Peer Review of the HB02 Pump Test (October, 2009) and the PB Report "Broke Groundwater Investigation and Monitoring Report - AGL Hunter Gas Project".

DRAFT FOR DISCUSSION AT 24 MARCH 2010 BCCC MEETING

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1. Background

In late 2008 Professor Garry Willgoose was contacted by the Bulga Community Consultative Committee (BCCC) to provide peer reviewing of the water resources impacts of proposed work by AGL as part of their exploration work for coal seam gas in the Broke region.

In the first instance a proposed program of work was agreed in December 2008 that involved:

1. Background monitoring during 2009 of the surface and near surface groundwaters in the vicinity of Broke and AGL's HB02 well. The objective of this work was to provide sufficient data to characterise the local surface groundwaters, a background sufficient to be able to monitor for any possible impacts from any of AGL's subsequent activities, and to provide a baseline against which an impacts from a pump test at HB02 could be monitored and assessed. In particular whether pumping from HB02 will have any impact on wells used by farmers or the local groundwater dependent ecosystems.
2. A pump test at HB02 to be carried out once sufficient background data had been collected.

Parsons Brinckerhoff (PB) described this work in detail in a program of work as part of a proposal to AGL at that time.

Subsequent to the approval of the PB program of work during early and mid 2009 PB collected the background data. On 17 September I assessed that adequate data (both quantity of data and range of environmental conditions) had been collected to allow any reasonable impacts from the pump test to be assessed and I advised BCCC that I was happy for the pump test to proceed.

The pump test was carried out during October, 2009. I was involved in oversight of the pump testing to ensure that no untoward impacts of the pump testing occurred.

In early February, 2010 PB delivered to me a draft copy (i.e. pre-AGL review) of the report discussed the background monitoring and pump testing. In 9 February a meeting was held in my office at the University of Newcastle with representatives from PB, AGL and BCCC to discuss the content of the draft report. In late February a final copy (i.e. post-AGL review) of the report was delivered to me. There were only minor copy editing differences between the pre- and post-AGL review copies.

On 9 March a meeting was held in my office between myself, PB and AGL, including one of AGL's reservoir specialists. Though invited Bob Campbell was unable to attend this meeting due to a pre-existing commitment. This meeting discussed technical issues arising out of preliminary results from the peer review.

On 10 March a preliminary report was provided to the BCCC meeting.

This peer review report provides an assessment of

1. The efficacy if the background monitoring.
2. The pump test carried out by PB at AGL's HB02 well in October, 2009,
3. A peer review of the report written by PB that summarises the background monitoring carried out at and near HB02 during 2009, and the analysis of the pump test results.
4. An assessment of any impacts on the surface waters from the pump test.

5. An assessment of the implications of these data for the future planned flow test at HB02 and other wells in the region proposed by AGL.
6. Recommendations with respect to continued monitoring at the pump test site.
7. Assessment of whether the pump test provides any insights into potential impacts and/or interactions with long-wall mining at some future time.

2. Background Monitoring

2.1 Geochemistry

There is nothing remarkable about the results from the background monitoring. The conclusions reached by PB with respect to interpretation of the geochemical and isotope data are consistent with the data.

Some notable results are:

1. Salinity increases as the depth of the well increases. This is consistent with the groundwater hydrology of the alluvials being dominated by rainfall recharge rather than groundwater from the deeper regional groundwater system. The gradient of conductivity and the consistency of the geochemistry suggest that there is some (minor) mixing of the water from the seams, as indicated by PB.
2. There appears to pollution of the alluvial aquifer with agricultural fertiliser or manure leachate at BM02. There are elevated nitrogen, phosphorus and potassium concentrations in the BM02S sample which is consistent with nutrient pollution.
3. The Sodium Absorption Ratio (SAR) for the alluvial aquifers indicates that it may suitable for irrigation (SAR < 5). The monitoring wells into rock are sodic and are not suitable for irrigation for extended periods of time without damaging the soil structure (SAR 5-15). The water from HB02 is extremely sodic (SAR=112), and would seriously damage soil structure and would be toxic to most vegetation.
4. The salinity of the waters is such that only water from the alluvials around BM03 would be suitable for human consumption, the water from all of the alluvial monitoring sites would be suitable for stock watering, and the deeper waters into rock are marginally suitable for stock watering (ANZECC, 2000).

2.2 Isotopes

The isotope testing is a state-of-the–art technique for understanding the sources, pathways and timing of the water recharge to the aquifers under natural conditions. As noted by PB the marked differences in the ages between the surface waters and the deeper aquifers is strongly suggestive that under natural head conditions the aquifers are disconnected. The tritium data in particular shows no movement from the alluvial groundwater (the tritium came from atmospheric nuclear testing in the period 1950-1970) in the 60 years since the start of nuclear testing.

There are three possible sources for the water in the Blakefield Seam.

(a) **Connate Water:** This is the water that is trapped in the aquifer when the sediments for the aquifer were laid down in the Permian. It is unlikely that the water is more than partially connate because the salinity is low relative to sea water level concentrations in the Permian than might be otherwise expected.

(b) **Vertical seepage from above:** The background gradients from the surface to the aquifer are a few 10's of metres so the driving gradient from the surface to depth is low. If the surface waters were significant component of the recharge to the aquifer then the 20,000 year age in the Blakefield would suggest an average conductivity from the surface to the Blakefield of about 0.06m/year or 2 x 10^{-4} m/day, which are so low that flow quantities would be insignificant. Moreover, the lateral conductivities measured in the alluvials by PB are several orders of magnitude higher than the conductivities of the Blakefield and aquicludes, suggesting that the preferred path for alluvial water would be laterally into the Creek. Accordingly I believe this mechanism is unlikely.

(c) **Horizontal along aquifer seepage from the recharge zone**: The dating and estimated lateral travel time are quite consistent suggesting that if this were not the preferred travel path for water under natural conditions then it is surprising coincidence.

The conclusion is that water in the Blakefield is likely to have travelled along the Blakefield seam from the recharge zone at the Blakefield outcrop about 7km to the NE.

2.3 Monitoring Well Heads

The data of the heads form the monitoring wells show two important features.

(a) The head differences in the aquifers from the surface alluvials down to the Wybrow seam is very small (less than a metre in most cases) suggesting that under natural conditions in 2009 that there is unlikely to be significant flow from the surface down to the deeper aquifers or vice versa. This is consistent with the evidence from the isotope data which also suggest no vertical movement.

(b) The heads in each of the wells vary only slowly under natural conditions, in most cases less than 0.1m over the monitoring period in 2009. This if there had been connection between the Blakefield seam and the shallower aquifers then the impact of drawdown from the pump test should have been visible in the water levels in the monitoring wells. Based on the cone of depression derived from the pump test analysis in Section 3 it is likely that BM03 and to a lesser extent BM01 should have seen some change in water levels if there had been significant leakage between the Blakefield and the surface. The more distant wells like P8 are unlikely to have seen any water level changes even if there were leakages because they were too far from the cone of depression.

3. Pump Testing

This section summaries the results of the analysis of the pump test done by the peer reviewer and the comparison of this independent analysis with the results derived by PB in their report.

3.1 Pump Test Interpretation

PB analysed the pump test using a method for pump test analysis, Jacob analysis, which assumes that the aquifer has constant conductivity and storativity in space and time, and that the pumping rate is constant in time (see Appendix A4 for a discussion of the definitions of conductivity, storativity and porosity). Using this method they then identified that in fact the conductivity is not spatially constant, invalidating the assumptions of the Jacob method used to derive this conclusion. I agree with PB’s qualitative conclusion that the conductivity of the aquifer reduces with distance with the well. The downward curvature of the drawdown in time is strongly consistent with this conclusion. However, I have difficulty supporting PB’s quantitative conclusions regarding the exact numbers derived for conductivity because of the invalidity of the use of the Jacob method in this application.

I concluded that the best way to check the derivation of the quantitative predictions for conductivity was to develop a computer model for flow into the well that correctly reflected the hydraulic conditions indicated by the qualitative conclusions in the previous paragraph. Much of the subsequent discussion in this section results from this analysis. The technical details are provided for the reader's interest in Appendix A.

3.2 Evidence for any pump test impacts in monitoring well water levels

The monitoring wells are the first indicator of aquifer leakage. Their response to the leak will be an almost instantaneous drop in water level. The level of drop is an indicator of the strength of the leak. There are a number of caveats to their use:

1. This method will only indicate if there are leaks within the range of the cone of depression within the aquifer as a result of the pumping. As will be indicated below this is a function of the storativity of the aquifer, and the variation of the conductivity of the aquifer with distance from the well (as a result of the fraccing process). Both of these properties are difficult to estimate from a single well pump test.
2. If the monitoring wells are too far from the well relative the cone of depression then the wells become less sensitive to any pressure drops due to leakage.

In both cases the peer reviewer believes that enough of the monitoring wells were close enough to the well to observe any potential impacts of aquifer leakage.

There is nothing in the monitoring data from other wells to suggest any impact from the pump test. Neither the geochemistry nor the water levels of the monitoring wells was impacted during the event. What little variation there is in well levels in entirely consistent with natural variations in rainfall recharge and evaporation, and atmospheric pressure variation. Recharge and evaporation tend to exhibit themselves as gradual variations in water level and sometimes a pulse of water level increase soon after a rainfall event. An atmospheric pressure increase will depress well levels by a little less than the increase in the atmospheric pressure and the impact is virtually instantaneous (a 10mbar pressure increase will result in a 100mm drop in water level in a well into a confined aquifer and somewhat less in an alluvial aquifer). The changes in the water level traces in the report are entirely consistent with these processes and the variations observed occur both during the pump test and before it. There is nothing in the data to suggest a direct link between the pumping and any property measured in the monitored aquifers during or immediately after the pump test.

3.3 Evidence for pump test impacts from the geochemistry data

The background monitoring data provides a baseline from which any changes of chemistry can be assessed. For each of the chemical species the background data provides a range and time trend against which any observed changes during the pump test can be compared. It should be noted that the geochemistry data is always a trailing indicator of leakage because it takes some time for the leaking water to travel the distance from the leak to the well, so geochemical indications of leakage will always occur after the leak is detected by pressure drops. Given that the seismic survey does not indicate any faulting in the region of HB02 it is highly unlikely that a geochemical change as a result of leakage would occur without a pressure drop in the monitoring wells, provided the wells are within the cone of depression, so geochemical changes on their own are unlikely to be an indicator of leakage.

During the pump test the conductivity of the water being extracted was monitored. This was done both inline in the outlet pipe of the well and in samples taken from the water discharged (these samples were also analysed for geochemistry). Neither of these results indicated any contamination by water with a different salinity or chemistry (which would have been indicative of leakage from an adjacent aquifer). This result is consistent with there being no leakage from an adjacent aquifer. However, it does not guarantee no leakage: e.g. if an adjacent aquifer had identical salinity and/or geochemistry leakage from this aquifer would not show up in this monitoring.

