APPLICABILITY OF CURRENT GROUNDWATER THEORIES FOR THE PREDICTION OF WATER INFLOWS TO SURFACE MINING EXCAVATIONS

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ABSTRACT

Surface mining below the local groundwater table invariably results in the drawdown of the water table or piezometric surface and a corresponding flow of groundwater into the mining excavation. Accurate design of the resulting mine drainage scheme requires the prediction of inflow rate and quantity. The paper presents idealized hydrogeological profiles of some surface mining situations regarding inflow prediction. Simple flow equations deriving directly from groundwater theorems are presented. Their suitability for inflow prediction is assessed. The equations fall into two groups on basis of approach - the equivalent well method and the two dimensional flow method. Input parameters in each case are the pit geometry and aquifer characteristics. Example computations show that inflow rate depends on the site geology which determines the aquifer types, the configuration of the hydraulic conductivity contrasts and hence the flow regime.

INTRODUCTION

In recent years, the importance of mine drainage control and the need for detailed design of mine dewatering systems during the mine feasibility study stage have been highlighted (Fernandez-Rubio 1978). Surface mining operations below groundwater table present a variety of operational, economical, safety and stability problems. Sudden inflow of water to a surface mining excavation can halt production, endanger the safety of men and machinery with the resultant economic consequences significantly reducing the over-all profitability of the project. Therefore, an accurate prediction of the rate of water inflow to surface mining excavation is an essential requirement for the design of new mining projects. Information concerning the inflow rate and quantity can be used for the following engineering purposes :

- The design of the pumping system
- The design of the storage facilities
- Estimation of pumping rate necessary to maintain a 'dry' excavation.

The paper briefly presents idealized hydrogeological profiles of common surface mining situations. The suitability of current groundwater theorems for the prediction of inflow quantities is assessed together with the conditions under which each equation is valid. Two-dimensional flow equations to a large surface excavation are described for confined, unconfined and leaky aquifers under both steady-state and transient flow conditions. Several refinements such as finite boundary conditions, fracture (turbulent) and linear flow conditions for single aquifer systems are also given.

IDEALIZED HYDROGEOLOGICAL PROFILES OF SOME SURFACE MINING PROJECTS REQUIRING INFLOW PREDICTION

The most commonly encountered hydrogeological conditions in which mine drainage and hence inflow prediction is necessary are outlined below :-

(i) One phase flow into a surface mining excavation :

This commonly occurs in two ways (Figure 1a and 1b respectively)

(a) Where the mineral deposit acts as an aquifer underlain by an impervious bed, any attempt to win the mineral by surface mining techniques invariably results in pit flooding unless advance dewatering is employed. For sedimentary deposits, flow is generally in one horizontal direction and intergranular and can hence be assumed to be laminar at points remote from the excavation face.

(b) If the mineral deposit occurs above a confined aquifer, the confining bed ruptures, as the overburden and mineral are stripped off in the process of mining, liberating pressurized water into the mining excavation. With the hydraulic characteristics of the aquifer and the mine geometry known, an estimate of inflow rate can be made direct from Darcy's law stated as follows :-

$$Q = KIA \tag{1}$$

where Q = Flow rate
K = Hydraulic conductivity of the aquifer
I = Hydraulic gradient producing flow
A = Area of the pit

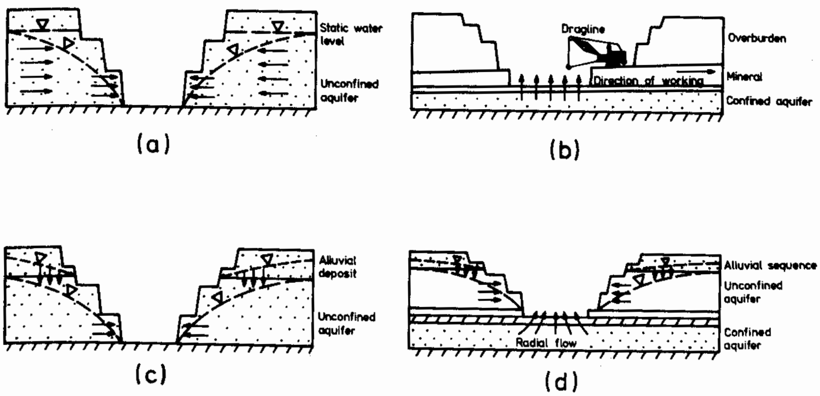

Figure 1. Idealized hydrogeological profiles of some surface mining projects requiring inflow prediction

(ii) Two-phase flow into a mining excavation :

This situation commonly occurs where mining takes place in an unconfined aquifer overlain by an alluvial sequence which maintains its own water table, Figure 1c. Horizontal flow into the excavation occurs from the unconfined aquifer which in turn receives vertical recharge from the overlying alluvial sequence. The rate of expansion of the cone of depression governs the size of the area from which vertical recharge from the overlying alluvial sequence contributes to the groundwater flow into the mining excavation.

