QGC
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6.0 Quantifying aquifer connectivity

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Condition 49b

6.1 INTRODUCTION

In 2011, QGC embarked on a number of aquifer connectivity studies to provide a scientifically rigorous foundation for predicting CSG extraction impacts and to frame an effective ongoing monitoring plan. Studies of varying durations are scheduled for completion within three to five years. This section describes activities completed during the Stage 1 WMMP, the ongoing Stage 1 WMMP tasks and future activities. The goal is to demonstrate that the effects of WCM depressurisation can be predicted adequately in space and time. Then early warning signals and subsequent appropriate response and remedial action plans can be implemented before unacceptable effects occur/emerge.

6.2 CONNECTIVITY PROGRAM OBJECTIVES

QGC's activities program is designed to achieve a detailed aquifer connectivity assessment:

- To develop a scientifically robust understanding of the nature and extent of any vertical leakage across QGC tenements and adjacent areas induced by CSG development
- To assess the most suitable methods of monitoring aquitard response to CSG water extraction (i.e. monitoring bores versus VWPs)
- To demonstrate via a comprehensive monitoring program, the nature and extent of any vertical leakage
- To characterise key factors (both natural and anthropogenic) affecting inter-formation leakage
- To characterise spatial and temporal variation that could occur in vertical leakage
- To identify risks associated with unacceptable vertical leakage and develop response plans
- To develop a detailed understanding of the potential for inter-formation leakage from the Condamine Alluvium due to extraction from the WCM on south-eastern QGC leases
- To confirm early warning approaches to inter-formation leakage that could impact on MNES.

6.3 CONNECTIVITY PROGRAM RATIONALE

Gas and water extraction from the WCM is expected to result in depressurisation of this heterogeneous unit and has the potential to induce vertical leakage from overlying and underlying units. The GEN2 model predicted the leakage amount and rate to be small and effects relatively localised.

However, the model assumes hydraulic properties (albeit a broad range) and so the connectivity program combined with the planned GEN3 modelling approach is designed to provide greater confidence in predicted hydraulic impacts.

Only small leakage rates are anticipated and any short-term monitoring (over days or weeks) as part of any normal testing program (e.g. conventional pump tests) would be unlikely to indicate leakage. Hence, central to the connectivity program is the detailed monitoring of production tests (of up to six months duration). It is possible that no observable impacts in adjacent aquifers will occur. The regional monitoring network now under construction will provide fundamental data relevant to understanding vertical leakage rates.

Meantime, important shorter-term studies being undertaken will provide greater confidence in our understanding of the hydrogeological framework and input parameters to ongoing groundwater modelling.

Groundwater age dating (and spatial distribution of salinity and major ions) will provide important conceptual information for the contextualisation and significance of leakage into the WCM. In short, old saline groundwater would suggest poor connectivity while young less saline groundwater would suggest greater connectivity.

6.4 KNOWLEDGE CYCLE AND LINKAGES TO OTHER PROGRAMS

The connectivity program comprises ongoing knowledge gathering to feed into other key applications. In Figure 25 the 'knowledge cycle' comprises six key stages which then project themselves in the longer-term. It is envisaged that each cycle would take about one to two years. This increasing knowledge evolution will equate to greater confidence in impact predictions. The five key applications fed by the knowledge cycle are not ends in themselves, but rather broad aspects to produce specific outcomes. These outcomes will directly influence operational decisions and environmental responses.

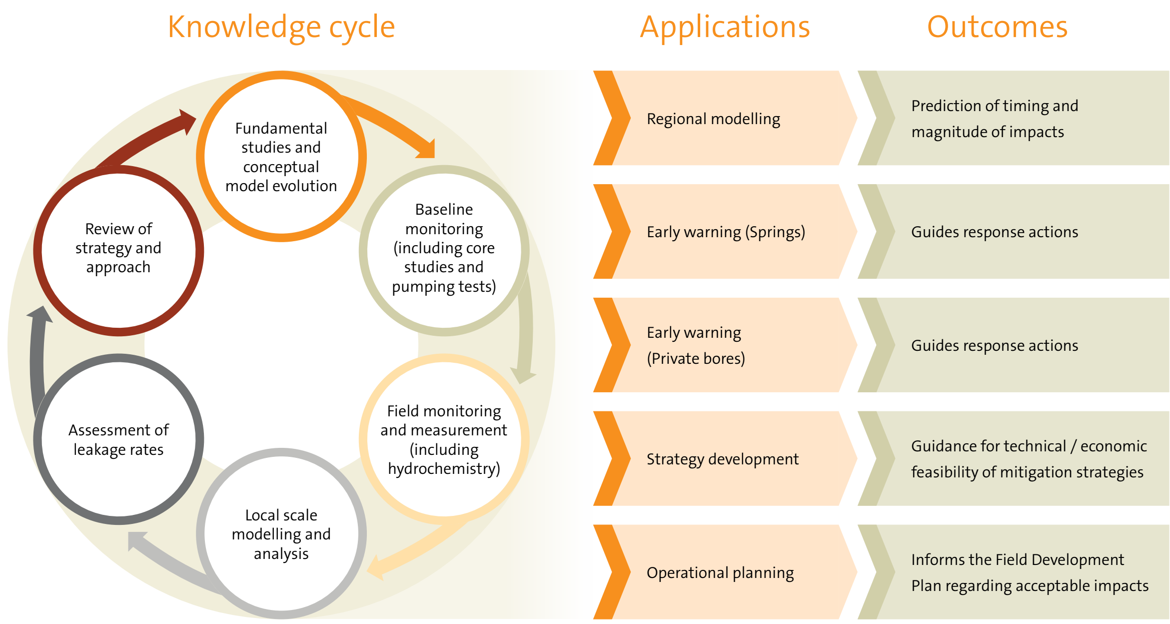

Figure 25 – The connectivity knowledge cycle

6.5 PROGRAM OF AQUIFER CONNECTIVITY INVESTIGATIONS

QGC has begun a program of field, laboratory and office-based investigations and analysis. The strategy is to complete a suite of complementary studies to obtain measurements for appropriate calculation of hydraulic leakage rates and flux due to CSG and groundwater extraction between the WCM and the overlying and underlying aquifers.

'Connectivity' is defined as the potential for (and magnitude and rate of) leakage to occur perpendicular to the natural bedding plane of the stratigraphy in the sedimentary sequence of concern – in this case, the Surat Basin sequence of the GAB.

This translates to the hydrogeological concept of vertical conductivity (qualified as vertical hydraulic conductivity) as contrasted to the horizontal hydraulic conductivity – or the ease with which water can move through pore spaces or fractures in a vertical or horizontal direction respectively.

The inter-formational connectivity assessment program investigates the measurement, calculation and independent modelling of predominantly horizontal hydraulic conductivity and, when readily possible, specific storage data on a variety of aquifers. This involves the use of laboratory testing and computer-based methodologies. All of this data will then be used in the Stage 2 program to estimate regional inter-formational leakage rates.

