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BASIC MINING HYDROGEOLOGY

A Study Guide For
A Mini-Course Given at the

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by

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TABLE OF CONTENTS

Page

I. INTRODUCTION 1
  - Basis and Purpose of Mini-Course 1
  - Mini-Course Principals.................. 1

II. BASIC HYDROGEOLOGY............................. 2
  - Aquifers, What Are They?................ 4
    - Soil or Rock Hydrogeologic Properties........................ 4
    - Areal Extent....................... 6
  - Recharge, Discharge and Dynamic Equilibrium.......................... 7
    - Energy............................. 8
    - Hydraulic Gradient................. 9
    - Divides............................ 10
  - Natural Ground-Water Flow Systems....... 11
    - Ground-Water Flow Through Rocks.... 12
    - Concept of a Point and the Flow Continuum........................ 13
    - Properties of the Flow Continuum........................ 14
    - Darcy's Law and General Flow Equations........................ 16
      - Storage....................... 18
      - Transmissivity and Storativity................. 20
      - Transient Water Levels........ 20
  - Ground-Water Management Concepts........ 21
    - Storage-Mining Concept............. 22
    - Dynamic-Equilibrium Concept........ 24
  - Hydrogeochemistry....................... 26
  - Analyzing Ground-Water Flow Systems..... 29
  - Pressure Distribution in Ground-Water Basins......................... 31

III. PRACTICAL APPLICATIONS OF GROUND WATER MANAGEMENT.............................. 37
  - Introduction............................ 37
  - Wet Pits................................ 38
  - Open Pit Dewatering..................... 40
    - Design of Investigations........... 44
    - Previous Work...................... 44
    - Data Synthesis..................... 44
    - Geophysical Data................... 46
    - Data Integration................... 49

Page

Ground-Water Monitoring................. 49
    Classification of Ground-Water Monitoring Systems............... 51
    Stress of Environment.............. 51
    Monitor Well Design and Installation..................... 52
    Well Development................... 54
Dewatering and Depressurizing Programs.. 59
    Modeling a Dewatering/ Depressurizing System............ 66
    Computer Modeling.................. 68
Case Histories: Dewatering/ Depressurizing Programs................ 72
    Basic Programs: Wells............. 72
    Other Programs: Ditches and Drains......................... 75

IV. PERMITTING (SMCRA REGULATIONS PL 95-87)...... 77

V. WHAT CAN GO WRONG?.......................... 77

VI. SELECTED REFERENCES

VII. ILLUSTRATIONS

Figures

Figure 1: The Hydrologic Cycle.......... 3
Figure 2: Subsurface Classification..... 4
Figure 3: Perched, Confined and Unconfined Aquifers......... 6
Figure 4: Comparison of Selected Fluid Flow Numerical Models Developed................... 33
Figure 5: Hydraulic Head Cross Section, Surat Basin, Queensland, Australia................... 37
Figure 6: Borehole Geophysical Logs and Their Typical Responses in Selected Rock Types..... 48
Figure 7: Typical Design of Monitoring Well...................... 52
Figure 8: Typical Design of Pore Pressure Monitoring Well... 57
Figure 9: Basic Well Point Configuration............. 63
Figure 10: Anticipated Mutual Interference of Well Point System Creating Composite Cone of Depression......... 63
Figure 11: Dewatering System Design Using Well Point Which Incorporated Two Stages of Excavation............. 64

Page

Figure 12: Variations in Design of Dewatering System in Response to Three (a,b,c) Different Subsurface Conditions.................. 65

Tables

Table 1: Terminology of Flow-Pattern Features..................... 34

Table 2: Calculated Uplift Pressures Vs. Overburden Weight....... 73

I. INTRODUCTION

Basis and Purpose of Mini-Course

The development of a natural resource into a minable reserve may require many drill-holes and cores to determine zone thickness, quality and areal extent. During the course of investigating the resource, conversion of some of the drill-holes into monitor wells will permit a baseline evaluation of ground water in the area under consideration (Reichel, et al., 1985).

The purpose of this mini-course is to discuss in some detail the basic concepts of ground-water flow and how to dewater and depressurize surface mines. Field techniques will be reviewed for well installation, and using these techniques in conjunction with data from previous resource (or developmental) drilling programs, we will examine the pressure distribution within the ground-water system and the altitude and direction of flow. Other topics include: 1) aquifer tests, 2) basic design of a dewatering/depressuring system, 3) typical applications and case histories of mine dewatering and depressurizing, 4) environmental permitting considerations of the PL 95-87, and 5) errors and omissions (or what can and does go wrong).

Mini-Course Principals:

Michael D. Campbell is known widely by industry, government and academe for his work in hydrogeology and in mining, both in the U.S. and overseas. He was the founder and first Director of Research for the National Water Well Association Research Facility and has published more than 100 major reports and publications including the popular texts: Water Well Technology (McGraw-Hill: 1973), and Geology of Alternate Energy Resources (Houston Geological Society: 1977). He is a graduate of The Ohio State University (1966) and Rice University (1976) with degrees in geology. Mr. Campbell is a Certified Professional Hydrogeologist (#480) and a Certified Professional Geologist (#3330).

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II. BASIC HYDROGEOLOGY

Water in the environment is in a constant state of motion. This is called the Hydrologic Cycle (see Figure 1). Water in the oceans and lakes is heated and evaporated or water is returned to the atmosphere through transpiration by

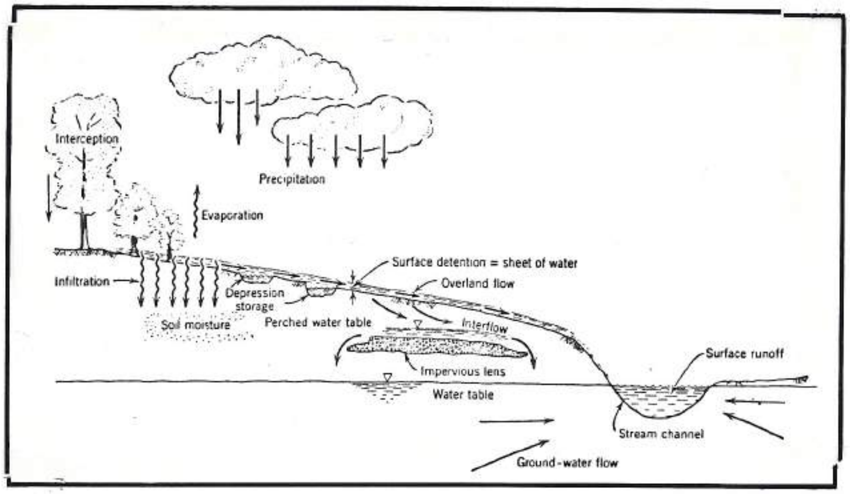


Figure 1:
The Hydrologic Cycle

plants. The water returns to the earth's surface as precipitation. Some of the precipitation flows overland through local streams and rivers and eventually to the ocean. Only a small portion infiltrates through the soil and rocks to become ground water (Ahrens, et al., 1981, Briggs, 1969, Freeze and Cherry, 1979, Davis and DeWiest, 1966).

As the precipitation infiltrates the soil and rocks, it moves vertically through the unsaturated zone until it reaches the water table, which marks the top of the zone of saturation (see Figure 2). The water table is also called the phreatic surface and is at the base of the capillary zone. The water table is defined as: the surface of useful." In a mining environment, an aquifer is a saturated bed, formation, or group of formations which yields water to a working face or pit. This water may occur as a seep flowing at a few gallons to a few hundred gallons per minute from rocks in the highwall or in the floor. An aquifer can be as porous as a limestone cave or as impermeable as a shale. The different types of material which either permit or inhibit flow are defined as follows:

Aquifer: a unit containing permeable material capable of storing and producing flow to a well or discharging flow at the ground surface.

Aquitard: a unit containing impermeable material which is capable of storing water but does not release a significant amount to wells or at the ground surface.

Aquiclude: a unit containing material which may have water in storage but is not capable of releasing the water to wells or at the surface under atmospheric conditions.

An aquifer that is at or near the surface and is in contact with the atmosphere is called unconfined. An aquifer which is at or near the surface but is separated from the atmosphere by an impermeable layer is called confined (see Figure 3). The water level in a well drilled in a confined aquifer will rise to the level of the water in the aquifer where it receives recharge. A perched aquifer

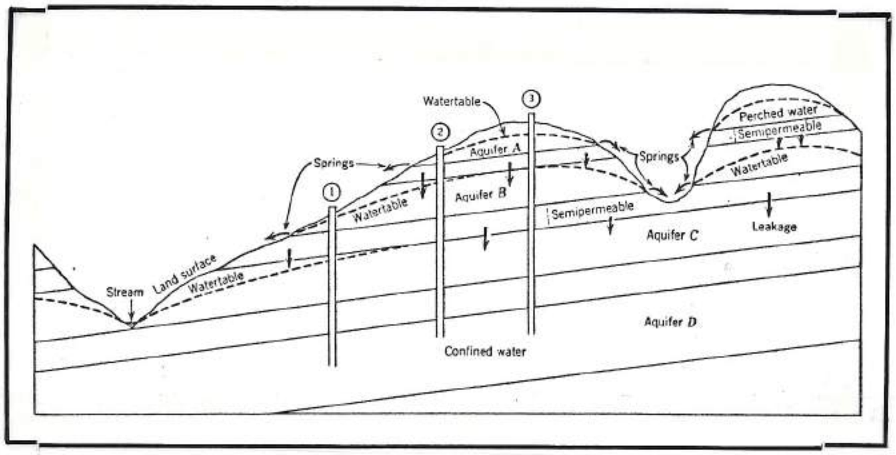


Figure 3:
Perched, Confined and Unconfined Aquifers

is an unconfined aquifer which may rest on an impermeable layer above the top of the water table. If a well were drilled at location "1" as indicated in the figure, the ground water in Aquifer B would be classified as perched water and the ground water in Aquifer C would be unconfined. At location "3", Aquifers B and C would be classified as having confined water while Aquifer A would be unconfined (or under water-table conditions). In other areas of more complex geology the terms "perched," and "confined," "unconfined," are difficult or impossible to apply (Davis and DeWiest, 1966).

Areal Extent

Aquifers may cover large areas in regionally continuous sands or may be confined to small areas such as an alluvial valley or glacial valley or, as will be discussed, may be found in fractures or channels of hard rocks.

Recharge, Discharge and Dynamic Equilibrium

The basic premise of hydrogeology is that under natural conditions part of the precipitation that falls in an area moves from the land surface down an energy gradient to the water table where it enters the zone of saturation. It then moves through the zone of saturation until it leaves this zone so that it may: (1) enter the overlying saturated zone, (2) become stream flow, or (3) become vapor and move directly to the atmosphere.

By definition, only the water in the zone of saturation is properly called ground water. The precipitation that moves to the water table is called recharge and the area over which percolation to the water table occurs is called the recharge area.

Recharge is both (a) the volume of water that moves from the land surface, usually through an unsaturated zone into the zone of saturation, and (b) the process by which water enters the zone of saturation. Recharge occurs only where a vertical component of the hydraulic gradient directed downward occurs at the water table.

Infiltration is the process by which water at the land surface moves into the unsaturated zone. Percolation is the process by which water moves between the land surface and the water table.

For convenience we classify recharge as follows:

Natural recharge is the recharge that occurs under natural conditions in recharge areas. It is devoid of the effects of the works of man;

Induced recharge is the recharge that occurs whenever ground-water discharged through the works of man causes a reversal of the vertical component of the hydraulic gradient at the water table, thereby inducing recharge into an area that is, under natural conditions, a discharge area;

Artificial recharge is the recharge that occurs whenever water is added to the zone of saturation with the intent to recover it later; and

Synthetic recharge is the recharge that occurs where a sustained unnatural release of water to the ground-water reservoir superimposes a new flow-system upon an existing one.

Energy

The energy to drive the water from the recharge area to the discharge area is primarily the potential energy due to gravity acting upon the mass of water.

In general, the energy at a point in a ground-water flow system is expressed as the sum of (1) a quantity that is a function of the mass of water, its altitude, and the acceleration due to gravity at the point, and (2) a quantity that is a function of the pressure exerted by the water at the point. The pressure depends in turn on a number of factors. However, by assuming (1) the acceleration due to gravity is constant, (2) the water is of uniform density, and (3) no unusual sources of pressure (such as the electroosmotic phenomena) exists one may represent the energy at any point in a ground-water flow system by associating with that point the altitude to which water would rise above the given point. This altitude is generally referred to as the head or potential. For the zone of saturation this altitude would be the altitude of the water level in a piezometer open only at the point. In the unsaturated zone, the determination of the value is much more difficult since capillary pressure must be measured and considered. At the boundary between the unsaturated zone and the zone of saturation there exists a capillary fringe. We, therefore, define the water table arbitrarily as the surface through those points where the pressure term is equal to local atmospheric pressure. At this surface and below, the effects of capillarity become negligible. Beneath the water table the pressure is larger than atmospheric pressure. Because head consists of an altitude term and a pressure term, ground water may move from low to high pressure as well as high to low pressure.

Hydraulic Gradient

The energy gradient, or hydraulic gradient as it is generally called, is a statement of the rate of change of energy along a given flow path. It may be considered to have two components -- one horizontal, the other vertical. where the vertical component is directed downward, the flow is downward; where it is directed upward, the flow if upward.