(iii) Three-phase flow of groundwater into surface mining excavation :

In some situations, mining can take place in an unconfined aquifer overlain by alluvial deposit and also underlain by a confined aquifer, Figure 1d. As mining removes the overburden and minerals, the confining bed ruptures and water is released into the pit. Meanwhile, horizontal flow takes place from the unconfined aquifer recharged vertically by the overlying alluvial deposits.

Accurate design of the drainage system in these situations requires an estimate of the inflow rate and quantity.

INTERACTIONS BETWEEN AQUIFER TYPE, AQUIFER CHARACTERISTICS, FLOW REGIME AND MINING EXCAVATION

The complexity of the relationship between aquifer type, aquifer characteristics, flow regime and mining excavation often complicates mine water inflow prediction. The aquifer characteristics are governed by the aquifer type. The flow regime depends on the type of conducting medium. In an unconsolidated sedimentary sequence where groundwater movement is through intergranular pore-spaces, flow is essentially linear. On the other hand, in a rock sequence in which it is the secondary processes like fracturing and faulting that provide the conducting medium, flow is predominantly non-linear. Surface mining excavation serves as a natural groundwater discharge point. Near the excavation, there is invariably, a vertical component of flow and high hydraulic gradient which often leads to turbulent flow and negates analysis by Darcy's law. Non-linear flow equations are therefore valid. The rate of inflow is generally computed from equations which relate the hydraulic head loss in and flow of groundwater through the porous geologic strata. Prior knowledge of aquifer hydraulic characteristics and pit geometry is necessary. The aquifer parameters are obtained from detailed hydrogeological investigation of the mine site and pit geometry from the mine plan.

ANALYTICAL APPROACHES FOR SURFACE MINE WATER INFLOW PREDICTION

The analytical approaches for estimating groundwater inflow to surface mining excavations are based on drawdown theory and can be broadly grouped into two as follows :-

(a) Equivalent Well Approach

This approach assumes that dewatering of the surface mine is carried out by use of an imaginary pumping-out borehole (fully penetrating the entire saturated thickness of the aquifer) from which water is pumped out at a uniform discharge rate in order to lower the piezometric level of the aquifer to below the mining horizon at the mine boundary. Input parameters for equations developed in this approach are aquifer characteristics (Transmissivity, Permeability, Storage-Coefficient and Leakage Factor) and mine geometry. Normally the mine excavation is envisaged as a large diameter well. Where the mine has the shape of a square or rectangle, as is the case in most strip mines, then, an equivalent radius for the well is calculated using the equation given by (Mansur and Kaufman 1962) :

$$r = \left(\frac{2}{\pi}\right) (Y.W)^{\frac{1}{2}} \tag{2}$$

where Y = length of the mine (m)
W = width of the mine (m)
r = equivalent radius (m)

Dudley (1972) discussed various methods of approximating a mine model to an equivalent cylindrical well and estimating input parameters for the equivalent well model.

(b) Two Dimensional Flow Approach

The past two decades have witnessed a major development in the determination of steady-state and transient drawdown in large earth excavations, Moody (1962), McWhorter (1981), Jenab et al (1969), Debidin and Lee (1980). These two-dimensional flow equations are simple to apply and provide an easy method of estimating inflows and drawdown for selected situations.

EQUIVALENT WELL APPROACH FOR ESTIMATING INFLOW QUANTITY INTO A SURFACE MINING EXCAVATION

In this approach, the surface mine excavation is envisaged as a large diameter well and by applying drawdown theory, approximate closed form equations have been developed for prediction of inflow quantity under different aquifer conditions and flow regimes. The notations used in the equations in this approach are defined as follows :-

B = leakage factor (m) = $(KLL'/k')^{\frac{1}{2}}$
D = drawdown (m) = $(H-h)$
H = original height of water table or piezometric surface above mine level (m)
h = piezometric head at a specific point in time (m)
K = coefficient of permeability of the aquifer (m/d)
K' = permeability of the aquitard (m/d)
$K_o(r/B)$ = Hantush-Jacob well function for steady state leaky aquifer (dimensionless)
ℓn = natural logarithm
L = thickness of the aquifer being dewatered (m)
L' = thickness of the aquitard (m)
n = recharge coefficient = unity for fully recharging system and zero when there is no recharge (dimensionless)
r = equivalent mine radius = radius at which drawdown is required (m)
r_w = radius of well (m)
R = effective radius of influence of the dewatering well (m)
S = storage coefficient of aquifer (dimensionless)
t = elapsed time (d)
T = KL = Transmissivity of the aquifer (m^2/d)
T_D = Linear transmissivity (m^2/d)

