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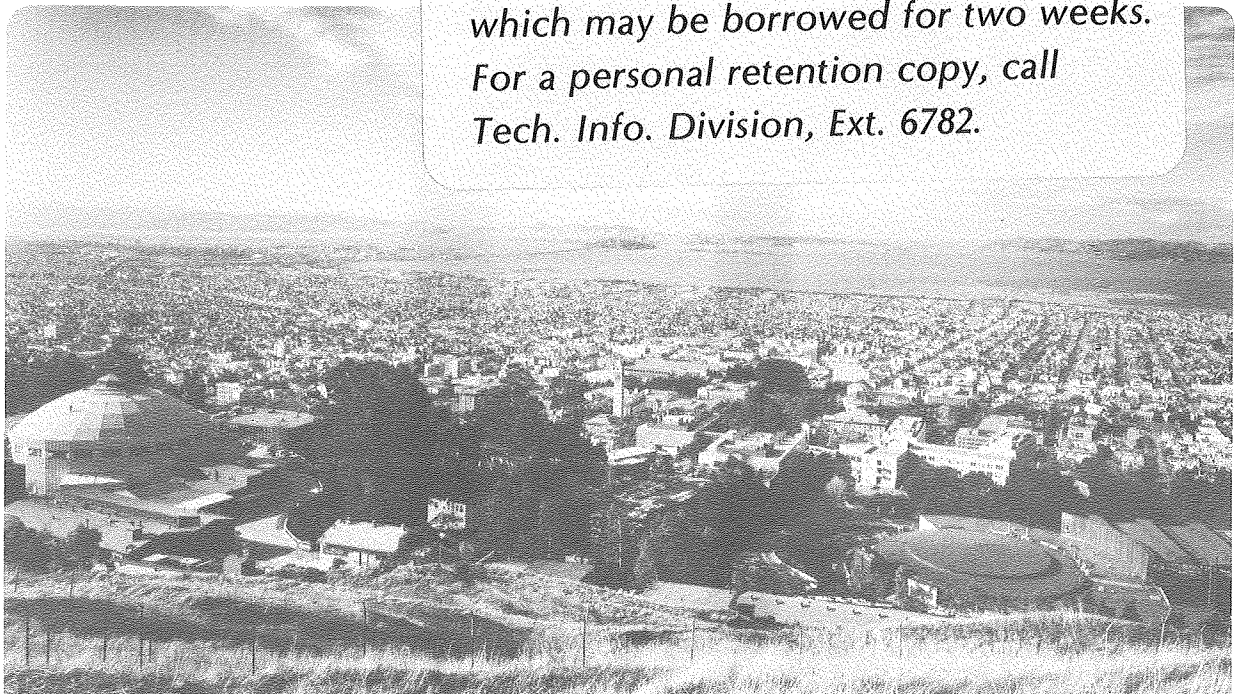
HYDROGEOLOGIC CONSEQUENCES OF THE MODIFIED IN-SITU RETORTING PROCESS, PICEANCE CREEK BASIN, COLORADO

M. Mehran, T.N. Narasimhan, and J.P. Fox

April 1981

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Hydrogeologic Consequences of the Modified In-Situ Retorting  
Process, Piceance Creek Basin, Colorado

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ABSTRACT

In the modified in-situ retorting process (MIS), the region of retorting will act as a large subsurface sink and lead to a massive dewatering of the surrounding hydrogeologic system. The present study has been aimed at studying the possible alteration of the groundwater regime in and around the C-a and the C-b tracts due to the proposed MIS strategies. Our approach has been one of scenario analysis and parametric studies, using a numerical model.

The flow region is idealized as a multi-layered, saturated-unsaturated system, within which the expanding disc-shaped retorted domain forms a cavity. Water drains into the disc-shaped region at atmospheric pressure. The material properties, such as saturation and permeability, are functions of fluid pressure head.

The results suggest that mine-inflow rates will gradually increase with time and that the phreatic surface will be drawn down significantly over several square kilometers around the C-a and C-b tracts. These drawdowns could have profound effects on the shallow groundwater and surface water supplies. The expected inflow rates may vary from 0.15 to 1.4 m<sup>3</sup>/sec at the C-a tract and from 0.5 to 0.9 m<sup>3</sup>/sec at the C-b tract. The computations suggest that over a 30-year period of activity at the C-a tract, the water table in the vicinity of a tributary to the Yellow Creek may be drawn down by as much as 31 m. Similarly, 60 years of MIS retorting at the C-b tract may

draw down the water table in the vicinity of the Piceance Creek by 100 m or more.

The studies indicate that in an expanding mine, the inflows are likely to be concentrated in the neighborhood of newly excavated regions where hydraulic gradients will be highest. It has been estimated that inflow into individual retorts may vary from  $0.15 \times 10^{-3}$  to  $0.95 \times 10^{-3}$  m<sup>3</sup>/sec. These inflow rates may or may not have significant effects on combustion efficiency, depending upon such factors as shale richness, uniformity of flow, and steam-air ratio.

In general, higher porosities, lower residual saturations, and higher permeabilities will tend to increase mine inflows. In view of the simplifying assumptions made in physical conceptualization of the system and the uncertainties in the input parameters, the results of the present study are only estimates, and the conclusions must be used or interpreted with caution.

INTRODUCTION

The Green River Formation of Colorado, Utah, and Wyoming is the largest and richest oil shale deposit in the world and is estimated to contain in excess of 600 billion barrels of high-grade, recoverable oil (Yen, 1976; Weeks et al., 1974). The recent energy crisis, increasing costs of crude petroleum, and high U.S. energy demand may make shale oil a cost-effective source of crude oil if economically feasible and environmentally acceptable methods of

recovery can be developed.

The C-a and C-b tracts in the Piceance Creek Basin are potential sites for the development of oil shale by the modified in-situ (MIS) retorting process. Proposed development plans for these tracts require the disturbance of large quantities of underground oil shale on an unprecedented scale. This disturbance coupled with removal of water (dewatering) which is required to prevent interference with mining operations and underground combustion, could profoundly alter the groundwater regime and could affect the surface waters of the surrounding area.

