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Project Summary

Procedures for Predictive Analysis of Selected Hydrologic Impacts of Surface Mining

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This report presents a methodology for the prediction of selected hydrologic impacts of surface coal mining. Procedures are provided for estimating the chemical and hydrologic parameters required by an algebraic water quality model. The model predicts the long-term mean dissolved solids concentration in combined direct and subsurface runoff from a watershed partially disturbed by mining. The computational procedure is demonstrated in a step-by-step calculation for a mine site in Colorado. The predicted results are in satisfactory agreement with short-term (2 and 3 year) observations.

Procedures for determining the transmissivity of coal and overburden aquifers from single-hole aquifer tests are provided. The procedures permit the analysis of recovery data, affected by well-bore storage, following a prolonged pumping period. Well-bore storage is an important effect in the recovery of low transmissivity aquifers often encountered in coal mining related hydrology. Several approximate, closed-form formulas for estimating selected impacts of surface mining on groundwater are provided. Among them are formulas for estimating groundwater inflows to an advancing pit and to a pit advancing parallel to an alluvial valley. Formulas for calculating the extent of the depressed piezometric surface as a function of time and distance from the pit are developed. These formulas can be used to assess the probable severity of corresponding impacts and to judge the need for additional data and more detailed models in site specific situations.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Federal and State regulations require an analysis of the potential influence of coal mining upon the hydrologic balance in the area affected by mining. Potential effects of coal mining upon the hydrologic balance include changes in the quality of ground and surface waters and a modification of the relative quantities of direct and groundwater runoff. Other possible effects are the modification of recharge to regional and local aquifers, a change in the pattern of groundwater flow, and a shift in the magnitude and peak of the runoff hydrographs. The changes that may be anticipated are different in the active mining phase than in the long-term, post-mining phase.

Implicit is the requirement that the influence of a particular mining project upon the hydrologic balance be predicted before mining is initiated. This can be accomplished only through the use of models, even if they are conceptual Each component of the hydrologic balance is a complex phenomenon that exhibits all of the vagaries of natural processes. Models range from simple, non-quantitative concepts through sophisticated stochastic models to detailed, physically-based descriptions. Those who are faced with the preparation and review of predictions relative to the hydrologic consequences of mining must select methods or models upon which to draw conclusions. The most useful set of models provides results in the desired, suitably reliable form, commensurate with the experience, technical knowledge, resources, and data that can be reasonably obtained by the user.

In keeping with this perception, this report presents a set of methods by which the influence of surface coal mining upon the hydrologic balance can be analyzed. The methods presented in this report are not applicable to all situations, of course, nor are they intended to be. The application of the methods is demonstrated through examples. It is anticipated that interested readers will devise ways to modify the procedures for site specific needs. It is hoped that a reasonable balance has been struck between the degree of rigor and realism in the methods and the knowledge, resources, and data required to apply them. The emphasis throughout the report is on guidelines for application rather than on theoretical justification.

A Combined Water and Salt Balance

Of interest is the change in the water quality hydrology that results from disturbing a portion of a watershed by surface mining. Based upon a simple water and dissolved solids balance, the long-term mean concentration of dissolved solids in total runoff (direct and subsurface) from a watershed partially disturbed by mining can be expressed as

$$P_t = \frac{KRP_n + P_m}{1 + KR}.$$

In this model, P_t is the mean concentration of dissolved solids in total watershed runoff, P_n is the mean concentration in combined direct and subsurface runoff from the undisturbed (natural) portion of the watershed, and P_m is the corresponding quantity for the mined portion. R is the ratio of the area of the natural land to the area of the mined land, while K is a hydrologic parameter that characterizes the relative quantity of total runoff on the undisturbed and disturbed portions of the watershed Both the relative quantity and quality of direct and subsurface runoff from the mined land are important determinants of the parameter P_m. The relationship is

$$P_m = f_{sm} P_{sm} + (1 - f_{sm}) P_{gm}$$

where f_{sm} is the fraction of the total runoff from the mined land that is direct runoff, P_{sm} is the dissolved solids concentration in direct runoff, and P_{gm} is the dissolved solids concentration in the subsurface runoff.

