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MATHEMATICAL MODELLING FOR ESTIMATION OF MINEWATER INFLOW TO A SURFACE MINING OPERATION

by

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ABSTRACT

Estimation of water inflow to a surface mining operation is a necessary requirement for mine drainage design. The water in a shallow surface mine may originate solely from a surface source and from the atmosphere in the form of precipitation. Water in deep mining excavations below the groundwater table may originate from a surface source or as atmospheric precipitation as well as from the groundwater system. Inflow of surface water to a mining excavation can be predicted by hydrological balance investigations of a mining catchment. The paper briefly describes the hydrological cycle of a mining catchment together with the technique of estimating inflow from a surface source.

The groundwater inflow to a mining excavation is mainly a consequence of the interaction of groundwater system, hydrogeological characteristics of the rock mass and the mining geometry. The water inflow regime is determined by the incision of one or more aquifers by the mining excavation and the relative hydrogeological characteristics of the various aquifers. The paper identifies various possible flow regimes in the vicinity of mining excavation. The groundwater inflow can be estimated by one of the following techniques:

- Equivalent flow approach
- Two-dimensional flow equations
- Numerical techniques incorporating the Finite Element Method, Finite Difference Method or the Boundary Element Method.

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The groundwater inflow equations use both linear flow as well as non-linear flow conditions. The effect of turbulence results in the reduction of inflow quantities because of the energy loss in the turbulent flow. The paper outlines the two-dimensional flow technique of estimating groundwater to surface mining excavations using both steady state and transient state equations for unconfined and confined aquifers. This approach provides a simple method of predicting first order estimates of groundwater inflow to mining excavations and provides a factor of safety by slightly over-estimating the inflow.

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INTRODUCTION

The prediction of water inflows into a surface mine excavation is one of the many components involved in mine design phase. Operations below the water table can pose several operational, economic and safety implications. Information from predicted inflows can be used for the following purposes, (Singh, Atkins and Ngah, 1985):

(i) Design of a pumping system
(ii) Design of storage facilities
(iii) Control of water pollution.

Water inflows into surface mines can be conveniently divided into two sources:

(a) Surface water (run-off)
(b) Groundwater.

Surface water occurs as a direct result of precipitation and catchment transmission, commonly anticipated by cut-off ditches running around the perimeter of the mine. Groundwater may enter the mine excavation from a variety of sources (Ngah, Reed and Singh, 1984):

(i) Mineral beds and underground aquifers
(ii) Geological and structural features
(iii) Abandoned deep mine workings.

The hydrological cycle of a quarry environment is detailed in Figure 1.

This paper discusses the prediction of both surface and groundwater inflows, detailing a number of mathematical models.

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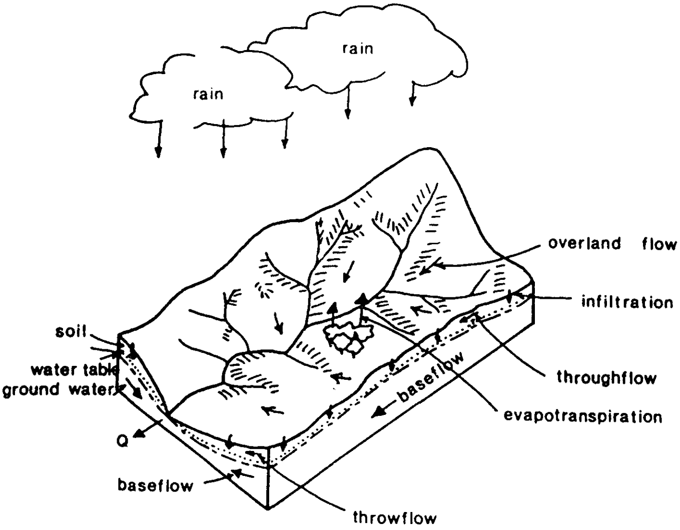

Figure 1. Catchment Hydrological Cycle.

ESTIMATION OF SURFACE WATER INFLOWS TO A MINING EXCAVATION

Two approaches to estimate flood discharge are used in the UK, analytical and empirical:

Analytical Methods

(a) Rational Method
(b) Time-Area Method
(c) Tangent Method
(d) Young and Prudhoe Method

Empirical Methods

(a) Guidelines of the NERC Flood Studies Report
(b) Poot's Three Variable Equation
(c) British Coal Method

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All methods involve the calculation of the maximum possible storm for a given return period based on meterological data and knowledge of catchment characteristics (size, slopes, retention capacity, etc).

Analytical Methods

(a) Rational Method

The method is based on the concept of the time of concentration, T_c. This is defined as the time required for a particle of water to flow from the farthest point of the catchment to the gauging station. The peak discharge occurs as time T_c from the onset of the storm.

