QGC
A BG Group business

# Appendix L
# Preliminary trend analysis methodology report

# Methodology for groundwater level trend analysis

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**GROUNDWATER PROJECT**

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# 1.0 GROUNDWATER LEVEL IMPACTS

It is recognised that there are a broad range of processes that could cause groundwater level fluctuations and trends. These operate at various spatial and temporal scales, as summarised in

Table 1, and include groundwater level fluctuations due to changes in air pressure, rainfall, land use change and groundwater pumping by water users, including CSG activities.

***Table 1 Summary of processes affecting groundwater levels***

| Temporal scale | Processes |
|---|---|
| **Small temporal scales** | Air pressure fluctuations<br>Earth tides, due to the moon's gravitational effects |
| **Medium temporal scales** | Seasonal recharge events<br>Local groundwater pumping<br>Recharge induced weight loading and discharge induced weight unloading |
| **Long temporal scales** | Regional groundwater pumping for water supply purposes (including stock and domestic pumping and free flowing bores, irrigation use, other users)<br>Land use changes affecting recharge<br>Groundwater pumping causing impacts by other CSG companies.<br>Groundwater pumping causing impacts by QGC |

It is intended that the QGC groundwater monitoring program will provide groundwater data suitable for analysis to identify any changes in groundwater levels over time. A rigorous method of trend analysis has been developed to help draw conclusions from the observed groundwater level data collected from monitoring network.

# 2.0 STATE GOVERNMENT GUIDANCE

The Queensland Department of Environment and Resource Management (DERM) has recently prepared a draft guideline which proposes the methods and inclusions for Underground Water Impact Reports and Final Reports (DERM, 2011). Included in this is guidance for the analysis of groundwater level trends in such reports. This includes:

- Preparation of underground water level (groundwater level) graphs using all data available;
- Presentation of underground water level trends along with rainfall (to display cumulative departure from the mean).
- Assessment of underground water level trends using data spanning pre- and post-commencement of CSG activities; and
- Assessment of underground water level trends using non-parametric statistical tests, such as the Mann-Kendall test described in Yue *et al*. (2002a), and linear regressions of the time series data.

The first reporting element above requires a simple plot of the raw data. Similarly presenting cumulative rainfall departure from mean rainfall conditions alongside the raw data is a simple technique that allows quick visual assessment of whether rainfall trends are strongly influencing groundwater level trends. Presenting trends in the data pre- and post-commencement of CSG activities is only dependent on knowing when the CSG activities commenced and whether there is sufficient data either side of this change point.

The last recommendation in the State Government guidance is to undertake a statistical trend analysis using tests such as a Mann-Kendall test and linear regressions.

# 3.0 TREND ANALYSIS

**Introduction to key statistical trend analysis concepts**

While a simple line of best fit through the observed data can help to determine the magnitude of any trend in that data, this approach has a number of shortcomings including that (i) it is not known whether the trend is discernable from the background noise in the data and (ii) the influence on this trend of factors other than QGC operations cannot readily be identified.

For this reason, DERM (2011) recommend the use of formal statistical tests (such as linear regression and the Mann-Kendall test) to assess whether observed trends can reliably be discerned from the background noise in the data. In order to apply and interpret statistical trend tests a number of key concepts need to be understood.

***The statistical significance of a trend is defined as the level of confidence that a detected trend is discernable from the underlying noise in the data***. Statistical significance is typically interpreted as per Table 2 (adapted from Chiew and Siriwardena, 2005). If the level of statistical significance is greater than 0.1, then a trend may be observed, but we cannot be confident that it is real. The trend could simply be due to random variation in the data. Importantly, if a trend is not statistically significant, it cannot confidently be attributed to any potential causes, including QGC operations.

