IMPACTS OF LONGWALL MINING AND COAL SEAM GAS EXTRACTION ON GROUNDWATER REGIMES IN THE SYDNEY BASIN PART 1 –THEORY

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ABSTRACT

The mathematics of steady state and transient downwards Darcian flow are given for full or limited recharge and saturated homogenous ground, layered ground, and for unsaturated flow. Data are presented from a physical model that supports the theoretical analyses.

A hypothesis is presented for unsaturated hydraulic conductivity in the Triassic rocks of the Sydney Basin. The theoretical analyses coupled with the important inferences from unsaturated hydraulic conductivity provide valuable aids to understanding possible impacts of depressurisation due to underground coal mining and coal seam gas extraction in the Sydney Basin.

It is acknowledged that flow through jointed rock masses is very complex, and there are limits to the applicability of the equations of flow through porous media. However, as with elastic theory in geomechanics analyses, it is considered that the rigor gained from Darcian flow analysis assists greatly in avoiding flawed thought processes in hydrogeology.

1 INTRODUCTION

Changes to groundwater regimes associated with underground mining in the Sydney Basin are a significant issue in the ongoing operation of existing mines, in the planning of new mines, and in the burgeoning industry of Coal Seam Gas (CSG) extraction. This issue has been alive since the time of the Reynolds Inquiry in 1975-1979, when there were concerns in relation to mining beneath the reservoirs in the Southern Coalfields.

Currently, Environmental Assessments for new mines and extensions to existing mines are typically accompanied by analyses of likely groundwater impacts using 3D numerical models (MODFLOW, FEFLOW or equivalent). However, large complex 3D models may mask important features regarding groundwater impacts. Cheng and Ouazar (in Bear *et al*, 1999, pp 163) wrote:

> *"… analytical solutions are useful in presenting fundamental insights, while numerical solutions are often not. In fact, a person without such physical insights should not be entrusted with a powerful numerical tool to solve complicated problems, as such a person can have blind spots that harbor catastrophic consequences"*

With respect for this comment, solutions to a range of idealised examples of vertical groundwater flow are presented in this paper, including:

- steady and non-steady (transient) flows;
- homogeneous and heterogeneous geology, and;
- saturated and unsaturated flow systems.

The equations presented herein are unapologetically simple, being devised with the purpose of providing a framework for explaining the observed effects on groundwater systems from large-scale depressurisation of underground regions, such as from longwall mining and coal seam gas production (CSG). The specialist literature contains many theoretical analyses of vertical flow, far more sophisticated than those presented herein (eg Philip,1986).

The findings, specifically those related to unsaturated groundwater flow, are considered to be of appreciable importance to those concerned with minimising impacts on groundwater from longwall mining or CSG, and it is believed that these findings have, at this time, not been fully appreciated or purposefully applied.

Due to publication constraints, this paper has been split into two sections. The first part, this paper, contains the theory. Equations are presented and are tested against the results of: physical model tests, based on those of Darcy and Baumgarten in 1833, and; against numerical solutions. Limitations in certain software packages, which are known to some specialists but may not be widely appreciated, are also briefly presented.

The mathematical results presented herein lead to some immediate practical conclusions that are touched on in this Part 1. However, field data and interpretative remarks, related to the topics of longwall mining and coal seam gas production are presented in Part 2. Those practical considerations make reference to the theoretical framework established herein.

2 STEADY STATE DOWNWARDS FLOW

2.1 VERTICAL FLOW TO UNDERGROUND WORKS

Longwall mining regions in the Sydney basin are typically 2km to 3km long and between 250m and 400m wide. In the Appin region of the Sydney basin (the Southern Coalfields) the longwalls are at a typical depth of 450m. At Ulan, north-west of Mudgee they are typically between 150m and 250m deep. Proposed longwalls in the Wyong area are about 500m deep.

In an isotropic homogenous world, the long term, steady state groundwater flow system in terrain similar to the Southern Coalfields area, is represented in Figures 1 and 2. Prior to mining, groundwater flows from high ground towards rivers and the ocean, but after depressurisation at depth, and in the long term, there is flow down to the depressurised zone. With layered stratigraphy the flow pattern is more complicated and the time frame may be longer, but conceptually the changes are similar.

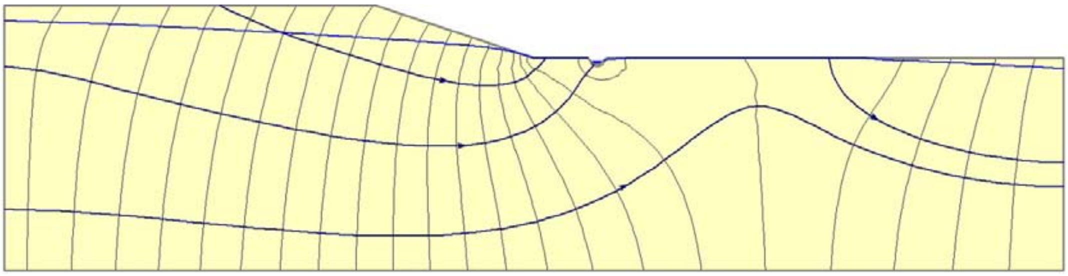


Figure 1 – Example flow regime prior to mining;

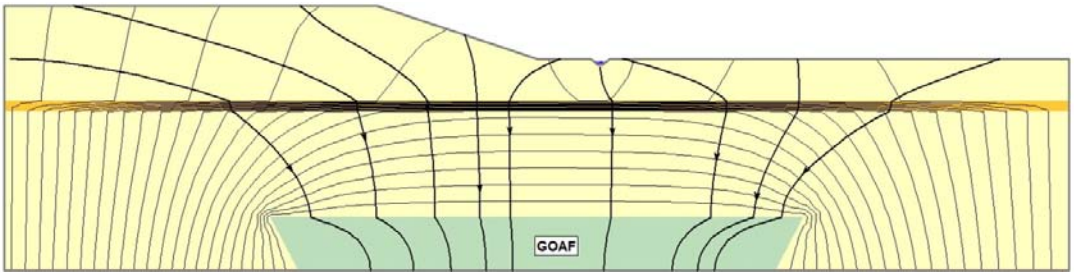
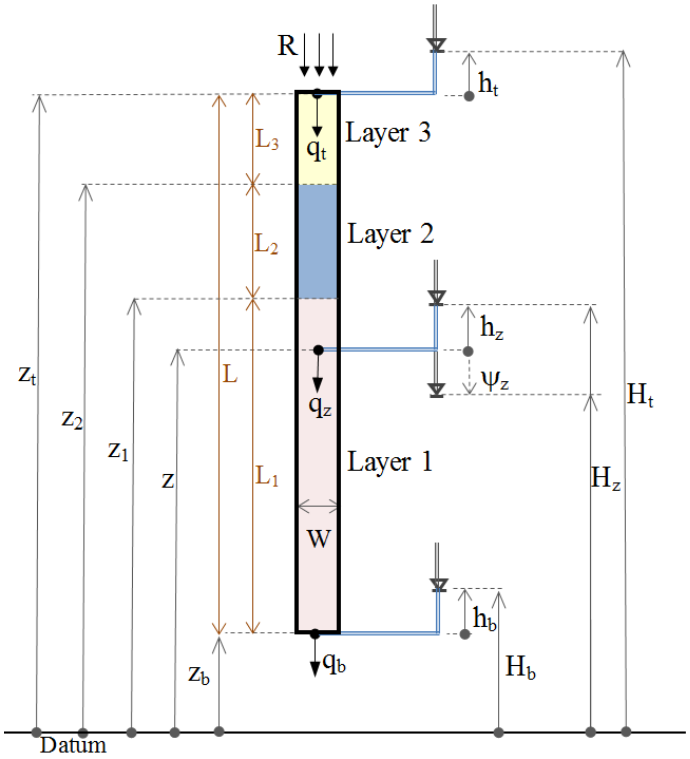


Figure 2 – Steady-state flow regime after mining 900m width of longwall panels

It can be seen that there is a central zone where the flow is close to vertical downwards, with horizontal flow into the sides of the set of longwalls and along the coal seam. We consider that proper understanding of this simple flow situation is critical to understanding the more complex picture.

2.2 PROBLEM CONCEPTUALISATION

We consider a stratified column of length “L”, width “W” and unit thickness (ie. into the page). The notation used to describe the column is as shown in Figure 3.



z = height of any position on the column above datum (L)

L = length of column (L)

W = width of column (L)

h = pressure head (L)

ψ = matric suction head (L) (i.e. when h < 0)

H = total head (L)

R = recharge (L/T)

q = discharge per unit thickness of column (L^2T^{-1})

Subscripts **b**, **z** and **t** refer to locations at the: bottom; height '**z**', and; the top of the column, respectively.