3.4 Region of impact from the pump test

As indicated in the PB report the region of impact of the pump test is largely a function of the storativity of the aquifer. This factor cannot be estimated using the techniques employed in the PB report. PB suggest that a typical storativity for coal seams is 10^{-4} to 10^{-6}. PB note that value is not derived from the pump test because the method they used for analysis of the pump test data does not provide information on that. However, they suggest that this is consistent with results from similar coal seam aquifers. On this basis PB indicate a region of influence of the pump test between 40-400m from HB02. However, it is believed that PB have used analytic solutions for region of influence that rely on there being a spatially constant conductivity in the aquifer. The cone of depression from the aquifer test is a function of both the conductivity and storativity, so the numbers quoted by PB should be viewed with a degree of caution. Even without the spatially variable conductivity issue the reliability of estimation of the storativity in the PB report is low (they have simply taken typical values for coal, because they cannot estimate it from the pump test) which leads to the large range of 40-400m estimated by PB.

The groundwater model used in this report was able provide a slightly better estimate of storativity. This was of the order of $10^{-3,}$ almost an order of magnitude larger than that suggested by PB. However, even for the model there is a degree of uncertainty because it is difficult to estimate the conductivity and the storativity independently of each other (see Appendix A), and this interdependence feeds into uncertainty of the size of the cone of depression.

Accordingly, the peer reviewer cannot provide a reliable estimate of the region of impact of the pump test within the aquifer. However, all of the results in the modelling suggest that it lies at the lower end of the range suggested by PB and probably in the range 20-50 m out from the well.

3.5 Any evidence for leakage from pump test data

There are four lines of evidence for leakiness in a pumped aquifer. In order of reliability they are:

(a) The first line of evidence is that the heads in the adjacent aquifer should drop while the pump is being carried out and then recover after the pump test is finished and as pumped aquifer recovers. This should occur for all forms of leaks that are within the cone of depression of the pump test.

(b) The second line of evidence is that there are various characteristic forms the well drawdown will take during a pump test if a leak occurs within the cone of depression of the pump test. Section A5 discusses this in some detail and provides some examples of what should be observed if this occurs.

(c) The third line of evidence is that the geochemistry of the water being pumped from the well might change. This depends on there being a contrast in geochemistry between the pumped and leaky aquifers. Secondly it depends on the water leaking from the adjacent aquifer actually being drawn into the well. If the pump test is short there may not be enough time for the water to travel from the leak to the well, in which case the leak will not be detected.

(d) The geochemistry of the water in the monitoring wells might be different before and after the test, indicating exchange between aquifers.

Examination of the monitoring wells shows no evidence of head changes consistent with that expected to be caused by the pump test if leakage were a factor.

The pump test drawdown curve has a downward curvature (i.e. its gets steeper with time). This is the exact opposite of what would occur if a leak was occurring within the cone of depression of the well.

The groundwater geochemistry monitored during the pump test did not change significantly through the pump test.

The geochemistry in the monitoring wells did not change significantly from that observed in the background monitoring.

Based on these four lines of evidence I conclude that the evidence is consistent with there being no significant leakage into the Blakefield seam during the pumped test from any form of leak with 20-50m of the well (my estimate of the extent of the cone of depression during the pump test).

3.6 Comparison of aquifer parameters with other regions

While the results of the peer review study are preliminary it appears that the upper bound on the groundwater conductivity is about 0.1m/day (and this high only in the immediate vicinity of the well) and it is more likely in the range 0.01 to 0.001m/day for much of the rest of the aquifer.

To put this value in context a recent study of groundwater impacts in the Powder River Basin used values (which were quoted as having been derived from pump tests) for conductivity of 0.1-8 m/day, or 10-1000 times higher than in the PB report (Wheaton and Metesh, 2001, 2002). They found storativities in the range 9×10^{-4} to 3×10^{-4}. Wheaton (personal communication) indicated that most of these data were for coal seams that were not gas generating (see Appendix A4 for a discussion of the importance of gas generation).

Weeks (2005) found conductivities for a pump test in a 7m coal seam in the Powder River Basin of 0.9-2 m/day and a storativity of $1.4\text{-}2 \times 10^{-5}$. Weeks compared his results with previous authors work in the Powder River Basin and found storativities in the range 1.5×10^{-4} to 2×10^{-5}. Notably Weeks excluded some pump test data on the basis that it was noisy as a result of gas generation. It is not clear whether the remaining pump test data used in his analysis included gas generating wells. Morin (2005), in a paired paper with Weeks, calculated storativities of 2.2 x 10^{-6} using a geophysical method that included only coal seam compressibility (see Appendix A4).

Myers (2009) in a regional groundwater model for the Powder River basin calibrated his model to observed drawdowns as a result of coal bed gas extraction. His estimated storativities were in the range 9 x 10^{-4} and 3 x 10^{-7}, and assumed a porosity of coal at depth of 0.02.

Rehm et al (1980) reviewed datasets on conductivity and storativity for coal and other materials in the Montana and North Dakota. The area considered included the Powder River Basin but also encompassed a number of other local coal provinces. They found conductivities for coal in the range from 0.8-2 m/day. They found storativities in the range of 10^{-4} to 10^{-8}.

In conclusion the conductivities found by PB and myself are significantly lower (by between 10x and 100x) than those estimated in the Powder Basin.

3.6 Conductivity estimates for the monitoring wells

While not a core part of the pump testing PB carried out, falling head tests (sometimes called slug tests) (PB's Appendix H) were performed on the monitoring wells (i.e. BM01, BM02, and BM03) and estimates of conductivity derived. For the alluvials conductivity results are in the region 20-150 m/day, consistent with published data for alluvial materials. For the deeper wells in the rock conductivities drop to about 1-5m/day, consistent with a shallow modestly impermeable rock. The analysis method did not allow the estimation of storativity for the deeper confined aquifers and specific yield for the alluvials.

4. The Regional Groundwater Regime

4.1 Possible interconnection between the deep aquifers and the surface

The pump testing did not show an obvious interconnection with adjacent aquifers (i.e. leakiness) but this conclusion can only be drawn for the small area of the aquifer that was impacted by the cone of depression of the pump test. The pump test does not provide any direct information on the leakiness outside of that cone of depression.

AGL provided the peer reviewer with seismic surveys of a transect that followed a route from east to west starting about 5 km east of Broke township. The route followed was Broke Road-Broke township-Charlton Road-Fordwich Road-Milbrodale Road-Putty Road and stopping near the entrance to Howes Valley. This transect is useful because it provides broadscale information about the geology down to 300-400m below the ground surface, and is sensitive enough to pick up large fault lines and other changes in geology. While there is a gap in the data directly under Broke township (the seismic survey was not done in the village) the stratigraphy on either side is horizontal, smooth and it appears to be continuous from one side of the town to the other. This suggests that the transect along Broke Road does not appear to be intersected by any problematic geology.

Moreover, the fact that the transect takes a right angle turn in the township provides some confidence that there is no faulting at the right angles to Broke Road. West of Broke along

Milbrodale Road there appear to be some small low angle faults that penetrate part way through the cross-section. Near the township of Bulga there is a large faulting structure penetrating the full depth of the cross-section.

The conclusion is that there appears to be no reason to believe that there are any major faults or interconnections between stratigraphy in the region of Broke. Given the uniformity of the seismic section this also suggests that the results from the pump test are likely to be typical of the region in the direct vicinity of Broke. More specifically this is within about a 3-4 km radius of the township in an easterly and northerly direction. The seismic data does not cover the western and southern directions from Broke so no statement can be made, based on the seismic data, for these directions.

4.2 Time of Travel of Pollutants from Mining to the Well Site

At a previous BCCC meeting the question was raised as to whether, how, and when potential pollutants might travel from local open cut mines to the well sites, and thus what the potential might be for open cut pollutants (e.g. acid mine drainage products such as high sulphates) to show up in the water pumped from the gas wells.

In Section 6.7 PB estimate the travel time under natural conditions from the recharge zone of the aquifer (to the NE) to the location of HB02. These calculations are incorrect and they are compounded by some inconsistencies in their regional groundwater model (Figure 3.2).

1. A dip of 5-10 degrees is quoted for the aquifer yet the elevation of the land 7km to the north and east of Broke (where the aquifer is quoted as recharging) is only marginally higher (0-50m) than the elevation at Broke (elevations from Google Earth). This yields a dip angle of about 2-3 degrees. This suggests that either the distance of the recharge area from Broke is incorrect or the average dip angle is incorrect. Since the surface exposure of the Blakefield seam is known with some certainty I conclude that the average dip angle is incorrect.
2. The head gradient within the aquifer is incorrectly calculated. It should be derived from the difference in the background head in HB02 and the recharge area, not from the dip of the aquifer. My estimate is that this is about 0.0143 m/m not the 0.1 quoted.
3. The velocity used should be the breakthrough velocity not the specific discharge (called darcy velocity by PB). The breakthrough velocity is higher than the specific discharge by a factor of (1/rock porosity) or by about a factor 10x.

Allowance for these effects changes the travel times derived by PB to between 3,000 and 27,000 years. This are similar to those calculated by PB and consistent with their isotope dating of the waters but are arrived at by what is believed to be a more correct reasoning.

To address the original concern of the BCCC members about mine water pollution during the pumping we can also estimate the travel time during the period that the wells are drawn down for gas extraction. During gas exploitation the aquifer at the well will be pumped down to the level of the aquifer so that the head gradient in the aquifer will be the dip of the aquifer (about 0.06 m/m). The travel time from the recharge area to HB02 will then be about 700 to 6500 years using the same conductivities used in Section 6.7 of the PB report. Accordingly I conclude that potential pollution of the HB02 well by mine water during the flow test and any coal seam gas field exploitation is unlikely.

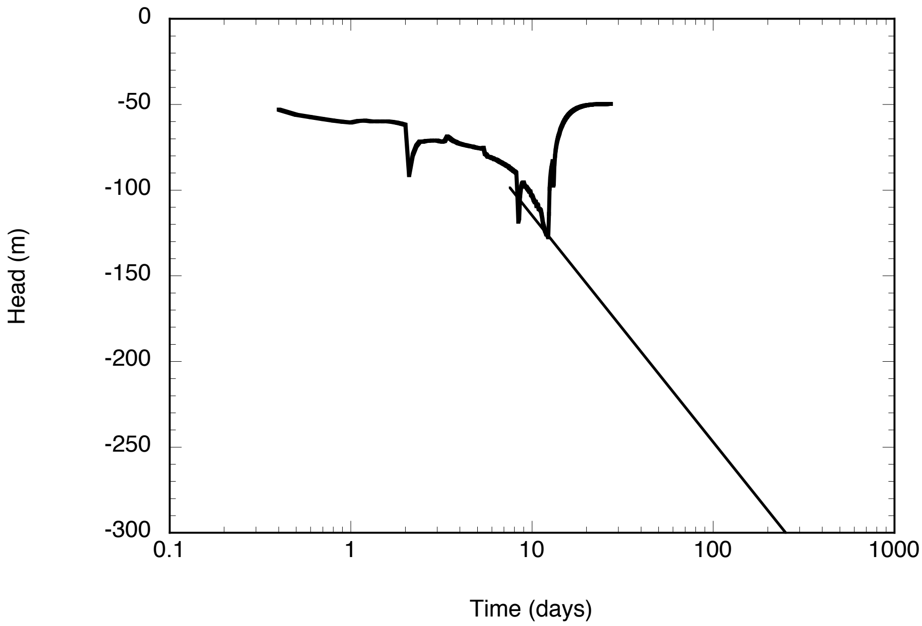


Figure 5.1: Projected drawdown over time for the flow testing.

