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Simple Mine Inflow Evaluation for Underground Oil Shale Mines

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INTRODUCTION

Developers of major oil shale mines in the Piceance Basin have already had some unpleasant surprises from ground water despite the early stage of these developments. These surprises include:

- C-a tract shaft sinking had to be halted to allow dewatering of near surface materials.
- C-b tract shaft sinking encountered considerably more water than was expected.
- The Colony mine, despite being on the edge of the Parachute Creek canyon, encountered measurable water inflow from the supposedly unsaturated roof strata.
- The U.S.B.M. Horse Draw Shaft encountered high pressure, methane-laden water when the proposed development level was opened, despite expectations that the target strata were impermeable.

This paper presents a simple approach to the evaluation of the geohydrology problems associated with underground oil shale mines. The basic analytical tools are presented, followed by a typical geohydrology model for an oil shale mining area. These are used to illustrate simple methods of computation of shaft inflows, shaft dewatering, mine inflows and ground water impacts of mining. After looking at the uncertainties associated with the results, some conclusions are drawn about mine geohydrology evaluations in this type of geological system.

ANALYTICAL TOOLS

There are a vast number of ways which geohydrology analyses can be performed. They can in general be characterized as:

i. Simple and Cheap, or
ii. Complex and Expensive

As a general rule, mining hydrology should be performed with the first type of approach, for two reasons. First the required accuracy of analyses of mining hydrological systems is usually not high; an order of magnitude estimate is often all that is needed for inflows or impacts. Second, the available accuracy of information - geology and parameters is usually not high, and thus it is inappropriate to use highly accurate analytical methods to compute results.

There are three main analytical tools which I use for mine hydrology analyses.

Darcy's Law

Darcy (1) had the great insight that the volumetric rate of flow of a fluid through a porous medium was proportional to the head gradient in the medium (i) and the area through which flow is taking place, (A), or

$$(1) \quad Q = kiA$$

where the constant of proportionality (k) is defined as the hydraulic conductivity. This is the fundamental relationship for mine geohydrologists. It is not always true (the relation is not always linear) but it always produces an upper bound to mine inflow and environmental impacts.

The Well Equation

Theis (2) performed an analysis of flow to a well in an infinite, homogeneous, compressible confined aquifer, and produced the classic well equation solution

$$\text{(2a)} \qquad D = \frac{Q}{4\pi Lk} W(u)$$

where D = drawdown

Q = flow to the well

L = thickness of the formation being dewatered

k = hydraulic conductivity

$W(u)$ = well function

$u = \dfrac{r^2 S_s}{4kt}$

r = radius at which drawdown is desired

S_s = specific storage

k = hydraulic conductivity

t = elapsed time

Values of W(u) are given as a function of u in Table I. This equation is very usable in this form, but it is also convenient when quoted in an approximate steady state form (3):

$$\text{(2b)} \qquad D = \frac{Q \ln(R/r)}{2\pi Lk}$$

where $R \div r_w \sqrt{\dfrac{4kt}{r_w^2 S_s} + 1}$ = effective radius of influence

r_w = radius of the well (or mine) and other symbols are as above.

This has the great attraction that it is readily computable using a programmable calculator, and the involvement of

TABLE I

VALUES OF $W(u)$

N \ u or u_{xy}	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
1.0	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.5	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	0.1000
2.0	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	0.04890
2.5	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	0.02491
3.0	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	0.9057	0.01305
3.5	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	0.7942	0.006970
4.0	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	0.7024	0.003779
4.5	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	0.6253	0.002073
5.0	20.8392	18.5366	16.2340	13.9314	11.6280	9.3263	7.0242	4.7261	2.4679	0.5598	0.001148
5.5	20.7439	18.4413	16.1387	13.8361	11.5330	9.2310	6.9289	4.6313	2.3775	0.5034	0.0006409
6.0	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	0.4544	0.0003601
6.5	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	0.4115	0.0002034
7.0	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.3916	2.1508	0.3738	0.0001155
7.5	20.4337	18.1311	15.8280	13.5260	11.2234	8.9209	6.6190	4.3231	2.0867	0.3403	0.0000658
8.0	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.2591	2.0269	0.3106	0.0000376
8.5	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.1990	1.9711	0.2840	0.0000216
9.0	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.1423	1.9187	0.2602	0.0000124
9.5	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.0887	1.8695	0.2387	0.0000071

TABLE II

VALUES OF $K_0(r/B)$.

N	$r/B = N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
1.0	7.0237	4.7212	2.4271	0.4210
1.5	6.6182	4.3159	2.0300	0.2138
2.0	6.3305	4.0285	1.7527	0.1139
2.5	6.1074	3.8056	1.5415	0.0623
3.0	5.9251	3.6235	1.3725	0.0347
3.5	5.7709	3.4697	1.2327	0.0196
4.0	5.6374	3.3365	1.1145	0.0112
4.5	5.5196	3.2192	1.0129	0.0064
5.0	5.4143	3.1142	0.9244	0.0037
5.5	5.3190	3.0195	0.8466	
6.0	5.2320	2.9329	0.7775	0.0012
6.5	5.1520	2.8534	0.7159	
7.0	5.0779	2.7798	0.6605	0.0004
7.5	5.0089	2.7114	0.6106	
8.0	4.9443	2.6475	0.5653	
8.5	4.8837	2.5875	0.5242	
9.0	4.8266	2.5310	0.4867	
9.5	4.7725	2.4776	0.4524	

each parameter is clear. The degree of approximation is small. Unlike the Theis form, it is valid for finite sized wells (or mines).

