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APPLICATION OF ANALYTICAL SOLUTIONS TO SIMULATE SOME MINE INFLOW PROBLEMS IN UNDERGROUND COAL MINING

R. N. Singh* and A. S. Atkins**

* Department of Mining Engineering, University of Nottingham, University Park, Nottingham. NG7 2RD.

** Department of Mining Engineering, North Staffordshire Polytechnic, College Road, Stoke-on-Trent, Staffs. ST4 2DE.

ABSTRACT

The paper considers the interaction of ground water flow characteristics, aquifer parameters and mining geometry in order to estimate mine water inflows. The ground water flow conditions include both steady and unsteady state flow in an infinite and finite aquifers to an imaginary pumping out well. Both linear and non-linear flow equations are discussed. The application of non-linear equations has indicated that with the use of appropriate terms in these equations both laminar as well as turbulent inflows can be simulated. Water inflow to underground dewatering tunnels are also discussed in terms of both laminar and turbulent flow. Mine water inflow to a mine discharging to multiple dewatering outlet is also included. The application of various techniques outlined enables a more realistic estimate of water inflow to be made which can be conducive to planning mine dewatering systems with reference to economics and safety.

INTRODUCTION

Mining under complex hydrogeological conditions may be extremely costly, influencing the overall viability of the project, and from past experience an accurate prediction of mine water inflow is necessary during the feasibility study. This paper deals with some of the advanced analytical methods for predicting mine water inflow. These techniques can be applied to a wide range of specific conditions and consequently more realistic inflow situations can be modelled. Thus, a better estimation of the ground water inflow to mining operations may be obtained, allowing for a cost effective design of mine dewatering systems.

INTERACTION OF AQUIFER PARAMETERS, MINING GEOMETRY AND GROUND WATER FLOW

Mine dewatering problems can be simulated either by imaginary pumping out wells and/or imaginary dewatering underground roadways.

(i) Dewatering wells :- Conventional approach is to calculate inflow from an aquifer to an imaginary well at a constant flow rate so as to lower the piezometric surface (or water table in case of unconfined aquifers) below the coal seam at an assumed mine boundary. The pumping out rate of the well is taken as inflow quantities.

(ii) Simulated dewatering roadways :- Recent approach is to simulate mine water inflow based on dewatering underground roadways, instead of the principle of imaginary pumping out wells and offers an alternative method requiring different flow equations.

For both approaches two types of flow conditions are usually considered; steady state flow where for a constant rate of discharge an equilibrium state of drawdown is achieved and unsteady state flow where drawdown is changed with time. The flow characteristics can either be linear or non-linear.

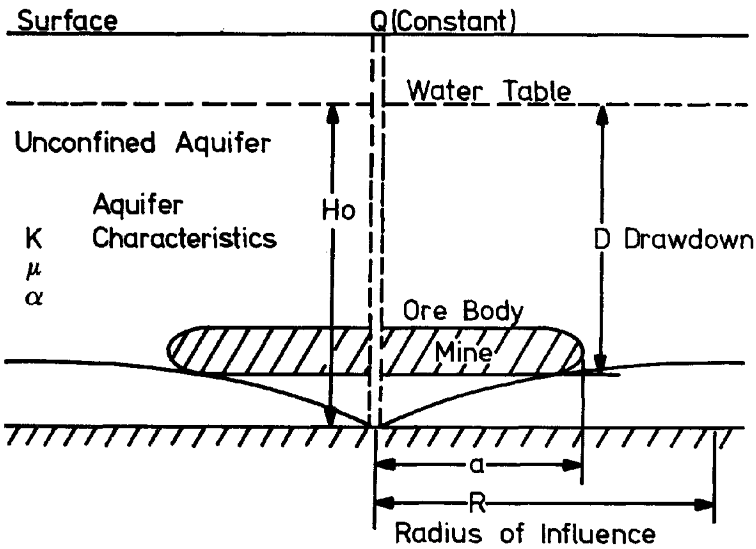
The type of aquifers considered for this analysis are unconfined; confined and leaky aquifers conditions. A simplified approach is to assume that the aquifer has an infinite boundary but in the presence of major geological discontinuities, faults and dykes the aquifer will behave as a finite one. Flow conditions will vary considerably and therefore, the appropriate flow equation should be used.

In mining operations to dewater an aquifer would require several pumping wells in close proximity which will have certain degree of interference. An outline of this technique is included in the present paper. Types of mining excavations which can be modelled are shafts, surface mines, underground mines and a large underground chambers. Mode of mine water inflow is also important and can range from uniform to a sudden inrush situation. The types of analytical solutions considered here are uniform flow models applied to shafts and underground mining operations.

The combination of the various flow conditions, aquifer characteristics and boundary, mining excavations, and the dewatering methods are extensive. Only those existing equations which are applicable to simulate mining operations are discussed.

LINEAR ANALYTICAL INFLOW SIMULATION MODELS

The linear analytical mine water simulation models are based on analogy of a single imaginary pumping out well. The aquifer characteristics (permeability, transmissivity and storage coefficient), the desired radius of mine boundary and the depth of dewatering below original piezometric surface are used as input quantities to estimate the pumping capacity for the mine. Simple analyses of this situation are based on linear flow conditions associated with steady state flow and unsteady state flow in unconfined and confined aquifer. This approach requires the preparation of a simplified hydrogeological section of the mine, determination of aquifer characteristics and assigning mean hydrogeological characteristics to the rock mass, and superimposing simplified mining geometry on the hydrogeological section. This enables an estimation of drawdown and mining radius to be determined for the calculation of mine pumping capacity.



$$D = Ho - [Ho^2 - (Q \ln R/a)/\pi K]^{1/2} \qquad [1a]$$

$$R = [\{K(2\,Ho - D)t/\mu\alpha\} - a^2]^{1/2} / (\ln R/a - 1/2) \qquad [1b]$$

(after Le'czfalvy, 1982)

Figure 1. Mine dewatering in an unconfined aquifer at a constant rate of discharge and steady state condition.