5. Flow Testing

To estimate the potential impact of the proposed flow testing by AGL, and to provide a baseline against which the results of the flow testing can be monitored the groundwater model was run with derived groundwater parameters for a period of 6 months.

To estimate the drawdown over time for the flow testing it is simply a matter of extending the drawdown plot on the semi-log plot from the observed data to the head that is the objective of the flow testing. If the pumping rate is 0.20 litres/s (the final pumping rate in the last two days of the pump test) then the drawdown with time is given by the line in Figure 5.1. It is projected that the will pump at the maximum rate of 0.20 litres/s until about 250 days after the start of the flow test at which time the pumping rate will decrease. It should be noted that the linear projection is highly dependent on the slope of the line and even small differences in the slope make a large difference in the time at which the well is pumped down to 300m. This is a reflection of the sensitivity of the drawdown rate to the groundwater parameters and is not dependent on the Jacob approximation used to make the projection.

The groundwater model discussed in Appendix A yields the same results for the same pumping rate and aquifer properties. The only difference is that the model can estimate what the pumping rate needs to be (and how it reduces with time) to maintain a drawdown of -300m once that level has been first achieved.

6. Other Issues

There are a number of issues that have been raised at previous BCCC meetings and that are beyond the scope of the PB report. In general they go beyond assuring that there is no leakage in the Blakefield seam, but for which the background monitoring and pump test analysis might provide information. In reading the sections that follow it should be noted that the primary reason for doing the pump test was to provide some guarantees of the environmental safety of the flow test. The issues below relate mainly to longer-term issues of gas field development and decommissioning, and the pump test was not specifically designed to address these issues, even though the pump test does provide spin-off insight into the technical issues related to gas field development.

6.1 Predicted Water Quantities from Gas Extraction

A question raised by the community is "how much water would be extracted from the well field over the life of the project in the Broke Valley if AGL were to proceed to production?" This is a relevant question because the PB assessment of the geochemistry analysis of the Blakefield water indicates that is unlikely to have any beneficial purpose to the Broke community, though it might be suitable for mine dust suppression. I agree with PB's assessment (see Section 2.1 for more details).

This water volume depends on a number of factors to do with the aquifer and also a number of factors that AGL will need to determine as part of their project design process. Nevertheless there are two main components to the answer.

1. The first component is the amount of water that would needs to be extracted at the start of the project to achieve the required aquifer depressurisation (i.e. drawdown) to achieve AGL's required gas flow.
2. The second component is the amount of water that needs to be extracted subsequent to this initial drawdown to maintain the aquifer heads at AGL's design levels

The first component can be estimated from reference to Figure 6.1 and using estimates of the storativity from the pump test. The volume of water is

Volume= (storativity within the field) * (initial drawdown) * (area of well field) * (aquifer thickness)

The thickness of the aquifer is 7m so we can provide estimates of the amount of water initially required and they are given in Table 6.1. Because Table 6.1 ignores water in the depressed region outside the well field (see Figure 6.1) it should be considered a lower bound estimate on the first component of water generation.

Table 6.1: Estimated water required to initially draw down the Blakefield aquifer per sq km for a range of storativity and design drawdown values. Volumes are Megalitres (Ml) per sq km.

	Design drawdown (m below background head)			
Storativity	50m	100m	200m	300m
0.01	3.5	7.0	10.5	21.0
0.001	0.35	0.7	1.05	2.1
0.0001	0.035	0.07	0.11	0.21

To place these numbers in perspective

1. The average yearly rainfall for Singleton is 649mm/year or 422 Ml/sq km/year.

2. The median flow in Wollombi brook at Brickmans Bridge is less than 13 ML/day or about 4700 Ml/year, and the median flow in January is less than 5 Ml/day (Hunter-Central Rivers Catchment Management Authority, 2005).

It is not possible to estimate (based on the results of the pump test) the second component which is the amount of water required to be pumped every year to maintain the design drawdowns in the gas wells. This is because it depends on knowing the hydraulic conductivity of the unfracced aquifer.

6.2 Recovery Time after Aquifer Depressurisation

A question raised by the community is "what is the period of time that the aquifer will be depressurised after the completion of pump testing, flow testing, and/or any potential gas field development?"

As explained in detail at the end of this section the analysis of the pump test indicates that it is not possible to provide accurate estimates of this recovery time.

The only method for estimation of recovery time is extrapolation from the observed recovery time of the pump test, which was a few weeks. The recovery time is a primarily a function of how much water has been withdrawn. As a first estimate the recovery time will increase proportionally with the volume of withdrawn water.

If the flow test occurs for 6 months at the maximum pump rate of 0.20 l/s used in the pump test then a first estimate of recovery time is about 6-12 months. This is based simply on an extrapolation of the pump test based on its observed recovery time and factoring up the recovery time by the extra water extracted in the flow test. If the flow test pumps at a lower rate then the recovery time will be reduced by an amount proportional to the reduction in the volume of water withdrawn. The main caveat on this estimate is that it assumes that the cone of depression of the pump test extended outside the fracced region of the aquifer and into the unfracced region of the aquifer. The reason this is important is that it then means that the pump test recovery time reflects the inflow from the unfracced aquifer not from localised effects around the well caused by the fraccing. If this caveat is not satisfied then the recovery time will be higher. There is no method to be certain that the cone of depression is in the

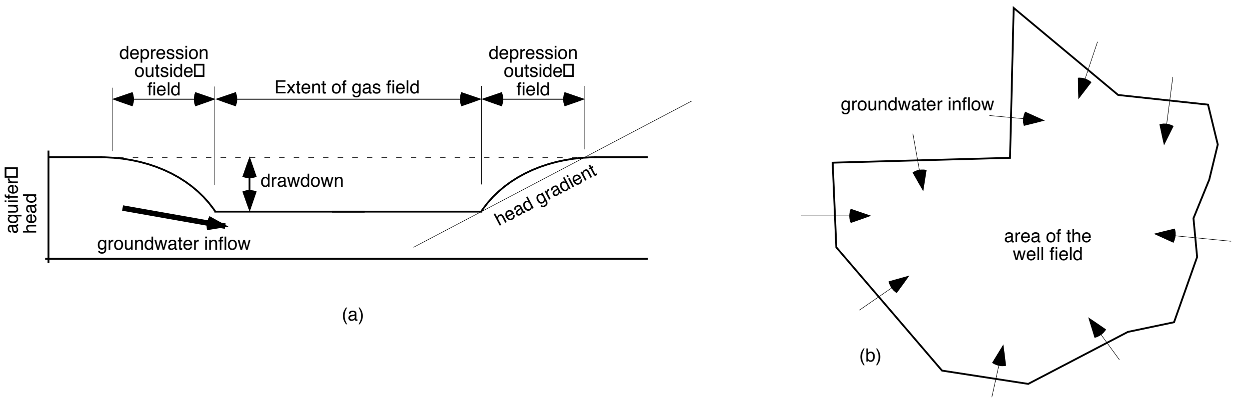


Figure 6.1: Schematic of a recovering well field (a) Cross-section (b) Plan

unfracced part of the aquifer so the 6-12 months should be seen as a lower bound estimate on the recovery time.

To more accurately estimate the recovery time two things need to be known (1) the volume of water that is needed to repressurise the aquifer back to background levels, and (2) the rate at which this water will be supplied from the surrounding aquifers. For a given drawdown in the aquifer (which will be determined by the gas flow design adopted by AGL) the amount of water that is needed to repressurise the aquifer is a function of the storativity of the aquifer within the well field (i.e. the fracced region of the aquifer). The rate of the refilling of the aquifer is a function of the transmissivity of the aquifer (transmissivity=conductivity *(aquifer thickness)) surrounding the well field, which is directly related to the conductivity of the aquifer surrounding the well field (i.e. the unfracced region of the aquifer). Everything else equal the time of recovery will increase approximately proportionally with storativity and decrease approximately proportionally with transmissivity/conductivity.

Using the terminology in Figure 6.1 the volume of water is approximately

Volume= (storativity within the field) * (drawdown) * (area of well field) * (aquifer thickness)

And the rate of recovery is determining by the groundwater inflow

Groundwater inflow = (aquifer thickness) * (conductivity at well field boundary) * (length of the boundary of the well field) * (head gradient)

In reality this a simplification of the actual complexity since a groundwater model is needed to determine (a) the head gradient and (b) the volume of water in the depression at the boundary field but Figure 6.1 satisfactorily captures the concept of the recovery problem and what needs to be known to estimate the recovery time.

As indicated in previous sections of this report neither of the storativity or conductivity properties for the un-fracced aquifer can be well estimated using the pump test. The importance of doing further pump testing for storativity estimation has been discussed in previous sections, and this section supports that recommendation. Furthermore this section highlights the need for pump testing in the un-fracced aquifer surrounding the edge of the well field to estimate the un-fracced conductivity of the Blakefield seam, and any other seams that will be part of a gas extraction scheme.

This storativity and conductivity estimations are critical requirements for any approval of a borefield development. For the recovery time from the flow test, no more accurate estimate of the recovery time than that quoted above (by extrapolating the HB02 pump test) is deemed possible by the peer reviewer without this information.