***Table 2 Assessment of statistical significance***

| Level of statistical significance ($\alpha$) | Interpretation |
|---|---|
| $\alpha < 0.05$ (statistically significant at the 5% level of significance) | Strong evidence for trend |
| $\alpha < 0.1$ (statistically significant at the 10% level of significance) | Moderate evidence for trend |
| $\alpha > 0.1$ (not statistically significant at the 10% level of significance) | No clear evidence for trend |

***Serial correlation*** is a measure of the correlation between one data point and the next. Consecutive data points above or below the mean of the dataset at the start or end of a time series will bias the trend analysis results. All statistical trend analyses require that data should not be serially correlated in order to be able to reliably quote the statistical significance of a trend. We consider re-sampling analysis and data aggregation to longer time steps appropriate techniques where serial correlation was high.

## 3.1 Influence of analysis period

The period of analysis can influence the trend analysis results, as illustrated by examining groundwater level behaviour in a long-term regional groundwater bore (4223024), shown in Figure 1.

The data record for the regional bore 42230204 was broken down into three discrete sample periods. A linear trend was identified for each of these sample periods, with the period of data selected for the trend analysis heavily influencing the resulting trend estimate. It can be seen from Figure 1 that there was an upwards trend from 1966 to the early 1990s, followed by a relatively steep increase in groundwater level to the mid-1990s. The most recent period displays a much flatter trend than both earlier periods. This example highlights the importance of the period of record over which a trend analysis is undertaken, as very different conclusions will be drawn about groundwater level behaviour based on examining the whole period of available data versus a shorter, more recent period.