T_T = Turbulent transmissivity (m^2/d)
$T_T = \frac{1}{2} / (T_D)^{3/4}$ (m^2/d)
$W(u)$ = Theis well function
$u = r^2S/4Tt$ (dimensionless)
$W(\lambda)$ = Jacob-Lohman well function (dimensionless)
$\lambda = Tt/Sr^2$ (dimensionless)
$W(u,r/B)$ = Hantush well function (dimensionless)
$B = (KLL'/k')^{\frac{1}{2}}$ (m)

(i) Linear Flow into a Surface Mining Excavation :

Figure 2 illustrates a frictionless imaginary well with equivalent mine radius, r, which fully penetrates a confined aquifer of permeability K and thickness L. If R is the radius of influence of the well, then an infinite source of water under head H enters the well horizontally if the well is being pumped out at a constant rate Q to reduce the head by D. Table 1 outlines the appropriate inflow prediction equations under stated flow regimes and aquifer types.

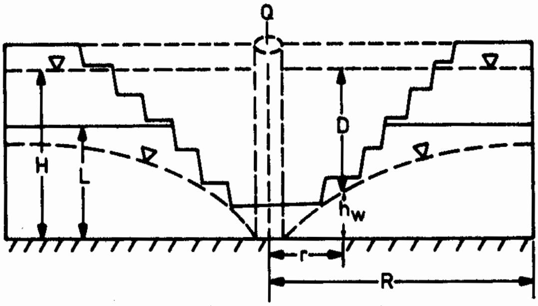

Figure 2 Definition sketch for equivalent well approach tor surface mine water inflow prediction

Flow regime	Aquifer type	Equation	Remarks
Linear steady-state	Confined	$Q = \frac{2\pi KLD}{\ell n(R/r)-\frac{n}{2}}$ (3)	After Peterson(1957)
Linear, steady-state	Leaky	$Q = \frac{2\pi TD}{K_o(r/B)}$ (4)	After Hantush & Jacob
Linear, steady-state	Unconfined	$Q = \frac{\pi K(H^2-h^2)}{\ell n R/r}$ (5)	Modified Dupuit's equation
Linear, transient state	Leaky	$Q = \frac{4\pi TD}{W(u,r/B)}$ (6)	After Hantush
Linear, transient state	Confined	$Q = 2\pi TDW(\lambda)$ (7)	After Jacob-Lohman
Non-linear, steady-state	Confined	$D = Q \ell n(R/r)/2\pi T_D + Q^2(R-r)/4\pi^2 T_T^2 Rr$ (8)	
Non-linear, transient-state	Confined	$D = Qr W(u)/2\pi T_D + Q^2(R-r)/4\pi^2 T_T^2 Rr$ (9)	

Table 1 Appropriate equations for water inflow prediction (equivalent well method) under stated flow regime and aquifer conditions

In equations (8) and (9) (after Schmieder 1978), the first term is Theis' equation for transient state linear flow while the second term gives the drawdown for turbulent flow.

By substituting the appropriate input parameters, into the appropriate equations, the inflow rate can be predicted.

TWO-DIMENSIONAL GROUNDWATER FLOW TO A SURFACE MINING EXCAVATION

When a surface mine works below the water table, groundwater flows from the incised aquifer into the excavation. Flow regime is essentially two-dimensional. Remote from the excavation, flow is linear but near the excavation there is vertical component of flow and flow is non-linear. This situation makes an exact analytical solution using the equivalent well method very approximate. In an attempt to provide a solution to this kind of problem, Dupuit (1863) made the following simplified assumptions :

- Thickness of capillary fringe above the phreatic surface is assumed to be much smaller than that of the saturated formation below the water table
- Flow is mainly horizontal and vertical flow is almost negligible
- Boundary conditions are very constricted. Dupuit assumed that the depressed water table is parabolic in shape. Dupuit-Forchiemer theory assumes an elliptical depressed water table
- Excavation face is vertical
- Excavation is emplaced instantaneously
- Geological strata are homogeneous and isotropic
- Excavation is long, linear in shape and symmetrical.

The problem was hence approximately solved utilizing a linearisation of boundary conditions and/or non-linear continuity equations describing unconfined flows.

