Prediction of Groundwater Flow in Fissured Limestone, Blendevale Prospect, Western Australia

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ABSTRACT

Based on both geologic and hydrologic investigations, predictions are made on how much water may flow into future underground excavations within fissured limestone at the Blendevale Prospect, Western Australia. A conceptual model of equivalent fracture flow is used rather than an equivalent porous medium model. One advantage of the present method is that transmissivity of individual fractures is estimated and hence possible sudden bursts of water can be predicted with more confidence. A second advantage is that the effect on flow caused by widening and narrowing of fractures around the perimeter of projected mining operations can be assessed more realistically in the future. Predictions are made both of flow from individual fractures as a function of depth and of average flow as a function of rate of a face advance. Three types of flow are distinguished, namely pressure-induced flow, gravity flow and long-term flow in response to regional recharge.

INTRODUCTION

One of the challenging problems facing hydrogeologists is how to estimate groundwater flow into future underground excavations within fissured limestone. The problem becomes more acute when faced with limitations of time and field data. The method of data interpretation which was developed to meet this challenge at the Blendevale Prospect, Western Australia (WA), is the subject of this paper. BHP Minerals Ltd. managed the project on behalf of a joint venture comprising BHP Minerals and Billiton Australia (Metals Division of Shell Aust.). The author acknowledges the Joint Venture's support and cooperation.

HYDROGEOLOGY

The lead and zinc prospect area near Fitzroy Crossing, WA, is characterized by highly fractured and fissured limestone [1]. A regional system of gravity faults form a structural graben whose strike and gentle plunge is northward. The limestone aquifer is exposed in the south and is confined beneath shale and mudstone in the north. Although karstic topography appears over the limestone outcrop areas, its development is shallow with no major caves. An access decline (Fig. 1) is proposed to be located near the southern edge of the overlying sediments.

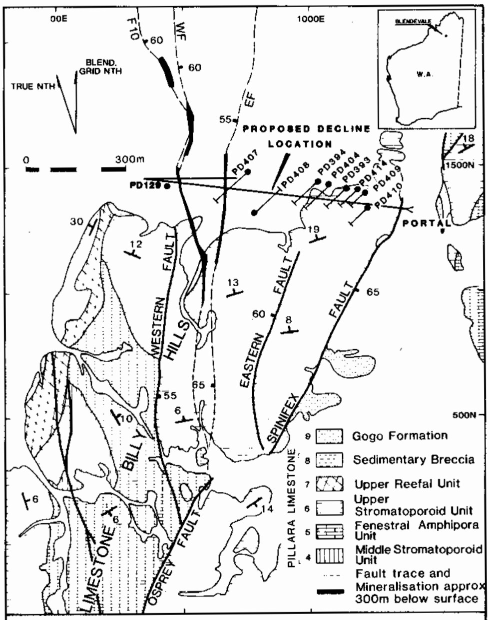

FIGURE 1. GEOLOGY [1] SHOWING BOREHOLE LOCATIONS

The average annual rainfall is approximately 600 mm with 80 to 85 percent falling between November and April during the hot summer. The water table in the limestone outcrop declines from a summer high of 0 to 1 metre below land surface to 5 to 8 metres during the warm dry winter. The potentiometric surface has a regional gradient to the north and east [2] indicating that the 4 km^2 limestone outcrop is an area of recharge. The total recharge area for the limestone aquifer is possibly 20 km^2 if surface lineaments within the sediments indicate vertical conduits.

Although the major normal faults themselves tend to be mineralized and are probably hydraulically tight, impression packer tests [3] indicate that the largest flows at depth occur within subvertical (>60° dip) fracture sets that strike approximately 30-70 degrees east of true north. Based on hydraulic fracturing tests, the direction of maximum principal stress is essentially parallel to this strike, the intermediate direction is vertical and the minimum direction is approximately Blendevale-grid east-west (Fig. 1). Aquifer tests [2] indicate the region within the graben area to be hydraulically connected with the north-south transmissivity to be much greater than the east-west.

Many holes were drilled in the area for the mapping of mineral deposit locations. Conventional injection tests between packers were conducted within five of these [3]. Borehole PD 129 (Fig. 1) was selected for analysis for two reasons. First, its four highly transmissive zones average one every forty to fifty metres which approximates the frequency expected to be encountered in the east-west decline. Second, it contains the most transmissive individual zone tested. This zone is used in the present paper to estimate likely events of sudden flow.