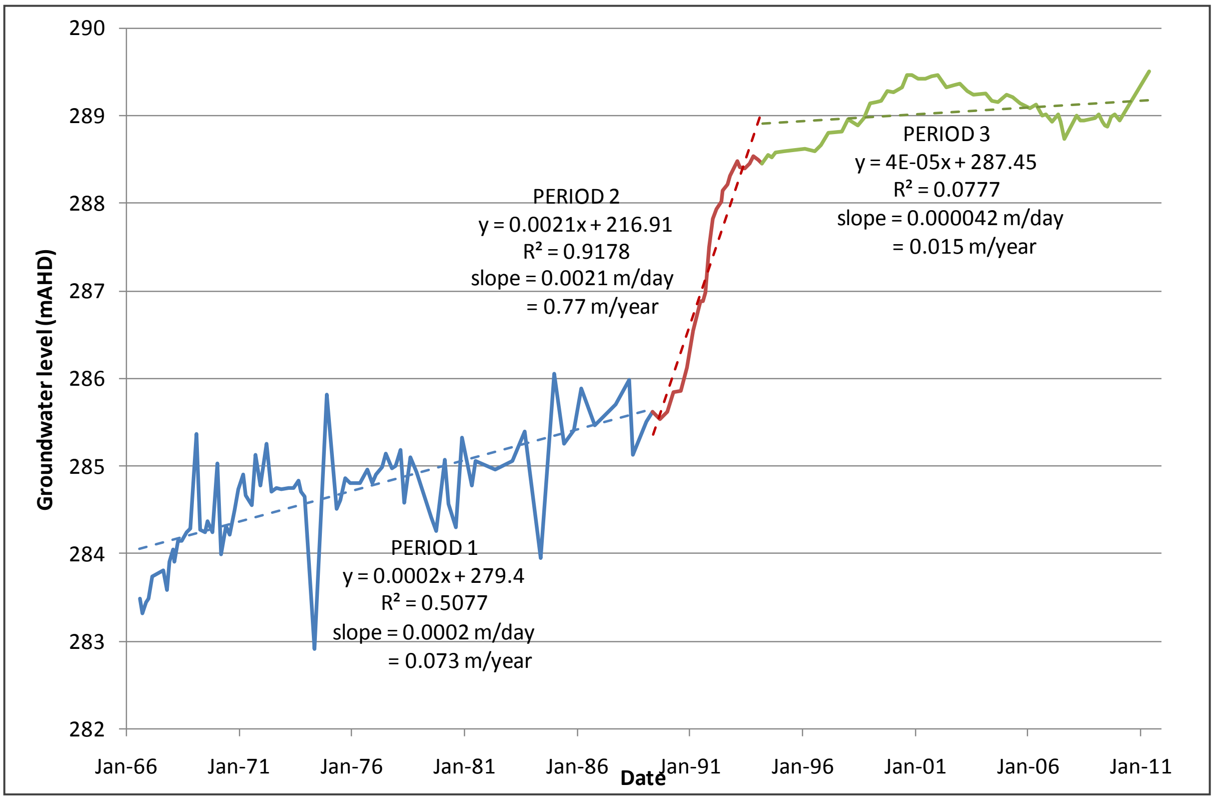


***Figure 1: Groundwater level trends for site 42230204***

Each of these three periods of data were analysed using the linear regression and Mann-Kendall tests. The results of this analysis are presented in Table 3. Using the linear regression and Mann-Kendall tests, a statistically significant trend to the 5% level of significance (strong evidence for trend) is observed for the first data period. During this time, groundwater levels were rising at a rate of 0.073 m/year. Analysis of the second period of data also indicates an increasing groundwater level, with both the linear regression and Mann-Kendall test indicating a trend that is significant at the 5% level of significance. During this period, the groundwater level was increasing at 0.77 m/year. For the third period, it is unclear whether the observed trend is discernable from the noise in the data, with the linear regression indicating moderate evidence for trend but the Mann-Kendall test indicating no evidence for trend over this 17 year period.

The analysis was undertaken by separating the data into three discrete periods by visual inspection, which is considered be suitable in this case given the obvious changes in trend in the data. However, where data contains high variability, break points may not be easy to visually detect and further analysis may be required to help identify whether a break-point exists. If required, we will apply relevant tests such as the Distribution Free CUSUM test, Cumulative Deviation test and the Worsley Likelihood Ratio test, which are all readily available in statistical analysis software packages such as the e-water CRC’s TREND package. Each of the above tests provides an indication of the timing of any break-point in the data, and notes whether this break-point is statistically significant. Whilst conceptually these tests perform similar analyses, the outcomes can differ. Visual inspection may still be required to confirm which test result is most appropriate for a given data set.

*Table 3 Summary of trend analysis results for bore 42230204 using three sample periods*

| Trend test | Period of analysis | Level of statistical significance | Trend magnitude |