Recharge occurs where the vertical component of the hydraulic gradient is directed downward. In this region, the water table is concave downward.

Discharge occurs where the vertical component of the hydraulic gradient is directed upward. In this area, the water table is concave upward. The line along which the vertical component is zero is an inflection line on a water-table map and can be used to distinguish the recharge from the discharge areas.

Since flow occurs in response to an energy gradient, horizontal flow through the unsaturated zone is possible and should never be categorically assumed to be negligible. Because vertical hydraulic gradients exist, the shape of the water table should be considered only a guide to the near-surface ground-water flow direction.

Divides

Ground-water flow is three-dimensional. Therefore, in any natural ground-water flow situation under dynamic equilibrium there exists a series of surfaces that extend from the recharge area to the discharge area in such a way that for the flow above the surface, recharge equals discharge. These surfaces are called divides. Between divides, recharge equals discharge. At the land surface, the ground-water divide need not follow surface drainage-basin divides.

Natural Ground-Water Flow Systems

Natural ground-water flow systems may be classified as simple or complex. They are also classified as local, intermediate, or regional. A simple or local flow system involves recharge and discharge over a relatively small area, relatively short flow paths, and shallow depth of circulation. Recharge occurs over an essentially continuous area. Discharge derives exclusively from nearby recharge.

A complex or intermediate flow system involves recharge and discharge over a larger area than a local flow system. Flow paths are longer. Circulation extends to greater depths. Recharge areas are not continuous; consequently, at least one local flow system is evident.

The most complex flow system is the regional system, which includes recharge and discharge over large areas, contains some very long flow paths that underflow at least one intermediate flow system and one local flow system.

Based on studies of (1) the distribution of head, (2) hydrogen-oxygen isotopes, (3) geochemistry of ground water, (4) age of ground water, (5) oceanic discharge of ground water and (6) paleohydrologic systems, we know that ground-water flow systems may extend to depths that reach to thousands of feet below sea level (Driscoll, 1986).

Ground-Water Flow Through Rocks

If we examine rocks closely, we find that they are made up of solid mineral grains, interconnected pores, and isolated pores. Water flows through the interconnected pores. These pores may be classified as intergranular, fracture, or tubular.

Intergranular pores are pores between minerals or other rock-forming particles. The ratio of the shortest to the longest dimension ranges from about 1:1 to 1:5. Usually the pore dimensions of intergranular pores are measured in microns or millimeters.

Fracture pores are all those planar pores such as bedding planes and cracks that develop in response to stresses (e.g., faults, sheetings, columnar joints). These pores have two very long dimensions and one very short dimension. The long dimension is usually measured in meters or tens of meters, whereas the short dimension is usually measured in millimeters or tenths of millimeters.

Tubular pores include such features as solution cavities and lava tubes as well as a host of trivial near-surface phenomena such as worm tubes. They may also include such items as geyser tubes and man-made wells or bore holes. Tubular pores have two relatively short dimensions and one very long dimension. The short dimensions are usually measured in centimeters or meters; whereas the long dimension is generally measured in meters, hundreds of meters or even kilometers.

Concept of a Point and the Flow Continuum

Any point in a ground-water flow system may be identified by arbitrary coordinates. For most purposes, rectilinear coordinates suffice. The x and y coordinates usually refer to the horizontal plane and use as a reference an arbitrary origin. The z coordinate is taken as the altitude of the point (elevation with respect to sea level). Thus, any property (P) of the flow continuum or the ground-water flow system may be measured at any point (x,y,z), and as a function of time, i.e., $P(x,y,z,t) = c$.

In the strictest sense, a point in a ground-water flow system must fall in either solid rock or in a pore. To describe accurately the flow of fluids through rock one would need to know the exact distribution of the pores. Clearly, this ideal is not possible, except possibly for extremely small laboratory-size efforts.

Fortunately, we may substitute the notion of a flow continuum in which every point is assigned values relating to both fluid and rock. The properties assigned are those of a REV (Representative Elementary Volume) for which the point is a centroid. The properties of a REV area: (1) it is small enough to be considered an incremental volume with regard to the entire volume of the flow system, and (2) it is large enough for the values assigned to be statistically meaningful. Thus, we see that the REV for an unconsolidatd sand may be a few cubic centimeters whereas that for fractured rocks may be as much as a few cubic meters.

The ground-water flow continuum is the continuous field of points x, y, z occupied by a ground-water flow system.

Properties of the Flow Continuum

To quantify the flow of water through the flow continuum at equilibrium requires two parameters:

(1) Effective porosity; and

(2) Hydraulic conductivity.

Effective porosity (Θ) is simply the ratio of the continuous void space (through which the water can move) to toal volume of the REV. Effective porosity can be expressed as a percent or as a decimal fraction.

Hydraulic conductivity (K) is the volume of water that will pass through the REV under a unit hydraulic gradient per unit of time. It is a function of both the rock and specific weight and viscosity of the water. For potable water moving through typical subsurface temperatures, the properties of the water are so nearly constant that we may treat them as constant. In some rocks, the value of the K will depend upon the direction the water flows through the REV.

The volume of water that will move through a cross-section of rock during a given time is:

$$Q = V/t = KIA$$

where:

Q = the discharge per unit time;

V = the volume of water crossing the unit area during the time;

A = area

t = time

K = hydraulic conductivity; and

I = hydraulic gradient.

The velocity (v) of the ground-water flow is given by:

$$v = KI/\Theta$$

where:

Θ = effective porosity (as a decimal fraction).

In other words, ground-water flow is dependent upon the porosity, permeability and available water in storage. This section discusses the various types of aquifers and some of the basic considerations in determining flow rates and volumes (Freeze and Cherry (1979) and Davis and DeWiest (1966) provide excellent treatment of the topics treated here.

Darcy's Law and General Flow Equations

Briefly, Henri Darcy (1856), a French engineer, determined that the flow of water through a column of saturated sand is proportional to the difference in the hydraulic head at each end of the column and inversely proportional to the length of the column. The following equation is known as Darcy's Law: $V = K(h_1 * h_2)/L$
where:

V = specific discharge
K = hydraulic conductivity
$(h_1 * h_2)$ = the difference in hydraulic head
L = the length of the flow path

The modified equation is:

$$Q = KIA$$

where:

Q = the flow velocity
I = the difference in hydraulic head divided by L
A = the cross sectional area

The latter equation is used because it allows the discharge of water to be calcuated in gallons per minute or other time increments.

Ground-water flow is determined by the hydraulic gradient. This hydraulic-gradient is the difference between elevation at the point of recharge and the elevation at the point of discharge in a regional or local system. It is determined from the water-level elevation in two wells divided by the distance between the two wells. The water will flow from topographic highs toward topographic low areas, but not always from areas of high to low pressure. The flow is induced into the system and is called the hydraulic gradient. The flow through any aquifer can be calculated: $Q = KmI$ where Q is the flow through each foot of aquifer, K is the hydraulic conductivity, m is the aquifer thickness and I is the hydraulic gradient.

Transmissivity was defined by Theis (1935) as the rate of flow in gallons per minute through the vertical section of an aquifer one foot wide and the saturated thickness of the aquifer under a hydraulic gradient of one. Storage in aquifers represents the amount of water released to pumping or other form of aquifer discharge and the amount of water taken into the aquifer.

In a confined (or artesian aquifer) the potentiometric surface is the level that water will rise in a well. The water is usually highest near the recharge point or where water is leaking through a confining zone. Seeps, bogs and swamps are often surface expressions of the water table and of discharge areas.

Water in the ground-water reservoir is said to be in transient storage. The water that leaves the zone of saturation is called discharge, and the area over which discharge occurs is called the discharge area.

Under natural conditions over a long period of time, a state of dynamic equilibrium exists in which recharge equals discharge and the volume of water in transient storage remains constant (or more precisely fluctuates about a mean).

Because modern hydrogeologists recognize that under natural conditions the water moves through the unsaturated zone, they now consider ground-water flow systems to include both saturated and unsaturated flow, so for the remainder of this discussion, ground-water flow systems shall be used in this larger context.

Storage

As dynamic equilibrium, the volume of water in transient storage must be constant. It has two components:

(1) A porosity-storage component, called specific yield (Sy); and

(2) An elastic-storage component, called specific storage (Ss).

The porosity-storage component consists of the volume of water contained in the void space at atmospheric pressure. The specific yield is the ratio of the volume of (a) the water that will freely drain from the REV at atmospheric pressure in response to gravity only to (b) the volume of the REV. Specific yield is expressed as a dimensionless decimal fraction. The volume drained is always less than the volume contained because of surface tension and capillary forces. Effective porosity, expressed as a decimal fraction, is, therefore, the upper limit of the specific yield.

The elastic-storage component comes about because pressure exerted by water on the REV causes contraction or expansion of the rock-matrix material (an elastic response) that permits an addition or subtraction of water to the REV without changing its effective porosity. Specific storage is the ratio of the volume of water that will be added to or released from a REV to the volume of the REV as a result of a change in pressure on the REV. The pressure change is usually expressed as the change in the height of a water column.

Transmissivity and Storativity

In practice, field tests usually provide the average or mean hydraulic conductivity ($\bar{K}$), mean specific yield ($\bar{S}y$), and mean specific storage ($\bar{S}_s$). We most often determine transmissivity, T, and storativity, S.

These are values derived from the assumption that the portion of the flow continuum impacted by some stress condition (such as a pumping test) has some constant thickness, m, such that $T = \bar{K}m$ and $S = \bar{S}_s m$.

Transient Water Levels

Although a natural ground-water flow system may be in dynamic equilibrium when considered for a long period of time, there may be substantial departures from equilibrium for periods ranging from a few minutes to a few years. During these periods, water levels change as water is taken into or discharged from storage.

Short-term changes in storage occur because pressure changes cause an elastic response in the rock so that water is taken into or released from storage with no change in the position of the water table. Changes of this sort are brought on by air-pressure changes, tidal fluctuations, earthquakes, short-term loading or unloading, and pumping or injection into wells. These water-level changes are here referred to as elastic-storage transient water levels.

Changes in the altitude of the water table, which cause changes in the volume of saturated rock, are here called porosity-storage transient water levels.

When the works of man -- such as the installation of a well, construction of a dam, or the creation of a sustained synthetic recharge condition -- create a long-term change in the flow regime, the elastic-storage transient water level changes are noted first and then porosity-storage transient water-level changes become evident. Finally, if the new condition is sustained for a sufficiently long period a new local flow system is created that is in dynamic equilibrium. The water-table shape adjusts to fit the new equilibrium. Energy distribution around the new feature also adjusts until a fixed divide becomes evident and measurable. In those cases where there are many wells or there are many recharge points, the short-term transients associated with individual wells will mask the developing long-term equilibrium of the new flow system.

Ground-Water Management Concepts

The works of man -- wells, irrigation systems, mines and excavations, dams, drains and canals, sewage disposal facilities, etc. -- alter natural ground-water systems by changing the location and amount of recharge and/or discharge, and by changing the energy distribution in the ground-water reservoir. Management of a ground-water resource consists of controlling the discharge and recharge rate and durations from, or the energy (water-level) distribution within the ground-water reservoir, or both, through the use of the works of man.

Management of a ground-water reservoir takes into account the consequence of changes in the discharge-energy relationship as a function of time that are a consequence of the works of man. Management may also take into account the changes in water chemistry and temperature of the water as a function of time due to the works of man.

The two concepts of ground-water management are:

(1) The storage-mining concept; and

(2) The dynamic equilibrium concept.

Storage-Mining Concept

The storage-mining concept presumes that all water pumped from (or into) a well comes from (or goes into) storage within the lithologic entity tapped by the well. . . the only movement of the water being that which is necessary to take the water from its place of storage to the well.

Advocates of the storage-mining concept recognize two states -- confined and unconfined. The confined state assumes that all the water derives from elastic-storage. The unconfined state assumes that some part of the water derives from porosity-storage. For the confined case, other assumptions that are generally made (at least for computational purposes) include:

(1) The water-bearing rocks are homogeneous and isotropic and extend in all directions infinite distance;

(2) All water is derived instantaneously from storage as water levels change;

(3) The water-bearing rock remains saturated at all times; and

(4) Before pumping begins, water levels throughout the water-bearing rocks are identical. This implies that no movement of ground water occurs prior to pumping of a well.

For the unconfined state, assumption (1) and (4) remain unchanged, assumptions (2) and (3) and modified as follows:

(2) Some delay may occur in the release of water from storage but such delays are of relatively short duration; and

(3) the thickness of saturated water-bearing rock at the well diminishes as water is pumped from the rock.

Under the storage-mining concept, water-level changes in and around a well are due exclusively to pumping water from the water-yielding rocks.

Water once removed may never be replaced (that is, it is mined) unless:

Case (1) The effect of the pumping well reaches a stream, lake, canal, or other body of water on the land surface; or

Case (2) Artificial recharge occurs; or

Case (3) Leakage occurs from overlying or underlying rocks into the rock tapped by the well; or

Case (4) Unique or site-specific natural recharge occurs.

Case (1) presumes the surface-water resources must be diminished, because part of the water -- instead of deriving from storage -- would be derived from the inflow of the surface water.

Case (2) calls for specific facilities such as wells, ponds, ditches, or septic tanks.

Case (3) presumes that the lithologic units that contain ground water are discrete and that any movement between them is caused exclusively by the well.

