prior to calibration have allowed a number of corrections to the model. An error plot for modelled versus observed groundwater levels for primary calibration targets is provided in Figure 6-9. For direct comparison with the QWC Surat Basin regional model (QWC 2012), tolerances of +/-10 m and 30 m of head are shown on the error plots.

Qualitatively, it can be seen that the majority of calibration targets sit within the +/-30 m of head tolerance. However there are outliers and this is a reflection of the regional nature of the model, the historical bore dataset and the preliminary stage of the matching process.

The model tends to under-predict water levels within regions of higher observed head causing a flattening of the scatter plot. This could be due to a number of causes (e.g. insufficient recharge, Kh/Kv relationship, large river inversion depth etc) and will be improved via the automated steady state calibration process to follow.

6.5.3 GROUNDWATER BALANCE

Modelled water-balance results for the steady-state testing runs prior to calibration of the GEN3 steady state model for the entire model domain are summarised in Table 6-4.

Component	Flow IN (ML/d)	Flow OUT (ML/d)	IN-OUT (ML/d)
Net outcrop recharge	+ 690.6	+ 0.0	+ 690.6
River drain boundary cells	0.0	- 226.0	- 226.0
Groundwater extraction	0.0	0.0	0.0
Constant head boundary cells	+ 1,114.5	- 1,576.8	- 462.3
Total	**+ 1,805.1**	**- 1,802.8**	**+ 2.3**

Table 6-4 – Long-term average modelled water balance – entire GEN3 domain

Total long-term average recharge to the modelled area which includes 197,000 km^2 of the Surat Basin in Queensland is estimated to be 690.6 ML/d (or 252,414 ML/yr). This is equivalent to an average rate of 1.28 mm/yr over the entire active model domain.

The water balance results suggest that about 33% of the applied recharge exits the model locally via shallow groundwater/river systems. The net recharge that reaches the confined aquifer systems of the GAB is therefore a substantial proportion of the total outcrop recharge that enters the model. The model results in a net recharge volume of 464.6 ML/d (or 169,811 ML/yr) to the GAB aquifer systems.

The steady-state water balance error for the Surat regional groundwater model is 0.1% (imbalance divided by total water input or output to the model) which corresponds to a disparity between input and output flows of +2.3 ML/d. This material balance error is generated as a result of residual errors generated from the simulation errors within ECLIPSE, and subsequently they are difficult (if not impossible) to eliminate. It is proposed that this imbalance is investigated further and related to formation pressure stability to ensure that water flows are sufficiently balanced to ensure pressure complete pressure stability of the model for prediction purposes.

Whilst the above results represent output from an uncalibrated model, they provide a reasonable starting point for future automated model calibration and illustrate the ability of the model to replicate the groundwater flow systems as detailed within the conceptual groundwater model.

6.5.4 MODEL CALIBRATION PLAN

In accordance with the Stage 2 WMMP Commitment 6, the model has been built and is undergoing testing. Dual-phase flow processes have been benchmarked in an accompanying research exercise. Resultant flow and water balances are consistent with the conceptualisation. Considering the regional nature of the model and the resultant coarse scaling adopted, the simulation is deemed a suitable starting point for commencement of computer assisted steady state calibration.

Moving forward, QGC will use a petroleum industry standard software tool called MEPO that will allow computer assisted (automated) optimisation for the steady state calibration. This process includes an uncertainty workflow which will optimise the calibration target match. The model will be run with constant boundary conditions over a period of time deemed long enough to satisfy the performance measures stipulated within the Australian Groundwater Modelling 2012 Guidelines.

The transient calibration will include the following actions:

- Single-phase single porosity calibration between 1912 and 1995 accounting for historical water extraction in the Surat Basin prior to CSG extraction; and
- Dual-phase, dual porosity calibration between 1995 and the end of 2012 accounting for historical water extraction associated with traditional use as well as QGC CSG gas and water extraction from 2005.

Successful calibration of the model will be confirmed by internal review processes and an independent external reviewer.