It is anticipated that pre-mine monitoring will establish the value of P_n, and the appropriate value for R is determined from the mine plan. The remaining parameters to be estimated are P_{sm}, P_{gm}, f_{sm} and K Probably the most reasonable estimate of P_{gm} can be made from a judicious study of the quality of spoil water from nearby mines in a similar hydrogeochemical environment. Sampling of springs formed on the interface between the spoil and the undisturbed underburden and/or of wells completed in the spoil aquifer is recommended. In the absence of this possibility, present experience suggests that the dissolved solids concentration in extracts from saturated drill cuttings will provide a reasonable lower limit for P_{gm}.

The hydrologic parameter K, being the ratio of total unit area runoff on the undisturbed ground to that on the mined land, depends directly on the relative consumptive use of water on the two portions of the watershed. The quantity of water consumptively used depends, in turn, upon the type and quality of vegetal cover, the potential evapotranspiration, and the timing and volume of infiltration into the soil. In arid and semi-arid climates, the potential annual evapotranspiration is larger than the mean annual precipitation. Considering the fact that a fraction of precipitation is lost by direct runoff instead of entering the root zone, it becomes apparent that the potential evapotranspiration is an even greater multiple of the volume of soil water available for plant use. At first glance it would seem, therefore, that no subsurface runoff would occur under such circumstances. However, the timing and volume of infiltration may be such that, at particular times, the water holding capacity of the soil is exceeded and percolation through the root zone occurs. This is especially true where a large fraction of the annual precipitation is in the form of snow that accumulates through the winter and melts quickly in the spring. Subsurface runoff may occur in response to percolation below the root zone during this period, even though there exists a deficit of available soil moisture on the average over the year. Thus, both K and f_{sm} are directly dependent upon the partitioning of precipitation into infiltration and direct runoff components.

The procedures used to estimate the long-term values for K and f_{sm} are based upon long-term mean water balance computations made for the surface and the root zone. The surface water balance is used to compute infiltration by subtracting direct runoff from precipitation. The infiltration is then used as input to the soil-water zone balance. The subsurface runoff is computed as the residual required to maintain a soil-water zone balance.

The first step in this procedure is to compute long-term mean monthly direct runoff The Soil Conservation Service Curve Number method is used to estimate daily direct runoff by month using the historical precipitation record as input. A histogram procedure is provided that minimizes the required computations. The mean monthly direct runoff is subtracted from the mean monthly precipitation to yield the mean monthly infiltration Table 1 shows the results of one such computation.

Infiltration is used as input to the soil-water zone balance computation. An accounting is kept of the available water in storage in the root zone as a means of determining when the evapotranspiration demand exceeds the quantity of water available. By this method, the actual evapotranspiration is calculated as being equal to the demand or to the quantity available, whichever is limiting. Percolation below the root zone occurs when infiltration is sufficient to exceed the evapotranspiration demand plus any deficit in available water storage. Table 2 shows the results of a computation on mined land.

The mean annual direct runoff, together with the mean annual subsurface runoff, are used to compute K and f_{sm} directly from the definitions of these parameters. The procedures outlined