Staging	Task
Stage 1	**May 2011 to April 2012 (desktop studies and field tasks)** • Aquitard vertical hydraulic conductivity review and analysis • Stage 1 drilling program and monitoring • Stage 1 pumping tests (short duration) and analysis • Borehole core testing and analysis (ongoing)
Stage 2	**May 2012 and ongoing** • Stage 2 drilling program and monitoring • Stage 2 pumping tests • Production testing monitoring and analysis • Additional pilot test monitoring and analysis • Hydrochemical analysis • Monitoring of the Condamine Alluvium and WCM • Springbok characterisation • Mapping of aquitard and aquifer distribution and characteristics • Ongoing regional groundwater monitoring • Ongoing numerical modelling and analyses

Table 9 – Schedule of connectivity studies

6.6 STAGE 1 TASKS NOW COMPLETED

During the course of the Stage 1 WMMP, a number of short-term tasks were completed and the results are summarised below.

6.6.1 AQUITARD VERTICAL HYDRAULIC CONDUCTIVITY REVIEW

An international literature review of publicly available reports on vertical hydraulic conductivity was completed in April 2012. Appendix O contains the full report. The review identified 180 published papers of interest and provided a range of vertical hydraulic conductivity (K_V') for aquitards in sedimentary basins with lithology similar to those encountered in the Surat Basin such as sandstone, silt, siltstone, mudstone, clay, claystone and shale.

The literature review showed that throughout the world, the range of measured or estimated vertical hydraulic conductivities of sedimentary facies typical of the Surat Basin is extremely wide, ranging between 1×10^{-9} mD (~1×10^{-12} m/day) and $3 \times 10^{+3}$ mD (about 3 m/day).

Units: m/day (mDarcy)		Median of lower values	Median of upper values
Fine grained lithology (mudstone, clay, claystone, shale)	**All methods** (193 citations)	10^{-6} (10^{-3})	2×10^{-5} (2×10^{-2})
	Laboratory tests (47 citations)	10^{-8} (10^{-5})	4×10^{-7} (4×10^{-4})

Note: Refer Appendix M for definitions of 'medians'

Table 10 – Vertical hydraulic conductivity values results from international literature review

Field measurements are shown to yield systematically higher values of K_V' (of approximately three orders of magnitude) than laboratory testing of core samples. It is fair to assume that a large proportion of field values collected in this review will contain results that are derived from shallow depths (because many more tests will have been undertaken at shallow depths). It should also be noted that as depth of burial increases, hydraulic conductivity typically decreases. These values therefore may not be as representative of aquitards that are located at greater depths.

Rock defects were shown to have a significant impact on regional K_V' (Snow, 1968 and Hart, 2006). A simple set of vertical non-intersecting vertical fractures of 0.1 mm (100 µm) openings spaced every 10 km in a virtually impervious matrix results in a regional K_V' of 5.8×10^{-3} mD (5×10^{-6} m/day).

6.6.2 EFFECTS OF INFRASTRUCTURE ON AQUIFER CONNECTIVITY

The literature review has highlighted the effect infrastructure could have on connectivity. For instance, poorly constructed, poorly decommissioned, abandoned or failed bores or those screened across multiple units, could be considered to have a similar impact on regional K_V' as those caused by rock defects.

The median K_V' value of 1×10^{-3} mD (1×10^{-6} m/day) used in the GEN2 model is consistent with values obtained by the literature review, however, the upper bound of the K_V' range used in the GEN2 groundwater model (5×10^{-6} m/day) may be too low if the aquitard is fractured or contains poorly constructed bores. The lower value of the range (5×10^{-7} m/day) can be regarded as appropriate.

QGC commits to assess the effects of infrastructure, in particular, leaking bores and wells and their effect on leakage and to use the GEN3 model (Commitment 6 in Table ES3) to assess impacts and to report the findings in October 2013 (Commitment 8 in Table ES3). Also, QGC will use all available field data to derive representative K values for use in its GEN3 model.

6.6.3 QGC WCM VERTICAL PERMEABILITY ANALYSIS

QGC has undertaken two studies into Walloon Subgroup vertical permeability. The first study is based on various geological evaluation techniques while the second is based on laboratory and field testing.

The first study aims to determine the effects of sedimentology and geological structure on vertical connectivity in the Walloon Subgroup and adjacent Surat Basin stratigraphic formations. Data is included from the Walloon Subgroup non-coal interburden, Walloon Subgroup coal seams, Springbok Sandstone Formation and Eurombah Formation. The study defines regional basin scale, field/block scale, and well bore scale features. Geological datasets including outcrop, subsurface core, core analysis, and well image logs are used to define small faults, fractures, lithology, and facies. At the regional and block scale geophysical two dimensional datasets define fault locations, fault offset, and folds.

Field evidence with core data, dynamic reservoir data and a dynamic production study, and tracer migration are used to show examples of system connectivity. The Walloon Subgroup interburden has a heterogeneous lithology, variable grain-size and relatively high clay contents making tortuous migration paths for gas and water molecules. The Eurombah Formation, at the base of the Walloon Subgroup, is considered an aquitard due to the high clay percentage, very small grain-size, and shale to siltstone lithologies.

The overlying Springbok Sandstone Formation is an aquitard interbedded with small aquifer units. It is a heterogenous system with lateral and vertical lithology changes, grain-size variations, and variable clay contents which can act as baffling effects and impede fluid movement. At the regional and field scales near vertical faults are found with vertical displacements up to 50 m through the coal zones and sometimes into adjacent stratigraphic layers. Transverse fault displacement, oblique movement relative to dip, is suspected due to the geological stress history. However it is difficult to image with the available seismic data. Fault displacement prevents lateral connectivity between the thinly bedded (<30 cm) coal seams as seen by dynamic production studies.

Faults are low population density and conceptualised to be fully effective sealing faults due to the high (>50%) clay content of fault affected lithologies. Faults in the Walloon Subgroup are not fluid migration conduits along and across the deformation zones. Coal fractures are found only in discrete coal seams providing the dominant permeability of the system. At the well and outcrop scale these fractures do not extend into adjacent substrates and are of variable population density due to intra-coal seam sedimentology changes. At depths less than 800 m, coal fractures can be open and allow fluid movement. As depth increases, effective stress decreases fracture aperture and exponentially diminishes fluid movement (refer Appendix N).

The second study uses recent Walloon Subgroup permeability data measured in the northern, central and southern areas. The analysis uses lithological log data, petrophysically derived porosity log data, laboratory core analysis (routine and special) and downhole reservoir test data i.e. DST (Drill Stem Test) data from QGC wells across the three main gas field areas. Methodology for deriving vertical permeability is demonstrated in Appendix O.