Table 1
Mine Dewatering in an Unconfined Aquifer at a Constant Rate of Discharge and Steady State Flow Condition (see Figure 1)

Problem	Equation	Solution
Mine excavation; radius 3000 m, 140 m below water table, desired drawdown 116 m. Aquifer characteristics $k = 32$ m/day $\mu = 0.01$ $\alpha = 0.3$ Calculate the quantity of water to be pumped out to dewater the mine.	$D = H_o - [H_o^2 - (Q \ln R/a)/\pi K)]^{\frac{1}{2}}$ [1a] $R = \frac{1}{(\ln\frac{R}{a} - \frac{1}{2})} [\{K(2H_o - D)t/\mu\alpha\} - a^2]^{\frac{1}{2}}$ [1b]	Assume R = 9000 m, t = 1825 days, Q = 50,000 m^3/d Substitute in Equation [1a] D = 2 m. Calculate R using above data in Equation [1b] R = 95036 m Re-substitute R = 95036 m in Equation [1b] Reiterate until R converges, i.e. R = 20189 m R = 21038 m R = 21008 m Substitute R = 21008 m in Equation [1a] D = 4 m Substitute D = 4 m in Equation [1b] R = 6595 m Substitute R = 6595 m in Equation [1b] R = 1.4 m Table 2 summarises various drawdowns and radius of influences for the following rates of pumping for 5, 10 and 15 years. Calculated by the above substitution and reiterative method.

Table 2
Required pumping rates for various drawdowns and radius of influence for 5, 10 and 15 year periods

Time (t) d	Quantity m^3/d	Drawdown D(m)	Radius of Influence R m
1825	50,000	1.4	6,595
1825	300,000	32.84	46,556
1825	600,000	74.67	43,018
1825	700,000	100.21	39,890
3650	50,000	5.6	64,546
3650	300,000	37.2	61,221
3650	600,000	91.68	54,133
3650	700,000	108.12	48,658
5475	50,000	5.875	76,440
5475	300,000	39.50	72,328
5475	600,000	99.95	60,847
5475	665,000	140.00	57,692

The general notations used in single well equations are given as follows :

D - Lowering of piezometric surface or water table to a level H from the Original head H_o (m)

D_o - Drawdown in a finite aquifer before mine boundary is reached (m)

i - Hydraulic gradient (dimensionless)

K - Aquifer coefficeint of permeability or hydraulic conductivity (m/d)

K' - Coefficient of permeability of aquifers (m/d)

g - Acceleration due to gravity (9.81 m/sec^2)

L - Thickness of formation being dewatered (m)

L' - Aquitard thickness (m)

Q - Quantity of mine inflow (m^3/d)

Q_o - Quantity of mine inflow in a finite aquifer before cone of depression reaches mine boundary (m^3/d)

R - Effective radius of influence of the cone of depression with time t (m)

R_o - Radius of cone of depression at mine boundary (m)

a - Mine radius where drawdown is required (m)

S - Storage coefficient (dimensionless) = $\mu\,\alpha$

T = KL Transmissivity of aquifer (m^2/d)

t - Time elapsed (d)

t_v - Time at which cone of depression reaches mine boundary

u - ($a^2S/4KLt$) a variable in Transient state equation

$W(u)$ Theis well function, dimensionless (Appendix 1)

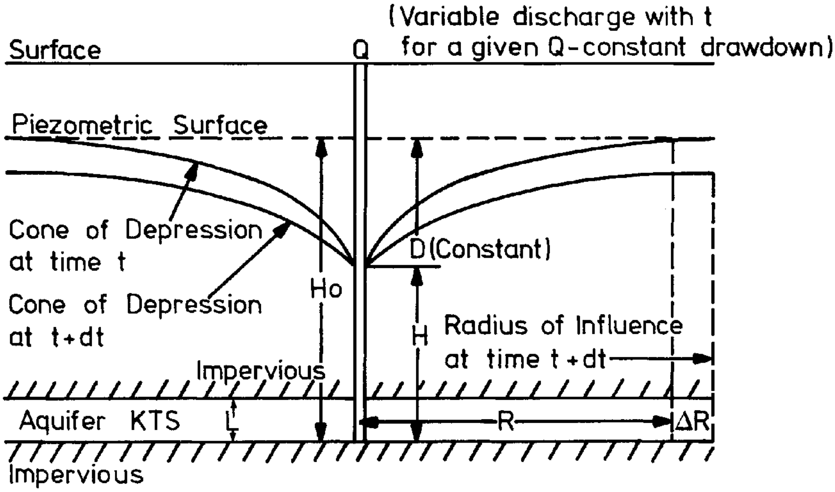
μ - Stressfree porosity of rock (dimensionless)

α - Shape factor (dimensionless)

Flow to a single well in Infinite Aquifer :-

Figure 1 shows the flow conditions for dewatering a mine in an unconfined aquifer. Equation [1a] and [1b] Le'czfalvy (1982) permit calculation of the steady state drawdown and the radius of the cone of depression. It can be seen that equation [1b] contains R in both sides of the equity sign and consequently, should be solved iteratively as given in Table 1. Table 2 summarises the results for assumed pumping times ranging from 5 to 15 years, at rates of pumping between 50,000 to 700,000 m^3/d and show the steady state drawdowns and radius of inflows.