In evaluating hydrogeologic consequences, the present study investigates the nature and impacts of dewatering that are likely to accompany the MIS process. Previous studies along these lines have been carried out by the U.S. Geological Survey (Weeks et al., 1974; Robson and Saulnier, 1980) and others. (Tipton and Kalmbach, Inc., 1977; Golder Associates, 1977; Banks et al., 1978). A detailed comparison of the modeling efforts by these investigators is given elsewhere (Mehran et al., 1980). Although the geologic idealization of the hydrologic system in the present study is similar to that used by previous investigators, we have attempted to overcome some of the earlier limitations.

In this study, the flow regions around the C-a and C-b tracts are idealized as a multi-layered system of aquifers separated by aquitards. Within this system, the expanding mine is represented as a disc-shaped opening which grows with time. Water from the surrounding region drains into the mine at atmospheric pressure. As internal drainage progresses, the region above the mine will desaturate. This study considers saturated-unsaturated flow under isothermal conditions. A variable number of layers is used, and interaction between the layers is permitted. Temperature effects accompanying the retorting process,

rock-water interactions, and chemical transport mechanisms are not considered. The present study investigates the disturbance of the subsurface fluid flow regime around the proposed MIS facilities at the C-a and C-b tracts. It also seeks to identify, through a parametric approach, the key variables that are required to characterize such systems. It is hoped that this study will eventually lead to the design of carefully controlled field experiments which will provide the critically required field data for long-term predictions.

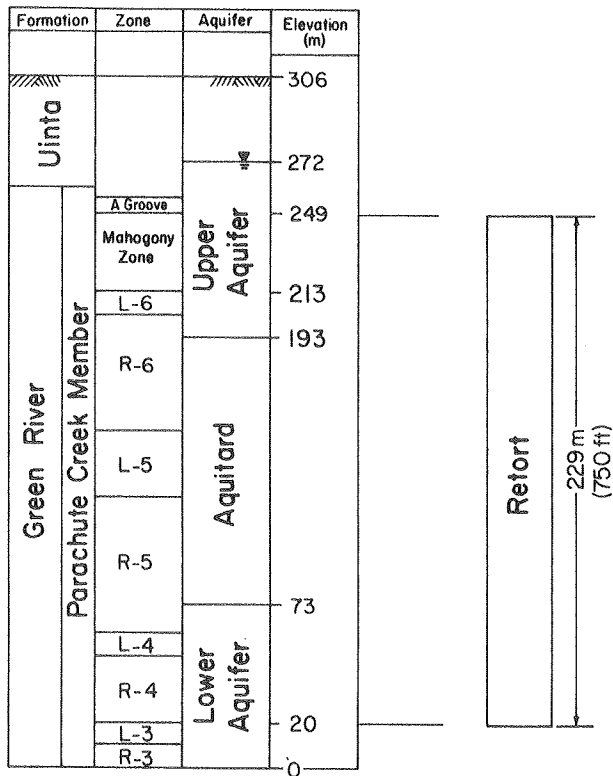
#### PROPOSED MINE DEVELOPMENT

The stratigraphy of the C-a and C-b tracts as well as available hydrologic data indicate that the medium is inhomogeneous and anisotropic. The general stratigraphic succession consists of an upper aquifer (including the alluvial zone), a confining layer, and a lower aquifer. The thickness of the flow region for the C-a and C-b tracts is taken to be 272 m (892 ft) and 690 m (2260 ft) from the bottom of the lower aquifer to the average position of the water table, which is about 34 m (111 ft) and 105 m (340 ft) below the land surface, respectively. The locations of the upper aquifer, the Mahogany Zone, and the lower aquifer and their thicknesses for the two tracts are given in Figures 1 and 2.

Internal drainage is used for dewatering at both tracts C-a and C-b in this analysis. Thus, underground mine development is the forcing function in our problem.

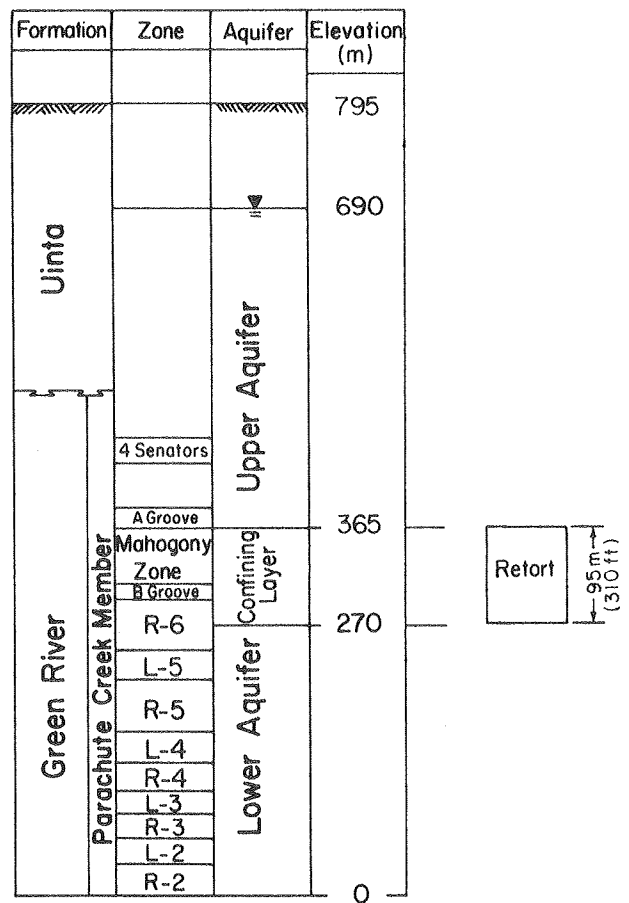
On the C-a tract, the retorts will have dimensions of 46 m x 92 m (150 ft x 300 ft) in plan and 229 m (750 ft) in height. On the C-b tract, the retort dimensions will be 61 m x 61 m (200 ft x 200 ft) in plan and 95 m (310 ft) in height.

Based upon data supplied in the Detailed Development Plan for the C-a tract (Rio Blanco Oil



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Figure 1. Stratigraphy of the C-a tract and location of the mining zone. R stands for the rich oil shale zone and L for a lean oil shale zone (After RBOSP, 1977). Datum is bottom of R-3 zone.



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Figure 2. Stratigraphy of the C-b tract and location of the mining zone. R stands for a rich oil shale zone and L for a lean oil shale zone. Datum is bottom of R-2 zone.

