Mine Water and the Environment (2019) 38:676–685
https://doi.org/10.1007/s10230-019-00627-z

TECHNICAL ARTICLE

Interpretations of Mine Water Pump-Out Data and Revisions to Caving and Fracturing Models for Longwalls

Ross Seedsman[1]

Received: 24 October 2018 / Accepted: 1 August 2019 / Published online: 12 August 2019

Abstract
A revised model for mine water inflows is developed for an Australian longwall mine. The measured inflows are primarily related to face-parallel fractures that progressively develop as the longwall face retreats. When open, these face-parallel fractures have very high transmissivity, so inflow to the mine is determined by the rate of drainage out of the unconfined near-surface aquifer. There is also evidence of reconsolidation of the low-strength fine-grained rocks immediately above the coal seam, such that vertical flow into previous extraction panels does not develop. A generalised hydrogeological model for longwall mining is proposed that incorporates enhanced conductivity zones of progressively decreasing hydraulic conductivity that can extend upwards to approximately twice the extraction width unless terminated by a near-surface thickly bedded unit.

Keywords Subsidence · Inflow · Consolidation · Spanning

Details of the Case Study

The case study involves a longwall coal mine operating at relatively shallow depths beneath an extensive unconfined aquifer. The mined coal seam is a Permian age coking coal that is typically 4.2 m thick with a 3.6 m section extracted by the longwall. In the area of the case study, the depth of cover varies between 145 and 80 m. Prior to moving to this area of the lease, longwall mining was conducted at depths between 220 and 90 m. The overlying coal measure rocks consist of interbedded and laminated sandstones, siltstones, and mudstones. Typical rock strengths range from 10 to 20 MPa, with the sandstones slightly stronger at 25–30 MPa.

There is a Tertiary age basalt unit at the surface with a typical thickness of about 40 m. There are a number of basalt flows in the unit and the oldest flow was deposited on a dissected weathering surface that had a topographic relief in the order of 20 m with steep-sided valleys having slopes of up to 45° (Fig. 1). There is a clayey weathering profile under the basalt unit and there is also a clay layer between the channel flow and the main basalt. As will be discussed below, the piezometric evidence suggests that this clay layer was not an aquiclude or aquitard during the mining process—either it was fractured by mining subsidence, was not continuous across the mining area, or was cut by joints and other geological features.

The basalts are columnar jointed and contain many vesicular horizons. The main basalt flow outcrops at the surface such that the water level in the basalt is recharged by occasional flows in a nearby ephemeral creek. The relative level of the base of the basalt is between reduced level (RL) 130 m and RL 190 m and the topographic surface lies between RL 187 m and RL 203 m. RL in this case refers to m above sea level. In the first 14 years of operation in a deeper area of the mining lease, it was observed that water pump-out rates increased markedly when the interburden thickness between the coal seam and the basalt was less than 105 m. This case study relates to the extraction of six longwall panels in an area of the mining lease where the thickness of the interburden between the top of the coal seam and the lowest basalt flow varied between 80 and 30 m (Fig. 2a). The seam geometry is in the form of a shallow syncline plunging to the left in the figure. In anticipation of higher water inflows, the mine design utilised longwall faces retreating to the top right of the figure and progressively up the synclinal axis with a pumping gallery installed at the lowest elevation of the seam. The pumping strategy included four pumps of 70 L/s

✉ Ross Seedsman
sgplross@bigpond.com

[1] Seedsman Geotechnics Pty Ltd, Mittagong, NSW 2575, Australia

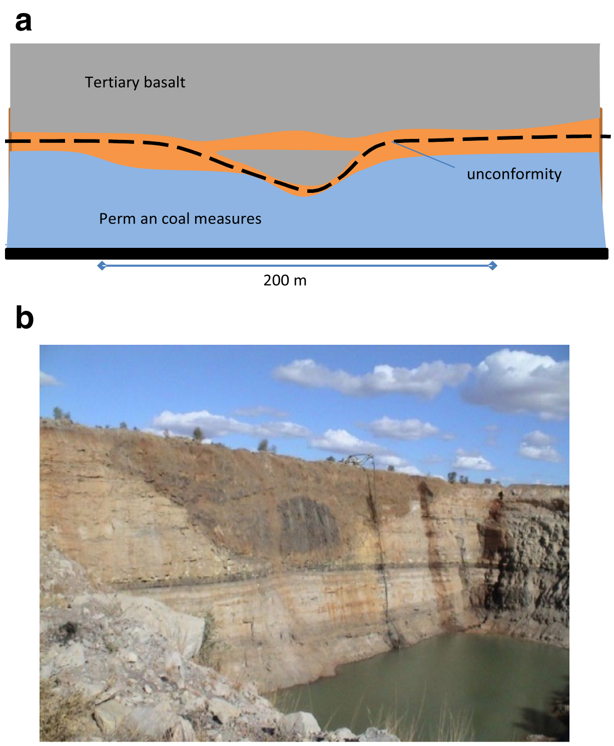


Fig. 1 Simplified geology at the case study with a photograph of the channel geometry in adjacent surface mine

capacity with an initial pipe line capacity of 105 L/s, which was subsequently increased to 210 L/s. Several piezometers were installed in the overburden; the location of the one referenced in this study is shown in Fig. 2b.

The longwall extraction width was 314 m and the pillars were 35 m wide. Longwall extraction results in the collapse of the near-seam overburden and a substantial disruption of the rock mass. The disrupted material is referred to as the goaf. For the case study mine, the disruption extended to the surface and the thickness of the upper basalt and its proximity to the surface resulted in a highly irregular surface subsidence profile (Fig. 3).