Steady State Leaky Aquifer Equation

Hantush and Jacob (4) presented the solution to the problem of flow to a well and its associated drawdown when the aquifer being pumped is overlain by a leaky layer. The leakage reduces the spread-out of the drawdown effect, and increases the flow to the well slightly. Unlike the non-leaky case, it also reaches steady state, when all water influent to the well is provided by leakage through the leaky layer. At steady state, the equation is given by:

$$\text{(3a)} \qquad D = \frac{Q}{2\pi Lk} K_o(r/B)$$

where D = drawdown

Q = flow

L = thickness of aquifer

k = horizontal hydraulic conductivity

K_o = Modified Bessel Function

r = radius

$B = \sqrt{k\ L\ L'/k'}$

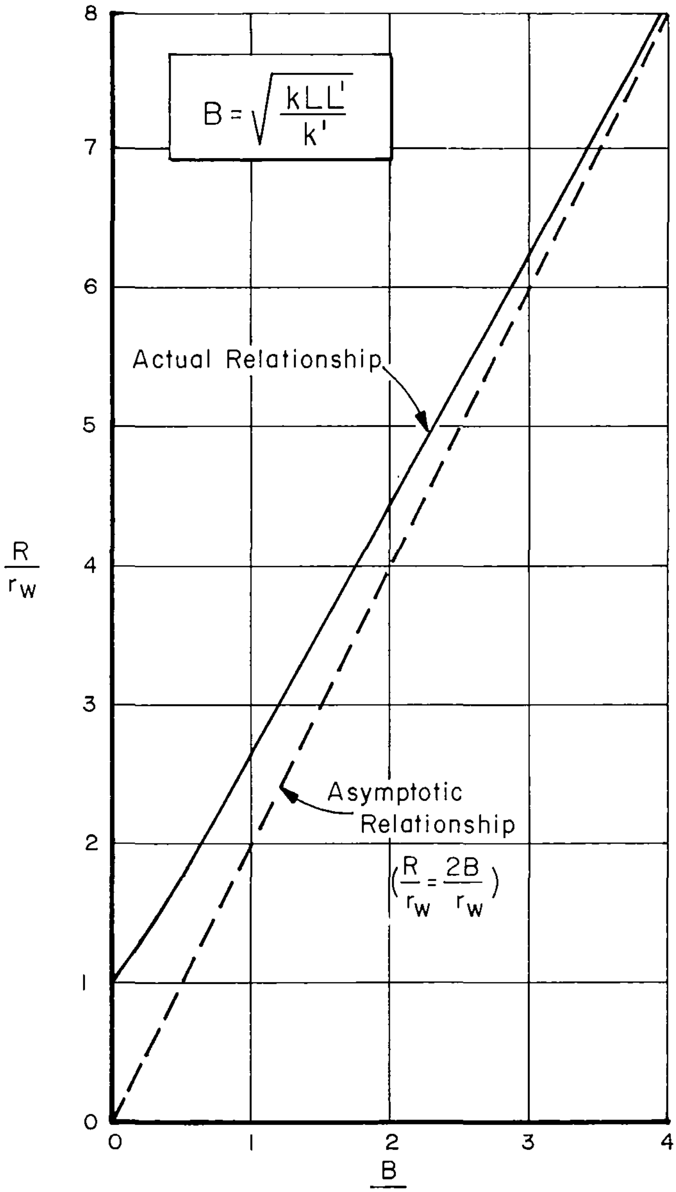
k' = vertical hydraulic conductivity of leaky layer

L' = thickness of leaky layer

The relationship between $K_o(r/B)$ and r/B is given in Table II. An approximate steady state form is possible (5) which is comparable with equation 2(b).

$$\text{(3b)} \qquad D = \frac{Q \ln(R/r)}{2\pi Lk}$$

where R = effective radius of influence of drawdown and other symbols are the same. The relation for R as a function of r_w and B is given in Figure 1. This equation is especially useful for computing environmental impacts. Note that it is an upper bound for flows, but a lower bound for impacts.



See reference (5) for derivation.

Figure 1 - Radius of Influence For A Leaky Aquifer (Approx.)

These then are the three fundamental tools. There are a vast array of other useful relationships and methods of analysis, but it is possible to perform most oil shale mining hydrology work with these.

THE GEOHYDROLOGY MODEL

Geology

The site chosen for presentation in this paper is in the Piceance Creek Basin of Northwest Colorado, just to the South of Piceance Creek (Figure 2). The typical geological column in the area is given in Figure 3. This comprises, from the surface,

i. The Uinta Sandstone. This is a fine to medium sandstone, extensively fractured, of late Eocene age. It was deposited in lacustrine to fluviatile environments.

ii. The Parachute Creek Member of the Green River Formation. This is a white to grey varved dolomintic limestone with varying amounts of kerogen intimately mixed with the matrix. The kerogen is a wax-like organic compound which decomposes to an oil like substance when heated. Sodium anhydrite minerals also occur in varying amounts.

iii. The Garden Gulch Member of the Green River Formation. This is a dark, finely laminated shale and dolomintic limestone, generally barren of kerogen.