6.3 Long-term interactions of gas extraction with future long wall mining

This section assumes that AGL goes ahead at some future time with commercial gas production. It is only tangentially of relevance to the current single extraction well exploration activity. Furthermore this section does not make any assesment with respect to the likelihood

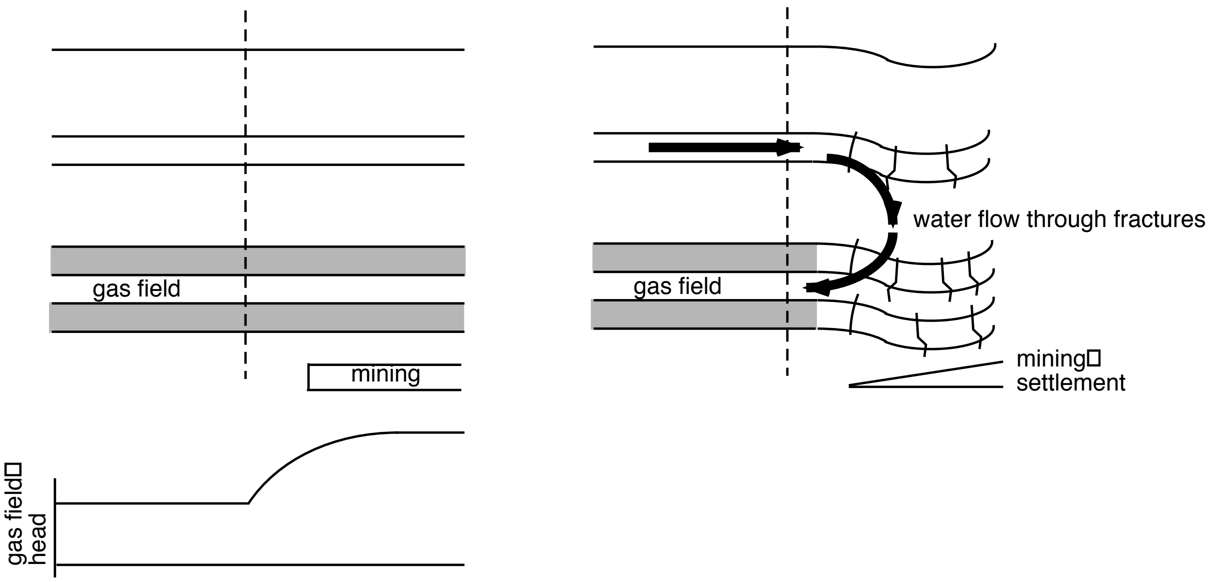


Figure 6.2: A schematic of how gas field aquifer head drawdowns might interact with long-wall mining.

of long wall mining near the gas extraction field, this being a regulatory issue beyond the scope of this report.

The conceptualised mechanism of interaction between the gas field and long-wall mining is as follows (Figure 6.2):

1. Long wall mining encroaches on the region of reduced aquifer heads around the field
2. The settlement from the mining fractures the overlying strata and this fracturing breaches the aquicludes between the aquifers allowing water to flow horizontally from the aquifers overlying the gas field through the region cracked by the long-wall and then into the aquifers that have low heads from gas extraction.
3. This mechanism would provide a means for the surface water aquifers to become connected to the gas field aquifers.

The pump test provides only limited information on the potential impact of any interaction between gas extraction and long wall mining into the future. The main issue is any potential interaction between the region of depressed aquifer heads within the well field and fracturing caused in the rock overlying long-wall mining. Both of these impacts are well known and it's the potential interaction between them that is the issue. The storativity and the conductivity of the unfracced aquifer determines how far offsite from the well field the depressed aquifer heads will propagate during the gas extraction. As noted above these values cannot be estimated with any reliability from the pump test. Thus we cannot estimate how close any long wall mining would need to be before interaction between the activities might start to occur.

Secondly after gas extraction is complete it will take some time for the aquifer heads within the decommissioned gas field to recover. It is only during that time that interaction between the recovering aquifers and long-wall mining will occur. After that recovery time there might still be aquifer impacts from long-wall mining but they will only be as a result of the long-wall mining and not as result of the interaction between the mining and gas extraction. As noted in the previous section the aquifer recovery time is a function of the storativity of the fracced aquifer and the conductivity of the unfracced aquifer. Neither of these values can be estimated with any reliability from the pump test. Thus it is not possible to estimate how long after gas extraction finishes there might be a risk of interaction between the decommissioned gas extraction and long-wall mining.

7. Recommendations

My comments specifically to do with the PB report are:

1. **Executive Summary**: The executive summary is an accurate representation of the results from the water quality monitoring, pump test, and the interpretation of the water quality data and pump test by PB. Moreover, the interpretation of the data by PB, in so far as what is described in the executive summary, is supported by the assessment of the peer reviewer.
2. **Section 9 Conclusions**: The conclusions are an accurate representation of the results of the report. Moreover, the conclusions of the report can supported by the peer reviewer at this stage in the peer review process with the exception of the 2nd paragraph in the section titled “Aquifer Permeability”. This exception is simply a result of the peer review of the pump test not being complete at this stage and nothing untoward should be read into this exception.
3. **Section 10 Recommendations**: The peer reviewer supports all of the recommendations of the report. Under Recommendation 2 HB01 is mentioned with a implied presumption that the work in the PB and peer report supports the flow testing of HB01. Neither the PB report nor the peer review analysis have examined HB01 so no statement can be made with respect to flow testing on HB01, though the peer review endorses the recommendation to continue to collect baseline data at HB01.

In addition, I have a number of further recommendations and conclusions as follows:

1. There is no evidence to suggest aquifer leakage during the well pump test. Furthermore the seismic survey data suggests that the geology tested during the pump test is typical of the region likely to be impacted by the flow test. Accordingly there is no evidence to suggest that there will be any impact of the flow test on the near surface and alluvial aquifers. I recommend that approval be given to allow the flow test in HB02 to commence for a period of up 6 months, subject to the following conditions.
2. The peer reviewer should monitor the flow test as outlined below. If untoward behaviour occurs then consideration would be given to terminating the flow test. The protocol of what constitutes untoward behaviour and how this termination would occur, if the peer reviewer felt it was warranted, should be discussed at the next BCCC meeting.
3. Monitoring at the observations wells (established by PB to collect baseline data and to monitor the pump test) should be continued. Current baseline data, while it was adequate to characterise the background for the pump test does not provide coverage of a sufficient range of wet and dry periods to reflect the full dynamics of the groundwater response to variation in weather extremes. This will be crucial to assessing the long-term impacts of the flow test and any subsequent gas field development.
4. Priority should be given to the establishment of a monitoring well in the Blakefield seam at a distance of 50-100m from HB02 prior to the commencement of the flow test. The use of a single well (as was done in the pump test) makes it difficult to estimate both the aquifer conductivity and the storativity independently, hence reducing the reliability of the aquifer parameters derived. Work by others (Wheaton and Metesh, 2001) indicates that the value of aquifer storativity is critical to determining the regional impact on groundwater levels and the amount of water generated from coal seam gas extraction schemes. While this report has not studied regional impacts the results from the more limited modelling in this study are

consistent with the conclusion that storativity is important and poorly estimated using the single well methodology in the pump test. Using a single well pump test, as done for the pump test, makes storativity difficult to estimate while two wells will allow storativity to be estimated.

5. The protocols for monitoring the electrical conductivity of the water being pumped out of the well, as used during the pump test, should also be applied to the flow test.
6. That water level drawdowns in the pumping and nearby monitoring well (if it is established) be available to the peer reviewer during the flow test (rather than only at the end as was the case in the pump test) to allow an assessment to be made as to any well level deviations from expected behaviour (expected behaviour would be assessed using, for example, the groundwater code in Appendix A, or any other model established in the groundwater community; e.g. MODFLOW). This may require technical modifications to the well head to allow online water level monitorring to occur.
7. That gas flow volumes and gas pressure be monitored and provided to the peer reviewer as part of the flow test monitoring process. This will allow an assessment of the effect of within-aquifer gas generation on the aquifer storativity.
8. That test be carried out to allow estimates be made of the conductivity of the (background) un-fracced aquifers. In combination with better estimates of storativity this will allow better estimates of the recovery time of the aquifer after the end of depressurisation.

8. References

ANZECC. 2000. *Australian and New Zealand Guidelines for fresh and marine water quality.* http://www.mincos.gov.au/publications/australian_and_new_zealand_guidelines_for_fresh_and_marine_water_quality

Hunter-Central Rivers Catchment Management Authority, 2005. *Water sharing in the Upper Wollombi Brook water source, Draft Macro Water Sharing Plan - Hunter unregulated water sources*, www.hcr.cma.nsw.gov.au/water_sharing/macro_hunter_wollombibrook.pdf.

Morin, R. H. 2005. Hydrologic properties of coal beds in the Powder River Basin, Montana I. Geophysical log analysis. *Journal of Hydrology* **308**:227-241.

Myers, T. 2009. Groundwater management and coal bed methane development in the Powder River Basin of Montana. *Journal of Hydrology* 368:178-193.

Rehm, B. W., G. H. Groenewold, and K. A. Morin, 1980. Hydraulic properties of coal and related materials, Northern Great Plains. *Ground Water*, **18,** 551-561.

Weeks, E. P., 2005. Hydrologic properties of coal-beds in the Powder River Basin, Montana. II. Aquifer test analysis. *Journal of Hydrology*, **308,** 242-257.

Wheaton, J. and J. Metesh, 2001. *Administrative Report to Bureau of Land Management: Potential ground-water impacts from coal-bed methane development in portions of Montana*, 30 pp. Montana Bureau of Mines and Geology, Butte, Montana.

Wheaton, J., and J. Metesh. 2002. *Potential ground-water drawdown and recovery for coalbed methan development in the Powder River Basin, Montana*. MBMG 458, Montana Bureau of Mines and Geology, Butte, Montana.

Appendix A: Technical Details of the Pump Test Analysis

This appendix describes the technical details of how the peer review of the pump test results was carried out. As noted in the main text the main outcome from the pump test is the quantitative assessment of the Blakefield Seam aquifer properties.

The Jacob method used by PB for determination of the aquifer's conductivity is a standard technique used in the groundwater industry to determine aquifer conductivity from water level observations made in a pumping well. However, it does have some limitations in the context of this study.

1. The Jacob method is based on asymptotic results to the groundwater flow field around the pumping well after a long period of pumping at a constant discharge. In the HB02 test the well discharge varied between 0.1 and 0.21 litres/second over the duration of the experiment and it is not clear that this assumption of the method is fully met.
2. The asymptotic nature of the solution means that effective use of the technique is only possible after a significant period of pumping at a constant rate. This time is expressed in units of the time taken to empty the well at the rate in the pump test. So the lower the pump rate relative to the volume of the well the longer the time required for asymptotic result to apply. In normal irrigation practice pumping rates are high and only a few hours of constant pumping are needed. In the PB pump test the pump test rate is low relative to standard irrigation practice.
3. The method assumes that the aquifer is of constant depth, conductivity and storativity within the cone of depression. Any potential effect of hydro-fraccing around the well on conductivity and storativity cannot be assessed. The derivation by PB of 3 different conductivities at different times during the experiment suggests that the requirement of spatially constant conductivity in the method is not met.
4. Since so much depends on the quantitative results of the analysis there is merit in using an independent quantitative method to check the results.

Accordingly, a computer code was written for the 2D depth averaged axisymmetric groundwater flow problem to a well. The full equations allow for spatial variability in conductivity, aquifer thickness and storativity. The axisymmetric formulation means that all water flows in a direction that is radial into the well and that flow is the same in all directions. The 2D depth averaged means that any vertical flow components are ignored (only likely to be important directly adjacent to the well casing where the flow will converge from the 7 metre thickness assumed for the aquifer to the 3 metre slotting in the casing). The axisymmetric ground water flow equation solved is

$$DxS\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(DK\frac{\partial h}{\partial x}x \right) + L$$

where D is the aquifer thickness, S the aquifer storativity, K the aquifer hydraulic conductivity, L is leakage per unit area from adjacent aquifers, h is the hydraulic head in the aquifer and x is the distance radially from the centre of the well. Aquifer properties S and K can be both spatially and temporally varying, and they are both isotropic. Thickness D could vary in space but not in time so that variable saturation with gas cannot be modelled. In the modelling that follows D was fixed at 7m.

