Hydrogeological properties and mining impacts on groundwater in the Bowen, Styx and Galilee Basins

George Klenowski
*Australian Mining Engineering Consultants*

John Bernal
*Waratah Coal Pty Ltd*

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HYDROGEOLOGICAL PROPERTIES AND MINING IMPACTS ON GROUNDWATER IN THE BOWEN, STYX AND GALILEE BASINS

George Klenowski¹ and John Bernal²

ABSTRACT: The results of extensive hydrogeological investigations in the Bowen, Styx and Galilee Basins are described in this paper. These are coal mining areas with saline groundwater resulting from predominantly marine deposition. Small aquifers occur in Quaternary and Tertiary deposits and within coal measures strata. Tertiary Basalt flows sometimes contain larger aquifers. Mining results in localised groundwater drawdown. Testing has included determination of in situ permeability, pump-out flow rates, salinity and pH values of groundwater. Piezometer monitoring of aquifer drawdown during mining has been completed. Computer modelling and inflow calculations have been used to determine inflow rates during longwall mining. Accurate permeability results are required to obtain design parameters for mine dewatering systems. Mining results in aquifer drawdown, surface subsidence and the formation of open tension cracks. Because significant leakages can occur into underground workings from overlying water bodies within the critical tensile strain zone, extensive modelling has been completed to obtain accurate inflow values. Results indicate that only minor aquifers occur within coal measures strata. The groundwater is generally highly saline and is classified as contaminated. It can only be used for washing coal. The main impact from mining is potential inundation of underground workings from subsided, overlying water bodies. Groundwater drawdown recharges back to original levels following mining.

INTRODUCTION

Comprehensive groundwater investigations have been completed in the Bowen, Styx and Galilee Basins, where economic coal deposits occur. Pump-out flow rates, permeability and conductivities have been determined. Aquifers within coal measures are generally small and highly saline because the depositional environment was predominantly marine /deltaic. This water is classified as contaminated and cannot be discharged offsite. It can only be used for washing coal or purified by reverse osmosis prior to discharge. Water with a salinity of greater than 3000 ppm total dissolved solids cannot be discharged off a mining lease. Local, saline aquifers occur within emplaced igneous sills. Small perched aquifers, which are present in overlying Tertiary and Quaternary deposits include sandy alluvium in water courses and gravel beds at the base of Tertiary Clay. The water quality varies from fresh to saline. Significant freshwater aquifers can occur in Tertiary Basalt flows which overlie coal measures.

DETERMINATION OF GROUNDWATER PARAMETERS

Aquifer constants

Flow rates from aquifers obtained by air lift pump-out testing of drill holes are measured using a V-notch weir (The Australian Institute of Mining and Metallurgy, 2011). Transmissivity and co-efficient of storage values are determined by pump-out testing of production bores with monitoring of drawdown and recovery in observation bores. Calculations are completed using the Jacob or This Method (Australian Mining Engineering Consultants, 2000). Division of transmissivity by aquifer thickness gives permeability.

Accurate permeability values can be obtained by pump-in testing. The open-end test is normally done in unconsolidated or weathered material (Australian Mining Engineering Consultants, 2000). The hole is fully cased and the amount of water retained by the ground through the open bottom is recorded. The permeability is then obtained from:

\[ K = \frac{Q}{5.5 \times r \times H} \]

¹ Manager, Australian Mining Engineering Consultants. Email: amec1@bigpond.net.au Tel: +61 4 1718 7149
² Geologist, Waratah Coal Pty Ltd. Email: j.bernal@waratahcoal.com Tel: +61 4 4985 0642
where \( K \) = permeability (m/sec)
\( Q \) = constant flow rate into hole (m³/sec)
\( r \) = internal radius of casing (metres)
\( H \) = differential head of water (metres).

A drilling rig is normally used to complete packer tests (Figure 1). In these tests a section of hole is isolated with a single (downstage testing) or double (upstage testing) packer arrangement (Figures 2 and 3). Packers are either inflated hydraulically or pneumatically (Figure 4). Water is then pumped down the hole within drill rods and the flow rate and pressure are recorded. Five consecutive tests, each of ten minutes duration are normally completed for each stage, with the first three tests being done at increasing pressures and the last two tests done at decreasing pressures. Permeability values can then be interpreted in terms of laminar flow, turbulent flow, dilation, wash-out and void filling (Houlsby, 1976), and appropriate values selected for inflow calculations. Prior to determining permeability values, the differential head values need to be corrected for friction losses in the system, which include flow meter, packer and rods (Figure 2).