All strata are flat bedded, except in the extreme north of the basin. Fracturing is in general slight, but bedding fractures are common. There is little evidence of deep seated fault activity in the basin. The Mahogany Zone is a particularly rich oil shale layer, and is shown shaded in Figure 3. It is considered to be the target of mining for the present paper, and it is also assumed that mining will be by room-and-pillar methods. (Note that other methods of mining can be, and are being, considered.)

Geohydrology

Once the geology has been determined it is necessary to assign the needed geohydrologic parameters to the various

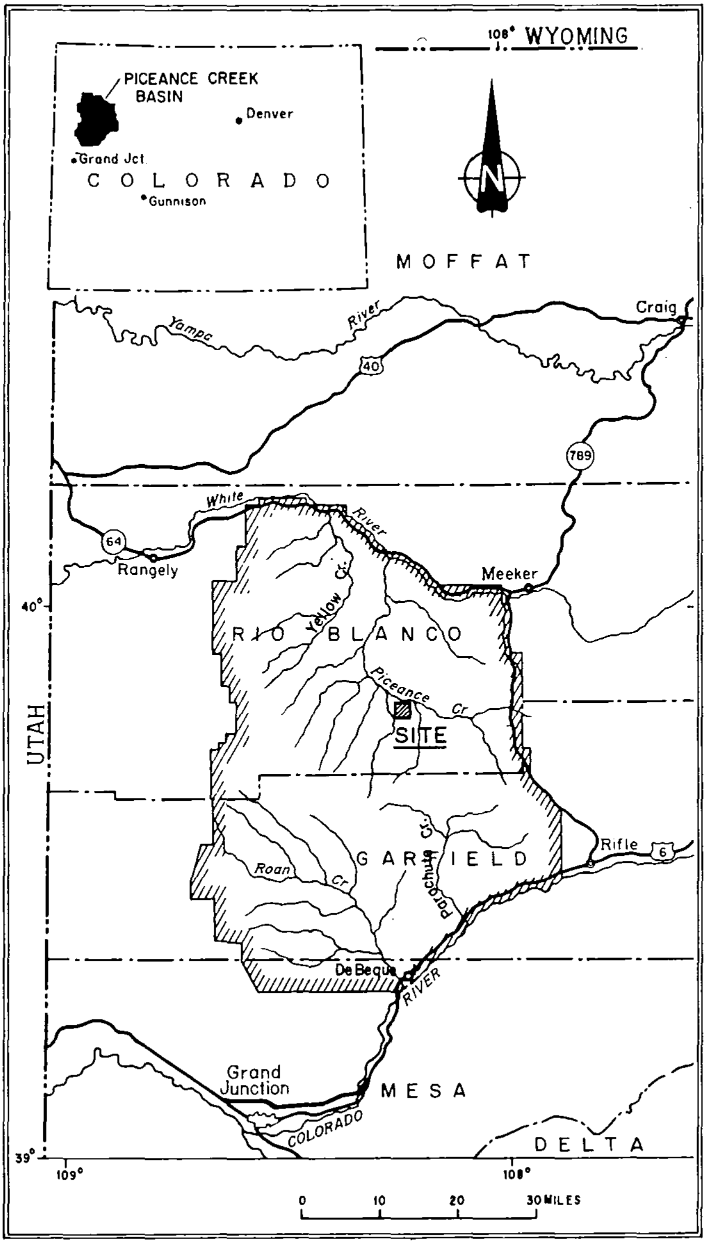


Figure 2 - Location Plan

GEOLOGIC UNIT	MATERIAL TYPE	FEATURE DESCRIPTION	ELEVATION (feet above Mean Sea Level)	DEPTH (feet)
UINTA FORMATION	Sandstone	Ground Surface	6740	0
		Water Table	6410	330
		Uinta Sandstone	5820	920
GREEN RIVER FORMATION: PARACHUTE CREEK MEMBER	Kerogenous Marlstone (Oil shale)	A Groove	5490	1250
		Mahogany Zone	5460	1280
			5410	1330
		B Groove	5310	1430
		R-4 Zone	4630	2110
			4500	2240
		Blue Marker	4200	2540
GREEN RIVER FORMATION: GARDEN GULCH MEMBER				

Source: Brown et al, Ref.(6)

Figure 3 - Geology Model

geological units. Four fundamental parameters are of relevance in this case, as follows:

i. Horizontal Hydraulic Conductivity

This parameter relates primarily to the ability of the unit to transmit water along the bedding direction. In this particular model horizontal hydraulic conductivity is assumed to be isotropic.

ii. Vertical Hydraulic Conductivity

This parameter relates to the ability of the unit to transmit water across the bedding plane direction - i.e. roughly vertically.

iii. Drainable Porosity

This parameter indicates how much water is available if a section of the unit de-saturates.

iv. Specific Storage

This parameter determines the amount of water which is released from a unit volume of rock when the water pressure is lowered by a unit of head. It is related to the compressibility of the rock.