The Rational formula can be presented as (Ngah, 1985):

$$Q = 0.2777\ C\ I\ A \qquad \ldots (1)$$

where Q = peak flow, $m^3 s^{-1}$
C = Coefficient of run-off, %
I = Intensity of rainfall, mm/hr during T_c
A = Area of Catchment, km^2.

Problems arise in that C is assumed constant over the area of the catchment. Variations in C occur owing to the following:

(i) At the onset of rainfall, virtually all rain is lost as infiltration
(ii) Run-off coefficient changes with rainfall intensity
(iii) Flow requires a build-up of standing water.

C can vary from 0.05 for flat sandy areas to 0.95 for urban surfaces.

Computation of Parameters

(i) Time of concentration, T_c

T_c is obtained from the Bransby-Williams formula:

$$T_c = \frac{L}{D} \left\{ \frac{A^2}{F} \right\}^{0.2} \qquad \ldots (2)$$

where L = Catchment length, km

D = Diameter of the circle whose area equals the area of the catchment, km

A = Area of catchment, km^2

F = Fall = channel slope, %.

(ii) Intensity of Rainfall, (Bilham's Formula), (I)

$$I = \left[\left\{ \frac{1.25\ T_c}{\frac{10}{N}} \right\}^{0.282} - 0.1 \right] \times \frac{25.4}{T_c} \qquad \ldots (3)$$

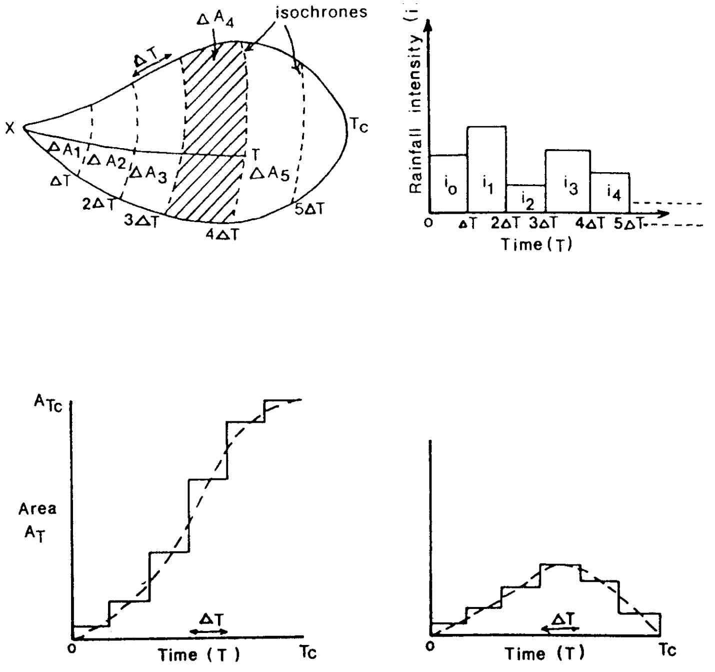
where N is a specified return period in years.

(iii) Coefficient of Run-off, (C)

Determination of C is a largely subjective estimation reliant on the experience of the engineer.

(b) The Time-Area Method

The time-area method is an extension of the rational method which defines time contours (isochrones). The method is illustrated in Figure 2.



(b) Time-area curve

(c) Time-area-concentration curve

Figure 2. The Time-Area Method.
(After Shaw, 1983)

The flow from each contributing area bounded by two isochrones, (T-ΔT, T) is equal to the product of the mean intensity of the effective rainfall (i), from T-ΔT to T and the area A.

ie $$Q_T = \sum_{k=i}^{T} i_{(T-k)} \Delta A_{(k)} \qquad \ldots (4)$$

Peak flow is given when the entire catchment contributes after a period T_c, ie

$$Q_{peak} = \sum_{k=i}^{n} i_{(n-k)} \quad \Delta A_{(k)} \qquad \ldots (5)$$

where $n = \dfrac{T_c}{\Delta T}$

The parameter n thus is equivalent to the number of incremental areas between successive isochrones. Difficulties arise in the assumption of uniform rainfall intensity over the entire catchment and during the entire period, T_c.

(c) The Tangent Method

A graphical method enabling the recognition of part of a catchment which is giving greatest discharge, (Reid, 1927; Norris, 1946). The rational method assumes that Q is equal to the mean intensity of rainfall during T_c, therefore a higher value of Q can be obtained for a part of the catchment than for the whole. This graphical method is available to correct for this effect, whilst not eliminating the original problem. This modification will not be discussed further.

(d) The Young and Prudhoe Method

Again a modification of the Rational Method, which uses Bilham's formula to calculate I. The relevant formula is as follows:

$$Q = \frac{F_A \,.\, \text{AREA} \,.\, R_B}{3.6\ T} \qquad \ldots (6)$$

where F_A = annual rainfall factor = $0.00127R_A - 0.321$
R_A = average annual rainfall, mm
R_B = expected rainfall, mm.