Figure 2 shows the dewatering of a mine situated in a confined, infinite aquifer, with steady state flow conditions (Leczfalry, 1982). Numerical application of equations [2a,2b] shown in Figure 2, is given in Table 3, and are solved iteratively. The results in Table 4 indicate that for a constant drawdown of 160 m, both the required pumping out quantity and radius of influence change with time.



$$Q = 2\pi LKD / \ln R/a \qquad [2a]$$

$$R = [(2LKt/S - a^2/S)/(\ln R/a - 1/2)]^{1/2} \qquad [2b]$$

(after Le'czfalvy, 1982)

Figure 2. Idealised conceptual model of dewatering of a confined artesian infinite aquifer at constant drawdown condition (steady state equation).

Table 3
Mine Dewatering Calculations in a Confined Artesean, Infinite Aquifer at Steady State (Constant drawdown) Conditions (see Figure 2)

Problem	Equation	Solution
Calculate the radius of influence and pumping rates for the following data : Aquifer thickness L = 15 m Permeability K = 6 m/d Radius of pumping well a = 0.1 m Storage coefficient S = 0.000015 Drawdown desired D = 160 m t = 1, 5, 10, 100, 1000 d	$Q = 2\pi LKD/\ln R/a$ [2a] $R = [(2LKt/s-a^2/2)/\ln\frac{R}{a} - \frac{1}{2})]^{\frac{1}{2}}$ [2b]	Assume R = 360 m, Substitute in Equation [2b] Calculated R_1 = 1249 m, Re-substitute in Equation [2b] Calculated R_2 = 1159 m, Re-substitute in Equation [2b] Calculated R_3 = 1164 m, Reiteration converges Substitute R_3 = 1164 in Equation [2a] $Q = 9666\ m^3/d$ Table 4 summarises the rate of pumping for a constant drawdown of 160 m for the various pumping times.

Table 4

Time t(d)	Radius of Influence m	Quantities m^3/d
1	1,163	9,657
5	2,492	8,940
10	3,472	8,654
100	10,420	7,834
1000	30,800	7,169

Figure 3 and Tables 5 and 6 show similar mine dewatering calculations for an infinite, confined artesian aquifer in unsteady state flow condition.

Flow to single well in finite aquifer :-

Figure 4 shows the dewatering of a mine in a finite aquifer for a steady state flow condition for a given rate of pumping 'Q', a constant drawdown is achieved but the radius of influence changes with time. The time (T_v) taken for the radius of influence R to reach the mine's finite boundary, is given by equation [3c] (Le'czfalvy, 1982). Flow equations for 't' between 0 to t_v are given by equations [2a,2b] and indicated in Table 7. For times greater than t_v flow quantity is reduced to main a constant drawdown, as given by equation [3a] and indicated in Table 8.

Figure 5 illustrates the dewatering of mine in a finite aquifer for unsteady state flow condition at a constant pumping rate. It can be seen that the drawdown changes with time until the mine boundary is reached at time (t_v) given by equation [3c]. The drawdown due to further pumping (> t_v) is given by equation [4]. These calculations are shown in Tables 9 to 11.

OPERATIONS OF MUTUALLY INTERFERING WELLS (CONSTANT DISCHARGE)

In a dewatering situation which requires the pumping of large quantities of water it may be necessary to use several pumping wells because of the limitation in capacity of individual pumps and in this situation the following equations would be applicable (Le'czfalvy 1982) as shown in Figure 6 and a numerical example is indicated in Table 12.

$$D_1 = (Q_1/2\pi LK) \ln R_1/a_{10} + (Q_2/2\pi LK) \ln R_2/a_{10} \quad (5.a)$$

$$D_2 = (Q_1/2\pi LK) \ln R_1/b + (Q_2/2\pi LK) \ln R_2/a_{20} \quad (5.b)$$

D_1 = drawdown of well I

Q = discharge from well I

r_{10} = radius of well I

b = distance between the two wells

Q_2 = discharge from well II

If $Q_1 = Q_2 = Q \quad R_1 = R_2 = R$

R_1 = radius of influence by well I

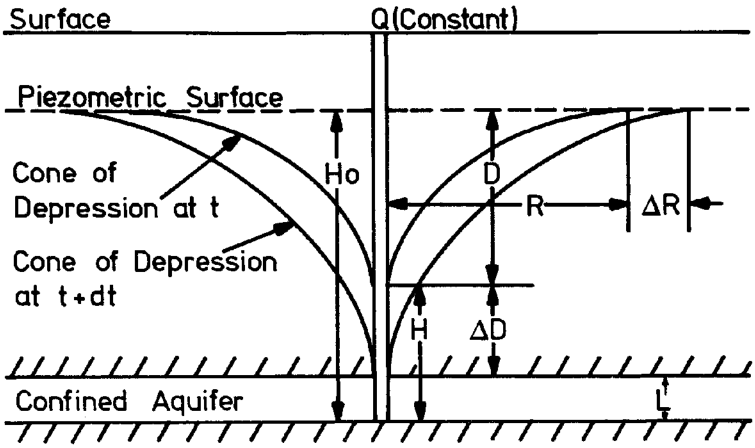
R_2 = radius of influence of well II

K = permeability coefficient of the aquifer

$$D_1 = (Q/2\pi LK) \ln(R^2/a_{10}b) \quad (5.c)$$

$$R = [\{(2LKt/s) - a^2/2\}/(\ln R/a - \tfrac{1}{2})]^{\frac{1}{2}} \quad [2.b]$$

$$D_2 = (Q/2\pi LK) (\ln R^2/a_{20}b) \quad (5.d)$$



$$D = Q \ln R/a \,/\, 2\pi LK \qquad [2a]$$

$$R = [(2LKt/S - a^2/2)/(\ln R/a - 1/2)]^{1/2} \qquad [2b]$$

(after Le'czfalvy, 1982)