Figure 4 shows the best estimates of each of the parameters for the geological units shown in Figure 3. The data is taken from a report by the Author and others (6). It should be noted in passing that a consistent set of units is used. I happen to have chosen the following set:

Length - Feet
Time - Days
Mass - Pounds

Using this set of units, flows come out as cubic feet per day, which can be converted as required. The important factor is that the units be consistent, as all the formulae presented in this paper are for consistent units. For the reader more used to oil field units, 1 foot per day is equal to 350 millidarcy (approximately). The testing with which the values in Figure 4 have been obtained is described in detail elsewhere. I have chosen to concentrate in this paper on the use of the data.

Geologic Unit		Feature Description	Depth (feet)	Hydraulic Conductivity: Horizontal (feet per day)	Hydraulic Conductivity: Vertical (feet per day)	Drainable Porosity	Specific Storage (feet^{-1})
Uinta Formation		Ground Surface	0				
Uinta Formation		Water Table	330				
Uinta Formation		Uinta Sandstone	330–920	.093	.03	.10	3×10^{-7}
Green River Formation	Parachute Creek Member		920–1020	.005	.003	.01	3×10^{-7}
Green River Formation	Parachute Creek Member	A Groove (1250)	1020–1280	.411	.008	.02	3×10^{-7}
Green River Formation	Parachute Creek Member	Mahogany Marker (1280)	1280–1330	.033	.0003	.01	3×10^{-7}
Green River Formation	Parachute Creek Member	B Groove (1430)	1330–1480	.586	.058	.02	3×10^{-7}
Green River Formation	Parachute Creek Member	Horizon X (1480)	1480–2110	.077	.008	.01	3×10^{-7}
Green River Formation	Parachute Creek Member	R-4 Zone (2110–2240)	2110–2540	.063	.008	.01	3×10^{-7}
Green River Formation	Garden Gulch Member	Blue Marker	2540	Assumed Functionally Impervious			

NOTES:

Not to Scale.

Quality of information for the purposes of this study:

- (blank box) "Based on acceptable test data"
- (grid box) "Estimated or based on poor data"
- (stippled box) "Experiential guess"

Source: Brown et al, Ref. (6)

Figure 4 - Geohydrology Model

ANALYSES

We have the geohydrology model, and some analytical tools, so it is now possible to compute some typical inflows and other results. The examples will be taken in order of the development of a mine in the Mahogany Zone, which is about 1,300 feet deep (Figure 3).

Shaft Inflow and Effect

Assume that a 24 foot diameter shaft is to be conventionally sunk without any prior dewatering. A maximum of fifty feet of the shaft is open to the formation at one time, and the shaft lining is fully sealed. What is the inflow likely to be? Shaft advance is assumed to be 5 feet/day.

The shaft constitutes a large diameter well. When the shaft is (say) at the 'B Groove' (Figure 4) the parameters are:

L = thickness open = 50 feet
D = drawdown = 1430-330 = 1,100 feet
k = hydraulic conductivity = 0.586 feet/day
r = "well" radius = 12 feet
S_s = specific storage = 3×10^{-7} feet^{-1}
t = time that shaft section is open = 5 days (average)

Applying equation 2(b) gives

$$Q = 32{,}500 \text{ feet}^3\text{/day} = 170 \text{ gallons per minute}$$

Performing this analysis for the entire shaft gives the result in Figure 5. Inrushes to the shaft might be ten times this amount for short periods.

Shaft Dewatering

The result in Figure 5 suggests that some flow control will be necessary for the shaft. Perhaps more important, pressure control would be advantageous in the vicinity of the shaft, to prevent failure of the floor materials, and to reduce the risk of very large, sudden inrushes. If a reduction of 90 per cent of the original pressure is considered necessary, how many wells will be needed, and what flows will they produce?