Case (4) includes those localities where, for some reason, recharge cannot be denied. A typical example is the well in an alluvial fan. An intermittent stream draining from a mountain will bring water to the fan which it infiltrates to become natural recharge.

Dynamic-Equilibrium Concept

The dynamic-equilibrium concept recognizes that under natural conditions ground water moves through a flow continuum from a recharge area to a discharge area in ground-water flow systems and that the flow continuum contains water in transient storage.

Under the dynamic-equilibrium concept, diversions by man disrupt the equilibrium. At first, water is taken from (put into) storage. But as time passes, less and less water derives from (enters into) storage and more and more ground water is derived from (entered into) the natural flow system.

Because the volume of water derived from storage is larger at first, the discharge rate from the system is larger than the recharge rate. . . restoring dynamic equilibrium. . . but in a synthetic flow system that is sustained by energy supplied to the system by the work of man.

A divide separates that part of the flow system that depends upon the work of man from that part of the system that depends upon natural phenomena. Consider a pumping well: If discharge is continuous, initially all the water discharged will derive from storage. But if pumping sustains long enough, a new equilibrium will develop. The natural discharge will be diminished by the discharge of the well.

If the discharge rate causes the divide to reach the land surface in a discharge area, the hydraulic gradient will be reversed and water at the surface will be induced to move toward the well. This induced recharge may diminish the flow of a stream. It may consist of precipitation previously discharged as surface runoff or evapotranspiration. Under conditions of induced recharge, the net discharge rate may exceed the net natural recharge rate. Sustained discharged will occur only if the average rate of withdrawal exceeds the average recharge rate (both natural and induced).

Hydrogeochemistry

Geochemists informally recognize two types of chemical analyses of ground water. The most common type is the analysis made to establish the character of the water as it will be used. These are water-quality analyses. The other type is rather rare for it reveals (hopefully) the chemical character of the water in the ground. These are hydrogeochemical analyses.

If the water sample represents only a small portion of the flow continuum, and if the sample did not age significantly before it was analyzed, it can be considered a hydrogeochemical analysis. Some water-quality analyses meet these criteria.

We can predict the chemical character of the water as it will be used, if we know the chemical character of the water in the ground. The inverse is not necessarily true.

We can use hydrogeochemical data, coupled with ground-water age determinations obtained by isotope methods, to interpret ground-water flow patterns because the ambient water chemistry in a particular part of the flow continuum depends on such factors as:

(1) the antecedent water chemistry;
(2) residence time of the water;
(3) the chemical composition of the continuum; and
(4) the temperature-pressure relationships in the continuum that control water-rock reactions, and
(5) sampling procedures

Because ground-water flow systems are three dimensional and flow may be across bedding or stratigraphic units, as well as parallel to them, the chemical character of water in a formation does not necessarily reflect chemical changes due exclusively to flow through that formation.

Conversely, local, intermediate, and regional flow systems can in some places be identified by their chemical characteristics, even though all flow is essentially horizontal.

Recharging ground waters are among the youngest waters in the ground-water flow system. Ideally, they have comparatively low concentrations of soluble salts and contain relatively few ionic species. They may not be at equilibrium with the surrounding rock.

As the waters move into and through the flow continuum, their residence times and travel paths become increasingly longer, and their concentrations of total dissolved solids increase, as does the diversity of ionic species. The water and rock tend to come to equilibrium. Thus, observed difference in water chemistry in a flow continuum may reflect distance traveled from the recharge area or residence time sufficiently to discriminate between flow systems.

In discharge areas waters of one or more flow systems, each with different chemistries, converge (so that water samples apparently from the same source have substantially different compositions). Discrimination of flow systems in a discharge area is difficult because water samples rarely represent one flow system exclusively. In arid or semi-arid climates, their discrimination is further complicated by the fact that ground water near or at the surface tends to discharge via evapotranspiration, so local near-surface build-ups of dissolved solids occur as the residual water is enriched in soluble salts.

Analyzing Ground-Water Flow Systems

For investigation purposes, we assume that the ground-water flow systems of any drainage basin were in dynamic equilibrium before man's modifying activities began. We do this for two reasons:

(1) The storage-mining concept is in many respects simply a special case of the dynamic equilibrium concept; that is, it is the case where natural recharge/discharge is negligible; and

(2) When our concern is with the potential flow paths that a pollutant might travel, if it were to enter the flow system, the storage-mining concept is inadequate.

From the discussion of the ground-water flow system concepts, the factors we need to quantitatively describe the ground-water flow systems of any region reduce to the following:

(1) The spatial distribution of the hydraulic properties of the rocks (the flow continuum);

(2) The shape and configuration of the water table and its temporal variations;

(3) The spatial and temporal distribution of head;

(4) The definition of recharge and discharge areas (both natural and those due to man's activities); and

(5) The spatial and temporal distribution of the properties of the fluid (water).

With these data we can develop hydrologic budgets, describe the consequences of changes in the systems, predict the yields of wells, and otherwise deal with problems that relate to quantities.

To deal with those questions that relate rock-water chemical reactions and the questions of the impact of pollutants or contaminants on the flow system, the list must be extended to include:

(6) The spatial distribution of the mineralogy and petrography of the rocks, and the reactions that potentially could take place between the rocks and the moving solution;

(7) The spatial and temporal characteristics of the solution; and

(8) The spatial distribution of the dispersion properties of the rocks.

This eight-item list forms the basis for developing a preliminary model of the ground-water flow systems. Most hydrogeologic investigations deal almost exclusively with the first five items.

The following questions must also be addressed:

(1) Is the number of measurements sufficient?

(2) Were the properties measured at an appropriate scale?

(3) Do the measurements actually reflect conditions in the flow system?

(4) How do existing measurements differ from the data ideally required?

Pressure Distribution in Ground-Water Basins

Prior to Hubbert's (1940) theoretical analysis of head (pressure) and flow in a ground-water basin, most studies of head dealt with the average head in a specific lithologic or stratigraphic unit (aquifer). Later workers recognized that ground-water flow was not confined to specific rocks and that ground-water flows updip, downdip, and across lithologic or stratigraphic boundaries. These studies have led to an understanding of the head distribution that one should expect in ground-water basins in dynamic equilibrium (Summers, 1981).

The initial efforts were theoretical. Hubbert attempted to find an exact solution to the problem of the head distribution when the flow system is in dynamic equilibrium. Toth (1962,1963) extended Hubbert's work through the formulation of flow patterns as analytic solution to formal boundary-value problems. He dealt exclusively with a Laplacian solution over a homogeneous and isotropic media. He also introduced the use of a sinusoidal representation of topographic effects on a regionally sloped water table. Toth segregated ground-water flow into regional, intermediate, and local systems controlled by both topography and the basin height and width. A collection of the important literature relating to aquifer analysis is presented by the NWWA and Senay (1987).

Freeze and Witherspoon (1966,1967,1968) critically reviewed Toth's models and extended the theoretical simulation of head distribution with analytic and numerical models of multilayer (non-homogeneous), anisotropic vertical sections with a general water-table configuration. Figure 4 shows example illustrations of the theoretical development of head distribution by Hubbert, Toth, and Freeze and Witherspoon. Table 1 defines some of the features labeled in Toth's illustrations.

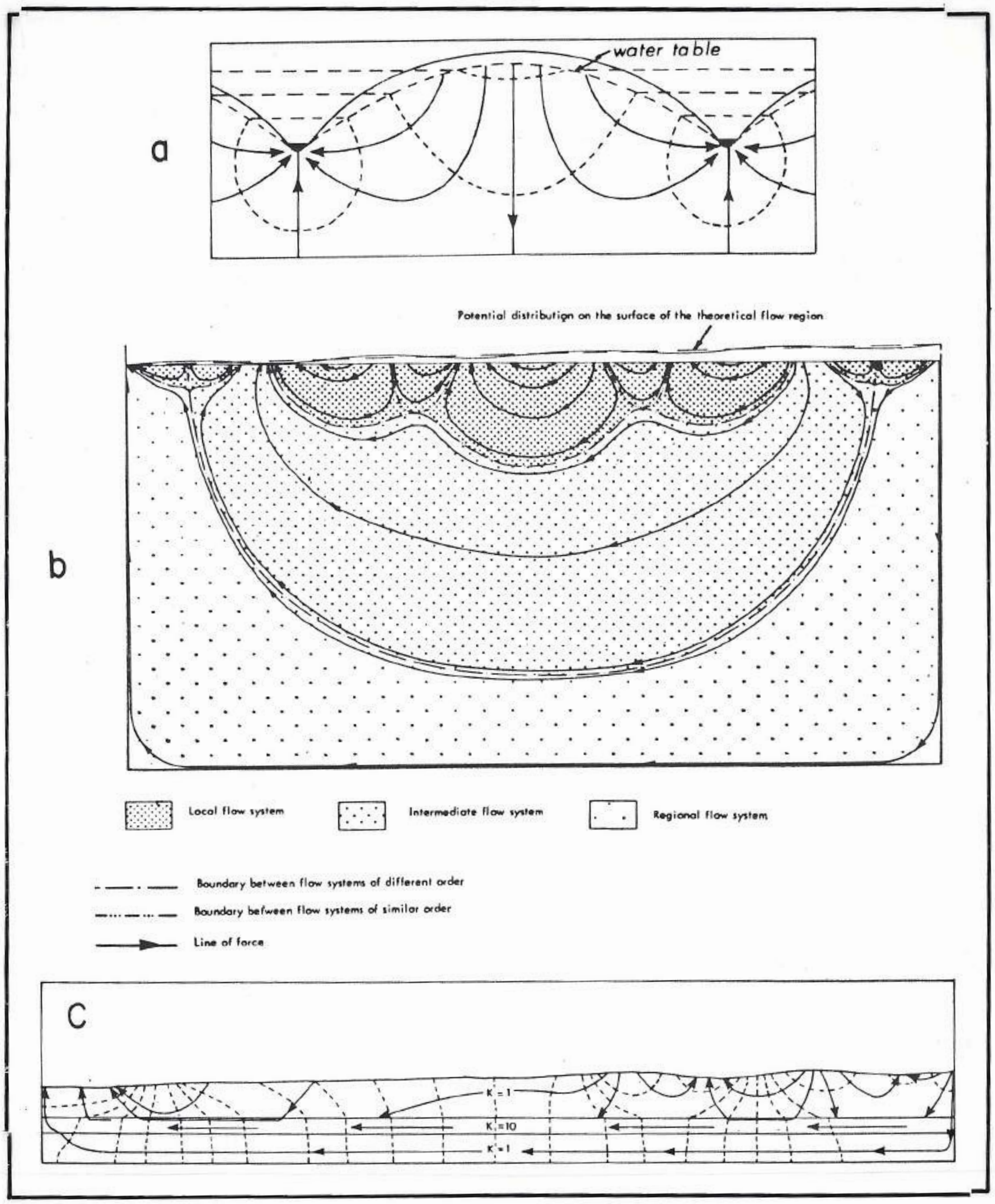


Figure 4:
Comparison of Selected Fluid Flow Numerical Models Developed
by a) Hubbert, 1940
b) Toth, 1963
c) Freeze and Witherspoon, 1966

The theoretical models gave insight into the head distributions to be expected within a ground-water basin and spurred hydrogeologists to develop methods to describe natural systems using extant data. Hitchon (1969a,b) developed one of the first empirical techniques for quantifying limited subsurface data into a coherent picture of basin-wide head distributions. He was interested in locating zones with high vertical hydraulic gradients in the Western Canada Sedimentary Basin that could be explored for hydrocarbons. He examined the separate effects of topography and geology and the regional head pattern by looking at head data in discrete altitude intervals (slabs) and litho-stratigraphic intervals (aquifers). He presented plan and cross-section views that demonstrate that topography exerted the dominant control on the head distribution. Later, Hitchon and Hays (1971) used slab-maps to evaluate hydrocarbon potential in the Surat Basin, Australia, where they had very little deep subsurface information.

Several hydrogeologists have studied relatively shallow ground-water flow systems and developed cross sections that describe ground-water flow in a vertical plane. For example, Nielson (1971) characterized the hydrogeology of an "irrigation study basin" in the Oldman River Drainage, Alberta, Canada, by comparing (a) vertical, two-dimensional, numerical and electric-analog models with (b) empirical head distributions compiled from piezometer arrays. Nielson recognized that piezometer arrays distributed over a basin would provide a three-dimensional picture of the head distribution in the basin.

More recently, hydrologists have used "slab-maps" to study ground water in other basins. Summers (1972) described the head distribution to an altitude of -10,000 feet in the Pecos River Basin, New Mexico, and Landers and Brimhall (1978) in an assessment of regional hydrology on the Navaho Indian Reservation used "slab-maps" combined with stratigraphic and topographic data to illustrate the subsurface head distribution in part of the San Juan River Basin Arizona and New Mexico.

These theoretical analyses and basin studies have led to the following conclusions:

> Ground water moves from recharge to discharge areas along flow paths governed by the potential-energy distribution provided by the topography;
>
> The saturated rocks make up a flow continuum that govern the rates of flow and exert only limited influence on the direction of flow;

Because the saturated rocks form a flow continuum (albeit of diverse water-bearing and water-yielding characteristics), the head distribution can be mapped as an independent variable. An example is shown in Figure 5.