The approach is advantageous in that it is often compatible with the quantity and quality of hydrogeological data available. However, under the conditions illustrated in Figure 3, the simplified flow assumptions become invalid. The conditions include the following : Near the seepage plane, at the crest in a phreatic surface with accretion, in the region of vertical impervious boundary.

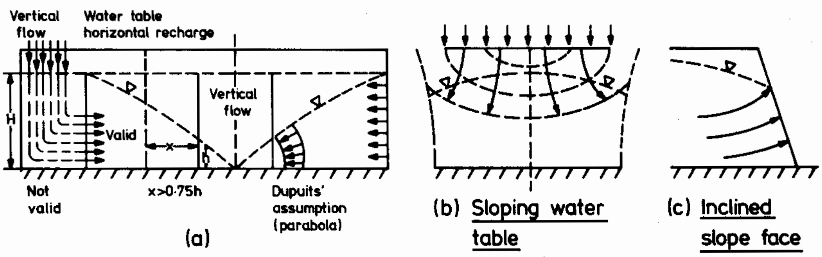

Figure 3 Conditions under which the simplified flow assumptions are invalid

The notations used in the two dimensional flow approach are defined as follows :

- Q = Total flow rate from both excavation faces (m^3/d)
- K = Hydraulic conductivity of the geologic formation (m/d)
- Y = Length of the cut or highwall (m)
- R = Radial distance (radius of influence) of the pit on surrounding piezometric level (m); usually assumed to be equal to 3H
- H = Undisturbed water table elevation or saturated thickness of aquifer above mining footwall (m)
- h = Dynamic water table at a distance X from the excavation face (m)
- D = Drawdown (H-h) at a distance X from excavation face (m)
- D_w = Drawdown at excavation face (m)
- S = Dimensionless coefficient of storage = $S_s.L$
- T = Transmissivity of aquifer (m^2/d)
- W = T/S = Hydraulic diffusivity

(i) Two-dimensional, Linear, Steady-state Flow into a Mining Excavation

The steady state linear flow from an unconfined aquifer into a surface mining excavation can be computed from the following equation :-

$$Q = \frac{KY(H^2-h^2)}{R} \qquad (10)$$

Figure 4(a) illustrates the situation and defines the parameters.

For a confined aquifer, the steady-state linear flow is given as follows :-

$$Q = \frac{2KLY(H-h)}{R} \qquad (11)$$

Figure 4(b) illustrates the situation and defines the parameters.

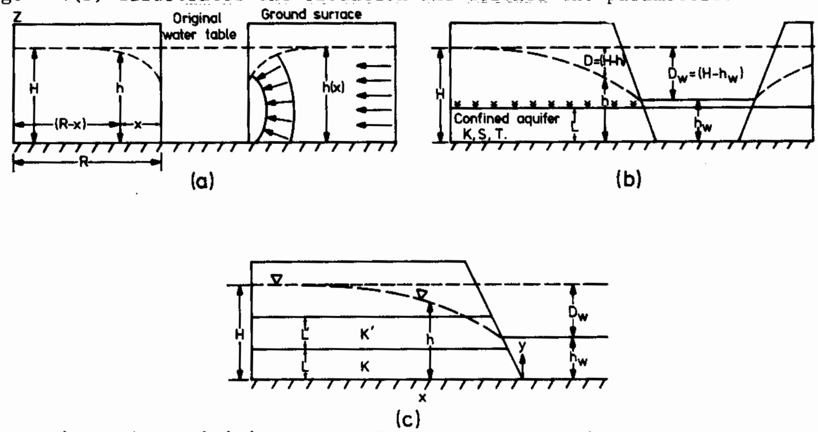

Figure 4 Definition sketch for steady-state linear flow from (a) an unconfined, (b) a confined, (c) a leaky aquifer into a surface mining excavation

Figure 4(c) illustrates steady-state flow from a leaky aquifer to a surface mining excavation. The drawdown at a distance X from the highwall face is given as follows :

$$D = D_w \exp(-X/B) \tag{12}$$

and the flow is given by the equation below

$$Q = 2\,\frac{T}{B}\,D_w.Y \tag{13}$$

where

$$B = \sqrt{\frac{LL'K}{k'}}$$

$$D_w = (H-h)$$

(ii) Two-dimensional, linear, Transient flow to a surface mining excavation

Recently, the problem of 2-dimensional transient flow to a large earth excavation has received a considerable attention. A set of equations derived for the calculation of drawdown and spatial variation of time-dependent horizontal flow in the rockmass assumes the following :

- Free surface flow boundary is time-dependent
- Discharge is due to the elastic storage and lowering of the water table
- There is negligible inter-relationship between the stress field and flow in the aquifer
- Effect of capillary fringe is negligible
- Both the aquifer and the water are incompressible and the vertical flow component is negligible
- Horizontal velocity is dependent upon hydraulic gradient
- The excavation is emplaced instantaneously.