Piezometer and Pump-Out Data

A data-logging system was installed to record the pump-out volumes and to monitor the piezometric level in the basalt aquifer (Fig. 4). It is emphasised that the pump-out values are a proxy for the inflow rates as there were significant opportunities for transient storage in the mine—such storage would have been available if the inflows were greater than the installed capacity of the pumps or the surface pipelines.

The basalt aquifer was recharged by flows in the ephemeral creek three times during the time period under consideration (April 2013, February 2014, and December 2014). Inspection of Fig. 4 reveals that sometimes the pump-out rates followed the trend of the piezometric level in the basalt. This is more clearly shown in Fig. 5, which presents a cross-plot of the piezometric level in the basalt vs. the pump-out rate, with each of the longwall panels (LW A, B, C, etc.) identified. In addition to several peak pump-out events that were independent of the piezometric level, there are also several curvilinear trends, with two highlighted by dashed lines.

The pump-out rates increased dramatically when the face positions were about 500–700 m from the end of the longwall panels. The timing of the deviations above the curvilinear trends is coincident with the longwall face having just passed under the thalweg of the basalt-filled channel. The fact that there were similar pump-out increases for LW A, B, and C indicates that the basalt unit in the base of the valley is hydraulically connected to the main basalt aquifer, so that it was also recharged when the main aquifer was recharged. This suggests that the clay layer between the basalt flows is not an aquitard: whether this was true before mining or was caused by subsidence is not known.

Another aspect of this plot is that the curvilinear trends are similar but slightly offset for the retreat of each of the three longwalls, with the pump-outs from LW C tending to be slightly less at a given head. There is also a possible linear trend for the background inflows to increase from 50 L/s during LW A to 75 L/s after LW F (the green line in Fig. 4 connects March 2013, December 2013, May 2014, December 2014, and May 2015).

The water level in two observation holes drilled into LW B was measured during the retreat of LW C. The relative level of the roof of the coal seam at this location was RL 73 m, the base of the basalt was at RL 132 m, and the water level was RL 93 m (Fig. 6); the disrupted zone above the longwall extraction was not free draining at this location at this time.

Analysis

Flows Out of the Basalt

The following analysis considers the possibility that inflow to the mine is determined by the outflow from the basalt aquifer and not the hydraulic conductivity of the disrupted zone. If the observed inflows were the result of vertical drainage through the disrupted zone above each longwall panel, then there would have been a progressively increasing inflow as each longwall panel was extracted and the pump-out rate would have remained at its maximum capacity after April 2013.

The outflow from an unconfined aquifer can be assessed in the context of flow into a trench (in this case

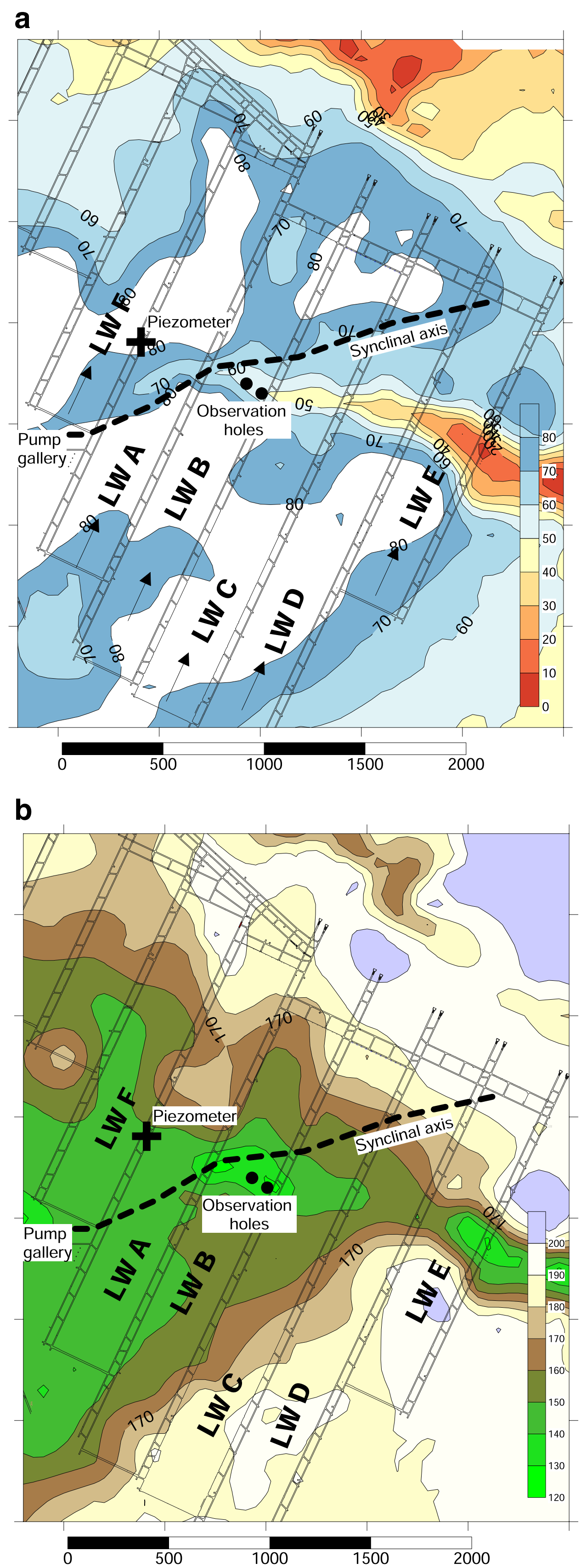


Fig. 2 Mine layout and the location of the main piezometer, the pump out gallery and observation boreholes: **a** distance between base of basalt and top of mined seam, location of synclinal axis, and the direction of longwall retreat, **b** RL of base of lowest basalt and surface drainage pattern