Numeric subscripts refer to each geologic layer.

Quantities are taken as positive in the directions shown.

Figure 3: Model for a Stratified Column

The total head is the sum of pressure head and elevation:

$$H_z = z + h_z \tag{1}$$

Steady discharge through the column "q" is given by Darcy's law as

$$q_{steady}(\text{for } q_t = q_b, when\ time \rightarrow \infty) = \text{R.W} = k.i.W \tag{2}$$

Where: i = the hydraulic gradient over the column $= \frac{H_T - H_b}{z_t - z_b}$ (3)

k = the hydraulic conductivity, and where, for a heterogeneous column k is taken as 'k$_{eff}$' which is given by:

$$\frac{L}{K_{eff}} = \left[\frac{L_n}{k_n} + \frac{L_{n+1}}{k_{n+1}} + \frac{L_{n+2}}{k_{n+2}} + \dots\right] \tag{4}$$

The total head at any point in the column is given by:

$$\begin{aligned} H_{z_n} &= H_{z_{n-1}} + \frac{q(z_n - z_{n-1})}{k_n W} \\ &= H_{z_{n-1}} + \frac{qL_n}{k_n W} \end{aligned} \tag{5}$$

where: subscript 'n' refers to the nth layer from the base.

For a homogeneous column, this can be reduced to:

$$H_z = H_B + \frac{q(z - z_b)}{kW} \tag{6}$$

The distribution of pressure head throughout the column can then be found by application of Equation (1).

2.3 SATURATED FLOW EXAMPLES WITH VARIOUS RECHARGE CONDITIONS

2.3.1 Saturated Vertical Flow in the Presence of Excess Recharge

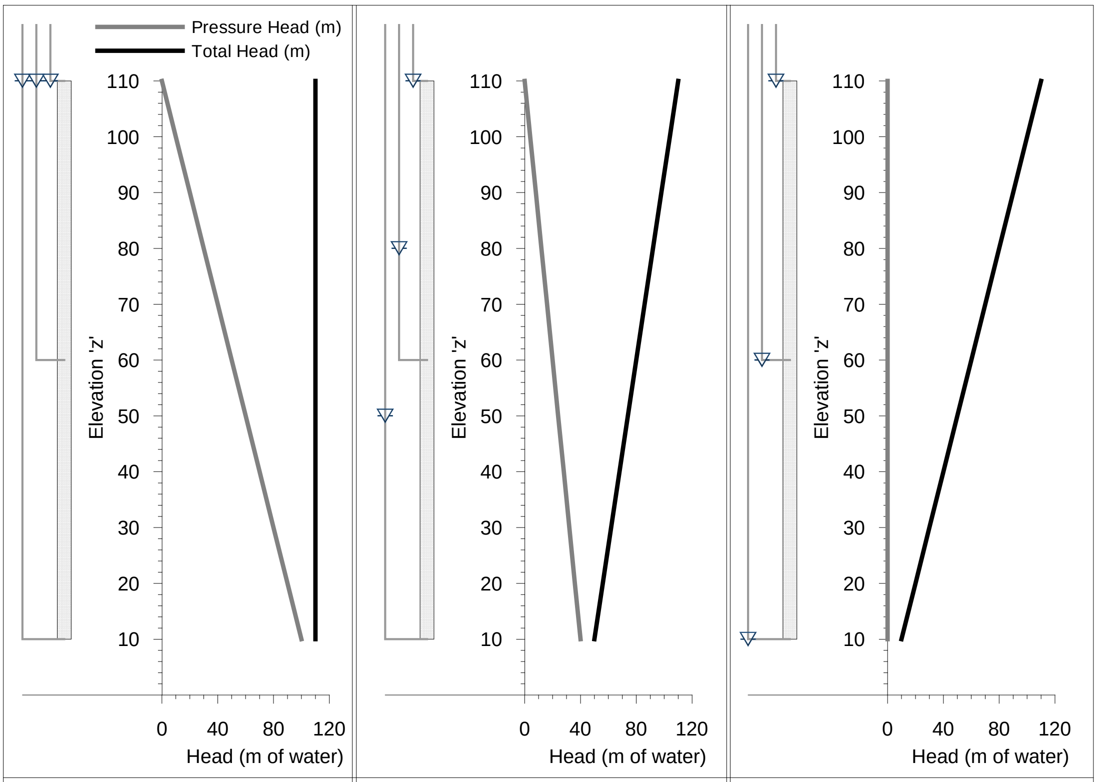
Many geotechnical texts present examples of groundwater flow which occurs in the presence of ‘excess recharge’. Under this condition, it is assumed that rainfall of a sufficient intensity is delivered to maintain saturation of the ground, but without any development of ponding at the surface. Excess rainfall moves away as runoff.

This creates an idealised condition such that the pressure head at the top of the column ‘$\mathbf{h}_t$’ remains constant at zero and, if the pressure at the base is zero, a hydraulic gradient of unity prevails. A common application of this assumption is demonstration of zero pore pressures behind a retaining wall in the presence of an idealised vertical flow field.

Equations (1) to (6) were solved for a number of generalised cases under the assumption of ‘excess recharge’ - pressure head at the top of the column ‘h_t’ was held constant at zero and the representation of underground works achieved by a reduction in the pressure head at the base (‘$\mathbf{h}_b$’).

Figure 4, Case A, shows an initial situation under hydrostatic conditions. Total head is constant, and pressure head increases linearly with depth. All the other cases presented in this paper should be compared, mentally, with the hydrostatic case. Cases B and C in Figure 4 are for partial and total depressurisation at the base under steady, saturated, homogenous conditions.

If the vertical column is layered (heterogeneous), then matters get a little more complicated, as indicated in the three examples in Figure 5, for different variations in permeability and basal depressurisation.

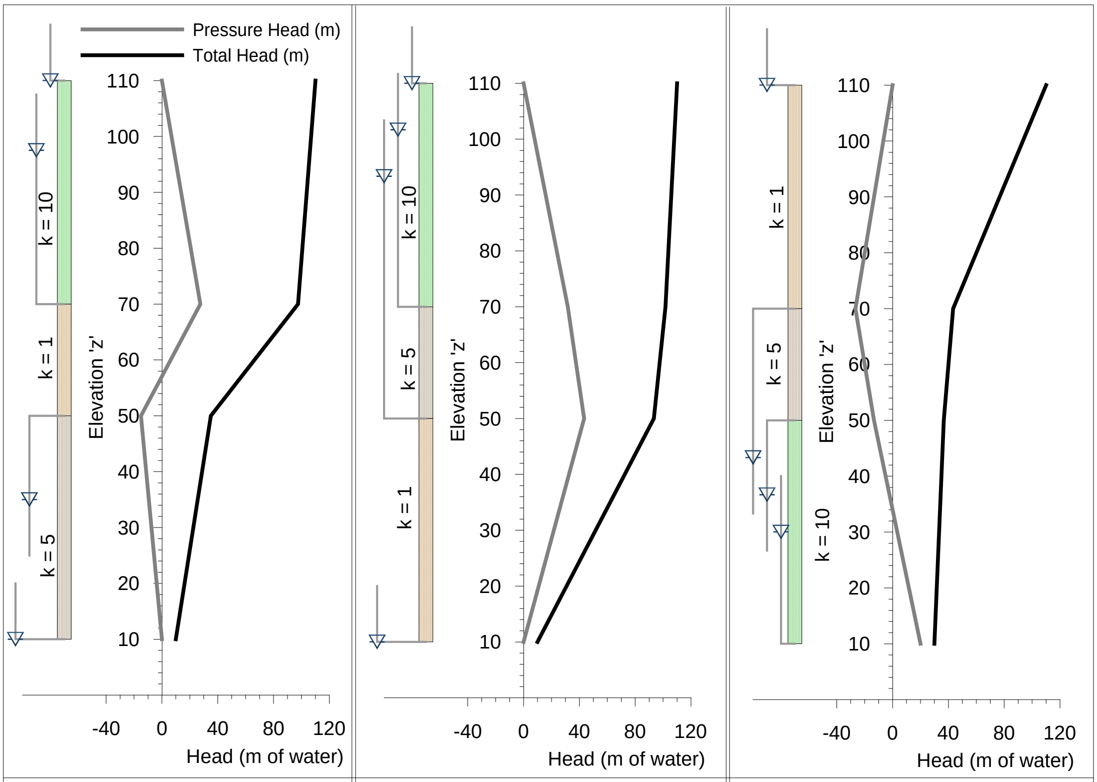


Case A
Hydrostatic
i = 0

Case B
Partially Depressurised At Base
i = 0.6

Case C
Fully Depressurised At Base
i = 1

Figure 4: Steady saturated downwards flow, homogenous earth and ‘excess recharge’



Case A
Fully Depressurised At Base
i = Varied

Case B
Fully Depressurised At Base
i = Varied

Case C
Partially Depressurised At Base
i = Varied

Figure 5: Steady, saturated downwards flow through layers of different permeability and with ‘excess recharge’

2.3.2 Saturated Vertical Flow in the Presence of Limited Recharge

In real-world conditions the assumption of excess recharge is not always valid. It can be shown from Equation 2 that when underground works reduce the local pressure to zero, the recharge required to maintain saturation throughout the column occurs when the ratio **R / k** (or $\mathbf{R / k_{eff}}$ for heterogeneous formations) is greater than unity.