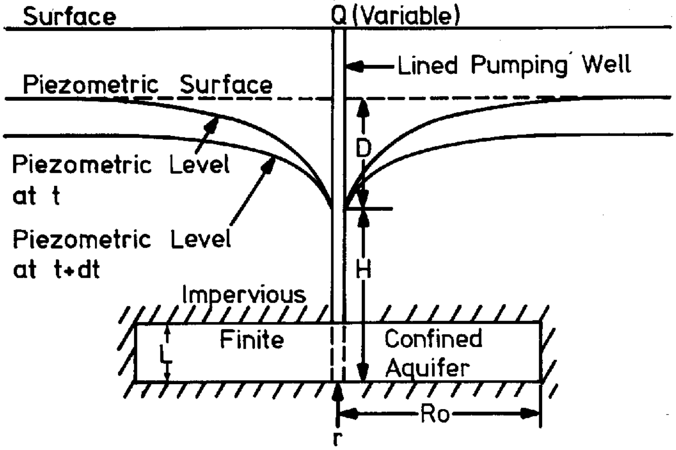
Figure 3. Mine dewatering in an infinite artesian confined aquifer with unsteady state flow.

Table 5
Mine Dewatering Calculations in a Confined Artesian Infinite Aquifer with a Constant Discharge and Unsteady Flow Condition [see Figure 3]

Problem	Equation	Solution
Calculate the variable drawdown in a well dewatering an artesian aquifer under constant discharge conditions Data as follows :- Aquifer thickness L = 15 m Permeability K = 6 m/d Radius of pumping well a = 0.1 m Storage coefficient S = 0.000015 t = 1, 5, 10, 100 & 1000 d Q = 10,000 m^3/d	$D = Q \ln R/a/2\pi LK$ [2a] $R = [(2LKt/s-a^2/2)\ (\ln\frac{R}{a} - \frac{1}{2})]^{\frac{1}{2}}$ [2b]	Assume R = 360 m, Substitute in Equation [2b] Calculated R = 1249 m, Resubstitute in Equation [2b] Calculated R = 1159 m, Resubstitute in Equation [2b] Calculated R = 1164 m, Reiteration converges Substitute R = 1164 m into Equation [2a] D = 166 m Table 6 summarises the corresponding radius of influences and drawdowns for various pumping periods.

Table 6

Time t(d)	Radius of Influence R(m)	Calculated Drawdown D(m)
1	1,164	166
5	2,479	179
10	3,472	185
100	10,420	204
1000	30,800	223

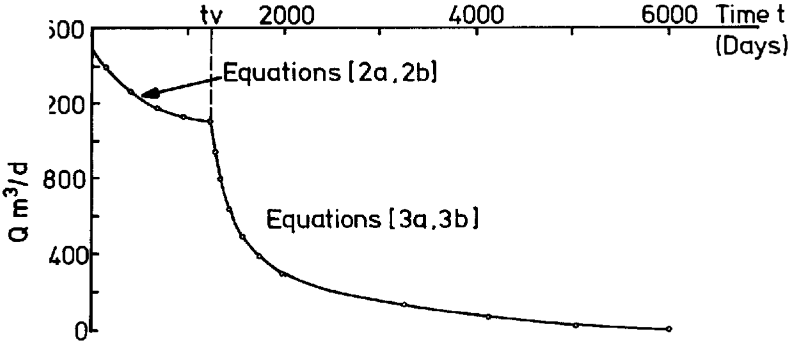


(a) Test conditions (Q-variable, D-constant)

Where $Q=[2\pi LKD\exp^{(-At/S)}]/\ln Ro/a$ [3a]

$A=2\pi LK/Ro^2 \ln Ro/a$ [3b]

$tv=Ro^2(\ln Ro/a-1/2)(S/2LK)+Sa^2/4LK$ [3c]



(b) Variable discharge time curve for a constant drawdown.

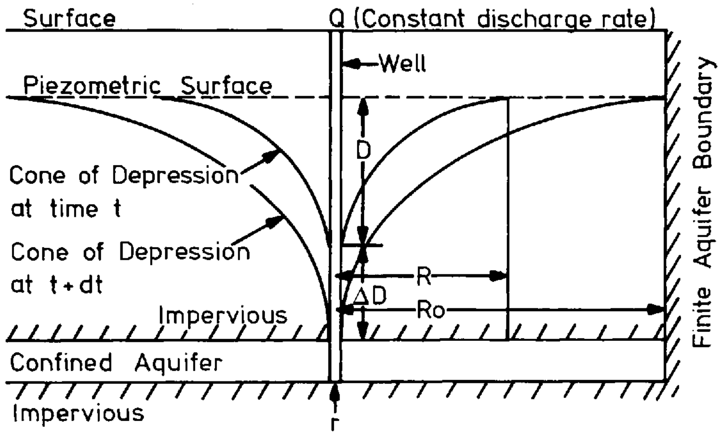
Figure 4. Dewatering a finite aquifer at a constant drawdown condition. (Steady state) (After Le'czfalvy, 1982)

Table 7
Mine Dewatering Calculations for a Finite Aquifer at a Constant Drawdown (Steady State) Condition
[see Figure 4]

Problem	Equation	Solution
Calculate the variable rate of discharge from a well at regular time intervals. Data as follows :- Aquifer thickness $L = 50$ m Permeability $K = 9$ m/d Original piezometric surface above the aquifer base $= 150$ m Radius of pumping well $a = 0.15$ m Aquifer boundary $R_o = 25000$ m Storage coefficient $S = 0.000015$ Constant drawdown $D_o = 5$ m	$Q = [2\pi LKD \exp(-At/s)]/\ln\frac{R_o}{a}$ [3a] where $A = 2LK/R_o^2 \ln R_o/a$ [3b] $t_v = R_o^2(\ln R_o/a - \frac{1}{2})(S/2LK) + Sa^2/4LK$ [3c] t_v is the time in which the cone of depression reaches mine boundary. At time > t_v quantity of inflow given by Equation [3a, 3b]. At time < t_v quantity of inflow given by Equation [2a,2b].	Using Equation [3c] $t_v = 1200$ days Assume time $t = 10$ d $\therefore < t_v$ use Equation [2b] Assume $R = 2500$ m. Calculated iteratively $R = 2548$ m. Corresponding Q from Equation [2a] $Q = 1451$ m^3/d. Similar calculation repeated for t ranging from 10 to 1200 days as outlined in Table 8. For $t > t_v$ (i.e. 1200 days) use Equation [3b] $A = 1.198 \times 10^{-7}$. Substitute $A = 1.198 \times 10^{-7}$ in Equation [3a] calculated $Q = 416.6$ m^3/d. Similar calculation repeated for t ranging from 1200 to 9000 days as outlined in Table 8.