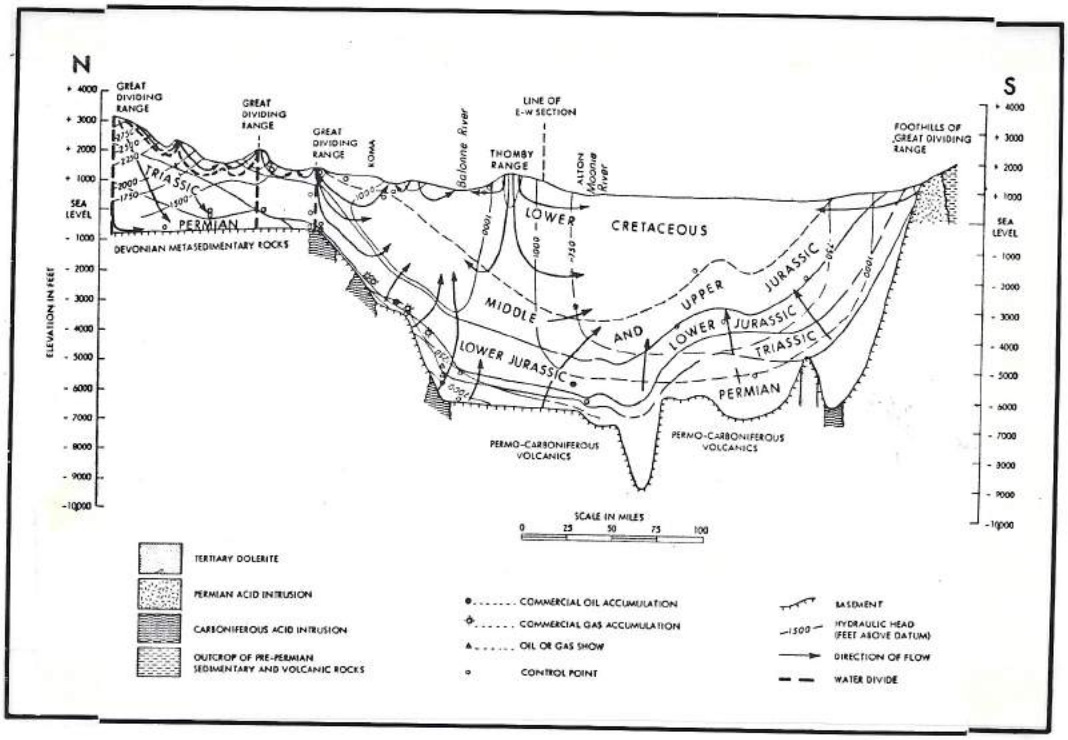


Figure 5:
Hydraulic Head Cross Section, Surat Basin,
Queensland, Australia (Hitchon and Hays, 1971)

Practical Applications of Ground Water Management

Introduction

With an understanding of the mechanisms of ground-water flow, we now can turn to practical applications in solving problems that confront industry. The necessity of dewatering and/or depressurizing areas below and around open-pit mines is dictated by the local hydrogeological conditions and by the cost of working in wet ground relative to dry ground. In areas where the commodity to be mined lies well below the local water table, there is no choice but to artifically lower the water table by dewatering through water wells or drainage trenches (Venburg, 1979). In other areas where the deposit lies at or near the water table, or lies below the upper artesian boundary, the cost of working in wet ground, compared to dry, can be more than the total cost of a dewatering and depressurizing program (after Cummins and Given, 1973, Stubbins, 1972).

Wet Pits

The following factors are affected by working in wet pits:

(1) Labor costs are higher because of lower efficiency, more absences, wet pay and waterproof allowance;

(2) Equipment such as belts, bins, chutes, trucks, screens, and crushers operate at lower efficiency;

(3) Equipment such as rubber-tired vehicles, can not be used on wet, sloppy and soft pit floors;

(4) Low-cost equipment such as truck-driven drill rigs and vehicles can not be used in wet, sloppy pits;

(5) Low-cost explosives can not be used under wet pit conditions;

(6) Blastholes will cave under wet conditions;

(7) Fine minerals will wash away and plug equipment;

(8) Some commodities mined under wet conditions will be diluted or damaged by the addition of fines or moisture;

(9) Drainage ditches would require costly cleaning and excavating slopes which may have stood if dewatered;

(10) Shipping a wet product costs more than a dry product;

(11) Drying a wet feed involves costs for power, drying equipment and personnel attention;

(12) Frozen "wet" ground is difficult to dig and to handle;

(13) Installation and maintenance of mine's power system in wet environment costs for establishing acceptable safety conditions;

(14) Building and maintaining roads, tracks and ditches cost more in wet conditions;

(15) During work stoppage, pumping requirements continue;

(16) Treatment of discharge water may be required;

(17) Liability related to dewatering, effluent discharge or preventing it costs, and

(18) Cost of engineering, planning, and consultants related directly or indirectly to wet conditions.

Open Pit Dewatering

In the control of water for most surface operations, open pits have been classified as follows:

(1) Pits requiring multiple benches involve ditches and small pumping plants to control minor inflow, rainfall and snow-melt. Among these are mines above the water table, on steep slopes, in rock of very low permeability, in areas of low precipitation. Pumps, if required, generally are located in the pit bottom; pumping rates are less than 200 gpm in such cases and dewatering costs are usually less than a few hundred thousand dollars per year.

(2) Pits with moderate to large inflow, probably the majority of the mines today, require some diversion of surface water and pumping not only to

keep the pit dry but for improvement of efficiency, maintenance, stability and to keep the commodity drier. Pumps may be in the pit bottom but dewatering through wells offers distinct advantages, which may justify additional preproduction time and cost. Pumping rates less than 50,000 gpm but greater than 200 gpm are common. Dewatering costs can be expected to be in the range of $500,000 to $1.5 million per year.

(3) Pits which can not be mined under water and are in ground so wet and, in some cases, weak also, that dewatering appears to be a necessary prerequisite to mining operations. Pumping rates in the range of 50,000 gpm to more than 200,000 gpm are not uncommon. Dewatering costs will be much greater than $1.0 million/year.

The advisability of dewatering through wells depends on each of the following conditions:

(1) The volume of water to be pumped must be within reasonable limits of plausibility;

(2) There must be no limitation to lowering the water table over a wide area; the extent of lowering the water table may extend beyond the mining property boundaries.

(3) The nature of the ground-water occurrence must be reasonably well known, i.e., a) recharge area, b) base-line water table representing pre-mining conditions, c) pre-mining water quality and d) direction of flow.

(4) Sufficient time for dewatering must be an integral part of the mining plan. Last minute planning even with a large budget will not increase the rate of dewatering and water-level decline and may lead to serious mistakes.

The above four factors in turn are influenced by the following factors:

(1) The cost of drilling, casing and completing the required number of wells;

(2) The availability of power, equipment and needed support services, e.g., the area is not in a remote or isolated region.

(3) The degree of communication between the hydrogeological team and mining operations team, i.e. consultants' work should not be presented in written report form only. Full verbal presentations combined with follow-up and ongoing

discussions should become standard operating procedure.

To implement a successful dewatering project, the plan should include the correct number of wells (to the appropriate depth) with the appropriate design and located properly, combined with pumping at sufficient rate for the appropriate duration.

Although drainage ditches offer economic advantages, dewatering via wells have additional advantages such as:

(1) Work areas in the pit are usually free of sumps, pumps and pipelines;
(2) Stability of pit's walls is usually better than if water were pumped from a sump at the lowest excavated elevation;
(3) Accumulations of water, mud and ice are reduced;
(4) Commodity is drier, and
(5) Produced water is cleaner.

There are, however, some disadvantages to dewatering by wells:

(1) Sufficient aquifer testing and associated investigations required time and money;
(2) The pre-mining investment in wells, pumps, power and consultants is likely to be substantial;

(3) The process of pumping and lowering the water level may require many months, usually longer than initially anticipated;

(4) Results may be disappointing, especially if the rocks to be dewatered are of low permeability in which case additional costs can be expected.

Design of Investigations

As a guide to your future projects, we have included a list of selected references. As a more specific guide to the approach we have taken over the past few years in various projects, we will discuss the major tasks performed in a hypothetical hydrogeologic investigation of a Gulf Coast Lignite dewatering project. This case is a combination of a number of investigations we have conducted over the past few years.

Previous Work

The first phase of an investigation in support of a dewatering program is to conduct a comprehensive literature search of the area and of the technical methods to be employed. The literature search will provide any existing base-line geologic or hydrologic data concerning the project area. Reports on previous investigations of an area usually contain general hydrogeologic data covering the type of rocks/sediments in the area and the location and description of the outcrops and of the geology in general (Walton, 1983).

Data on the water-bearing intervals in the subsurface are often provided in very general terms, i.e., such as sands which are used locally for water supply, areal extent and thickness, etc.

Data Synthesis

The next step in an investigation is to define the local and/or regional hydrogeology, depending upon the scope of the project. All of the water wells in the area are plotted on a project map. This information may be available through the State Office of Water Resources or the United States Geological Survey. Once the inventory has been completed the data collected can be combined with any other published data. A generalized cross section through the project area will indicate the geology in general and the probable water-bearing units in the are under review.

During lignite investigations hundreds of exploration drill holes will be completed. The holes will be geologically and geophysically logged (Campbell, 1977). Core samples from the holes are often preserved for laboratory analysis. Some of the tests conducted may be for purposes of obtaining geotechnical data for studies on highwall stability. Grain-size analyses of the sediments sampled may also be performed to aid in subsequent reclamation studies and later hydrogeologic investigations of the project. The grain-size analyses conducted in the laboratory and also described in the field during drilling can then be used in well design to determine the thickness and nature of the sand or gravel pack and slot size of the well screen to be used in the well design.

Geophysical Data

The data from the geophysical logs of the borings will be used to identify the sands, silts, clays and other lithologic types in each drill hole. The most widely used geophysical logs in exploration programs are: 1) Natural Gamma, 2) Gamma Gamma Density, 3) Spontaneous Potential and 4) Resistivity. The following is a brief description of the logs listed above and their use in a hydrogeologic investigation (Campbell and Lehr, 1973).

The Natural Gamma Log is used for several purposes in hydrogeology. They are used for general geologic correlation of lithologic types, in defining sand-body geometry and in distinguishing between shale and sand units as well as gradations between members.

The log is used to identify marker beds which can be correlated over the project area. Sand, silt and clay zones or beds are correlated and used in the construction of cross sections. Clean sands are identified by the lack of natural background radiation. A clean sand will contain lower amounts of natural radioactive material than a silt or clay bed. Dense sands or calcified zones in sand bodies will not be as readily distinguishable as in a Gamma Gamma Density log.

The Gamma Gamma Density (Density) Log is used to identify lithologic types which are more dense than others in the bore hole. The density log is an expression of the rock type in grams per cubic centimeter. This is a measure of the specific gravity of the rocks in each bore hole. A clay is much more dense than a clean sand, coal or lignite seam. The calibrated log will also identify small clay or silt lenses within a sand body or calcified zones in a sand.

The Spontaneous Potential (SP) log is used to determine the base of the fresh water zone or identify areas of salt water intrusion. It is also used to determine the rate at which a lithologic unit will conduct a current. This current flow is recorded on a log and can be used to determine the electrochemical traits of the unit. The electrochemical properties of the rock are a result of the salinity of the formation. The contacts between sands, silts and clays usually can also be determined from this log.

The Resistivity Log records the resistance of a rock to the flow of an electrical current. The resistivity log is a reciprocal of the conductivity log and often mirrors the SP log. It is a log that can be used to estimate the amount of cations present in the formation fluid. The resistance is related to the pore spaces in a rock and the type of fluid contained in the pore spaces of the rock. A fresh water sand with 25% porosity will not conduct current as readily as a similar sand containing a salt water solution. The resistivity log is used in conjunction with the Natural Gamma log to determine sands to be screened in a hydrogeologic investigation. Figure 6 illustrates the typical responses in selected rock types.

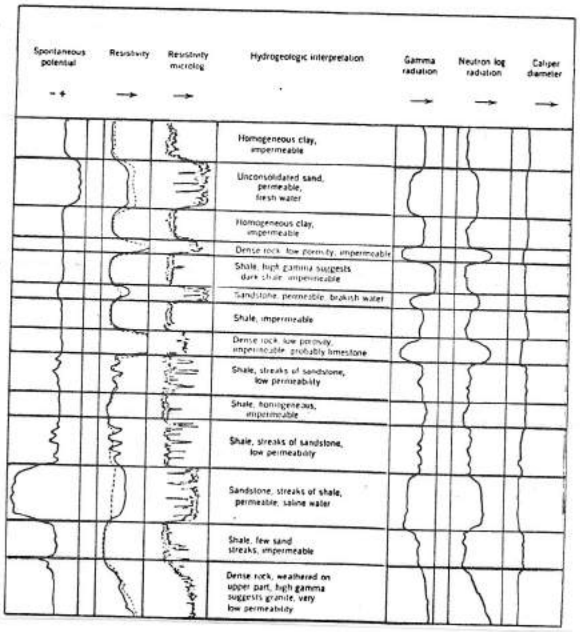


Figure 6:
Borehole Geophysical Logs and Their Typical Responses in Selected rock Types (Campbell and Lehr, 1973)

same way, 4) to the same precision, and 5) with an accuracy sufficient to detect significant differences. Programs adequate for one purpose may be inadequate for others. For example, an agency of the federal government measures quarterly the tritium concentration of precipitation samples collected at selected locations in the United States. The purpose of the program is to compare ambient concentrations with human-health hazard levels. So measurements to the nearest 100 picoCuries per liter are adequate. But for ground-water programs, we need two significant figures' precision with an accuracy of about ±5.0 picoCuries per liter. Clearly, data collected to establish the human-health hazard are unsatisfactory for ground-water purposes.