Shale Project, 1977) and for the C-b tract (Energy Development Consultants, Inc., 1980), the areal expansion of retorted area will be 26 hectares (64 acres) per year on the C-a tract and 38 hectares (94 acres) per year on the C-b tract. Figures 3 and 4 show this expansion as an equivalent increase in the radius of the disc-shaped retorted domain with time. Although the actual areal development will not strictly be an expanding circle, the radial geometry used here is assumed to be a reasonable approximation of the proposed temporal expansion.

#### THE NUMERICAL MODEL

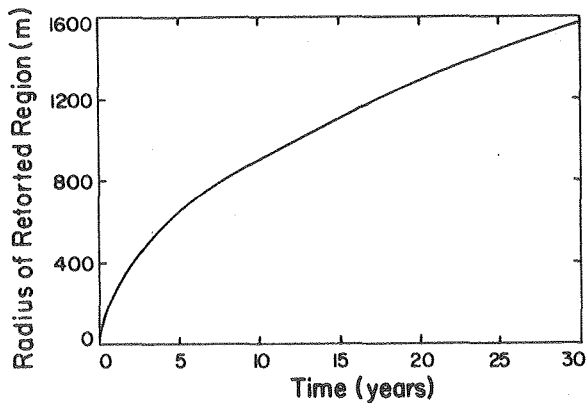
Dividing the flow region into appropriately small elements, the equation of conservation of mass

combined with Darcy's law yields:

$$G + \int_{\Gamma} \frac{k\rho_w g}{\mu} \nabla(z+\psi) \cdot \vec{n} d\Gamma = \frac{d}{d\psi} (\rho_w V_s e S) \frac{D\psi}{Dt} \quad (1)$$

where

- $\rho_w$  = density of water,
- $k_w$  = intrinsic permeability,
- $g$  = acceleration due to gravity,
- $\mu$  = fluid viscosity,
- $z$  = elevation head,
- $\psi$  = pressure head,
- $\vec{n}$  = outward unit normal to  $d\Gamma$ ,
- $\Gamma$  = the bounding surface of volume element,
- $V_s$  = volume of solids,
- $e_s$  = void ratio,
- $S$  = degree of saturation,
- $t$  = time,
- $G$  = volumetric rate of fluid generation,
- and  $D/Dt$  = the material derivative.



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Figure 3. Rate of expansion of the retorted area with time at the C-a tract.

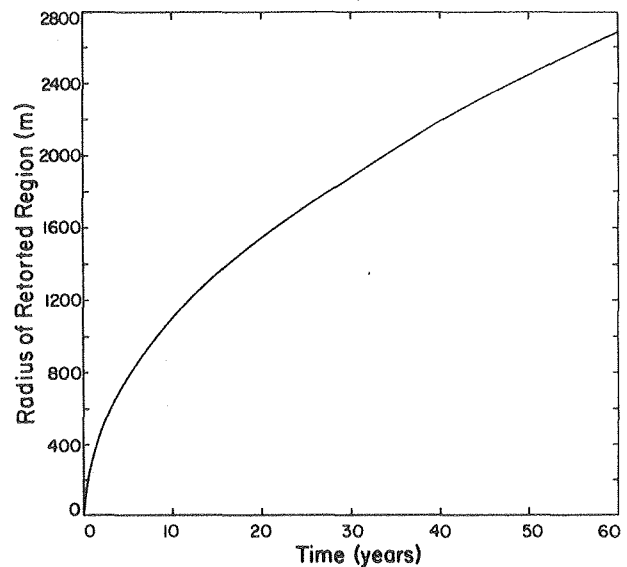
In Eq. (1),  $\frac{d}{d\psi} (\rho_w v_e s) = M_c$  is defined as the fluid mass capacity of the volume element. Upon differentiation and simplification, the following expression for  $M_c$  is obtained (Narasimhan and Witherspoon, 1977):

$$M_c = V_s \rho_w \left( \text{Sep}_{wo} \beta g + \frac{S y_w \chi'_c}{2.303 \sigma'} + e \frac{ds}{d\psi} \right) \quad (2)$$

where

$\beta$  = compressibility of water,  
 $\rho_w$  = density of water at atmospheric pressure,  
 $\gamma_{wo}$  = specific weight of water,  
 $C_w^c$  = coefficient of consolidation,  
 $\sigma'$  = effective stress,  
 and  $\chi'$  = parameter relating pore pressure and effective stress.

The three terms on the right-hand side of Eq. (2) represent three distinct quantities. The first term expresses the expansion of water as fluid pressure changes. The second term represents the deformability of the soil skeleton, and the last term denotes desaturation of the pores. Under many circumstances where flow takes place in an unsaturated state, the last term of Eq. (2) is dominant. However, some workers (e.g., Golder Associates, 1977) choose to approximate the desaturation term through an equivalent specific yield coefficient. Equation (1) is highly nonlinear because  $M_c$  and  $k$  are both strongly dependent on  $\psi$ . The resulting equations are



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Figure 4. Rate of expansion of the retorted area with time at the C-b tract.

solved by an integrated finite difference scheme using a Point Jacoby type accelerated iterative procedure with a mixed explicit-implicit strategy (Edwards, 1972; Narasimhan et al., 1978).

Analysis of flow in an unsaturated state requires a knowledge of the relationship between saturation and pressure head on the one hand and between permeability and pressure head on the other. These material properties can be obtained through laboratory or field experiments. Alternatively, one could also attempt to theoretically compute unsaturated hydraulic conductivity from saturation-pressure head data and other fundamental properties. In the present study, we have used the Millington-Quirk (1961) formula which is based on Poiseuille's equation for flow through a narrow tube.

Since the mined region is assumed to be a disc-shaped volume expanding with time, a procedure must be implemented to handle the time-dependent geometry of the opening. In the present work the dependence of geometry on time has been handled as a series of discrete jumps by stopping and restarting the problem

at appropriate intervals.

The numerical model presented here solves transient saturated-unsaturated flow in an axisymmetric flow region containing a time-dependent disc-shaped opening under various initial and boundary conditions. Anisotropy can be handled by the model by orienting volume elements in such a manner that their boundary surfaces are perpendicular to the principal direction of anisotropy.

## RESULTS

The numerical model described above has been used to study dewatering at the C-a and C-b tracts. These studies involved a parametric approach to ex-

plore the relative importance of various parameters. Long-term effects of dewatering and subsequent reinvansion were also investigated.