|---|---|---|---|
| Regional groundwater bore 42230204 raw data – Period 1 | | | |
| **Linear Regression** | 1/8/1966-7/2/1989 | 5% (strong evidence for trend) | 0.073 m/yr |
| **Mann-Kendall** | | 5% (strong evidence for trend) | N/A |
| Regional groundwater bore 42230204 raw data – Period 2 | | | |
| **Linear Regression** | 25/5/1989-31/1/1994 | 5% (strong evidence for trend) | 0.77 m/yr |
| **Mann-Kendall** | | 5% (strong evidence for trend) | N/A |
| Regional groundwater bore 42230204 raw data – Period 3 | | | |
| **Linear Regression** | 6/4/1994-9/6/2011 | 10% (moderate evidence for trend) | 0.015 m/yr |
| **Mann-Kendall** | | Not statistically significant (no evidence for trend) | N/A |

## 3.2 Raw groundwater trends

The raw groundwater level data for Berwyndale South GW1 is presented in Figure 2. A line of best fit is fitted to the data in Figure 2, which indicates a general increase in groundwater levels over time. The magnitude of this trend over the 6 week period of available data was an increase of 0.57 m/year. Fluctuations in the data are evident on a number of temporal scales including hourly, daily and weekly.

Rainfall has the potential to influence recharge, although this is not generally significant in the short term for bores located in confined aquifers or some distance from recharge sources. In these situations, rainfall can drive seasonal changes in groundwater level, and rainfall trends can affect groundwater levels on a long term (annual to decadal) timescale.

Figure 3 presents rainfall and groundwater level data for the Berwyndale South bore. The upper panel indicates the timing of rainfall events at this location, while the lower panel presents the cumulative deviation from the mean daily rainfall. Over most of the 6 week period of analysis, the rainfall is in deficit at this site. The groundwater level data is presented for comparison. Further analysis was undertaken by considering the possible relationship between absolute rainfall and the cumulative difference from the average rainfall conditions with the groundwater bore level, including assessment at different time lags. No relationship was identified at this location.