study, the trench being an open subsidence crack at the base of the basalt (Fig. 7), with the flow rate given by the Dupuit equation:

$$Q = K * \left(h_2^2 - h_1^2\right)/(2 * L)$$

where Q the discharge through the cross-section per unit thickness (m^2/d), K the hydraulic conductivity of aquifer (m/d), h_2 and h_1 = the steady-state heads measured along the flow path (m), and L = the distance between steady-state head measurements (m). As is typical in mining, the required data to apply an analytical model is limited both in terms of the amount of data and in its direct applicability. The head values depend on the accuracy of the relative level of the base of the basalt, which itself depends on the interpolation of widely-spaced drill holes. Furthermore, the point at which the subsidence crack intersects the basalt is not necessarily directly above the face line, and there is a lag between the timing of inflow to the crack and the arrival of the water at the pump gallery, during which the longwall face will have retreated some distance.

The following simplifications were made:

- A value of 50 m/day (6×10^{-4} m/s) for the hydraulic conductivity of the basalt, based on a reasonable match to the data. This is considered acceptable for columnar and partly vesicular basalt.
- A face-parallel subsidence crack with a length of 305 m.
- Full draw-down at the subsidence crack, $h_1 = 0$.
- The observation piezometer is 400 m distant, estimated by fitting the data and recognising that there is continuous variation in the distance to the active longwall.
- A background inflow of 45 L/s.

The results from this analysis for the subsidence crack/basalt intersection at RL160 m and RL150 m are shown in Fig. 5 as the two dashed black lines, where it can be seen that there is a reasonable match in terms of the pumping rate, the piezometric level, and the relative level of the basalt. It was therefore concluded that inflow to the mine can be considered in the context of outflows from the basalt. The higher inflow rates while under the thalweg of the basalt channel relate to the higher differential head in the basalt and not the reduced thickness or increased transmissivity of the interburden.

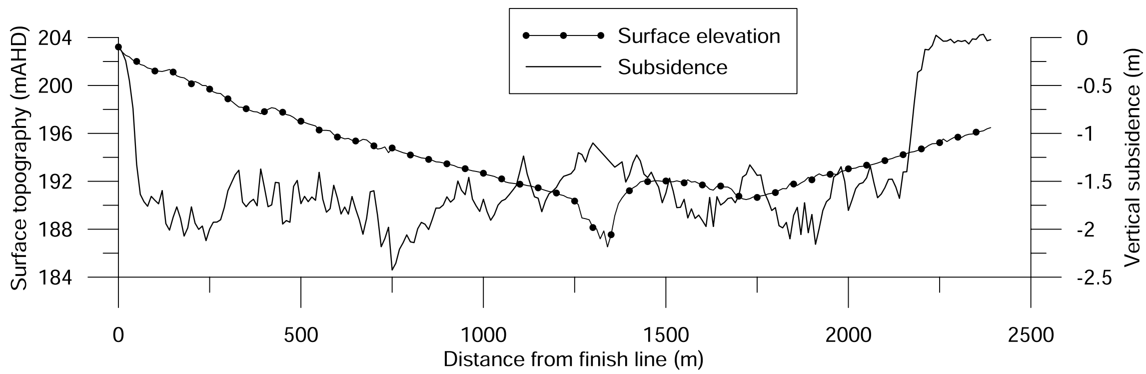


Fig. 3 Subsidence along the centreline of LW A

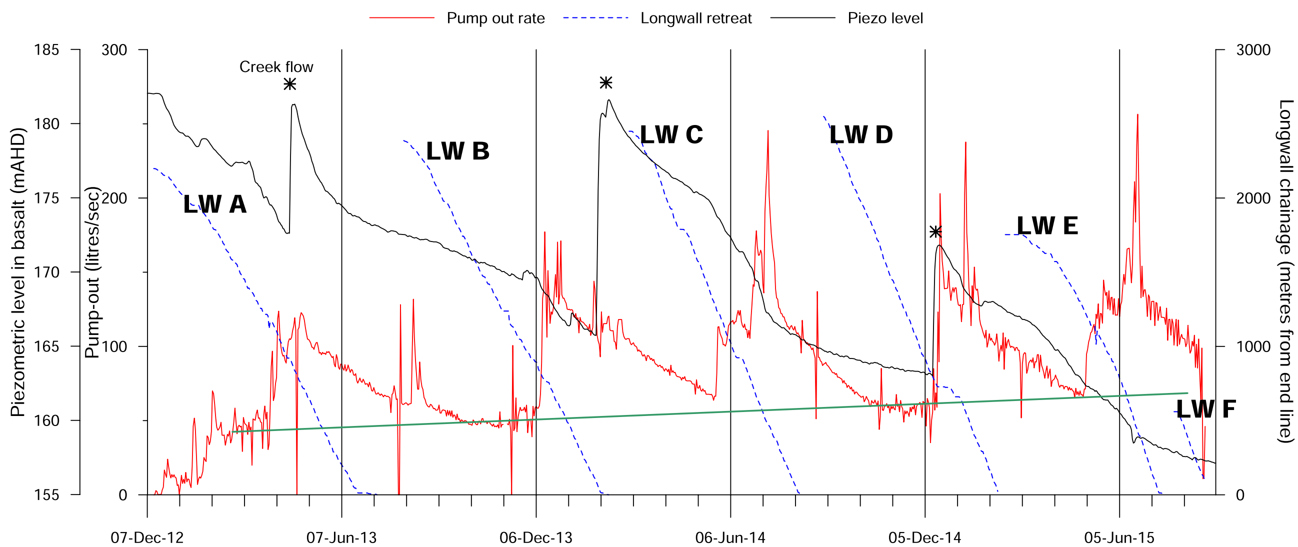


Fig. 4 Piezometric levels in the basalt (black line), the pump-out data (red line), the face positions for each of the longwalls (LW A through to LW F) relative to the finish location (dashed blue lines), and the trend of increasing background flows (green line)