Figure 5 illustrates the situation in a confined and leaky aquifer respectively.

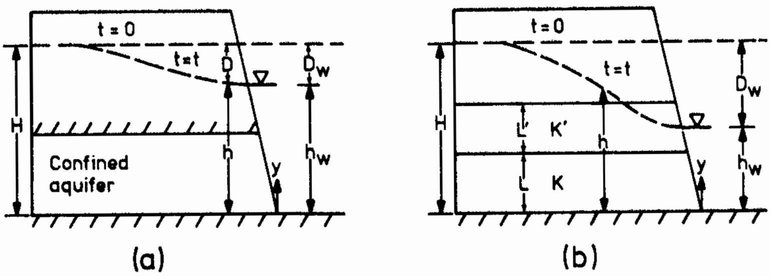

Figure 5 Definition sketch for transient flow in (a) Confined, (b) leaky aquifer

For the drawdown and flow remote from the excavation face, the 2-dimensional transient flow equation can be expressed as follows :

$$D = D_w \text{ erfc } (X/2(\omega t)^{\frac{1}{2}} \tag{14}$$

where

$$D = q\,\frac{W^{\frac{1}{2}}}{T}\,\{2(t/\pi)^{\frac{1}{2}}\exp(-X^2/4\omega t)-(X/\omega^{\frac{1}{2}})(\text{Erfc}X/2(\omega t)^{\frac{1}{2}}\} \tag{15}$$

ω = T/S = Hydraulic diffusivity

erfc = complimentary error function

The total flow into the excavation initially under static condition is given by

$$q = 2T\partial D/\partial x|_{x \to 0}$$

Similarly, the 2-dimensional transient flow in a leaky aquifer is given by

$$q = 2TD_w[\frac{1}{B} + \frac{\sqrt{\pi}}{4}\,\{\frac{2}{\sqrt{\pi}}\,\frac{\exp(-\frac{\omega t}{B^2})}{(\omega t)^{\frac{1}{2}}} - \frac{2}{B}\text{ erfc }\frac{(\omega t)^{\frac{1}{2}}}{B}\}] \tag{16}$$

$$D = D_w\{\exp(-X/B) - (\sqrt{\pi}/4)\text{Erfc}[X/2(\omega t)^{\frac{1}{2}}]\} \tag{17}$$

For a finite aquifer the 2-dimensional transient flow into an excavation can be computed from the following equation (Ibrahim and Brutsaert 1965) :-

$$Q = \frac{H^2K}{S_yR}\,\gamma \tag{18}$$

$$\tau = \frac{KH}{S_yR^2}\,t \tag{19}$$

where τ = Dimensionless time calculated from prior knowledge of K, H and S_y, the specific yield of the aquifer
γ = Dimensionless discharge
R = Radius of influence
t = assumed value of t

Figure 6 illustrates the situation. Table 2 shows the dimensionless drawdown for given values of dimensionless distance (X/R).

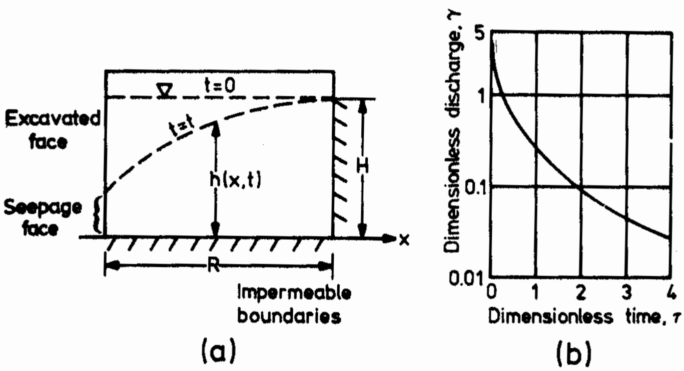

Figure 6 Prediction of transient groundwater flow into a surface excavation (after Ibrahim and Brutsaert 1965)

τ/X/R	0	0.25	0.5	0.75	1.0
5	0.025	0.095	0.1335	0.1500	0.1775
2.5	0.045	0.1557	0.2150	0.2500	0.2500
1.0	0.0875	0.2950	0.4050	0.4550	0.5000
0.5	0.1125	0.4250	0.5700	0.6450	0.6950
0.25	0.1750	0.5315	0.7075	0.8200	0.8500
0.10	0.1825	0.6750	0.8650	0.9350	0.9550
0.05	0.2875	0.7750	0.9200	0.9700	1.0000
0.025	0.4000	0.8625	0.9550	1.050	1.0375