In general, this assessment indicates confirms that rainfall does not significantly influence trends in groundwater levels at this site. While this could be a function of the distance of the rainfall gauge from the bore site, analysis of local rainfall data indicated that the behaviour was generally consistent in the region. This rainfall site was used in the analysis as it provided a period of data concurrent with the available bore data.

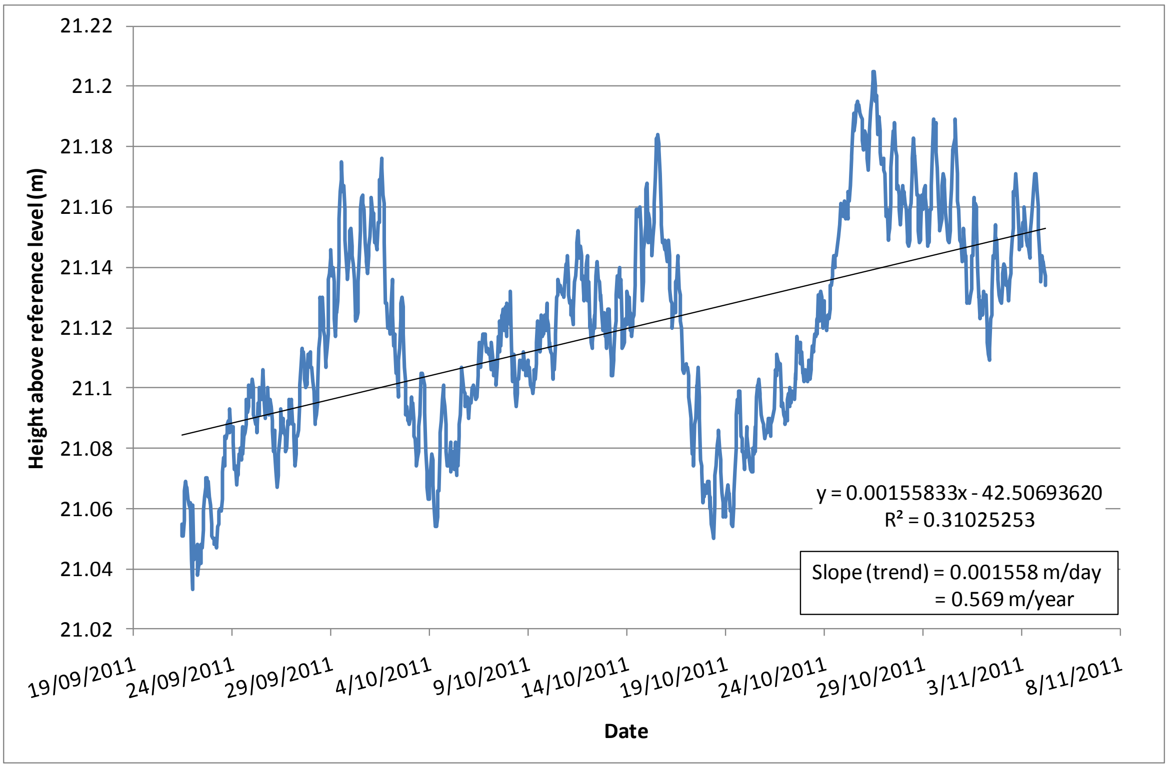


***Figure 2: Groundwater level time series and linear trend for Berwyndale South GW1***

## 3.3 Accounting for external influences on groundwater levels

The identification of a trend in bore does not provide information on any potential cause of that trend. Further details are required to better understand the influence of particular physical and anthropogenic processes on the groundwater level. This section provides an example investigation into the influence of air pressure and earth tides on groundwater levels.