The second type of monitoring programs involves periodic measurements of some parameters at random points and then drawing of contours to depict the parameters' distribution. The data can be handled statistically, spatial-temporal relations can be expressed, and future relationships predicted. Periodic random-point measurements show patterns and identify the extent of some on-going change. They serve to state the case, but for a variety of reasons they cloud the details.

Classification of Ground-Water Monitoring Systems

Ground-water monitoring systems come about because someone somewhere wants to know something for some reason (Earl, 1983, Halepaska, 1983). We may therefore classify ground-water monitoring systems according to:

A. Who wants to know;
B. Why they want to know;
C. What they want to know;
D. What they expect to find out; and
E. What political or engineering consideration motivated the initiation of the monitoring program in the first place.

We may also classify ground-water monitoring systems according to stress and the expected response to that stress. Stresses may be classified as: (a) direct or indirect, (b) simple, compound, or complex, and (c) short term, intermittent, or continuous.

Stress of Environment

Stress is any activity that forces a change or response in the environment (i.e., the ground-water system). Pumping wells are the most common stress. Other common stresses include mines, injection, wells, feed lots, sanitary-waste disposal facilities, reservoirs, septic tanks and tile fields, salt water disposal ponds, and irrigation. Virtually every change in land use generates a stress on the ground-water flow system. The stresses may be unique -- generating specific, expectable, and easily measured changes. Or, as is the case in many areas, so many stresses occur that the discrimination of individual responses becomes difficult and may even be impossible.

Monitor Well Design and Installation

Monitor wells are installed in selected borings after they have been reamed to a sufficient size to permit the installation of a four-inch diameter well (see Figure 7).

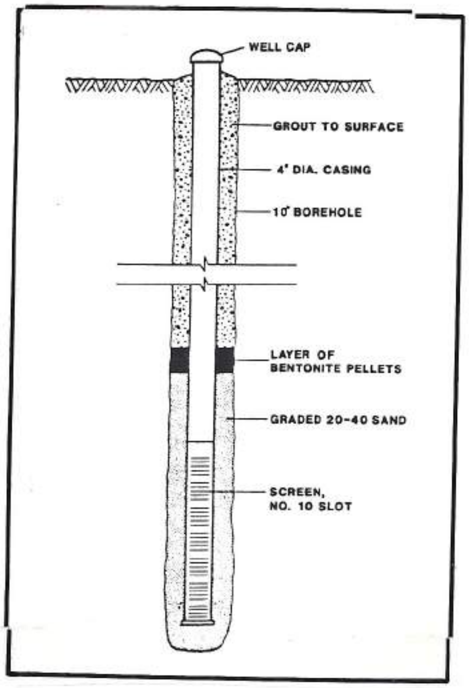


Figure 7:
Typical Design of Monitoring Well

The hole should be reamed to permit the sand or gravel pack in the well to be a minimum of two inches thick (i.e., between the formation and the well screen). Four-inch PVC pipe has an outside diameter of approximately four and one half inches. So the diameter of the well bore should be 4.5 plus 4 or 8.5 inches in diameter minimum. The four-inch diameter well is recommended because submersible pumps are commercially available which can be lowered into the wells to perform aquifer tests later. At this point is should be noted that during the initial drilling of the holes that have been selected for conversion to monitor wells a drilling mud which is biodegradable is often used. This drilling mud contains bacteria that will thicken the drilling fluid like a bentonite mud but will die and turn to water after 72 hours. This type of drilling mud will form a wall cake like a bentonite mud but it will break down and aid in well development later.

Centralizers are used to maintain the proper distance between the well casing and the formation. In wells where a natural sand pack is used centralizers are not often used. This method of well construction involves the placement of a well seal (inflatable packer) at the top of the screen. The sand is then allowed to collapse around the well screen or the natural sand can be separated at the surface and placed back in the hole after the boring is reamed and the well screen is in place.

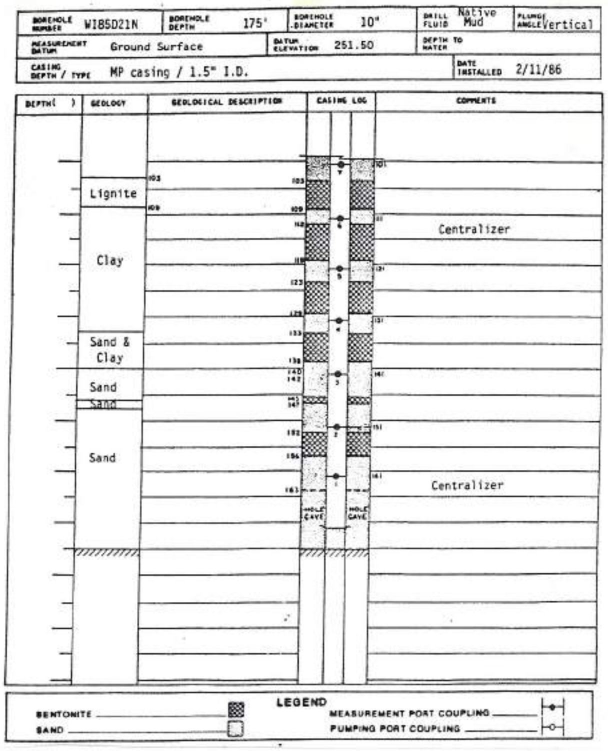
During the installation of the sand pack the top of the sand should be monitored as it is being installed. The sand or gravel is placed in the annular space with a trimme line which is used to tag the sand as it fills the annular space or by pouring the sand in the annulus at the surface and tagging as it fills the annular space. The sand pack is sealed from the formation with bentonite placed on top of the sand either by the trimme method or pouring it at the surface. The bentonite may be in its raw form in angular fragments up to 3/4 of an inch in size. A bentonite mud slurry can also be made and pumped into place at the top of the sand pack. After the sand pack and bentonite seal are in place the annulus should be grouted from the top of the bentonite seal to the surface. A cement bentonite mixture should be used. The bentonite will help to thicken the grout mixture and to reduce seepage of the water from the grout into the formation.

Well Development

Well development is the most important part of the well installation process (Campbell and Lehr, 1973). The biodegradable drilling mud can be reduced to water more rapidly by adding a chlorine solution to the well bore. The chlorine can be pumped into the well through a one-inch pipe placed at the bottom of the well. The addition of this solution to the well will cause the fluid in the well to rise. The greater head in the well will force the chlorine solution out through the well screen into the sand pack and formation. The chlorine will kill the bacteria and will be removed from the well bore and formation during development. After approximately one half hour the solution should be removed from the well bore. The fluid in the well bore should be removed by air lifting. The air-lift method will cause the formation fluid to flow toward the well and remove the drilling mud and fine material from the well bore. The movement of fluid from the well bore back toward the formation can cause the screen to become blocked and additional development time will be required to clear it.

Air-lifting is completed by one of two methods. The first is to place a well cap on the top of the well with a one-inch PVC pipe lowered inside the well two or three inches from the bottom of the well. Compressed air is then pumped into the top of the well cap and the pressure inside the well will force the fluid out through the one-inch pipe. The other method is to lower the one-inch pipe to the bottom of the well and compressed air is pumped through the one-inch pipe. This will force the fluid out the top of the well. The next step in well development is to swab the well. The swabbing is completed by mechanically moving the swab up and down in the well. This motion will open up the sand pack to the formation and permit formation water to enter the well more freely. The swab should be lowered into the well to the bottom of the screen and swabbed up and down over the entire screened interval. The well should be swabbed slowly so that the vacuum created on the up stroke does not collapse the screen. A submersible pump or compressed air should be used in the well after swabbing to remove the water and remaining drilling fluid until the water clears up.

A different type of monitor or observation well that can be installed in a boring is called a pore pressure well (see Figure 8). This type of well contains multiple screened intervals over the length of the well (Johnson, 1983). As shown sand is placed around the measurement port and bentonite is placed above and below the sand to isolate the port from other parts of the formation. To measure the water level in this type of well a probe is lowered into the well and is attached to each measurement port with a pneumatic tool. The water level and water samples can also be obtained from each port in the well. The water level is determined by sealing the probe at each port and measuring the formation pressure in psi. This pressure is then converted to a water level from this point in the well. The



BOREHOLE NUMBER WI85D21N	BOREHOLE DEPTH 175'	BOREHOLE DIAMETER 10"	DRILL FLUID Native Mud	PLUNGE ANGLE Vertical
MEASUREMENT DATUM Ground Surface		DATUM ELEVATION 251.50	DEPTH TO WATER	
CASING DEPTH / TYPE MP casing / 1.5" I.D.			DATE INSTALLED 2/11/86	

Figure 8:
Typical Design of Pore Pressure Monitoring Well

advantages of this type of well are that the drilling and installation time is less than a series of monitor wells or nest of piezometers. Less time and cost are required to monitor water-level changes in one well.

During an aquifer test changing water levels reduce formation pressures. The reduction of pressure will cause sands above and below to react to these changes. The pressure changes will occur at a greater rate than changes in water levels. The pressure changes that occur are like the ripples or waves on a pond. The waves spread in all directions without affecting the water level.

After the monitor wells have been installed and developed, the water levels in the wells can be measured and recorded. This data will be plotted over the project area and a contour map created. This "water-level" map illustrates the potentiometric surface. The water levels from sands above and below the lignite can be reviewed to determine how much water, if any, will be encountered in the overburden during mining, or if the water will have enough head to flow upward through the pit floor during mining. Data for the uplift maps are generated by numerically subtracting the elevations of the potentiometric surface of the water below the lignite seam from the elevation of the base of the lignite. The water level in the well minus the base of the lignite will indicate the amount of uplift pressure that is on the base of the lignite. In areas of the project where the sand below the lignite has a high hydraulic conductivity there is potential for the water to flow upward from the underlying sand into the pit during mining, creating wet conditions.

Aquifer tests are conducted on the monitor wells to determine the <u>hydraulic conductivity</u> of the sands. Aquifer tests can be conducted on specific wells that have had an observation well drilled near the monitor well. An observation well is necessary to determine the hydraulic conductivity and storage coefficient of the aquifer. The methods used to analyze the results of these aquifer tests are discussed later. These observation wells are completed in the same sands as the monitor wells. The data collected from the aquifer tests are used to determine the flow rates in the sands that will be encountered during the mining operation and the volume of water that may move upward from sands below the lignite seam into the pit during mining (Patton, 1979).

Dewatering and Depressurizing Programs

The mining project has water above the minable lignite seam as well as confined water in sands below the minable lignite seam. The water level in the sand below the lignite seam exerts as much as 70 feet of uplift pressure on the base of the lignite. In this case a dewatering and a depressurizing system to remove the water from the area near the mining area is required. If, however, the rocks between the sand with the uplift pressure is overlain by several feet of clays and silts then the flow into the pit during mining may inhibit leakage unless they fracture in response to the uplift pressure and leak into the pit. This often occurs as small fountains of water emanating from selected fissures in lignite or underclay.

A dewatering system is designed to remove the water from the overburden. The system should be located close enough to the mining operation so that is can, if possible, transmissivity, also calculated from pumping test data, is used to estimate the rate at which the wells must be pumped over the long term to maintain the cone of depression.

For many dewatering situations, the pumping rate required to establish a pre-drained condition may be far higher than the rate required to sustain the drawdown. This is because the initial volume of water within the cone of depression is usually far greater than the volume of water entering the cone as recharge.

As a variation and expansion of basic flow equtions used in hydrogeology, the volume of water that a dewatering system will have to pump from an unconfined aquifer to produce a certain drawdown is as follows:

$$Q = \frac{K(H^2-h^2)}{1055 \log R/r}$$

where:

Q = discharge, in gpm
K = hydraulic conductivity, in gpd/ft^2
H = saturated thickness of the aquifer before pumping in ft.
h = depth of water in the well while pumping in ft.
R = radius of the cone of depression, in ft.
r = radius of the well, in ft.

A similar equation for confined conditions is:

$$Q = \frac{Km(H'-h)}{528 \log R/r}$$

Where:

m = thickness of the aquifer in ft.
H'= distance from the static water level to the bottom of the aquifer in ft.

The selection of which major type of dewatering design to use, that is well points or wells, depends on many factors. Some of the factors depend on the hydrogeologic conditions at the site, the length of time pumping is required at the site, the volume of water to be removed, and whether pumping equipment can be installed in the site.

Dewatering designs based on well points systems usually involve a number of closely spaced wells connected to a header pipe or manifold and pumped by suction lift (see Figure 9). Mutual interference of the individual well's cone of depression creates a composite cone of depression (see Figure 10). Multi-stage dewatering programs using well points are often required because of high subsurface permeability (see Figure 11).

In other conditions, where the subsurface interval to be dewatered is of high permeability, only one line of well points could be necessary (see Figure 12a). In conditions where a clay layer exists above subgrade, sand drains can be used to drain perched water (see Figure 12b). When the clay is at and below subgrade, a line of well points set partially into the clay on both sides has been found to be effective (see Figure 12c). Powers (1981) explores a host of variations in design for construction purposes, which have direct application to mining needs and requirements.