Reconsolidation at the Base of the Goaf

For the same head in the basalt, the pump out for LW C was not three-fold that for LW A, which suggests that there was no significant concurrent flow into LW A and LW B extraction areas (similarly for LW B with respect to LW A). Separate from the peak flows, there was also an increase in the background flows from about 45 L/s for LW A to 75 L/s after LW F. Some of this could have been lateral flow from the coal seam and minor aquifers in the overburden and some could have been vertical seepage through the disrupted rock mass. If a lateral inflow of 10 L/s is assumed, then the balance would be vertical seepage: if so the vertical permeability of the disrupted zones was $1.6-3\times10^{-8}$ m/s.

In the context of predicting inflow to a longwall coal mine, the conventional view is that permeability and porosity is greatest in the disrupted rock mass immediately above the extraction level. Current hydrogeological models invoke the highest permeability at the seam level and by implication the highest porosity. If an analogy is made between the disrupted rock mass and rock fill, then the greater stresses at the base of the goaf should result in less porosity and permeability. Furthermore the near–seam mudstones have strengths on the order of 20 MPa and are likely to soften in the presence of water.

Samples of similar strength mudstones (25 MPa) from an adjacent mine were subjected to one-dimensional consolidation tests in 150 mm diameter cells after screening to a maximum particle diameter of 26.5 mm. Water was added and then standard consolidation tests were conducted at 500, 1000, and 2000 kPa. The calculated permeabilities (Table 1) were on the order of 10^{-8} m/s, which is typical for clays and intact claystones and siltstones.

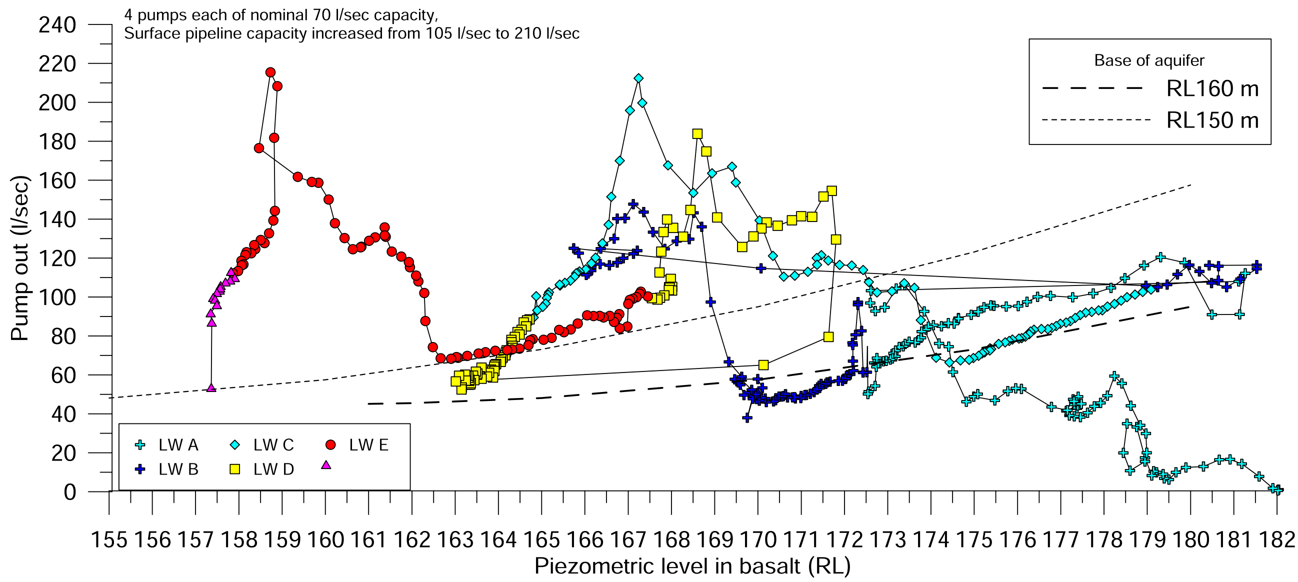


Fig. 5 Cross plot of piezometric level and pump-out rates as a function of time superimposed with trends calculated using the Dupuit relationship for the base of the aquifer at RL160 m and RL150 m

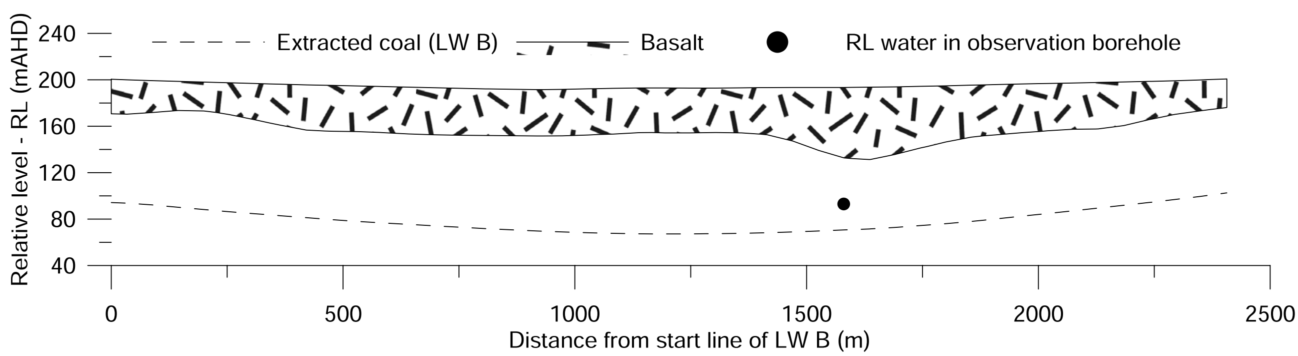


Fig. 6 Section along the centreline of LW B showing relative level of water in the observation boreholes during the extraction of LW C