Typical values for hydraulic conductivity for various formations are presented in Figure 6 in terms of metres per second ($m.s^{-1}$) and metres per day ($m.day^{-1}$). For reference, a scale in units of millimetres per day ($mm.day^{-1}$), the typical units of recharge, is also shown.

Typical recharge values in the Sydney Basin are less than 40 mm per year (Australian Rainfall and Runoff, 1987). Therefore, according to Figure 6, it would not be possible to maintain saturation at or near the surface, in the long term, if depressurisation occurs at depth. Desaturation of part, or all, of the column must ensue.

This can also be explained in terms of a “continuity of mass” principle, which states that the change in storage for a closed system is equivalent to the difference between inflows and outflows. Depressurisation at the base of this ideal column will, eventually, maintain an outflow velocity equivalent to the hydraulic conductivity of the formation (or k_{eff}, for a heterogeneous formation). The inflow, on the other hand, is limited by recharge availability which, in the Sydney basin, is typically a lesser quantity. Hence, over time, the storage of water in the column will decrease. Under a steady state condition (ie in the ‘long term’), the storage will be completely depleted.

How long is ‘long term’, is dealt with later is this paper.

Examples using recharge values less than the critical value for ‘excess recharge’ are presented in Figure 7. These analyses allow negative pore pressures to develop but do not allow air to enter the system. In other words saturated permeability is maintained.

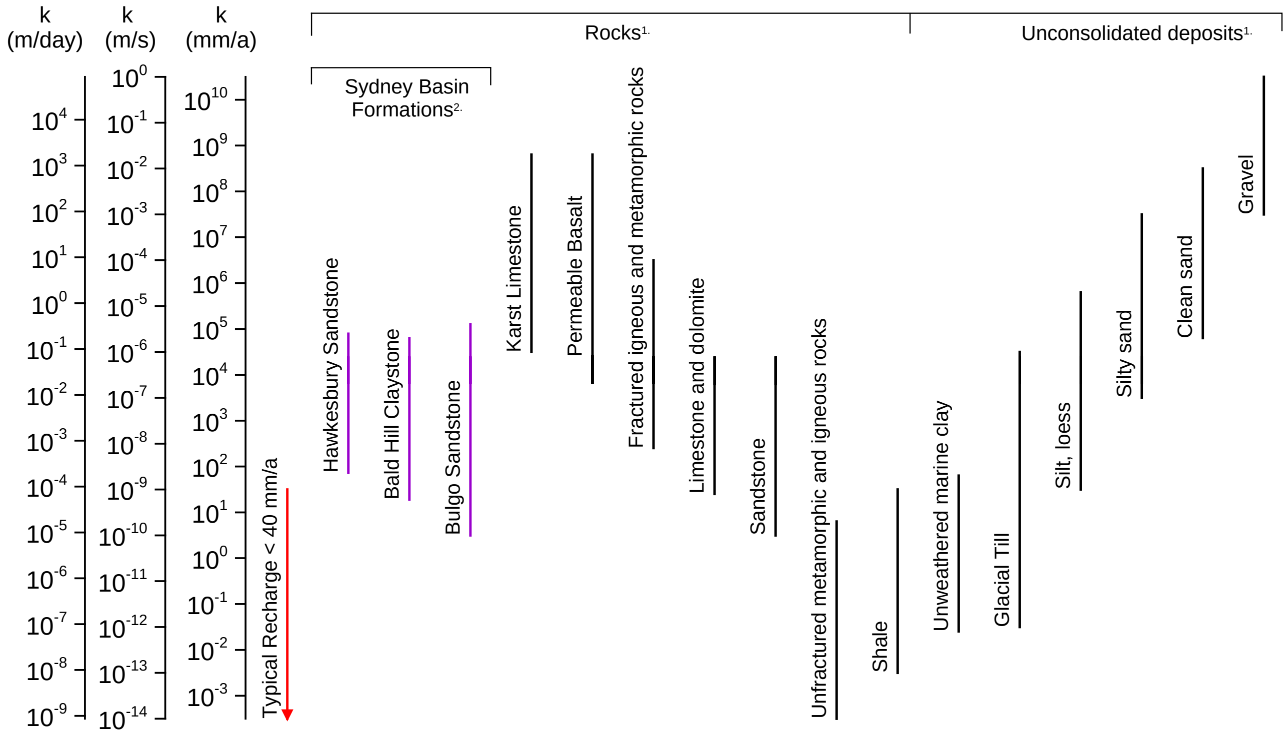
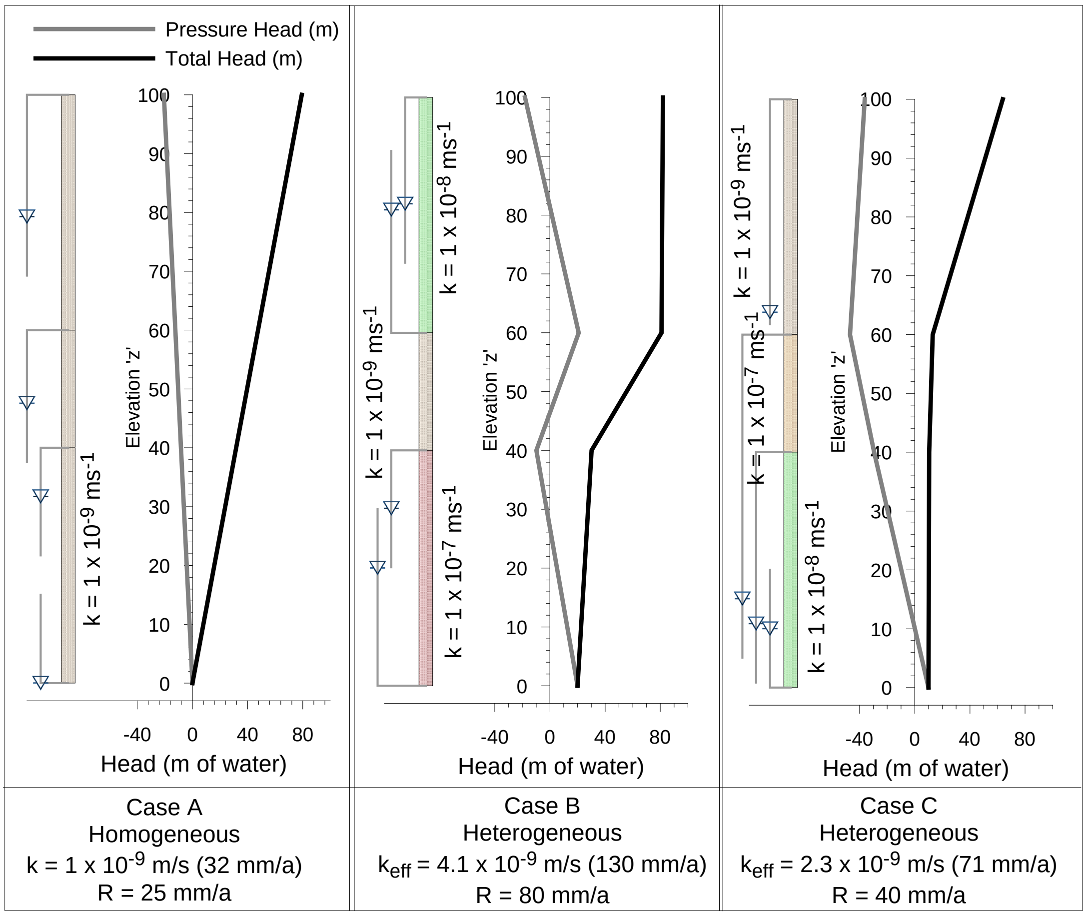


Figure 6: Hydraulic conductivity and recharge
(1. Freeze and Cherry, 1979; 2. Part 2 of this paper)



Case A
Homogeneous
$k = 1 \times 10^{-9}$ m/s (32 mm/a)
R = 25 mm/a

Case B
Heterogeneous
$k_{eff} = 4.1 \times 10^{-9}$ m/s (130 mm/a)
R = 80 mm/a

Case C
Heterogeneous
$k_{eff} = 2.3 \times 10^{-9}$ m/s (71 mm/a)
R = 40 mm/a

Figure 7: Effect if limited recharge, using 'real world' values ($R < k_{eff}$)

