

A GENERIC STUDY OF STRIP MINING
IMPACTS ON GROUNDWATER RESOURCES

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Energy Laboratory
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ABSTRACT

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This report evaluates the influence of strip mining features, commonly found in the Northern Great Plains Coal Region, on groundwater hydrology. The features examined are: reclaimed mine geometry, relative transmissivity between the reclaimed spoil and the surrounding unmined coal bed aquifer, anisotropy, the gravity sorted rubble layer, coal wedges left between trench cuts, and the position and size of an operational mine in the regional flow system.

A finite element computer model was used to simulate the groundwater flow field from three frames of reference: a local plan view of the mine site (local hydrology), a cross sectional view of flow through the reclaimed mine interior (interior flow), and a cross sectional view of a regional flow system (regional hydrology). The simulation model solved for the piezometric head distribution in each system. For each simulation the piezometric head contours were plotted, and in some cases, the increase in flux induced by the mine properties, and the contact time of water passing through the reclaimed spoil were calculated. Although only the flow of water through the spoil was modeled, water quality effects were inferred through a set of indices dealing with the reclaimed mine size and amount of water passing through it. The effects of a reclaimed mine were studied in the local and interior flow simulations. The influence of an operational mine was examined in the regional simulation. In all cases, the long term impacts were simulated by solving for the steady state condition.

Regional location is found to be the most important factor in the influence of an operational mine on groundwater resources. Relative transmissivity is the most important factor in determining the influence of a reclaimed mine. When present, the rubble layer

dominates the flow pattern through the mine spoil. The coal wedges are apparently of little hydrologic consequence. Equidimensional mine shapes are preferred to elongated shapes because they induce the least amount of flow through the spoil per unit extracted coal.

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We would also like to thank Messrs. Antonio Sa da Costa and Pedro Restrepo for their invaluable assistance in the computer programming aspects of this study.

Our understanding of the strip mining process and its impact on groundwater was greatly improved by a visit of one of the authors to the Montana and Wyoming coal regions early in the spring of 1977. The assistance of all the people visited is greatly appreciated, and we would especially like to thank Dr. Wayne Van Voast of the Montana Bureau of Mines and Geology, Dr. Richard Davis, a private consultant in Laramie, Wyoming, Dr. Don Alfred of the Peter Kiewit Co., and Dr. Ted Terrel of the AMAX Coal Company.

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LIST OF PRINCIPAL SYMBOLS

A	= area of reclaimed mine in plan view [L^2]
d	= largest of L or W for a plan view geometry [L]
F_r	= relative flux ratio
J	= hydraulic gradient [L/L]
K	= hydraulic conductivity [L/T]
L	= length of mine parallel to flow (Chapter 4), trench width (chapter 5), and length of regional systems (Chapter 6)
Q	= volumetric flux, when presented without subscript it is total volumetric flux through the aquifer [L/T]
q	= specific discharge [L/T]
T	= transmissivity [L^2/T]
T_r	= relative contact time of water passing through the mine, weighted by the mine area
t	= travel time [T]
W	= width of reclaimed mine normal to ambient flow [L]
ϕ	= piezometric head [L]
Subscripts:	
A,a	= ambient flow conditions
c	= coal bed aquifer
fs	= finer spoil above the rubble layer
S,s	= reclaimed mine spoil aquifer
R	= rubble layer

w = coal wedge
x = direction parallel to ambient flow
y = direction orthogonal to ambient flow

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CHAPTER 1

INTRODUCTION

1.1 Perspective: Energy and Environmental Demands

The changing dynamics of world wide energy consumption, production and economics are forcing the United States for the first time to formulate an energy policy. Because of the large coal reserves found in this country it is natural to plan our energy policy for the near future around rapid development of these resources. Past experience, however, has shown that the rapid exploitation of natural resources, based solely on economic motivations, results in long term environmental degradation in exploited areas. The classic and well documented case in point is the Appalachian region. The adverse effects from unrestrained mining, such as acid mine drainage, high sediment loading of streams, and unproductive, unreclaimed strip mine sites, are still often felt decades after the mining operation ceases. To prevent this from happening again, we must carefully plan our resource extraction to minimize all harmful impacts and insure that the long term usefulness of an area is not destroyed for a temporary economic benefit.

The rapid development of coal resources is already beginning in the Western United States. It first surged as power companies began to seek low sulfur coal to air pollution requirements, and currently it is being accelerated by shortages and high costs of other fossil fuels. The sheer magnitude of Western coal reserves and ease with

which they may be extracted, seem to guarantee their prominence in all future coal development. In 1974 the National Academy of Science reported that Western coal accounts for 57% of total U.S. reserves, and twenty percent of the Western coal is strippable with current technology and economics. Figure 1.1 shows the generalized locations of the major Western coal reserves.

Past experience with strip mining has been concentrated in the East. The environmental impacts were neglected for generations until it was realized that such destruction and neglect of the environment could not be sustained indefinitely. Today, methods have been found and implemented which minimize environmental damage from mining. Many Eastern coal companies proudly display their reclaimed lands.

This experience, however, is largely non transferable from the East to the West because of the vastly different climates. The Western climate is semi-arid to arid. Water is a scarce and valuable commodity; it cannot be taken for granted, as it is in the East.

1.2 Objectives of this Report

This report is a generic study, designed to isolate and examine the strip mining features which most significantly affect groundwater resources. The lignite and sub-bituminous coal fields of the Northern Great Plains serve as the field examples upon which the study is based. In this region, shallow groundwater is frequently found in low yield aquifers with fairly low quality water. The coal seam it-

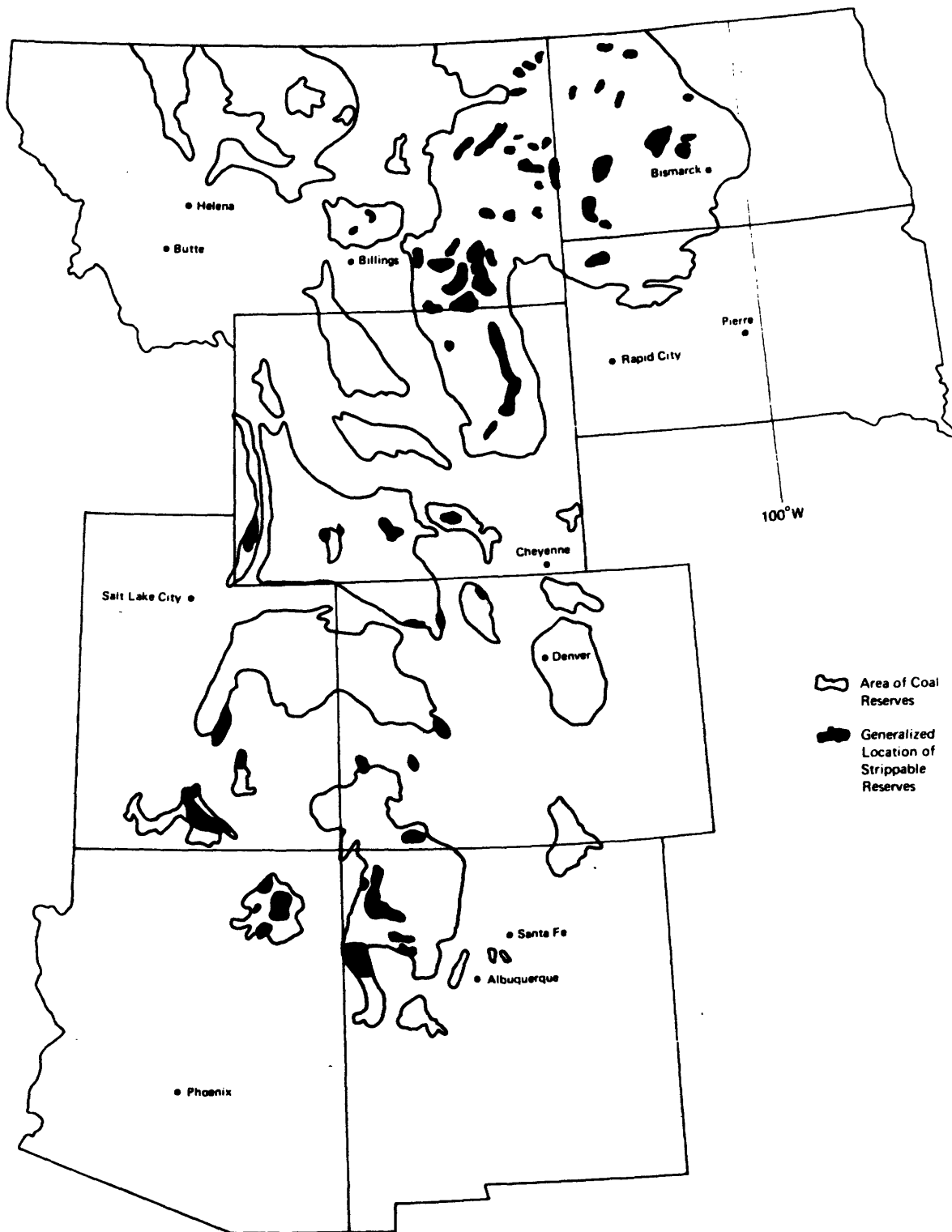


Figure 1.1 Western Coal Reserves. Sketch of strippable coal reserves west of the 100th meridian (from National Academy of Science, 1974).

self often represents the best shallow water source (U.S. Geological Survey, 1974) and is of considerable importance as a domestic and agricultural water supply. This aquifer and all above it, are intercepted, locally dewatered, and the natural aquifer material replaced with fractured and broken spoil material, by strip mining operations.

By identifying the important features of mining operations and describing their effects on the groundwater flow system it is hoped to give the mine operators and government regulators a better, qualitative understanding of how a proposed mine may affect the groundwater system. The results should also aid field investigators by directing their efforts toward the areas where the most significant impacts are likely to occur.

The ultimate goal of MIT research in this field is to establish the long term effects of strip mining on groundwater resources. Water quality degradation is generally considered the most significant potential long term impact. Most other impacts caused by mining, such as the lowering of groundwater levels are expected to be minimal once the mining operation has been completed and the groundwater system returns to a steady state condition.

1.3 Scope

This report examines the groundwater levels and flow fields associated with operational and reclaimed mines. This leads to an assessment of groundwater quality degradation by establishing the volume of water that comes in contact with spoil and its

contact time. Actual quality modeling is not involved in the current study. Rather it concentrates on describing the interrelationships between strip mining characteristics and the ensuing flow field patterns. To accomplish this, typical strip mining situations are idealized from three perspectives:

1. A plan view to study the mine influence on the local hydrology,
2. A cross sectional view of the mine interior to study flow behavior within the mine,
3. A cross sectional regional view, to the potential impact of a mine on a regional scale.

These situations are modeled using a numerical simulation model. The methodology is explained in detail in Chapter 3.

1.4 Organization of this Report

Following this brief introductory chapter, background information is given relating typical mining procedures and their hydrologic properties. Other research concerning the impact of strip mining on groundwater resources is discussed. Then Chapter 3 defines the methodology employed in this study, describes the simulation model and explains some of the evaluation procedures. Chapters 4 through 6 present the simulation results from the local, interior and regional studies. And finally conclusions and recommendations are discussed in Chapter 7.



CHAPTER 2

BACKGROUND

Strip mining affects both the quantity and quality of groundwater. Wells have gone dry and water quality has been measurably degraded at some mine sites. But as of yet, there are no general rules to predict how a given strip mine will affect a specific area. If this predictive capability is ever to be achieved, even in a rudimentary fashion, those features of strip mining which most directly influence groundwater must be identified and understood. In the light of current knowledge, three principal features are mine location, mine geometry, and the hydraulic properties of the reclaimed spoil. This chapter explains the relationship of these features to strip mining operations typical of the Northern Great Plains. The remainder of the report seeks to increase the overall understanding of how these features affect groundwater resources.

2.1 Effects of Strip Mining on Groundwater

A strip mine has two distinct stages, and each stage exerts a different type of influence on the groundwater system. The first stage is during actual mine operation. Its major impact is to lower the piezometric surface around the mine site. Quality degradation of surface and groundwaters, which are intercepted by the mine, may also occur. The second stage takes place after the mining operation has ceased and reclamation has been completed, the post mining period. A new steady state is achieved, and the piezometric

surface re-established. But the properties of the spoil which replaced the original aquifer material may affect the groundwater flow field and quality. Water quality is affected in several ways. In the West the principal problems are total dissolved solids (TDS) and alkalinity. The most common problem found in Eastern coal mines, acidity, is usually not significant because of the alkaline environment and typically low sulfur content of Northern Great Plains coal. A third quality problem, sediment loading, affects only surface streams.

2.1.1 Effects of an Active Mine on Piezometric Surface

An active mine lowers the piezometric surface to the bottom of the operational pit or trench. This induces the groundwater to flow from the surrounding material into the mine where it is collected in a sump, pumped out, and discharged to a surface drainage system. In some operations dewatering wells are used. A cone of depression forms in the piezometric surface, with the mine as its sink. Well water levels located within this depression are lowered, and, depending on their depth and proximity to the mine they may go dry. The extent of this drawdown depends on local aquifer characteristics. At the Belle Ayr mine near Gillette, Wyoming, drawdown has not been observed beyond about 300 meters from the mine edge (Davis, 1977, personal communication). The extent of the drawdown is limited by the presence of impermeable sediments. In contrast, at the Decker Mine in Southeastern Montana, the piezometric surface has declined

more than 3 meters within 2.4 kilometers of the site (Van Voast and Hedges, 1975). It is located in a much more permeable and extensive aquifer system.

2.1.2 Groundwater Quality

The amounts and kinds of dissolved material in groundwater reflect its history of contact with minerals, organics, inorganic salts and gases. In an aquifer, with slow water movement and a large surface area for the liquid-solid interface, there is a long contact period which allows the establishment of a chemical equilibrium between the liquid and solid phases. Consequently water tends to exhibit chemical characteristics imparted to it by the media it has flowed through. Thus, water taken from different aquifer materials will have different chemical compositions. Even within a given aquifer formation the natural water quality varies greatly with location and depth.

An active mine intercepts both groundwater and surface runoff. This water may potentially be contaminated through contact with spoil and chemical residues associated with mining, such as blasting compounds. If a large quantity of water is intercepted, it is pumped from the mine and discharged to surface water drainage. This discharge water is a potential source for surface water degradation.

According to Van Voast et al. (1976b) this problem has not been significant in the active mines he has studied in Montana. The discharged mine effluent is not chemically different from natural

groundwater baseflow, except for temporary high concentrations of nitrates, which are probably dissolved residuals from the ammonium-nitrate explosives. Although the discharge is principally composed of groundwater, there evidently is not enough contact time with spoil material to change its chemical composition at the studied Montana sites.

Groundwater flow through spoil material after reclamation is another matter. The water has time to react with the spoil and change in composition. Spoil can be significantly different from the original aquifer material. For example, based on descriptions from Van Voast and Hedges (1975), Davis (1976) and the U.S. Geological Survey (1974), the coal beds in the Northern Great Plains may be described as confined aquifers with the water flowing through fractures; the coal is an organic material and water in such an aquifer tends to be less mineralized than water in inorganic aquifers. This points out one of the important aspects of coal aquifers: they frequently have the best quality water in the shallow aquifer system. After strip mining the coal is replaced with inorganic material that has been fractured and oxidized, some of which has never been exposed to saturated water conditions. This spoil contains many readily soluble substances.