Table 1. *Summary of Surface Water Balance*

Total	*Total Prec (cm)*	*Loss from Snow Pack (cm)*	*Available Prec*		*Direct Runoff*		*Infiltration*	
			Snow (cm)	*Rain (cm)*	*Spoil (cm)*	*Natural (cm)*	*Spoil (cm)*	*Natural (cm)*
Jan	*4.6*	*1.5*	*0*	*0*	*0*	*0*	*0*	*0*
Feb	*4.5*	*1.5*	*0*	*0*	*0*	*0*	*0*	*0*
Mar	*5.6*	*1.5*	*0*	*0*	*0*	*0*	*0*	*0*
Apr	*5.0*	*1.5*	*17.5*	*1.3*	*0.58*	*0.29*	*18.2*	*18.5*
May	*3.6*	*0*	*0.8*	*2.8*	*0.04*	*0.03*	*3.6*	*3.6*
Jun	*3.8*	*0*	*0*	*3.8*	*0*	*0*	*3.8*	*3.8*
Jul	*3.3*	*0*	*0*	*3.3*	*0*	*0*	*3.3*	*3.3*
Aug	*4.3*	*0*	*0*	*4.3*	*0*	*0*	*4.3*	*4.3*
Sep	*4.4*	*0*	*0.6*	*3.8*	*0.05*	*0*	*4.3*	*4.4*
Oct	*4.2*	*0*	*1.3*	*2.9*	*0*	*0*	*4.2*	*4.2*
Nov	*4.0*	*1.5*	*0*	*1.0*	*0*	*0*	*1.0*	*1.0*
Dec	*5.1*	*1.5*	*0*	*0*	*0*	*0*	*0*	*0*
	52.4	*9.0*	*20.2*	*23.2*	*0.7*	*0.3*	*42.7*	*43.1*

briefly above and given in detail in the report were used to predict P_t for a mined area where measured values of P_t were available for comparison. The comparison is shown in Table 3. It is believed the agreement is satisfactory considering that the measured values are not long-term averages.

Table 2. *Soil-Water Balance in Spoil**

Month	*AW† (cm)*	*Deficit† (cm)*	*I (cm)*	E_{tp} *(cm)*	E_t *(cm)*	E_{ta} *(cm)*	ΔS *(cm)*	*W (cm)*
Oct	*0*	*6.6*	*4.2*	*5.3*	*2.6*	*2.6*	*+1.6*	*0*
Nov	*1.6*	*5.0*	*1.0*	*0*	*0*	*0*	*+1.0*	*0*
Apr	*2.6*	*4.0*	*18.2*	*5.4*	*3.2*	*3.2*	*+4.0*	*11.0*
May	*6.6*	*0*	*3.6*	*10.0*	*7.2*	*7.2*	*–3.6*	*0*
Jun	*3.0*	*3.6*	*3.8*	*14.8*	*10.7*	*6.8*	*–3.0*	*0*
Jul	*0*	*6.6*	*3.3*	*16.4*	*11.8*	*3.3*	*0*	*0*
Aug	*0*	*6.6*	*4.3*	*14.1*	*9.2*	*4.3*	*0*	*0*
Sep	*0*	*6.6*	*4.3*	*9.6*	*4.9*	*4.3*	*0*	*0*
			42.7	*75.6*	*49.6*	*31.7*	*0*	*11.0*

**AWC = 6.6 cm*
†Evaluated at beginning of month

Single-Well Aquifer Tests in Coal Hydrology

Aquifer tests are the primary means of determining the hydraulic parameters of water-bearing strata that are required for projecting the effect of mining on the groundwater regions and for estimating the quantities of groundwater inflow that can be anticipated in the mine workings. Single-well aquifer tests have found substantial use in coal hydrology where permeabilities are low and drawdown cones are excessively steep.

Single-well aquifer tests may be performed by "instantaneously" changing the water level in the well and monitoring the recovery or by pumping the well for a prolonged period before monitoring the recovery. The first method is a slug test and the response is reflective of the aquifer properties in a small volume of aquifer in the immediate vicinity of the well bore. This disadvantage is offset to some degree by pumping for a prolonged period prior to monitoring the recovery. This report presents two methods by which the recovery data collected after a prolonged pumping period can be analyzed. The first method is an extension of existing theoretical response functions for the pumping period to application to the recovery period. Full consideration is given to the effects of afterflow caused by non-zero well-bore storage. Figure 1 shows the theoretical response functions superimposed on a set of recovery data collected after a prolonged pumping period.