The analysis of the pump test with the computer model is more complex and computer intensive (runs took up to 4 hours on a desktop computer) than the Jacob method used by PB. However, it

1. Provides greater insight into the aquifer properties.
2. Provides a tool with which you can model the potential impact of the flow test proposed by AGL.
3. It may also be useful to provide insight into the potential interaction with long wall mining, though it is likely that full 3D model (i.e. not axisymmetric) such as MODFLOW is likely to be necessary for fully understanding this problem.

In the analyses that follow the parameters of the model were as in listed in Table A1 unless otherwise noted.

Table A1 Parameters used in the Groundwater Modelling

Parameter	Value
Conductivity	As noted in the text, but assumed constant in space unless otherwise noted.
Depth of the aquifer	7m (as in the PB report) and constant in space.
Storativity	10^{-5} (mid range value in the PB report) and constant in space unless otherwise noted.
Pumping Rate	As noted in the text.

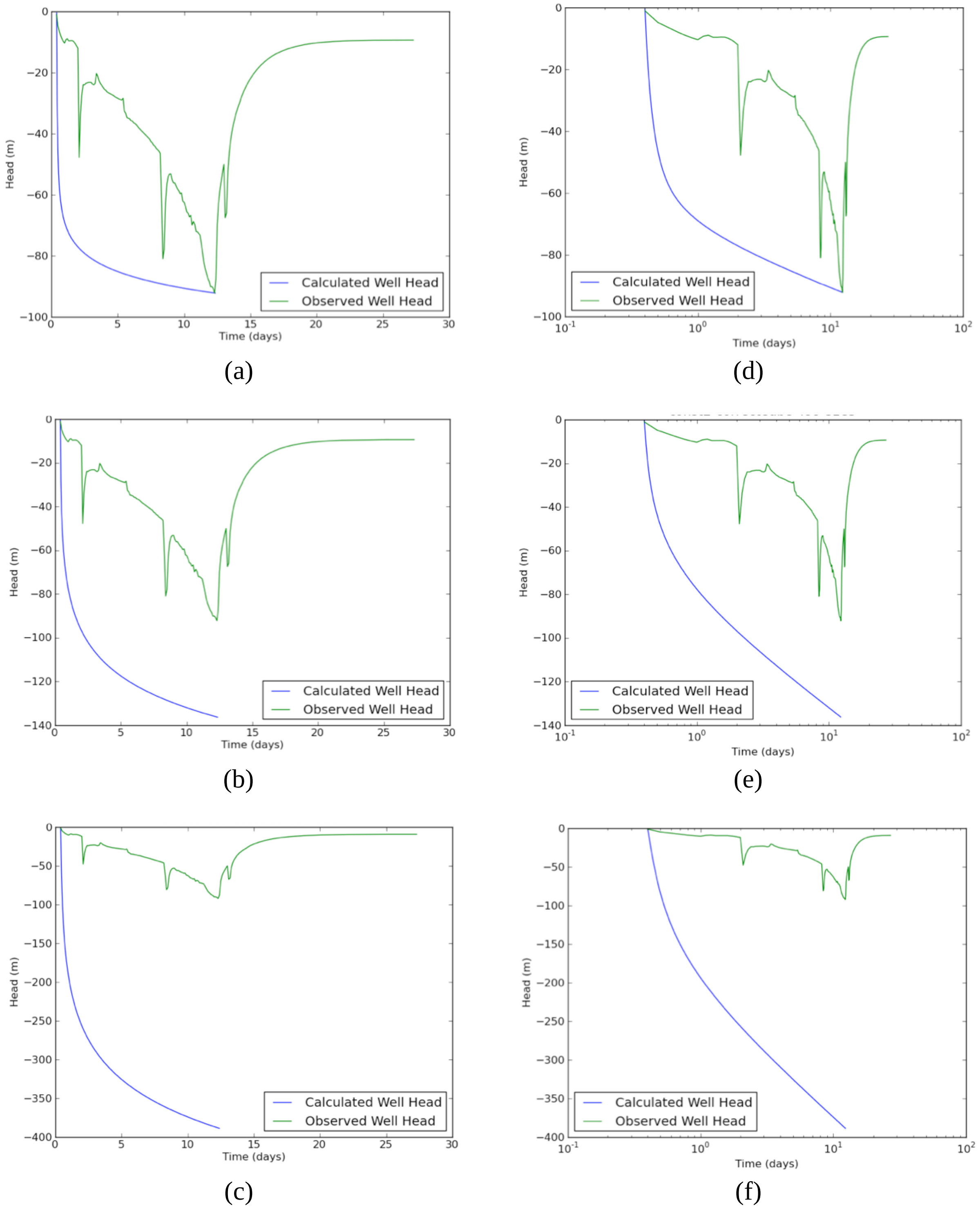


Figure A1: Simulated well drawdown using the three conductivities derived in the PB report and constant pumping rate. Hydraulic conductivity is as indicated in the title for each figure (a) K=0.043 m/day. (b) K=0.014m/day, (c) K=0.005 m/day. (d), (e), (f) are the same data plotted on a semi-log scale to allow application of the Jacob method used by PB. The asymptotic part of the curve is the straight line in lower right of the blue curve. In all cases it takes more than a day to reach linearity.

A1. Checking the PB derived conductivities

The hydraulic conductivity of the aquifer is important because it determines how rapidly water can be extracted from the aquifer. If the conductivity is higher then more water will need to be extracted to achieve design depressurisation in the aquifer.

The PB analysis provides three different conductivities for different periods during the pump test. To test the sensitivity of the model to these conductivities two sets of three simulations were carried out using these parameters. In each simulation the conductivity was assumed constant within the aquifer. A mid range storativity (as per the PB report) of $S=10^{-5}$.

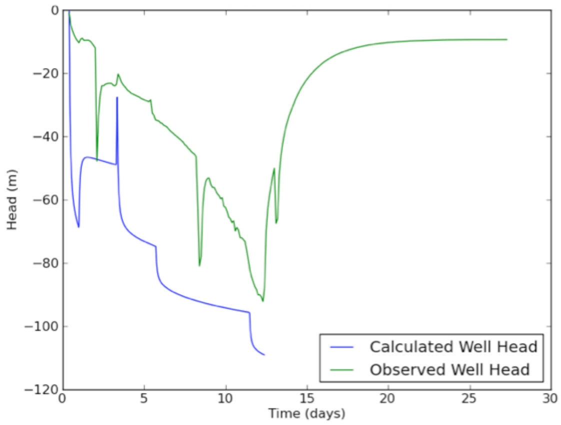
Table A2: PB estimated parameters

Dataset	Estimated Conductivity (m/day)	Time Period of Analysis (days)	Pump Rate (litres/s)
Early dataset	0.043	0.4-1.0	0.17
Mid dataset	0.014	3.8-5.2	0.15
Later dataset	0.005	5.2-6.5	0.18

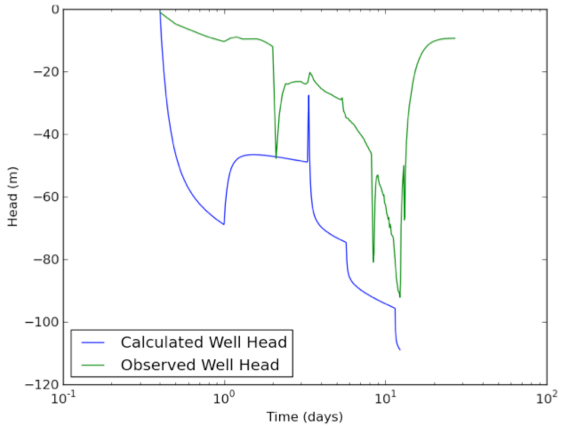
The first set of simulations used the 3 conductivities as derived by PB in their Table 6.5 and listed in Table A2. The pumping rate was the pumping rate for the period of the pump test for which the conductivities were derived. The time period listed in Table A2 is the simulation time used in the all of the figures below, which are relative to the start of the pump test. The results are shown in Figure A1.

The reader is cautioned that it is not expected that these results will fit the pump test data (also plotted in the Figures) because the simulations do not use the actual pumping rates (that change in time through the test). The figures are provided simply to show the rate at which convergence to asymptotic behaviour (i.e. linearity on the semi-log plot in Figure A1) occurs. It is clear that that in all cases it is several days, and in cases longer than the period over which the three conductivities are derived. This impacts on the conductivities derived by PB analysis, as it means that one of the assumptions of the Jacob method is invalidated. Finally, the asymptotic slopes of the 3 computer simulated drawdown curves are the same as the slopes of the regions of the pump test from which the conductivities were derived. This confirms that the computer code is yielding correct results given the conductivities used in the modelling.

The second set of simulations repeated the first set of simulations but used the actual pumping rate as performed during the pump test. These results would be expected to provide a good fit to the observed well drawdown if the aquifer had the same conductivity everywhere in the aquifer as used in the computer model. These results are shown in Figures A3 and A4. None



(a)



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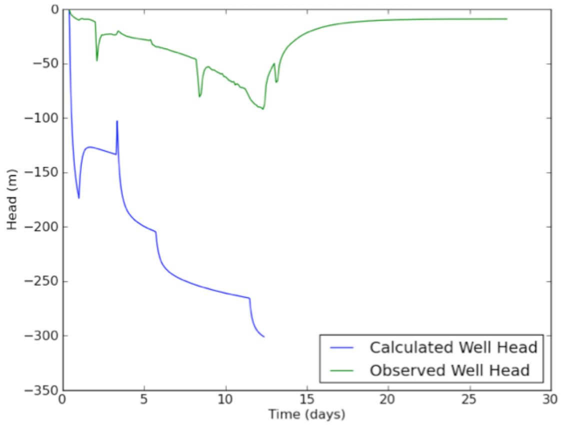

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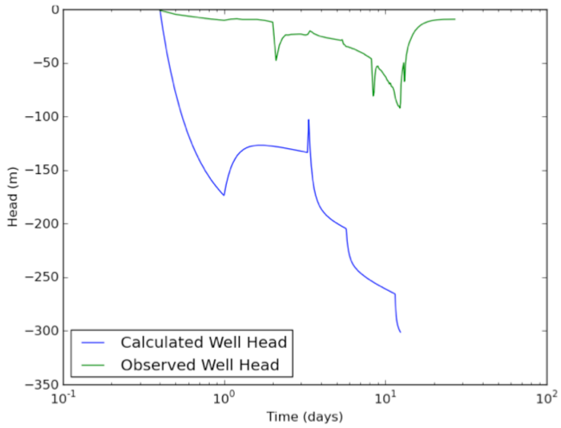