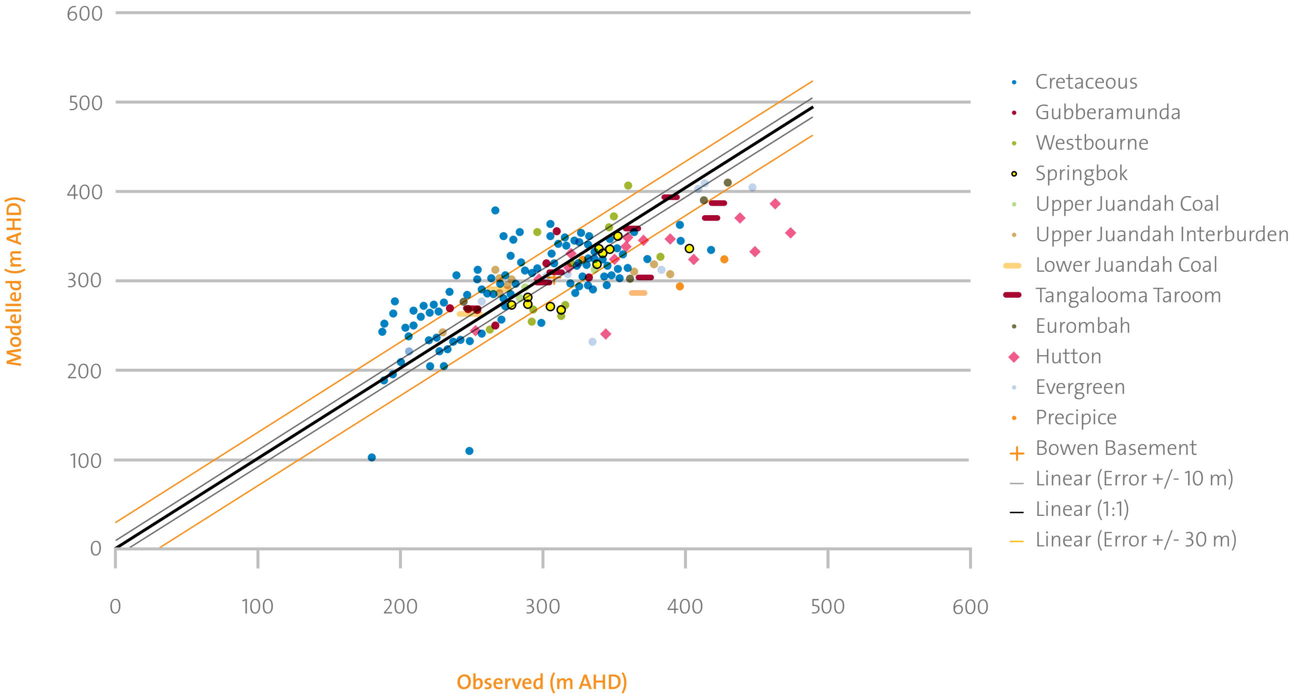

Figure 6-7 – Groundwater level error plot for GEN3 prior to finalised steady-state calibration: Primary calibration targets

6.6 DISCUSSION OF MODEL LIMITATIONS

At the end of Stage 1 reporting of the GEN3 model the following observations on its limitations can be made:

- The spatial and vertical distribution of the bores used to calibration the model is not uniform. While the use of an objective function with formation-normalising weightings will compensate for this in the steady-state calibration optimisation process, having a more even distribution of bore data would increase confidence in the model;
- In the majority of the formations within the model, 'tank' parameters have been used (i.e. one parameter per formation with no lateral spatial variability) with the exception of the Springbok Sandstone and Walloon Subgroup. Constant parameters mean that no geological heterogeneity is modelled, including such relationships as change in permeability with formation depth. As a revised hydrostratigraphy is developed these 'tank' values will be refined using more appropriate layering;
- The model is regional in nature and not designed to investigate local hydrogeological phenomena – either confined or unconfined;
- The GEN3 model has been built with a focus on data derived from the QCLNG project development area with no data input from other CSG operators and is not suitable for cumulative impact assessment;
- Groundwater/surface water interactions are not explicitly simulated in the GEN3 model;
- Surface alluvium deposits, including the Condamine Alluvium, are not explicitly modelled as a separate unit;
- The Surat Basin shallow aquifers have been amalgamated into one layer;
- To simulate steady state conditions, ECLIPSE must simulate all time-steps. This results in relatively time-intensive simulation periods both in terms of execution of model runs and analysis of the results; and
- The formation geometry and fluid flows at the southern boundary of the model are uncertain.

6.7 CONCLUSIONS

The work undertaken to date for this stage of the GEN3 model allows the following conclusions to be drawn:

- Current groundwater levels within bores and interpreted groundwater flow directions within the Surat Basin are unlikely to be representative of equilibrium conditions. Incomplete datasets (pumping rates and water levels) exist for the past 130 years of groundwater extraction within the basin. This complicates the interpretation of the current (2013) groundwater system;
- Permeability (horizontal and vertical) is key to achieving adequate isolation between the shallower unconfined to confined groundwater system and the deeper artesian flows;
- Recharge and permeability for any given unit are intimately related;
- Lateral flow dominates over vertical flow;
- Two hydrogeological systems (a shallow non-artesian and deeper artesian system) represent a valid initial hydrogeological conceptualisation of groundwater pressures in the Surat Basin; and
- The conceptualisation of recharge in the north at outcrop and drainage to the north and south can be honoured in the model.

A higher level assessment indicates that dual-phase simulations produce significantly different pressure drawdown conditions than estimated by existing single-phase models. This has important implications for impact prediction. QGC will progress this exercise by:

- Continuing internal and external research into upscaling;
- Implementing rigorous uncertainty analysis; and
- Assisting research organisations and regulators with their implementation of dual-phase simulations.

The status of the Commitments relevant to GEN3 is as follows:

#	Department Condition		Description	Completion date	Status
	Pre-Dec 2012	Post-Dec 2012			
6	**49b**		Completion and reporting on GEN3 model build	April 2013	🟢
9	**49b**	**53B a**	Submission of consolidated Surat Basin Hydrogeological Model and recalibration of GEN3 model. Commitment to ongoing model recalibration and reporting with annual report. Reporting of connectivity studies.	October 2014	🔴
50	**49i**		Submission of Annual Report including (from October 2013) reporting results of ongoing GEN3 model recalibration	October 2013 and annually thereafter	△

🟢 Commitments completed
○ Commitments work in progress
△ Evergreen Commitments
🔴 Firm deliverables for that month

Going forward the calibrated model will be used to run a number of simulations and test hypotheses developed during complementary technical studies, including:

- The propagation of drawdown under single and dual-phase conditions;
- The change in pressure, drawdown and flow characteristics under single and dual-phase conditions; and
- Assessment of vertical hydraulic connectivity.

A progress report on the model stimulations will be presented in April 2014.

Overall the model will be used as a tool to enhance QGC's understanding of the Surat Basin groundwater flow system.