PARAMETERS BASED ON EQUIVALENT APERTURE THICKNESS

The first assumption is that groundwater in the vicinity of the Blendevale Prospect occurs in fractures and the rest of the rock mass contributes insignificantly to underground flow. The second assumption is that the flow obeys Darcy's law. The induced flow between packers during water pressure tests is assumed to be adequately described mathematically by axially symmetric flow between "equivalent" parallel plates. Finally, it is assumed that during the tests there exists an effective radius r_e at some distance from the wellbore where water pressure in the fractures remains unperturbed.

The relation between the hydraulic conductivity K_i of the ith fracture and the aperture thickness b_i can be derived from the Navier Stokes equation for single-phase, non-turbulent flow of a viscous incompressible fluid to be

$$K_i = \rho g b_i^2 / 12\mu \qquad (1)$$

where ρ is fluid density, g is gravitational acceleration, and μ is dynamic viscosity of the fluid. Transmissivity of a single fracture is defined by the product

$$T_i = K_i b_i . \qquad (2)$$

From these relations and Darcy's law one can derive

$$b_i = \{[C \log_{10}(r_e/r_w)] \frac{Q}{\Delta P} \}^{1/3} \qquad (3)$$

where r_w is the radius of the wellbore, Q is the volume rate of flow and ΔP is the excess pressure in the section between packers. C equals 5.1×10^{-2} when Q is expressed in m^3/day, ΔP in MPa and b_i in mm. The ratio $Q/\Delta P$ is known from field tests (Table 1). For computational convenience, let $\log_{10}(r_e/r_w)$ equal 4.

Table 1. Initial Pressure-Induced Flow and Hydraulic Parameters Estimated from Injection Tests within PD 129

Depth Interval, m	Static Pressure Head, MPa	Observed $Q/\Delta P$, m^3/day/MPa	Anticipated Pressure Induced Q, m^3/day	Calculated Fracture Width b_i, mm	Calculated Hydraulic Conductivity K_i, cm/sec	Calculated Transmissivity T_i, m^2/day
81.5 - 83.5	.78	4,900	3,870	1.0	83.5	72.2
105.5 - 107.5	1.02	2,400	2,470	.79	51.4	34.9
110.0 - 112.0	1.07	1,900	2,040	.73	43.9	27.5
132.5 - 134.5	1.28	3,300	4,280	.88	64.	48.
153.0 - 155.0	1.49	80	114	.25	5.2	1.1
163.0 - 165.0	1.59	8	13	.12	1.1	.11
167.5 - 169.5	1.63	3	4	.08	.53	.036
178.0 - 180.0	1.74	120	210	.29	7.2	1.8
228.5 - 230.5	2.23	24	54	.17	2.4	.35
248.5 - 250.5	2.42	3	8	.09	.65	.050
Sum ($T = \Sigma T_i$)						186.

Table 1 lists the calculated values of b_i, K_i and T_i in a selected borehole, namely PD 129, in accordance with equations (1),(2) and (3). The value of b_i is the thickness of an idealized equivalent fracture sufficient to account for the observed $Q/\Delta P$ (Table 1). Figure 2 shows the fracture transmissivity values listed in Table 1.

Flow rates in fractured rock depend on aperture thickness. Aperture thickness, in part, depends on effective stress. Effective stress varies with depth. Hence it is possible to estimate the depth dependence of parameters that control maximum and average flow rates if an additional series of simplifying assumptions is made.

The Blendevale aquifer tests [2] make it possible to derive properties of idealized equivalent "fractures". Of particular interest are the values for specific yield S_y and storativity (or storage coefficient) S.

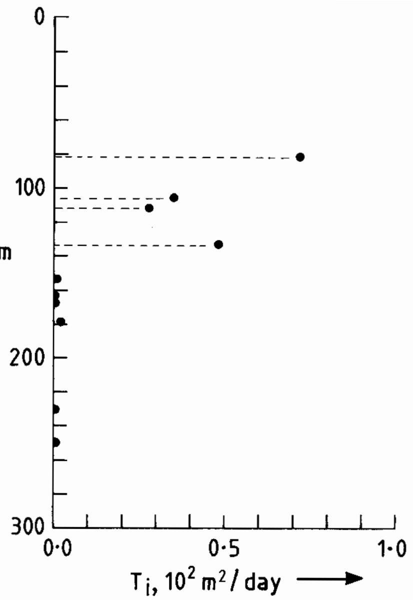

FIGURE 2. TRANSMISSIVITY OF EQUIVALENT APERTURES, PD129

From these values, compressibility β_f and transmissivity T_i values can be found for an idealized fracture.