## Parametric Studies

The sensitivity analysis of dewatering was carried out for two years for an expanding retort at tract C-b. The following properties and parameters of the flow region are examined: 1) degree of saturation and its pressure head dependency, 2) hydraulic conductivity and its pressure head dependency, 3) material distribution, and 4) porosity. Table 1 summarizes the various cases that are considered in the sensitivity analysis and gives the magnitude of the

Table 1. Saturated-unsaturated properties considered in the sensitivity analysis.

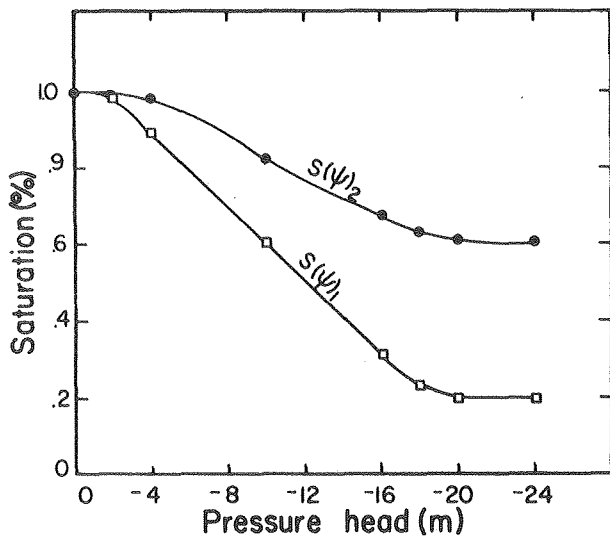
| Case | Layering        | Unsaturated Properties |                          | Saturated Properties  |                                   | Porosity | Coefficient of Compressibility<br>Pascal <sup>-1</sup> |
|------|-----------------|------------------------|--------------------------|-----------------------|-----------------------------------|----------|--|
|      |                 | Saturation<br>(Fig. 5) | Permeability<br>(Fig. 6) | Specific Storage      | Permeability<br>(m <sup>2</sup> ) |          |  |
| A    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.28     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0*                   | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| B    | Upper Aquifer   | $S(\psi)_2$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.28     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| E    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-15}$            | 0.28     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| F    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_3$              | --                    | $4.80 \times 10^{-14}$            | 0.28     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| C    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.28     | $10^{-9}$  |
|      | Confining Layer | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-15}$            | 0.01     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| G    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.10     | $10^{-9}$  |
|      | Confining Layer | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-14}$            | 0.01     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| H    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.01     | $10^{-9}$  |
|      | Confining Layer | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-14}$            | 0.01     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |
| D    | Upper Aquifer   | $S(\psi)_1$            | $k(\psi)_1$              | --                    | $4.80 \times 10^{-14}$            | 0.28     | $10^{-9}$  |
|      | Blanket         | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-15}$            | 0.01     | $10^{-9}$  |
|      | Mahogany Zone   | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-15}$            | 0.01     | $10^{-9}$  |
|      | Blanket         | $S(\psi)_1$            | $k(\psi)_2$              | --                    | $1.30 \times 10^{-15}$            | 0.01     | $10^{-9}$  |
|      | Lower Aquifer   | 1.0                    | --                       | $1.14 \times 10^{-5}$ | $1.28 \times 10^{-14}$            | 0.01     | --   |

\*The lower aquifer is assumed to remain saturated at all times.



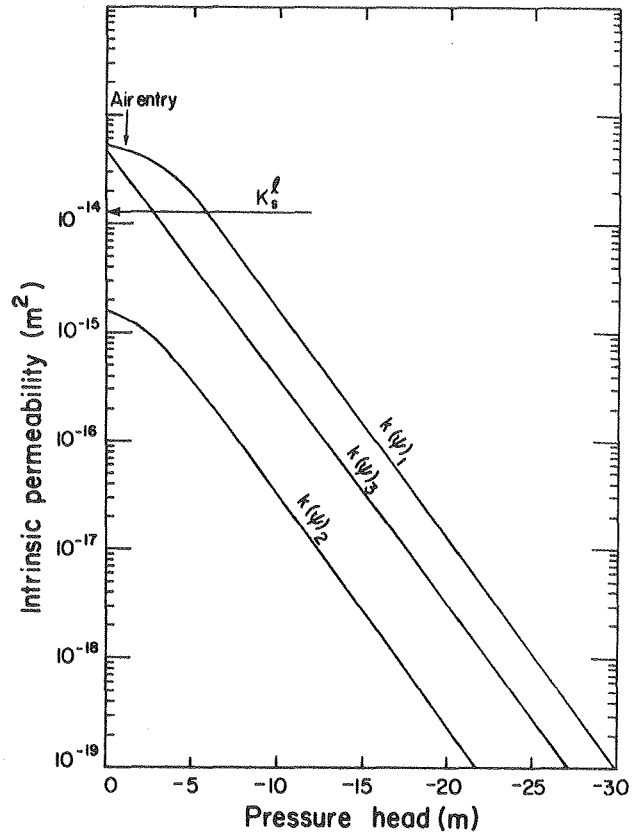
saturated and unsaturated properties. Figure 5 shows saturation-pressure head relationships,  $S(\psi)_1$  and  $S(\psi)_2$ , for two distinct material properties. The relationship between absolute permeability and pressure head is shown in Figure 6. The lower aquifer is assumed to remain saturated at all times with a saturated permeability of  $k_s^l = 1.28 \times 10^{-14} \text{ m}^2$ .

Figure 7 represents the variation of inflow rate with time for a two-year simulation of internal drainage into an expanding opening. The periphery of the retorted area after two years is at a radial distance of 500 m (1640 ft) from the axis of symmetry. The effect of saturation-pressure head relationships can be observed by comparing cases A and B. In the case B, pertaining to higher residual saturation,  $S(\psi)_2$ , both the inflow rate and its increase with time are smaller and tend to stabilize sooner. The influence of saturated permeability and the permeability-pressure head relationship can be seen by comparing cases A, F, and E. The difference in flow rate between cases A and F is due to the difference in the permeability-pressure head relationship



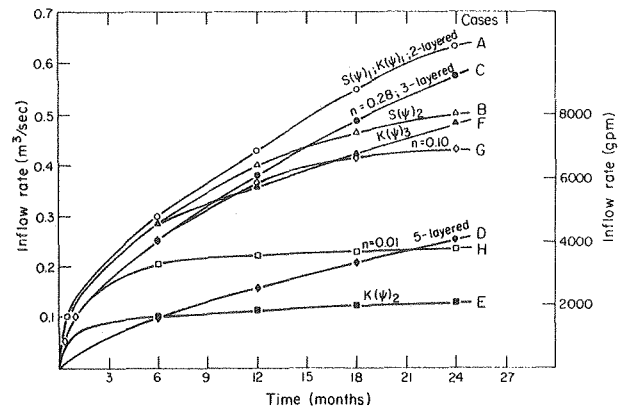
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Figure 5. Percent saturation as a function of pressure head for two different materials assumed in this study.