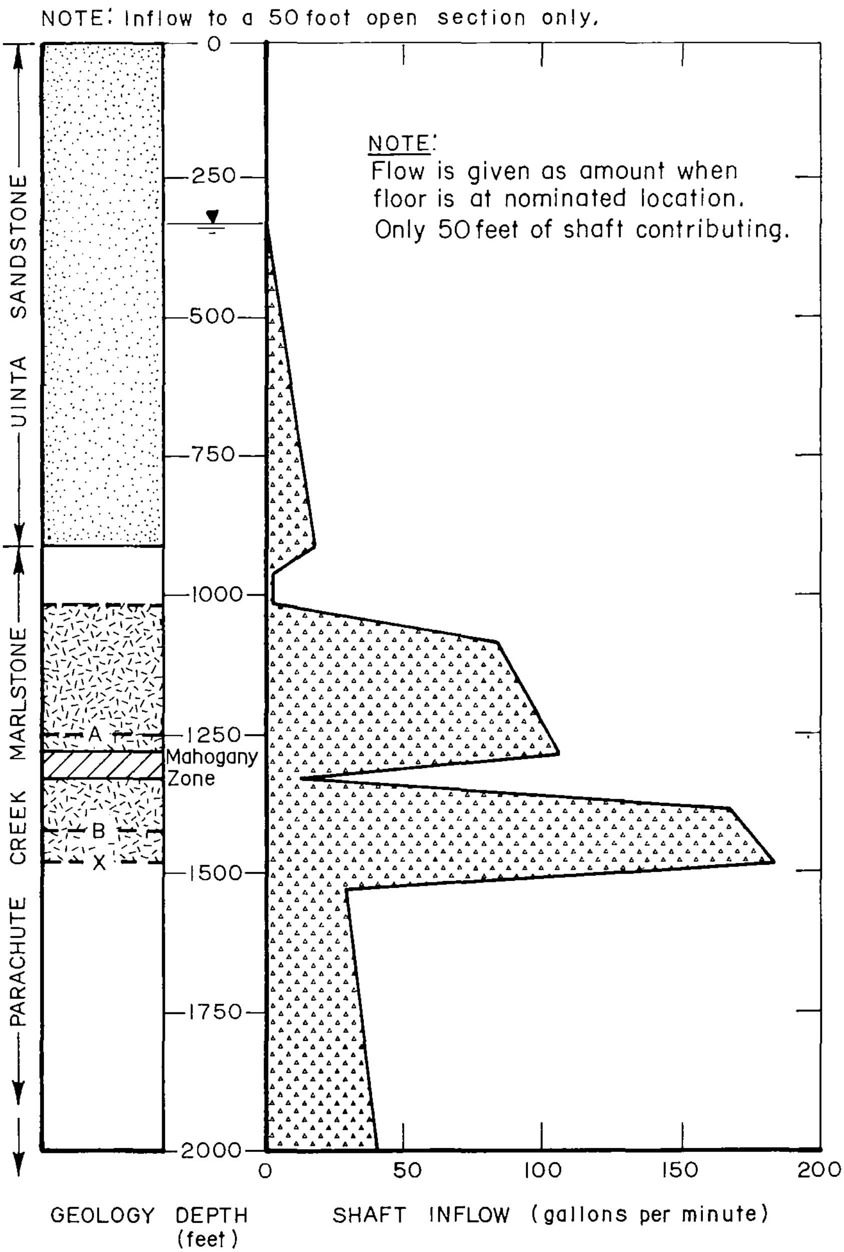


Figure 5 - Average Flow To Shaft Without Dewatering

By way of example, consider one fully drained well. The distance drawdown characteristic near the 'B' Groove is shown on Figure 6A. Applying this curve to drawdown at the shaft center, with dewatering wells located at 100 feet from the centerline (for blast protection) shows that a single well reduces the head about 52 per cent. A second well can be shown by superposition to reduce the head at the shaft by a further 20 per cent to 72 per cent, and so on as shown in Figure 6B. For 90 per cent reduction in head (the design requirement), about 6 wells are needed. Flow from each of these wells can be found by integrating the flow to a single well over its full depth, and taking 10 per cent of it, giving 70 gallons per minute per well (after 30 days). The wells would reduce the maximum steady flow to the shaft to about 20 gallons per minute. After dewatering, inrushes might be ten times that amount for short periods.

Underground Mine Inflow

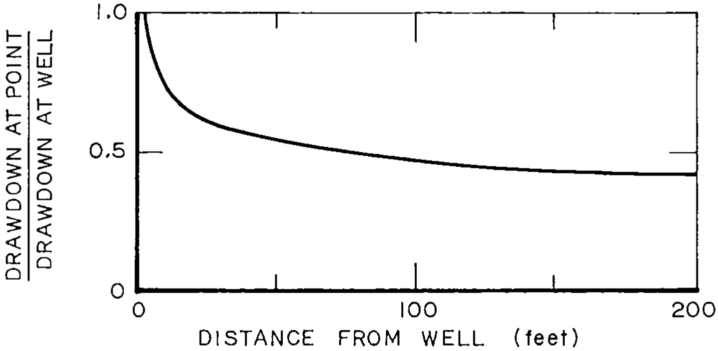
Inflow to an unsubsided underground mine comes in this environment from two sources; horizontal flow along the strata disturbed by mining, and vertical flow from the roof. The general scheme of flow is shown in Figure 7. Each component can be relatively easily computed as follows.

Horizontal Flow. For inflow purposes the mine can be considered as a large well. Consider a two mile diameter mine extracting the Mahogany Zone, and with roof drains dewatering up to the 'A' Groove (Figure 3). In addition, it seems reasonable to assume that the stress relief in the floor will influence a thickness of the floor material equal to about half the roof span, or about 50 feet.