R_B is calculated from Bilham's formula for the duration T_c for a selected return period of N years. T_c is computed as follows:

$$T_c = 2.48 \cdot (LY)^{0.39} \qquad \ldots (7)$$

where L = catchment length, km
$Y = \frac{L}{Z}$ where Z = rise from the outfall to the average upstream divide.

Figure 3 indicates a method of determining T_c from the product of L and Y. The formula is widely applicable, but if a catchment contains a significant area of permeable strata such as sand, gravel or chalk, AREA is replaced by A_L where A_L is the area of the catchment, (km^2), covered by impermeable deposits.

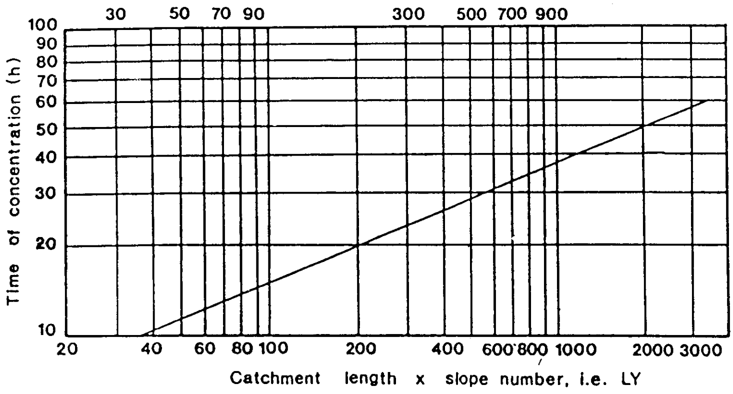


Figure 3. Determination of Time of Concentration, T, from the Product of Catchment Length, L, and Slope Number, Y. (after Young and Prudhoe, 1973)

Unit Hydrograph Theory

The cases so far discussed are particular examples of the application of the Unit Hydrograph Theory. The use of the theory involves the following:

(i) Assessment of total precipitation over a catchment area in a suitably short time interval, T.

(ii) Separation of this total from effective precipitation, ie the determination of loss.

(iii) Obtaining the time distribution of the volume of effective precipitation according to the unit hydrograph or its equivalent, the distribution graph.

(iv) The superposition of all hydrographs so obtained and of base flow, suitably displaced in time.

Evaporation

Other methods exist which consider evaporation and evapotranspiration effects, Penman's Evaporation Formula and Thornwaites evapotranspiration formulae being examples, these will not be considered in this paper but are well detailed in hydrogeological texts, (Ngah, 1985).

EMPIRICAL APPROACHES

Empirical methods are based on satisfactory statistical records. Results from one catchment can be extrapolated in space and time to another. The most important technique is that outlined by the Guidelines of the National Environment and Research Council (NERC), Flood Studies Report (FSR) (1975). Figure 4 illustrates the design flood procedure, indicating four scenarios:

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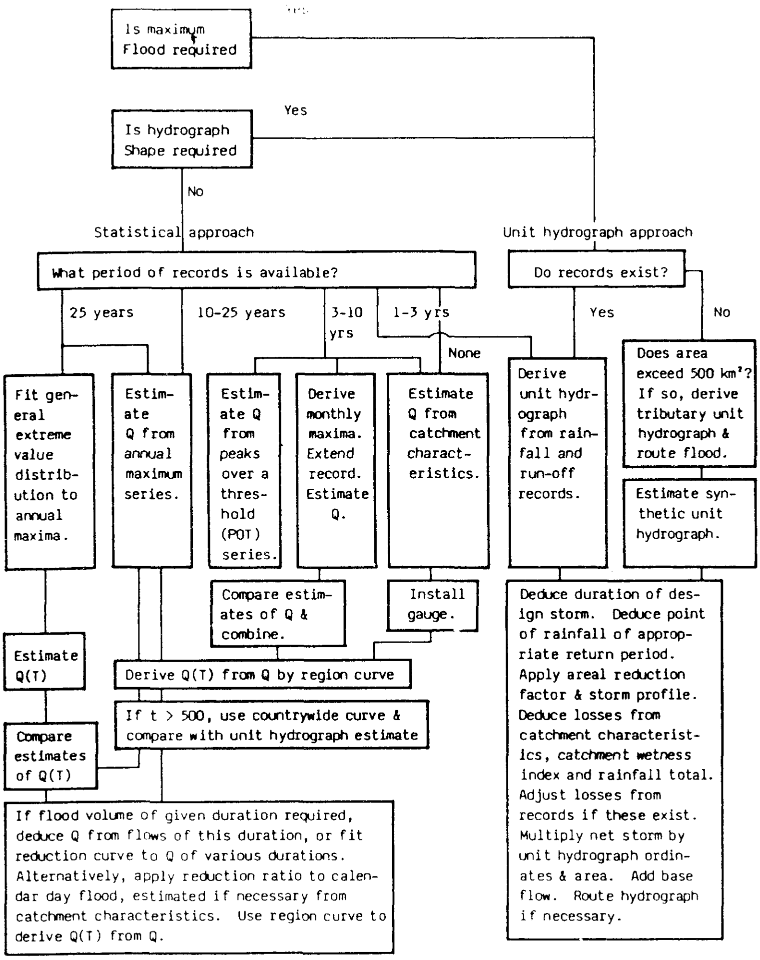