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Figure 6. The relationship between permeability and pressure head for three different materials undergoing desaturation. Saturated permeability of the lower aquifer,  $k_s^l = 1.28 \times 10^{-14} \text{ m}^2$ . Values shown were used in parametric studies only.



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Figure 7. Inflow rate as a function of time for various cases considered in the parametric studies.

in the negative range since they both have the same saturated permeability ( $k(\psi)_1$  and  $k(\psi)_3$ ). The large difference between the inflow rates in cases A and E are attributed to saturated-unsaturated permeabilities of  $k(\psi)_1$  and  $k(\psi)_2$ . The effect of material distribution, or number of layers with various physical properties, is investigated by comparing cases A, C, and D. In the two-layer case (A), only the upper aquifer is subject to desaturation.

In the three-layer case (C), a confining layer is introduced between the upper and the lower aquifers. In the five-layer case (D), it is assumed that part of the confining layer which has a smaller permeability remains intact as a blanket around the mining region. This simulates leaving a cap rock in place to minimize flow through the mining zone. The result, as expected, shows that introducing a confining layer with a low permeability largely reduces the flow over a long period of time. A drastic reduction in flow is observed in the five-layer case (D) where the retorted region is protected by a blanket of low permeability. This result may be important in situations where significant reduction of mine inflow rate is desired. The effect of porosity of the upper aquifer is studied by comparing the cases C, G, and H which are all three-layered and have the same saturated-unsaturated properties. It is evident from Figure 7 that in the initial stages of dewatering, the inflow rate for all three cases is the same, indicating that flow takes place in a saturated state. The deviations of inflow rates for the three cases becomes pronounced when the desaturation term  $e \frac{dS}{d\psi}$  of the fluid mass capacity becomes appreciable.

#### Long-Term Simulations

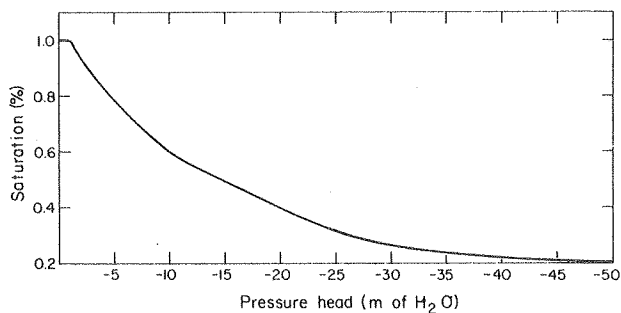
To understand long-term consequences of dewatering for MIS retorting, 30- and 60-year simulations were carried out for the C-a and C-b tracts, respec-

tively. The properties of the aquifer system used for these simulations are given in Table 2. The saturated hydraulic conductivities are within the range of values used by other workers (Tipton and Kalmbach, Inc., 1977; Golder Associates, 1977; Robson and Saulnier, 1980). The assumed, hypothetical, unsaturated properties of the medium are given in Figures 8 and 9 for saturation-pressure head and permeability-pressure head relationships, respectively. To avoid boundary effects, the modeled zone extends radially to a distance of 25 km (16 mi) from the center of the tracts. It is assumed that no other sinks exist in

Table 2. Properties used for long-term dewatering simulations.

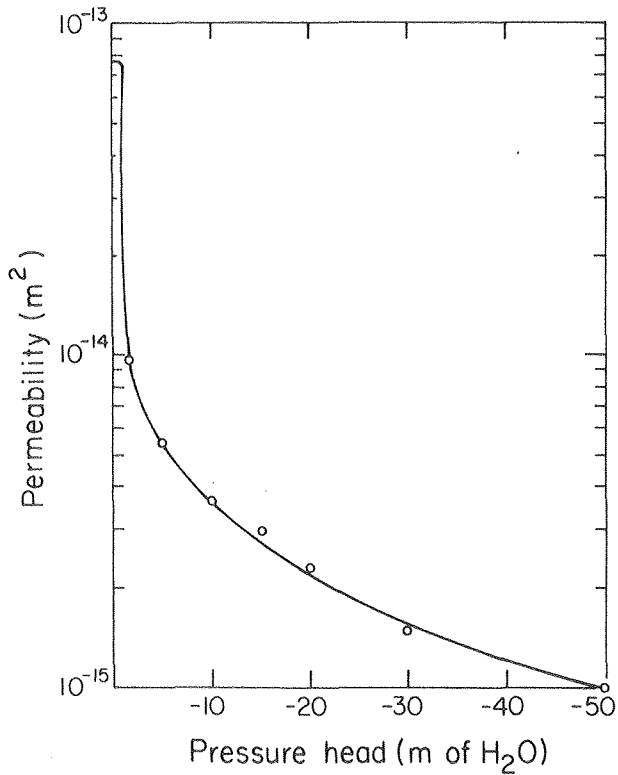
| Property   | Upper Aquifer           | Confining Layer        | Lower Aquifer           |
|--|-------------------------|------------------------|-------------------------|
| Saturated Permeability ( $m^2$ )                       | $7.64 \times 10^{-14a}$ | $2.00 \times 10^{-15}$ | $2.45 \times 10^{-14a}$ |
| Storage Coefficient                                    | --                      | --                     | $1 \times 10^{-4}$      |
| Coefficient of Compressibility (pascal <sup>-1</sup> ) | $1 \times 10^{-9}$      | $1 \times 10^{-9}$     | --                      |
| Porosity   | 0.15                    | 0.01                   | 0.01                    |
| Residual Saturation                                    | 0.20                    | 0.20                   | --                      |

<sup>a</sup>Based on Tipton and Kalmbach, Inc. (1977).