Groundwater quality degradation has been measured at some mines. Examples are given here for the Decker Mine in Southeastern Montana; the Edna Mine, near Steamboat Springs, Colorado; and the Gascoyne Mine in Southwestern South Dakota.

At the Decker Mine, Van Voast et al. (1976b) reports water coming into contact with the spoils has been measurably degraded. Water from the coal-bed aquifers contain about 1,000 mg/l (milligrams per liter) of total dissolved solids (TDS), with primary constituents of sodium and bicarbonate. The spoil water quality varies between 1,500 and 6,000 mg/l TDS, averaging about 3,300 mg/l, with the concentrations of magnesium, calcium, and sulfate ions substantially increased from the natural coal-bed values. The spoil water TDS concentrations are surprisingly similar to those of groundwater in the undisturbed inorganic overburden, with slightly higher concentrations of some salts such as calcium and magnesium. Figure 2.1 compares the concentration of several constituents for coal, overburden, and spoil groundwater in the Decker area.

McWhorter and Rowe (1976) studied surface and groundwater runoff at the Edna Mine. They compared runoff water quality from undisturbed and reclaimed areas. The weighted, mean concentration of dissolved solids in combined overland flow and groundwater runoff from the mined area is about 2,500 mg/l greater than from undisturbed ground. Ninety-nine percent of the TDS pickup is attributable to the groundwater flow. This again emphasizes the direct impact mining has on groundwater quality. The primary dissolved constituents are calcium, magnesium, bicarbonate and sulfate. McWhorter et al. (1975) also observed the formation of a salt deposit at a seepage face down-gradient from the Edna Mine.

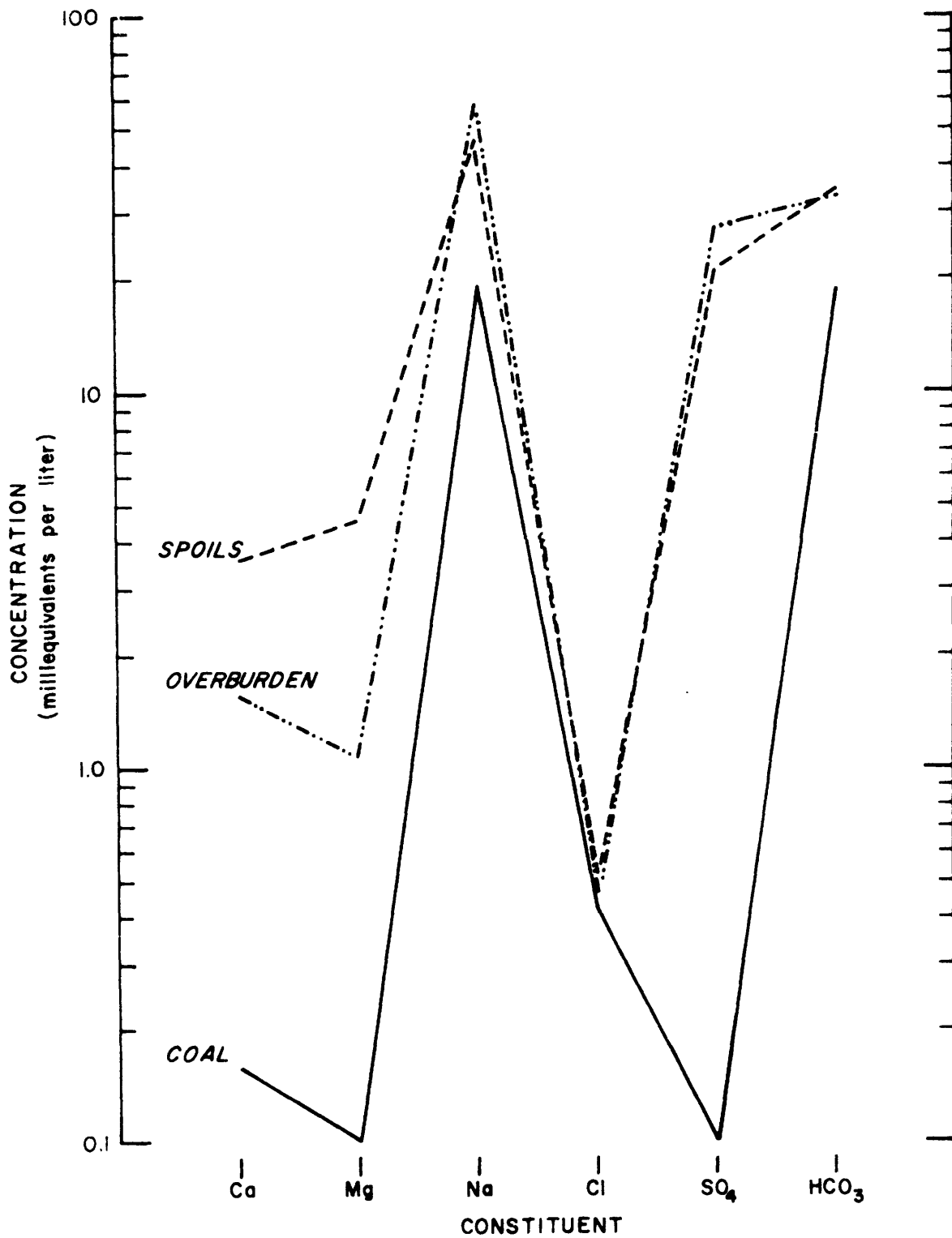


Figure 2.1 Comparison of Groundwater Chemical Compositions for Different Aquifer Material. Decker area groundwater from coal (TDS = 1050 mg/l), overburden (TDS = 3800 mg/l), and spoil (TDS = 3300 mg/l) aquifers (from Van Voast et al., 1976b).

Croft of the U.S. Geological Survey (personal communication, 1977) is monitoring a sodium sulfate plume formed at the Gascoyne Mine site. Two sources are suspected. The first is gypsum, which is present in the spoil and lemerdite (weathered coal), which dissolves when it comes into contact with the groundwater. The second possible source is fine pyritic material found in the upper few feet of the coal seam, which is rejected and cast into the spoil because of its high sulfur content. As it weathers it forms sulfuric acid, which is readily neutralized in the alkaline environment, forming calcium or magnesium sulfate. The clay present in the spoil then exchanges these cations for sodium.

The plume intercepts a small stream passing through the mine area. In the fall the stream is supplied by base flow from groundwater. Normally the creek water has a conductance of 3,000 to 4,000 $\mu\text{mhos/cm}$ during this period. Because of the higher sodium sulfate concentrations in the groundwater plume, the conductance now measures 7,000 to 8,000 $\mu\text{mhos/cm}$ during the fall.

The three cases described above illustrate that strip mining can have a significant impact on water resources, especially through the groundwater. In the Northern Great Plains, strip mining replaces good organic material with inorganic material containing readily leachable salts and minerals. The handling and placement of spoil containing soluble material, such as pyrite, also has a strong influence on groundwater quality. As groundwater flows through spoil material, it picks up leachable and soluble material,

thereby lowering its quality to downstream users. This degraded water also poses a threat to surface water quality as the groundwater base flow feeds streams.

2.2 Typical Mining Operations

The techniques and equipment used in a mine operation influence the final spoil hydraulic properties. Area and pit mining techniques have distinctive spoil handling methods. Each machine or combination of machines used to handle the overburden have characteristic patterns in spoil placement. Draglines, trucks, shovels and scrapers are specifically discussed below with regard to their spoil placement characteristics, and how these characteristics may influence future groundwater flow.

For detailed descriptions of the mining procedures the reader is referred to such works as Grim and Hill (1974) or "An Analysis of Strip Mining Methods and Equipment Selection" (1973). Rahn (1976) discusses the relationship between spoil handling and its permeability.

2.2.1 Area Strip Mining

The general strip mining method employed in the West is called "area strip mining," which is suitable on flat to gently rolling terrain. A trench is cut through the overburden to expose the coal. The coal is removed and the overburden from the next parallel cut is used to fill the first trench. Once its been handled the overburden is described by the term spoil. This operation continues

over and over again until the mine boundary is reached or the coal becomes too deep to extract economically. Figure 2.2 depicts a typical area strip mining operation.

2.2.2 Open Pit Strip Mining

Open pit mines are commonly used in the West where the coal seams are unusually thick, often 15 meters or more. Here, rather than digging trenches, a large pit is excavated. As the operation proceeds, one face of the pit is continuously excavated, the overburden is removed and the coal mined. The spoil from this operation is dumped back into the other end of the pit. Figure 2.3 depicts this type of operation. A Western coal mine frequently covers over 2.5 square kilometers.

2.2.3 Dragline Operations

The dragline is very widely used and is the primary tool for cutting trenches in area method mines. Spoil from a dragline operation is cast in a series of intersecting cones (see Figure 2.4). The bucket is dumped at one point until a large cone is built up. The dragline then moves back several meters and continues the operation of removing the overburden and casting it onto the side of the previous pile, creating a long continuous spoil pile with cone shaped peaks.

This handling procedure encourages the formation of a gravity sorted rubble layer. The spoil which has been fractured and broken by blasting and handling from the dragline is released from the

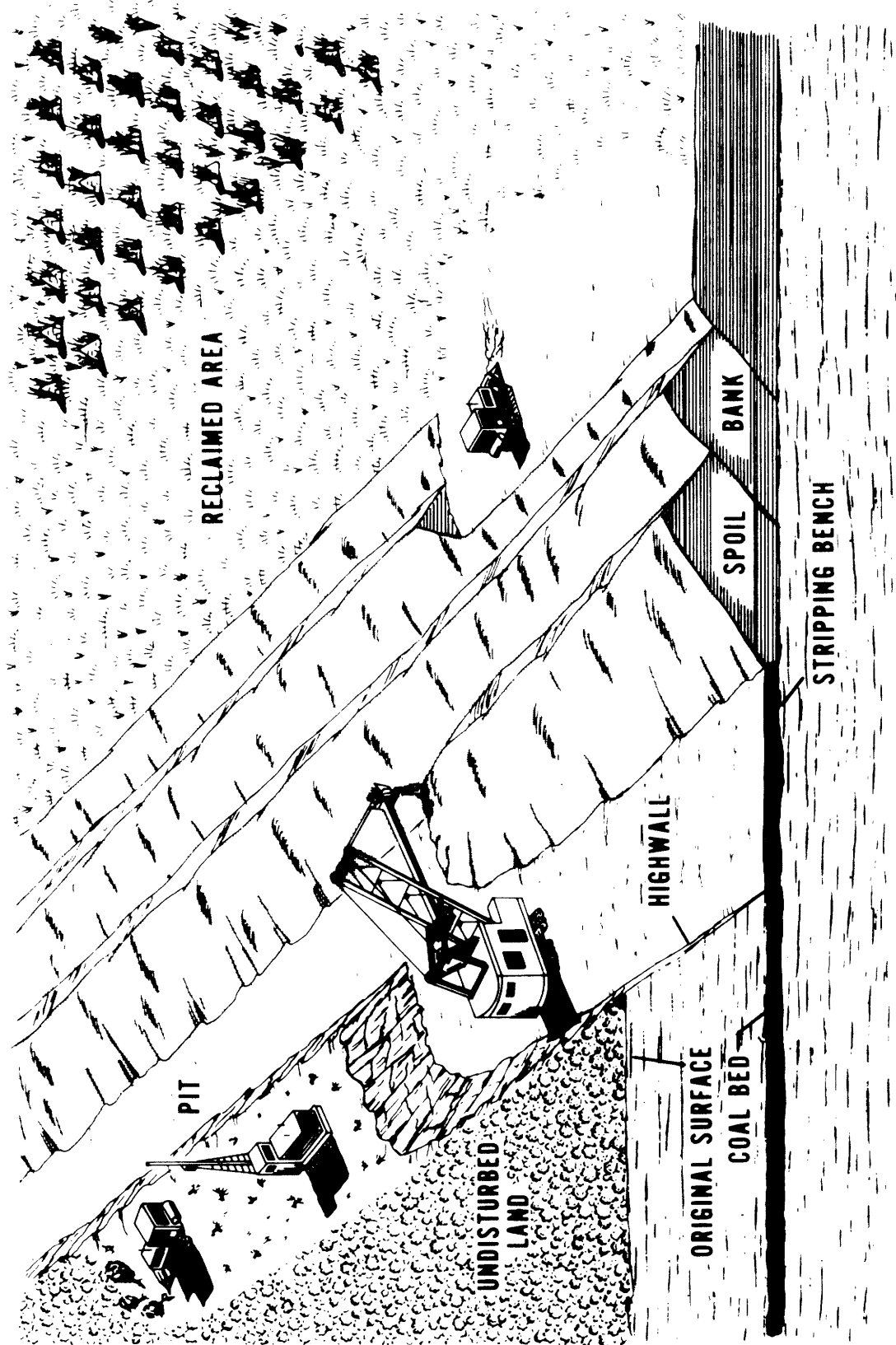


Figure 2.2 An Area Strip Mine with Concurrent Reclamation (from Grim and Hill, 1974).

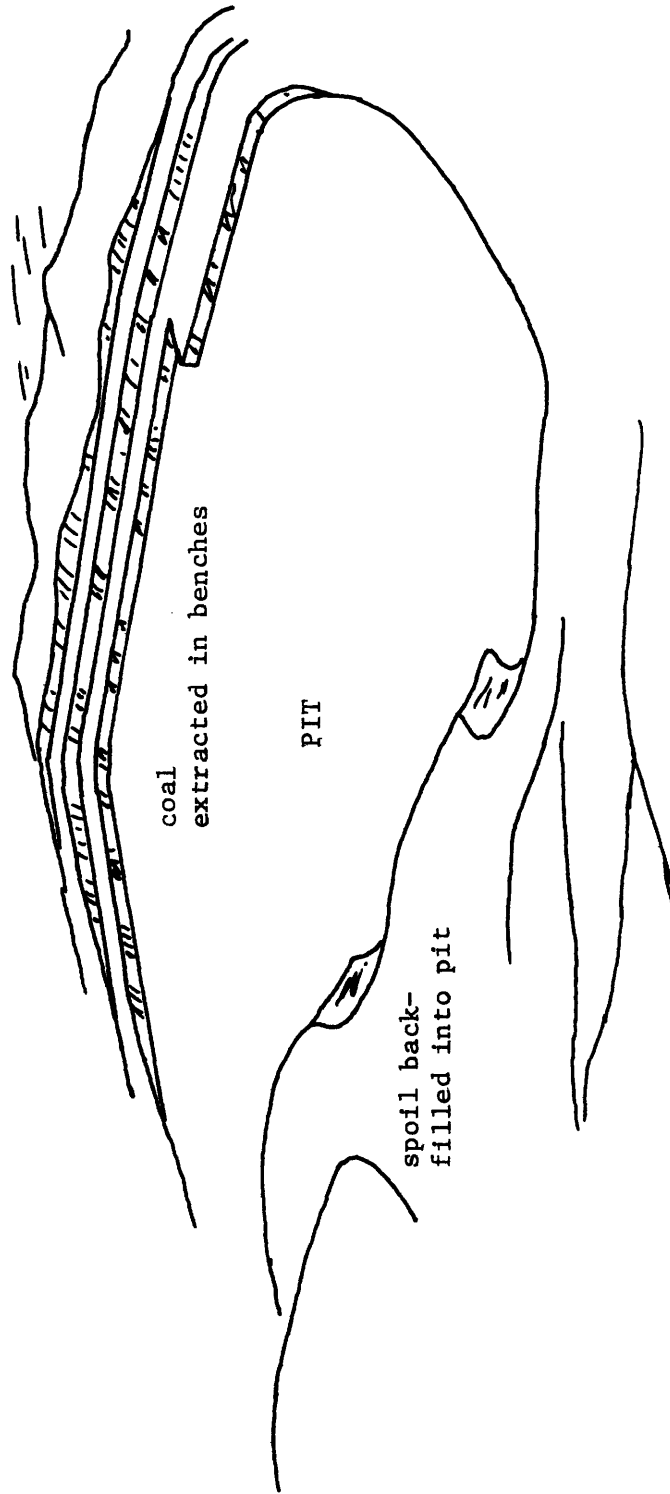


Figure 2.3 Open Pit Strip Mine. Overburden and coal are removed from the operational face of the pit and spoil is back filled into the other side.