On the basis of reservoir data characterisation, vertical permeability ranges for the highly interbedded non-coal facies are considered low and range from 7.6×10^{-4} mD to 1.9×10^{-6} mD (7.6×10^{-7} m/d to 1.9×10^{-9} m/d). Coal facies range from 1.4×10^{0} mD to 3.5×10^{-6} mD (1.4×10^{-3} m/d to 3.5×10^{-9} m/d).

Literature review and GEN2 model values and QGC measured values are compared in Figure 26.

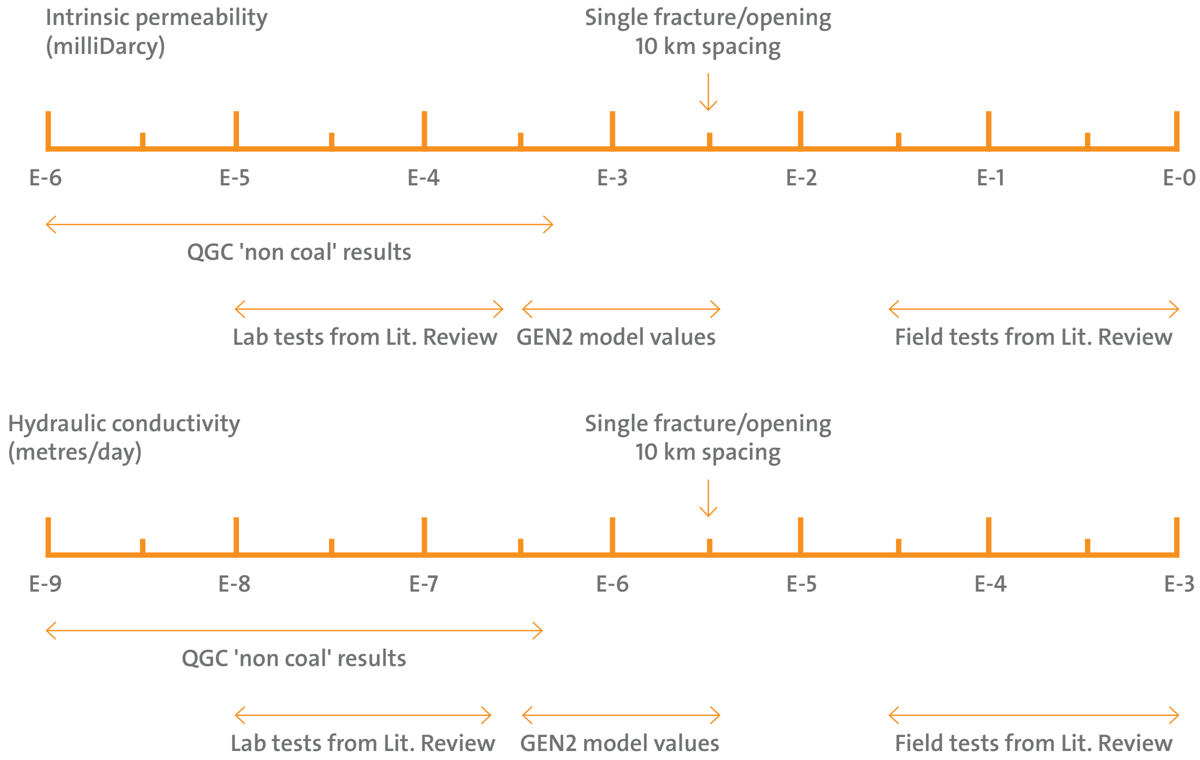

Figure 26 – Vertical hydraulic conductivities in sedimentary basins – linking literature review results with Walloons Formation K_v values

6.6.4 STAGE 1 DRILLING PROGRAM AND MONITORING

The Stage 1 drilling program undertaken during 2011 consisted of 13 shallow observation wells in the Central and Northern Gas Fields. Findings are summarised in Section 6.7. A report on the drilling program is in Appendix H.

6.6.5 STAGE 1 PUMPING TESTS (SHORT DURATION) AND ANALYSIS

Short-term pumping tests were undertaken within seven observation wells within the Gubberamunda Sandstone and the Springbok Sandstone. The aim of the pumping tests was to establish the horizontal hydraulic conductivity of the tested formations, and provide better data for input to the GEN3 modelling. As short-term tests only, vertical leakage was not expected to occur. Findings are summarised in Section 6.7 while pumping test results are reported in Appendix I.

6.6.6 NUMERICAL ANALYSIS OF PRODUCTION DATA

During 2011, QGC collated a production-related monitoring dataset from a number of VWP pressure monitoring points in the Central Gas Fields. One such well, Argyle 6, yielded useful post-2005 time-series head data (from VWP) at three coal seam locations in the WCM. Detailed analysis has shown that the data could not be used to estimate vertical hydraulic conductivity at that location. This was because there is major extraction of gas and water from a nearby (non-QGC) tenement where the volumes extracted are unknown. Hence the observed drawdown in Argyle 6 cannot be analysed by consideration of QGC information alone.

However, VWP monitoring data from the Isabella and Jen pilot production test will provide a useful insight into pressure relationships between the Springbok Sandstone and WCM.

6.6.7 BOREHOLE CORE TESTING AND ANALYSIS (ONGOING)

A comprehensive program of coring and associated laboratory testing of core samples is being undertaken to provide lower bound 'end member' results for vertical and horizontal permeability.

During Stage 1, some 50 m of coring was collected from the Gubberamunda Sandstone in bore GW1 at Woleebee Creek. Testing and analysis of this core is reported in Appendix P. This report describes the detailed lithological variations in the core and presents the results from 45 horizontal permeability and five vertical permeability tests. The overall high permeability of this relatively coarse aquifer is evident.

During Stage 2, extensive coring is planned, including a continuous core (about 1,200 m) from bore GW4 at Woleebee Creek. There will also be extensive coring in two Central and Southern Gas Fields' wells. Total length of coring in the Stage 2 drilling program will be in the order of 3,000 m.

Core samples for testing will be selected for using industry-standard methods for permeability and porosity. The dataset of localised hydraulic conductivity information will be used to validate input data in the GEN3 numerical model.

In the past few years, a significant number K_v and K_h of laboratory test results for both coal and non-coal core have been collected. The Stage 2 drilling program in 2012 will provide significant new data and be presented in the consolidated hydrogeological model report as described in Section 6.8.7.