For material whose apertures constitute the principal source of water during aquifer tests,

$$S \approx \rho_w g(\beta_w+\beta_f) \sum_{i=1}^{N} b_i = \rho_w g(\beta_w+\beta_f)b \quad (4)$$

where β_w is the expansion of water and β_f is the average compressibility of N fractures. The product $\beta_f b_i$ is simply the inverse of the coefficient of normal fracture stiffness of the ith fracture. For a stratified porous medium, specific storage S_s is defined by the ratio S/b where b is the aquifer thickness. From (4), an equivalent fracture specific storage can be introduced to equal

$$S_{sf} = \rho_w g(\beta_w+\beta_f). \quad (5)$$

Conceptually our simplified aquifer is an assemblage of deformable fractures within which porosity n is equal to unity surrounded by rock whose porosity is negligibly small. If we lower the water table a distance z, the specific yield approximately equals an effective porosity

$$S_y \approx \frac{1}{z} \sum_{i=1}^{N} b_i . \quad (6)$$

Combining (4), (5) and (6) for a fractured system yields

$$S_{sf} = S/S_y z \approx 1/10z. \quad (7)$$

It has been tacitly assumed that a lowering of the water table in (6) can be extended conceptually downward to represent a more generalized depth term z. The unexpected result in (7) that the ratio of storativity to effective porosity is not sensitive to depth can be shown to follow directly from a commonly assumed and empirically based semilogarithmic stress-strain relation. Storage coefficient S for the confined aquifers in the north was estimated [2] from aquifer tests to be roughly an order of magnitude smaller than the specific yield S_y values in the unconfined south.

Substituting (7) into (5) yields for Blendevale a normal fracture compressibility of

$$\beta_f = 1/(10\rho_w gz) \quad (8)$$

which for depths of interest is much larger than the compressibility of water. This contrasts with the bulk compressibility of limestone itself which is an order of magnitude smaller than water [4].

One can derive how an equivalent aperture thickness decreases with depth. To do this, fracture compressibility is expressed as

$$\beta_f = \frac{db_i}{d\sigma'} / b_i = \frac{db_i}{dz} / \frac{d\sigma'}{dz} b_i \qquad (9)$$

where σ' is effective stress. The change in effective stress with depth $d\sigma'/dz$ can be approximated by $(1-n)(G-1)\rho_w g$ for a horizontal fracture where G is the relative density of the solid component. For vertical north-south fracture zones (namely, those perpendicular to the direction of minimum principal stress), *in situ* stress measurements suggest that

$$d\sigma'/dz \approx 1.1\ \rho_w g. \qquad (10)$$

By substituting (8) and (10) into (9) it can be shown that transmissivity T_i for an idealized vertical north-south fracture decreases approximately with the cube root of depth, namely

$$T_i = C_1 z^{-1/3} \qquad (11)$$

where the constant C_1 equals $T_o\ z_o^{1/3}$ and T_o is an empirically determined representative transmissivity for a reference depth z_o. The aperture b_i of a vertical fracture decreases with depth as a function of $z^{-1/9}$ and

$$K_i = C_2 z^{-2/9}. \qquad (12)$$

To "predict" the largest T_i that might possibly occur in a single fracture, the largest observed T_i (Table 1) is used as a reference value to find

$$T_i \approx 314/z^{1/3}\ m^2/day \qquad (13)$$

for vertical fractures perpendicular to the direction of minimum principal stress. It can also be shown that T_i for an equivalent horizontal fracture is inversely proportional to the square root of z.

AVERAGE HYDRAULIC CONDUCTIVITY

Fracture transmissivities T_i listed in Table 1 and plotted in Figure 2 are additive. One can divide the total T by a representative thickness interval in order to calculate an equivalent uniform hydraulic conductivity K_{bulk} value for borehole PD 129, namely

$$K_{bulk} = \frac{1}{z_2 - z_1} \sum_i^N T_i = \frac{186}{250.5 - 81.5} = 1.1\ m/day. \qquad (14)$$

The concept of effective hydraulic conductivity K_{eff} is introduced by rewriting from (12) the relation

$$K_{eff} = Cz^{-2/9}. \qquad (12')$$

One value of C represents flow within a specified fracture (namely, C = C_2). Another value can represent "average" flow. The latter option is somewhat analogous to searching for the hydraulic conductivity of an equivalent porous medium. In the present case the search is restricted to finding an oriented component of average hydraulic conductivity.