An algebraic method applicable to recovery analysis was developed also. This method is based on superposition of the familiar line-sink solutions to account for the variable afterflow discharge. The algebraic method is an approximate procedure easily adaptable for desk-top computer calculations. This method does not require the somewhat subjective matching of type curves. The range of applicability and accuracy of the algebraic method were investigated by comparison with the exact solution used by the first method; guidelines for use are provided.

Analysis of Selected Flow Problems

Aspects of groundwater hydrology that may be important during the mining phase include: 1) the quality and quantity of inflows to pits, shafts, or other excavations, 2) the resultant lowering of the piezometric surface in the affected aquifers, 3) inflow to the mine from fault zones, 4) the lowering of water levels in infrequently recharged alluvial aquifers adjacent to the mine, and 5) sustained inflows from frequently recharged alluvial aquifers. This report presents analyses and solutions that are specifically oriented toward such problems that are known to have been encountered in surface mining projects.

Flow to an advancing pit that incises one or more aquifers is treated. The method of succession of steady states is used to calculate the inflow as affected by the rate of advance of the pit and the conversion of the aquifer from confined to unconfined in the vicinity of the pit. Figure 2 shows the cross section through the pit that is used in the analysis and is typical of the degree of idealization utilized in all of the developments. The results of an example computation of inflows to an advancing pit are shown in Figure 3.

A similar analysis was used to develop formulas for inflow to a mine that is initiated on a crop line. The method accounts for the fact that successive pits constructed in the down-dip direction will induce incrementally greater draw-downs in the affected aquifer. The problem of inflow to a pit advancing parallel to an alluvial valley is treated. The results can be used to estimate the quantity of alluvial groundwater induced into the pit as affected by the width and hydraulic properties of the buffer zone. Also, a formula is developed for prediction of the lowering of the water table in an alluvial aquifer as the result of nearby mining. Finally, an analysis of the groundwater buildup and discharge from spoil banks subjected to periodic recharge is provided. Example applications and computations for each of these problems are presented.

Table 3. *Comparison of Predicted P_t with Measured Values*

Watershed No.	R	Predicted P_t (mg/l)	Avg. Meas. P_t (mg/l)	Range of Meas. P_t (mg/l)
C 3	0.47	2220	1840	1610-2030
C 5	0	2860	2910	2830-3080
C 9	1.86	1450	1240	1190-1290
C10	1.27	1670	1850	1850-1860
C 9 + C 10	1.44	1600	1550	1520-1580