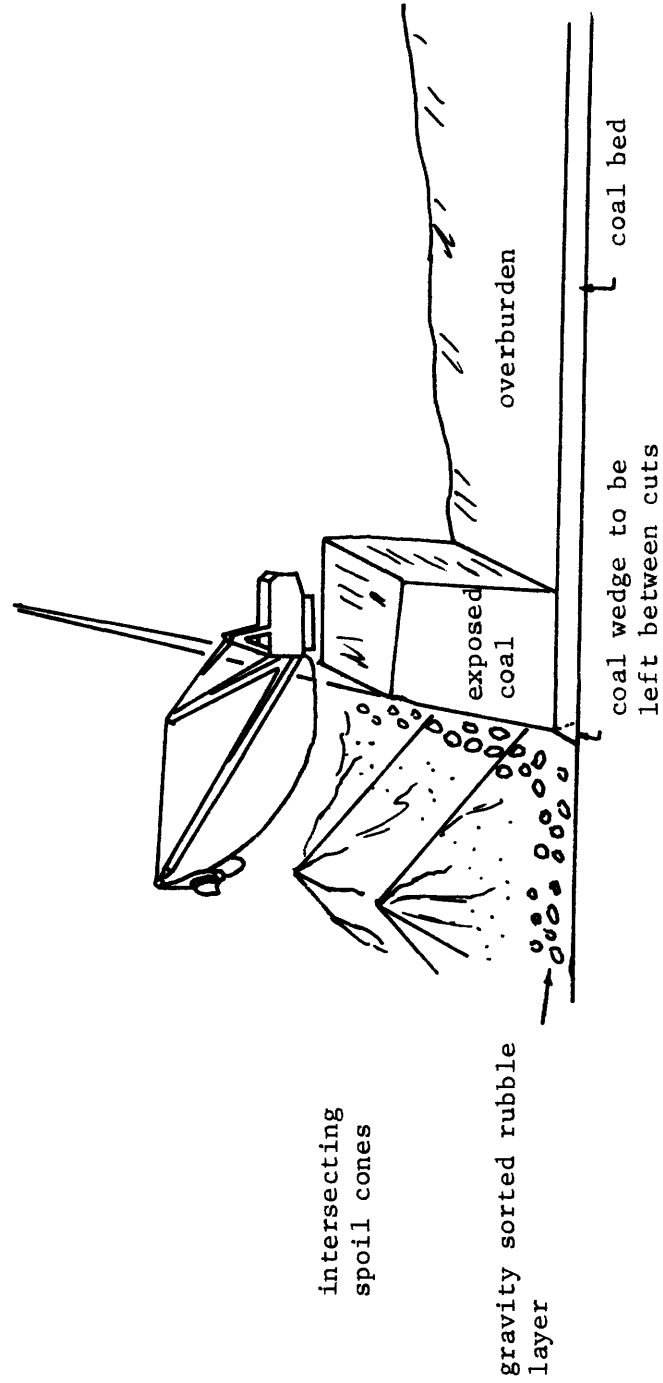


Figure 2.4 Dragline Operation. The formation of the rubble layer and coal wedge is shown.

bucket well above the spoil pile. When the spoil hits the pile the larger, heavier fragments tend to roll to the bottom of the pile. When the dragline backs to start the next cone, the material it dumps usually strikes the previous cone somewhere along its side. Again the larger fragments tend to roll down the side to the bottom. This seems to form a fairly uniform layer along the mine floor of the larger spoil fragments, with the finer material above it.

Little is actually known about this layer. The gravity segregation is readily observable in dragline operations, but the continuity and hydraulic properties of the layer are matters of speculation. The net hydrologic effect apparently is the formation of a highly permeable zone along the mine floor (Van Voast et al., 1975, 1976b), called the rubble layer.

Some mining operations also leave a small coal wedge between cuts. The wedge prevents the spoil in the previous cut from contaminating the coal being removed. During the coal removal, the wedge may be six meters high. After the coal has been extracted along the trench, the spoil on the other side of the wedge is cleared back from the wedge by a back hoe. Most of the wedge is then salvaged, leaving only a small wedge, less than two meters high between the trenches. Depending on its permeability, this coal wedge may affect the flow field through the mine and introduce a preferred direction of groundwater flow parallel to the wedges in the direction of least resistance. This property is referred to as coal wedge induced anisotropy.

Figure 2.4 depicts the features of a dragline operation. The Decker Mine is a good example (Rahn, 1976).

2.2.4 Truck and Shovel Operations

In the truck and shovel operation, the shovel excavates the overburden and loads it on trucks. This type of operation is commonly used in open pit mining (see Figure 2.3). The spoil is used to refill the pit. As the spoil builds up, bulldozers start to level the top and the trucks then drive on the spoil, dumping new spoil over the edge. This spoil layer is also called a "lift." These spoil lifts tend to be 25-40 m thick, with some gravity sorting expected at the bottom, but not as much as in the dragline case. The top of the lift is compacted by the trucks driving over it. Usually there are only one or two spoil lifts at any one location. This type of operation tends to give up to two rubble layers, one over the mined coal bed and the other immediately over the compacted surface formed by trucks driving on top of the first lift. As a result layered, horizontal flow would possibly be encouraged and vertical flow discouraged. The actual hydraulic characteristics of these features are currently unknown. The Belle Ayr Mine near Gillette, Wyoming, and the Bighorn Mine near Sheridan, Wyoming, are good examples of this type of operation (Rahn, 1976).

2.2.5 Scraper Operations

A scraper operation lays down the spoil in lifts between 2 and 6 meters thick. Since no long fall is involved, no gravity sorted

rubble zone is formed. Layered horizontal flow is most likely to be predominant, with relatively little vertical flow because of the thin layers a scraper forms. The Wyodak Mine in Northeast Wyoming principally uses scrapers to move the overburden (Rahn, 1976).

2.3 Generalized Mine Location and Geometry

Mine location and geometry can each independently influence the groundwater flowfield, and the amount of water contacting the spoil. Together with the reclaimed spoil hydraulic properties, they effectively determine the impact of a mine on the groundwater system.

Mines are located in many different settings in the West, from groundwater recharge areas in uplands, to groundwater discharge areas in alluvial valleys. Their areal shapes seem almost random at times. But the overall mine shape tends to be square when the mining operation is limited by property lines. When burnlines, faults, increasing coal depth determine the boundaries, almost any shape can be observed.

2.3.1 Strip Mines and Regional Groundwater Flow

A regional groundwater system extends from a recharge area at the major topographic high to a discharge area at the basin bottom. It normally includes several local systems of recharge at local topographic highs and discharge at the adjacent topographic lows. Recharge areas are characterized by declining piezometric head with depth, or by the presence of a groundwater divide and are found in topographically high regions. Discharge areas are similarly char-

acterized by topographically low regions, areas of increasing piezometric head with depth, and receiving bodies of water such as streams.

Figure 2.5 is a schematic of a generalized regional groundwater system. Groundwater flows from recharge to discharge areas. Water enters the system through infiltration and leaves by evapotranspiration and direct discharge to surface water.

Mine location in the regional flow system may influence how the mine affects the groundwater. Strip mines are currently located in both recharge and discharge areas. Two examples of mines in recharge areas are the mines near Colstrip, Montana; and the Gascoyne Mine in Southwestern South Dakota (U.S. Geological Survey, 1974). The Decker Mine is an excellent example of a mine in a discharge area (Van Voast and Hedges, 1975).

Many researchers have examined theoretical regional groundwater flow both analytically and through numerical computer models. For example, Toth (1962) investigated regional groundwater flow in a small drainage basin using analytical models. Freeze and Witherspoon (1967) used a numerical model to investigate the effects of water-table configuration, and the subsurface hydraulic properties on groundwater flow. These works explain some of the basic principles of regional flow. A summary of the literature is given by Domenico (1972).

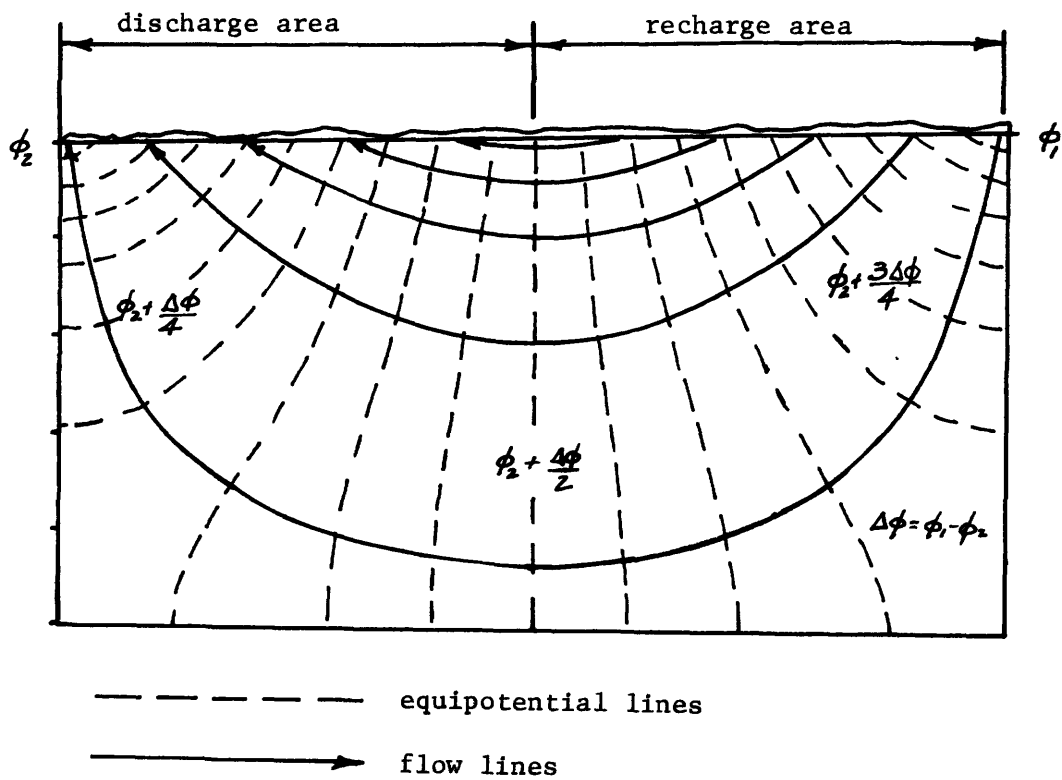


Figure 2.5. Generalized Regional Groundwater System. (From Toth 1962.)

2.3.2 Areal Mine Geometry

Individual mine geometry is far from simple and extremely dynamic. Mining plans change with economic and political pressures. A mine may or may not reach its initially proposed boundaries, or may eventually expand far beyond them. Rather than try to describe proposed mine shapes in detail, a very generalized approach will be taken based on operating mines pictured in the "Surface Coal Mining in the Northern Great Plains of the Western United States--An Introduction and Inventory Utilizing Aerial Photography Collected in 1974 and 1975" (1976). Two main geometries will be emphasized. When length and width are roughly equivalent, these shapes can be idealized as circles, squares or diamonds. When mine length is much greater than the width, these shapes can be idealized as rectangles. However, many mines do not easily fall into a simple geometrical configuration.

The significance of geometrical configuration will be analyzed in detail in the following two chapters. Some mines which tend toward the general square geometry are: East Antelope, Converse County, Wyoming; Belle Ayr, Cambell County, Wyoming; Wyodak, Cambell County, Wyoming; Glenharold, Oliver County, North Dakota; and Underwood, McClaim County, North Dakota. Some that tend toward the rectangular category are: Dave Johnston, Converse County, Wyoming; Big Sky, Rosebud County, Montana; Lehigh, Stark County, North Dakota; Center, Oliver County, North Dakota; Beulah, Mercer County, North Dakota, Velva, Ward County, North Dakota; and Noonan,

Burke County, North Dakota. Figure 2.6 schematically portrays several of these mines.

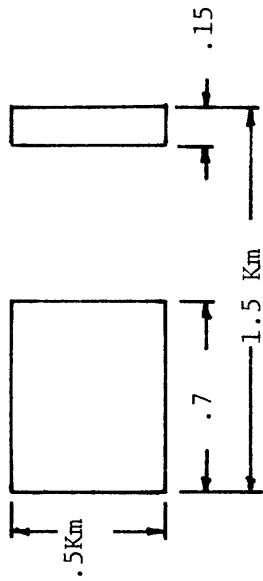
2.4 Other Research on Strip Mining Impacts on Western Groundwater Resources

Little is actually known about how a strip mine affects the groundwater system. Data has been collected only within the last few years, and most of it is uncollated and lies in scattered coal company and governmental regulatory agency files. Currently there are many researchers and groups investigating various aspects of the environmental impact of strip mining. A few of the more pertinent projects to this report are discussed here.