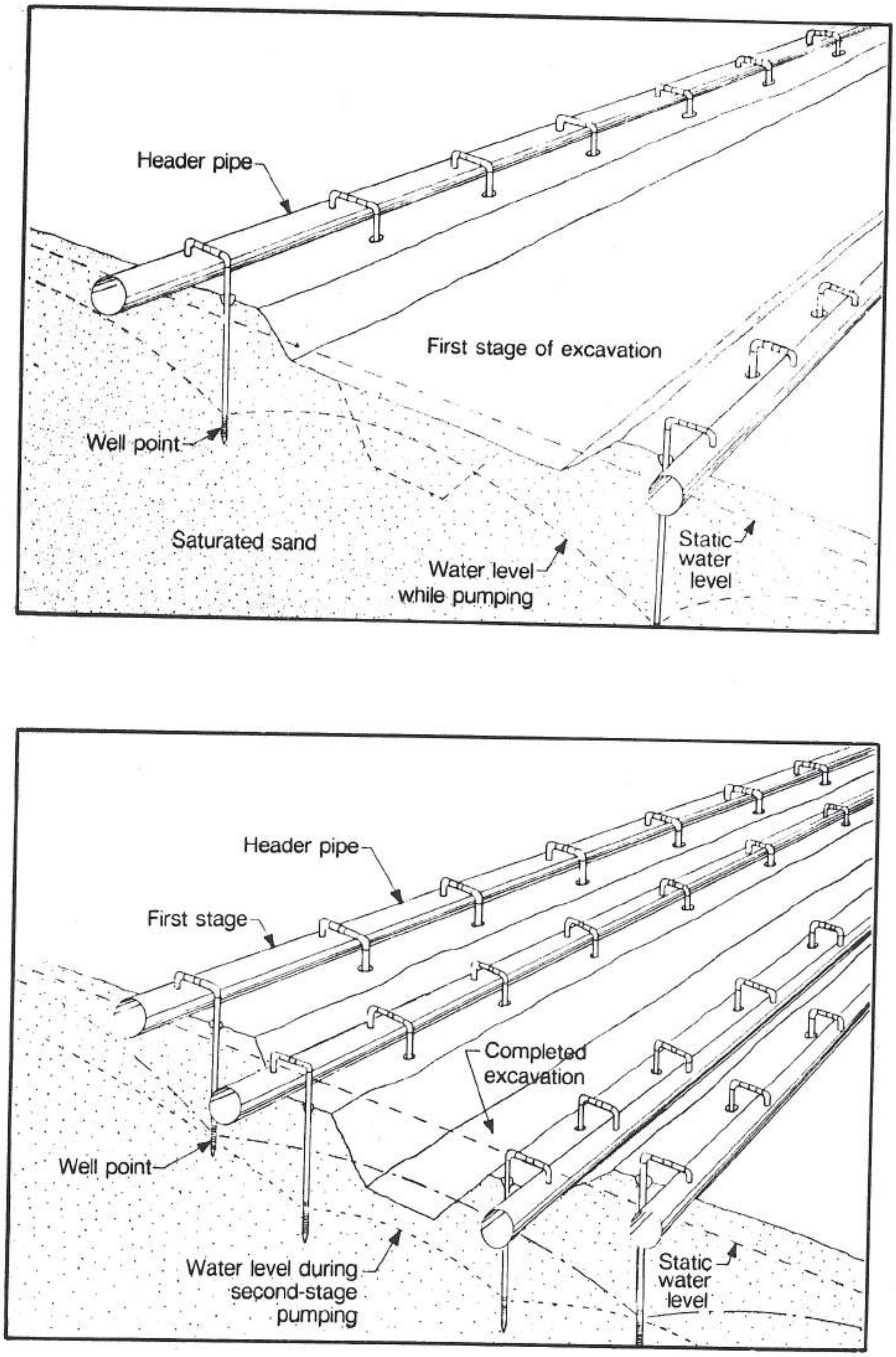


Figure 11:
Dewatering System Design Using Well Point Which Incorporated Two Stages of Excavation. Upper View Illustrates First Stage. Lower View Illustrates Second Stage.

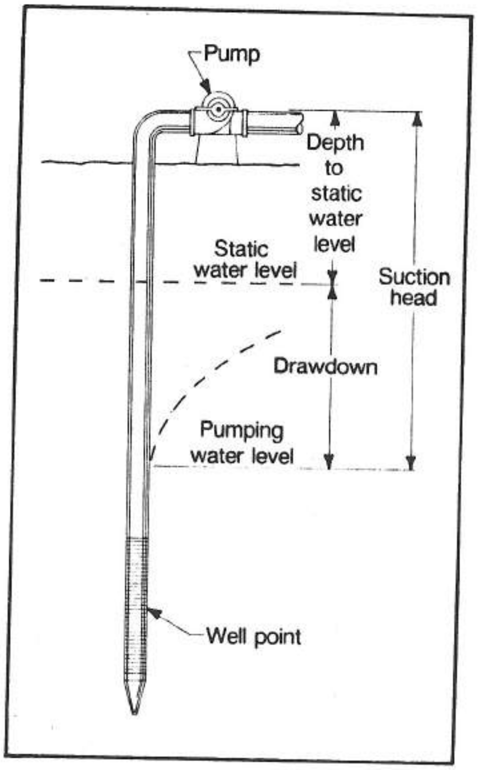


Figure 9:
Basic Well Point Configuration

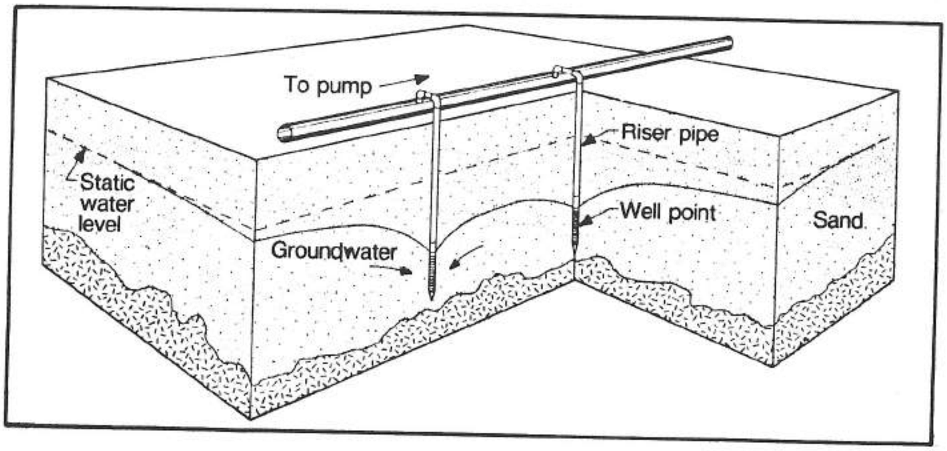


Figure 10:
Anticipated Mutual Interference of Well Point System
Creating Composite Cone of Depression.

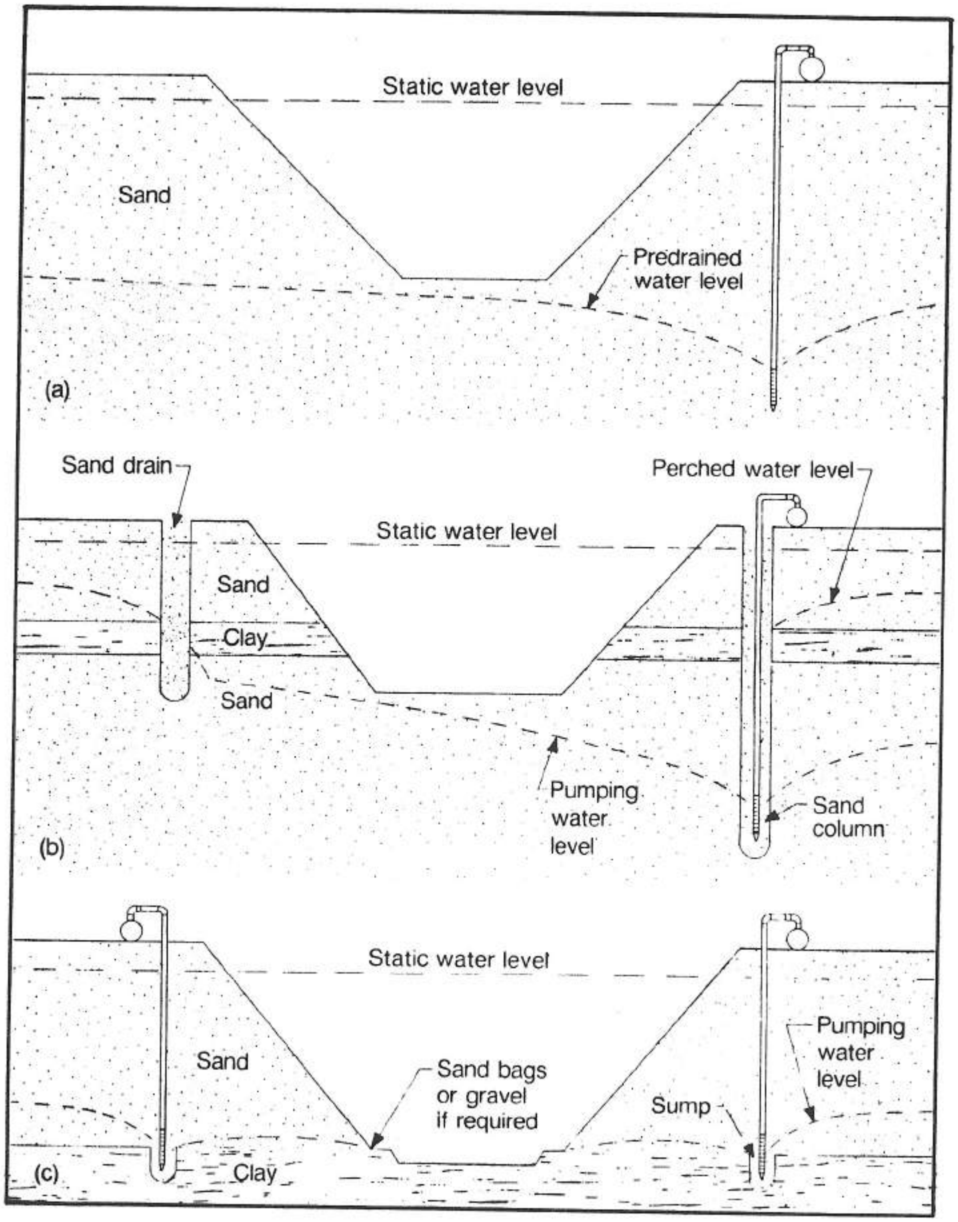


Figure 12:
Variations in Design of Dewatering System in Response to Three (a,b,c,) Different Subsurface Conditions

In high-capacity wells, the production is usually much higher than well-points. One of the most important aspects in employing wells in dewatering projects is the necessity to predict drawdown at various pumping rates. Because specific capacity may decrease significantly as drawdown increases and the saturated thickness decreases, the results from step-drawdown tests may be required to estimate the actual well yield necessary to achieve a specific drawdown over a broad area. Optimization of a dewatering program involving many wells is best implemented by the aid of appropriate computer programs.

Modeling a Dewatering/Depressurizing System

Designing a dewatering/depressurizing system will utilize all of the data gathering methods and well installation techniques described previously. The aquifer data acquired from the project area are used in computer modeling to simulate the flow through the area to be dewatered during the pumping of the wells and to simulate changes in the pressure distribution system. The lithologic characteristics of the sands in the project area and whether they are regional or discontinuous in nature are also included as data for modeling.

The computer model will be based on a grid system with all of the aquifer characteristics, recharge areas and discharge areas identified. Usually aquifer data on adjacent properties are not as useful as within the project area so some assumptions must be made. The basic premise in modeling in areas of limited data is to assure that the aquifer conditions are based on data from areas of greatest hydraulic conductivity.

In most of the ground water flow models the pumping rates of the wells can be adjusted (Bair and O'Donnell, 1983, Hall and Achilles, 1986, King, 1984). Some of the pumping rates that are "modeled" may cause the wells to be pumped dry while other may not lower the water enough. The process is trial and error. When the simulated pumping of the wells has lowered the water level in the model to the desired level the actual pumping rates (gpm) of the wells in the model should be checked with the actual rates of the wells in the field. In most cases it is better to start with a small number of wells to reduce the water level in a large area than to have too many wells. In most cases the wells simulated in the model use the location and aquifer data from wells already in place.

In an ongoing dewatering/depressurizing system that we have recently installed, the method described above was employed. The model was constructed with aquifer data from four wells. One of the pumping wells in the model utilized data from the project area because no aquifer tests had been performed on the well. The well is located in an area that will intercept approximately 50% of the recharge to the area which contains the significant uplift pressure on the lignite bed.

After the model had been completed, the pumping rate input for this well was field checked by performing an aquifer test. The results of the aquifer test verified the pumping rate that was assumed for the well in the model.

The dewatering/depressurizing system that is currently in place on the project was designed utilizing the methods described above. With the aid of computer modeling the effects of pumping the area could be estimated with existing wells before drilling any additional wells. The system uses two wells to reduce the uplift in a 50-acre area. The wells pump at approximately 4 gpm. During a subsequent drilling program completed outside the area containing the dewatering wells we learned that the aquifer properties assumed in constructing the computer model were approximately correct.