Table 2 Dimensionless drawdown for given values of dimensionless distance (X/R) (after Ibrahim & Brutsaert 1965)

The discharge into the mine excavation from the seepage face per unit length of excavated face perpendicular to it can then be calculated from equation (18). Nguyen and Raudkivi (1983) solved two dimensional flow problems to a surface excavation using Laplace type formulation. Using a closed function, a quick and easy method of estimating flow rate and drawdown as a function of time was evolved. The drawdown at a distance X from the pit at a time t is given as follows :-

$$D = (H-h_w)\ [1-G(X/H,\tau)] \tag{20}$$

where $\tau = (K/S_y H)t$
$\lambda = aH$
a = dummy variable which vanishes in integration

and

$$Q = (4T/\pi H)(H-h_w) \int_0^\infty \exp(-\tau\lambda \mathrm{Tanh}\lambda)d\lambda \tag{21}$$

which for a given time can be evaluated with the aid of Table 3. Figure 7 gives G(X/H,τ) for given values of τ and X/H. The equation however assumes large time increment and that at the outflow region, a uniform rate of flow is established.

τ:	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010	0.025	0.050
∫:	999.9	500.0	333.3	250.0	200.0	166.7	142.9	125.0	111.1	100.0	40.00	20.00
τ:	0.100	0.250	0.500	1.0	2.0	4.0	6.0	8.0	10.0	20.0	30.0	40.0
∫:	10.04	4.081	2.133	1.188	0.723	0.474	0.379	0.326	0.291	0.201	0.164	0.141
τ:	60.0	80.0	100.0	200.0	300.0	400.0	500.0	600.0	700.0	800.0	900.0	1000
∫:	0.115	0.099	0.089	0.063	0.051	0.044	0.040	0.036	0.034	0.031	0.030	0.028

Table 3 Table of values of $\int_0^\infty \exp(-\tau\lambda\tanh\lambda)d\lambda$ (after Nguyen and Raudkivi, 1983)

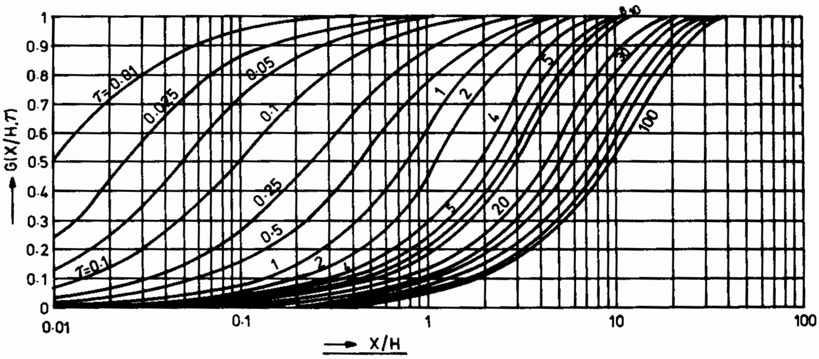

Figure 7 Values of the integral $G(X/H,\tau)$ for given values of τ and X/H (after Nguyen and Raudkivi, 1983)

(iii) Non-linear two-dimensional flow to a surface mining excavation :

The equation for non-linear flow into a surface mining excavation penetrating the full thickness of a confined aquifer is given below (Perez-Franco, 1982).

$$Q = 2LYK_n \left(\frac{h-h_g}{X}\right)^n \tag{22}$$

Using exponential law of flow; for pure linear flow,

$$K_n = K_D,\ n = 1,\ h = H \text{ and } X = R.$$

$$Q = 2LYK_D \left(\frac{H-h_g}{R}\right) \tag{23}$$

In case of pure turbulent flow, n = 0.5 and $K_n = K_T$

$$Q = 2LYK_T \left(\frac{H-h_g}{R}\right)^{\frac{1}{2}} \tag{24}$$

Using binomial law of flow,

$$D = \left(\frac{q}{LK_D} + \frac{q^2}{L^2K_T^2}\right)R \tag{25}$$

For an unconfined aquifer, the non-linear flow equation per unit length of a surface mining excavation penetrating the full saturated thickness (Figure 8a) is given as follows :-