6.7 KEY RESULTS TO DATE

The completed program to date and the ongoing studies provide an emerging picture as to the nature of the hydraulic interaction (connectivity) between the WCM and the overlying and underlying aquifers. The broad conclusions presented here are tentative and subject to revisions as more data becomes available. Key conclusions are:

- Studies undertaken to date support the nature of the impacts as broadly described in the GEN2 modelling, as reported in the Stage 1 WMMP. The general hydraulic parameters used, principally K_v, are supported by the literature review.
- Gubberamunda and Springbok groundwater monitoring indicate a general upward hydraulic gradient
- Pumping test results and the Springbok characterisation study suggest the Springbok Formation as being a poor aquifer in general and an aquitard over much of its thickness. Nonetheless there is, as expected, significant spatial variability in thickness and properties and larger localised variations are possible.
- Faults of widely varying size and throw are widespread across the QGC tenements and have potential to act as barriers to groundwater flow and pressure change.

The limited hydrochemistry data analysed to date indicate that groundwaters in the Gubberamunda and Springbok Formations are alkaline with pH ranges between 8 and 9. The Springbok groundwaters are typically more saline than Gubberamunda groundwaters. In both formations groundwaters are either sodium-chloride or sodium-chloride-bicarbonate or sodium-bicarbonate types. Cation concentration ratios are very similar across formations and all bores are dominated by sodium.

The presence of bicarbonate in a formation appears to be a key indicator of hydrogeochemical processes, with different mechanisms depending on whether aerobic or anaerobic conditions predominate. Possible methods of bicarbonate enrichment in the Springbok include water and rock interactions, methanogenesis, sulphate reduction or mixing with deeper high-bicarbonate Walloon groundwater. It is possible that all four mechanisms contribute to Springbok bicarbonate concentrations.

Table 11 describes how the various physical and chemical properties of aquifers or formations are measured and how that information is used to assess aquifer connectivity.

Aquifer or formation property	Activity	What the activity tells us	Observations	What can be inferred or deduced about aquifer connectivity	Implications	Other works planned or underway
Groundwater head or standing water in bores	Bores drilled and sealed into different formations or at different depths in the same formation at the same location.	If at a particular location there is a vertical downward gradient between formations, no gradient or an upward gradient.	Upward vertical gradients observed in monitoring bores between Springbok and Gubberamunda Formations at Berwyndale South, Kenya East and Lauren.	Potential for upwards leakage from Springbok to Gubberamunda. Gubberamunda heads have been depleted over time due to groundwater extraction. Time series data gives response to natural and anthropogenic stressors.	Assignment of initial head conditions in groundwater models.	Analysis of Walloons DSTs. Develop understanding of groundwater flow gradients between Walloons, Springbok and Eurombah/ Hutton. Development of methodology to assess time series data (complete) analysis of time series data.
		Assessment of regional groundwater flow directions.	Two generalised distinct regional flow systems are present across QGC acreage which reflect topographical influences. Northerly flow to the Dawson River Valley. Westerly to south-westerly/southern flow to the MDB in the central and southern lease areas.	A third subregional flow system likely to exist in the southern lease areas in a north-easterly direction towards the Condamine River. Localised flow patterns in Walloons, Springbok and possible Hutton influenced by CSG water extraction in central, southern areas by Origin Energy (Talinga, Condabri) and Arrow Energy (Kogan North, Daandine and Tipton).	Assignment of initial head conditions in groundwater models. Groundwater model calibration (steady and transient states). Provides clues to potential recharge mechanisms of deeper formations and hence connectivity with overlying formations. May challenge views of recharge mechanisms to Springbok and Walloons.	Analysis of Walloons DSTs. Regional potentiometric surface maps for Gubberamunda, Springbok and Walloons. Analysis of monitoring bore and VWP data.

Aquifer or formation property	Activity	What the activity tells us	Observations	What can be inferred or deduced about aquifer connectivity	Implications	Other works planned or underway
Hydraulic conductivity	Test pumping of Gubb and Springbok bores (13 bores).	A measure of the ability of water to flow in porous or fractured rock media.	Gubberamunda generally (but not always) higher K_h than Springbok. Gubberamunda K_h range 0.02 to 8.3 m/d. Springbok K_h range 0.003 to 0.1 m/d.		Better definition of spatial K_h values for modelling.	Assessment of Springbok K_h versus Walloons K_h. Need for additional test pumping to be considered.
	Literature review of vertical leakage assessment.			Regional K_v values in aquitards generally orders of magnitude greater than laboratory-based data. Benchmarks K_v values used in GEN2 model.	Selection of K_v values for GEN3 model.	Literature review report (finalised).
Springbok Sandstone Aquifer versus leaky aquitard	Assessment of basal Springbok thickness and hydraulic characteristics.	Thickness of lower Springbok and areas where 'connectivity' most likely to occur or where further information required.		Leakage more likely to occur in certain areas (e.g. Central than Southern).	Allows identification of potential high risk areas and hence areas to target additional groundwater head, quality monitoring.	Apply approach to Westbourne and Gubberamunda.
Groundwater chemistry	Analysis and interpretation of Gubb, Springbok groundwater samples. Interpretation with spatially related Walloons samples.	Gives information on the likely hydrogeochemical and biogeochemical processes that influence groundwater chemistry spatially.	Gubb, Springbok and Walloons are either Na-Cl, Na-Cl-HCO^3 or low Na-HCO^3 and low in SO^4. Salinity ranges from low to moderately high (check) and is dependent on HCO^3 conc. HCO^3 presence due to both aerobic and anaerobic processes depending on sample depth in formation and proximity to subcrop, outcrop. Salinity and HCO^3 increases with depth from Gubb to Walloon. Potential conceptual hydrobiogeochemical models have been identified.	Groundwater are geologically young. Some Gubb data influenced by surface recharge. Salinity (bicarbonate) is a function of organic matter breakdown. Coals relatively low in Sulphur content. Salinity of Walloons at depth is often less than Walloons at surface (based on data from open cut coal mine developments).	Provides clues to potential recharge mechanisms of deeper formations and hence connectivity with overlying formations. May challenge views of recharge mechanisms to Springbok and Walloons. Uncertainty with respect to recharge sources. Need to develop a holistic model that considers hydrochemistry of Walloons at the surface (i.e. behaviour in coal mines) as well as at depth to close the loop.	More detailed spatial analysis of Walloons and bore baseline chemistry and groundwater chemistry data from Stage 2 Monitoring Program. Consideration of published data on shallow Walloons chemistry.
Isotope analysis	Analysis of Gubb, Springbok and Walloons groundwater samples from spatially similar locations.	Age of groundwater. Similarities of groundwater type in various formations.			Provides evidence to support recharge mechanisms of deeper formations and hence connectivity with overlying formations.	

Table 11 – Overview of aquifer connectivity studies

6.8 PLANNED STAGE 2 TASKS

6.8.1 STAGE 2 DRILLING PROGRAM AND MONITORING

The Stage 2 drilling program comprises 24 new wells over the next two years as outlined in Section 5.5.

6.8.2 STAGE 2 SHORT DURATION BORE PUMPING TESTS AND ANALYSIS

It is proposed that selected observation wells will have short duration pumping tests.