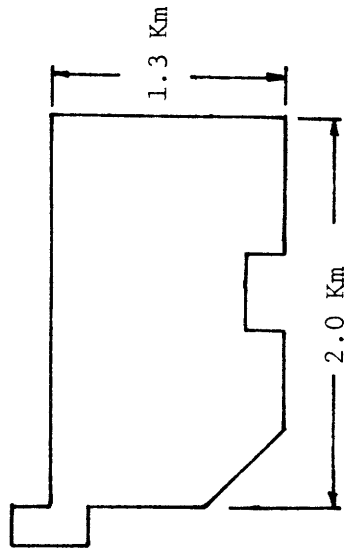
Wayne A. Van Voast in the Montana Bureau of Mines and Geology (1974, 1975, 1976a, 1976b) is conducting a very extensive investigation into the hydrologic impacts of strip mining. Starting in 1973 he has carefully instrumented the Decker and Colstrip Mines and has compiled the most comprehensive data base available. His data and findings have provided the basis from which this report was launched. In summary Van Voast has observed:

- 1) that spoil material tends to have a greater hydraulic conductivity than the original coal bed aquifer
- 2) the spoil aquifer is confined
- 3) a highly permeable rubble zone may form at the spoil base
- 4) the spoil tends to lower water quality
- 5) individual mine sites are extremely complex and difficult to model

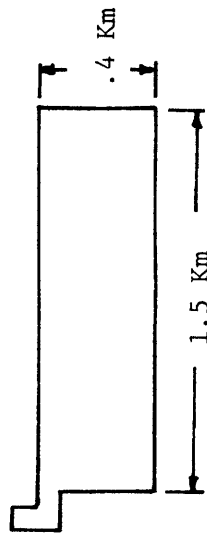
Wyodak Mine,
Campbell Co., Wyoming



Savage Mine
Richland Co., Montana



Big Sky Mine
Rosebud Co., Montana



Dave Johnston Mine
Converse Co., Wyoming

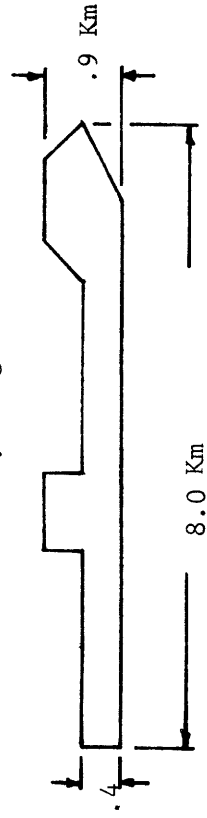


Figure 2.6 Schematics of Several Northern Great Plains Strip Mines. Based on aerial photos in Surface Coal Mining in the Northern Great Plains of the Western United States (1976).

6) and the spoil tends to consolidate with time.

The work of others confirms and extends the information on these trends.

Perry A. Rahn at the South Dakota School of Mines and Technology (1976) has investigated spoil permeability and spoil water quality. David W. McWhorter at Colorado State University (1975, 1976) has been primarily investigating water quality in runoff from mine areas, and spoil leachate. Paul Rechar and the Wyoming Water Resources Research Institute; Argonne National Laboratories; the General Electric Tempo Study; the United States Geological Survey; and several other universities, consultants, and many of the coal companies are presently conducting research on some aspects of this problem area. As demonstrated by this short review, there is only a limited amount of published literature on the subject.

The previous work tends to be very site specific, with the emphasis on field data acquisition. Now that a data base has been established, more attention is being paid to analysis and modeling but it is still based on a site specific basis, absorbed with the inherent complexities of each situation.

Since only a limited amount of work has been done in this field, there is little "feel" for which characteristics are significant, or how the system will respond as a given characteristic changes. This report will seek to provide a systematic evaluation of the relative significance of common strip mine characteristics.



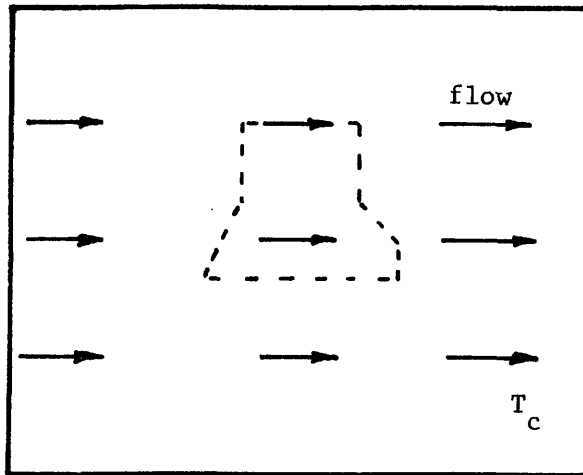
CHAPTER 3
METHODOLOGY

The influence of strip mines on groundwater hydrology, during and after mining, was investigated by idealizing typical Northern Great Plains mining situations, and simulating them using a numerical model. Certain important characteristics were isolated for careful examination:

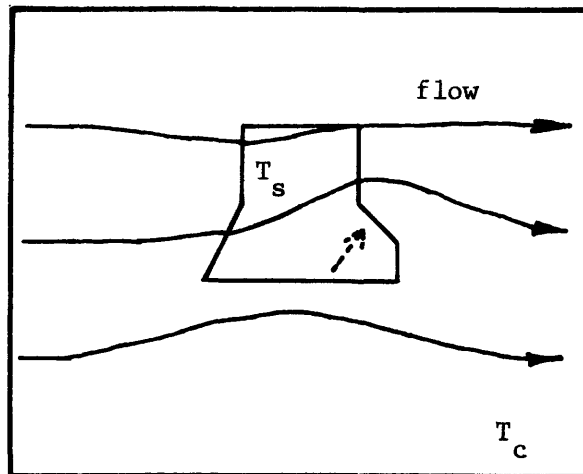
1. mine geometry,
2. relative transmissivity of the spoil and surrounding material,
3. spoil anisotropic properties induced by mining operations,
4. internal features such as the rubble layer and coal wedges,
5. relative regional location and mine size,

and the results analyzed in terms of the effect of a mine on aquifer flow patterns and potential water quality degradation.

Several reference frames were selected to study the influence of each mine characteristic. A plan view of the mine and surrounding aquifer was selected to investigate the long-term effects of external mine geometry, spoil transmissivity and spoil anisotropy on a local hydrologic system involving a coal bed aquifer (see Fig. 3.1). These three characteristics may greatly influence the amount of water entering the spoil and its contact time with the spoil in the post mining period, after reclamation has been completed. Therefore, a



a. Ambient flowfield before mining operation. The proposed mine outline is dashed in.



b. Possible post mine flowfield with $T_s > T_c$ and dashed arrow indicates preferred direction of flow through the spoil.

Figure 3.1 Influence of Reclaimed Mine on Local Hydrology. A reclaimed mine site may influence the local hydrology by its geometry, transmissivity and anisotropy.

steady state condition was assumed to simulate the long-term effects. The plan view is referred to as "local hydrology" in this report.

A cross sectional view was used to investigate the long-term effect of the rubble layer and coal wedges on the flow pattern through spoil in contact with a coal bed aquifer (see Fig. 3.2). The highly permeable rubble layer is believed to concentrate a large portion of the total flow through the mine. The less permeable coal wedge may be responsible for forcing some of this water back into contact with the finer spoil. Since these characteristics of the interior view are significant in the post mining period, a steady state was assumed. This situation is termed "interior flow".

Long-term effects on the regional flow field are probably not significant when considering a reclaimed mine, because local hydrologic property changes are too small to lead to any appreciable re-direction of the flow. A different situation would be an operational mine that significantly lowers the piezometric head, and therefore would affect the regional system. This possibility was examined in a cross sectional view of a regional groundwater aquifer system (see Fig. 3.3). The water table of the system's uppermost aquifer was taken as the upper boundary for the entire regional system. Because a mine has a relatively long operational life (30-50 years), the maximum impact of a site was assumed to occur when the flow field reaches a steady state. This situation is termed "regional hydrology".

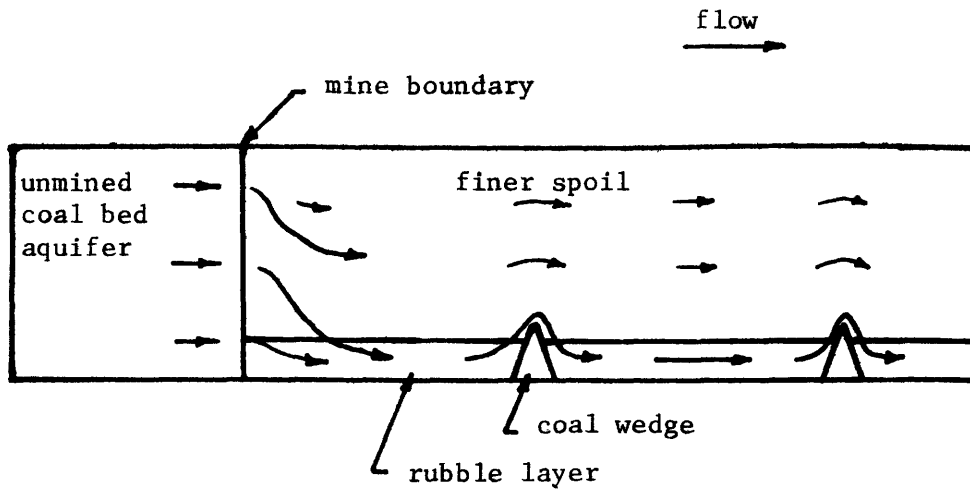


Figure 3.2 Cross Sectional View of an Aquifer in Reclaimed Spoil. The dominant features shown are the gravity sorted rubble layer and coal wedges left by dragline trenching operations.

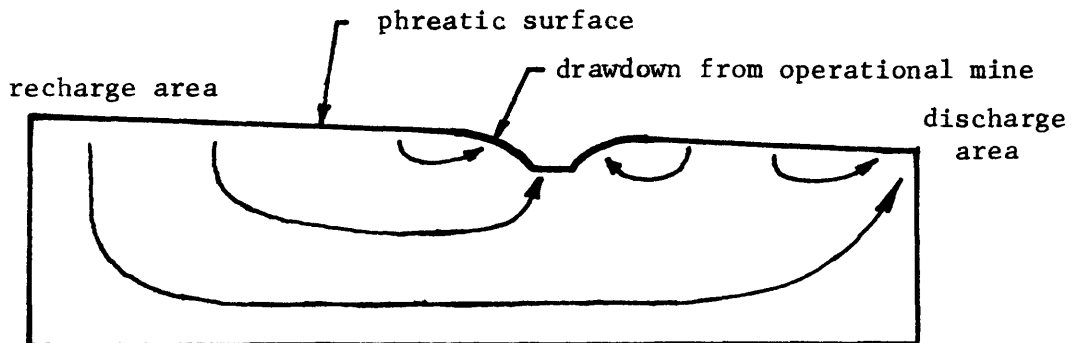


Figure 3.3 Influence of an Operational Mine on the Regional Groundwater System. Water is diverted from the regional system and discharged into the mine.

These three situations were simulated using a computer model to solve the governing equations for groundwater flow. The general solution methodology and techniques are discussed in the following sections.

3.1 Methodology

A systematic methodology was used to investigate each of the mining situations chosen for simulation. For each view the overall geometry was idealized and regions of special interest were identified. To a large extent these regions comprised those portions of the geometry where large hydraulic gradients were expected. Yet, they also included those portions of the overall geometry which were designed for small scale geometric changes, such as the introduction of different mine shapes and sizes.

A finite element grid, composed of triangular cells or elements, was designed to incorporate the idealized geometry and to provide detailed information in the regions of special interest. To achieve the latter, smaller elements were used, leading to a locally finer grid.

Boundary conditions were chosen to realistically simulate typical mine settings. The most commonly used boundaries were specified piezometric head and specified zero flux (discharge) normal to the boundary. A specified positive flux was used for one boundary of the local hydrology simulation (plan view).

For each situation appropriate governing equations for flow were developed, considering the objectives of the study and assumptions regarding geometries and hydraulic properties. Some of the important considerations were: vertical or horizontal flow, steady or transient, homogeneity, anisotropy and pumpage. All the situations studied were two-dimensional. For the local hydrology study, a two-dimensional horizontal flow situation, the hydraulic equation is appropriate (Bear, 1972, also see Section 3.2). This equation is based on the Dupuit approximation and assumes vertically averaged properties. Since the mine spoil has properties different from the coal bed, and since it may also have coal wedge induced anisotropy, the hydraulic equation must be formulated to handle heterogeneity and anisotropy. However, it need only consider steady flow. The interior flow and regional hydrology studies require a two-dimensional vertical flow solution and the hydrodynamic equation for a heterogeneous, possibly anisotropic medium (see Section 3.2). However, steady flow can be assumed. A finite element model capable of modeling these features was selected and implemented. It is described in the next section.

For each simulation, the mine characteristics under study were reproduced in the computer model to assess the impact of the mine on the flow field. Each mine characteristic was varied and sensitivity analyses were conducted. The results were evaluated, using techniques described later in this chapter, and additional simulations run when appropriate.

The finite element grid, boundary conditions, mine characteristics investigated and results for each simulation are discussed in the following chapters.

3.2 Simulation Model

The principal tool used in this analysis was a finite element model developed at the Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology (Sa da Costa and Wilson, 1977). The model is called AQUIFEM-1, an acronym for AQUIifer Finite Element Model. The numerical code solves basic differential equations governing two-dimensional vertical or horizontal groundwater flow using the Galerkin finite element method. The aquifer is subdivided into simple linear triangular elements, and a numerical approximation to the governing equations is made. A detailed description of the model is given by Sa da Costa and Wilson(1977). The following is only a brief account to put the model into perspective.

AQUIFEM-1 solves the hydraulic equation for two-dimensional horizontal groundwater flow in a non-homogeneous, anisotropic aquifer,

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(T_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(T_{yy} \frac{\partial h}{\partial y} \right) - Q \quad (3.1)$$

where:

$$T_{xx} = T_{xx}(x,y,t) = \text{aquifer transmissivity in the x direction} \\ [L^2/T];$$

$T_{yy} = T_{yy}(x,y,t)$ = aquifer transmissivity in the y direction
[L²/T];

$S = S(x,y,t)$ = aquifer storage coefficient [L/L];

$h = h(x,y,t)$ = depth averaged piezometric head [L];

$Q = Q(x,y,t)$ = net groundwater withdrawal or recharge
including pumping [L/T];

x,y = horizontal Cartesian coordinates (principal
axes of the hydraulic conductivity/
transmissivity tensor) [L];

t = time [T].

The aquifer may be anisotropic and non-homogeneous with respect to hydraulic conductivity (or transmissivity) and non-homogeneous with respect to the storage coefficient. The code is also capable of simulating vertical leakage, but this feature was not used in this application.

Similarly, the hydrodynamic equation for two-dimensional cross sectional flow in a non-homogeneous, anisotropic aquifer is

$$S_s \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial x} (K_{xx} \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial z} (K_{zz} \frac{\partial \phi}{\partial z}) - Q \quad (3.2)$$

where:

$K_{xx} = K_{xx}(x,z,t)$ = aquifer hydraulic conductivity in the x
direction [L/T];

$K_{zz} = K_{zz}(x,z,t)$ = aquifer hydraulic conductivity in the z
direction [L/T];

$S_s = S_s(x, z, t)$ = specific storage capacity of an aquifer
[1/L];

$\phi = \phi(x, z, t)$ = piezometric head [L];

x, z = Cartesian coordinates (principal axes of the
hydraulic conductivity tensor) [L];

$Q = Q(x, z, t)$ = net groundwater withdrawal or recharge
including pumping at a point [L/T];

z = vertical Cartesian coordinate [L];

and all other symbols are as described by Eq. 3.1.

Solution of this equation requires that the location of the free surface be specified, along the water table, i.e., $\phi = z$.