In order to calculate the average hydraulic conductivity of a north-south vertical fracture between two specified depths z_a and z_b, one simply integrates equation (12'), namely

$$K_{avg} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} K_{eff}\, dz = \left[\frac{9}{7} C \right] \left[\frac{z_2{}^{7/9} - z_1{}^{7/9}}{z_2 - z_1} \right] \tag{15}$$

which becomes

$$K_{avg} = 4.4 \frac{z_2{}^{7/9} - z_1{}^{7/9}}{z_2 - z_1} \tag{15a}$$

for C equal to 3.4. This constant allows theoretical K_{avg} of (15a) to equal the empirical K_{bulk} of (14). A sample calculation between a depth of 60 m and an assumed water table at land surface yields

$$K_{avg} = (4.4) \frac{(60)^{7/9} - (0)^{7/9}}{(60) - (0)} = 1.8 \text{ m/day.} \tag{15b}$$

PRESSURE-INDUCED FLOW FROM A SINGLE FRACTURE

The largest estimate of anticipated pressure-induced Q in Table 1 is 4,300 m^3/day and is from a fracture encountered in PD 129 at a depth of between 132.5 and 134.5 m. Note in Table 2 that the zone at a depth of between 132.5 and 134.5 m is actually less permeable than the zone between 81.5 and 83.5 m. What makes the estimated pressure flow larger for the deeper zone is precisely because it is deeper and hence supports a larger initial pressure head.

The duration τ of single-event pressure flow can be estimated by

$$\tau \approx A' H^2 \rho_w g(\beta_f + \beta_w)/K_f \tag{16}$$

where the maximum distance of water flow H equals z/sin α_i and α_i is the dip of the ith fracture zone. In the unconfined case z equals the vertical distance to the overlying water table; in the confined case, z equals the vertical distance to the base of the overlying confining bed. For an extensive horizontal fracture zone that is isolated from other fracture zones, τ is of infinite duration because sin α_i is very small. For such a zone, analysis for transient flow in a confined horizontal aquifer of infinite radial extent is justified. Pressure flow would decrease with time in accordance with equations for transient flow [5]. During early time, Q is inversely proportional to the square root time regardless of the inclination of the fracture. In all cases, a large permeability value acts not only to increase the rate of pressure-induced flow, but also to decrease the duration of such flow.

Conversely, the smaller the sudden rush of flow, the longer its duration.

Assuming $\beta_w < \beta_f \approx 1.5 \times 10^{-2}$ MPa^{-1} at z ≈ 130 m (see (8))

$$\tau \approx 40.A' \text{ sec.} \tag{16a}$$

For flow from a radially extensive idealized fracture [5], the pressure-head gradient at the drainage face reduces to unity when A' equals 8π or about 25. This implies for an 0.88 mm fracture at a depth of about 130 m that after 17 minutes the pressure-induced component of flow will have diminished sufficiently to equal the flow due to gravity. For this example, it will have decreased from about 18,000 to 48 m^3/day per metre of exposed fracture length. By choosing A' equal to 100, one can reasonably expect that gravity flow will dominate for $t > \tau$.

Figure 3 shows the calculated time required for estimated pressure-induced flow to reduce to the estimated maximum gravity flow within an idealized fracture encountered at a depth z. This estimate is made substituting (8) and (12) into (16a) for a vertical fracture to get

$$\tau = A'z^{11/9}/C_3. \tag{17}$$

For the most permeable zone encountered (namely at z = 82.5 m in Table 1), the ratio A'/C_3 in (17) equals 2.4×10^{-2}.

It is possible to derive an expression for the cumulative pressure-induced volume of water that is produced during an early time period

$$\text{Vol} = 2B(\tau)^{\frac{1}{2}}. \tag{18}$$

For an extensive idealized fracture, B equals $4b_i L\Delta h(\pi K_f S_{sf})^{\frac{1}{2}}$ and

$$\text{Vol} \approx 7.3 \times 10^{-2} L z^{8/9} \tag{18a}$$

for the 82.5 m fracture zone. Figure 4 shows the estimated total volume of water per metre of exposed fracture length expected from a single fracture during the early time period τ. The cumulative gravity flow volume during τ is only seven percent of the pressure flow volume. Gravity flow, however, continues beyond τ and will be discussed later.