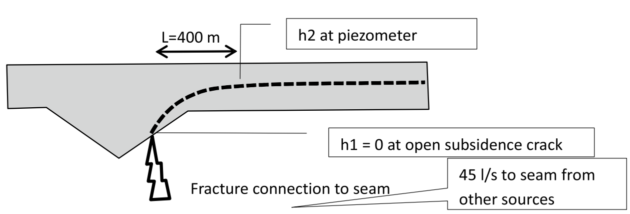


Fig. 7 Simplified model for drainage of basalt aquifer by a face-parallel fracture

These permeabilities are similar to those estimated from the inferred background inflow in the case study.

Although the water saturation/stress path adopted in the laboratory cannot represent the complex history of a longwall goaf, such tests are generally indicative of what can happen at the interfaces between large blocks. The main result of the lab tests is that the disrupted rock mass has very low permeability near the seam level—one that is closer to silty soils than to rock fill.

A Revised Water Inflow Model

Model for the Case Study

Similar to the zones introduced by Colwell and Harman (1993), the model for the case study identifies the first subvertical breaks behind the longwall face line as the primary water flow pathways (Fig. 8a). To some degree, these breaks also exploit the joints in the overburden sequence. These breaks have very high hydraulic conductivity, such that inflow to the mine is determined by the discharge from the basalt aquifer. The material in Zone D acts as a surcharge

Table 1 Summary of consolidation testing

	Fine sand/siltstone	Siltstone	Siltstone
Lump density (t/m^3)	2.41	2.45	2.19
Density before test (t/m^3)	1.24	1.17	1.21
Density after test (t/m^3)	1.88	2.12	1.91
Permeability at 500 kPa—nominal 25 m high goaf pile (m/s)	$5.03*10^{-8}$	$8.76*10^{-9}$	$1.18*10^{-8}$
Permeability at 1000 kPa—nominal 50 m high goaf pile (m/s)	$2.74*10^{-9}$	$2.44*10^{-8}$	$1.74*10^{-8}$
Permeability at 2000 kPa—nominal 100 m high goaf pile (m/s)	$3.99*10^{-10}$	$2.06*10^{-8}$	$0.34*10^{-8}$

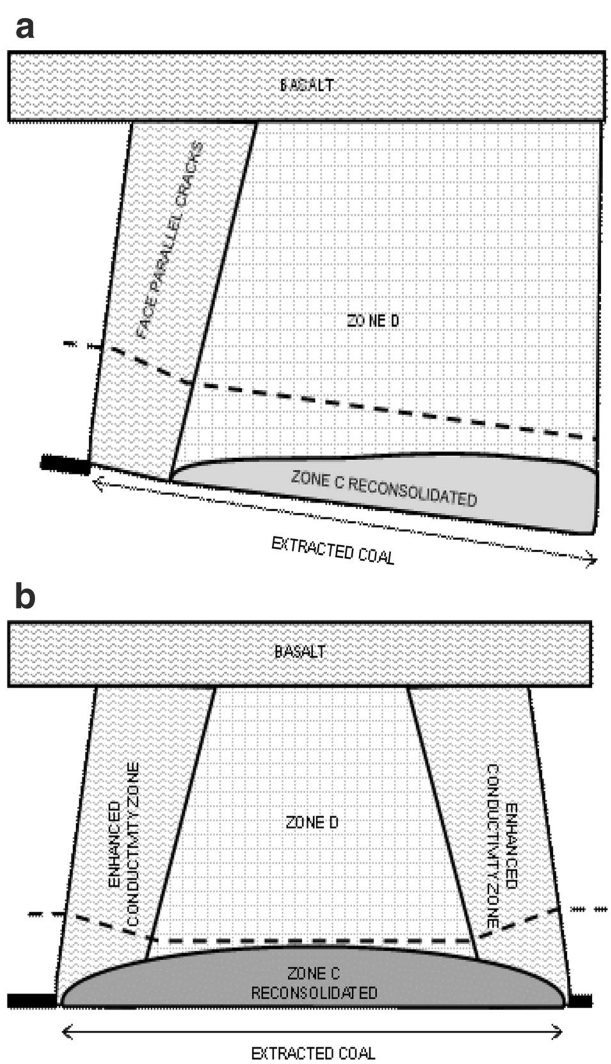


Fig. 8 Model for a resealing goaf in the case study mine (dashed lines show trend of bedding)

loading on Zone C, and as the rock near the coal seam is of low strength, it softens in the presence of water, allowing the goaf to compress and reconsolidate. In this model, Zone C prevents vertical inflows relatively soon after the longwall passes. In cross section, there are also enhanced conductivity zones (Fig. 8b) and the reconsolidation of Zone C may not continue all the way to the sides of the coal pillars, where the vertical loading may be much lower. There has been no attempt at this time to allocate hydraulic conductivity values to the various zones as the key determinant for mine inflow is the release rate from the basalt aquifer.