Figure 4. Design Flood Estimation Procedure.
(After Sutcliffe, 1978)

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(i) where records exist in excess of 25 years old
(ii) 10 - 25 years
(iii) 3 - 10 years
(iv) no records exist.

Estimates should be made by more than one method, if possible and a comparison of the results made. In surface mining environments it is common for scenario (iv) to apply, ie no records have been kept.

Estimation of Mean Annual Flood from Catchment Characteristics

This method gives a preliminary estimate of Mean Annual Flood, (MAF(Q)), when no records are available. The catchment characteristics required are as follows (Jackson and Walton, 1983):

Catchment Parameter	Notation (FSR)	Unit	Derivation
Area	AREA	km^2	Directly from available plans min = 0.038 km^2, max = 9868 km^2
Stream Length	MSL	km	Directly measured from plans min = 0.27 km, max = 238.75 km
Stream Slope	S1085	m/km	Ground elevation obtained from plans at 10 and 85% of MSL from gauging point min = 0.19, max = 117.78 m/km
Stream Frequency	STMFRQ	Junctions/km^2	A counting task, artificial channels ignored. Only significant functions counted min = 0.01, max = 7.54 Junction/km^2

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Soil Index	SOIL	-	Weighted average of the 5 class of soil types, S1 - S5 $\text{SOIL} = \dfrac{0.15S1 + 0.3S2 + 0.4S3 + 0.45S4 + 0.5S5}{S1 + S2 + S3 + S4 + S5}$ Classification of Soils given in Table 1.
Lake Index	LAKE	-	The proportion of the catchment which drains through a lake or reservoir. Any body less than 1% of the area drained is discounted.
Urban Development	URBAN	-	Proportion of catchment in a built up area. Values in the range of 0 - 0.808.
Net 1 day return for a 5 year return period, minus mean soil moisture deficit	RSMD	(mm)	Index of catchment rainfall. Values in the range of 15.6 mm - 117.5 mm. Evaluated from FSR.

The final equation is obtained by a multi-regressional analysis from catchments with satisfactory records:

$$\bar{Q} = 0.0201\ \text{AREA}^{0.94}\ \text{STMFR}^{0.27}\ \text{S1085}^{0.16}\ \text{RSMD}^{1.03}\ (1+\text{LAKE})^{-0.85}\ \text{m}^{3}\text{s}^{-1} \qquad \text{... (8)}$$

This is an average countrywide equation, however, regional multipliers may be used instead of 0.0201 (Figure 5). For the Thames, Lee and Essex regions the equation can be altered to:

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Drainage Class	Depth to impermeable layer (cm)	Slope Classes								
		0 - 2°			2 - 8°			>8°		
		Permeability rates above impermeable layers								
		(1) Rapid	(2) Med.	(3) Slow	(1) Rapid	(2) Med.	(3) Slow	(1) Rapid	(2) Med.	(3) Slow
1	> 80	1	1	2	1	2	2	1	2	3
	40 - 80	1	1	2	2	2	3	3	3	4
	< 40	-	-	-	-	-	-	-	-	-
2	> 80	2	2	3	3	3	4	-	4	5
	40 - 80	2	3	3	3	4	4	4	4	5
	< 40	3	4	4	4	4	4	4	5	5
3	> 80	4	4	5	5	5	5	-	5	5
	40 - 80	4	5	5	5	5	5	-	5	5
	> 40	5	5	5	5	5	5	5	5	5

1, very high; 2, high; 3, moderate; 4, low; 5, very low.
Upland peat and peaty soils are in Class 5.
Urban areas are unclassified.

Table 1 Classification of Soils by Winter Rain Acceptance Rate from Soil Survey Data (reproduced from FSR (1975))

$$\bar{Q} = 0.373\ \text{AREA}^{0.70}\ \text{STMFR}^{0.52}\ (1+\text{URBAN})^{2.5} \qquad \ldots (9)$$

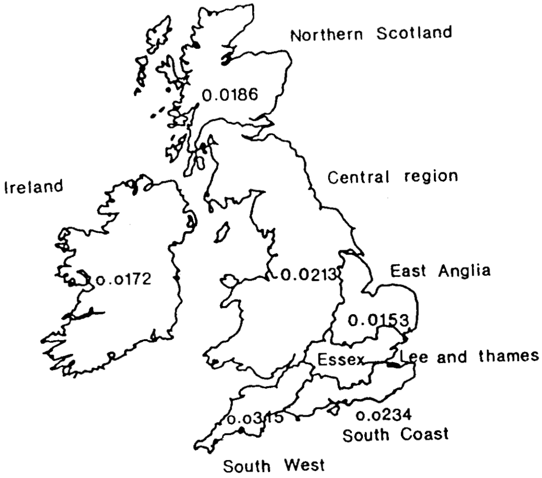


Figure 5. Multipliers for Regional Equations.