Pumping tests are the most reliable available method for assessing mesoscopic and macroscopic (bulk) hydraulic conductivity values for rock sequences. QGC routinely completes hydraulic testing of installed monitoring wells.

Specific testing is planned for several routine appraisal and investigation situations.

QGC will undertake drill stem tests of selected observation wells in the Gubberamunda Sandstone, Springbok Sandstone, Hutton Sandstone and Precipice Sandstone. A drill stem test is an 'in situ' test conducted down a borehole to measure specific rock properties, typically permeability. The test isolates a several-metres length interval using inflatable packers. The drill string and packer set-up, being in an evacuated condition without water and therefore at atmospheric pressure, is opened to the aquifer and the formation flow rate from the formation into the drill string cavity is measured.

A flow-to-surface drill stem test is a variation where a formation with artesian pressure is allowed to flow to ground surface through the drill string and the flow rate or water level rises together with well and test equipment specification to estimate the requisite parameter values.

Where appropriate, it is planned for falling head permeability measurements to be undertaken.

6.8.3 LONG DURATION PRODUCTION PUMPING TESTS AND ANALYSIS

Once depressurising for CSG extraction (production) has commenced, field monitoring of coal seam and surrounding aquifer groundwater pressures and heads is considered the best method of determining vertical and horizontal hydraulic connectivity (K_v and K_h) and hence leakage between the WCM and the overlying and underlying aquifers.

Data will be analysed by analytical and/or numerical methods as appropriate to derive K_v and K_h values for affected hydrogeological layers (aquitards and aquifers).

This information is then used:

- To explain bore complaints, access 'make good' agreements and in MNES considerations and satisfies Australian Government concerns under the Water Act
- To help calibrate and further refine QGC's regional and local numerical models used internally to predict groundwater impacts due to CSG activities and so better quantify inter-formational leakage on a local and regional scale
- To provide information to QWC on regional groundwater modelling.

Purpose-built monitoring piezometers and open monitoring wells are being constructed progressively before extraction commences so that actual production pumping data is captured and monitored.

The 'three-spot' and 'five-spot' appraisal and well testing program is used for QGC's pumping test program. This CSG reservoir appraisal method comprises three or five gas production wells – each about 750 m apart and in a regular pattern to optimise gas yields – with a central well and up to four outer wells.

In the Stage 1 WMMP, it was proposed that three initial production tests were planned, being one for each of QGC's production regions (northern, central and southern). Additional monitoring wells are being installed in the currently operating Lauren field to enable later analysis of the possible leakage effects. Over the course of the Stage 1 WMMP, there have been ongoing delays at the Broadwater P2 site due to land access problems. These issues are still not resolved. This has significantly delayed the pilot testing program so the decision has been made to abandon the pilot and instead proceed into full production in this region. Consequently, it has been decided to proceed with the planned intensive Groundwater Monitoring Program at Broadwater to establish baseline monitoring prior to production commencing. The only drawback is that no recovery will be measured, albeit the ongoing depressurisation will be intensively monitored and, as this will be for much longer than six months, greater stress will be imposed. Hence this test has the potential to provide useful data on vertical leakage rates.

In addition to monitoring at Broadwater, it has been decided to extensively monitor the Ruby-Jo P2 pilot. The exact nature of the monitored formations is provided in Appendix C.5.

At each site, the general monitoring regime is adopted although site variations are often necessary to optimise location and new well depth in relation to existing wells. For example:

- At a pumping test site, one monitoring well monitors the WCM with (VWP) constructed opposite selected and relevant parts of Taroom Coal Measures grouping coal seams
- At the central pad (100 m by 100 m drill and well site area at the centre of a 'five-spot' appraisal site) two standard cased monitoring wells are constructed into the Gubberamunda and Springbok Sandstones. They are open wells for groundwater quality sampling.
- At an outer pad (about 750 m from the central pad) two standard cased monitoring wells or a VWP are constructed into the Gubberamunda and Springbok Sandstones
- At the central pad, two standard cased monitoring wells are constructed to monitor the Hutton and Precipice Sandstones
- At several sites, VWPs or standard cased monitoring wells will be constructed into the Westbourne Formation
- At one site, a standard cased monitoring well will be installed into the Eurombah Formation.

The layout of existing and proposed monitoring bores at Kenya East are show in Figures 27 and 28. Similar information for Woleebee Creek, Broadwater, Lauren and Ruby-Jo are shown in Appendix C.5.

The program usually comprises four to six program-specific monitoring wells at each pilot test site in addition to standard WCM monitoring. The aim is to construct all monitoring wells and gather background water level and quality data ahead of production testing program start-up. VWP or standard cased monitoring well installation into the aquitards at three sites will assist test result interpretation.

A full groundwater quality baseline suite is taken during construction and a reduced suite is sampled each month during pumping tests. Near-continuous monitoring of electrical connectivity (EC) is also proposed.