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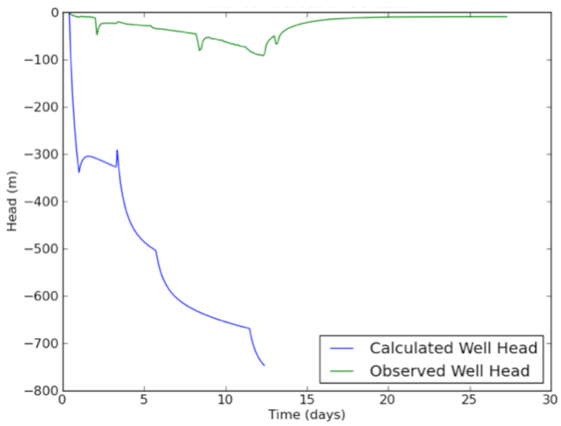
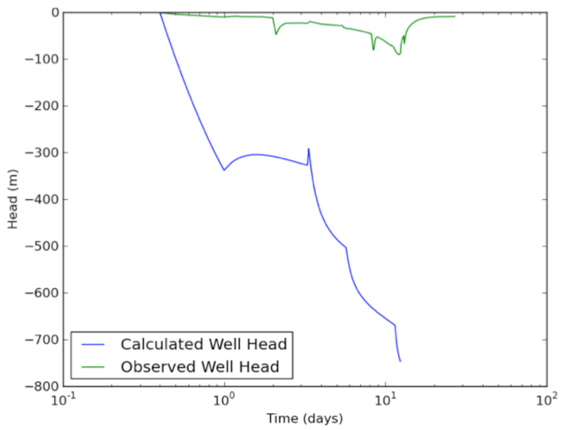


(c)



(f)

Figure A2: Simulated well drawdown using the three conductivities derived in the PB report and observed varying pumping rate. Other than the time varying pumping this figure is identical to Figure A1. Hydraulic conductivity is as indicated in the title for each figure (a) K=0.043 m/day. (b) K=0.014m/day, (c) K=0.005 m/day. (d), (e), (f) are the same data plotted on a semi-log scale to allow application of the Jacob method used by PB. Only for the high conductivity case in (f), and perhaps for (e), does the drawdown reach linearity.

of the conductivities provide a good fit to the data and in the following sections explore some alternative conductivity cases will be explored. The poor results in Figure A2 confirm that the aquifer conductivity is not constant in space.

However, one important conclusion is consistent with the PB interpretation of the time trend of the pump test. As the pump test proceeds the observed rate of well drawdown steepens (i.e., the drawdown curve gets steeper with time, particularly obvious in Figure A2d-f). Figures A1 and A2 show that this steepening is unlikely to be a result of the increasing pumping rate during the test because the model does not show a similar trend. Rather it is likely to be a result of a decreasing conductivity of the aquifer with distance from the well. This supports the conclusions in the PB report that, even though they misapplied the Jacob method (and thus their conductivity estimates are likely to be inaccurate so their conductivities are likely to be too low), their conclusion that the aquifer conductivity decreases with distance from the well is likely to be correct.

A2. Deriving best fit conductivities

The main problem with the simulations using the PB parameters is that it is not possible to match both the initial drawdown in the first day and the rate of drawdown in the well at subsequent times. Since the drawdown on the first day will not impact greatly on the longer-term characteristics of the well, the best fit is that plot that:

1. As a first priority that best matches the slope of the drawdown curve
2. Once the rate of drawdown is matched the best result is the one that has the best match for the drawdown on the first day.

As a first step in better estimating the parameters of the model some runs were done with PB conductivities (considering them constant in space) exploring for an optimal value of storativity.

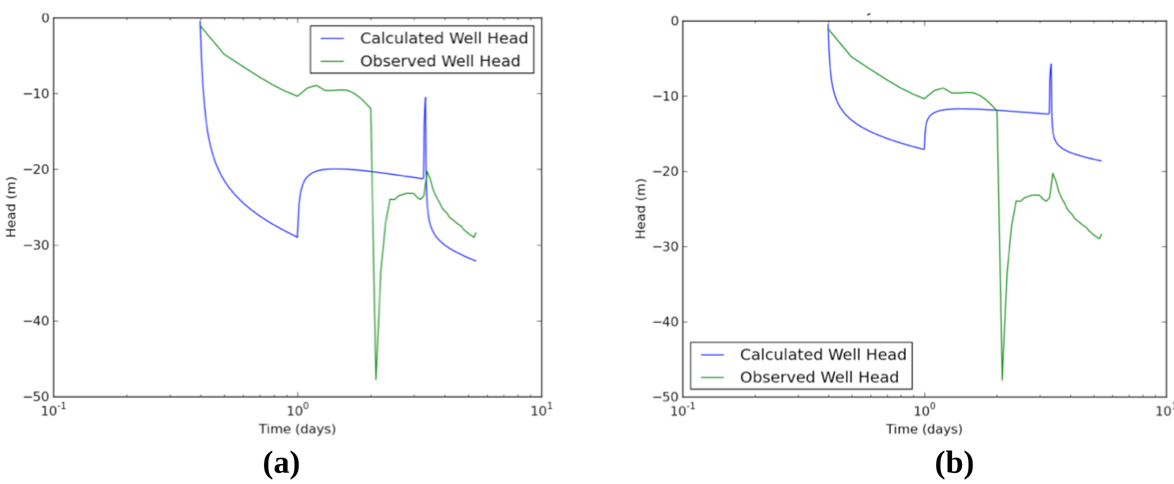
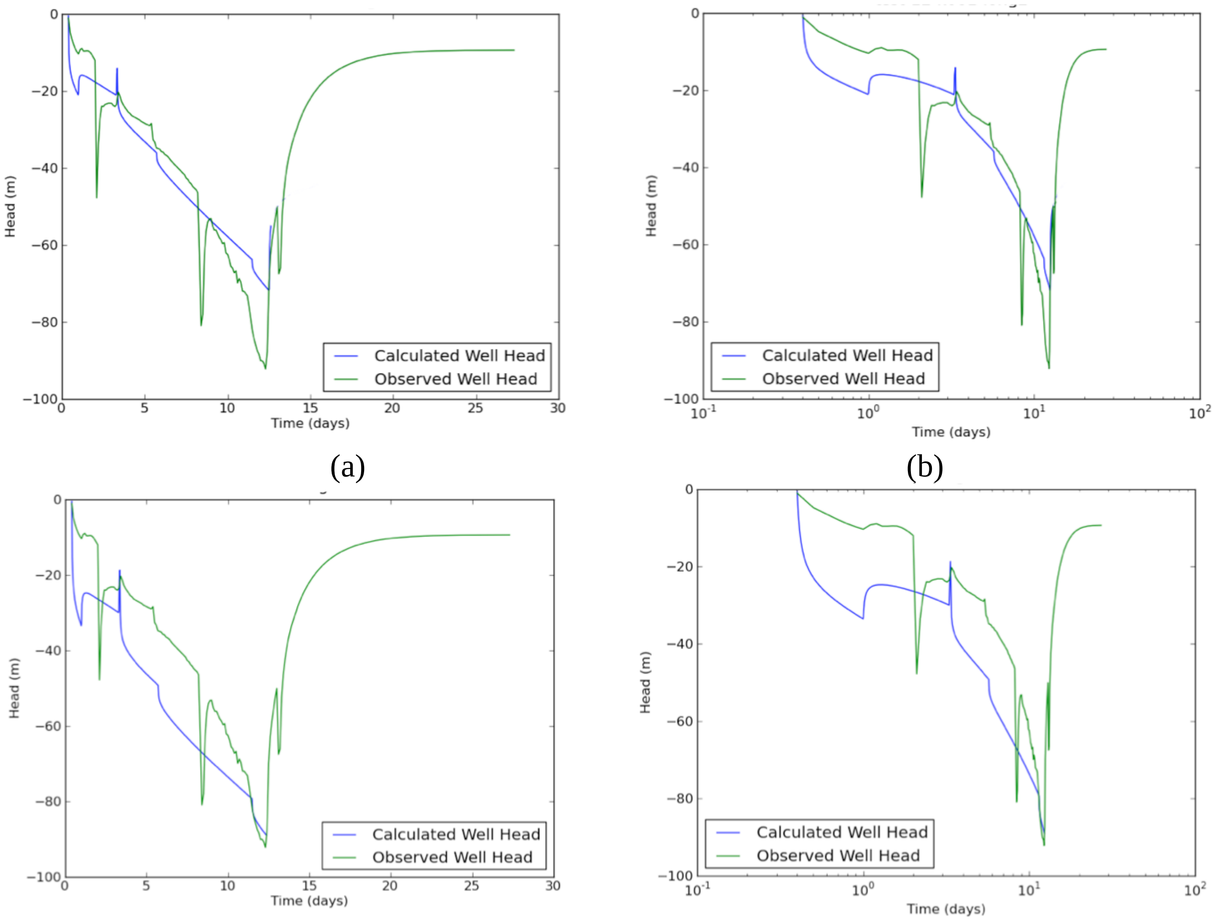


Figure A3: The best fit parameters for the first 5 days of the pump test (a) the PB conductivity K=0.043m/day (b) a sensitivity study with K=0.08m/day



(a) (b)

(c) (d)

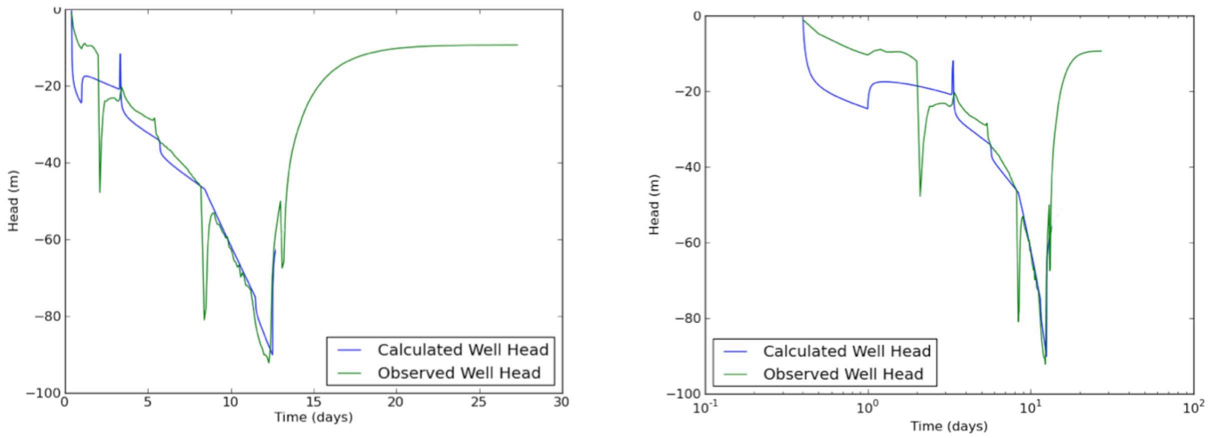
Figure A4: Best spatially variable conductivity (a) (b) K=0.08m/day at well, (c) (d) K=0.043 m/day at well.