It is readily observed that the following substitutions convert Eq. 3.2 to Eq. 3.1: $\phi = h$, $S_s = S$, $K_{xx} = T_{xx}$, $K_{zz} = T_{yy}$ and $Q = Q$. Therefore, AQUIFEM-1, which was developed to investigate in a 2-D horizontal aquifer, can be used to study 2-D vertical cross sectional flow, provided the location of the phreatic surface is assumed.

When solved for a steady state $\frac{\partial h}{\partial t} = 0$, and assuming there is no groundwater withdrawal, $Q = 0$, Eqns. 3.1 and 3.2 become, respectively:

$$\frac{\partial}{\partial x} (T_{xx} \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (T_{yy} \frac{\partial h}{\partial y}) = 0 \quad (3.3)$$

and

$$\frac{\partial}{\partial x} (K_{xx} \frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial z} (K_{zz} \frac{\partial \phi}{\partial z}) = 0 \quad (3.4)$$

Eq. 3.3 was solved by AQUIFEM-1 for the local hydrology (plan view) simulation, and Eq. 3.4 was solved for the cross sectional view simulations.

Assuming that head varies linearly across each element, AQUIFEM solves for the piezometric head at the nodes (corners of the triangles). In this way, the model produces a piecewise, linear continuous approximation of the actual piezometric head. When plotted as a function of the spatial coordinates, say x and y, this approximation appears as a multi-faceted surface, with one surface for each element. A finer grid provides a closer approximation to the actual head, and, therefore, a more accurate solution.

The solution requires the reduction of Eqs. 3.3 and 3.4 to a numerical form using the method of weighted residuals and the Galerkin approximation (see Sa da Costa and Wilson, 1977). In matrix form they become

$$\underline{B} \underline{H} = - \underline{F}^b$$

where the subscript represents a matrix. The coefficient matrix B represents the conductance or transmissive terms of Eqs. 3.3 or 3.4, respectively. The F^b matrix represents specified flux boundaries. Specified head boundaries are already included in the left-hand side of the matrix equation. Since heads are solved for at the nodes, it is evident that H represents a vector of the head values at the node. The solution for H is easily computed using direct substitution, using subroutine DIRECT of AQUIFEM-1. The output includes not only the head values at the nodes, but specific discharge values in nodes and elements.

For the matrix B, AQUIFEM assumes that the transmissivity

(hydraulic conductivity) of the aquifer is an element property. In other words, it assumes that the transmissivity is constant over each element, although there may be differences between elements. In the original version of the code (Sa da Costa and Wilson, 1977) these properties initially are assigned to the nodes in the input, then the model mathematically averages nodal values over each element to define the element property. Since AQUIFEM was designed to model natural aquifer systems using the hydraulic equation, where sudden changes in properties are uncommon, this was one way of simplifying the input. However, fault zones and the sharp contact between the spoil and the coal present a different situation. To account for the latter, the AQUIFEM-1 code was modified to bypass the nodal averaging process and properties were directly input as element values.

3.3 Evaluation Techniques

The simulations were designed to give both quantitative and qualitative insights into how strip mine characteristics influence the groundwater system. The effects of greatest concern were:

1. flow field distortion,
2. amount of water contacting spoil,
3. water/spoil contact time.

These were all analyzed in dimensionless terms, with the results normalized on a common basis. The methodology used in obtaining and evaluating these results are presented in this section.

3.3.1 Piezometric Head Contours

Flow field distortion may be observed graphically through the use of equipotential lines, or piezometric head contours. Under isotropic conditions, water flows perpendicular to these lines as shown in Fig. 3.4 for the case of an AQUIFEM simulated regional flow system. The equipotential lines in the figure are plotted using a contour plotting computer routine which linearly interpolates piezometric head between the nodes for each element. The contour interval, or piezometric head loss, may be arbitrarily selected. The plotting program is listed in Appendix B. Flow lines in the figure are drawn in by hand for interpretive and illustrative purposes.

Though actual streamlines are not generated in this study, their properties merit brief mention. For an isotropic media, with known equipotentials, streamlines can be drawn everywhere orthogonal to the piezometric head contours. If this procedure is carefully carried out, in a homogeneous media, it results in a flow net with approximate curvilinear squares formed by the equipotential and streamlines. In this case the flow between any two streamlines is constant. When streamlines converge, the specific discharge (velocity) increases. When they diverge the specific discharge decreases. Figure 3.5 presents the local hydrology flow pattern (plan view) near a circular shaped, reclaimed mine that is located in a uniform flow field. This pattern is calculated analytically in Appendix C, and presented for the case of spoil transmissivity, T_s ,

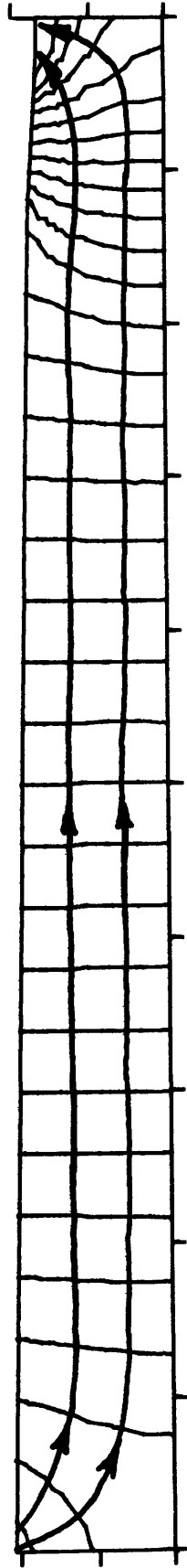
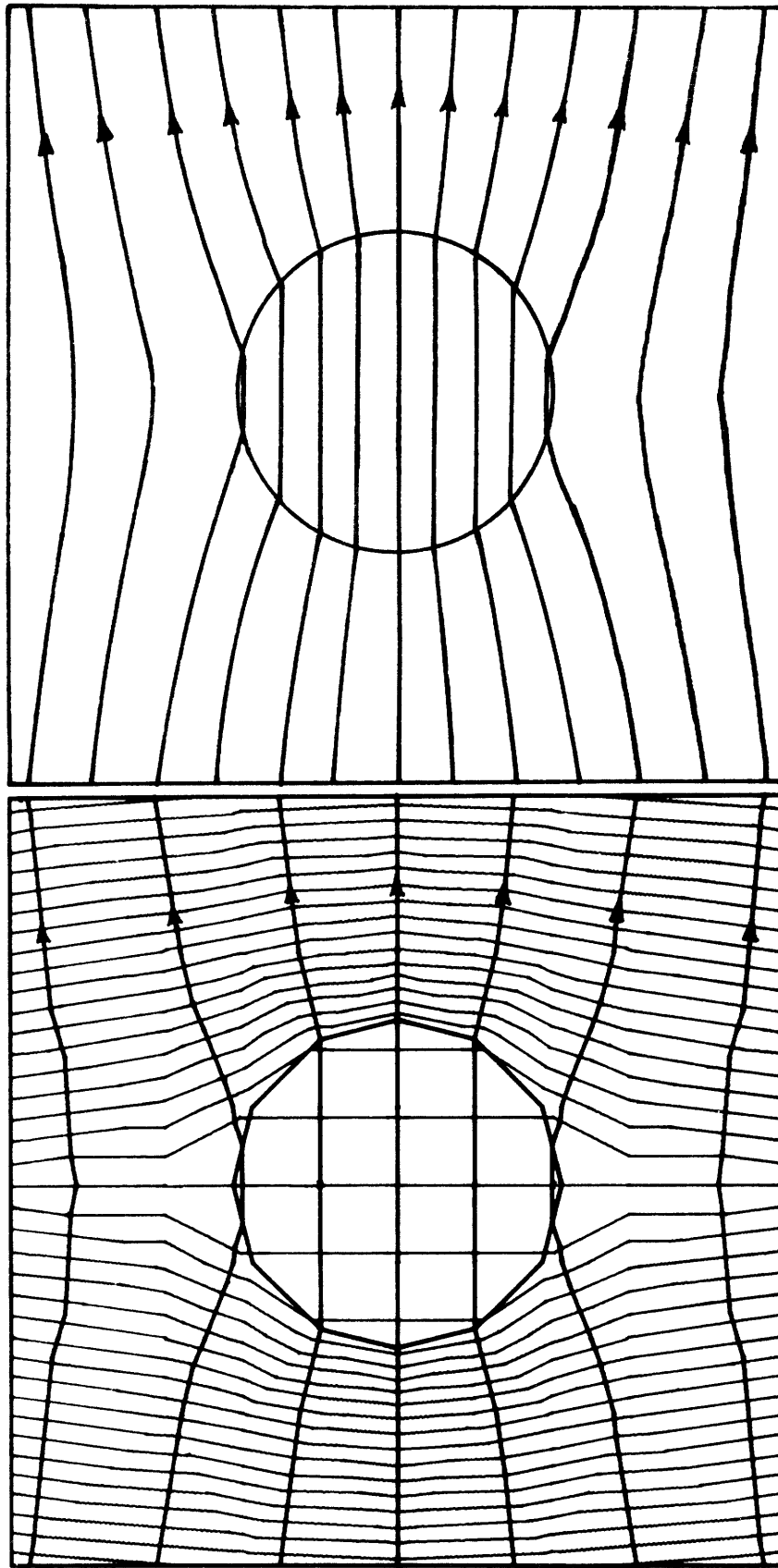


Figure 3.4 Example of Equipotential Lines Generated in Regional Cross Sectional Simulation. Flow lines are drawn in by hand, perpendicular to the equipotential lines.



a. Equipotential lines and flow lines drawn using the finite element grid and CONTOUR. b. Flow lines from the exact solution, twice as many flow lines are presented as in a.

Figure 3.5 Analytical Solution to Reclaimed Circular Mine.

six times greater than the surrounding coal bed transmissivity, T_c . The figure shows that the greater transmissivity of the spoil concentrates water flow in the mine.

In systems involving non-homogeneity, streamlines are refracted at the boundary between the transmissivity (permeability) discontinuity. In two dimensions, this is typically described by the law of refraction of streamlines. When water passes from a less pervious to a more pervious material, the streamlines are refracted toward a direction parallel with the boundary. In the case of water passing into a less pervious formation, streamlines are refracted toward the normal. These kinds of cases are discussed in Bear (1972).

Anisotropic systems are more difficult to deal with because streamlines are no longer orthogonal to equipotential lines. Assuming principal axes, that is, the coordinate system is alligned on the preferred direction for flow, the angle between the streamlines and equipotential lines is given by θ , where

$$\cos \theta = (K_x J_x^2 + K_y J_y^2) / (|\vec{q}| \cdot |\vec{J}|) = -(K_x J_x \vec{i} + K_y J_y \vec{j})$$

and \vec{q} is the specific discharge vector, $\vec{J} = -\nabla\phi$ is the hydraulic gradient, and ϕ is the peizometric head. Bear (1972) and Freeze and Witherspoon (1967) describe techniques for the construction of flow nets in anisotropic systems.

On a number of the equipotential maps generated by the simulations, random streamlines appear. Their only purpose is to elucidate the direction and pattern of flow.

3.3.2 Flux Calculations and Model Verification

The volume of water, during a given interval of time, that passes through a two-dimensional area, such as the cross sectional slice across a reclaimed mine, is defined as a volumetric flux. For example, consider the local hydrology of a symmetrical, reclaimed mine (plan view), in a uniform flow field. The maximum flux through the mine is found at the halfway point along a line normal to the flow direction (see Fig. 3.6). This centerline mine width is denoted by the symbol W in this report and the flux passing through it is designated as Q_S , representing the flow through the reclaimed mine spoil. The flux through an equivalent width W under ambient conditions in the uniform flowfield is Q_A . The ratio Q_S/Q_A is a measure of flux concentration attributed to the mine spoil. When its value is unity, there is no change in the flowfield. When it is greater than unity the flow has converged toward the mine, and similarly, when less than unity, flow has diverged around the reclaimed mine site. A larger Q_S/Q_A ratio implies a greater degree of flux concentration, bringing more water into contact with the spoil material.

Accurate flux calculation is sometimes a problem in finite element formulations at the boundaries between domains, such as at the mine boundary investigated in this report, across which transmissivity may vary significantly. Larock and Herrmann (1976) discuss this problem and suggest that weighted averages from different types of flux calculations offer the most accurate solutions. Two types of fluxes are calculated in AQUIFEM based on nodal and elemental specific dis-

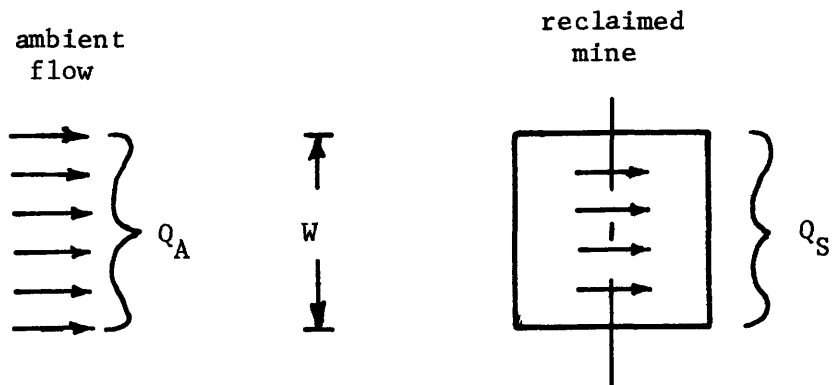


Figure 3.6 Definition of Q_A and Q_S . Q_A is the flux under ambient conditions through a width W , and Q_S is the flux through a reclaimed mine of width W .

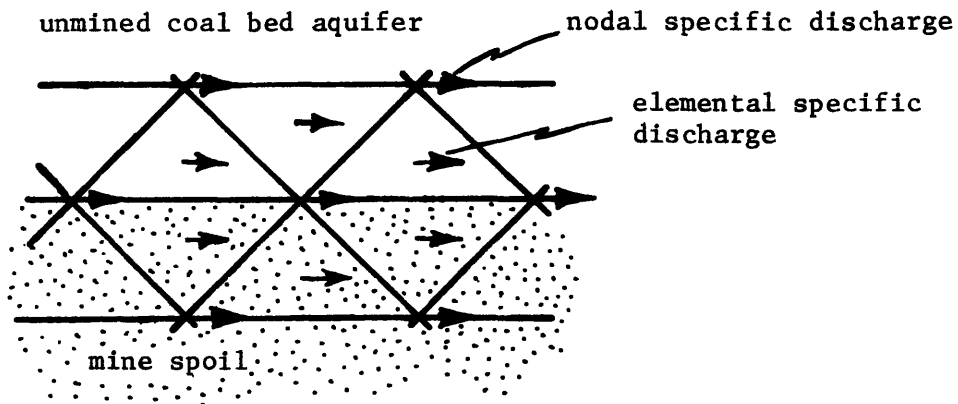


Figure 3.7 Nodal and Elemental Specific Discharges.