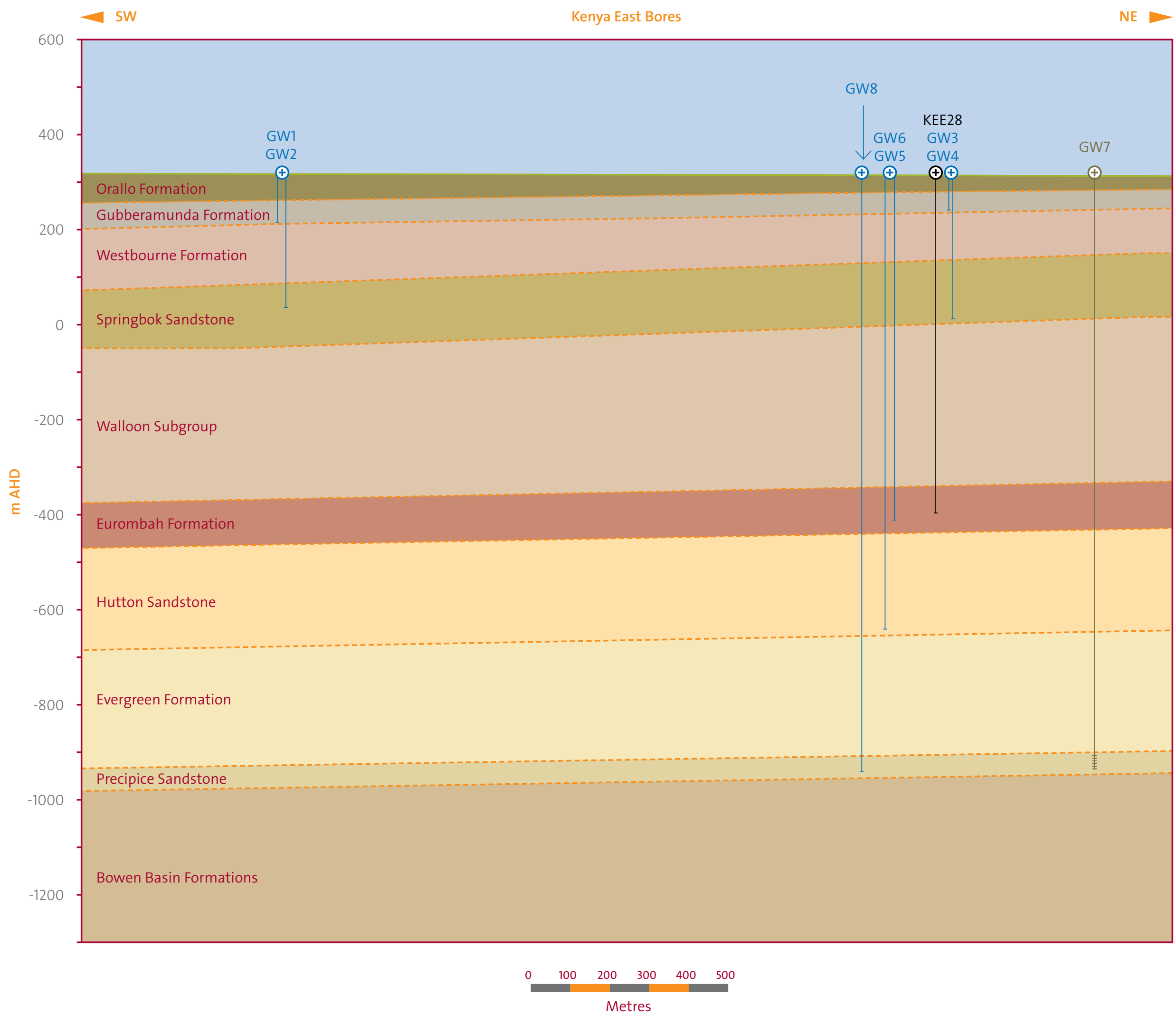

Figure 27 – Kenya East P3 pilot monitoring bores

The following sites (refer Table 12) will be used for production pilot tests or long-term monitoring of production:

Block location	Block / Location (tentative)	Purpose
South-east of Chinchilla	Kenya East P3 Ruby-Jo P2	Pilot production
South-west of Chinchilla	Lauren (initial production for domestic gas sales has commenced)	Production monitoring
South-west of Wandoan	Woleebee Creek P1	Pilot production

Table 12 – Connectivity studies test sites

These blocks and the intended long-term production pumping test sites and associated monitoring are shown in Appendix C.5.

Figure 28 – Kenya East P3 pilot groundwater monitoring bores layout

Anticipated timing for the monitoring wells and the start of the production testing is shown in Table 13.

Block	Complete observation well construction	Commence production test / Long-term production
Woleebee Creek P1	July 2012	November 2012
Kenya East P3	August 2012	January 2013
Lauren	January 2013	Minor 2007, Major 2011-13
Ruby-Jo P2	November 2012	January 2013

Table 13 – Anticipated timing for production tests

At the start of production testing, standard practice is to extract water from any or all of the three-spot and five-spot wells at irregular times and differing rates. This requires careful monitoring of water and gas extraction volumes and timing in conjunction with water pressure monitoring. The early part of the pumping cycle, say the first 40 to 60 days, is the more relevant part of the test because it involves pumping water only (i.e. there is no gas production). The monitoring will continue for about six months after the pumping test program completion. However, monitoring will continue for at least three years, whether or not CSG production extraction is initiated.

Pumping test analysis needs specific local numerical models for each test location. A numerical modelling method is the most appropriate means of simulating various aquifer and aquitard responses (where applicable) and thereby derive the most reliable K_h, K_v and S value estimates. This is because of the irregular starting and stopping of production bores at early times in the test. MODFLOW is the most appropriate numerical model for analysing pumping test responses as long as there is no gas production. Conventional analytical methods will also be used, including the DeGlee analysis method.

Required monitoring will run for a year, followed by six months of numerical modelling reporting of analysed results may take a total of two years. For Lauren and Broadwater, results after one year of production will be initially analysed and ongoing production results analysed biannually.

6.8.4 MONITORING OF THE CONDAMINE ALLUVIUM AND THE WCM

Various authors (e.g. Hillier, 2010) assert that depressurisation of the WCM could cause leakage from the Condamine Alluvium (CA) into the WCM. Hillier suggested that there is an upward hydraulic gradient from the WCM into the CA. To enable QGC to assess possible effects of WCM depressurisation in the Southern Gas Fields a monitoring and assessment program is being developed in conjunction with Arrow Energy.

For development of the Broadwater Block, detailed monitoring will be extended to the CA and all the underlying formations. This will include two monitoring bores into the CA on the Broadwater's eastern side in the vicinity of WCM monitoring wells. These bores will be regularly monitored for level and quality.

To Broadwater's immediate east lie Arrow Energy tenements. It is understood that Arrow Energy is considering the installation of six monitoring bores into the CA. These monitoring bores would be complementary to QGC's monitoring and would enable early identification of any possible groundwater level declines.

Once sufficient data is available, an analysis and reporting of the results will follow. QGC monitoring bores are planned for late 2012. At least one year of data will be necessary for analysis.

6.8.5 MAPPING OF AQUITARD DISTRIBUTION AND CHARACTERISTICS

Review of core that has been collected from several locations within the Surat Basin indicates that the classical stratigraphic nomenclature used historically to describe the alternating aquifer and aquitard units is likely to be a poor descriptor of groundwater flow behavior. The complexity of rapidly alternating sand and clay units, combined with lateral facies changes and common fining upward units is evident. Section 3.6 on the Springbok Sandstone characterisation study illustrates the complexity well.

New data arising from the drilling program will produce detailed lithologically based aquitard distribution maps similar to that undertaken for the Springbok Sandstone. This will be applied in low permeability sequences, such as the Westbourne, Eurombah and Evergreen Formations. The primary aim is to identify regional spatial variations in vertical hydraulic conductivity. This will be inferred from interpretation of geophysical logs, core analysis, seismic results and limited field pumping tests.

6.8.6 ONGOING REGIONAL GROUNDWATER MONITORING AND NUMERICAL MODELLING ANALYSES

On a regional scale, the only longer-term definitive proof of leakage rates between key hydrogeological units is from analysis of ongoing groundwater level monitoring data. This might show both lateral and vertical depressurisation effects. Regional monitoring results will be used to regularly recalibrate the regional groundwater model with the aim of improving leakage rate estimates.

6.8.7 CONSOLIDATED HYDROGEOLOGICAL MODEL OF THE SURAT BASIN

Through the course of the Stage 1 and Stage 2 programs, QGC (and other proponents) have been collecting large amounts of data. Furthermore, the analysis and interpretation of this data forms the fundamental basis for a detailed conceptual hydrogeological report. Hence, it is proposed that QGC produce an interim hydrogeological report in April 2013 with the reporting of the GEN3 model based on all hydrogeological and groundwater chemistry data available at the time. A consolidated report will be submitted in October 2014, as by that time the Stage 2 drilling will be completed and all chemistry and age dating will have been analysed and sufficient detailed potentiometric surface data will have been gathered.