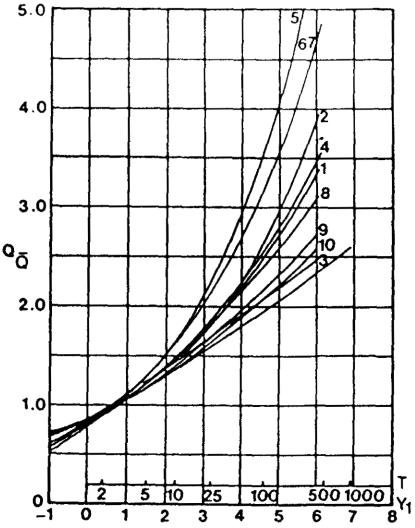
Once the mean flood $\bar{Q}$ is estimated, the maximum flood $\bar{Q}_T$ can be obtained over a selected return period using Figure 6.

Poot's Three Variable Equation

Poots (1979) evolved a model best fitted to small rural catchments. From FSR, AREA, SOIL and RSMD were chosen as the most important parameters, and a regression equation evolved as:

$$\bar{Q} = 0.015\ AREA^{0.882}\ SOIL^{1.904}\ RSMD^{1.462} \qquad \ldots (10)$$

The method is best applied to catchments < 20 km^2.



1 = Northern Scotland
2 = Southern Scotland
3 = North East England
4 = Severn Trent
5 = East Anglia
6 = Thames, Lee Essex
7 = South Coast
8 = South West England
9 = Wales
10 = North West England
11 = Ireland

Figure 6. Regional Curve Showing Average Distribution of $Q/\bar{Q}$. (After NERC, 1975)

The British Coal Technique

British Coal utilise a combination of the Rational Method and the

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guidelines of the FSR, to calculate run-off from tips, etc (NCB, 1982).

The basic rational formula exists:

$$Q = 2.78\ A\ C\ I \qquad \ldots (1)$$

where Q = peak flow, l/s
A = catchment area, ha
C = run-off coefficient
I = rainfall intensity, mm/hr.

C can be obtained from a nomogram, Figure 7, from a knowledge of soil type and ground slope. Once again the time of concentration must be determined, T_c. This is split into two components:

T_e the time of overland flow to drainage system (ditch)
T_d the time of channel flow via ditch to gauging station.

T_e can be determined from the following equation (Ragan and Duru, 1972):

$$T_e = 7(Ln)^{0.6}\ S^{-0.3}\ I^{-0.4} \qquad \ldots (11)$$

where L = length of overland flow
n = Manning roughness coefficient (Table 2)
I = rainfall intensity, mm/hr
S = overland flow slope.

This equation must be solved iteratively as T_e is a function of I. T_e is first estimated and a value of I obtained for a given return period (Figure 8). Values of T_e and I are tested in equation (11) until a final value of T_e is obtained. The time of flow in the cut-off ditch/channel is computed for Mannings equation:

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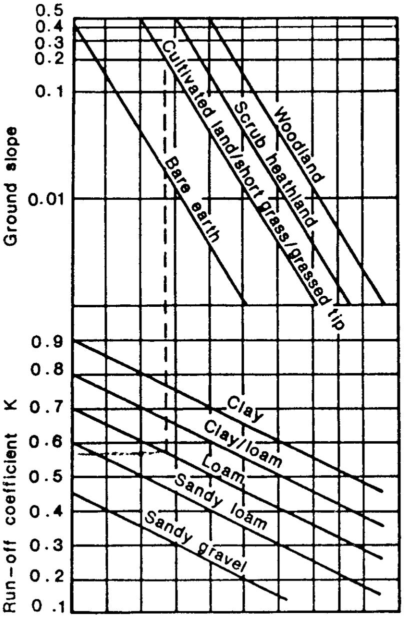

Figure 7. Nomogram to Determine the Run-Off Coefficient.
(After NCB, 1982)

Smooth concrete channel	0.013
Spoil, earth or masonry channel	0.020
Short grass	0.030
Clean, straight natural stream	0.030
Clean, winding natural stream	0.040
Overgrown stream or channel	0.100

Table 2 Manning roughness coefficients (NCB, 1982)

$$V = \frac{R^{0.67} S^{0.5}}{n} \qquad \ldots (12)$$

where V = velocity of flow, m/s

R = area ÷ perimeter of ditch

S = slope of ditch

n = Manning roughness coefficient.