2.4 EFFECT OF UNSATURATED FLOW

2.4.1 Permeability Changes Due to Desaturation in Soil and Rock

It is well established that, for a given material, the hydraulic conductivity when partly saturated is much lower than the saturated hydraulic conductivity. Various equations have been proposed to represent the change in hydraulic conductivity as a function of matric suction in soils. The Van Genuchten (1980) solution is given as Equation (7) below.

$$\mathrm{k}_{unsat}(\psi) = k_{sat}.k_r(\psi) \tag{7}$$

where: $\mathrm{k_{sat}}$ = saturated hydraulic conductivity

$$\mathrm{k_r}(\psi) = \left[\frac{\{1-(\delta\psi)^{n-1}[1+(\delta\psi)^{n}]^{-m}\}^{2}}{[1+(\delta\psi)^{n}]^{m/2}}\right]$$

n and δ are factors and m = 1-1/n

In Figure 8, the relationship of $\mathrm{K_r}(\psi)$ to matric suction (m head) is presented, based on solution of Equation (7) using various of Van Genuchten's values for n and δ. The fitted data come from University California, Davis (Course SSC107, Chapter 4, 2000). It can be seen from Figure 6 that there can be many orders of magnitude reduction of hydraulic conductivity due to desaturation., and these can occur at quite small matric suctions.

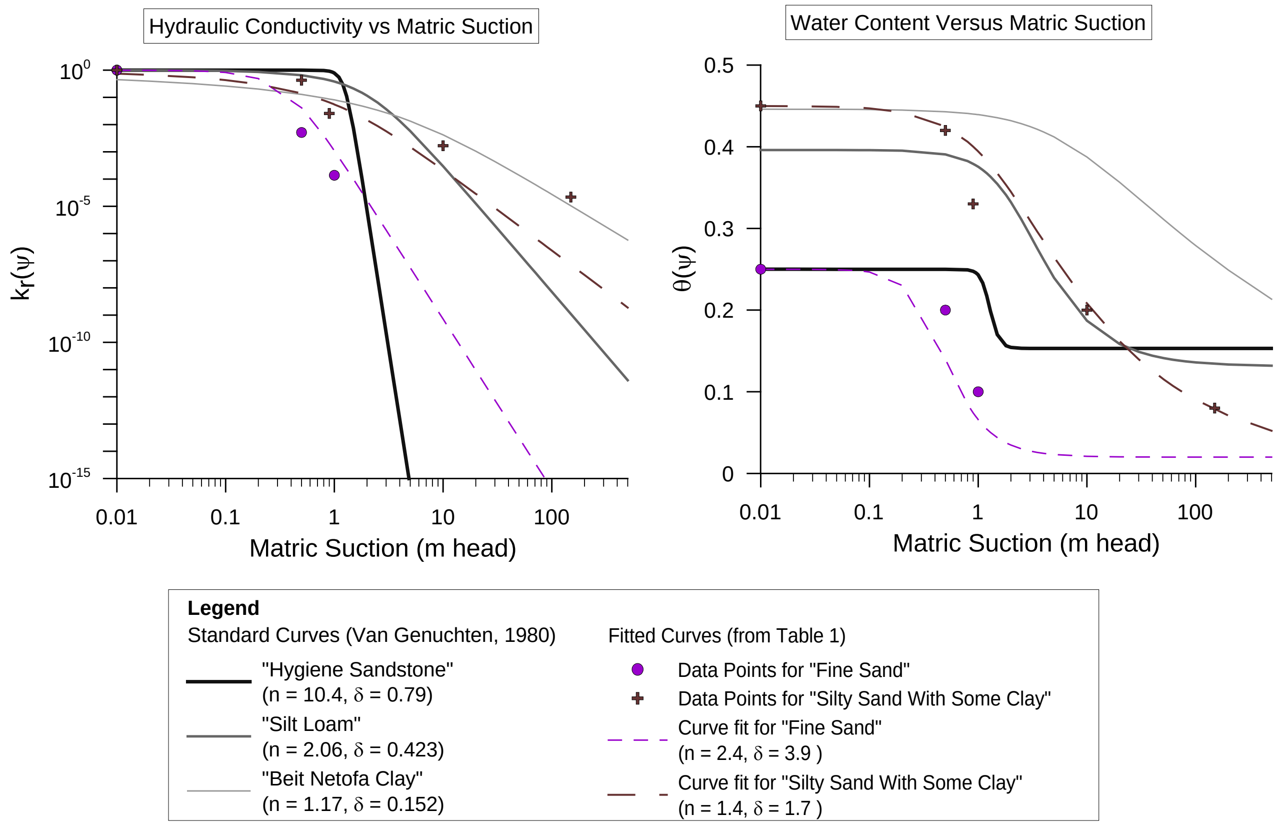


Figure 8: Hydraulic conductivity and soil moisture content versus matric suction (m)

There is scant knowledge as to the appropriate functions for jointed rock masses, and this is an area requiring substantial research. Our present understanding, as discussed below, is that, in a jointed rock mass, permeability reduction when desaturated is similar to the dramatic reduction indicated by the Van Genuchten equation.

Consider a borehole intersecting fissures in a rock mass, as shown in Figure 9. If we have ‘N’ fissures over a length ‘L’, then from the fluid mechanics of flow (Morgenstern, 1967) along a planar gap we have:

$$Q = \frac{NL(P_0 - P_r)d^3\,\Pi}{6uLog_e(\frac{r}{r_o})} \tag{8}$$

Where: u =viscosity

P =pressure

$d, P_0,\ P_r,\ r,\ r_0$ as shown in Figure 7

If the same borehole were in a uniform permeability, porous, medium we would have:

$$Q = \frac{2\,\Pi L\;k(P_0 - P_r)}{\gamma_w Log_e(\frac{r}{r_o})} \tag{9}$$

Where: k = hydraulic conductivity = $\frac{K\gamma_w}{u}$

K = true ‘Darcy’ permeability having the units L^2

Thus from equations 8 and 9 the hydraulic conductivity for the simple jointed model is

$$k = \frac{Nd^3\,\gamma_w}{12u} \tag{10}$$

So we see that the hydraulic conductivity is a function of the cube of joint opening.

In real rocks the joints are not smooth, and equation 9 can be written

$$k = \frac{cNd^3\,\gamma_w}{12u} \tag{11}$$

Where: c = roughness value, equivalent of tortuosity.

The fundamental permeability is:

$$K = \frac{cNd^3}{12} \tag{12}$$

Equation (12) can be used to demonstrate why fissure flow dominates rock mass permeability. For example, suppose we have a rock substance with hydraulic conductivity of 10^{-10} m/sec. If we have one fissure with a gap of .0075mm (7.5 micron) every 0.3m then the mass permeability is 10^{-6} m/sec.

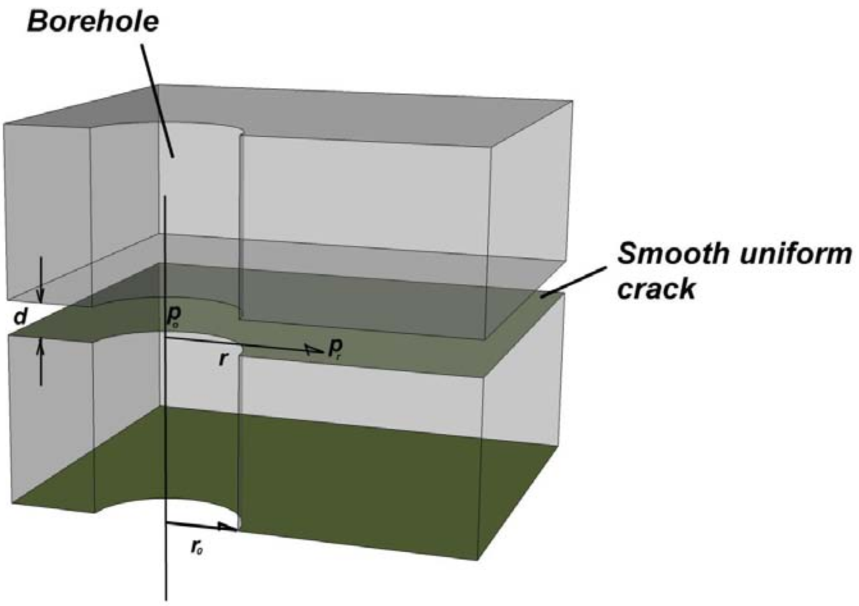


Figure 9: Model of fracture flow in rock.