A data logger located close to the Berwyndale South GW1 site provides a time series of air pressure over a period concurrent with the Berwyndale South groundwater level data. Manual analysis of this data can be undertaken to determine the link between groundwater level and barometric pressure, however specific software is also freely available. In this instance, we used the BETCO program developed at the University of Georgia to remove fluctuations due to barometric pressure and earth tides in aquifer water level measurements using a multiple regression technique. Further information on the software is available online: http://www.hydrology.uga.edu/rasmussen/betco/.

Applying this software with the Berwyndale South GW1 bore data and local barometric pressure data generates a time series that reflects adjusted groundwater levels to account for the pressure fluctuations. A trend analysis was undertaken using this modified time series, and the results are presented in Table 4. Both the linear regression and Mann-Kendall test identify a statistically significant trend at the 5% level of significance. The linear relationship indicates that groundwater levels are rising at a rate of 0.55 m/year independent of air pressure fluctuations.

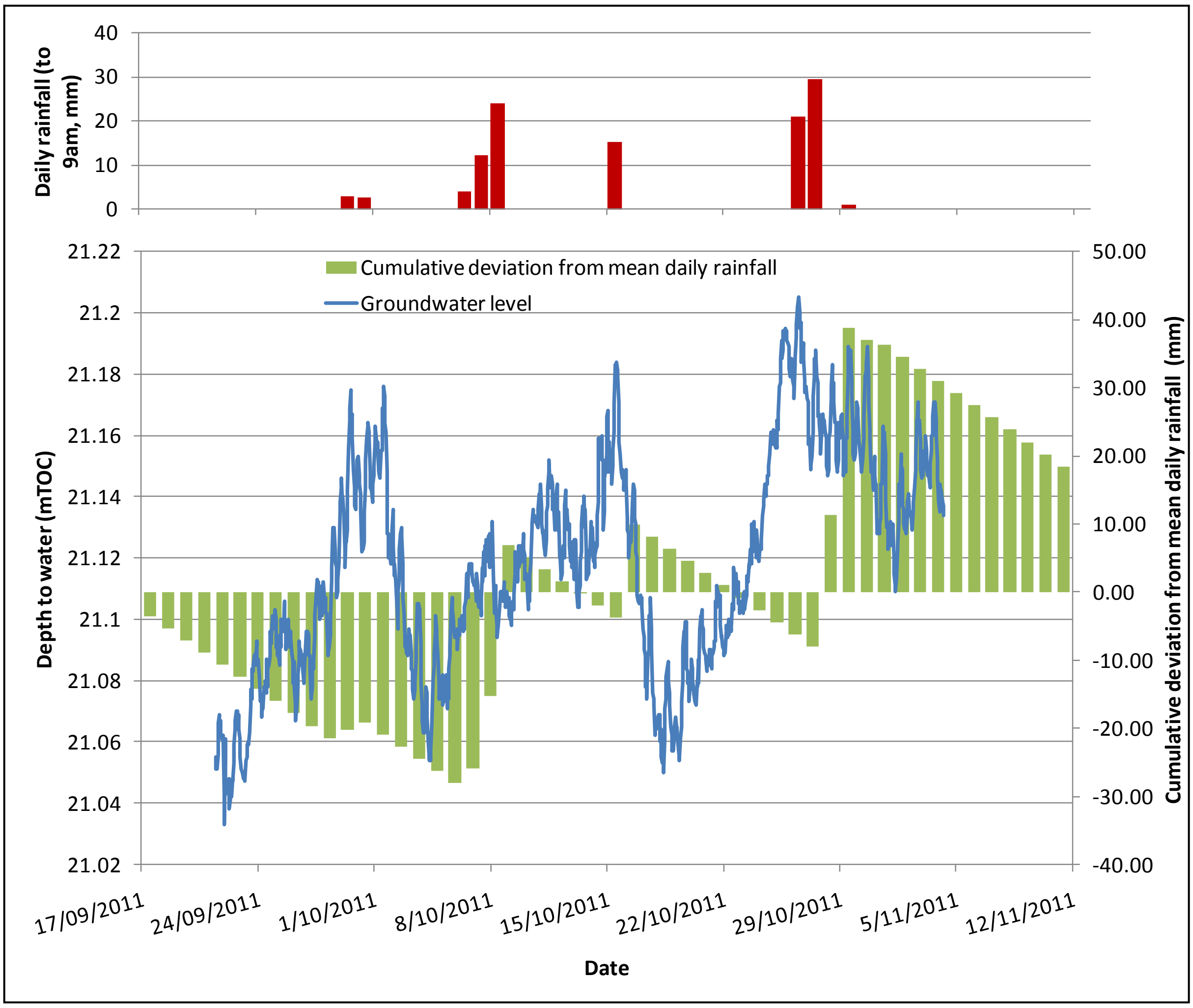


***Figure 3: Groundwater level, daily rainfall and cumulative deviation from the mean daily rainfall for Berwyndale South GW1***

Water-level changes can occur due to aquifer deformation of which the main causes are earth tides,. The tidal effects on groundwater, commonly called earth tides, have nothing to do with the oceans, but are related to the gravitational effects of the Moon and Sun. Changes in gravitational attraction causes a slight dilation of some aquifers, which in turn temporarily changes the aquifer porosity a slight amount. Wells showing tidal effects show two maximum and two minimum water levels per day, each of which are about 6 hours apart.

The effect of earth tides on groundwater level data can be considered using existing, readily downloadable software packages, including the BETCO tool. Time series data on earth tides is also available to be generated using various online software products. The TSOFT product developed at the Royal Observatory of Belgium was utilised in this assessment (http://seismologie.oma.be/TSOFT/tsoft.html). A synthetic time series of earth tides was obtained using TSOFT, and applied in the BETCO software to generate a modified time series of groundwater levels that account for both barometric pressure and earth tides.

Figure 4 presents the adjusted time series data with the raw groundwater level data for comparison. A linear trend line has been fitted to the adjusted groundwater level data, which accounts for the influence of both air pressure and earth tides. The trendline for the air pressure adjusted data is also very similar to this line. Table 4 presents the outcomes from this trend analysis assessment. Both the linear regression and the Mann-Kendall indicate strong evidence of an upwards trend in this adjusted data. A trend magnitude of 0.58 m/year is observed.