Computer Modeling

Computer modeling is of growing importance to dewater/depressurizing ground-water projects. Large, expensive main-frame computers are no longer required to effectively model a dynamic project (Bise and Van Scyoc, 1984, Bradbury and Rothschild, 1985).

What is a ground-water model?

A ground-water model is the conceptualization of an underground-water flow region, i.e. where the water flows from and to. We derive our conceptualization of the ground-water flow system from hydrologic and geologic data.

What is a mathematical model?

A mathematical model in hydrogeology includes a flow equation and boundary conditions. Typical boundary conditions are: no flow across the boundary, constant head (water-level) at the boundary, or constant flow across the boundary. An infrequent boundary condition is a variable flow rate across the boundary. The mathematical model describes the conceptual ground-water model in mathematical terms. With mathematical expressions for the ground-water model we can predict water-level responses in the flow domain due to pumping wells.

How do you predict water-level responses?

Typically we use three methods: analytical, numeric, and resistance-inductance-capacitance (RLC) analog. With the widespread availability of high-speed computers the RLC analog method is rarely used now. The analytical techniques derive an equation that predicts water levels anywhere in the model domain. The numerical methods predict water levels at isolated points in the flow domain.

What are the differences between analytical and numerical models and which is best?

Both methods are based on solving the ground-water flow equations with boundary conditions. The analytical method yields a formula from which predictions are made, while the numerical method makes predictions for particular problems. For most cases the flow-domain parameters (hydraulic conductivity and storage) and the boundary conditions are too complex to yield an analytical solution. In a few simplified cases though, the flow domain and the boundary conditions are simple enough that we can obtain an analytical solution. The numerical method approximates the flow domain and flow equation at specific locations. When given flow-domain parameters and boundary conditions, we apply a numerical technique and predict water levels. As for which method is best, we prefer to use an analytical solution if our conceptual ground-water model justifies it. We can justify an analytical method in only a few cases and hence we use numerical methods for most regional ground-water models.

When do you need to use a numerical model?

When the ground-water system has different regions of hydraulic conductivity or storage, or where the boundaries of a system are irregular. In general we use a numerical model for most ground-water systems; only for the simples cases and quick back-of-the-envelope calculations do we resort to analytical methods.

How does the computer predict water levels?

A number of numerical techniques exist for solving ground-water flow problems. The four common techniques are: finite difference method (FDM), integrated finite difference method (IFDM), finite element method (FEM), and boundary element method (BEM).

What are the differences between these techniques and which is best?

The difference between these techniques lies in the way the flow equation is discretized. For the most part not one method is better than any other method; however the IFDM, FEM, and BEM usually take into account more of the surrounding points than the FDM. For very complicated flow systems the IFDM and FEM are used almost exclusively. The BEM is relatively new to hydrogeology and has not yet gained as widespread acceptance as the other methods.

How good is the prediction we get from a numerical model?

With good data and a calibrated model (a calibrated model is one that mimics past water levels given the pumping rates in the past), the prediction is useful for about twice the length of the water level history of an area. With bad input data all you get from the model is incorrect results (Martin, 1984, McClure, et al., 1985).

Case Histories: Dewatering/Depressuring Programs

The problem of water-bearing and water-yielding rocks overlying a minable commodity occurs in many areas in the world, and hydrogeologists have documented many case histories. In these case histories the hydrogeologic conditions were made an integral part of developing a mine plan.

Basic Programs: Wells

Mines in Australia, India, Germany, and Poland which now remove lignite from altitudes which are near sea level had to remove substantial volumes of overlying saturated sediments. Through well construction and high-volume pumping such operations lowered the water levels to an elevation below the pit floor. Typical conditions involved highly permeable sands above and below the lignite. In Australia, hydrogeologists developed a dewatering system that decreased artesian water levels to maintain stability against excessive floor heave, pit flooding and loss of toe supports for mine slopes (Fraser and Pitt, 1979).

To maintain slope and floor stability the pressure exerted by water at any point must be lower than the corresponding equilibrium pressure exerted by the lignite and overburden. The critical location is where the weight overlying the base of the lignite is at a minimum. . . the deepest part of the open cut. Table 2 illustrates the uplift pore pressures that a range of overburden thickness wil create over uplift pressure on the pit floor. Note that unity (1.00) indicate failure due to uplift is possible. Pore-water pressure is also a common problem in underground mines (Cartwright, 1983).

Obl Thickness(ft):		1	5	10	15	20	25	30	50	75	100
Obl Weight(#/sqft)		125	625	1250	1875	2500	3125	3750	6250	9375	12500
Uplift Pore Pressure(Uplp)											
Uplp(ft)	Uplp(#/sq.ft.)										
75	4688	0.03	0.13	0.27	0.40	0.53	0.67	0.80	1.33	2.00	2.67
70	4375	0.03	0.14	0.29	0.43	0.57	0.71	0.86	1.43	2.14	2.86
65	4063	0.03	0.15	0.31	0.46	0.62	0.77	0.92	1.54	2.31	3.08
60	3750	0.03	0.17	0.33	0.50	0.67	0.83	1.00	1.67	2.50	3.33
55	3438	0.04	0.18	0.36	0.55	0.73	0.91	1.09	1.82	2.73	3.64
50	3125	0.04	0.20	0.40	0.60	0.80	1.00	1.20	2.00	3.00	4.00
45	2813	0.04	0.22	0.44	0.67	0.89	1.11	1.33	2.22	3.33	4.44
40	2500	0.05	0.25	0.50	0.75	1.00	1.25	1.50	2.50	3.75	5.00
35	2188	0.06	0.29	0.57	0.86	1.14	1.43	1.71	2.86	4.29	5.71
30	1875	0.07	0.33	0.67	1.00	1.33	1.67	2.00	3.33	5.00	6.67
25	1563	0.08	0.40	0.80	1.20	1.60	2.00	2.40	4.00	6.00	8.00
20	1250	0.10	0.50	1.00	1.50	2.00	2.50	3.00	5.00	7.50	10.00
15	938	0.13	0.67	1.33	2.00	2.67	3.33	4.00	6.67	10.00	13.33
10	625	0.20	1.00	2.00	3.00	4.00	5.00	6.00	10.00	15.00	20.00
8	500	0.25	1.25	2.50	3.75	5.00	6.25	7.50	12.50	18.75	25.00
5	313	0.40	2.00	4.00	6.00	8.00	10.00	12.00	20.00	30.00	40.00
3	188	0.67	3.33	6.67	10.00	13.33	16.67	20.00	33.33	50.00	66.67
1	63	2.00	10.00	20.00	30.00	40.00	50.00	60.00	100.00	150.00	200.00

Weight of Overburden + Lignite(Obl:#/sq.ft.)

Water Density#/cft	62.5
Obl Ave. Density:	2.00
#/ cu.ft.:......	125

Table 2:
Calculated Uplift Pressures Vs. Overburden Weight

To allow for the uncertainty in the assessment of the forces involved, i.e. actual weight of material above the base of the lignite and the actual force exerted by the water, Fraser and Pitt, (1979) applied safety factors to the determination of the equilibrium pressure in their Australian project. These safety factors involve: 1) "target" water levels for normal mining operations, and 2) maximum "security" levels for safety. If the "security" level is exceeded (pump failure or electrical outages), emergency procedures are instituted to re-establish safe water levels. If "emergency" levels are subsequently exceeded, they anticipate serious disruption and probable failure of either the pit floor or slopes.

Under normal operating conditions, the Australians pump from 16 wells approximately 18,000 gpm to maintain the water levels at a safe distance below the mine workings (i.e., approximately 350 feet below surface). To achieve sufficient water-level change, the Australians had to pump water for approximately five years. They used four observation wells equipped with continuous water-level recorders and monitored well discharge on a weekly basis.

In India, the Neyveli lignite mine required an even more substantial dewatering program (Jones and Subramanyam, 1961). To lower local ground-water levels 200 feet, the Indians used 70 large-diameter wells with a combined production rate of about 50,000 gpm. The cost was approximately $0.34 per ton of produce produced (1961 dollars). Experiences in lignite mines of Germany (Voigt, 1976; Boehm, Schneider and Voigt, 1979) and in Poland (Libicki, 1979) involve similar large-scale dewatering programs and well systems.

<u>Other Programs: Ditches and Drains</u>

Other dewatering methods in common use today include Straskraba, 1979):

1. Drainage ditches at the surface of the mine (for modest water-level changes (Forster, 1987, Grigorev, 1983),
2. Drainage ditches on the pit floor (also for modest water-level changes),
3. Dewatering shafts and galleries (for competent rocks),
4. Horizontal drains (Ginzburg and Shvets, 1984, Soegmiller, 1979, Stanic, 1984) and
5. Combinations of the above with well systems.

To emphasize what has been previously stated, the case histories clearly demonstrate that mine dewatering serves the following functions (in order of decreasing emphasis):

1. Improved slope stability

2. Improved floor stability

3. Improved mining conditions

4. Ground-water quality protection

Moreover, a dry mine keeps rolling-stock from bogging down and dewatered product weighs less.

Well systems reduce pore pressures in underlying rocks and increase slope stability. The case histories also show that wells need not drain a large amount of water to reduce pore pressure, and conversely, high water production does not necessarily insure a reduction in pore pressure. The volume pumped and the following reduction in pore pressure depend on regional and local hydrogeologic conditions. The adequacy of the design of the well field (and the pumping rates) depends upon how effectively the design actually fits the conditions.

To design an appropriate installation to dewater and depressure the rocks above and below the commodity requires an understanding of both: 1) the water regime and water-yielding properties of the rocks, and 2) the ground-water pressure distribution throughout the area.

Permitting (SMCRA Regulations - PL 95-87)

The Surface Mining Control and Reclamation Act (PL 95-87) requires certain permitting and environmental performance standards. Not withstanding recent efforts to limit the requirements for the smaller mining companies, the following sections of PL 95-87 affect all proposed mining operations to one extent or another:

1) Section 507(b)(11) Application Requirements
2) Section 508(a)(13) Reclamation Plan Requirements
3) Section 510(b)(3) Permit Approval (or Denial)
4) Section 515(b)(10) Environmental Protection Performance Standards
5) Section 517(b)(2) Inspections and Monitoring

A review of these sections is presented in the following articles prepared by personnel of the U. S. Office of Surface Mining in 1983. Updates on the regulations and requirements presently in force can be obtained in the literature, e.g., Day (1984).

What Can Go Wrong?

The problems specifically associated with dewatering projects are due to a combination of technical, natural and personnel-related factors (Cook, 1982; Norton, 1982). Technical problems can develop in sampling or collecting the necessary data for later analysis (Henning, et al., 1983). Inexperienced personnel often can not recognize faulty data and continue to collect unaware that the data are faulty. Problems related to natural phenomena contribute to the complexity of the hydrogeologic system under investigation (Wilson and Rouse, 1983; Rodriquez, 1983). Finally, personnel problems can develop between the mine management intent on spending as little money as possible and their consultants who make every effort to accommodate the desires of management but also who react to such pressures by not conducting the type or extent of investigations necessary for the generation of proper data.

VI SELECTED REFERENCES

Ahrens, T. P., et al., 1981, Ground Water Manual, A Water Resources Technical Publication, Water and Power Resources Service, U.S. Dept. Interior, Chapter 13, pp. 351-170.

Ali, M. S., 1985, "Water-Bearing Zones in the Mining Area of the Northern Region of Bangladesh with Regard to Utilisation of Mine Water for Irrigation and Other Uses Hydrogeological Mapping in Asia and the Pacific Region," Proceedings of the ESCAP-RMRDC Workshop, Bandung, (International Contributions to Hydrogeology, Volume 7), pp. 61-75.

Bair, E. S., O'Donnell, T. P., 1983, "Uses of Numerical Modeling in the Design and Licensing of Dewatering and Depressurizing Systems," Ground Water, Vol. 21, pp. 411-420, January.

Bise, C. J. and R. L. Van Scyoc, 1984, "Computer-Aided Analyses of Mine Drainage Systems," Mining Engineering, Vol. 36, No. 9, pp. 1346-1349.

Boehm, G., D. Schneider, and R. Voight, 1979, "Dewatering Techniques for Rheinbraun's Open Pit Lignite Symposium," in Proc. First International Mine Drainage Symposium, Denver, Colorado, May, Miller-Freeman Publications, Inc., San Francisco, California, pp. 437-462.

Bradbury, K. R., E. R. Rothschild, 1985, "A Computerized Technique for Estimating the Hydraulic Conductivity of Aquifers from Specific Capacity Data," Ground Water, Vol. 23, No. 2, pp. 240-246, March-April.

Brawner, C. O., 1982, "Control of Groundwater in Surface Mining," International Journal of Mine Water, No. 1, pp. 1-16, March.

Bridgwood, E. W., et al., 1983, "Selection and Optimization of Mine Pumping Systems," International Journal of Mine Water, Vol. 2, No. 2, pp. 1-19.

Briggs, G. F., 1969, "Ground Water Wells Service the Mining Industry," Industrial Water Engineering, Vol. 34, No. 7, pp. 22-25.