![Figure 1: Drilling rig used for packer permeability testing](image1)

![Figure 2: System for determining packer losses](image2)

![Figure 3: Testing packers](image3)

![Figure 4: Monitoring equipment and nitrogen cylinder used for packer permeability testing.](image4)

The formulae for this test (Australian Mining Engineering Consultants, 2000) are:

\[
K = \frac{Q}{2\pi r L H \log e X \frac{L}{r}} \quad \text{where} \quad L \geq 10r
\]

\[
K = \frac{q}{2\pi r L H \sin h^{-1} X \frac{L}{2r}} \quad \text{where} \quad 10r > L \geq r
\]
where $K$ = permeability (m/sec)
$Q$ = constant flow rate into hole (m$^3$/sec)
$L$ = length of test section (metres)
$H$ = corrected differential head of water (metres)
$r$ = radius of hole tested (metres)
$log_e$ = natural logarithm
$sinh^{-1}$ = arc hyperbolic sine.

The relationship between permeability and aquifer drainage is described in Figure 5.

![Figure 5: Permeability and drainage systems](image)

**Inflow calculations**

A number of assumptions need to be made when using steady state type inflow equations for dynamic situations involving tensile fracturing during extraction mining. Calculated inflows should only be used as a guide. More accurate calculations can be obtained using models with accurate permeability values and sophisticated computer programs.

Darcy’s equation can be used to calculate inflow from subsurface aquifers, as follows:

$$Q = KI A \times 1000$$

where $Q$ = flow rate (litres/sec)
$K$ = permeability (m/sec)
$I$ = hydraulic gradient
$A$ = cross-sectional area of aquifer ($m^2$).

Inflows into a longwall mine can be computed using the formula for flow into a slot from a two line source (Australian Mining Engineering Consultants, 2000) as follows:

$$Q = K(2 x Hr x Hw - Hr^2)/2L x I x 10^3$$

where $Q$ = rate of inflow per panel length (litres/sec)
$K$ = weighted permeability of overburden (m/sec)
$Hr$ = height to rockhead (i.e. base of Tertiary or $2/3$ Hc, whichever is less (m))
$Hw$ = height to water table (m)
$L$ = drawdown function

$$= 5 x Hw$$
$I$ = panel length
$Hc$ = critical caving height (height at which maingate and tailgate caving angles intersect the surface).

For first panel extraction the above value of $I$ is doubled to allow for inflow from both sides. For subsequent panels inflow occurs from one side, the other side being goaf.

**INFLOW MONITORING**

Monitoring of inflows into open cut and underground workings has been completed. Sources of water include surface storages, aquifers and inundated underground workings. Surface ponded water which
can flow into underground mines originates from open cut final voids, internally draining spoil piles, subsidence troughs, natural depressions, flowing creeks, dam reservoirs and ungrouted boreholes in topographically low areas. A number of monitoring techniques have been used including V-notch weirs, flowmeters on pump pipelines, piezometers and measurements of water level falls in surface ponds of known volumes. A method has been developed to calculate goaf storage volumes (Australian Mining Engineering Consultants, 2000). The main aim of inflow monitoring has been to measure water inflow rates from sources located at different heights above underground workings and relate the inflow rates to measured and calculated tensile strain values. Although it is known that tensile strain and inflow rates decrease with increasing overburden thickness, quantification of these values is required to improve inflow predictions.

MINING INDUCED GROUNDWATER CHANGES

Mining causes fluctuations of the groundwater regime due to dewatering of aquifers. These changes are reversible and post-mining recharge results in the return to original water levels with salinities similar to previous values.

Open cut mining

Minor seepage of saline groundwater occurs during open cut mining, mainly from coal seams. Local aquifers occur at the base of Tertiary Clay and within weathered coal measures strata. The water table generally occurs between 10.0 m and 30.0 m below the surface with some seasonal fluctuation. Ponded, saline water in final voids can have pH levels as low as 2.5 (Australian Mining Engineering Consultants, 2000), due to the presence of oxidisable pyrite which reacts to form sulphuric acid.

Groundwater drawdown curves adjacent to open cut voids are generally steep due to the very low permeability of the strata. Drawdown curves can be generated by computer modelling using programs such as the SEEP/W portion of the GeoStudio package. Detailed sections with accurate permeability values are required to produce valid results (Figure 6). Results from Australian Mining Engineering Consultants, 2020, show that during mining groundwater drawdown occurs for about 40 m outside of the excavated profile after exposure for one year and about 550 m from the excavated profile after 13 years. During post-mining recharge the phreatic surface would return to the original level with similar salinity.