The parameters fit by PB to the first day of the drawdown do provide the best fit to the first 5 days of the data (Figure A3). The initial amount of drawdown is too large, but this is function of the storativity not the conductivity. The match in conductivity is indicated by the match between the slopes of the data and model results. Figure A3 also shows a result for a slightly higher conductivity of K=0.08m/day, which shows the sensitivity to a change in conductivity. The initial drawdown is less but the rate of subsequent drawdown is too low.

However, as indicated in the PB report their estimate of conductivity reduces as the pump test proceeds indicating that the conductivity drops as you move away from the well. Figure A1 confirms this result.

Accordingly a number of configurations for the spatial variation in conductivity were investigated. It was not possible to obtain a good fit to the overall drawdown if the initial conductivity of K=0.043m/day was used but good fits were obtained with an initial conductivity of K=0.08m/day (Figure A4).

The result in Figure A4 uses a linear drop in conductivity with distance from the well. The conductivity at the well is 0.08 m/day, dropping down to 0.005 m/day at 10m and dropping to 0.001m/day at 12m and then 0.0001 m/day at 18m and further out. This suggests that as the



(a) (b)

Figure A5: The best-fit parameters for conductivity with a reduced storativity in days 9-12.

cone of depression from the well expands with time it "sees" lower conductivity materials. This is consistent with the conclusions of PB, though the numbers here are somewhat different from what they calculate.

The conclusion of this analysis is that the conductivity of the aquifer is not constant in space or with distance from the well. This is consistent with the idea that the hydro-fraccing has increased the conductivity of the aquifer near the well. This is unsurprising because this is the intention of hydro-fraccing.

A number of other simulations were also performed and are useful in that they allow us to reject various alternative hypotheses for the behaviour of the aquifer

1. The way (linear, step change) that conductivity changes away from the well is relatively unimportant. The impact on simulations is small.
2. The simulations are insensitive to the conductivity beyond 12m provided it is less than 0.001m/day. Thus the pump test cannot be used to reliably estimate the conductivity of the background, unfracced aquifer. This lack of sensitivity is because the subtle impact of the conductivity far from the well is swamped by the high conductivity response close to the well.
3. The results were sensitive to the value of storativity in the first few days but relatively unresponsive until days 9-12. While reliable estimates of storativity can only be obtained by a two well pump test, the results seem to strongly suggest a value of storativity of about 0.001. Values suggested by PB of 10^{-4} to 10^{-6}, which are numbers taken from the literature for non-gas producing wells in confined aquifers, cannot be supported with the analysis here.
4. With respect to the sensitivity to storativity in days 9-12 it can be observed in Figure A4(a) that the model does not track the increase in slope of the drawdown. No combination of reduced conductivity at a far distance allowed accurate tracking of days 9-12 without negatively impacting on the rate of drawdown in days 5-9. This contradicts the conclusions of PB that this steepening is a result of a further reduction in conductivity. The only way to better match this result was to apply a reduction in the storativity by a factor of about 3 (storativity reduced from 0.001 to 0.0003) after the gas spike on day 8 (Figure A5). No explanation for this behaviour is proposed here other than referring to the discussion in Section A4 and suggesting that it might have

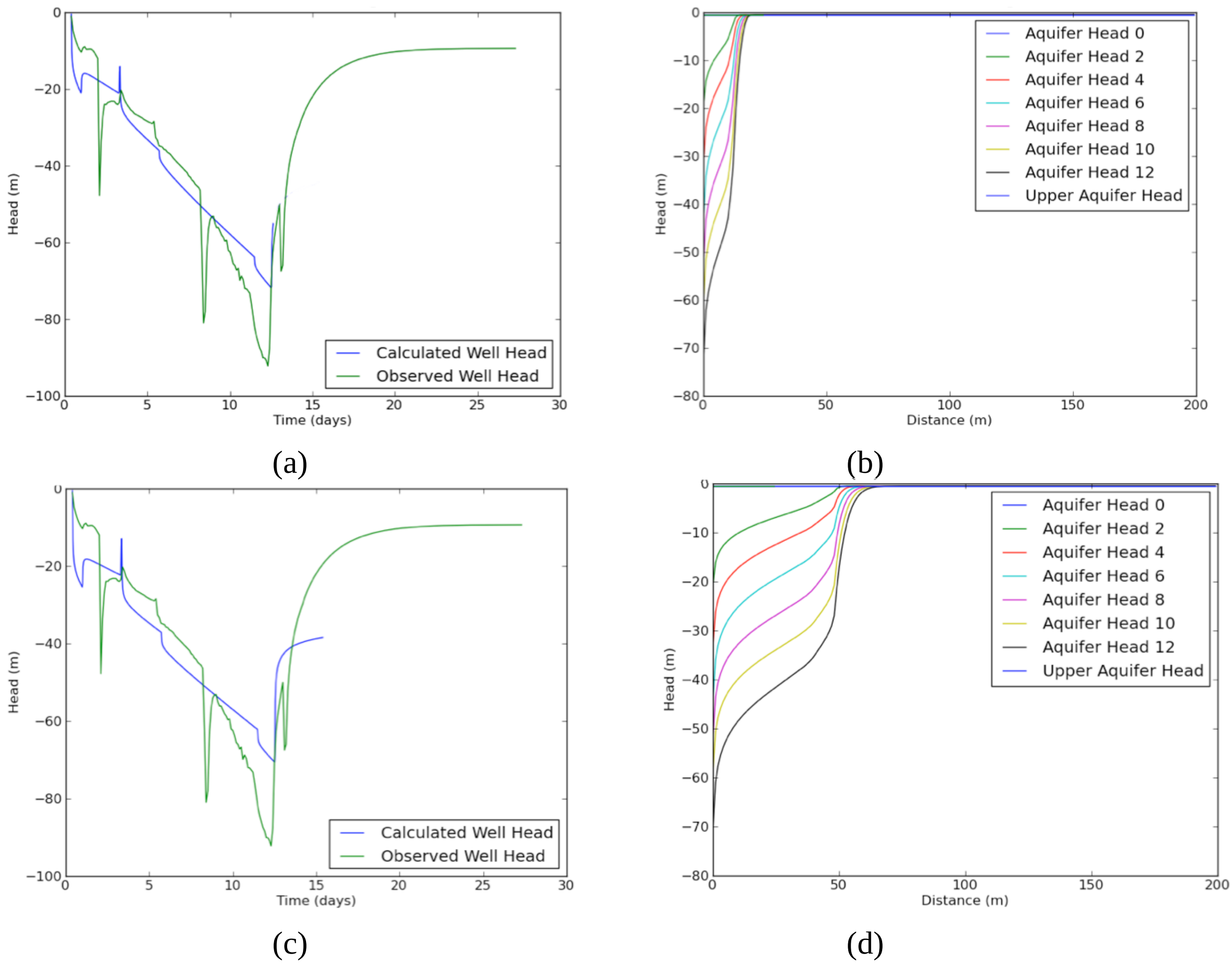


Figure A6: Plots showing the lack of uniqueness of the parameters (a) the well head for the best-fit parameters (b) the head in the aquifer with distance from the well (time steps are every 2 days) showing the cone of depression over time, (c) the well head for the alternative parameters, (d) the head in the aquifer for the alternative parameters.

been due to the gas spike. However, the peer reviewer concludes that this one of the unresolved issues from this pump test. This characteristic of the well draw down could not be identified using the techniques used by PB for estimated conductivity using the Jacob method and could only be identified with a groundwater model.

A3. Uniqueness of parameters

Are the best-fit parameters from the previous section unique? In other words can we uniquely define what the groundwater is doing given the head levels from the pump test alone? A preliminary analysis would suggest some interaction between the estimates of conductivity, storativity and the distance that the region of fracced aquifer extends away from the well. Figure A6 shows the results from the best parameters (from Figure A4) and an alternate set of parameters that give very similar results. The main differences of the alternate parameter set are that (1) the initial drawdown in the first day is slightly greater and it provides a poorer match to the first day, (2) the slope of the drawdown over 12 days is flatter and provides a slightly poorer match to the rate of drawdown (which determines conductivity), and (3) the recovery is a poor match to the observed recovery. It's on this basis that the original parameters are preferred.

The parameters of the best-fit and alternative parameter sets are in Table A3.

Table A3: Best fit and alternative parameters

Parameter	Best-fit parameter set	Alternative parameter set
Storativity	1×10^{-3}	8×10^{-5}
Conductivity (at well)	0.08 m/day	0.08 m/day
Conductivity Zone 1	0.005 m/day at 10m	0.005 m/day at 40m
Conductivity Zone 2	0.001 m/day at 12m	0.0025 m/day at 48m
Conductivity Zone 3	0.0001 m/day at 18m	0.00025 m/day at 72m
Conductivity (far from well)	0.0001 m/day	0.00025 m/day

One significant implication of the different parameters is that the cone of depression for the pump test is estimated to be significantly different between the models. For the best fit parameters the cone of depression extends 20m out from the well, while for the alternative parameter set the cone of depression extends 50m out from the well. Without data from a second well this non-uniqueness cannot be resolved.

A4. Storativity

The value for storativity estimated in this report is at the upper bound of generally accepted values for storativity in confined aquifers (see Section 3.5). Since the value of storativity is so critical for determining the amount of water to be generated by a given aquifer drawdown it seems worthwhile to briefly discuss its components.

The storativity is the amount of water that is displaced from an aquifer for every metre of reduction in the head of the aquifer. It is expressed as the cubic metres of water that is displaced for every cubic metre of aquifer.

In traditional irrigation or water supply contexts the storativity is the sum of two mechanisms:

1. Elastic expansion of the water as the aquifer pressure is reduced.
2. Elastic compression of the aquifer as the aquifer pressure is reduced and more of the load from the overlying rock is transferred to the rock matrix.

Later in this section a third mechanism is identified, specifically related to coal seam gas fields, which appears to be commonly ignored in water analyses of gas fields.

Elastic Expansion of Water

As the water pressure in the aquifer drops, the water within the pores of the aquifer expands. When the pressure in the aquifer is reduced this water can longer fit in the pores of the aquifer so that the excess water that can no fit within the pores of the rock is forced out of the aquifer. Elastic expansion of water does not involve any change in the amount of volume available to store water (i.e. the volume of pores) but a change in the mass of water that can be stored in the pores as a result of a change in the water pressure (measured in metres of water head). If only this factor is at work then typically storativity is 10^{-6} or less.