Table 8
Mine dewatering calculations for a well discharge for constant drawdown condition (variable discharge)

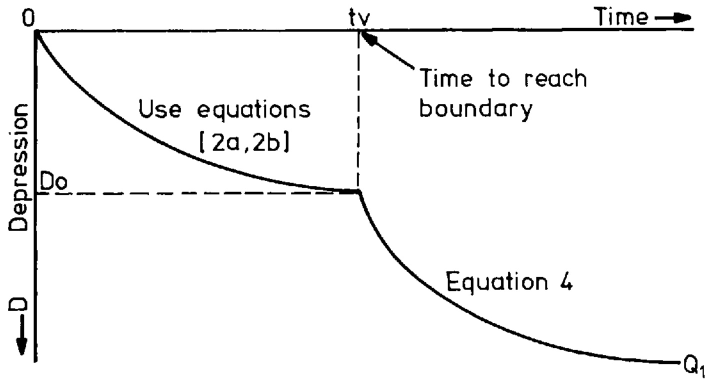
	Time Elapsed after pumping started t (days)	Radius of Influence 'm'	Discharge m^3/d
Eq. 2a,2b	10	2548	1451.0
	50	5476	1345.0
	100	7619	1304.0
	250	11800	1254.0
	500	16435	1218.3
	750	19958	1198.2
	1000	22905	1184.4
	1200	25000	1175.8
Eq. 3a,3b	1300	25000	416.6
	1400	25000	384.6
	1500	25000	354.9
	1600	25000	327.4
	1700	25000	302.7
	1800	25000	278.5
	2000	25000	238.2
	2500	25000	159.8
	3000	25000	107.2
	4000	25000	48.25
	5000	25000	32.50
	5500	25000	21.64
	6000	25000	9.73
	7000	25000	4.38
	8000	25000	1.96
	9000	25000	0.88



(a) Dewatering of a finite aquifer at a constant discharge

$$tv = Ro^2(\ln Ro/a - 1/2)(S/2LK) + Sa^2/4LK \quad [3c]$$

$$D = Do + (Qot/SRo^2) \quad [4]$$



(b) Time-depression curve at a constant discharge

Figure 5. Idealised conceptual model of dewatering a finite aquifer at a constant discharge rate. (Unsteady state flow) (After Le'czfalvy,1982)

Table 9
Mine Dewatering Calculations in a Finite Artesian Aquifer under Constant Inflow Rate and Unsteady Flow Condition (see Figure 5)

Problem	Equation	Solution
Calculate the variable drawdown/time curve from a well at regular time intervals. Data as follows :- Aquifer thickness L = 50 m Permeability K = 9 m/d Original piezometric surface above the aquifer base = 150 m Radius of pumping well a = 0.15 m Aquifer boundary R_o = 25000 m Storage coefficient S = 0.000015 Quantity Q = 1300 m^3/d	$t_v = R_o^2(\ln R_o/a - \frac{1}{2})(S/2LK)+Sa^2/4LK$ [3c] Equation [2a-2b] $D = D_o + \frac{Q_o t}{SR_o^2}$ [4] t_v is the time in which the cone of depression reaches mine boundary. At time > t_v quantity of inflow given by Equation [4]. At time < t_v quantity of inflow given by Equation [2a,2b].	Using Equation [3c] t_v = 1200 days. Assume time t = 10 days (∴ < t_v use Equation [2b]). Assume R = 2000 m. Calculated iteratively R = 2549 m. Corresponding D from Equation [2a] D = 4.47 m. Similar calculations repeated for t ranging from 10 to 1200 days as outlined in Table 10.

Table 10

t(days)	R(m)	D(m)
10	2540	4.47
50	2476	4.83
100	7630	4.97
500	16437	5.33
1000	22905	5.48
1200	25000	5.53

For t > t_v (i.e. 1200 days) use equation (4) taking D_o = 5.53 (from Table 10) Calculated D = 11.26 m. Similar calculation repeated for t ranging from 1200 to 20,000 days as outlined in Table 11

Table 11

t(days)	D(m)
1,300	11.26
1,500	12.15
1,750	13.25
2,000	14.36
2,500	16.56
3,000	18.77
4,000	23.18
5,000	27.60
6,000	32.01
7,000	36.42
8,000	40.84
9,000	45.25
10,000	49.66
15,000	71.74
20,000	93.80

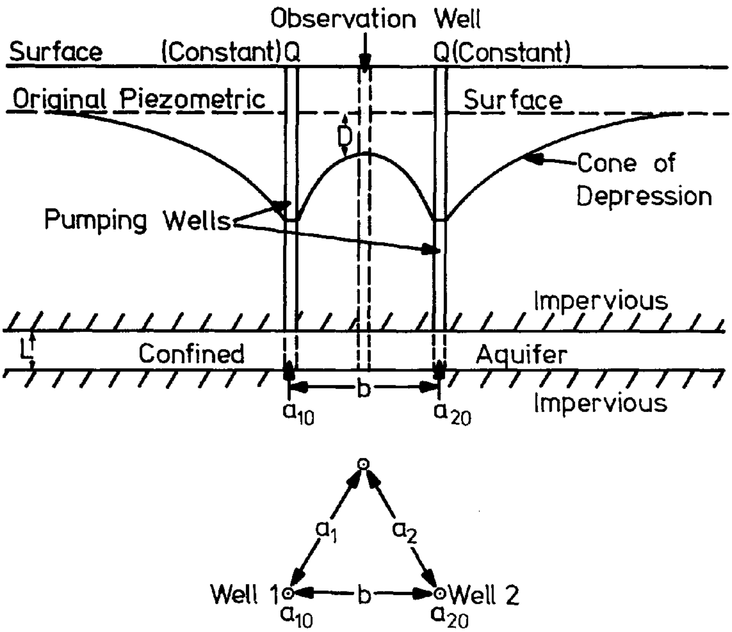


Figure 6. Dewatering of an infinite confined aquifer by mutually interfering wells.