TABLE 3.1

Comparison of Analytical and Simulation Solutions for a Circular Reclaimed Mine

T_s/T_c	Q_S/Q_A Calculated from Elemental <u>Specific Discharges</u>	Q_S/Q_A Calculated from Nodal <u>Specific Discharges</u>	Q_S/Q_A <u>Averaged</u>	Q_S/Q_A Theoretical <u>(Eq. C.13)</u>
100/1	2.13	1.81	1.97	1.98
6/1	1.81	1.64	1.72	1.71
1/1	1.00	1.00	1.00	1.00
1/6	0.27	0.43	0.35	0.28

charges (see Fig. 3.7). For a circular mine in a uniform flow field, Table 3.1 compares simulated nodal and element based flux values to the analytical solution of Appendix C. When the reclaimed mine spoil transmissivity is greater than the ambient, an equal weighting between the nodal and elemental fluxes provides an excellent correspondence with the theoretical flux. When the mine spoil transmissivity is less than that of the surroundings, the elemental flux alone accurately matches the analytical solution. In this case, the nodal flux along the mine border is heavily influenced by the much larger specific discharges around the mine. Including these into the calculation of flux through the spoil overweighs their importance and leads to a high average flux.

Averaged flux values are used for the local hydrology flux calculations in Chapter 4, when the transmissivity of the reclaimed spoil (T_s) is greater than the natural coal bed aquifer transmissivity (T_c). Elemental fluxes are used when $T_s < T_c$. Fluxes are also calculated using element values in the analysis of interior flow presented in Chapter 5.

3.3.3 Contact Time Estimation

The contact time for a water parcel following a streamline is properly calculated by the integral:

$$t_c = \int_{s_0}^s \frac{n}{q(s)} ds \quad (3.5)$$

where: t_c = contact time [T]
 s = streamline the water parcel is following [L]
 $q(s)$ = specific discharge [L/T]
 n = effective porosity
 s_o = initial parcel location [L]

For this investigation, Eq. 3.5 was solved only for flow along the centerline of mines in the local hydrology simulations. By substituting $v = K_s J_s$, where J_s is the hydraulic gradient through the mine and integrating over the mine length L , Eq. 3.5 becomes:

$$t_c = \frac{L^2 n}{K_s \Delta\phi} \quad (3.6)$$

where: $\Delta\phi$ = change in peizometric head. The contact time is normalized by t_a , the time it would take a water particle to traverse L under ambient conditions, assuming equivalent effective porosities. This provides a relatively simple and accurate means of comparing contact times between simulations.

Some may question the accuracy of assuming J_s to be constant along the mine centerline. For a circular mine, it can be shown (see Appendix C) that $J_s \equiv \text{constant} \equiv \frac{K_c J}{K_c + K_s}$, where J is the hydraulic gradient in the ambient uniform flowfield. The simulation results of Chapter 4 indicate that in approximation J_s remains valid for other symmetric shapes.

CHAPTER 4

LOCAL HYDROLOGY SIMULATION

After a mining operation ceases and reclamation is complete, the replaced spoil forms a new hydrologic unit in the local groundwater system. Flow patterns and rates, and the piezometric surface, are affected. A plan view, local hydrology simulation was used to identify how mine properties, such as mine geometry, relative transmissivity and anisotropy, influence the re-establishment of groundwater flow through the mine site and affect the local flowfield. For comparison purposes, the local hydrologic effect of an operational mine was also simulated.

4.1 Simulation Formulation

The reclaimed mine was placed in the center of a two dimensional, uniform, steady flow field modeled by a symmetrical finite element grid composed of 200 elements and 109 nodes (Fig. 4.1). The smaller elements in the center of the grid were designed to give detailed information on the piezometric head distribution near the mine and allow easy variation of its shape. Most mine shapes were accommodated by varying aquifer properties in these center elements. However, for a circular mine, a few of the nodes were moved. Figs. 4.2 and 4.3 illustrate the detailed grid in the mine vicinity and show the location of square and circular mine geometries, respectively.

Two types of boundary conditions were considered to impose a uniform flow field: specified flux on the left side of the grid

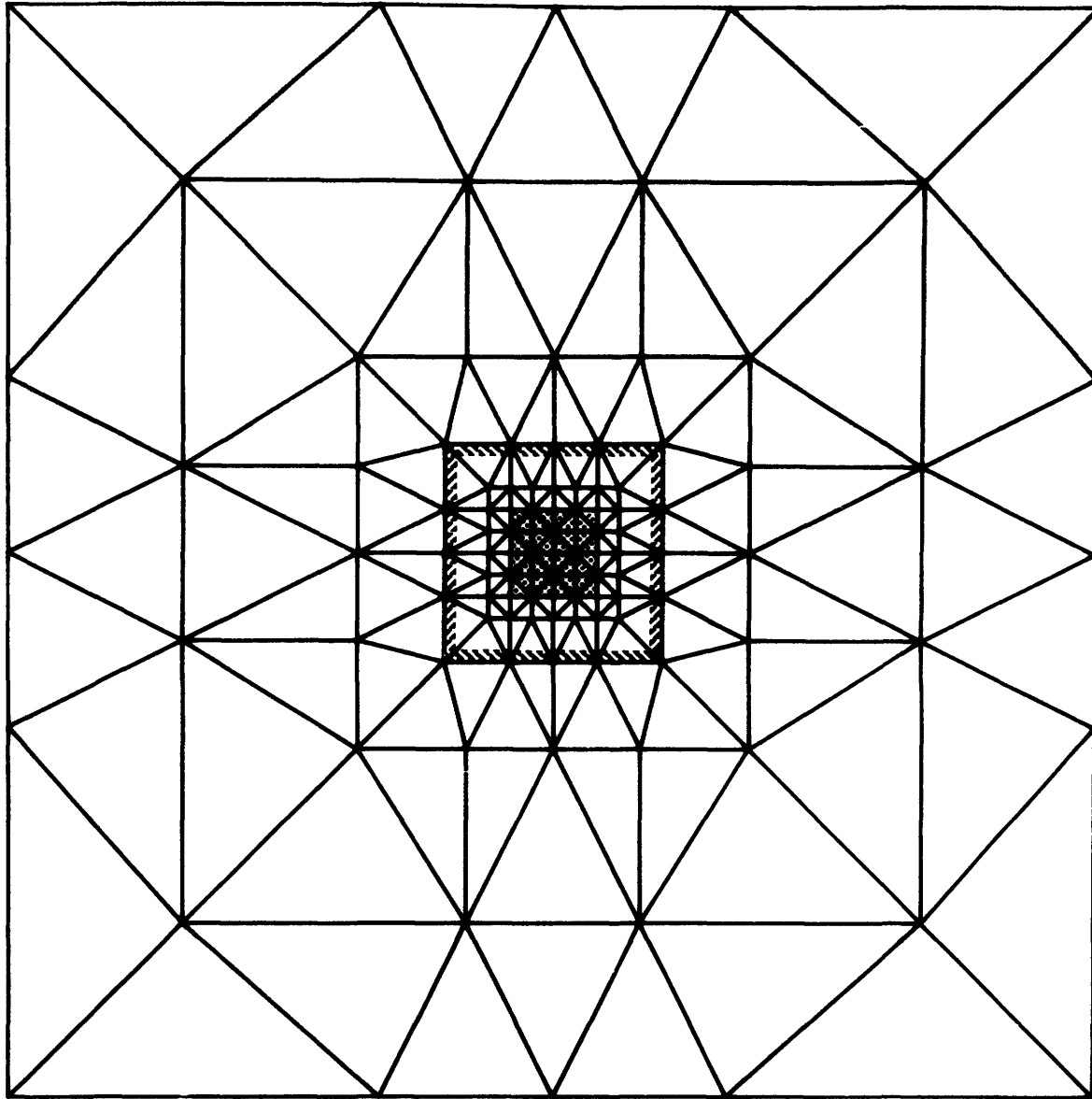


Figure 4.1 Local Hydrology Finite Element. The mine is located in the shaded center portion. A close up of the bordered region is presented in the next two figures.

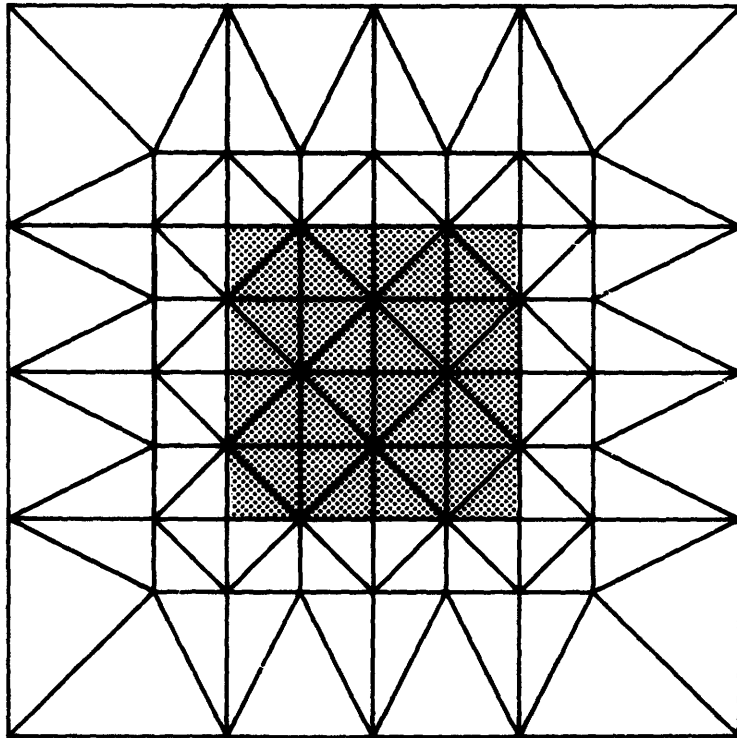


Figure 4.2 Detailed Grid Near the Mine Site. Elements representing the square mine are shaded.

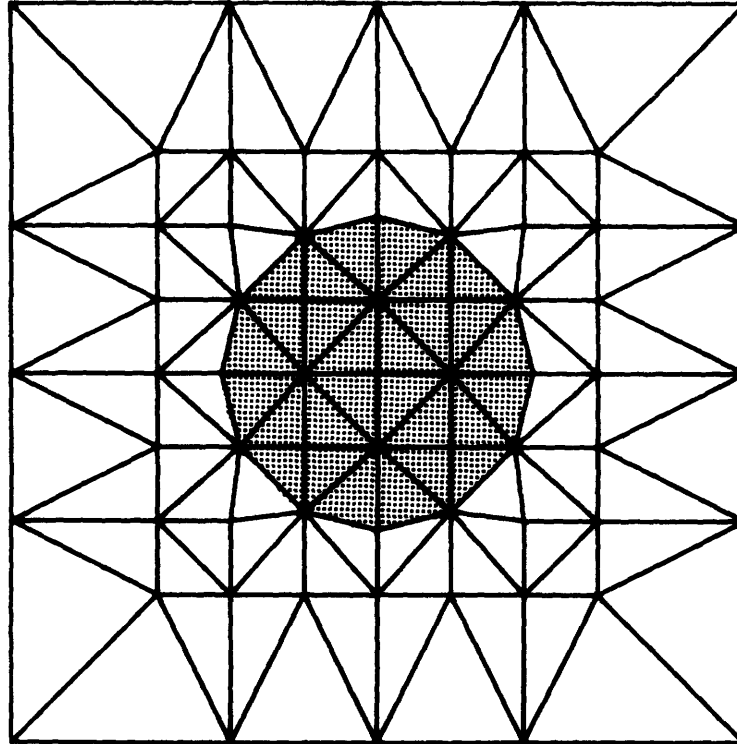


Figure 4.3 Detailed Grid Near a Circular Mine Site. Elements representing the circular mine are shaded in. Only a few nodes were moved to form the circle, otherwise the grid is the same as in Figure 4.2.

and specified head on the right; or specified head on both sides. Test runs using each set of boundary conditions yield essentially identical results. The mixed boundary condition of specified head/flux was selected to insure a constant flux through the flow field for all mine geometries and degrees of non-homogeneity. These boundary conditions are analogous to choosing an aquifer flowing with a constant total discharge (and ambient specific discharge) to a discharge area with a constant head, such as a reservoir, river or well drained topographic low. To insure that the boundary conditions were placed far enough from the mine to prevent interference, simulation results were compared for a mine simulation run with the full grid and rerun with the outer element layer removed. The results were almost identical.

The equipotential patterns generated by the simulations are dimensionless and indicate patterns of head distribution and inferred flow directions, rather than particular numerical values. In all cases shown, the flow is from left to right, the direction of decreasing peizometric head.

4.2 Influence of Relative Hydraulic Conductivity/Transmissivity

There is an ambiguous relationship between measured values of hydraulic conductivity found in spoil and natural aquifer material. The values range widely, reflecting the complexities inherent in actual settings. Generally the spoil has a higher hydraulic conductivity than the original material.

Hydraulic conductivity ranges and means for coal and mine spoils in Southeastern Montana are shown in Fig. 4.4. The means were weighted by the number of tests at the Decker and Colstrip Mines. By combining the weighted means for the two sites, the hydraulic conductivity of the spoils was found to be about six times greater than that for the coal ($K_s/K_c \approx 6$). It must be emphasized that this is only an estimate from a sample with a large variability, and the actual number is not the primary concern in this study. Rather it is the general effect resulting from spoils with hydraulic conductivity larger than that found in the surrounding aquifer material that is of interest here. Also almost all the data is from relatively new spoil, where little time has passed for settling.

As discussed in the next chapter, the saturated thickness of Northern Great Plains spoil is often equal to the thickness of the coal bed aquifer. Thus the hydraulic conductivity and transmissivity ratios between spoil and coal are equal, $K_s/K_c = T_s/T_c$. Using the average value of $K_s/K_c = 6$ of a previous paragraph, a transmissivity ratio $T_s/T_c = 6$ was derived and used as a standard in the model simulations. The ratio was varied to test its effect on the flow field and to gain a better understanding of how the system may change if significant consolidation lowers the spoil conductivity.