Some quite substantial research has been conducted on fissure flow taking into account that real fissures are rough and in contact in many places over diverse areas. Kilbury, Rasmussen and Evans (1986) conducted field measurements in a welded tuff that supported the cubic relationship of Equation 10. They computed fissure apertures of between 10 and 35 micron (m^{-6}). Moreno et al (1988) pointed out that flow channelled through the most open areas of joints, with many dead areas of almost no flow. Clearly their findings must be taken into account in assessing joint permeability under partial saturation, as air first forms flattened bubbles in the most open parts of fissures.

Most of the above material is drawn together by Peters and Klavetter (1988) in conjunction with research done for a nuclear water repository in Yucca Mountain. The gist of their findings is that fissures dewater at suction of less than 1m and thereafter flow along fissures is trivial, and flow through a rock mass is controlled by hydraulic conductivity of the matrix.

Based on the test data, and theory, presented by Peters and Klavetter, it hypothesised that the relationship between hydraulic conductivity and matric suction for Triassic rocks of the Sydney Basin as set out in Table 1.

Table 1 Hypothesized hydraulic conductivity versus matric suction, Triassic rocks of the Sydney Basin

Matric Suction metres	**Hydraulic Conductivity**
0	Saturated value for the jointed rock mass as measured by field tests; typically about 1 x 10^{-8} to 1 x 10^{-9} for Hawkesbury Sandstone
-1.0	As above
-5.0	Matrix permeability. This is between 5 x 10^{-11} and 1 x 10^{-9} m/sec for Hawkesbury Sandstone.
-10	About 10^{-11} to 10^{-12} m/sec
-100	About 10^{-14} m/sec

As will be shown below, and in Part 2 of this paper, this is a very important area warranting research, because reduction in permeability in unsaturated zones can be, in-effect, a form of self-grouting

However, one word of caution is warranted. Major fault structures can dominate field behaviour because their saturated hydraulic conductivity may be orders of magnitude greater than the typical rock mass.

2.4.2 Examples Highlighting the Effects of Desaturation on Vertical Flow

Consider Case B from Figure 7 above. Saturated flow theory predicts that, over time, the pressure will decrease below atmospheric pressure at the elevation of approximately 40 m in the column, due to the characteristics of the layering relative to recharge. If air (or gas) is allowed to enter, the formation may begin to desaturate at this location.

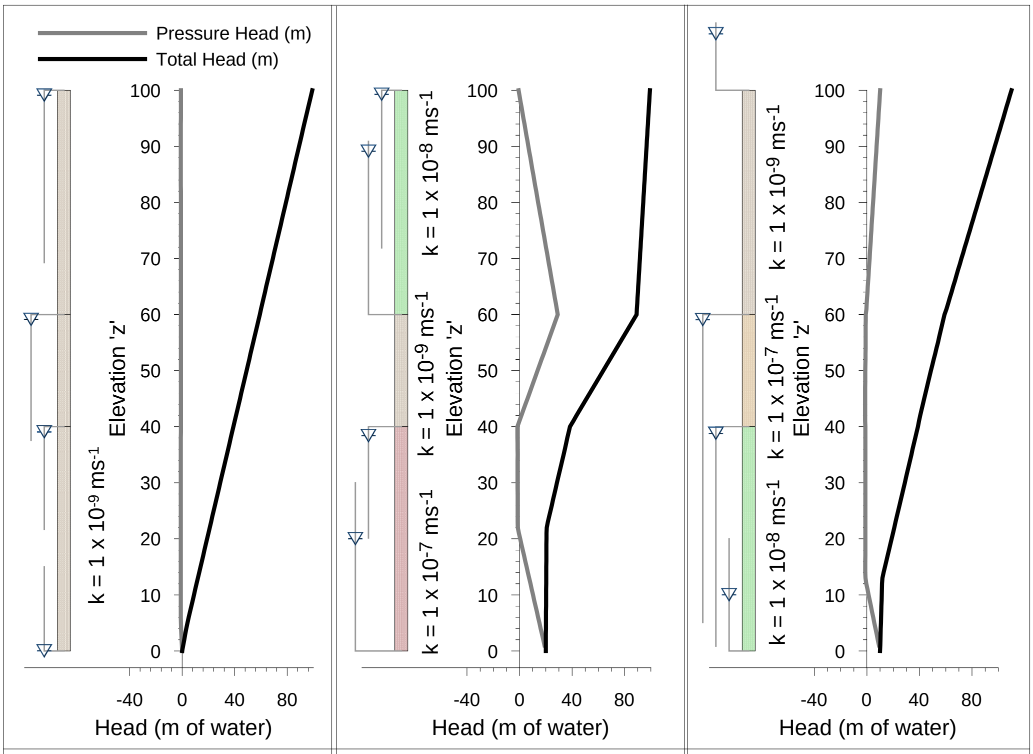
Desaturation lowers the hydraulic conductivity at this location, forming, in effect, a new layer retarding vertical discharge. The column below the new retarding layer, starved of flow from above, but still capable to transferring flow downward, will begin to desaturate further. A positive feedback loop is thus formed, as further desaturation leads to further reductions in hydraulic conductivity, and so on.

Above the obstruction, downflowing water will begin to gather, increasing the potential to resaturate the obstruction. Depending on: the nature of layering; the available recharge, and; the relationship of hydraulic conductivity to matric suction, a number of outcomes may occur.

Interestingly, one possible outcome is the rapid formation of a self-sealing system. Continuing with the concept of Equation 3, the occurrence of de-saturation will change the effective hydraulic conductivity 'k_{eff}' of the column, and therefore control to what extent, if any, groundwater resources at the surface are affected. Inflow into a longwall mine, for example, may be reduced significantly due to the nature of any such desaturation.

The effect of unsaturated flow is therefore of key interest to this study. Desaturation introduces a new facet of heterogeneity. In hydrogeologists terms, processes of desaturation and re-saturation potentially have the power to dynamically create and extinguish aquitards.

Analyses of unsaturated flow for the same conditions as given in Figure 7 are summarised in Figure 10, by application of Equations (1) to (7), and using the Van Genuchten relationship given in Figure 8 (values for 'Hygiene Sandstone' assumed). It can be seen that the development of unsaturated flow conditions are effective in reducing the extent of depressurisation. This effect of unsaturated flow was examined with a physical model, as described below.



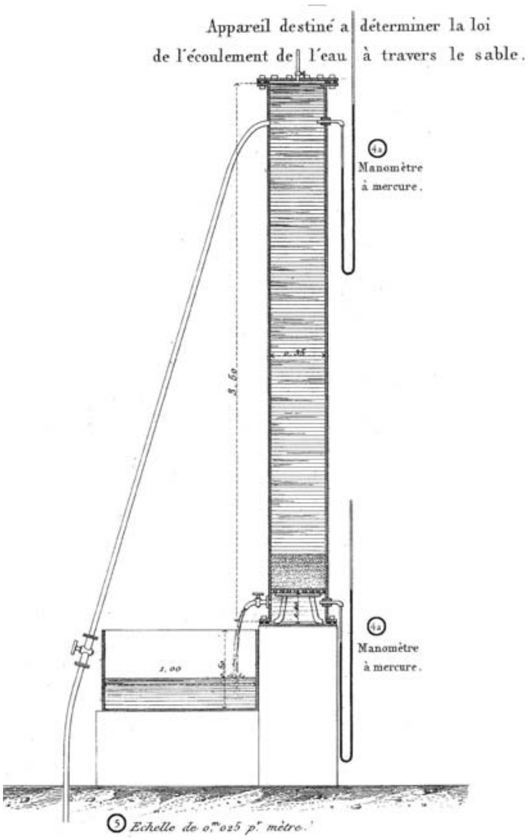
Case A
Homogeneous
k_{unsat} » R (25 mm/a)

Case B
Heterogeneous
$k_{eff, unsat}$ » R = 80 mm/a

Case C
Heterogeneous
$k_{eff, unsat}$ » R = 40 mm/a

Figure 10: Steady state unsaturated flow examples (cf to Figure 7)

3 PHYSICAL EXPERIMENT



The test apparatus shown in Figure 11 is that used by Henry Darcy in 1855, from which were developed the widely used equations of groundwater flow.

Darcy's column was made of steel, with sealed, bolted plates, top and bottom. Darcy used a coarse sand and he did his initial tests with pressures at the top of the column of between 1m and 12m excess head, and free flow through a tap at the base. Subsequently his offsider, Ritter, repeated the experiments with heads between - 3m and + 10m at the base. An important consideration is that there was no means for air to enter the sand column, even when Ritter had negative heads up to 36kPa.

We constructed a similar test apparatus, featuring a 240mm internal diameter acrylic tube. The column was filled with a 1.875m height of coarse river sand. Manometers were connected at: 385mm; 781mm, and; 1183mm above the base of the sand (see Fig 12). The coarse sand was not expected to exhibit a great reduction in hydraulic conductivity with increasing matric suction, but we hoped to see some effect.