Table 12
Mine dewatering using multiple interferring boreholes constant rate of pumping
(Steady state flow (see Figure 6)).

Problem	Equations	Solution
<u>Example</u>		
The pumping data for two interferring wells	$D_1 = \frac{Q_1}{2\pi LK} \ln R_1/a_{10} + (Q_2/2\pi LK) \ln R_2/a_{10}$ [5a]	D_1 is calculated using equation [5a] $D_1 = 1.85 + 2.77$ $= 3.62$ m
$Q_1 = 600$ m^3/d $Q_2 = 900$ m^3/d $L = 50$ m	$D_2 = (Q_1/2\pi LK) \ln R_1/b + (Q_2/2\pi LK) \ln R_2/a_{20}$ [5b]	D_2 is calculated by equation [5b] $= 3.48$ m
$R_1 = 2695$ $R_2 = 2720$ $b = 50$ m $r_{10} = 0.17$ m $r_{20} = 0.20$ m $K = 10$ m/d $L = 50$ m $S = 0.00015$		
Calculate the drawdowns for pumping period of 10 days		

NON-LINEAR INFLOW MODELS SIMULATING FLOW TO A WELL

The development of non-linear theory of mine water inflow can be attributed to Schmieder (1978a, 1978b, 1979) and Perez-Franco (1982). The analytical solution based on unsteady flow condition given by the following equation

$$D = \frac{aQ}{2\pi\ LgK}\ W(U) + \frac{C}{gK^{\frac{1}{2}}}\ \frac{Q^2}{4\pi^2 L^2}\ \frac{R-a}{Ra} \qquad [6.a]$$

$$D = \frac{Q\ W(u)}{4\pi\ T_D} + \frac{Q^2}{4\pi^2 T_T^2}\ (\frac{R-a}{Ra}) \qquad [6.b]$$

where $u = \frac{a^2S}{4KLt}$ [6.c]

W(u) = Theis Well function

T_R & T_D = Turbulent and linear transmissivity coefficient respectively(m^2/d)

$$T_T = \frac{1}{2\pi}\ (T_D)^{3/4} \qquad \text{(Schmieder 1978a)} \qquad [6.d]$$

$$R = [(2KLt/S-a^2/2)/(\ln R/a - \tfrac{1}{2})]^{\frac{1}{2}} \qquad [2.b]$$

The first term of equation [6.b] is Theis equation for unsteady linear flow and the second term is drawdown for pure turbulent flow. Equation [6.b] can therefore be used to predict laminar flow by neglecting the second term, whereas for turbulent conditions, the first term can be ignored.

Similarly steady state flow equation is given by equation [7] and [2.b] and illustrated in Figure 2.

$$D = \frac{Q}{2T_D}\ \ln\frac{R}{a} + \frac{Q^2}{4\pi^2\ T_T^2}\ (\frac{R-a}{Ra}) \qquad [7]$$

It is apparent from the calculation in Table 13 that the application of linear flow equations to practical situation where mixed flow or turbulent flow conditions exist results in a substantial over estimation of inflow quantity.

WATER INFLOW TO AN UNDERGROUND TUNNEL

Non-linear inflow to an underground tunnel below a Karst aquifer

A non-linear flow to an underground tunnel working below a Karst aquifer as illustrated in Figure 7 and is given by the folllowing equation after (Schmieder, 1978a) :-

$$D = [(Q/2\pi(K'L'))\ \ln R/X_o + (Q/2\pi(KL)\ \ln R^2/2da + Q^2/a(KL)^{3/2}] \qquad [8]$$

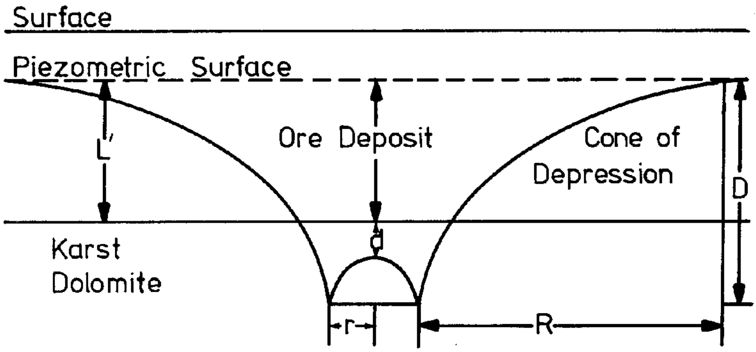
L' = thickness of aquifer

K' = permeability of aquifer m/s

a radius of underground gallery m

Table 13
Non-linear mine inflow calculations to an imaginary well for unsteady flow conditions (see Figure 3)