Day, M. J., et al., 1984, "An Assessment of Office of Surface Mining's Upgraded Numerical Ground Water Model for Evaluating Impacts of Mining Operations," in *Proc. NWWA Conf. on the Impact of Mining on Ground Water August 27-29, Denver Airport Hilton, Denver, pp. 263-274.*

Dhamotharan S, et al., 1985, "The Design and Implementation of a Dewatering/Depressuring system for an Open-Pit Lignite Mine in Southeastern Texas," *The Impact of Mining on Ground Water*, Proceedings of the NWWA Conference, August 27-29, The Denver Airport Hilton, Denver, pp. 196-216.

Driscoll, F. G., 1986, *Ground Water and Wells*, 2nd Ed., Johnson Division, 1089p.

Durston, K. J., 1979, "Open Pit Dewatering at Pine Point," in *Proc. First Int. Mine Drainage Symposium*, Denver, Miller Freeman Publishers, San Francisco, pp. 275-303.

Earl, T. A., 1983, "Mine-Site Monitoring -- A Systems Approach," *GWMR*, Vol. 3, No. 1.

Everett, L. G. and E. W. Hoylman, 1980, "Ground Water Quality Monitoring of Western Coal Strip Mining: Preliminary Designs for Active Mine Sources of Pollution," U. S. Environmental Protection Agency, Las Vegas, EPA-600/7-80-110, pp. 1-104, June.

Farr, J. M., et al., 1985, "Shallow-Aquifer Dewatering for Source-Area Control," *Groundwater Contamination and Reclamation*, Proc. of a Symposium Held in Tucson, AZ, pp. 167-174, August 14-15.

Fawcett, R. J., et al., 1984, "An Appraisal of Mathematical Models to Predict Water Inflows into Underground Coal Workings," *International Journal of Mine Water*, Vol. 3, No. 2, pp. 33-54, June.

Fernandez-Rubio, R., Singh, R. N., 1983, "Slope Stabilization Using Advance Dewatering Techniques in a Large Opencast Mine in North-Western Spain," *International Journal of Mine Water*, Vol. 2, No. 4, pp. 35-51, December.

Fernandez-Rubio, R., 1979, "Drainage of Coal and Lignite Mines," in *Proc. First International Mine Drainage Symposium*, Denver, Colorado, May, Miller-Freeman Publications, Inc., San Francisco, California, pp. 492-505.

Forster, K., 1987, "The Hydrogeologic Investigations Conducted to Estimate Ground-Water Flow Rates into a Surface Mining Pit Using a Computer Model," Proc. Am. Water Resources Assoc. 23rd Annual Conference and Symposium, Salt Lake City, November 1-6, 5p.

Fraser, C. J., and J. Pitt, 1979, "Artesian Dewatering Operations at Morwell Open Cut," in Proc. First Int. Mine Drainage Systems, Denver, May, Miller-Freeman Publishers, San Francisco, pp. 362-382.

Freeze, A. R. and John A. Cherry, 1979, Groundwater, Chapter 10, "Groundwater and Geotechnical Problems," pp. 492-496.

Freeze, A. R. and P. A. Witherspoon, 1968, "Theoretical Analysis of Regional Ground Water Flow: 3. Quantitative Interpretations," Water Resources Res., Vol. 4, pp. 581-590.

Freeze, A. R. and P. A. Witherspoon, 1967, "Theoretical Analysis of regional Groundwater flow: 2. Effect of Water-Table Configuration and Subsurface Permeability Variation," Water Resources Res., Vol. 3, pp. 623-634.

Freeze, A. R. and P. A. Witherspoon, 1966, "Theoretical Analysis of Regional Groundwater Flow: 1. Analytical and Numerical Solutions to the Mathematical Model," Water Resources Res., Vol. 2, pp. 641-656.

Ginzburg, L. K. and V. B. Shvets, 1984, "Lowering the Water Table with Radial Drains," Soil Mechanics and Foundation Engineering, Vol. 21, No. 5, pp. 200-203.

Grigorev, V. M., 1983, "Calculation of Complete Interception of Ground Water Inflow to 'Perfect' Trenches by Light Wellpoint Installations," Hydrotechnical Construction, Vol. 17, pp. 618-626, December.

Halepaska, J. C., 1983, "A Manager's Monitoring Model," GWMR, Vol. 3, No. 1, pp. 57-58.

Hall, P. and J. Achilles, 1986, "The Use of Microcomputers in the Design of Dewatering Systems," Third Canadian Hydrogeological Conference Proceedings, pp. 211-220.

Hardaway, J., 1981, "Coal Mining and Ground Water," Chapter in Surface Coal Mining Technology: Engineering and Environmental Aspects, R. Fung (ed.), Noyes

Data Corporation Pub, Park Ridge, N.J., pp. 350-361.

Hargis, D. R., 1983, "Depressuring of a Confined Leaky Aquifer System to Accommodate Mining Operations," Atlantic Coastal Plain, North Carolina Society of Mining Engineers of AIME Preprint No. 83-111, 11p, March.

Hellmann, D. H. and D. Tams, 1986, "Submersible Motor Pumps for Mine Drainage Applications," *International Journal of Mine Water*, Vol. 5, No. 1, pp. 33-44, March.

Henning, R. J., et al., 1983, "Monitoring Data for Other Than Regulatory Purposes," *GWMR*, Vol. 3, No. 1, pp. 37-41.

Henry, C. D. and M. L. W. Jackson, 1982, "Application of Environmental Geology to Lignite Mines in Texas," *Soc. Min. Engineers AIME Preprint 82-9*, SME-AIME Annual Meeting, Dallas, February 14-18, 9p.

Hitchon, B. and J. Hays, 1971, "Hydrodynamics and Hydrocarbon Occurrences, Surat Basin, Queensland, Australia," *Water Resources Res.*, Vol. 7, pp. 658-676.

Hitchon, B., 1969a, "Fluid Flow in the Western Canada Sedimentary Basin: 1. Effect of Topography," *Water Resources Res.*, Vol. 5, pp. 186-195.

Hitchon, B., 1969b, "Fluid Flow in the Western Canada Sedimentary Basin: 2. Effect of Geology," *Water Resources Res.*, Vol. 5, pp. 460-469.

Hofedank, R. H., 1979, "Computation of and Experience on Lignite Open Cast Mine Drainage," in *Proc. First Int. Mine Drainage Symposium*, Denver, Miller-Freeman Publishers, San Francisco, pp. 383-408.

Howard, J. F. and R. E. Wright, 1974, "Evaluation Procedure of Critical Factors of Mining Impact on Ground Water Resources," in *Proc. Symposium on Water Resources Problems Related to Mining*, Am. Water Resources Assoc. Proc. No. 18, R. F. Hendley and D. T. Snow (ed.), pp. 22-31.

Hubbert, M. K., 1940, "The Theory of Groundwater Motion," *Journ. Geol.*, Vol. 48, pp. 785-944.

Libicki, J., 1979, "The Design of Mine Dewatering Systems in Poland," in *Proc. First Int. Mine Drainage Symposium*, Denver, May, Miller-Freeman Publishers, San Francisco, pp. 304-323.

Lopaschuk, R. S., 1979, "Drainage Control and Mine Dewatering at Faro Open Pit Mine," in *Proc. First International Mine Drainage Symposium*, Denver, May, Miller Freeman Publishers, San Francisco, pp. 233-257.

Lynch, S. D., et al., 1985, "Ground Water Management at the Sishen Mine by Finite Element Modelling," in the *Proceedings of the International Conference on Ground Water Technology*, VI, pp. 155-163.

Mathewson, C. C., 1982, "Maximization of Exploration Programs (or How to Get Your Mine for the Smallest Bucks)," in *Proc. Gulf Coast Lignite Conf.*, Houston, Nov. 3-5, C. T. Main (ed.), pp. 69-92.

Martin, P. L., 1984, "The Use of a Numerical Model in Predicting the Effectiveness of a Dewatering System," in *Practical Applications of Ground Water Models*, pp. 759-777, August.

McCallum, R., 1982, "Well Point Systems for Water Supply and Water Level Control," *Arab Water World*, Vol. I, No. 31, p. 67, 64, 62, January-February.

McClure, C. R., et al., 1985, "Numerical Analysis and Implementation of a Permanent Dewatering System," *Bulletin of the Assoc. of Engineering Geologists*, Vol. XXII, No. 3, pp. 241-257, May.

McKee, D. M. and P. J. Hannon, 1985, "The Hydrological Environment of the Gays River Mine," *International Journal of Mine Water*, Vol. 4, No. 2, pp. 13-34.

Miller, G. G., 1981, "Selective Overburden Placement," Chapter in *Surface Coal Mining Technology: Engineering and Environmental Aspects*, R. Fung (ed.), Noyes Data Corporation, Park Ridge, N.J., pp. 343-349.

Nielsen, G. L., 1971, "Hydrogeology of the Irrigation Study Basin, Oldman River Drainage, Alberta, Canada," *Brigham Young University, Geology Studies*, Vol. 18, No. 1, 98p.

Noebs, N. N., Clar, M. L., 1985, "Feasibility of Water Diversion and Overburden Dewatering" Bureau of Mines Information Circular 9024, 94p.

Norton, P. J., 1982, "Groundwater Problems in Surface Coal Mining in Scotland," International Journal of Mine Water, No. 1, pp. 17-24.

Nowacki, P. (ed.), 1980, Lignite Technology, Noyes Data Corporation Publishers, Park Ridge, N.J., pp. 14-41.

Olsthoorn, T. N., 1985, "The Power of the Electronic Worksheet: Modeling Without Special Programs," Ground Water, Vol. 23, No. 3, May-June, pp. 381-390.

Patton, F. D., 1979, "Ground Water Instrumentation for Mining Projects," in Proc. First Intl. Mine Drainage Symposium, Denver, May, Miller-Freeman Publishers, San Francisco, pp. 123-153.

Pentz, D. L., 1979, "Case Examples of Open Pit Mine Drainage," in Proceedings First Int. Mine Drainage System, Denver, May, Miller-Freeman Publishers, San Francisco, pp. 324-341.

Plukowsky, E. J. and Kantrowitz, I. H., 1964, "Hydrology of the Babilon-Islip Area, Suffolk County, Long Island, New York, U. S. Geological Survey Water Supply Paper 1768, 117p.

Powers, J. P., 1981, Construction Dewatering: A Guide to Theory and Practice, John Wiley and Sons, Inc., New York, 484p.

Randall, A., et al., 1978, "Estimating Environmental Damages From Surface Mining of Coal in Appalachia: A Case Study," U. S. Environmental Protection Agency, Cincinnati, EPA-600/2-78-003, January, Environmental Protection Tech. Services, pp. 1-131.

Rehm, B. W., et al., 1980, "Hydraulic Properties of Coal and Related Material, Northern Great Plains," Ground Water, Vol. 18, No. 6, pp. 551-561, Nov.-Dec.

Reichel, F., et al., 1985, "Estimation of the Required Amount of Hydrological Exploration in Lignite Mining Areas on the Basis of Hypothetical Hydrogeological Models," International Journal of Mine Water, Vol. 4, No. 4, pp. 1-20, December.

Rodriguez, J. D., 1983, "The Noordbergum Effect and Characterization of Aquitards at the Rio Jaior Mining Project," *Ground Water,* Vol. 21, No. 2, pp. 200-207, March-April.

Rushton, K. R., Senarath, D. C. H., 1983, "A Mathematical Model Study of an Aquifer with Significant Dewatering," *Journal of Hydrology*, Vol. 62, No. 1/4, pp. 143-158, April.

Sanderson, E. W., Schock, M. R., 1986, "Dewatering Well Assessment for the Highway Drainage System at Four Sites in the East St. Louis Area, Illinois," *Third Canadian Hydrogeological Conference Proceedings*, pp. 227-237.

Saulnier, G. J., Jr. and K. E. Goddard, 1982, "Use of Mathematical Models to Predict Impacts of Mining Energy Minerals on the Hydrologic System in Northwestern Colorado," *Mining Engineering*, Vol. 34, No. 3, pp. 285-293, March.

Saunders, G. P., 1983, "Aquifer Dewatering and Drawdown at an Open Pit Mine in Northwestern Colorado," *GWMR*, Vol. 3, No. 1, pp. 122-127.

Schmidt, R. D., 1985, "Fracture Zone Dewatering to Control Ground Water Inflow in Underground Coal Mines," U.S. Bureau Mines Report of Investigations #RI 8981, pp. 1-83.

Schmidt, R. D., 1984, "A Flow Model Application to Mine Dewatering," *Practical Applications of Ground Water Models*, August 15-17, Columbus, Ohio, pp. 307-326.

Senay, Y., 1987, *Aquifer Analysis, A Comprehensive Collection of the Most Important Literature Relating to Aquifer Analysis*, Aquifer Analysis Short Course, NWWA, 600p.

Sherard, J. L., et al., 1963, "Theoretical Seepage Analysis," Chapter 5, *Earth-Rock Dams*, John Wiley and Sons, Inc., New York, pp. 311-322.

Shumate, K. S., et al., 1976, "Resources Allocation to Optimize Mining Pollution Control," U. S. Environmental Protection Agency, Cincinnati, EPA-600/2-76-112, November Envir. Prot. Tech. Services, pp. 1-477.

Slayback, R. G., 1979, "Hydrogeologic Investigations for Mine Dewatering," in *Proceedings First International Mine Drainage Symposium*, Denver,