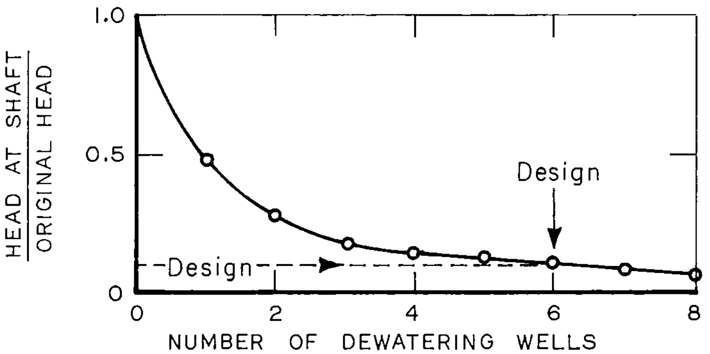
Flow could be computed asuming confined conditions, giving about 450 gallons per minute. However the significant vertical permeability of the model creates a situation where leakage is coming from the Uinta Sandstone. Accordingly, the conditions are leaky, with the following parameters:

- k = average horizontal hydraulic conductivity of aquifer = .333 feet/day (average)
- k' = vertical hydraulic conductivity of roof material = 0.01 feet/day (average)
- L = aquifer thickness = 130 feet

NOTE: These curves are valid only for parameters given in Figure 4.



A) DRAWDOWN AROUND A WELL AFTER 30 DAYS PUMPING.



B) HEAD AT SHAFT IN LOWER AQUIFER VERSUS NUMBER OF DEWATERING WELLS.

Figure 6 - Shaft Dewatering Design

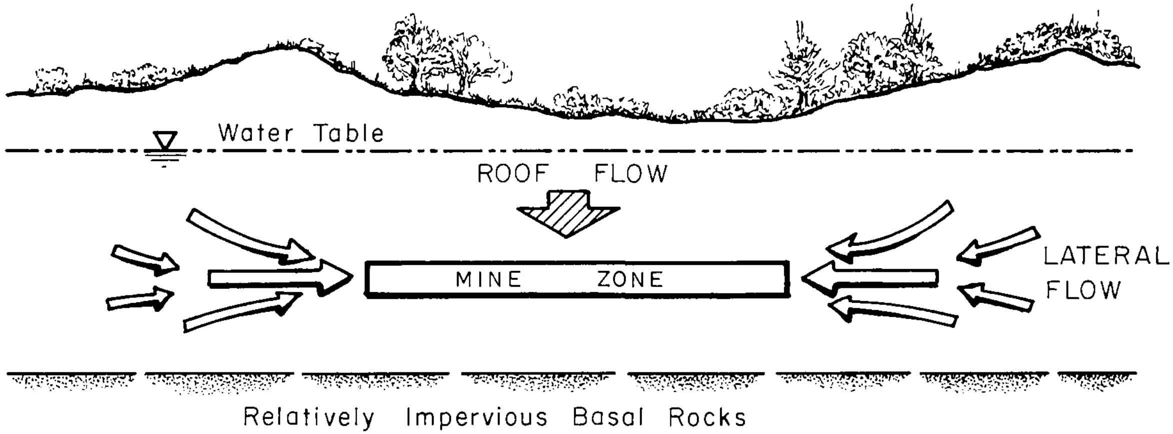


Figure 7 - Scheme Of Flow To A Mine

L' = aquitard thickness = 920 feet
r_w = mine radius = 5,280 feet
D = drawdown at mine = 975 feet (average)

Using Equation 3(b) and Figure 1, for B = 1,995 feet,

$$Q = 575{,}000 \text{ feet}^3/\text{day} = 3{,}000 \text{ gallons per minute}$$

Flow From Roof. The flow from the roof occurs under conditions of gravity drainage. Vertical hydraulic gradients are about equal to unity, and the water pressure above the mine approaches zero. While this is approximate, it becomes more true for mines whose extent is large compared with the depth below the water table. The vertical inflow can be computed using the following parameters:

k' = average vertical hydraulic conductivity to water table = 0.01 feet/day
i = hydraulic gradient = 1 approximately
A = mine area = 3.14 square miles

Thus, using equation 1,

$$Q = 963{,}000 \text{ feet}^3/\text{day} = 5{,}000 \text{ gallons per minute}$$

This flow is proportional to the area of the mine, and originates from movement of the water table as a result of drainage.

Total Flow to the Mine. The total flow to the mine is therefore made up as follows:

i.	Horizontal flow	3,000 gallons per minute
ii.	Roof flow	5,000 gallons per minute
	Total	8,000 gallons per minute

This is a modest flow by comparison with similarly sized mines in pervious media.

Impact of Drawdown

The simple equations and the model can be used to make a first cut at environmental impact of the mine. In the case under study the impact of drawdown is primarily as a result of vertical seepage to the mine. The maximum rate of movement of the water table is found by evaluating the real rate of vertical seepage, which is given by:

$$V_{real} = V_{Darcy} / n$$

$$= k'i / n$$

As in the section on flow to the roof, we have

k' = vertical hydraulic conductivity = 0.01 feet/day (average)
i = vertical hydraulic gradient = 1 (average)
n = drainable porosity of Uinta Sandstone = 0.1 (Figure 4).

These parameters give

V_{real} = 40 feet/year

and at that rate it would take a minimum of fifteen years for the Uinta Sandstone to de-saturate over the mine itself.