Several simulations were performed for circular and square geometries over a wide range of T_s/T_c , and flux concentration and relative travel time (see Chapter 3) were calculated. The results, presented in Fig. 4.5 and Table 4.1, lead to the following comments:

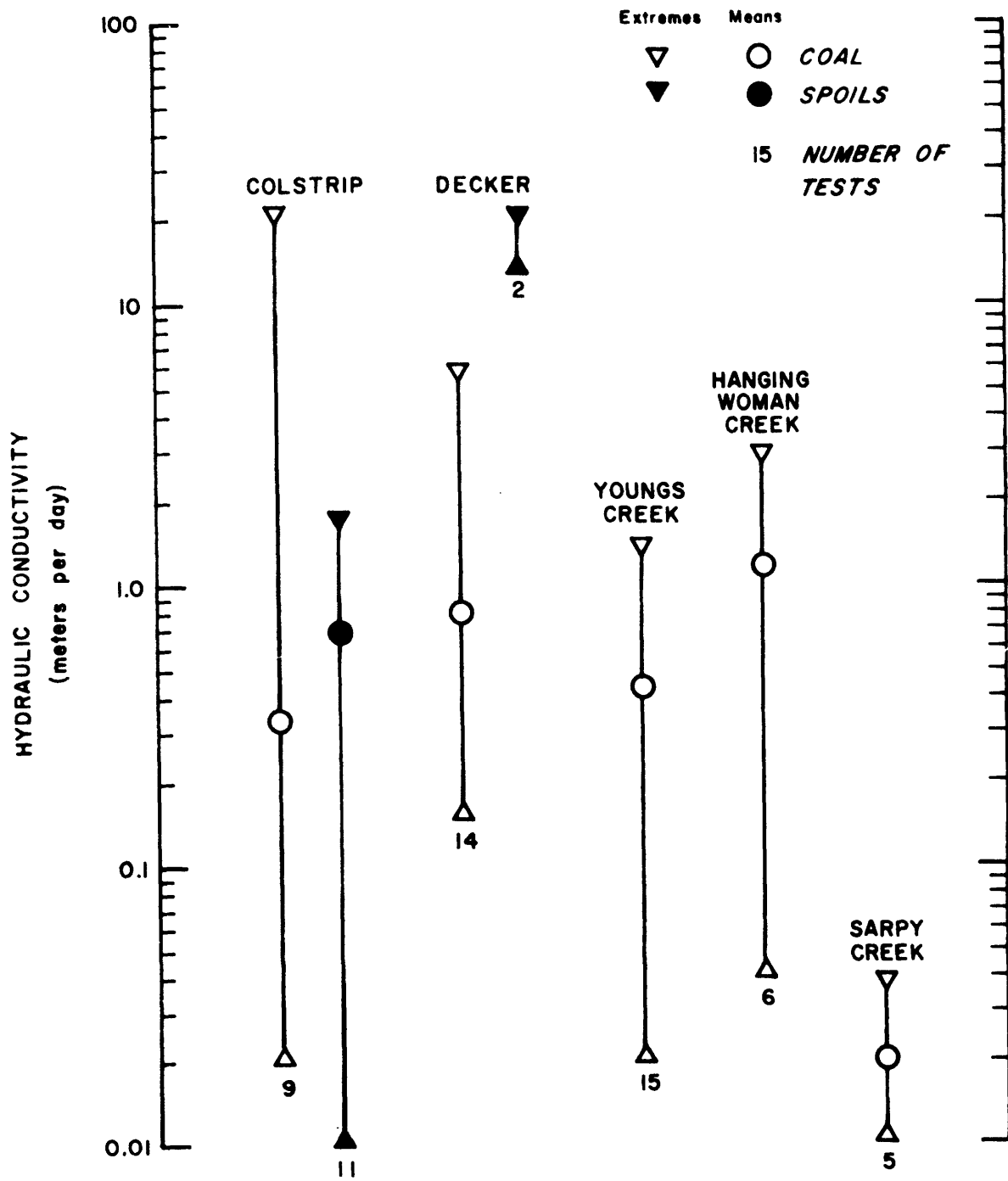


Figure 4.4 Hydraulic Conductivity Ranges for Coal and Spoil Aquifers. The mines are located in Southeastern Montana, and the figure is from Van Voast (1976b).

- simulation results for circular mine
- theoretical circular results (Eq. C.13)
- simulation results for a square mine

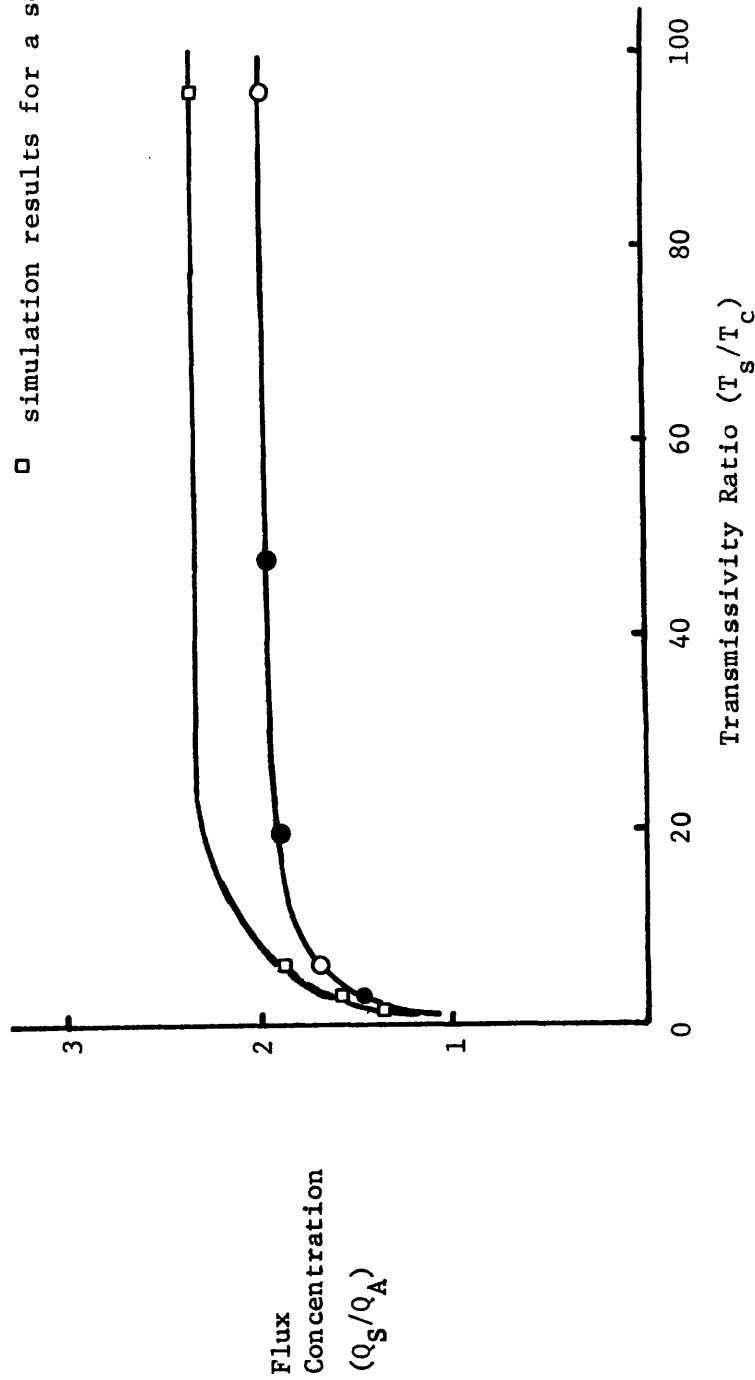


Figure 4.5 Relation Between Transmissivity Ratio and Flux Concentration. The transmissivity ratio between the spoil and coal bed aquifers is plotted against the resultant flux concentration.

TABLE 4.1

Influence of Relative Transmissivity

Transmissivity Ratio T_s/T_c	Flux Concentration Q_s/Q_A		Relative Contact Time t_s/t_a	
	Circle*	Square	Circle**	Square
100	1.98	2.35	0.50	0.50
6	1.71	1.87	0.58	0.59
3	1.50	1.58	0.67	0.67
2	1.33	1.37	0.75	0.75
1	1.00	1.00	1.00	1.00
1/6	0.28	0.26	3.50	3.30
↑ increasing T_s	↑ increasing	flux concentration	↑ decreasing	relative contact time

*Theoretical calculations based on Eq. C.13

**Theoretical calculations based on the relationship $\frac{t_s}{t_a} = \frac{K_c J_c}{K_s J_s} = \frac{K_s + K_c}{2K_s}$

1. The relationship between transmissivity ratio and flux concentration is asymptotic, with a maximum value of 2.0 for a circle (see Appendix C) and 2.4 for a square.
2. The simulation model of a circle accurately reproduces theoretical conditions of flux concentration and relative contact time.
3. The flux concentration for a square is larger than that of a circle. The reasons for this difference are discussed later in this chapter.
4. Flux concentration and relative contact time are sensitive to changes in transmissivity ratio for $T_s/T_c \leq 6$, with an increasing sensitivity as $T_s/T_c \rightarrow 0$.

Figures 4.6, 4.7 and 4.8 present equipotential lines for square mines with $T_s/T_c = 6, 100$ and $1/6$, respectively.

If one assumes chemical equilibrium between spoil and water, then as a first approximation, the concentration of chemicals in the water leaving the mine spoil, called the effluent, will reach a constant value independent of contact time. All of the water passing through the spoil will reach this concentration which, however, may slowly decrease over time as material is leached out of the spoil. Thus, the more water passing through the spoil, the more water undergoing chemical changes. Flux concentration is a measure of the volume of water degraded. A flux concentration of 2.0 indicates a downstream area at least twice as large as the mine width is being affected, but because of dispersion (Bear, 1972), the area may be larger.

Non-equilibrium conditions may prevail in mines with high flow rates. Then, the contact time plays a role in quality degradation and the tradeoff with flux concentration becomes important. Very small contact times will mean minimal degradation of relatively large volumes of water. In this case, however, the net contamination is almost independent of the transmissivity ratio. This can be seen by looking at an index of contamination, for the non-equilibrium situation, composed of the product of relative contact time, weighted along each streamline in the mine spoil, and flux concentration. For a circular mine with its straight parallel streamlines through the spoil, the weighting factor is simply the area of the mine. Thus, for circular mines of equal areas, the area factor can be ignored and the index of net contamination is:

$$\frac{Q_S}{Q_A} \times \frac{t_s}{t_a} = \frac{2K_s}{(K_s + K_c)} \frac{(K_s + K_c)}{2K_s} = 1$$

where $t_s/t_a = K_c J_c / K_s J_s$ and J , Q_S/Q_A and J_s are derived in Appendix C. The index is a constant, invariant with transmissivity ratio. The same result is found through numerical approximations of the square mines shown in Figs. 4.6 through 4.8.

4.3 Influence of Reclaimed Mine Geometry

To investigate the influence of reclaimed mine geometry on the final flow field, five standard geometries with several variations were simulated: a circle, a square, a rectangle oriented perpend-

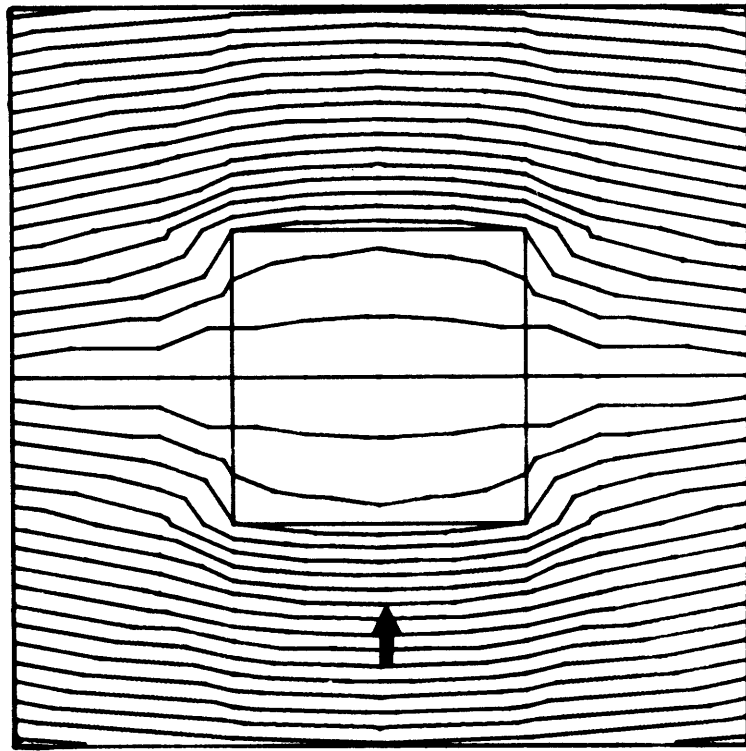


Figure 4.6 Square Mine with $T_s/T_c = 6/1$.

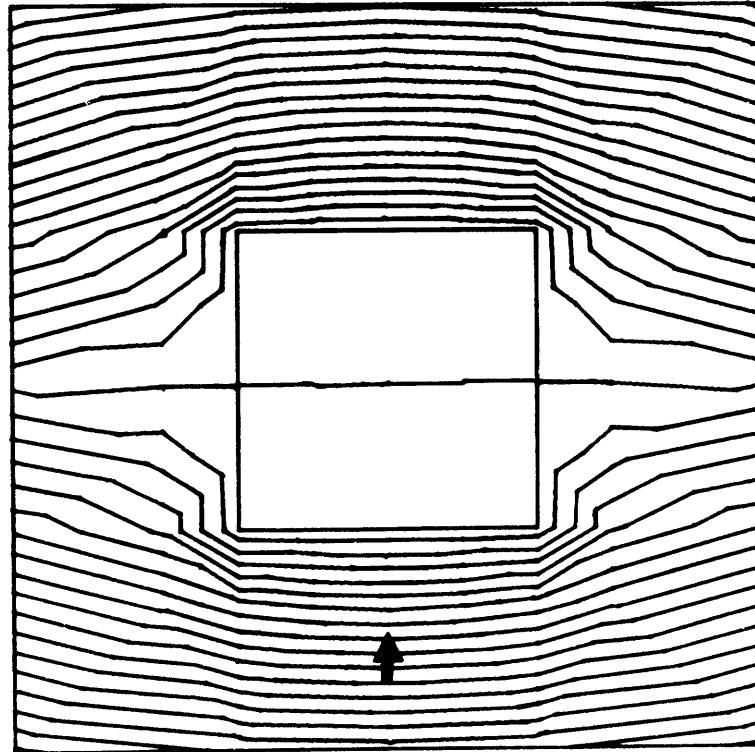


Figure 4.7 Square Mine with $T_s/T_c = 100/1$.

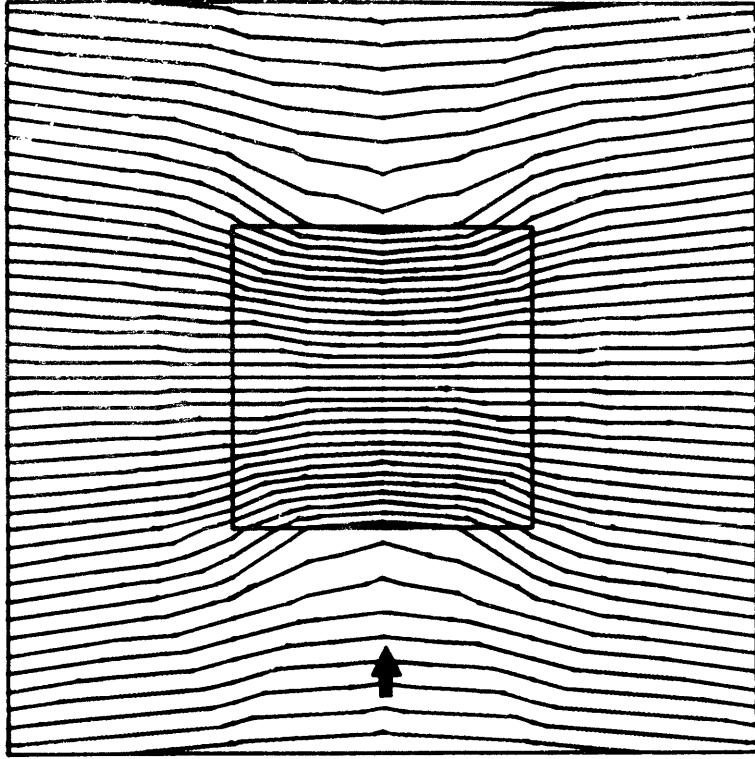


Figure 4.8 Square Mine with $T_s/T = 1/6$.
Flow diverges around the less permeable mine.