Problem	Equation	Solution
Calculate the quantity of inflow to a mine shaft from the information given	$u = \frac{a^2 S}{4KLt}$ [6.c]	Calculate $u = 3.78 \times 10^{-8}$. Theis well function = 14.2133
(i) Non linear flow conditions	Equation [2b]	W(u) obtained from Appendix 1 using $u = 3.78 \times 10^{-8}$. R calculated from equation [2b] using t = 5 days and assuming R = 2500 m until iteration converges. R = 1928.6 m.
(ii) Turbulent flow (iii) Linear transient flow conditions.	$D = \frac{QW(u)}{4\pi T_D} + \frac{Q^2}{4\pi^2 T_T^2} \left(\frac{R-a}{Ra}\right)$ [6.b]	Substitute R = 1928.6 m into Equation [6b] $0.095\ Q^2 + 0.595\ Q - 300 = 0$
Aquifer thickness L = 10 m		Solving quadratic equation
Drawdown requirement D = 300 m		(i) $Q = 53.6\ m^3/d$ non linear flow
Shaft radius a = 4 m		Assume linear term to zero
Storage coefficient $S = 9 \times 10^{-7}$		(ii) $Q = 56.2\ m^3/d$ Turbulent flow
Time t = 5 days		Assume turbulent component to zero
$T_D = 1.9\ m^2/d$ $T_T = 0.2575\ m^2/d$		(iii) $Q = 504.2\ m^3/d$ linear transient flow



$$D = [(Q/2\pi K'L')\ \ln R/Xo + (Q/2\pi Kl)\ \ln R^2/2dn + Q^2/a(Kl)^{3/2}]$$

Figure 7. Mine dewatering by an underground gallery below an unconfined aquifer.

Table 14

Dewatering a mine using draining galleries below a Karst aquifer (see Figure 7)

Problem	Equation	Solution
Calculate mine inflow quantity Data given as follows $K'L' = 6.5 \times 10^{-3}\ m^2/sec$ $\ell = 2500\ m$ $K = 1.2 \times 10^{-5}\ m/sec$ $d = 9\ m$ $D = 200\ m$ $R = 10500\ m$ $a = 1.8\ m$ $X_o = 1000\ m$	$D = (Q\ \ell n\ R/X_o)/(2\pi K'L') +$ $(Q\ \ell m\ R^2/2da)/2\pi K\ell +$ $Q^2/(K\ell)^{3/2}\ a$ [8] D = Fracture flow + linear flow + pure turbulent flow	Substituting in equation [6] $106.9\ Q^2 + 79.8\ Q + 57.6\ Q - 200 = 0$ Solving quadratic equation $Q = 0.869\ m^3/s$ - non-linear flow Importance of non-linear flow in mine inflow estimation can be demonstrated as follows :- Pure linear flow $= 2.50\ m^3/sec$ Pure fracture flow $= 3.46\ m^3/sec$ Pure turbulent flow $= 1.36\ m^3/sec$ Non-linear flow $= 1.45\ m^3/sec$ An error of 70% is apparent.

X_o = half distance of fault zones

K'L' = transmissivity of the aquifer m^2s^{-1}

d = depth below the ore deposit in the aquifer m

R = effective radius of the zone of influence m

ℓ = length of draining gallery m

A numerical example of dewatering a mine gallery below a karst aquifer is indicated in Table 14.

NON-LINEAR FLOW TOWARDS AN UNDERGROUND GALLERY FULLY PENETRATING A CONFINED AQUIFER

The equation of non-linear inflow of water to an underground gallery fully penetrating a confined aquifer as illustrated by Figure 8 under unsteady condition is given by the following equation (Perez-Franco 1982)

$$D = [q/LK_d + q^2/L^2K_t^2]\ R \qquad [9a]$$

or

$$q = [-1/LK_d + (1/L^2\ K_d^2 + 4RD/L^2K_t^2)]^{\frac{1}{2}}\ .\ \frac{L^2K_t^2}{2} \qquad [9b]$$

$$Q = 2\ 1q$$

where

q = discharge per unit length at one side of the gallery (m^3/d/l)

Q = quantity of inflow for the whole length of tunnel (m^3/d)

h = piezometric height at a distance x (m)

r = distance measured from the face of the gallery (m)

R = distance from the face of trench to the place where drawdown is zero (m)

K_d = linear hydraulic conductivity (m/d)

D = drawdown at the gallery at r (m)

K_t = turbulent hydraulic conductivity (m/d)

In this case R is given by equation [2b]

$$R = [(2LK_D\ t/s - a^2/2)/(\ln R/a - \tfrac{1}{2})] \qquad [2b]$$

A numerical example of this flow condition is presented in Table 15.

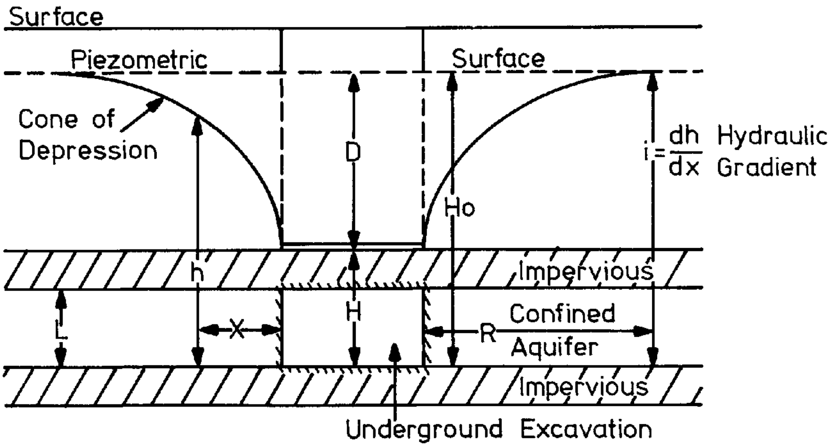
LIMITATIONS OF ANALYTICAL TECHNIQUES IN MINE WATER INFLOW SIMULATION

The analytical approach in simulating mine water inflow has a severe limitation in oversimplifying mining geometry, strata section, mine and hydrogeological boundaries, assumptions made in the derivation of the analytical equations used may not conform with the actual field conditions and hence the calculated inflow quantities may be distorted. Regional variations in the aquifer characteristics (K, S, T) cannot be easily incorporated in the analytical techniques. The most important variables are as follows

(i) Lateral variation within the same lithological unit.