The impact would spread out from the mine as the drainage took place. Perhaps the easiest way to get a feel for the maximum extent of this effect is to analyze the entire system as a two mile diameter well in an unconfined aquifer. Parameters are:

Q = flow = 8,000 gallons per minute = 1,500,000 feet^3/day
k = average horizontal hydraulic conductivity = 0.164 feet/day
L = total thickness = 1,000 feet
n = drainable porosity = 0.1
S_s = effective specific storage = n/L = 10^{-4} feet^{-1}
r_w = radius of mine = 5,280 feet
t = time elapsed = 20 years = 7,300 days

Using equation 2(b) gives that the 8,000 gallons per minute flow would cause a drawdown after 20 years of 700 feet at the edge of the mine, and that the cone of depression would not extend much beyond 2 miles from the edge of the mine. This result fits well with the vertical seepage result above. The impact of mine seepage on ground water levels would be substantial over the mine, but would rapidly diminish away from the mine.

It goes without saying that much better analyses of ground water depletion impact, both local and regional, are needed for full mine design. The above approach does, however, indicate the likely flavor of the end result. (For examples of basin-wide analyses see, Weeks et al (7) and Brown et al (6)).

ACCURACY AND UNCERTAINTY IN THE RESULTS

How accurate are the above results? Or put another way; how much variability could there be in the answers? Uncertainty as to the results can arise from a number of sources:

i. Inaccuracies introduced by the use of an idealized geohydrology model.

ii. Inaccuracies introduced by the analytical evaluations performed with the model.

iii. Uncertainties associated with the measurement of parameters for the model.

While the model and the analytical methods used in this paper are deliberately crude, most of the uncertainty in the final result derives from the parameters. This section briefly reviews the accuracy of some of the above evaluations.

Shaft Inflow Accuracy

Review of the analysis presented above shows that the variability of shaft inflow is mainly dependent upon the variability of the horizontal hydraulic conductivity.

There are three forms of variability of this parameter:

i. It is variable on a macroscopic scale in the vertical direction, due to gross lithological changes. This variability is reasonably quantifiable and is presented on Figure 4.

ii. It is variable laterally in the same lithologic unit. As an example, consider the results presented in Figure 8, of tests of a highly permeable, confined unit at C-a Tract at 22 different locations. Depending on where a shaft happened to be located in this unit, there is a reasonable probability that the flow might be as little as 1/3 or as much as 3 times that expected at the median hydraulic conductivity.

iii. It is variable locally in the same lithologic unit. Due to the fractured nature of the medium, it would be reasonable to expect to find differences in inflow of perhaps an order of magnitude on a 50 foot sampling basis due to random intersection of major joint or fracture systems.

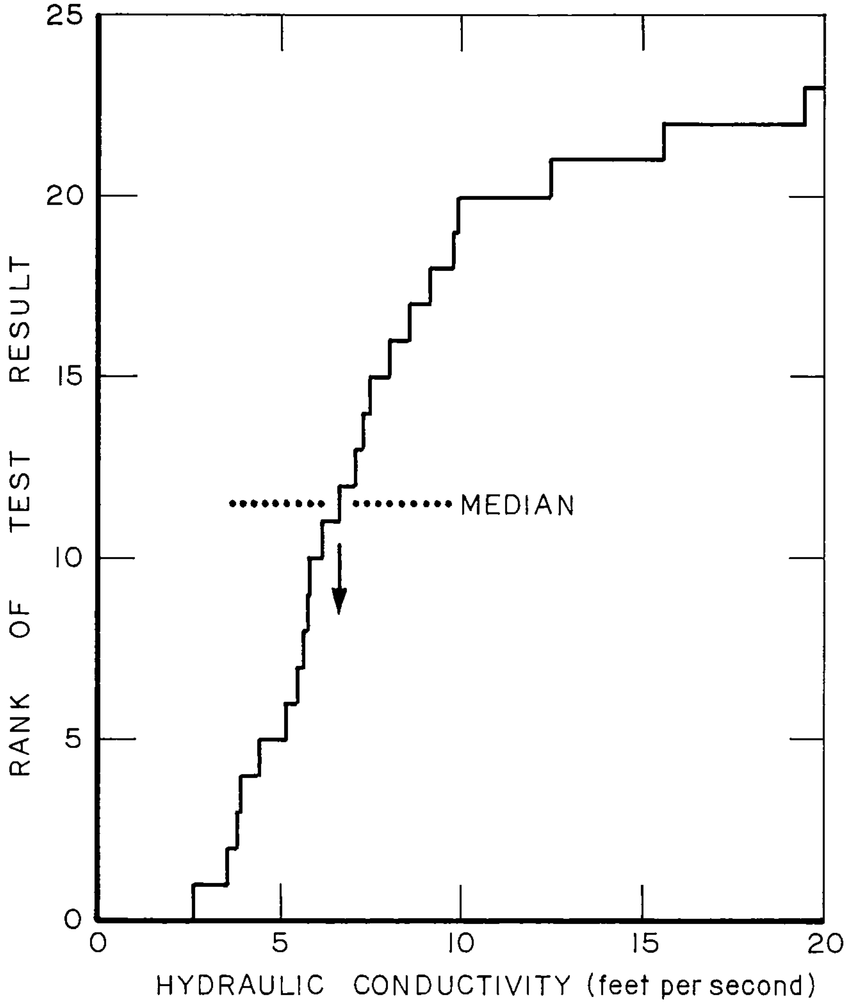
Thus the average flow to the shaft may vary, by perhaps a factor of five either way from the flows shown in Figure 5 and the flow at any given time may vary a factor of perhaps ten either side of this average, at least for short periods. For design purposes a carefully tested pilot hole on the centerline of the shaft can evaluate the expected average flow to good precision, but an allowance of a factor of something like five for inrushes should be made in these materials.