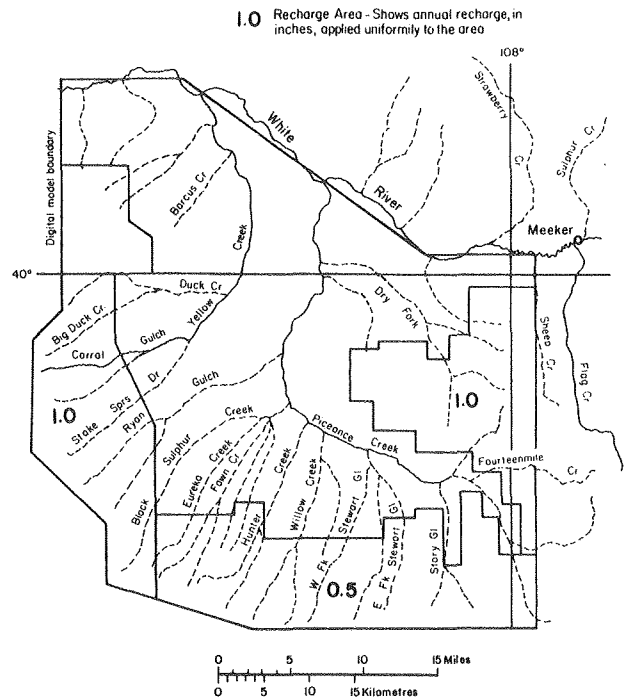
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Figure 8. Saturation-pressure head relationship for the unsaturated zone used for long-term simulations of dewatering and reinvasion.



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Figure 9. Variation of intrinsic permeability with pressure head computed from Millington-Quirk formula.



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Figure 10. The pattern and intensity of recharge in the Piceance Basin (after Weeks et al., 1974).

the modeled zone. In this analysis, surface recharge due to infiltration is based on the values and the pattern given by Weeks et al., (1974) as shown in Figure 10. Although there is sufficient evidence to show that the medium is anisotropic, due to lack of consistent data, this effect has not been considered in the long-term simulation analysis.

In the present investigation, actual modeling of the interaction of Yellow Creek and Piceance Creek with groundwater has not been carried out. Instead we have analyzed the cone of pressure depression caused by dewatering. The cone of depression indirectly helps to evaluate the potential for hydrologic consequences to the surrounding surface water bodies.

#### The C-a Tract

In the dewatering simulations of the C-a tract, it is assumed that the thickness of the retort interval is 229 m (750 ft) extending from the top of the Mahogany Zone to the bottom of the R-4 layer as shown in Figure 1. The variation of inflow rates for the 30-year simulation of dewatering is shown in Figure 11 using two different saturated permeabilities for the lower aquifer. The smaller inflow rate, which corresponds to hydraulic properties given in Table 2, reaches a value of  $0.15 \text{ m}^3/\text{sec}$  (2300 gpm) at the end of 30 years. The transmissivity of the lower aquifer is  $1.23 \text{ m}^2/\text{d}$  (99 gpd/ft). The larger inflow rate ( $1.38 \text{ m}^3/\text{sec}$  or 21,800 gpm) corresponds to the case where the transmissivity of the lower aquifer is assumed to be  $87 \text{ m}^2/\text{day}$  (7000 gpd/ft) (Rio Blanco Oil

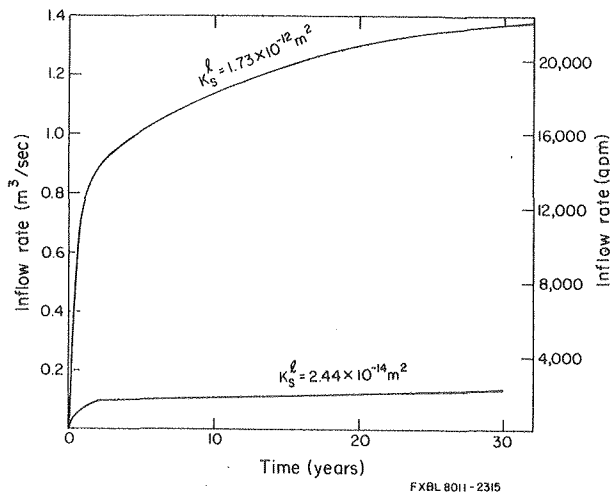


Figure 11. Variations of inflow rates with time over the C-a tract for two permeabilities for the lower aquifer.

Shale Project, 1977). The inflow rate in this case is about 10 times the previous case, indicating that the lower aquifer plays a significant role in the dewatering operation at the C-a tract. This behavior is expected because the thickness of the upper aquifer is very small, and the aquitard constitutes a large portion of the overall aquifer system. It is clear that since the contribution of the upper aquifer to the total inflow into the mine is small, the effect of porosity and unsaturated properties of the upper aquifer on flow rates would also be less significant. At the C-b tract, on the other hand, the situation will be different due to the greater thickness of the upper aquifer.

According to Rio Blanco (1977), water use on the C-a tract during the commercial phase will be 0.0875 m<sup>3</sup>/sec (1400 gpm). The results of this study show that even the lowest estimates of lower aquifer permeability can furnish more than the required water for consumption.

The position of the phreatic surface at various times, along with the advancement of the retorted area, are shown in Figure 12. Due to the small thickness of the upper aquifer, the medium above the retorted region always exists in a desaturated state. As will be seen, this is not the case for the C-b tract, and this effect may give MIS retorting on the C-a tract an advantage.

The fluctuation of the water table at a radial distance of 5 km (3.1 mi) from the center of the tract (approximate location of waters tributary to Yellow Creek) for the high permeability case is shown in Figure 13. The water table initially rises because of the effect of recharge up to about 15 months after which the influence of dewatering becomes dominant. The maximum drawdown of the phreatic surface after 30 years of dewatering is estimated to be 31 m (100 ft).