![Figure 6: Plan and section computer model, Central Queensland Coal Project](image-url)
Underground mining

Longwall mining is the most common underground extraction method. Localised bord and pillar mining is also practiced. During longwall mining the overburden subsides and longitudinal and arcuate tensile fractures form (Australian Mining Engineering Consultants, 2000). Goafing results in a primary caving zone where the failed material is rubbly and an overlying, secondary caving zone when the overburden subsides en-masse along longitudinal fractures, parallel to the gateroads (Figures 7 and 8, Australian Mining Engineering Consultants, 2000). In the critical tensile strain zone which occurs to a height of about 180 m above the mining horizon, tensile fractures are interconnected, allowing downward flow of groundwater or ponded water into the goaf (Figure 8). Above this zone water does not flow into the goaf.

![Diagrammatic representation of longwall subsidence](image1)

![Section through subsided igneous sill aquifer](image2)

Computer modelling has been used to calculate inflow rates for increasing depth of cover. Figure 9 is a typical geotechnical section. A program based on MAP3D, which has been developed incorporates all the major components of the rock strata that are required to simulate ground response to underground multi-seam mining (Australian Mining Engineering Consultants, 2000). The program used to investigate transient and steady state water flow mechanisms is the 3-D finite element program London University Stress Analysis System (LUSAS) developed by Finite Element Analysis (Australian Mining Engineering Consultants, 2000).

Inflow rates have been calculated using the MAP3D and LUSAS seepage flow models. Results are tabulated in Table 1 and are compared with maximum recorded inflows.

<table>
<thead>
<tr>
<th>Depth of cover (m)</th>
<th>Seam thickness (m)</th>
<th>Inflow rate (l/sec)</th>
<th>Maximum recorded inflow (l/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>2.8</td>
<td>165</td>
<td>140</td>
</tr>
<tr>
<td>100</td>
<td>2.7</td>
<td>76</td>
<td>83</td>
</tr>
<tr>
<td>120</td>
<td>2.8</td>
<td>39</td>
<td>45</td>
</tr>
<tr>
<td>140</td>
<td>2.8</td>
<td>30</td>
<td>27</td>
</tr>
<tr>
<td>175</td>
<td>2.7</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

Computer modelling indicates that there is a good correlation between predicted and maximum recorded inflow rates. The modelling has been refined using ongoing subsidence, strain and inflow monitoring data. The inflow rates in Table 2 require assessment because they are affected by the type of ponded floor material, degree of clogging of open tension cracks and hydrostatic head.

In the Styx Basin computer modelling of groundwater drawdown during mining has been completed using the SEEP/W portion of the Geostudio package. Two dimensional finite element seepage analyses were performed. Computed drawdown was minimal.
Table 2: Recent inflow monitoring data

<table>
<thead>
<tr>
<th>Mine</th>
<th>Date</th>
<th>Location</th>
<th>Depth of cover (m)</th>
<th>Inflow rate (litres/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oaky No.1, panel 19</td>
<td>2000</td>
<td>Highwall mining entries, Stuart Pit</td>
<td>110</td>
<td>45</td>
</tr>
<tr>
<td>Grasstree</td>
<td>2011</td>
<td>Grasstree North Pit above Southern Colliery</td>
<td>105</td>
<td>65</td>
</tr>
<tr>
<td>Oaky North, 400's panels</td>
<td>2011 – 2015</td>
<td>Oaky Creek</td>
<td>160 – 180</td>
<td>Negligible</td>
</tr>
<tr>
<td>Oaky No.1, panel 32</td>
<td>2013</td>
<td>Aquila Low, A7 Pit</td>
<td>105</td>
<td>30</td>
</tr>
<tr>
<td>Oaky No.1, panel 36</td>
<td>2014</td>
<td>Highwall mining entries, Pit A6 South</td>
<td>105</td>
<td>20</td>
</tr>
<tr>
<td>Oaky North, panel 308</td>
<td>2014</td>
<td>Grasstree South Pit and spoil piles</td>
<td>130</td>
<td>23</td>
</tr>
<tr>
<td>Oaky No.1, panel 33</td>
<td>2015</td>
<td>Aquila Low Pit</td>
<td>105</td>
<td>20-30</td>
</tr>
<tr>
<td>Oaky No.1</td>
<td>2016</td>
<td>Tailings in Talagai (A4) Pit</td>
<td>120</td>
<td>60</td>
</tr>
</tbody>
</table>