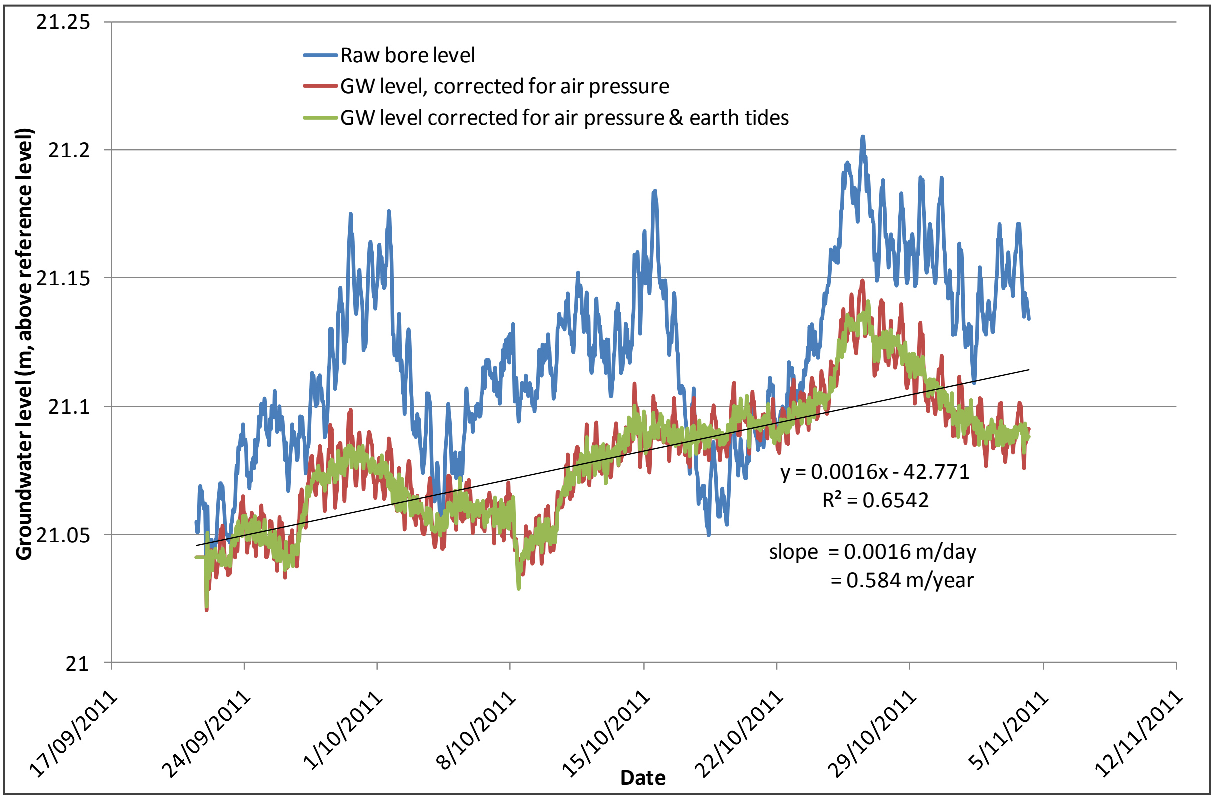


***Figure 4: Groundwater level accounting for air pressure and earth tides***

***Table 4 Summary of trend analysis results using groundwater level, accounting for air pressure and earth tides***

| **Trend test** | **Period of analysis** | **Level of statistical significance** | **Trend magnitude** |
|---|---|---|---|
| **Accounting for air pressure** | | | |
| **Linear Regression** | **21/9/2011-4/11/2011** | **5% (strong evidence for trend)** | **0.55 m/yr** |
| Mann-Kendall | | 5% (strong evidence for trend) | N/A |
| **Accounting for air pressure and earth tides** | | | |
| **Linear Regression** | **21/9/2011-4/11/2011** | **5% (strong evidence for trend)** | **0.58 m/yr** |
| Mann-Kendall | | 5% (strong evidence for trend) | N/A |

## 3.4 Frequency of monitoring required for trend analysis

Data at the Berwyndale South groundwater bore was available on an hourly time step. The process of assessing whether a trend is discernable from the background noise in the data (i.e. the statistical significance of trends) is invalidated when the input data is highly serially correlated. We examined the lag-1 serial correlation (i.e. the correlation between a given data point and the preceding data point) at this bore to identify whether averaging data over a longer time interval may help to avoid serial correlation in the data. The results of this analysis are shown in Table 5.

The hourly data recorded exhibits high serial correlation, reflecting the high frequency of monitoring. A revised time series was generated by taking time weighted averages on a daily and weekly time step. The Berwyndale South data is still highly correlated when revised to a daily basis, however the data points were considered independent when the data is revised to a weekly time step. Based on the results presented in Table 5, weekly averages are considered sufficient for trend analysis at this site.

***Table 5 Summary of serial correlation tests***

| Data analysed | Serial correlation result |
|---|---|
| **Berwyndale South GW1 bore site** | |
| Hourly groundwater level | Serially correlated |
| Average daily groundwater level, calculated from hourly data | Serially correlated |
| Average weekly groundwater level, calculated from hourly data | Independent |

The frequency of monitoring in regional bores is considerably longer than that collected for the bores within QGC development areas, and the two data sets do not easily align. For this reason, we seek an increased monitoring frequency in a selection of regional DERM groundwater bores to better align local and regional data sets for trend analysis.