Generalised Model

Based on this interpretation of the case study data and observations made at other mines, an alternative generalised hydrogeological model for longwall extraction is proposed. The author has observed fracture zones in roadways formed about 35 m above earlier longwall extraction and has also observed remarkably intact bedding stratification only 5–10 m above longwall panels subsequently exposed in highwalls. When assessing flows into another nearby mine, Colwell and Harman (1993) conducted packer tests and found that the bulk of the disturbed ground had hydraulic conductivities similar to those before mining and suggested flow paths down zones along the edge of the extraction. With the case study and these observations, a generalised model (Fig. 9a) has six components:

- Potential consolidation zone—the highly disrupted zone immediately above the coal seam. This material may or may not reconsolidate; reconsolidation occurred with 25 MPa rock at the case study mine, but may not occur with higher strength sandstones.
- Enhanced conductivity zones—these hade (are inclined) over the extraction at a nominal 15° from the vertical (referred to as the break angle). These zones can be conceptualised as where the bedding layers are tilted and bounded by brittle fractures. At 15°, the two zones intersect at an extraction width/depth ratio of 0.54. The zones may be steeper if the extraction panel is parallel to any joint set in the overburden, or may be flatter (possibly down to 25°) if the panel is aligned closer to 45° to the strike of the joints. Progressive reduction with height in the aperture of the fractures is to be expected. Mine inflow/inrush hazards are possible if the apertures are wide enough and in such cases, the flows are likely to be non-Darcian. A similar zone will also progressively form

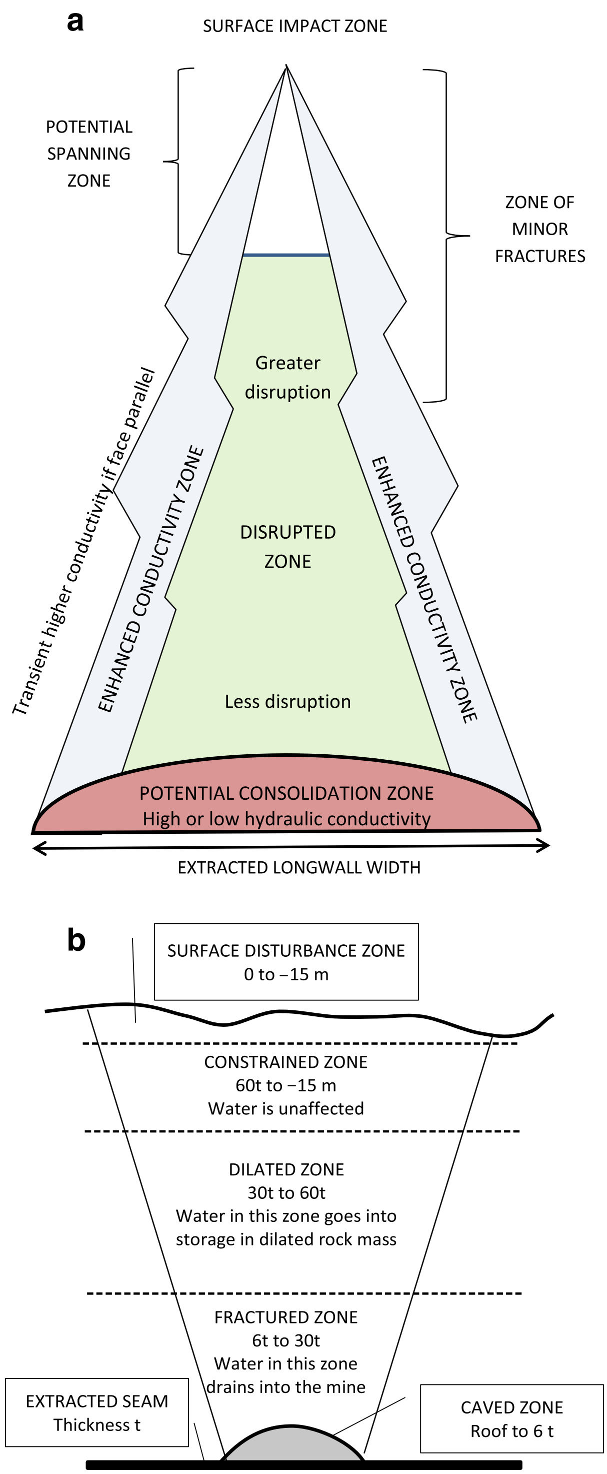


Fig. 9 **a** Six zones in a generalised hydrogeological model for a longwall panel; **b** standard hydrogeological model based on Bai and Kendorski (1995)

parallel to the longwall face, with the contained fractures having larger apertures.

- Disrupted zone—this is the zone directly above the extraction where bedding has returned to close to its original orientation and bulking is low. Some increased conductivity should be anticipated but much less than that in the enhanced conductivity zones. Towards the base, this zone may be saturated. Towards the top of this zone, and particularly if there is a spanning unit above, there will be less overburden loading and more bulking, such that fracture flow conditions would dominate.
- Minor fracture zone—this continues along the trend of the enhanced conductivity zone but occurs where the fracture conductivities are low and the width of the fractures may allow them to be sealed with soil clays. It is noted that the pore pressure gradients across such clay seals could be high and there is a need to consider the possibility of piping failures.
- Potential spanning zone—assuming the overburden consists of numerous jointed rock beams, it is possible that the progression of the enhanced conductivity zones can be stopped by a spanning unit. Subsidence surveys suggest that about 65% of the extraction void height is potentially available above the disrupted zone. An implication of the enhanced conductivity zone is that the effective span above the longwall extraction decreases with height above the mined seam. While spanning represents a barrier to fracture propagation upwards from the seam, the impact on the hydrogeological regime will depend on the hydraulic conductivity of the spanning unit.
- Surface impact zone—this lies above the intersection of the two enhanced conductivity zones or above the spanning unit, if present. The vertical subsidence in this zone is low and relates to either elastic compression of the rock mass or deflection of the spanning unit. If there are thinly bedded units above the spanning unit, there may be some localised zones of elevated tensile or compressive strain that will affect the surficial groundwater table. Over the long term, there may be adjustments to the regional groundwater regime related to the changed hydraulic conditions below.