6.9 SUMMARY

A potential comprehensive program of investigation, monitoring and analysis to understand the impact of CSG extraction from the WCM on pressures in adjacent formations has been devised. The program comprises many aspects from laboratory testing of core, to large scale field tests involving extensive monitoring (the scale of which has rarely been seen in Australia), to detailed chemistry and hydraulic analysis. A key aspect of this program is the integration of a diverse range of geological, chemistry, reservoir engineering and hydrogeological data to produce a consistent hydrogeological conceptual model. The evolving knowledge then feeds into many of the issues to be addressed in this WMMP. This work is specifically designed to enable early warning for unexpected impacts to be identified and appropriately dealt with. Regular reporting of both progress and results will enable dissemination of information on progress being made.

Commitments	Target completion date
Submission of aquifer connectivity studies progress report	April 2013
Submission of infrastructure connectivity report	October 2013
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

The above commitments are aimed at satisfying Condition 49b.

7.0

Groundwater quality monitoring and hydrochemistry program

7.0 Groundwater quality monitoring and hydrochemistry program

Condition 49d, 52, 62 and 65

Hydrochemical studies are a key component of QGC's wider aquifer connectivity studies and longer-term hydrochemistry programs will inform our understanding of water chemistry and water rock reactions in aquifer systems.

7.1 HYDROCHEMICAL TESTING PROGRAM

Discernible differences may exist in the hydrochemical signatures of water from different aquifers in the Surat Basin aquifer system. Significant differences in adjacent layers (e.g. aquifer against aquitard) allow calculation of vertical mixing rates where natural and/or induced vertical pressure differentials induce flow between underlying and overlying hydrochemical systems. This yields vertical leakage rates.

In the Stage 1 WMMP, QGC committed to a preliminary hydrochemical study, groundwater sampling, and a detailed analysis to define a hydrochemical model for establishing leakage rates and potential connectivity.

7.2 PROGRAM OBJECTIVES

The programs primary objective is to use available hydrochemical datasets to assess potential aquifer connectivity and this, in turn, rests on fulfilling these key secondary objectives:

- To evaluate hydrochemistry as a means of identifying specific water 'signatures' for each aquifer of interest
- To identify possible areas of preferential groundwater migration (highlighted by chemistry)
- To determine water quality as an accurate measure of K_v/K_h or, ultimately, flux
- To use hydrochemistry results to identify possible salinity changes within aquifers due to migration of adjacent poorer quality groundwater
- To determine groundwater ages in different aquifers via isotope fingerprinting.

7.3 SCOPE OF WORKS

To meet the objectives defined above the following scope of work has been proposed, namely:

- Hydrochemistry data compilation
- Desktop hydrochemistry study
- Preliminary hydrochemistry conceptual model
- Isotope studies
- Integrated hydrochemistry study/report.

7.4 HYDROCHEMISTRY DATA COMPILATION

Hydrochemistry information is being compiled using these water chemistry datasets:

- Datasets from previous reports
- Existing water analysis results from QGC CSG wells in the WCM
- Analysis of results from farm bore assessments on both QGC and non-QGC owned land
- Analysis of results from QGC's monitoring bores
- Analysis of results from other relevant QGC programs – pond monitoring, shallow aquifer works, etc.
- Analysis of results from springs assessments and rainfall chemistry data (towards establishing water inflow/outflow characteristics)
- Aquifer water chemistry analysis results from other industry proponents
- Analysis of results from relevant DNRM monitoring bores.

Datasets need to be verified, validated and evaluated for accuracy and reviewed for limitations on applicability. Collection methodology, bore knowledge, field and laboratory QA/QC processes and data processing need to be considered. Preliminary datasets from QGC's Stage 1 monitoring bores have been compiled and a brief analysis completed and reported in Section 3.16.

7.5 DESKTOP HYDROCHEMISTRY STUDY

A desktop hydrochemistry study will use compiled and validated datasets along with other validated reports:

- To determine if sufficient chemical differentiation between aquifers can be identified
- To identify key individual parameters for use as aquifer 'signatures'
- To identify and discuss spatial and temporal trends occurring within and between aquifers
- To determine if migration of poorer quality groundwater into adjacent better quality aquifers might be an issue. This involves an assessment of possible mechanisms for groundwater salinisation and of the timing and magnitude of any possible changes. Results will feed into the groundwater quality response plan described in Section 12.0.

7.6 PRELIMINARY HYDROCHEMISTRY CONCEPTUAL MODEL

As part of the previously developed regional conceptual hydrogeological model (Golder Associates, 2011), QGC will develop a basin-wide hydrochemistry conceptual model using data and results from studies already completed. Data from other studies will also be used, including available springs water chemistry data (for 'start' points for water chemistry at discharge/recharge environments).

Conceptualisation begins with a series of key cross sections running throughout the basin. These will be selected to characterise basin hydraulic regimes and include any significant structural or geologic features. This will potentially enable water to be traced 'hydrochemically' from inflow/recharge zones (streams, creeks and springs) through the basin and water chemistry results from various aquifers and surface water bodies. Graphical representations include Stiff/Piper and Durov plots. This cross section study will be expanded as part of an integrated program.

7.7 ISOTOPE STUDIES

Groundwater isotope analysis is a long lead-time activity, with laboratory analysis taking three to six months from the time of sample collection. So a staged approach has been adopted, with initial studies to be completed without isotope data. In this way, preliminary hydrochemical conceptual models can be developed and isotope work brought into models to support and define conceptualisation.

Isotope studies involve defining data sources and raw results, detailing the analysis method(s) and processing the data to determine water ages. Reports are then generated detailing this process and presenting a discussion and interpretation of age results.

7.8 INTEGRATED HYDROCHEMISTRY STUDY

This study will link the isotope works to ongoing water sampling programs and associated hydrochemistry studies and bring the programs together. The aim is to generate an integrated hydrochemical conceptual model for the basin supported by water chemistry and isotope data.

7.9 PROGRAM PROGRESS

The following hydrochemistry following tasks have been completed:

- Water samples collected and analysed from the first 13 Stage 1 (shallow aquifer) bores installed Q3/Q4, 2011
- A preliminary hydrochemistry assessment of the water chemistry results. This assessment is discussed further in Section 3.16.
- Water samples collected from the first 13 Stage 1 (shallow aquifer) bores for isotope analysis with results pending
- Water samples collected and analysed from farm bores located on QGC-owned land. This data will be analysed as part of the Stage 2 WMMP.
- Water samples collected and analysed from a number of private bores throughout the tenements.