The C-b Tract

The variation of inflow rate for the 60-year life of the project at the C-b tract is shown in Fig-

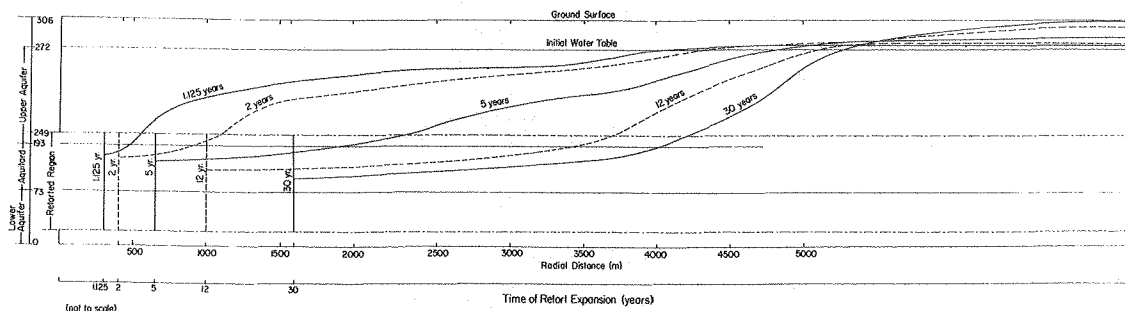
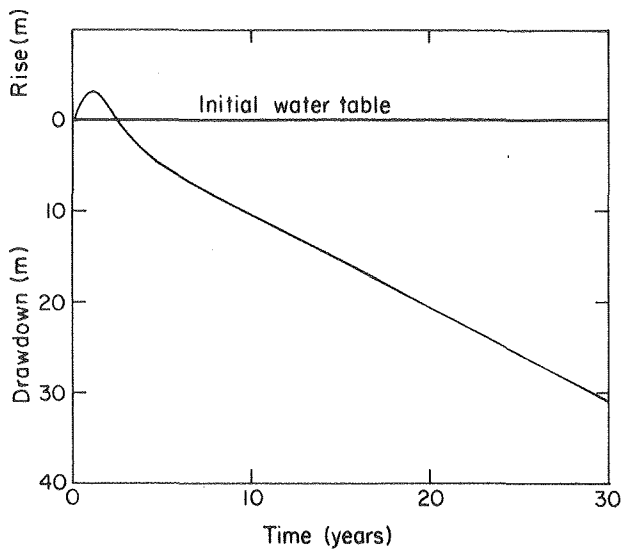
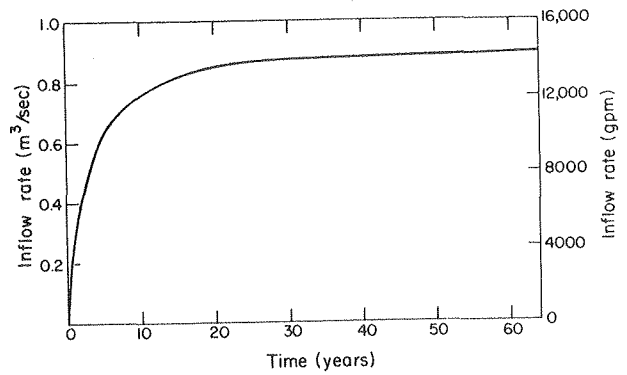


Figure 12. The position of the phreatic surface for dewatering the C-a tract in an expanding retort scenario. (Note: Figure not to scale).



FXBL 8011-2316

Figure 13. Water table fluctuations at a radial distance of 5 km from the center of the C-a tract.



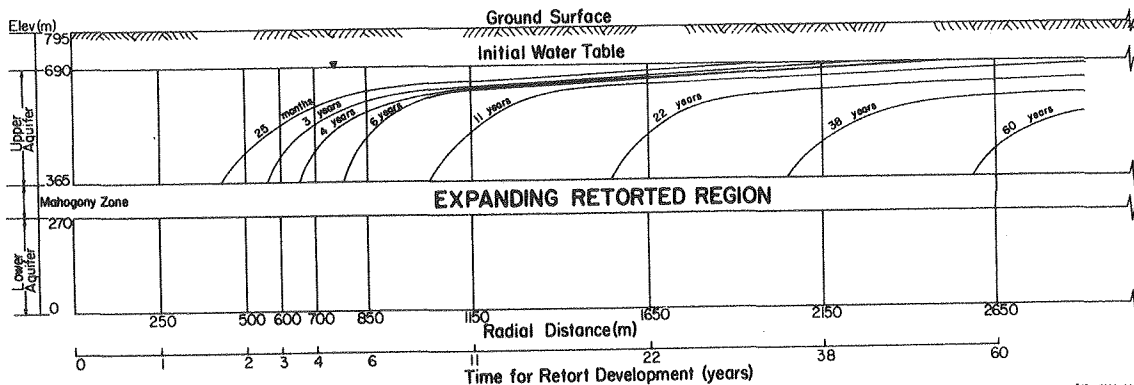
FXBL 8011-2319

Figure 14. The 60-year simulation of dewatering for the C-b tract.

ure 14. The expansion of the mine is the primary reason for the continuous but gradual increase in mine inflow rate which reaches at  $0.9 \text{ m}^3/\text{sec}$  (about 14,200 gpm). Assuming a production level of 50,000 barrels per day and a maximum water consumption of 6.6 barrels per barrel of oil (Fox, 1981),  $0.62 \text{ m}^3/\text{sec}$  (9800 gpm) of pumped water will be used. Therefore, the balance is excess water at the site and could either be reinjected into the ground, used for stream flow augmentation, used by another oil

shale plant, or disposed of as waste. Considering the large drawdowns of the water table in the vicinity of the Piceance Creek, the options of reinjection or stream flow augmentation appear most likely. In our analysis, it is assumed that there is no interference from any other mining activity requiring dewatering of the modeled area.

As desaturation proceeds, the phreatic surface becomes dynamic and moves downward as shown in Figure 15. The position of the periphery of the retorted region and corresponding position of the phreatic surface are shown in this figure as a function of time. This figure demonstrates that at the C-b tract, the tail of the phreatic surface intersecting the roof of the retort lags the front of the mined



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Figure 15. The position of the phreatic surface for dewatering the C-b tract in an expanding retort scenario.

region. This perhaps can give an indication of the proper timing for the retorting process. This means that the actual retorting process can be delayed until the phreatic surface reaches the expected periphery of the caved region causing a considerable reduction in retort inflow rate. The primary reason for the difference between the location of the phreatic surface relative to the position of the front of the mined region for the C-a and C-b tracts (see Figures 12 and 15) is the thickness of the overburden above the excavated region which is about 10 times greater at the C-b tract.