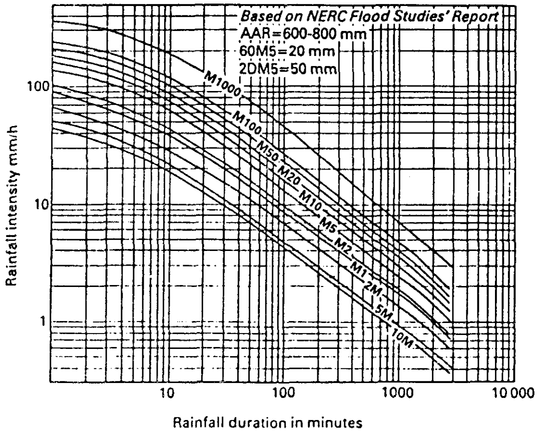

Figure 8. Rainfall Intensity vs. Storm Duration vs. Return Period.

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Prediction of Groundwater Inflows into Surface Excavations

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 flow regime depends on the type of conducting medium. In an unconsolidated sedimentary sequence where groundwater movement is through inter-granular 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 geological 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

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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):

$$r = \left[\frac{2}{\pi} \right] (Y.W)^{\frac{1}{2}} \qquad \ldots (13)$$

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. 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 full 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 = elasped 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)

λ = Tt/Sr^2 (dimensionless)

$W(u,r/B)$ = Hantush well function (dimensionless).

Figure 9 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 3 outlines the appropriate inflow prediction equations under stated flow regimes and aquifer types.

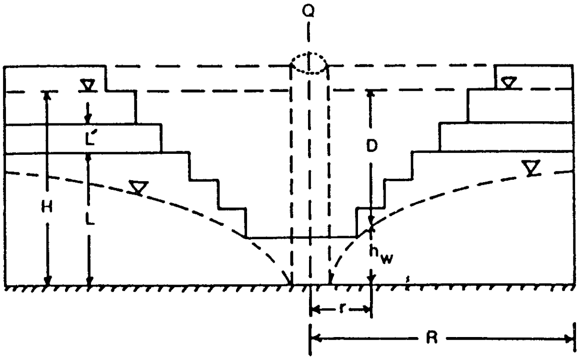

Figure 9. Equivalent Well Approach for Surface Mine Water Inflow Prediction.

Flow regime	Aquifer type	Equation	Remarks
Linear, steady-state	Confined	$Q = \frac{2\pi KLD}{\ell n(R/r) - \frac{n}{2}}$	(14) After Peterson (1957)
Linear, steady-state	Leaky	$Q = \frac{2\pi TD}{K_o(r/B)}$	(15) After Hantush and Jacob
Linear, steady-state	Unconfined	$Q = \frac{\pi K(H^2 - h^2)}{\ell n\ R/r}$	(16) Modified Dupuit's equation
Linear, transient state	Leaky	$Q = \frac{4\pi TD}{W(u, r/B)}$	(17) After Hantush
Linear, transient state	Confined	$Q = 2\pi TDW(\lambda)$	(18) After Jacob-Lohman
Non-Linear, steady-state	Confined	$D = Q\,\ell n(R/r)/2\pi T_D + Q^2(R-r)/4\pi^2 T_T{}^2 Rr$	(19)
Non-linear, transient-state	Confined	$D = Qr\,W(u)/2\pi T_D + Q^2(R-r)/4\pi^2 T_T{}^2 Rr$	(20)

Table 3 Appropriate Equations for Water Inflow Prediction
(equivalent well approach)

(b) Two-dimensional Groundwater Inflows

Recent research has witnessed major developments in the application of two-dimensional flow equations to the determination of steady state and transient drawdown in large earth excavations (McWhorter, 1981; Nguyen and Raudkivi, 1983).

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. The approach is advantageous in that it is often compatible with the quantity and quality of hydrogeological data available. However, under certain conditions 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.

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
T = transmissivity of aquifer (m^2/d)
ω = T/S = hydraulic diffusivity
L = thickness of aquifer being dewatered.

A summary of two-dimensional approaches can be given as follows:

Conditions	Equation	
(1) Linear, Steady State Unconfined aquifer	$Q = \frac{KY\,(H^2 - h^2)}{R}$	... (21)
(2) Linear, Steady State Confined aquifer	$Q = \frac{2KLY\,(H - h)}{R}$	... (22)
(3) Linear, Steady State Leaky aquifer	$Q = 2\,\frac{T}{B}\,D_w\,Y\,, \quad B = \left\{ \frac{LL'K}{k'} \right\}^{\frac{1}{2}}$	... (23)
(4) Linear, Transient State Confined aquifer	$Q = 2\,T\,\frac{\partial D}{\partial x / x \to 0}$	... (24)
(5) Linear, Transient State Leaky aquifer	$Q = 2TD_w \left\{ \frac{1}{B} + \left\{ \frac{\sqrt{\pi}}{4} - \frac{2}{\sqrt{\pi}}\,\frac{\exp \frac{-\omega t}{B^2}}{(\omega t)^{\frac{1}{2}}} \right\} - \left\{ \frac{2}{B}\,\mathrm{erfc}\,\frac{(\omega t)^{\frac{1}{2}}}{B} \right\} \right\}$	... (25)

where erfc is the complimentary error function.