Subsidence monitoring indicates that longitudinal tension cracks occur parallel to gateroads along zones of maximum tensile stress. Full subsidence generally occurs above the panel centre line and is related to height of overburden, panel width and extracted seam thickness. Due to the panel widths in Queensland mines, strata bridging does not occur, except for minor goaf hang up. Yield pillars crush under abutment load.
TESTING RESULTS FOR THREE BASINS

Extensive testing has been carried out in the Bowen and Styx Basins. Preliminary hydrogeological work has commenced in the Galilee Basin. Groundwater chemistry, pump-out testing flow rates and permeability have been determined.

Bowen Basin

Hydrogeological investigations were completed at the German Creek and Oaky Creek Mines prior to longwall mining and are ongoing.

Groundwater chemistry

Salinities of local, near surface aquifers range from 2000 to 6000 ppm. Coal measures and spoil piles groundwater salinities range from 12 000 to 25 000 ppm (Australian Mining Engineering Consultants, 2000 and Klenowski and Phillips, 1988). Ponded, saline water in final voids can have pH values as low as 2.5 (Australian Mining Engineering Consultants, 2000 and Capricorn Management, 1993). At the German Creek Mines about 5000 megalitres of acid water with a pH of 2.5 was dosed with lime to increase the pH to 6.9, prior to being used for washing coal (Capricorn Management, 1993). Post-mining infilling of final voids with rejects, tailings or spoil is recommended, prior to topsoiling and seeding. At the Moranbah North Underground Mine groundwater salinity ranges from 8000 to 9000 ppm (Shell Company of Australia, 1995).

Pump-out testing flow rates

The maximum recorded pump-out flow rate in coal measures at the German Creek and Oaky Creek Mines was 10 litres/sec in the Fairhill Formation. At Southern Colliery a flow rate of 37.5 litres/sec was measured during pump-out testing of saline water in the Aquila Sill aquifer. Pre-drainage was completed prior to longwall undermining (Klenowski & Phillips, 1988).

Throughout the Bowen Basin flow rates from coal measures are low and the groundwater is generally highly saline. At the German Creek and Oaky Creek Mines pit water can only be used to wash coal and the latter mine has installed a reverse osmosis plant to treat contaminated water.

Permeability

A typical stratigraphic section with permeability for the German Creek and Oaky Creek Mines is shown in Figure 10. These results are typical for the Bowen Basin and recent data from the Styx and Galilee Basins are compatible. Measured permeability values for surface alluvium, Tertiary Clay and weathered bedrock are 1.3 x 10⁻⁵, 2.3 x 10⁻⁶ and 8.5 x 10⁻⁷ m/sec respectively (Figure 10, Australian Mining Engineering Consultants, 2000). Coal measures permeability ranges from 1.7 x 10⁻⁶ to 4.1 x 10⁻⁸ m/sec.

At the Moranbah North Underground Mine and the Goonyella / Riverside Project measured permeability is 5.0 x 10⁻⁵ m/sec for Tertiary and Quaternary Clay and 1.5 x 10⁻⁶ to 3.0 x 10⁻⁸ m/sec for coal measures strata (Shell Company of Australia, 1995). The low permeability results indicate limited groundwater drawdown during mining with rapid, post-mining water table recovery.

Styx Basin

The Styx Basin is being investigated for the production of PCI (pulverised coal injection method) coal. Extensive groundwater investigations have been completed at the Central Queensland Coal Project (Australian Mining Engineering Consultants, 2020).

Groundwater chemistry

Coal measures groundwater is highly saline with salinities ranging from 8 400 ppm to 15 700 ppm. Minor seasonal fluctuation of groundwater occurs (Australian Mining Engineering Consultants, 2020). The pH is neutral (6.8 to 7.6, Australian Mining Engineering Consultants, 2014). Isolated water pools which occur along water courses have salinities ranging from 135 ppm to 950 ppm (Australian Mining Engineering Consultants, 2020). The pools dry up due to evapotranspiration and are recharged by rainfall runoff.
**Figure 10: Stratigraphic section with permeability, German Creek and Oaky Creek Mines**

**Pump-out testing flow rates**

Pump-out testing has been completed in five drill holes. Air-lift flow rates ranged from 0.002 litre/sec to 0.15 litre/sec, indicating very tight, coal measures strata. All discharged water was highly saline.