Figure 11: Darcy's experimental setup, 1855

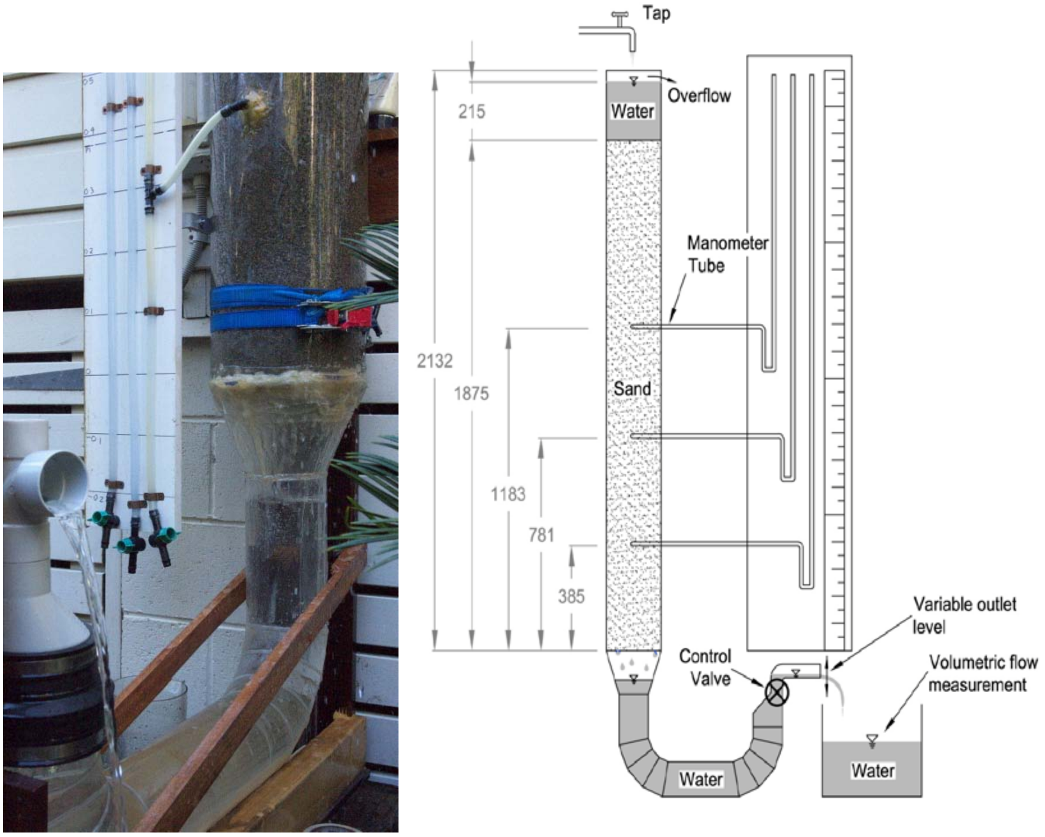


Figure 12: Details of the Model

The tests were conducted with a constant head of 215mm above the top of the sand. The initial tests maintained the head at the base equal to base level, therefore giving a head loss of 2.09m over the sand column of 1.875m (i=1.115). Tests were also run with the outlet throttled so as to decrease the gradient, which was then measured using the manometers. These measurements gave an average permeability of 2.1×10^{-4} m.sec^{-1}. Using the throttled outlet manometer measurements showed that the upper part of the column was slightly less permeable than the lower

With constant upper head level, the conditions at the base of the column were changed to cascading flow (see Fig 13).

Figure 13: Final test; water allowed to cascade from base of column

Three things happened:

1. The total flow decreased by about 3% - consistently and repeatably
2. The pressures in the upper two manometers increased a small amount; about 5mm of water
3. The lowermost manometer, 385mm above the base, sucked in air; it could be seen through the perspex that most of the lower part of the sand column contained void air.

The *reduction* of flow observed alongside an *increase* in the head potential is not explained by saturated flow theory. The observations are consistent, however, with the unsaturated flow processes as described above. Specifically, the desaturation of the base of the column resulted in lowering of the hydraulic conductivity at this location, reducing outflow and simultaneously increasing potential further up the column. The experiment was simulated near perfectly by finite element analysis using software by Rocscience.

4 NON-STEADY VERTICAL FLOW

The above steady-state analyses show the ultimate predicted effect on the draining of the column due to underground works. Non-steady (transient) flow analyses were also undertaken to examine how long it takes for these effects to develop.

To examine transient flows, consideration must be given to the changes that occur over this time in water stored within the geological material. We have to consider the volume of water that a unit volume of ground will release under a unit decline in hydraulic head, plus water that may drain from voids.

The specific storage “S_S”, is defined as:

$$S_S = \rho_w g(\varepsilon + \emptyset\beta) \qquad (13)$$

$$= \rho_w g m_v$$

where:
S_S = specific storage (L^{-1})
r_w = mass density of water ($M.L^{-3}$)
g = acceleration due to gravity ($L.T^{-2}$)
ε = compressibility of the aquifer matrix ($T^2.L.M^{-1}$)
ϕ = porosity
β = fluid compressibility ($T^2.L.M^{-1}$)
m_v = coefficient of compressibility ($T^2.L.M^{-1}$)

Transient groundwater flow through a column can be described by the diffusion equation which is, (in 1D):

$$\frac{d^2h}{dz^2} = \frac{S_S}{k}\frac{dh}{dt} = \frac{1}{\alpha}\frac{dh}{dt} \qquad (14)$$

where:
S_s is the aquifer specific storage (L^{-1})
α is called the hydraulic diffusivity (L^2/T)

Hydraulic diffusivity “α”, is permeability divided by specific storage, and, as such, takes into account the compressibility of the skeleton. Equation 14 is the same as Terzaghi’s equation for consolidation, with hydraulic diffusivity being the inverse the Coefficient of Consolidation.

In the real world, hydraulic diffusivity varies by over 8 orders of magnitude. Hence, the rate of change in pressure in an aquifer due to seepage processes also varies by this range from site to site, depending on the geological characteristics. As such, there is no simple one-off description of the time frame of impacts from underground works.

The process of depressurisation of a homogeneous column can be estimated using Equation (15).

$$\Delta H_{z,t} = \Delta H_{b,t=0} \times erfc(\lambda) \qquad (15)$$

Where: erfc( ) is an error function (note: an existing Microsoft Excel function)

$$\lambda = \frac{z}{2\sqrt{\alpha t}}$$

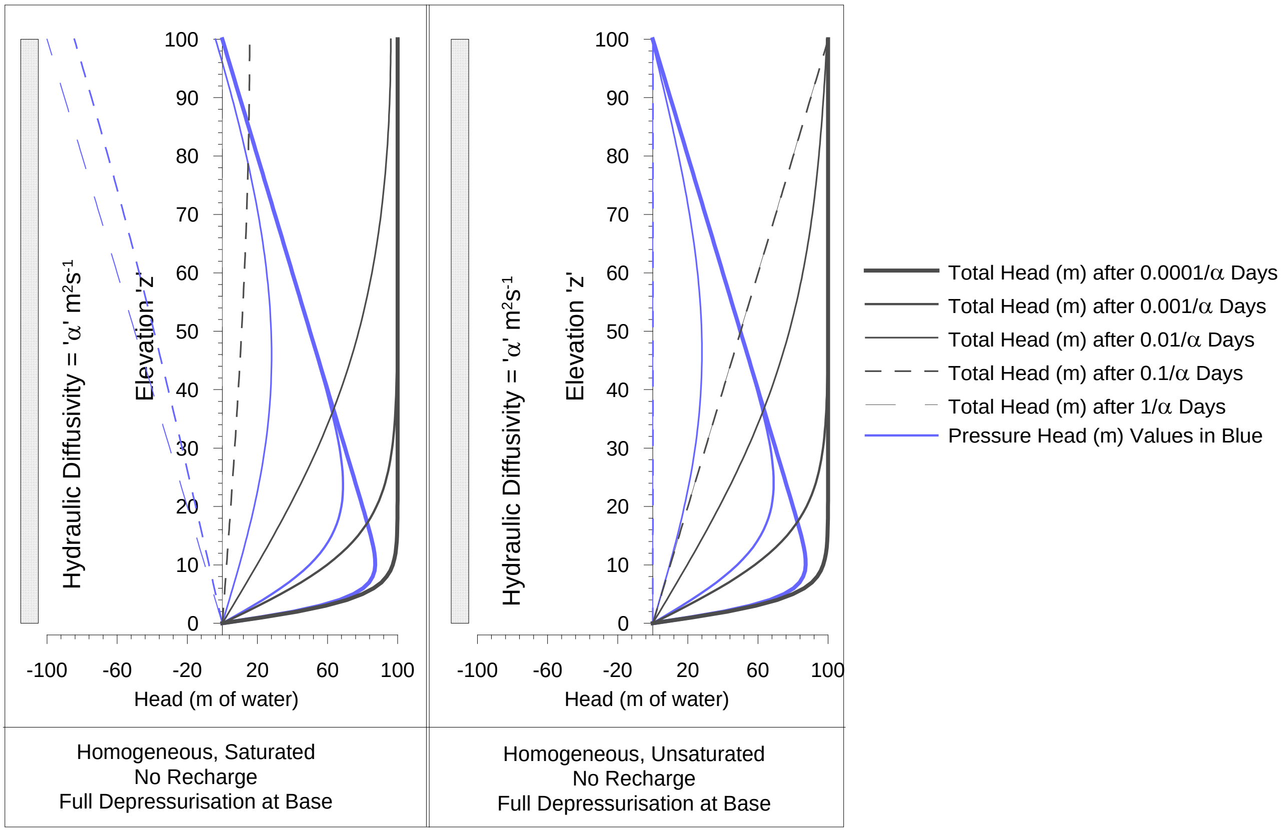
Equation (15) is modified from one commonly provided in hydrogeological texts as a solution to aquifer flow due to sudden change at a boundary (In Kresig (2007), the equation is credited to Lebedev, in Huisman (1972) it is credited to Edelman). It accurately simulates transient flow through the column as validated against various numerical solutions.