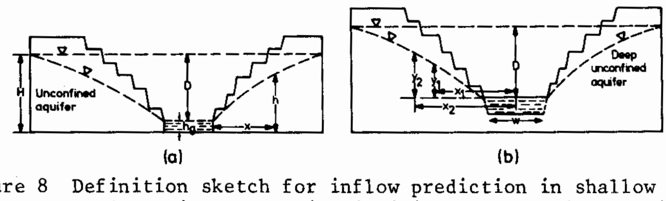

Figure 8 Definition sketch for inflow prediction in shallow surface mine excavation incising an unconfined aquifer under non-linear flow conditions

$$Q = 2LK\,K_n\left[\frac{H^{(1+1/n)} - h_g^{(1+1/n)}}{(1+1/n)X}\right]^n \qquad (26)$$

For linear flow $n = 1$, $X = R$ and $h = H$, $K_n = K_D$

$$Q = LYK_D\,[H^2 - h_g^2] \qquad (27)$$

For turbulent flow condition, $K_n = K_T$ $n = 0.5$, $h = H$ and $X = R$. Then,

$$Q = K_T\left(\frac{H^3 - h_g^3}{3H}\right)^{\frac{1}{2}} \qquad (28)$$

For shallow surface mine at the upper part of a deep aquifer, the general equation for non-linear flow in the vicinity of a circular pit bottom is given as follows (Figure 8b)

$$Y_2 - Y_1 = \frac{Q}{\pi K_D}\,\ell n(X_2/X_1) + \frac{Q^2(X_2 - X_1)}{\pi^2 K_T^2} \qquad (29)$$

(iv) Modified 2-dimensional flow approach

McWhorter (1981) applied the concept of successive steady states flow to predict surface mine inflow from a confined aquifer incised by mining excavation as shown in Figure 9. This approach assumes that the variation of piezometric head (drawdown) with time corresponds to the steady state instantaneous drawdown caused by a particular rate of groundwater inflow.

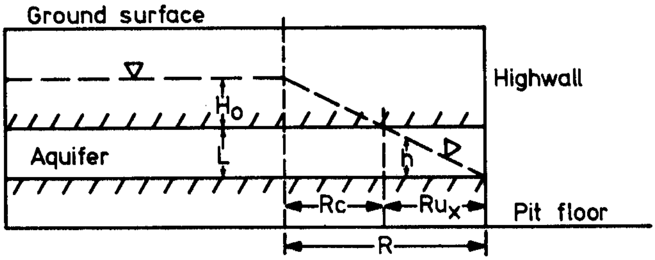

Figure 9 Definition sketch for inflow from a confined aquifer incised by surface mining excavation (after McWhorter, 1981).

Part of the aquifer near the excavated face becomes unconfined while remote from the excavated face the aquifer remains confined. The rate of inflow on the highwall face per unit length is given as follows -

$$q = At^{-\frac{1}{2}} \qquad (30)$$

where

$$A = \{0.083\ S_y TL^2 + 0.25ST\ H_o^2 + 0.25\ ST\ H_o L\}^{\frac{1}{2}}$$

$Ru = TL/2q$ = Interval in which aquifer is unconfined

$Rc = TH_o/q$ = Length of the depressed part of the confined aquifer.

Equation (30) can be modified to predict inflow to a surface mine where the length of the pit increases with time by considering the flow from different increments of exposed face. The total discharge to the mine from both sides of the excavation after time 't' at which the pit ceases to elongate is given by the following equation -

$$Q = 4Y_1At^{\frac{1}{2}} \quad , \quad t \leqslant Y/Y_1 \tag{31}$$

where

Y_1 = average rate of elongation of the pit (m/d)

Y = maximum length of the pit (m)

Y/Y_1 = period during which the pit is advancing (d)

Similarly, the discharge from two sides of the excavation after elongation has ceased is given by -

$$Q = 4Y_1A\ \{t^{\frac{1}{2}} - (1-Y/Y_1)^{\frac{1}{2}}\},\ t \geqslant Y/Y_1 \tag{32}$$

$$Ru = \frac{TL}{2A}\ (1 - Y/Y_1)^{\frac{1}{2}}$$

$$Rc = TH_o\ (t-Y/Y_1)^{\frac{1}{2}}\ /A$$

The advantage of this approach is that it considers the effect of time and face advance on the inflow quantity.

(v) Limitations of two-dimensional flow equations

The following assumptions implicit in two-dimensional flow equations for surface mine-water inflow prediction place serious limitations to this approach.