**Permeability**

Recent permeability testing has been completed for the full mining horizon at the Central Queensland Coal Project (Australian Mining Engineering Consultants, 2020). Surface clay and weathered
bedrock have permeability values ranging from $3.7 \times 10^{-8}$ to $1.0 \times 10^{-9}$ m/sec. Permeability of fresh surface bedrock is $3.73 \times 10^{-7}$ to $1.33 \times 10^{-7}$ m/sec. Fresh coal measures strata have permeability of $2.6 \times 10^{-6}$ to $3.96 \times 10^{-6}$ m/sec. All permeability is very low indicating limited groundwater drawdown during mining (Figure 6). Post-mining recovery would be rapid.

**Galilee Basin**

Economic thermal coal deposits occur in the Galilee Basin. Construction has commenced at the Carmichael Mine and investigations are proceeding at the China Stone, Kevin’s Corner and Galilee Coal Projects.

![Map of Galilee Basin with water bores](image)

**Figure 11: Galilee water bores drilled in 2019**

Groundwater chemistry

Original groundwater investigation was completed at the Galilee Coal Project in 1994 (Bridge Oil Limited, 1994). Work continued in 2007 (Australian Mining Engineering Consultants, 2007) and is ongoing. Groundwater salinity is variable ranging from 170 ppm to 19 300 ppm. Where sandstone beds are more permeable, groundwater tends to be less saline. The Colinea Sandstone Member is a typical example. Seven groundwater investigation holes were completed in 2019 (Figure 11). Salinites ranged from 290 ppm to 19 400 ppm. Measured pH values were 7.45 to 8.7. These results are preliminary and ongoing testing is proceeding.

**Pump-out testing flow rates**
Previous pump-out testing at the Galilee Project gave values ranging from 1.5 litres/sec to 12.6 litres/sec with an average flow rate of 6.5 litres/sec (Bridge Oil Limited, 1994). Maximum flow rate was in the DL2 to E interval. No pump-out tests were completed in the seven holes completed in 2019 because flows were too small to measure.

Permeability

Permeability results for the Galilee coal measures range from $6.0 \times 10^8$ to $8.0 \times 10^8$ m/sec (Bridge Oil Limited, 1994). Recent testing of coal seams gave an average permeability of $1.3 \times 10^{-7}$ m/sec (Ward pers. comm (2020)).

**SUMMARY OF TEST RESULTS**

A summary of test results is included in Table 3. Pump-out flow rates are determined by air-lift testing. Results are for coal measures strata. Low pH values occur where oxidisable pyrite is present.

Table 3: Summary of test results for the Bowen, Styx and Galilee Basins

<table>
<thead>
<tr>
<th>Basin</th>
<th>Maximum pump-out rate (litre/sec)</th>
<th>Salinity range (ppm)</th>
<th>pH range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowen</td>
<td>10.0</td>
<td>12 000 to 25 000</td>
<td>2.5 to 8.5</td>
</tr>
<tr>
<td>Styx</td>
<td>0.15</td>
<td>8400 to 15 700</td>
<td>6.8 to 7.6</td>
</tr>
<tr>
<td>Galilee</td>
<td>12.6</td>
<td>290 to 19 400</td>
<td>7.45 to 8.7</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

Hydrogeological investigations in the Bowen, Styx and Galilee Basins indicate that the groundwater in coal measures is generally highly saline and is classified as contaminated. Such water cannot be discharged off mining leases but can be used for washing coal or purified by reverse osmosis, prior to release. Ponded pit water can have pH levels as low as 2.5 due to the presence of oxidisable pyrite. Acidic water can be dosed with lime for neutralisation, prior to being used for washing coal. Final voids should be backfilled with rejects, tailings or spoil.

Coal measures strata have very low permeability with local, minor aquifers. Larger saline aquifers can occur in emplaced igneous sills. Small, freshwater aquifers sometime occur in overlying Tertiary and Quaternary deposits. Significant freshwater aquifers may be present in Tertiary Basalt flows.

Groundwater drawdown around open cut voids is localised due to the low permeability of the strata. Post-mining recovery of saline water is rapid.

The critical tensile strain zone which forms during longwall mining occurs for a distance of about 180 m above the mining horizon. Within this zone, subsidence tension cracks are interconnected to the goaf allowing downward flow of water. Flow rates into the goaf from an overlying water body decreases as the overburden thickness increases. Monitoring indicates that following mining the saline, phreatic surface returns to its original level.

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Capricorn Management, 1993. A new integrated tailings disposal and water management system for the German Creek Mine.