Modified Two-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 10. This approach assumes that the variation of piezometric head (drawdown) with time corresponds to the steady

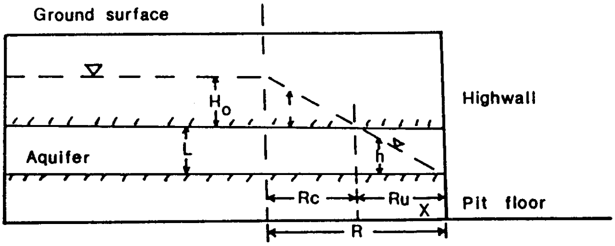

Figure 10. Inflow from a Confined Aquifer Incised by Surface Mining Excavation. (After McWhorter, 1981)

state instantaneous drawdown caused by a particular rate of groundwater inflow. Part of the aquifer near the excavated face becomes unconfined while remote from the excavated face the aquifer remains unconfined. The rate of inflow on the highwall face per unit length is given as follows:

$$q = At^{-\frac{1}{2}} \qquad \ldots (26)$$

where $A = (0.083\ S_yTL^2 + 0.25ST\ H_o^2 + 0.25\ ST\ H_oL)^{\frac{1}{2}}$

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

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

This equation 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:

$$Q = 4Y_1At^{\frac{1}{2}}\ ,\ t < Y/Y_1 \qquad \ldots (27)$$

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:

$$Q = 4Y_1A\,(t^{\frac{1}{2}} - [1-Y/Y_1]^{\frac{1}{2}}),\quad t > Y/Y_1 \qquad \ldots (28)$$

$$Ru = \frac{TL}{2A}\,(1 - Y/Y_1)^{\frac{1}{2}} \qquad \ldots (29)$$

$$Rc = TH_0\,(t-Y/Y_1)^{\frac{1}{2}}/A \qquad \ldots (30)$$

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

Comparison of Equivalent Well and Two-dimensional Approaches

The simplest comparison between the two approaches can be made using equations for linear, steady state flow in a leaky aquifer. The relevant equations using standard notation are as follows:

Equivalent well approach, $$Q = \frac{4\pi TD_w}{W(u,r/B)} \qquad \ldots (17)$$

Two-dimensional approach, $$Q = 2\frac{T}{B}D_w Y \qquad \ldots (23)$$

$$B = \left[\frac{LL'K}{k'}\right]^{\frac{1}{2}}$$

Consider inflows into a pit 1000 m long with an open cut width of 25 m.

Notation and Values

T = transmissivity of aquifer = 10 m^2/day
D_w = drawdown at excavation face = 50 m.
B = leakage factor = 500 m
Y = length of cut = 1000 m
W = width of cut = 25 m
S = storage capacity of aquifer = 1.7×10^{-3} (dimensionless)
$W(u,\frac{r}{B})$ = Hantush Well function, obtainable from hydrogeological table (Kruseman and DeRidder, 1979)

where $u = \frac{r^2S}{4Tt}$

t = time elapsed, (days), say 100 days.

Determining r: $r = \frac{2}{\pi}(Y.W)^{\frac{1}{2}}$

$= \frac{2}{\pi}(1000.25)^{\frac{1}{2}} = 100.66$ m

Determining u: $u = \frac{r^2S}{4Tt} = \frac{100.66^2 \;.\; 1.7 \times 10^{-3}}{4 \times 10 \times 100}$

$= 4.3 \times 10^{-3}$

$$\frac{r}{B} = \frac{100.66}{500} = 0.201$$

From hydrogeological tables : $W(u,\frac{r}{B}) = 3.48$

Calculation by equivalent well method thus gives:

$$Q = \frac{4\pi T D_W}{W(u,\frac{r}{B})} = \frac{4.\pi.10.50}{3.48} = 1{,}805 \text{ m}^3\text{/day}$$

Calculation by two-dimensional method gives:

$$Q = 2\frac{T}{B}D_W Y = \frac{2.10.50.1000}{500} = 2{,}000 \text{ m}^3\text{/day}$$

The two-dimensional approach can thus be seen not only in this case to be a simpler method to use than the equivalent well method, it also provides a factor of safety by estimating inflows to be slightly higher.