Discussion

The existing caving and fracturing models for longwalls (Bai and Kendorski 1995; Ditton and Merrick 2014; Tammetta 2013) are all empirically derived and based on interpretations of drill hole data such as fracture logs, lugeon tests, and piezometers. This paper has examined the pump-out records of an operating longwall mine and as such, negates some of the need to speculate on how isolated borehole measurements relate to actual rock mass properties. With the high water volumes involved, the pump-out volumes are considered to be a very good measure of the groundwater inflows, such that the complexities of unaccounted-for water within the ventilation air, the mined coal, and that introduced for cooling and dust control can be ignored.

The standard conceptual model for the source of water inflow to a longwall coal mine from either the surface or groundwater identifies the key role of the so-called "dilated" and "constrained and unaffected" zones in limiting the inflows at the mining horizon (Fig. 9b). In this figure, any water that arrives at the "fractured zone" will report to the mine.

There are a number of empirical models for estimating the dimensions of the various zones based on the thickness of the extracted coal seam, the depth of cover, and the width of the extraction panel. The onset of water inflow at the case study mine from earlier and deeper parts of the mining lease compares well with Bai/Kendorski and Ditton/Merrick empirical models (Table 2), but is significantly different from that predicted by the Tammetta model. The Tammetta database was reported to be based on post-mining hydraulic head measurements and was partially based on multiple measurement devices that supposedly spanned the interfaces between drained and undrained zones. Close examination of the supporting references revealed that in many cases, and especially for those with reported high values of complete groundwater drainage, piezometers destroyed during the mining operation were ascribed zero head values. A more rigorous interpretation of the database would be that the non-functioning piezometers indicate failure of the cabling to the surface and perhaps indicate bedding separations and shears within the disrupted rock mass. It is considered that the Tammetta database has no merit.

Both the Bai/Kendorski and Ditton/Merrick models were developed primarily in the context of high and unmanageable water inflows to longwall mines. With such high inflows, the extent of the disruption (specifically the width and distribution of fractures) is likely to be of such a scale that it becomes possible to characterise the disruption using borehole observations. Disrupted rock masses with lower hydraulic conductivities (and lower mine inflows) may be somewhat more difficult to characterise with vertical boreholes. It is suggested that the Bai/Kendorski and Ditton/Merrick models may have merit in dimensioning the height to the minor fracture zone and hence identifying inrush hazards, but that they should not be used to assess other possible impacts.

Table 2 Prediction of the height of fracturing above case study mine (observed value is 105 m)

Reference	Range	Central prediction
Bai and Kendorski (1995)	21–105 m	
Ditton and Merrick (2014)	68–139 m	104 m
Tammetta (2013)	260–285 m	270 m

The revised model suggests that there may be increases in vertical conductivity high in the overburden that do not present a threat of high inflows to the mining operations but may have adverse surface environmental impacts. To limit the impact on shallow groundwater regimes, a key requirement becomes the presence of a unit within the rock mass that, while it may deflect, does not fracture. From a geotechnical perspective, such a unit would be referred to as spanning. Coal measure sequences can contain thickly bedded units, although massive units with bedding partings greater than 5–10 m are uncommon. For a 5 m thick sandstone unit assumed to be 25 m below the surface, Fig. 10 suggests that the maximum allowable span at the base of the unit would be 46 m and such a unit could deflect 0.87 m; a 10 m thick unit at a depth of 50 m could span 75 m and deflect 1.15 m.

Longwall extraction widths in Australia range from 160 to 410 m with mining economics requiring faces to be as wide as possible. The break angle that determines the trend of the enhanced conductivity zones can also be invoked to reduce the effective span higher in the overburden (Fig. 11). For example, if there was a requirement to prevent enhanced conductivity zones from intersecting the surface where a 5 m thick unit was present at a depth of 25 m (allowable span = 46 m) and mining was conducted at a depth of 325 m (interburden = 295 m), the maximum allowable extraction width would be 210 m.

Conclusions

The data in the case study required substantial modifications to the current hydrogeological model for the impact of longwall mining. Key aspects of the revised model as they relate to managing mine inflows are:

- If the potential consolidation zone does reconsolidate, mine water inflows do not increase progressively with successive longwall extraction. At this time, it is not known if there is a strength limit to such reconsolidation; intuitively, it would be expected that high strength rock—say in excess of 50 MPa—may not reconsolidate. Reconsolidation of the base of the goaf is relied on to give acceptable longwall face conditions in multi-slice longwall operations in Poland (Prusek et al. 2014). The major unanswered question is at what strength would there be insufficient reconsolidation of the caved zone to prevent high water inflows.
- For high inflow events, there is a need to consider flows associated with the active mining face and not just the sides of the extraction panels.