7.10 IMPLEMENTATION SCHEDULE

The hydrochemistry program implementation schedule is:

- Ongoing water sampling: Q1, 2013
- Preliminary Hydrochemistry Model: April 2013 in line with GEN3
- Isotope Studies: April 2013 – April 2014
- Integrated Hydrochemistry Study: October 2014 (including update of relevant datasets).

7.11 PROPOSED ANALYTICAL SUITES

The current hydrochemical analytical suite comprises:

- Field Suite: Physical measurements and observations during routine field (on-site) monitoring; and,
- Groundwater Baseline Suite: Field parameters and laboratory analyses including volatile and semi-volatile organic compounds. These results enable definition of groundwater characteristics.

Analytical suite details are shown in Tables 14 and 15. Sampling and analysis frequency is bi-annually.

Field suite	
Odour	Carbon Dioxide (CO_2) [1]
Appearance/colour	Methane (CH_4) [1]
Temperature	Hydrogen Sulphide (H_2S) [1]
Electrical Conductivity (EC)	Oxygen (O_2) [1]
pH	Carbon Monoxide (CO) [1]
Redox potential (Eh)	Peak LEL [1]
Dissolved Oxygen (DO)	
Depth to Water	

1. Gas concentrations, can be monitored using a calibrated gas meter.

Table 14 – Field suite

Groundwater baseline suite
Lab pH
Lab Electrical Conductivity (EC), Lab Total Dissolved Solids (TDS)
Total Alkalinity, Bicarbonate/carbonate (HCO_3- /CO_3 2-)
Sodium (Na+), Potassium (K+), Calcium (Ca2+), Magnesium (Mg 2+)
Chloride (Cl-), Sulphate (SO_4 2-)
Fluoride (F-)
Sodium Adsorption Ratio (SAR)
Ionic Balance
Metals (dissolved): aluminium, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, lithium, manganese, mercury, molybdenum, nickel, selenium, silver, vanadium, zinc, uranium
TPH, BTEX, PAH, including naphthalene, benzo(a)pyrene, VOCs, Phenols

Table 15 – Groundwater baseline suite

7.12 ISOTOPE PROGRAM

Groundwater was sampled at selected wells during 2011 for a series of naturally occurring isotopes. This will yield the age and origin of groundwater and becomes an important tool in identifying potential cross-aquifer leakage.

Isotope suite	Purpose	Application
Carbon-13 / Carbon-14	Provides age of groundwater, up to approximately 40,000 years.	Indicates residence times and hence recharge rates can be inferred.
Chlorine-36	Provides age of groundwater, from approx 100,000 to 1 million years.	Indicates residence times.
Deuterium	To characterise groundwater from specific aquifers.	Usually used in conjunction with Oxygen-18. Varies due to evaporation upon recharge.
Oxygen-18	To characterise groundwater from specific aquifers.	Usually used in conjunction with Deuterium. Varies due to evaporation upon recharge.
Strontium-86 / Strontium-87	May provide a 'signature' for groundwater coming from specific aquifers.	May indicate leakage between aquifers.

Table 16 – Environmental Isotopes

QGC has made arrangements with APLNG and the CSIRO for isotope sampling across a number of bores for the next two years. The company also has an agreement with the University of Queensland to fund isotope analysis of 50 samples from various aquifers in selected bores.

7.13 GROUNDWATER MONITORING PLAN

QGC provided an initial Groundwater Monitoring Plan as part of its Stage 1 WMMP (Appendix D). This plan was amended and resubmitted with Stage 2 WMMP (Appendix G.1). The plan will be further upgraded as part of Stage 2 activities with two upgrades coinciding with new groundwater data available from bore construction and baseline bore assessment programs. The first upgraded plan is scheduled for April 2013 with the final version planned for April 2014.

The interim Groundwater Monitoring Plan will be prepared in April 2013. At this time, QGC is of the view that the ongoing groundwater sampling program will comprise down hole data loggers with continuous (i.e. hourly) logging temperature and EC (if technically feasible) in all QGC monitoring bores. A telemetry system will be used to transmit this data. This will be underpinned by six-monthly sampling of the groundwater baseline suite. A review of existing groundwater quality data by APLNG, as shown in Appendix G.2, shows that for a sample of seven bores from various Surat Basin formations that have multiple laboratory water quality analyses available on the DNRM database, there is an average coefficient of variation (i.e. standard deviation/mean) of only 6% for total dissolved ions and only 4.2% for total dissolved solids. This data, which has been collected over decades, demonstrates that the water quality does not change greatly over the long term. Hence it is considered that very frequent sampling (e.g. monthly) is not necessary. The groundwater quality data will be evaluated and reported on an annual basis.

Many of the sub-programs detailed in Revision 0 of the GWMP (e.g. subsidence monitoring program, and springs monitoring program) are now covered under separate QGC monitoring plans developed during 2011 and 2012. As such, Revision 1 of the GWMP (April 2012 – Appendix G.1) is significantly revised from Revision 0. The GWMP is a live document and will be updated on an annual basis to account for the development of CSG field activities and regulatory changes. A number of the monitoring locations included within the current plan are still 'proposed'. Optimisation of the monitoring programs (the programs developed in the GWMP) will be carried out with consideration of the ongoing monitoring results.

Various modifications have also been made to the GWMP, including to the number and location of proposed groundwater monitoring bores, to take into account factors such as the latest numerical modelling results, directives from regulatory bodies, and land access, technical and geological constraints.

The Interim Groundwater Monitoring Plan will include monitoring bore and VWP locations as agreed in the Monitoring Network Implementation (MNI) Report in February 2013. Any proposed changes agreed for the MNI will be incorporated in the Stage 3 WMMP.

7.14 SUMMARY

The following hydrochemistry programs are proposed for the WMMP:

- Ongoing water sampling
- Preliminary hydrochemistry model
- Integrated hydrochemistry study
- Isotope studies.

Upgrades of the Groundwater Monitoring Plan are proposed for April 2013 and April 2014 as monitoring programs are implemented and new data collected, processed and assessed.

Commitments	Target completion date
Completion of interim Groundwater Monitoring Plan. QGC will continue to monitor the Walloon Coal Measures, Springbok and Gubberamunda Formations. Monitoring of the Mooga Sandstone where appropriate.	April 2013
Collection and analysis of six-monthly groundwater quality samples	Bi-annually
Implementation of the telemetry system for continuous groundwater level monitoring	Bores brought online progressively from March 2013
Completion of preliminary hydrochemistry conceptual model. Justification of water quality trend indicators	April 2013
Completion of Isotope studies	April 2013 / April 2014
Submission of integrated hydrochemistry report. Commitment to provide baseline definition of groundwater quality in the Northern Gas Fields.	October 2014

The above commitments are aimed at satisfying Conditions 49b and 52c (i) - (iv).

QGC is **investing in Queensland's future** by creating a new resource for beneficial use.