Mine Inflow

As is clear from the analysis, the mine inflow is an almost total function of vertical hydraulic conductivity. Figure 9 shows this dependence. Only three meaningful tests of this parameter are known to have been conducted in the Basin (Ref. 6, p. 114), all of them on the Mahogany Zone, which for this evaluation is not particularly useful. Thus the estimates given in Figure 4 are only order of magnitude estimates. We believe that they are close to the upper bound; the lower bound may be up to two orders of magnitude lower. Accordingly it might be reasonable to expect inflows in the range 1,000 gallons per minute to 10,000 gallons per minute. While this sounds like a huge range, it is probably about as good a prediction as can be obtained with anything but the most extensive (and expensive) testing program.

CONCLUSIONS

The conclusions of this paper are, I believe, straightforward:



Data from Reference (8)

Figure 8 - Horizontal Hydraulic Conductivity Results - Lower Aquifer, C-a Tract

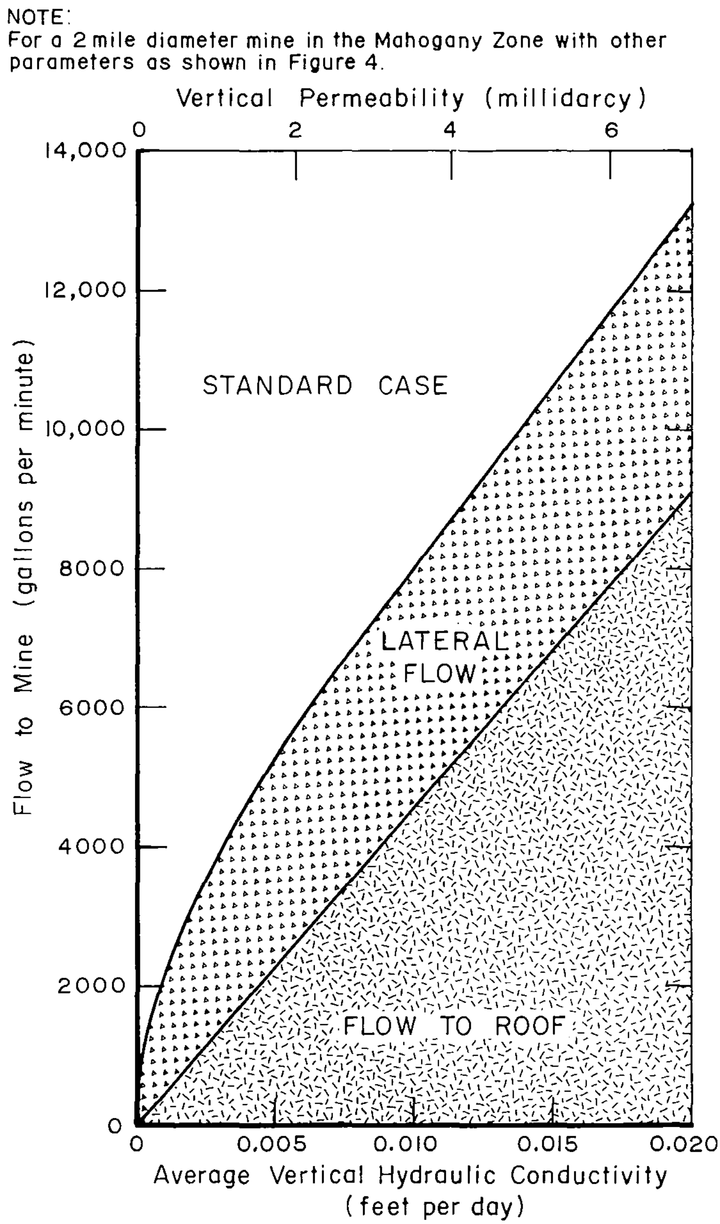


Figure 9 - Relationship Between Inflow and Vertical Hydraulic Conductivity

i. For oil shale geohydrology analysis, the use of simple models and simple analytical relationships produces results which are of a degree of accuracy which is appropriate to the accuracy of the parameters, and in general to the needs of mine planners.

ii. Use of these simple model forces the analyst to recognize the major parameters influencing the results. This is of great value when an investigation program is being planned, as much money can be, and often has been wasted refining non-critical parameters.

iii. An analysis of uncertainty is essential to this (or any) mining geohydrology study. The responsible engineer must not only produce a best estimate, but also an indication of the spread of possible results of actual mining.

The methods used in this paper are applicable to a wide range of mining geohydrology studies in sedimentary systems. I trust that the methods are of use to those whose responsibility it is to plan mining evaluations, as well as those whose profession is geohydrology.

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