Care must be taken in using both approaches to define parameters accurately. Values of parameters such as R may differ for the two approaches owing to slightly different definitions.

Limitations of Two-dimensional Flow Equations

The following assumptions implicit in general 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 has 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 coefficient in the unconfined zone is much greater than in the confined zone.

Numerical Methods

It is beyond the scope of this work to deal with numerical methods in detail. Many numerical calculations have been reported within the mining and water engineering literature. The application of finite difference, finite element and boundary element techniques predict the likely quantities of inflow, elucidate the pattern of water movement and identify regions where flow rates are particularly large. Flow calculations using mainframe computer packages are quick and cheap to perform, making it possible to analyse water problems associated with several scenarios. Many of the problems associated with analytical solutions can be overcome using numerical methods, changes in permeability, aquifer thickness and excavation dimensions, being amongst the parameters which can be incorporated into such models.

CONCLUSIONS

The paper has attempted to detail the various methods available to predict mine water inflows from surface and groundwater sources into an

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open excavation. It is stressed that great care has to be used when applying the equations presented to real-life problems. A thorough knowledge of the groundwater/surface water system is required so to enable realistic estimates to be achieved. Analytical equations such as equivalent well and two-dimensional approaches provides quick first order estimates for use in a field situation. The two-dimensional approach has been shown to give a slightly larger inflow for the same conditions as the equivalent well method, thus a factor of safety is introduced. Numerical techniques provide powerful predictive tools able to model a number of scenarios efficiently. Consequently they are particularly valuable during mine design.

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REFERENCES

Dudley W W (1972)
Technique for Predicting Groundwater Inflow to a Large Underground Opening.
Trans. Soc. Min. Eng., AIME, 1972, pp.152-153.

Jackson E and Walton G (1983)
Note on a Possible Approach to the Assessment of Surface Water in Opencast Mines in the British Isles.
International Journal of Mine Water, Vol. 2, No. 1, March 1983.

McWhorter D B (1981)
Predicting Groundwater Response to Disturbance by Mining Selected Problems.
Symp. Surface Mining, Hydrology, Sedimentology and Reclamation, University of Kentucky, 1981, pp.89-95.

Mansur C I and Kaufman R I (1962)
Dewatering in Foundation Engineering.
McGraw Hill Book Company, New York, Chapter 3.

Reproduced from best available copy

National Coal Board (1982)
Technical Management of Water in the Coal Mining Industry.
NCB Mining Department, 1982, 129 pages.

National Environmental Research Council (1975)
Flood Studies Report, 5 volumes.

Ngah S A (1985)
Hydrogeological Aspects of Surface Mine Dewatering.
Unpublished M.Phil. Thesis, University of Nottingham, 1985.

Kruseman G P and DeRidder N A (1979)
Analysis and Evaluation of Pumping Test Data.
Bulletin 11, International Institute for Land Reclamation and Improvement, ILRI, PO Box 45, 6700A Wageningen, The Netherlands, 1979, pp.193-194.

Ngah S A, Reed S M and Singh R N (1984)
Groundwater Problems in Surface Mining in the UK.
International Journal of Mine Water, Vol. 3, No. 1, pp.1-12.

Nguyen V U and Randkivi A J (1983)
Transient Two-Dimensional Groundwater Flow.
Hydrological Sciences, Vol. 4, pp.427-435.

Norris W H (1946)
Estimation of Run-off from Impervious Surfaces.
Proc. Inst. Min. Co. Engrs., Vol. 72, p.501.

Perez-Franco D (1982)
Non-Linear Flow of Groundwater During Mine Dewatering Operations.
First International Conference of the International Mine Water Association, Budapest, Vol. 2, pp.195-198.

Poots A D (1979)
A Flood Prediction Study for a Small Rural Catchment.
M.Sc. Thesis, Queens University, Belfast, 1929.

Ragan R M and Duru J O (1972)
Kinematic Wave Nomogram for Times of Concentration.
Journal of the Hydraulics Division, AMCE, 1972.

Reid J (1927)
The Estimation of Storm-Water Discharge.
Proc. Inst. Min. Co. Engrs., Vol. 53, 1927.

Shaw E M (1983)
Hydrology in Practice.
Van Nostrand Reinhold (UK) Co. Ltd., Berkshire.

Singh R N and Atkins A S (1984)
Analytical Techniques for the Estimation of Mine Water Inflow.
Int. Journal of Mining Engineering, Vol. 2, pp.1-13.

Reproduced from best available copy

Singh R N, Ngah S A and Atkins A S (1985)
Applicability of Current Groundwater Theories for the Prediction of Water Inflows to Surface Mining Excavations.
Proc. of the Second International Congress of the International Mine Water Association, Granada, Spain, pp.553-571.

Sutcliffe J V (1978)
Methods of Flood Estimation : A Guide to FSR.
Institute of Hydrology Report, No. 49.