## 3.5 Missing Data

Missing data can confound a trend analysis by introducing bias into the trend results. For example, if data is missing towards the end of the period of analysis and that corresponds to a period of relatively high groundwater levels, then excluding that data from the analysis will reduce any observed trend. If missing data is randomly distributed throughout the period of analysis then it may not necessarily affect the trend analysis results. As a rule of thumb, it is proposed that where groundwater level data in the bore of interest is missing for less than 5% of the record over the period of analysis, that data should be infilled. The technique for infilling will depend on the site of interest. Where the amount of missing data is more than 5% of the record, particularly where that missing data is at the start or end of the record, then the trend analysis should not be undertaken.

# 4.0 METHOD OF ANALYSIS FOR ONGOING APPLICATION

A method for ongoing application has been developed to provide a mechanism to monitor and assess changes in groundwater levels over time. The QGC approach takes into account DERM (2011) draft guidelines on underground water impacts, and includes the following key steps:

- **Collate available data for analysis**. This data will include groundwater levels, rainfall, atmospheric pressure, earth tides, and groundwater pumping data as available. Data will be reviewed for any obvious data anomalies, and any missing groundwater level data will be infilled up to not more than 5% of the record over the period of analysis. The resulting data set will be aggregated to a suitable time step for trend analysis. Based on a review of data currently available from bore loggers, an average weekly time step has been identified as being suitable to reduce serial correlation in the groundwater level data. The time step applied will be adapted as more data becomes available if required to maintain the statistical assumptions inherent in the trend analysis.
- **Plot groundwater level against the cumulative deviation from mean rainfall conditions**. This provides a coarse overview of the relationship (if any) between rainfall and groundwater level, as specifically recommended in DERM's guidelines.
- **Select periods of analysis for raw data trends**. The periods of analysis ideally need to be a minimum of 12 months, however initially the period of analysis should cover the period of all available data. A break-point analysis can be undertaken to identify whether recent periods of data are significantly different to earlier periods, thereby allowing the separate identification of current trends over a shorter, more recent period of analysis.
- **Develop and apply a multiple regression model** between groundwater level and other data sets, such as rainfall, air pressure and earth tides as available, over the period of analysis covering the whole period of available data. A time series of change in groundwater level independent of fluctuations in known non-QGC influences will be calculated, and the break-point analysis repeated using this time series. Existing software tools such as BETCO and TSOFT may be used for this step.
- **Undertake statistical analysis to assess trends.** This will utilise statistical tests such as linear regression or the Mann-Kendall trend test. We intend to use the eWater CRC TREND software package to undertake this analysis. As relevant, this analysis may consider the raw data and the time series of change data sets for the full period of record and the data following any break-point.
- **Repeat this process on an annual basis**. The results from the analysis will be collated. Where bore level data for both pre- and post-pumping periods is used for analysis, the trend analysis results can provide an indication of changes relative to the conditions prior to any CSG development. In locations where data is only available after pumping has commenced, the trend analysis outcomes can only provide an indication of changes relative to the conditions at the start of data collection.

This method has been developed and tested using currently available groundwater level data. As more information is collected about groundwater level behaviour in the vicinity of QGC activities, this method may be refined to provide an adaptive approach to the management of potential groundwater impacts. In particular, alternative data treatments or statistical tests may be more informative if the observed long-term trends are non-linear or if groundwater level responses occur at intervals shorter than 12 months.

## 5.0 CONTROL CHARTS

Control Charts offer an alternative or complimentary approach to trend analysis, which may be more suitable to provide an early warning signal in real time on groundwater level changes to minimise the risk of non-compliance with licence conditions. Control charts are similar to parametric trend analysis in that they rely upon a model fitting procedure, but instead of identifying historical trends looking backwards, they identify deviation from reference behaviour moving forward. They also allow greater engagement with the model and an understanding of the behaviour of individual data points. We will evaluate the use of control charts as an additional tool to assist in monitoring groundwater levels.

## 6.0 INDUSTRY COLLABORATION

QGC has been actively discussing various groundwater level trend analysis approaches with Santos and Origin. General agreement has been reached with our industry collaborators on the overall methodology which is presented above. Consistent with this methodology, QGC plans to undertake the first trend analysis of groundwater level behaviour when 12 months of data has been collected."

## 7.0 REFERENCES

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