- The excavation is made instantaneously.
- Drawdown in the mining excavation is instantaneous along the entire length of exposed face. In practice, a gradually increasing length of exposed aquifer is subjected to the prescribed drawdown as the pit advances with time. It is therefore necessary to consider the flow from different increments of the exposed face. Otherwise, this results in the prediction of excessively high inflow quantities.
- That an aquifer is confined throughout is not necessarily true. An initially confined aquifer will become unconfined in the immediate vicinity of the pit; the storage co-efficient in the unconfined zone is much greater than in the confined zone.
- The inflow to the pit through the ends of the excavation is not accounted for in the formulae. It is assumed that the length to width ratio is always large.

DISCUSSIONS

Table 4 shows an example computation (using equivalent well approach) of inflow quantities from an aquifer incised by a surface mining excavation. The equations used for the computation define the aquifer conditions and flow regimes. The input parameters are given as follows -

$T = 75m^2/d$; $r = 400m$; $D = 50m$; $t = 100$ days; $S = 0.15$; $R = 2050m$;

$Y = 1000m$; $W = 395m$; $L = 20m$; $L' = 15m$; $K = 3.5m/d$; $K' = 1.0m/d$

Under these conditions, the equivalent well radius r, computed from equation (2) = 400 metres.

The first five equations yield higher discharge figures because they describe

Table 4 Example computation, using equivalent well approach, of inflow quantities from an aquifer incised by a surface mining excavation

Definition Sketch	Aquifer Characteristics	Pit Geometrical Parameters	Equation	Predicted inflow Quantities (m^3/d)	Remarks
Fig.2 with the upper bed as a totally confining bed.	D,K,L,R,r	Y,W	3	14418.60	Linear, steady-state, confined flow.
Fig.2 with leakage from upper bed.	T,D,r,k,L,L',K'	Y,W	4	110205.54	Linear, steady-state, leaky flow.
Fig.2	K,H,h,R,r	Y,W	5	16821.75	Linear, steady, unconfined flow.
Fig.2 with leakage from the upper bed.	T,D,r,L,L',K,K'	Y,W	6	586847.94	Linear, transient-state leaky flow. t = 100 days
Fig.2 with upper bed impermeable and confining	T,D,S,t	Y,W	7	34801.00	Linear, transient state confined flow
				64.04	Non-linear steady-state flow. Linear component of the equation neglected, i.e. inflow is due only to turbulent transmissivity.
-	T_D,T_T,R,D	Y,W	8	14419.90	Non-linear component neglected, i.e. inflow is due to linear transmissivity alone.
				2.74	Non-linear transient flow. Linear part of equation neglected, i.e. inflow is due to turbulent transmissivity.
-	T_D,T_T,R,D	Y,W	9	189.65	Non-linear component neglected, i.e. inflow is due only to linear transmissivity.
				2.72	Total non-linear Q.

linear and friction-less flow in which the aquifer transmits water horizontally, through its entire saturated thickness, into the mining excavation. Transient flow involving leakage results in even higher inflow quantities. As the cone of depression expands, more surface area of the leaky aquifer recharges the underlying aquifer. Turbulence also affects the inflow quantity. Energy is lost due to turbulence and this explains the very low yield in situations where only the turbulent transmissivity is considered. Generally in non-linear flow, the total inflow approximates the inflow due to turbulent transmissivity alone. The difference between inflow quantities from confined and unconfined aquifer results from the difference in storativity in the two aquifer types.

Since this is an on-going research programme, results of example applications using the two-dimensional flow method and actual field data form the subject of a future paper.

Limitations of equivalent well approach

The equivalent well approach is based on drawdown theory. The reliability of the results obtained using this approach is limited by the numerous assumptions of drawdown theory including the following :

- The aquifer has a seemingly infinite areal extent.
- The aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by mining.
- Prior to pumping, the piezometric surface and/or phreatic surface are horizontal over the area influencedby mining.
- The aquifer is pumped at a constant discharge rate.
- The imaginary well fully penetrates the aquifer and water flows to the well from the entire thickness of the aquifer by horizontal flow.
- Water removed from storage is discharged instantaneously with decline of head.

These assumptions are seldom met in practical mining situations. Results obtained using this approach represent the order of magnitude of inflows.

CONCLUSIONS

Simple flow equations deriving from groundwater theorems have been presented. Their suitability for mine water inflow prediction has been assessed. Example computations have shown that the inflow rate depends on the local geology of the site which governs the configuration of the hydraulic conductivity contrasts. The authors believe that when data from a site of known geology are used in the equations, order of magnitudes of inflow can be reasonably predicted, the accuracy depending on how close the site geology and working conditions approach the numerous assumptions implicit in the formulation of these equations. However, used with care, these simple equations can offer a cheap, yet reliable working basis for a more accurate design of surface mine drainage systems.

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