Equation (15) was used to solve some examples of depressurisation and dewatering of a homogeneous formation shown in Figure 14. The analysis of depressurisation and dewatering of a heterogeneous formation is more complex, and numerical techniques (using SEEP/W) were adopted to solve the selected examples given in Figure 15.

The hydraulic diffusivity “α” was kept as a variable in Figures 14 and 15. The reader can apply values applicable to their region of interest to view estimates of the timing of depressurisation of an aquifer due to vertical flow into an underground cavern.

To give further indications of the range of rates of depressurisation, the time taken for the depressurisation through a one dimensional profile was assessed using numerical techniques, for cases as presented in Figure 16.

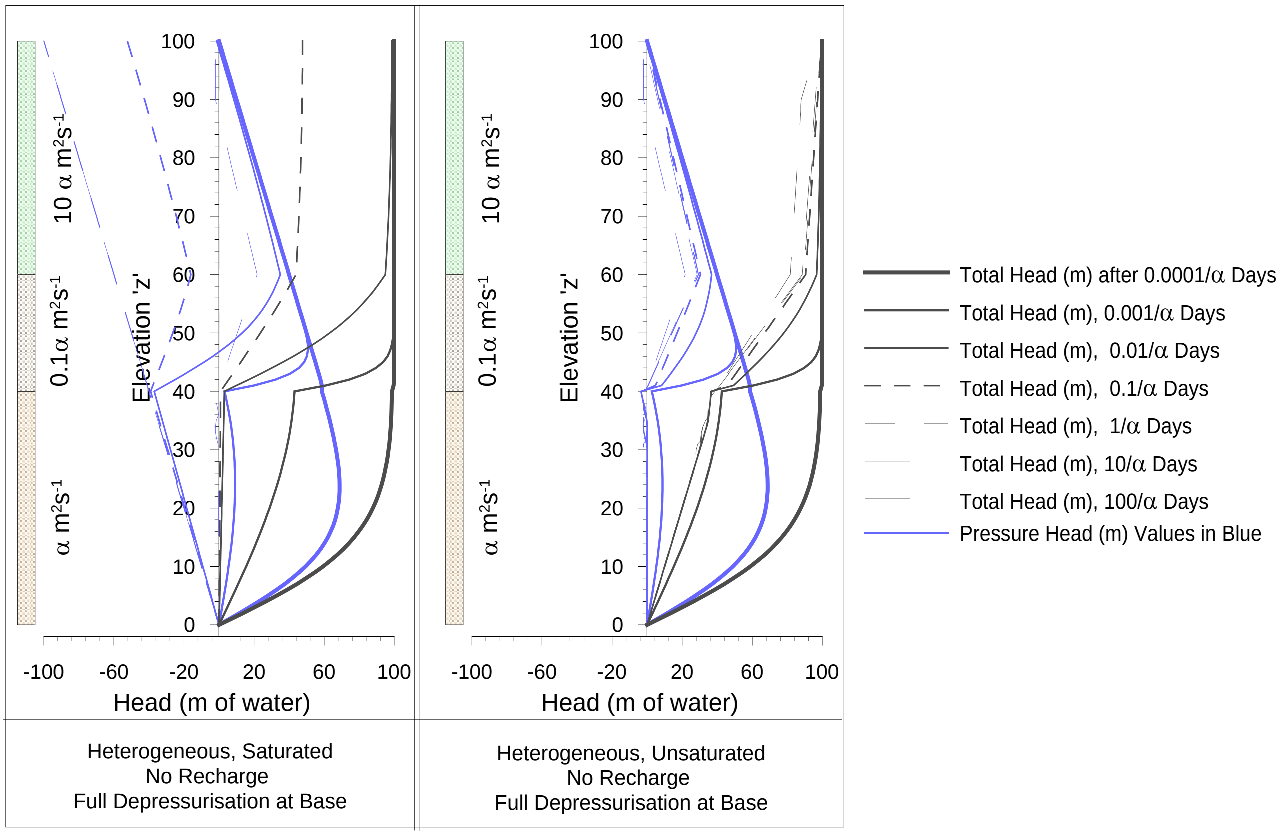
The initial conditions for each column comprised a hydrostatic pressure distribution with a water table at the ground surface. At t=0, the pressure at the base was instantaneously reduced to zero, and the time taken to reduce the head by 0.1 m, 1 m and 10 m, at a location at 80% of the column height was assessed, and is tabulated in Table 3 below. This was repeated for analyses based on saturated and on unsaturated flow mechanics.



Homogeneous, Saturated
No Recharge
Full Depressurisation at Base

Homogeneous, Unsaturated
No Recharge
Full Depressurisation at Base

Figure 14: Transient depressurisation of a homogeneous column



Heterogeneous, Saturated
No Recharge
Full Depressurisation at Base

Heterogeneous, Unsaturated
No Recharge
Full Depressurisation at Base

Figure 15: Transient depressurisation of a heterogeneous column

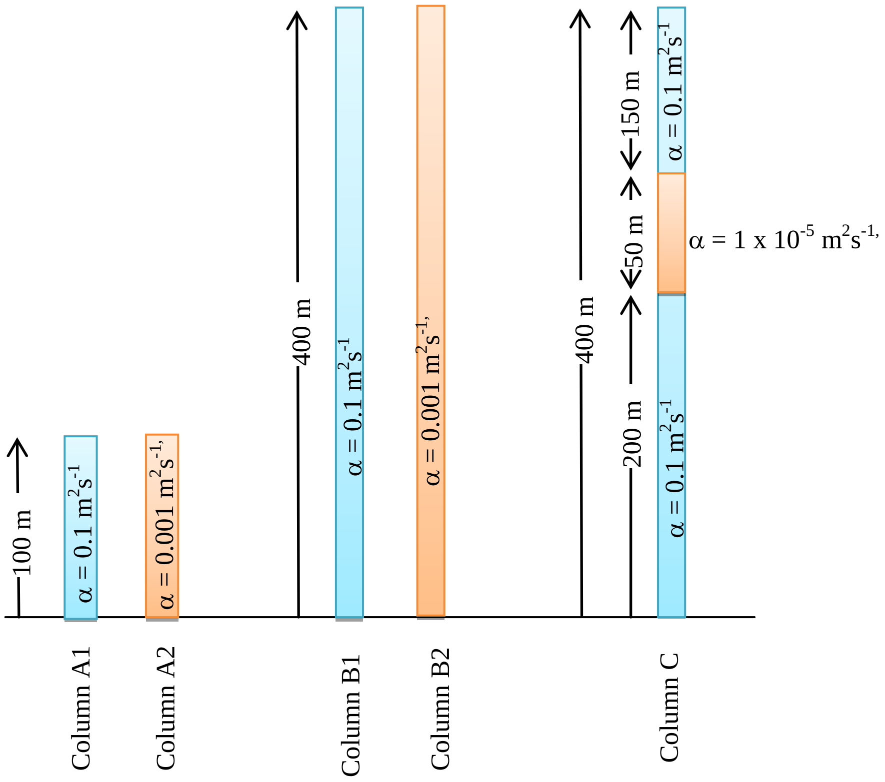


Figure 16: Some cases that may represent profiles above a depressurised coal seam

With reference to Table 3, it is noted that the inclusion of unsaturated flow equations does not significantly alter the result. The exception is where an aquitard is present (Case C), for which the effects of unsaturation which develop below the aquitard have a profound effect of delaying the process of depressurisation of upper formations, as discussed in Section 2.4.2.