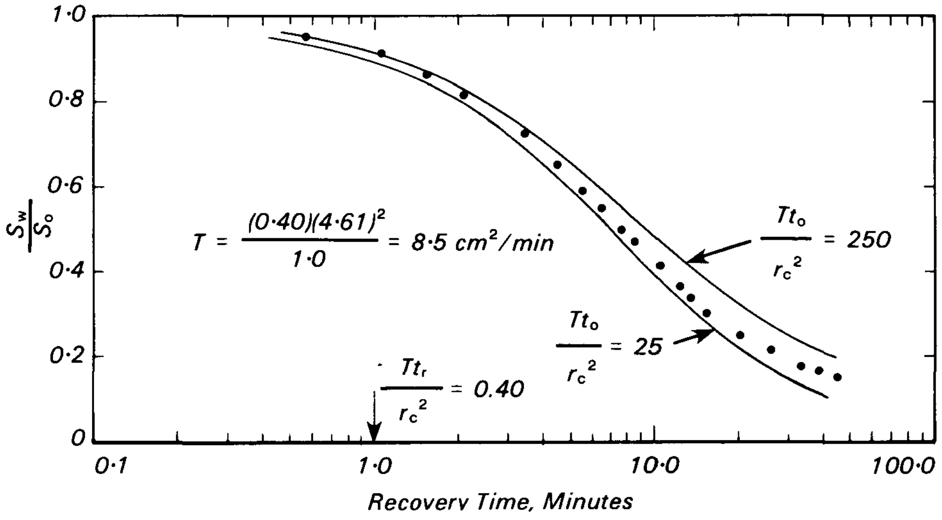

Figure 1. *Superposition of response functions on data plot for Example 1.*

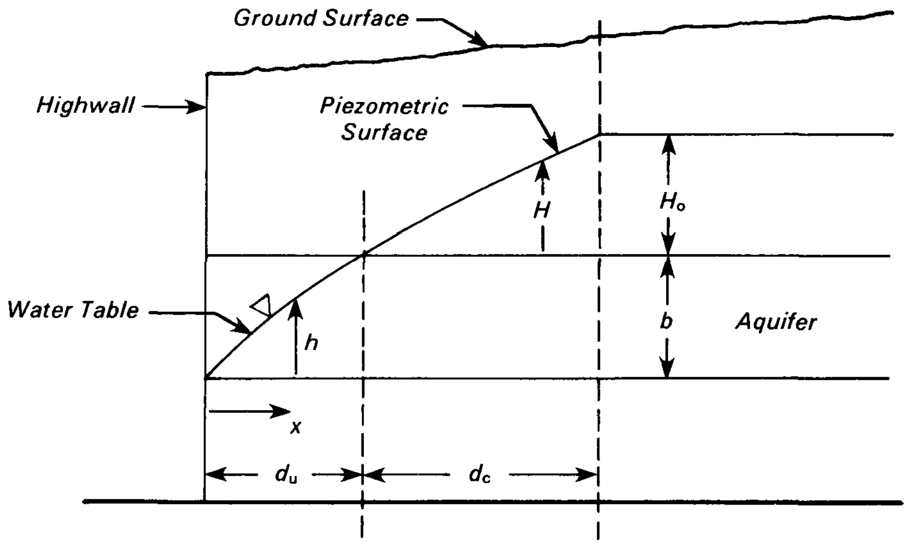

Figure 2. *Definition sketch for flow to the first cut.*

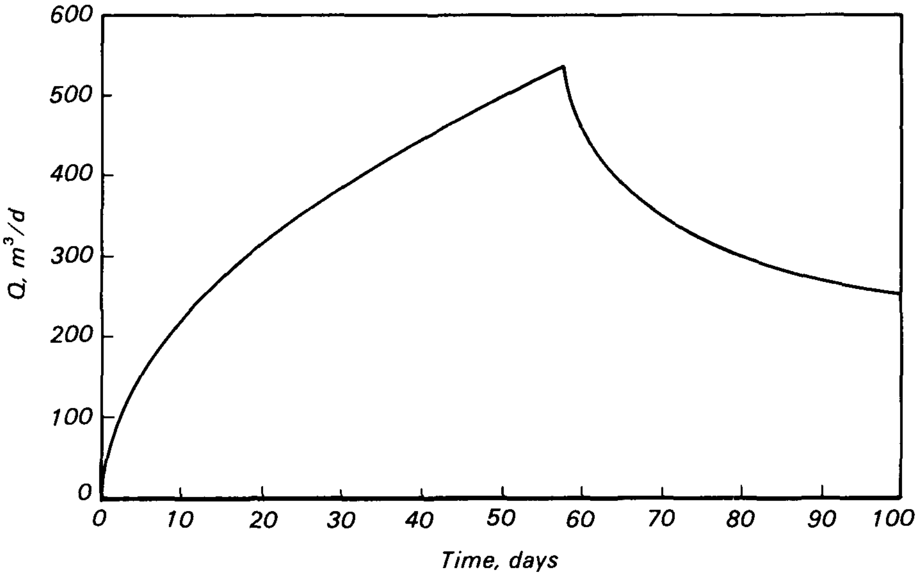

Figure 3. *Calculated inflows to box cut for Example 1.*

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The complete report, entitled "Procedures for Predictive Analysis of Selected Hydrologic Impacts of Surface Mining," (Order No. PB 82-258 476; Cost: $11.50, subject to change) will be available only from:

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