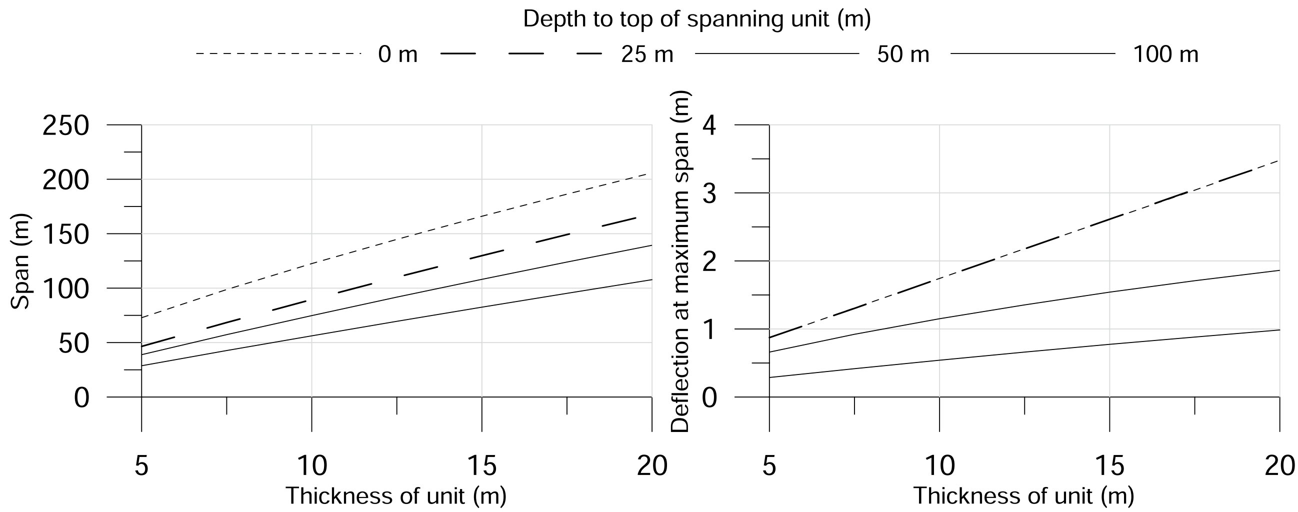
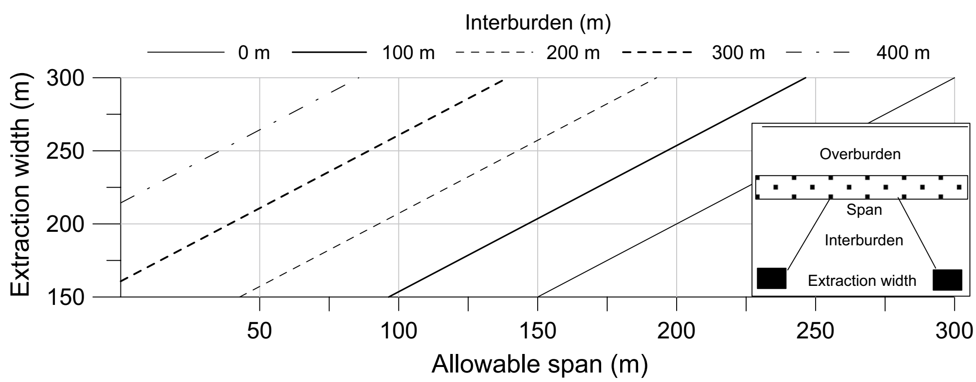


Fig. 10 Relationships between the thickness and depth of a unit and its maximum span and the associated defection (method of Sofianos and Kapenis 1998, Uniaxial Compressive Strength = 60 MPa, Young's Modulus = 12 GPa)

Fig. 11 Relationship between allowable span and extraction width for a break angle of 15°



- After mining, the major pathways for mine water inflow are possibly located at the ends of each longwall panel. There could be higher inflows into the up-dip areas of the mine if there has been no reconsolidation due to the absence of water.
- The Ditton/Merrick database and its associated prediction equation can be used to locate the extent of high conductivities within the enhanced conductivity zone. Care is needed if there is to be a reliance on a clay seal in the minor fracture zone.

From the perspective of assessing environmental impacts, predicting the extent of the enhanced conductivity zones is critical. In the model, their height is determined not only by the break angle, which itself may be related to the orientation of the longwall extraction relative to the joint field in the overburden, but also by the presence of massive units relatively close to the surface.

Acknowledgements The permission of the management of the case study mine to publish the data is acknowledged. Dr. Steven Pells introduced the author to the concept of an inlet controlled system.

References

Bai M, Kendorski FS (1995) Chinese and North American high-extraction underground coal mining strata behaviour and water protection experience and guidelines. In: Peng SS (ed) Proc, 14th International Conf on Ground Control in Mining. University of West Virginia, Morgantown, pp 209–217

Colwell MG, Harman JA (1993) Water inflow investigation for a longwall operation. Extended Abstract, Recent Developments in Underground Coal Mining in the Bowen Basin, AusIMM Central Queensland Branch

Ditton S, Merrick NP (2014) A new sub-surface fracture height prediction model for longwall mines in the NSW coalfields. Paper presented at the Australian Earth Science Convention, Newcastle

Prusek S, Lubosik Z, Plonka M, Syrek B (2014). Multislice longwalling for thick seam extraction—properties of goaf in the roof and gate roads behavior. In: Hagan PC, Saydam S (eds), Proc, Ausrock 2014: 3rd Australasian Ground Control in Mining Conf, AusIMM publication, pp 359–365

Sofianos AI, Kapenis AP (1998) Numerical evaluation of the response in bending of an underground hard rock voussoir beam roof. Int J Rock Mech Min Sci 35(8):1071–1086

Tammetta P (2013) Estimation of the height of complete groundwater drainage above mined longwall panels. Ground Water 51(5):723–734