Table 3: Indicative times for depressurisation to travel upwards from coal seam level

Analysis	Column	Hydraulic Diffusivity m^2/sec	Indicative of:	Time Taken to Reduced Head at 80% Column Height by		
				0.1 m	1 m	10 m
Saturated	A1	0.1	Medium grained sandstone	45 Minutes	1.3 Hours	3.1 Hours
	A2	0.001	Fine grained sandstone	3.2 days	5.4 Days	12.7 Days
	B1	0.1	Medium grained sandstone	10 Hours	14 Hours	1.1 Days
	B2	0.001	Fine grained sandstone	40 Days	60 Days	115 Days
	C	Layered	Medium grained sandstone with shale band	170 Days	290 Days	1.8 Years
Unsaturated	A1	0.1	Medium grained sandstone	45 Minutes	1.3 Hours	3.7 Hours
	A2	0.001	Fine grained sandstone	3.2 days	5.4 Days	15 Days
	B1	0.1	Medium grained sandstone	10 Hours	14 Hours	1.1 Days
	B2	0.001	Fine grained sandstone	40 Days	60 Days	115 Days
	C	Layered	Medium grained sandstone with shale band	190 Days	76 Years	1350 Years

It should be noted that, in the numerical code MODFLOW (in its standard ‘saturated flow’ state), development of negative pressure heads results in ‘drying’ of cells which causes the cessation of any further flows past the dry cells. For example, where recharge is insufficient, and /or where layers of higher hydraulic conductivity underlie layers of lower hydraulic conductivity, cells will dry out and vertical flows will cease. This is illustrated in Figure 17 below. This drying mechanism mimics, but overstates, the sudden lowering of hydraulic conductivity due to desaturation. There are some ‘work-arounds’ in MODFLOW, but it is cautioned that this cell-drying error would give an erroneous (ie very optimistic) representation of the effects of longwall mining on groundwater resources.

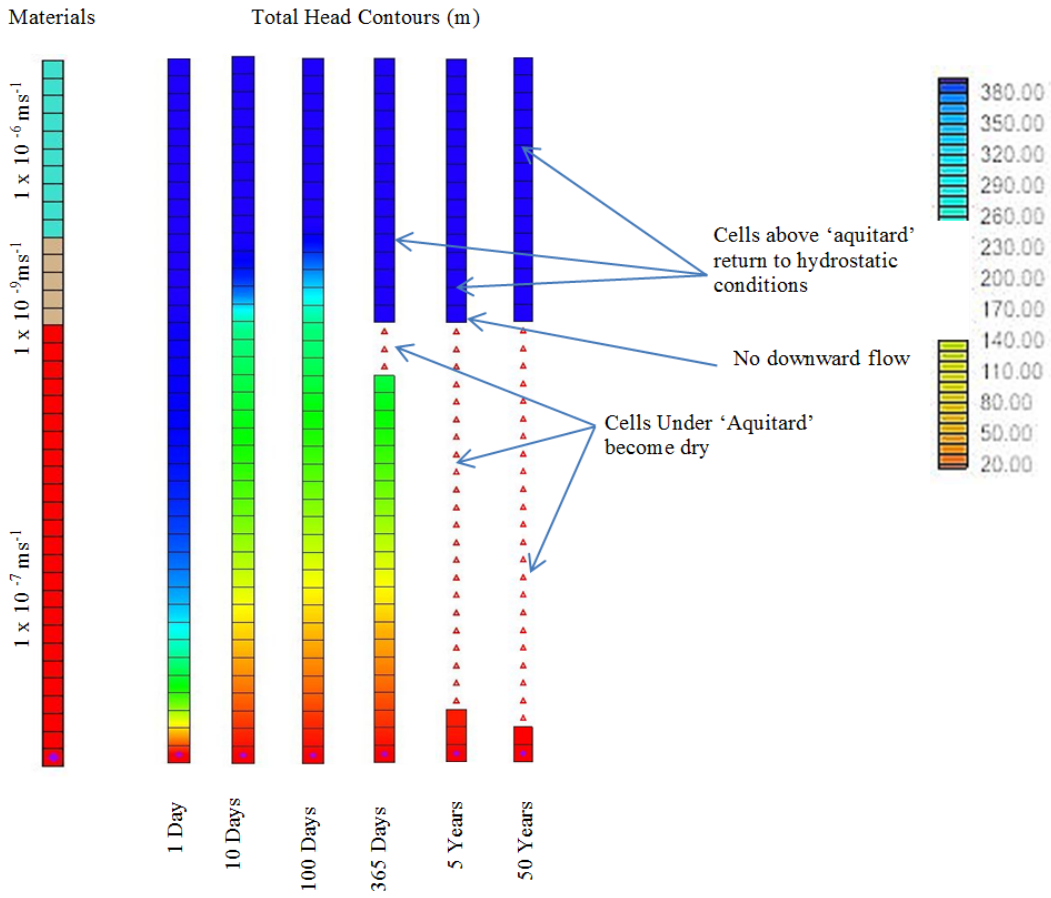


Figure 17: Example of Erroneous Representation of Vertical Seepage Flow in MODFLOW

5 SUMMARY OF FINDINGS

A range of analytical solutions have been presented for idealised cases representative of purely vertical groundwater flow from the land surface to a depressurised cavern. These solutions were validated against a physical model and numerical solutions. The solutions serve to highlight a number of interesting properties of vertical flow, which have important implications for design and assessment of longwall mining and coal seam gas projects. These are:

1. When vertical flow is present, the level of water that would be encountered in a bore is not equivalent to the position of the phreatic surface.
2. Piezometric heads throughout the column will ultimately be reduced significantly due to depressurisation at the base of the column. This impacts on the water levels encountered in bores placed in the column, as evidenced by the ‘stick plots’ shown in Figure 4. In cases where zero or negative pressures are developed, bores placed in the column could have no water at all despite the possibility of a water table being maintained at the surface.
3. Layering of the geology (heterogeneity) can result in a wide range of hydraulic gradients and development of negative pressures, leading to creation of a perched water table. This occurs in the presence of purely vertical flow - the presence of a perched water table does not indicate that vertical flow has ceased.
4. The effective saturated vertical hydraulic conductivity of a heterogeneous column can be estimated using Equation 4.
5. When excess rainfall recharge is available, the rate of vertical flow under a steady state condition is limited to the value of the effective saturated vertical hydraulic conductivity.

6. In many real-world cases, the quantum of recharge is less than the saturated vertical flow rate. In such cases, the impacts of depressurisation at depth are more severe than with 'excess recharge' - the steady state condition for homogenous formations is complete desaturation of the entire column. Regions of desaturation will also develop for heterogeneous formations, although a perched water table can still be maintained in perpetuity, depending on the nature and distribution of geological layers.

7. In regions where desaturation occurs and air is allowed to enter the formation, the hydraulic conductivity will be reduced in accordance with unsaturated flow theory. This reduction can be large.

8. The reduction of hydraulic conductivity can, in certain circumstances, lead to a positive feedback loop, allowing the formation to approach a self-sealing condition. This feature could be used purposefully by the mining industry to reduce mine inflows and impacts from mining activities.

9. There is a paucity of data on unsaturated hydraulic conductivity values applicable to fractured rock. Some guideline values applicable to the Sydney basin are proposed in Table 1, but further studies are required.

10. An estimation of the transient process of depressurisation through a homogeneous column can be calculated using Equation 15. For heterogeneous formations, numerical solutions are required. Estimations of the nature and rate of depressurisation through a vertical column can be found by using Figures 14 and 15.

11. The time taken for a depressurisation wave to move through a column is directly related to the hydraulic diffusivity of the formation, which ranges over many orders of magnitude in nature. Hence it follows that the rate of depressurisation will vary significantly (i.e. by orders of magnitude) from site to site.

12. The velocity that the wave of depressurisation moves through a formation is significantly faster that the velocity of seepage flow. This is analogous to comparing the water hammer wave propagation against the flow velocity in a pipeline.

13. The aquifer characteristics (ie hydraulic conductivity) does not alter the ultimate (ie steady-state) pattern and extent of depressurisation that occurs, it alters only the discharge under which is occurs. The quantity of water drawn by the underground works is therefore not, alone, a good indicator of the extent of depressurisation in the aquifer that is incurred.

14. The complexities of saturation and desaturation that are important for proper representation of vertical flow are not always represented well in popular numerical solutions. One important and common cautionary example is presented for the case of the MODFLOW numerical model.

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