Elastic Compression of the Aquifer

Under natural conditions the rock overlying an aquifer is partly supported by the pressure of the water in the aquifer and part of is supported by the rock of the aquifer. When the pressure in the aquifer is reduced then the rock of the aquifer must take more load from the overlying rock because the water is supporting less because its pressure is less. As a result of the rock taking more load the rock compresses slightly. Part of the compression of the rock comes about as result of the compression of the solid rock particles (i.e. reduction in size of each sand grain in a sandstone) but most of it comes about as result of a compression of the voids between the rock particles (i.e. rearrangement of the sand grains so that the void space between the grains is reduced). These are the same voids that contain the water and as the voids compress some of the water in voids must be displaced. The more elastic the rock (i.e. the softer the rock) the more water it expels per metre drop in head. For very stiff rocks (sandstone, granite) this process may be unimportant relative to the elastic expansion of water, while for softer rocks like coal this effect may add up to 10^{-4} to the storativity. Elastic compression of the aquifer involves a decrease in the amount of volume available to store water within the aquifer so that excess water is displaced.

The storativity when both processes above are combined is the sum of the storativity for each component. For soft rocks (like coal) most water is displaced by compression of the rock. This elastic compression component will result in settlement because of the compression of the aquifer. For a storativity of 10^{-4} and a 7m deep layer (about the thickness of the Blakefield Seam) the aquifer will compress by 0.7mm per metre drop in the aquifer pressure. This will be observed at the surface as settlement if the depressurisation is widespread in the region. Very significant settlements have been observed worldwide where significant quantities of water have been extracted from deep aquifers for irrigation (e.g. San Joaquin Valley in California where in extreme cases settlements of several metres have occurred over the last 100 years).

The two mechanisms above together typically yield a maximum storativity of about 10^{-4}, which is an order of magnitude lower than the value calibrated in this report.

The discussion above ignores the gas generation process in the aquifer. Very little has been written about this and it seems to have been ignored in previous studies of coal seam gas water generation.

Gas generation in the Aquifer

The gas generation process occurs as follows. The gas is stored in the aquifer sorbed to the coal particles, and held in that form by water pressure in the aquifer. As the aquifer is depressurised the sorbed gas diffuses to the surface of the coal particles and forms bubbles between the coal particles. The formation of these gas bubbles forces water out of voids between the rock particles. This will occur before the gas starts to flow to the well. Gas generation involves an increase in the volume of gas and water competing to be stored in the voids in the aquifer. In the period before gas flow (i.e. before the gas starts to be removed from the aquifer) this process displaces water. In the pump test three gas spikes were observed indicating that gas formation was definitely occurring during the pump test. This confirms that water would have been displaced as part of the aquifer depressurisation. The literature provides no guidance on this process, and in the case studies that I have found it has been ignored as a component of storativity (Wheaton, personal communication). However some

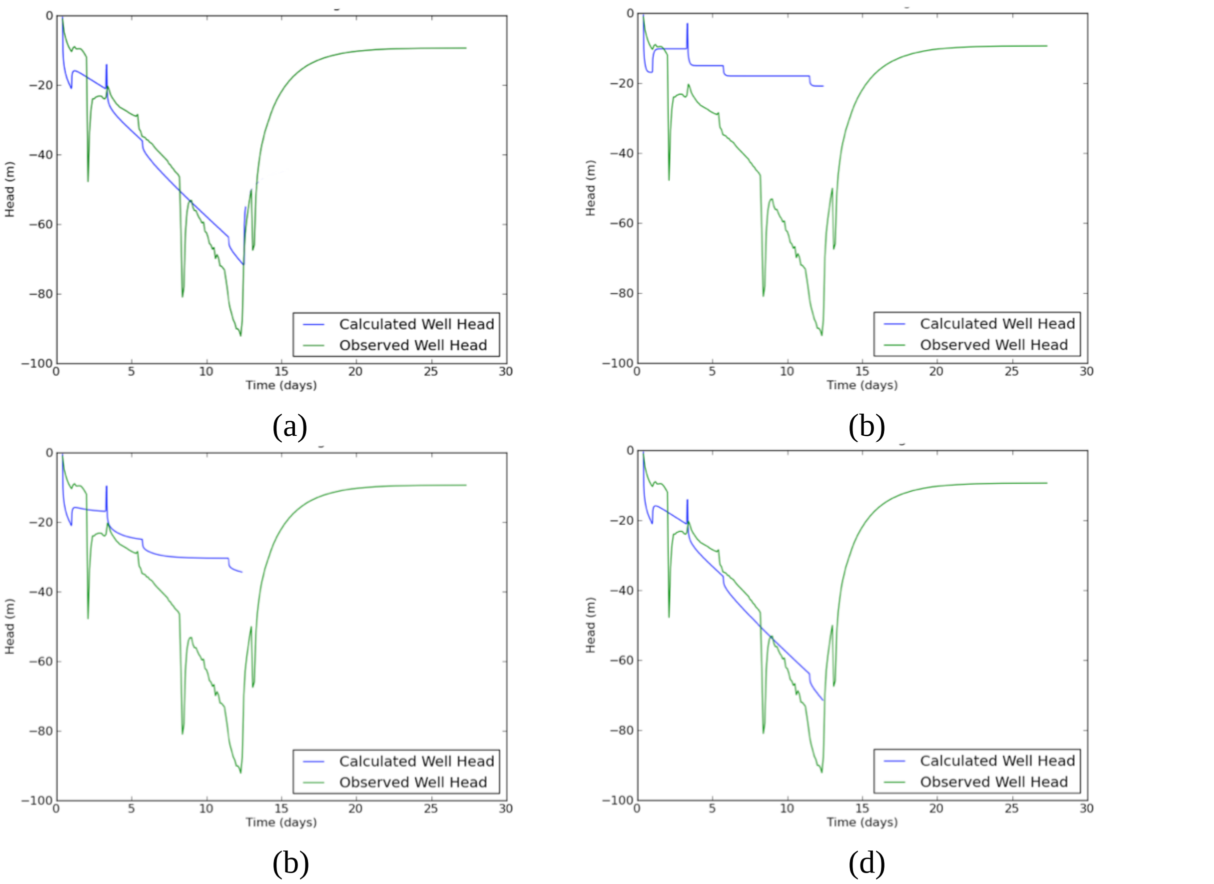


Figure A7: Simulations of well drawdown in the presence of leaks at (a) No leak baseline case, (b) 5m from well, (c) 10m from well, (d) 20m from well.

preliminary estimates of its importance can be made. It is important that this effect be taken into account because gas generation is the whole point of the process.

If we assume that for the Blakefield the gas will displace all water once the aquifer is completely depressurised (i.e. drawdown of 360m) and that the porosity of the aquifer is 10% and that all the aquifer pores are filled with before the pump test then the storativity from gas generation alone will be 0.1/360 or 3 x 10^{-4}. If less than 360m of drawdown is required to have gas flow then the storativity will be higher than this. 100m of drawdown would yield the storativity value of 0.001 obtained in the groundwater model fitting in this report. If this is the case then gas generation will be the dominant contributor to storativity in coal seam gas extraction projects, overwhelming the effect of elastic expansion of water and elastic compression of the aquifer.

To correctly model gas interactions would require a two-phase flow model involving both gas and water transport and how they interact. This would be a non-trivial exercise as these models can be extremely complex and it is outside of the scope of this study. Rather what the calculation in the previous paragraph indicates is that gas generation may be an important contributor to aquifer storativity and that we should use standard values for storativity from non-gas wells with considerable caution.

In the recommendations of the report the peer reviewer accordingly considers better estimation of storativity for *gas generating* wells a high priority.

A5. Leakage Simulations

This section presents the results from leakage simulations. The intent of this section is to demonstrate how the model provides information about whether leakage may have occurred into the aquifer during the pump test. There are two forms of leakage that were considered.

(a) Point leakage: This where there is some form of concentrated leakage. This might, for instance, be a fault intersecting that aquifer that allows water to be transported along the rubble within the fault line, or a gap in the aquiclude (it pinches out or just simply ends) so that water can flow freely from one aquifer to another through the gap.

(b) Distributed leakage: This is where there the aquiclude, while it is continuous, is not completely resistant to flow (the general rule of thumb is that the aquiclude's hydraulic conductivity should be a factor 10 less than the aquifer to be considered an aquiclude) and it allows some water to leak through everywhere.

The axisymmetric formulation of the groundwater model limits its ability to simulate point leakage but it is still useful to show the types of well drawdown behaviour during a pump test that result from point leaks. These point leaks have been extensively studied by groundwater specialists using more complex groundwater codes than the one used here and similar results are found. Figure A7 shows the results for well drawdown for the best-fit parameters without leakage, and the same model with leaks at a distance 5, 10 and 20m from the well. The leakage occurs from an aquifer with the same head as that in the pumped aquifer before pumping started.

These figures show the classic symptoms of point aquifer leakage.

(a) The first is that the simulation with a leak at 20m shows no impact of the leak. This because the cone of depression induced by the pump test only just reaches out to 20m towards the end of the pump test. The lesson from this is that while a leak may exist it is only once there is head gradient across it (driven the by cone of depression at the leaky point) that any impact is observed.

(b) The second is that a point leak exhibits itself as a reduced drawdown in the well. This is because the leak means that it is easier to extract water from aquifer because you are not only drawing from the aquifer but from the leaky point. This is because the leak is replacing water that has just been pumped out.

(c) The classic symptom of a point leak is that the drawdown curve is concave up (i.e. its get less steep with time) and it tends to a horizontal line with time (the steps in the horizontal line in Figure A7 reflect changes in the pumping rate during the test). After the time the drawdown has reached a constant value there is balance in the aquifer with the amount of water being pumped equal to water leaking into the aquifer. Note that this is not the same as saying that we are pumping out water from the leak because, at least initially, it will take some time for the water at the leak to travel to the well. The geochemistry of the water will be the geochemistry of the aquifer not the leak. So that at least initially the geochemistry of the water won't change. The lesson is that geochemistry is a lagging indicator of leakage.

The conclusion of this analysis is that the well drawdown from the pump test does not show any of the classical symptoms of a point leak located within the cone of depression created by the pump test. Accordingly I conclude that there are no point leaks within the cone of depression (within about 20-50m of the well) created by the pump test.

Distributed leakages are much more difficult to distinguish with a groundwater model of a pump test, and any arguments on the amount of leakage typically revolve around (1) laboratory measurements of the conductivity of the aquiclude material and the contrast between the aquiclude's conductivity and that of the aquifer, and (2) head measurements in the adjacent leaky aquifer. However, in the case where there is a distributed leak the storativity and conductivity estimated by the model using the pump test data (as done in this report) will include these effects. This is rather difficult to demonstrate but a simple example should suffice. A very leaky aquifer will simply look like the two aquifers stacked on top of each without the intervening aquiclude. Mathematically as far as the pump test is concerned they are indistinguishable from a single aquifer with the same thickness as the two aquifers combined. This inability to distinguish a single aquifer from a distributed leaky aquifer has been a cause of some debate at Powder River, specifically because it has an impact on the estimated time for the well field to recover after gas extraction is complete (Wheaton, personal communication).