The model results show that the contribution of the<sup>8</sup> unsaturated region of the upper aquifer to the overall inflow into the mine is substantial at the C-b tract primarily because of the large thickness of the upper aquifer.

Figure 15 also demonstrates the effect of dewatering at distances away from the center of the tract. The drawdown of the phreatic surface at 3.5 km (2.2 mi) from the center of the tract, which is the approximate location of the Piceance Creek, is shown in Figure 16. Our computations indicate that the phreatic surface could be lowered by as much as

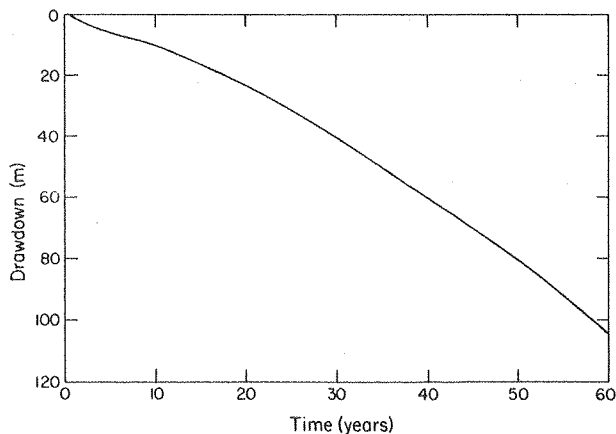


Figure 16. Drawdown of the phreatic surface for the 60-year simulation of dewatering at a radial distance of 3.5 (2.2 mi) km from the center of the C-b tract.

100 m (330 ft) or more after 60 years of dewatering. This suggests that water may be lost from the Piceance Creek and its tributaries and that flow from local wells may be reduced. Additional work is required to quantify the effect of drawdown on stream and well flow. The estimates of drawdown by Tipton and Kalmbach, Inc. (1977) at the end of 60 years is less than 60 m (200 ft) at a distance of 3 km (2.2 mi) from the center of the tract.

#### Estimation of Inflow into Retorts and Implications for Combustion

The model results of the 60-year simulation of dewatering at the C-b tract indicate that about 44% of total inflow into the mine passes through the roof of the excavated region and 53% through the floor. The remaining 3%, the inflow which intersects the periphery of the retorted region, is governed by low permeability of the confining layer. The results also demonstrate that as we approach the center of the retorted area, the inflow rate into the mine decreases rapidly. It is evident that in the vicinity of the newly excavated region, the induced gradients are very high, causing large contributions of flow into the mine.

For mining and retorting purposes, it would be useful to know approximately what fluxes (inflow rate per unit cross-sectional area of flow) exist at the surfaces of the newly excavated regions. This would provide some insight into the expected combustion efficiency as a result of mine inflow.

The results obtained for both tracts show that although the inflow rate increases with time as the retorted region expands, the flux decreases, since in an axisymmetric system, areas expand geometrically with increasing radius. Knowing the inflow rate into the newly excavated region, the flux has been computed and shown in Table 3 for certain selected times at both tracts.

Recent work by Braun et al. (1980) indicates that the acceptable inflow rate into a retort to sustain combustion efficiency depends on the uniformity of flow, richness of the oil shale, steam-air mixture, and other factors. Assuming a uniform water flow into the Zero Retort recently burned at the C-a tract and assuming a steam-air mixture of 30% and 70%, respectively, a total inflow rate of  $1.9 \times 10^{-4} \text{ m}^3/\text{sec}$  (3 gpm) over the entire retort having plan dimensions of 9.1 m x 9.1 m (30 ft x 30 ft) appears to be acceptable. According to Table 3, during the early periods of the project, one might expect total inflows of  $0.47 \times 10^{-4} \text{ m}^3/\text{sec}$  (0.75 gpm). The inflow rate will decrease with time toward the end of the project as fluxes gradually decrease. The flow rate for the commercial-size retorts in the early stages of dewatering will be higher since the plan area is larger.

At the C-b tract, the flux into an individual retort with plan area of 61 m x 61 m (200 ft x 200 ft) varies from more than  $0.946 \times 10^{-3} \text{ m}^3/\text{sec}$  (15 gpm) in the first 10 years of dewatering to less than  $0.126 \times 10^{-3}$  (2 gpm) at the end of the project. More detailed simulation of individual retorts is required for better estimates.

Table 3. Flux into the newly excavated regions at the C-a and C-b tracts.

| C-a Tract                    |   | C-b Tract                    |   |
|------------------------------|---|------------------------------|---|
| Time after Dewatering (year) | Flux ( $\text{m}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ ) | Time after Dewatering (year) | Flux ( $\text{m}^3 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ ) |
| 1.125                        | $0.573 \times 10^{-6}$  | 6                            | $0.125 \times 10^{-6}$  |
| 2                            | $0.239 \times 10^{-6}$  | 11                           | $0.057 \times 10^{-6}$  |
| 5                            | $0.177 \times 10^{-6}$  | 22                           | $0.028 \times 10^{-6}$  |
| 12                           | $0.104 \times 10^{-6}$  | 38                           | $0.0196 \times 10^{-6}$                                       |
| 30                           | $0.030 \times 10^{-6}$  | 60                           | $0.0146 \times 10^{-6}$                                       |

## CONCLUSIONS

The above-described analyses lead to the following conclusions:

1. The results of the parametric studies indicate that the nature of the desaturation process could play an important role in the flow behavior of thick unconfined aquifers.
2. The long-term simulations of dewatering show that although inflow rate into an expanding mine could be high and that it increases with time, the flux (inflow rate per unit area) is relatively low and decreases as mine development proceeds.
3. The fluctuations of the phreatic surface indicate that large drawdowns may be observed even at large distances from the center of the tracts. These could affect the surface water bodies in the region.
4. The credibility of the predictive models is greatly dependent upon their conceptual soundness which in turn depends on the manner in which: a) the system is geometrically idealized, b) the distributed material properties are generalized, and c) the completeness with which the physical phenomena are considered. The present analysis indicates an urgent need for realistic characterization of large-scale field problems such as those at the C-a and C-b tracts. Particular emphasis should be directed toward measurements of directional transmissivities of the aquifers and vertical permeability of the Mahogany Zone.
5. The conclusions drawn from this study should be exercised with caution primarily because of the uncertainties in the field data and the simplifying assumptions made in the physical conceptualization of the system.

#### ACKNOWLEDGEMENTS

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