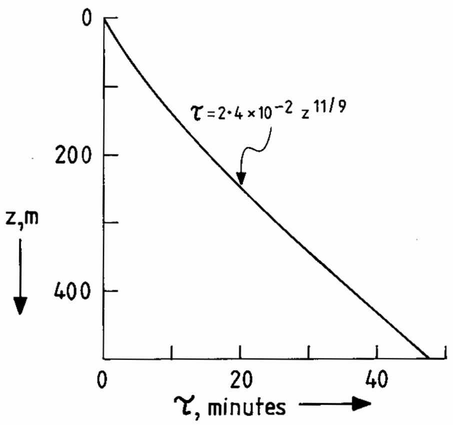

FIGURE 3. τ VERSUS z FOR MAXIMUM PRESSURE-INDUCED FLOW

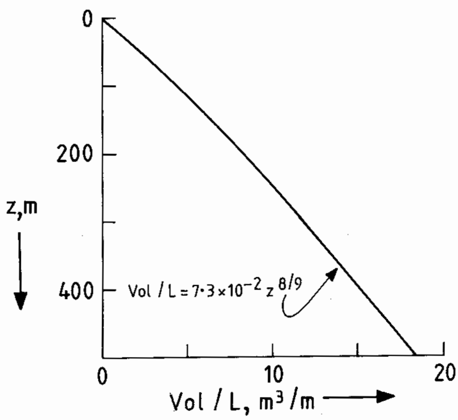

FIGURE 4. Vol/L VERSUS z FROM A VERTICAL FRACTURE DURING τ

A major hydrologic problem is the occurrence of sudden outflows. By multiplying the centre column of Table 1 by the factor 4.2 one can estimate such Q per metre of exposed fracture length. When any specified fracture continues deeper, one would expect the sudden Q from such a fracture to increase by a function of the depth. Based on (13), the largest initial burst of flow expected at Blendevale (Fig. 5) is

$$Q = 8.6 \times 10^2 \ Lz^{2/3} \ m^3/day. \tag{19}$$

GRAVITY FLOW

Darcy's law is $Q/A = -K\nabla h$ where the cross-sectional area A for a single fracture equals the product $(b_i L)$ where L is the exposed length of effective thickness b_i. Hence the flow volume from the ith fracture is

$$Q_i = -L(K_i b_i)\nabla h. \tag{20}$$

After an initial period of pressure flow, the flow becomes steady-state Darcian due to gravity. This implies the maximum gradient of head $\partial h/\partial z$ equals unity. Hence for any inclined fracture,

$$Q_i = -LT_i \sin \alpha_i . \tag{20a}$$

To calculate gravity flow from a single fracture use equation (20a) with T_i estimates such as those listed in Table 1. Whenever transmissivity is a function of depth, so is gravity flow.

How long would such gravity flow persist? Assume the volume of saturated interconnected voids averages about one percent of the bulk volume. This is twice the largest specific yield value estimated from long term aquifer tests [2]. If all water within a gradually widening "angle of draw" is free to flow under gravity, then the volume of water that is available above any anticipated excavation can be estimated. Depth dependence, orientation of excavations, effects of lower ladders being in the drainage shadow of upper ladders are accounted for in Figure 6 which reflects only one of several possible excavation geometries. If water is withdrawn at rates calculated for Figure 6, the durations of flow needed to drain this volume are also shown in Figure 6. If the overall volume of interconnected saturated voids is actually less than one percent of the total bulk volume, then the duration of flow in Figure 6 would probably be smaller. The converse is also true. The area under any curve in Figure 6 equals the total volume of water withdrawn.

SUSTAINED FLOW

Steady flow to a well discharging from an unconfined aquifer can be expressed by

$$Q = 2\pi rKh\partial h/\partial r + \pi r^2 W \tag{21}$$

where W is the average rate of recharge such as infiltration due to rainfall. For a partitioned unconfined aquifer with impermeable boundaries the recharge area A equals πr_o^2 which in turn equals the ratio Q/W. The value r_o is the radius of influence where $\partial h/\partial r$ in (21) equals zero.

The recharge area at Blendevale is estimated to be about 20 km^2. Only a long-term discharge of between 3,000 and 4,000 m^3/day can be maintained by the estimated regional recharge of 60 mm per year over this area.

FIELD CORROBORATION

The selection of borehole PD 129 [6] to represent average groundwater flow into an east-west decline has been corroborated by subsequent field tests [7]. The transmissivity along the first 325 m of the anticipated decline was estimated by airlift tests on groundwater flow. The boreholes were inclined and oriented northeast-southwest (Fig. 1). The calculated transmissivity value for each borehole represents an integral sum of fracture and background transmissivities that are tapped by the open borehole.