(ii) Macroscopic changes in the aquifer characteristics with depth depending upon changes in lithology.

(iii) The effects of discontinuities, fractures and faults in the same lithological unit.



$$D = [q/LK_d + q^2/L^2 K_t^2]R \qquad [9a]$$

$$q = [-1/LK_d + (1/L^2 K_d^2 + 4RD/L^2 K_t^2)]^{1/2} L^2 K_t^2/2 \qquad [9b]$$

$$Q = 2lq$$

D = Draw down

H = Piezometric surface after dewatering

Figure 8. Non-linear flow to an underground excavation fully penetrating a confined aquifer.

Table 15
Mine dewatering using underground galleries fully penetrating a confined aquifer
(see Figure 8)

Problem	Equation	Solution
The following data applies to an inflow to underground gallery fully penetrating a confined aquifer :- Drawdown required D = 300 m Aquifer thickness L = 12 m K_d = 0.5 m/d K_T = 0.0946 m/d Storage coefficient S = 0.00015 ℓ = 2500 m a = 1.5 m t = 10 d Calculate the mine inflow quantity	Equation [2b] $D = [q/LK_d + q^2/L^2 \, {}_t^2] R$ [9a] $q = [-1/L K_d + (1/L^2 K_d^2 + 4RD/L^2 K_t^2)]^{\frac{1}{2}}$ $[L^2 K_t^2/2]$ [9b] Equation [9b] is the solution of equation [9a] for q.	Assume R = 200 m after a pumping interval of 10 days (given). Calculated from equation [2b] R = 427 m. Solving iteratively until R converges R = 397 m. Substitute R = 397 m into equation [9a] $307.96 q^2 + 66.14 q - 300 = 0$ Solving quadratic equations q = 0.89 m^3/d (non linear flow) Neglecting q^2 term of equation q = 4.5 m^3/d (linear flow) Neglecting linear term (i.e. 66.14 q) q = 0.98 m^3/s (turbulent flow). Total turbulent quantity Q_T = 2 x 2500 x 0.98 = <u>4900 m^3/d</u> Total linear flow Q_L = <u>22500 m^3/d</u>

(iv) Induced mining fractures and zones of consolidations particularly in the vicinity of longwall faces.

(v) These techniques can only be applied to uniform inflow conditions and are not applicable to inrush situations.

CONCLUSIONS

The paper describes various analytical solutions to simulate some practical mine inflow predictions problems associated with underground coal mining operations. Both, linear and non-linear flow conditions to an imaginary well and dewatering roadways are given in the form of numerical examples. Non-linear flow equations have been used to incorporate intergranular laminar, fracture and turbulent flow conditions. This approach enables a more realistic estimation of the quantity mine inflow to be calculated with its obvious economic and safety implication to the design of mine water control systems. Non-linear flow equations simulate the most prominent flow conditions by neglecting the insignificant modes of inflows.

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REFERENCES

1. Kruseman, G. P. and Ridder, N. A. De., (1979), 'Analysis and evaluation of pumping test data", International Institute for Land Reclamation and Improvement/ILRI, P.O. Box 45, BXO AA Wageningen, The Netherlands, p.200.

2. Le'czfalvy, S. (1982), 'Simplified mathematical models for the calculation of dewatering', 1st International Mine Water Congress of the International Mine Water Association, Budapest, April, Vol.C, p.28-46.

3. Perez-Franco, D. (1982), 'Non-linear flow of ground water during mine dewatering operations', 1st International Conference of the International Mine Water Association, Budapest, April, Vol.2, p.195-198.

4. Schmieder, A. (1978a), 'Forecasting the rates of water inflowing into mines', SIAMOS, 1978, Water in Mining and Underground Works, Granada, Spain, September, Vol.2, p.510-533.

5. Schmieder, A. (1978b), 'Water control strategy of mines under strong karstic water hazard', SIAMOS, Water in Mining and Underground Works, Granada, Spain, September, Vol.1, p.535-552.

6. Schmieder, A. (1979), The effect and utilization of protective layers in mine water control,' Selected Papers on Mine Water Control, Proceedings, Mining Development Institute, Budapest, Hungary, May, pp.175-187.

APPENDIX 1

Theis Well Function W(u) after Theis (1935) [adapted from Kruseman and Ridder 1979][1]

N \ μ or μ_{xy}	$N \times 10^{-14}$	$N \times 10^{-12}$	$N \times 10^{-10}$	$N \times 10^{-8}$	$N \times 10^{-6}$	$N \times 10^{-4}$	$N \times 10^{-2}$	N
1.0	31.6590	27.0538	22.4486	17.8435	13.2383	8.6332	4.0379	0.2194
2.0	30.9658	26.3607	21.7555	17.1503	12.5451	7.9402	3.3547	0.04890
3.0	30.5604	25.9552	21.3500	16.7449	12.1397	7.5348	2.9591	0.01305
4.0	30.2727	25.6675	21.0623	16.4572	11.8520	7.2472	2.6813	0.003779
5.0	30.0495	25.4444	20.8392	16.2340	11.6280	7.0242	2.4679	0.001148
6.0	29.8672	25.2620	20.6569	16.0517	11.4465	6.8420	2.2953	0.0003601
7.0	29.7131	25.1079	20.5027	15.8976	11.2924	6.6879	2.1508	0.0001155
8.0	29.5795	24.9744	20.3692	15.7640	11.1589	6.5545	2.0269	0.0000376
9.0	29.4618	24.8566	20.2514	15.6462	11.0411	6.4368	1.9187	0.0000124