The average K equals the cumulative T (Table 2) of 552 m^2/day divided by the 325 m length and equals 1.7 m/day. This is actually a lower limit because the entire 325 m was not tested. The depth of the proposed decline at the end of the 325 m length is expected to be roughly 60 m. The empirical average K estimated above is close to the theoretical average K which was calculated by (15b) to be 1.8 m/day. This indirectly corroborates (12) upon which the predictions of Figure 6 are based.

Table 2. Transmissivity Estimates Based on Airlift Tests

Fracture Zone	Estimated T, m^2/day	Borehole
1st	160	PD 409, PD 410
2nd	200	PD 393, PD 414
3rd	60	PD 404
4th	27	PD 394
5th	100	PD 408
Other	5	PD 407
Sum	552	

PREDICTIONS

Pressure-induced flow from a single fracture (Fig. 5) can be expected to increase in rate with depth from a maximum value of about 13 m^3/minute/metre of fracture length instantaneously exposed at 100 m depth to about 38 m^3/minute/metre of fracture exposed at 500 m depth. Pressure flow dissipates rapidly with time, so that the cumulative volume of pressure-induced flow (Fig. 4) from an extensive but isolated fracture is likely to be only about 4 m^3/metre of fracture length exposed at 100 m depth and about 18 m^3/metre at 500 m depth. Gravity flow from a single fracture (Fig. 5) can be expected to be fairly steady with time but to decrease with depth from a maximum rate of about 70 m^3/

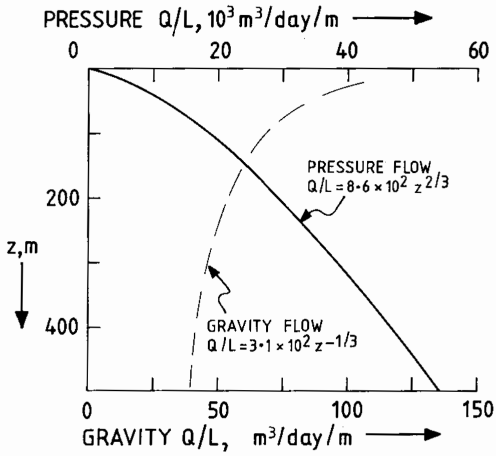

FIGURE 5. MAXIMUM Q/L VERSUS z FROM A VERTICAL FRACTURE

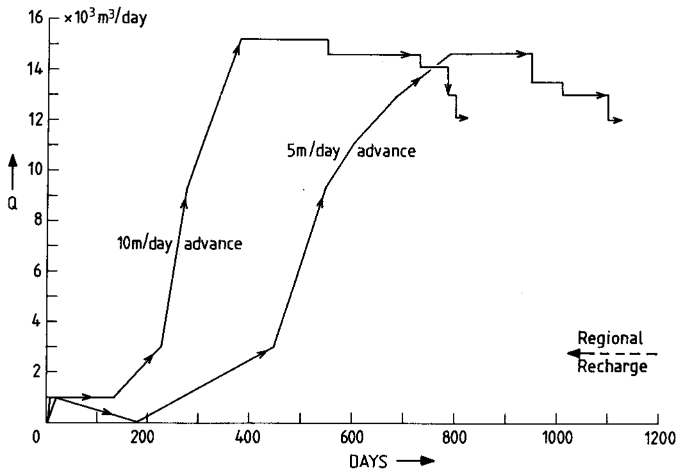

FIGURE 6. CUMULATIVE GRAVITY FLOW ESTIMATES

day/metre of fracture length exposed at a depth of 100 m to a maximum of about 40 m^3/day at 500 m. These quantities can be used to make an estimate of "back-up" pumping capacity necessary to cope with sudden increases in flow encountered when a fracture is intersected.

Long term cumulative gravity flow into the decline (Fig. 6) is likely to reach about 1.5×10^4 m^3/day within a year assuming 10 m per day rate of advance to a depth of 500 metres. Half this rate of advance would lead eventually to 96 percent of this maximum flow after about two years. For both cases flow should remain at this high rate for possibly another year before gradually decreasing to a long-term sustained flow rate of less than 4×10^3 m^3/day in response to current estimates of regional recharge. These estimates of flow can be used to plan long term pumping requirements or design preliminary dewatering strategies.

Unlike earlier estimates [2], the current predictions are made from interpreting injection tests and are able to provide predictions of specific events, such as sudden inundations, that can be updated as further geological and hydrological information is obtained.

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