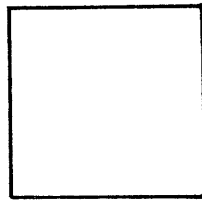
icular to flow, a rectangle oriented parallel to flow and a diamond (see Fig. 4.9). While each mine has a unique geometry, these particular shapes represent an effective means for testing the relative importance of geometrical properties. The important features tested were roundness, relative width to length, and orientation to the uniform flow field.

4.3.1 Standard Geometries

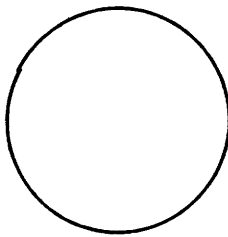
The five standard geometries were evaluated on the basis of four normalized indices, presented in Table 4.2 and discussed in the following comments. The flow fields are shown in Figs. 4.6 and 4.10-4.13 for comparative purposes.

1. Flux concentration, Q_S/Q_A , is a measure of flow field distortion and flux increase through a given width of aquifer, due to the presence of a reclaimed mine. It does not depend on mine size, but does depend on mine shape and the area to width ratio, A/W^2 . The rectangle oriented normal to the flow, shown in Fig. 4.10 has the least increase of flux concentration over ambient, and least influence on the flow field. This is attributed to its relatively short length and low $A/W^2 = 0.5$ ratio. Conversely, the rectangle oriented parallel to flow (Fig. 4.11) has the greatest influence and largest A/W^2 ratio = 2.0. The equidimensional geometries have flux concentrations falling between those for the rectangles. In order of increasing mine flux, flow field distortion, and A/W^2 ratio, the shapes are rated: normal rectangle < diamond < circle < square < parallel

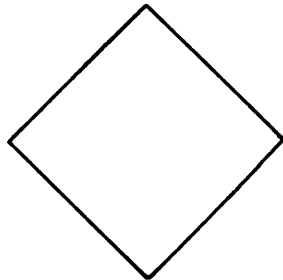
direction of ambient flow
↑



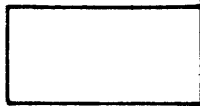
square



circle



diamond



rectangle
normal to
flow





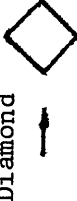


rectangle
parallel
to flow

Figure 4.9 Standard Geometries Simulated.

TABLE 4.2

Influence of Standard Reclaimed Mine Geometries*

Geometry	A/W^2	Flux Concentration	d/L	Relative Flux Ratio F_r	A/L^2	Relative Contact Time t_s/t_a	Area Weighted Contact Time T_r
Circle 	0.79	1.72 (1.71)	1.00	1.10 (1.10)	0.79	0.56 (0.58)	1.07
Square 	1.00	1.87	1.00	1.00	1.00	0.59	1.00
Rectangle normal to ambient flow 	1.50	1.57	2.00	1.68	2.00	0.74	0.89
Rectangle parallel to ambient flow 	2.00	2.25	1.00	1.20	0.50	0.44	1.05
Diamond 	0.71	1.61	1.00	1.15	0.71	0.43	1.03



*Note: The analytical solutions are presented in parentheses for the circle.

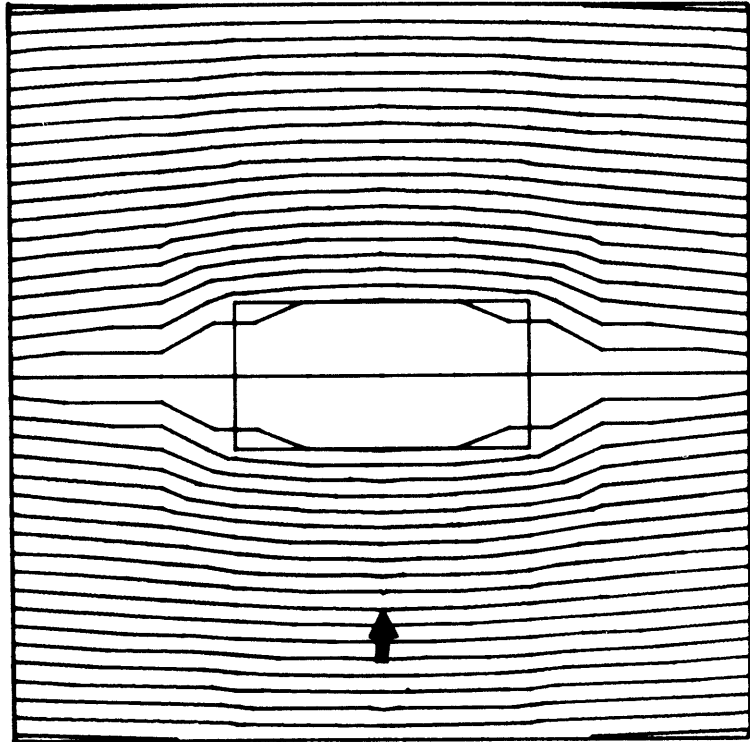


Figure 4.10 Rectangle Oriented Normal to Flow.

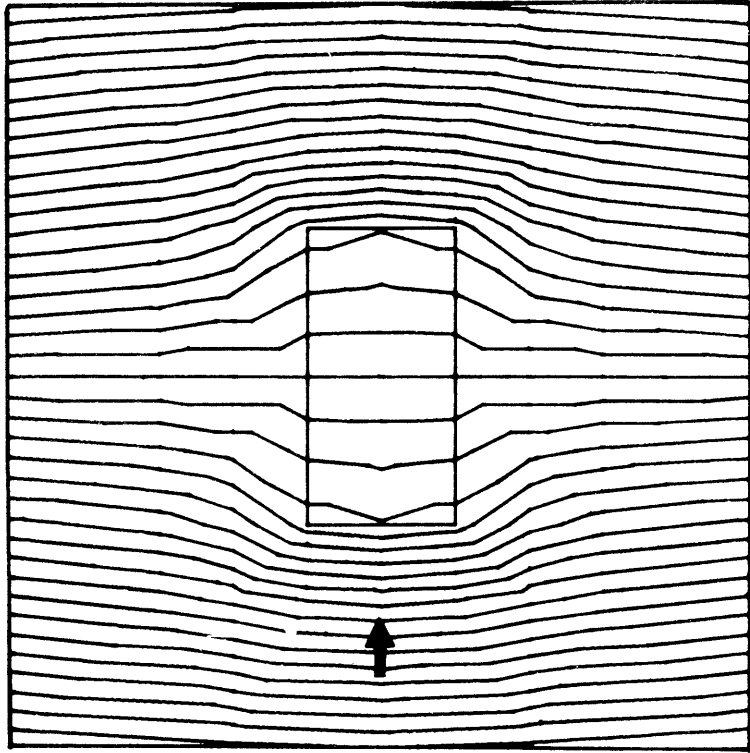


Figure 4.11 Rectangle Oriented Parallel to Flow.

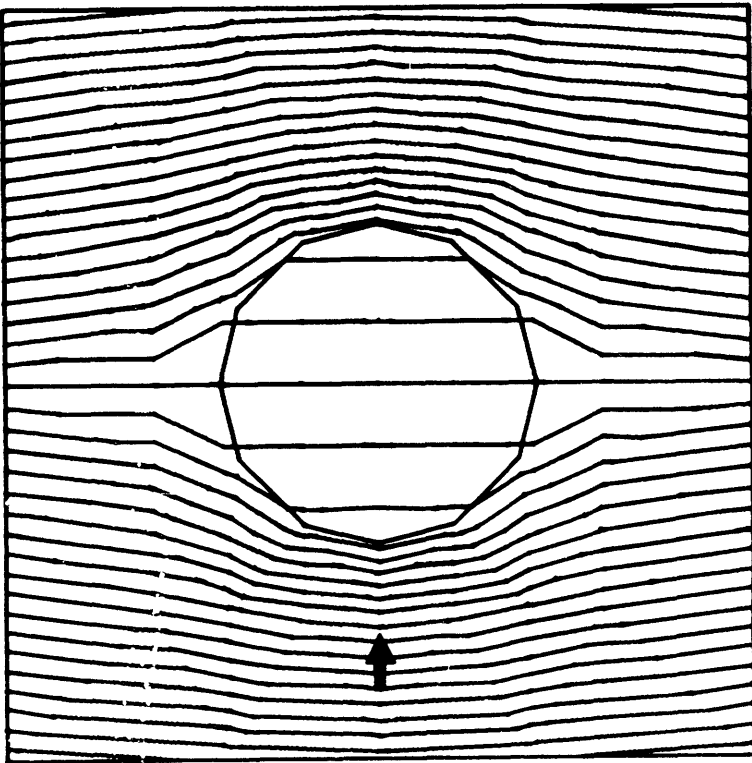


Figure 4.12 Circular Mine.

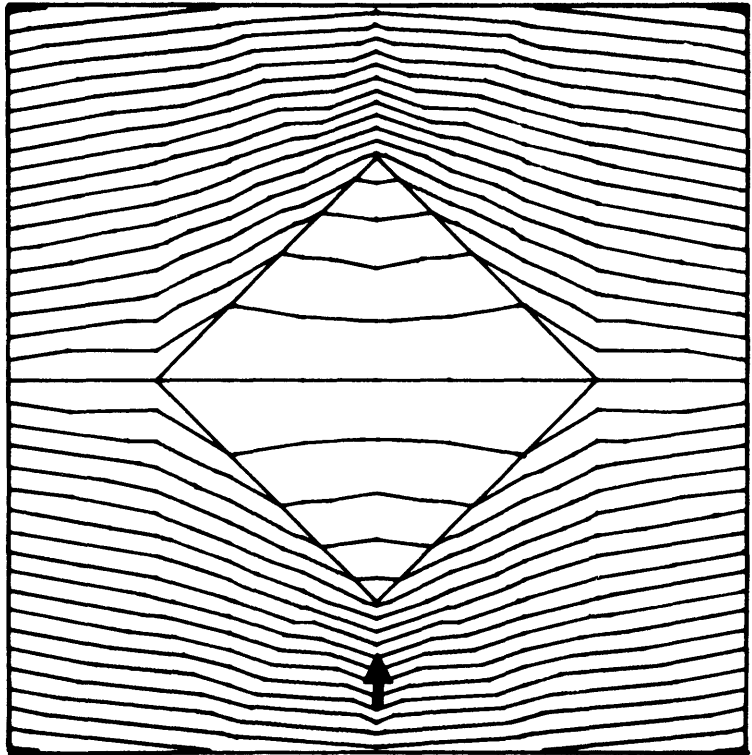


Figure 4.13 Diamond Shaped Mine.

rectangle. The ordering of the geometries for the flux concentration is obvious, since it is also the order of increasing size of the high permeability area, given a fixed mine width, as shown in the figure at the bottom of the flux concentration columns of Table 4.2.

2. The relative flux ratio F_r is a measure of the amount of water that comes into contact with the spoil per unit of mined coal, per unit time. It is calculated from

$$F_r = \frac{(Q_S/A)}{(Q_S/A)_{\text{square mine}}}$$

which is normalized by the flux through a square mine. A is the plan view area of the mine. F_r depends on the length to width ratio of the mine, and its shape. The square mine has the lowest F_r , indicating that with this shape the most coal can be extracted while exposing the least water to degradation. The other geometries have only slightly higher flux ratios, except for the rectangle oriented normal to the flow. Because of its large relative width, it intercepts much more water for a given amount of extracted coal. This sensitivity, and the relative insensitivity of the other geometries to F_r , is reflected in the d/L ratio, where d is the largest of L or W for each shape. The relative ordering of F_r for the various shapes is: square < circle < diamond < parallel rectangle << normal rectangle.

3. The relative contact time, t_s/t_a , is a measure of the decreased time a water parcel takes to travel distance L along the mine's center streamline, due to the change in aquifer properties caused by the spoil. Like flux concentration, relative contact time

does not depend on mine size. It does depend on the area to length ratio, A/L^2 , which is an index of increasing size of the high permeability area for a fixed mine length, as shown in the figure at the bottom of the t_s/t_a column in Table 4.2. The relative contact time is also a measure of the distortion of the flow inside the mine due to the highly permeable spoil. Thus, $t_s \rightarrow t_a$ for flow through the relatively "short" rectangle oriented normal to the flow. The ranking of residence time and A/L^2 ratio for the various shapes is: parallel rectangle < diamond < circle < square < normal rectangle.

4. The area weighted, relative contact time, T_r , is a measure of the residence time of water in mines of different shape, from which equal volumes of coal have been extracted. It is given by the normalized ratio

$$T_r = \frac{(t_s/A)}{(t_s/A)_{\text{square mine}}}$$

and is relatively insensitive to mine shape, with a range of values from 0.89 to 1.07. The ordering of T_r is: normal rectangle < square < diamond < parallel rectangle < circle.

Inside each mine the equipotential lines are almost parallel. Since these are isotropic situations, with streamlines orthogonal to the equipotentials, streamlines must also almost be parallel to each other. For a circular mine, the theoretical results of Appendix C, demonstrate that this is true for all transmissivity ratios. But it is remarkable that this condition approximately occurs for the

wide range of other standard geometries. It is clear that a program of piezometers used to monitor water levels inside reclaimed mines of different shapes would find similar patterns of piezometric contours, but different hydraulic gradients.

All of the indices of mine performance referred to in Table 4.2 are based on the maximum flux at the center of the mine, Q_S , or travel time, t_s , along the center streamline. These indices reflect extreme conditions. For non-circular mine shapes with their slightly distorted interior flow fields, flux values calculated for other cross-sections, or travel times taken along other streamlines, will be smaller. Thus the indices presented are conservative in nature.

The area weighted indices (F_r , T_r) show that, in general, mine shape has no significant effect on water quality degradation. The major exception is the rectangular mine oriented normal to flow which, per unit of mined coal, leads to the contamination of much larger volumes of water than any of the other shapes, albeit with a slightly smaller contact time. It's interesting to note that this is a common mine shape and orientation. As for flow field distortion, flux concentration values clearly indicate that mines with narrow widths cause the most significant distortion of the exterior equipotential lines.

Based on these comments, is there a preferred mine shape? The answer to this question requires a weighting of the several indices, which depends on factors like spoil chemistry, aquifer use, ambient flow rate, etc., which are not addressed here. Assuming an equal

weighting, the equidimensional geometries seem superior, primarily because they intercept less water (low F_r) with only a moderate influence on the equipotential pattern (mid range Q_S/Q_A). Giving equal weighting to indices F_r and T_r , which are on a per unit of extracted coal basis, the superior mine would receive a low $F_r T_r$ product. From Table 4.2 the actual ratings for this product are square < circle < diamond < parallel rectangle < normal rectangle. A square mine is apparently preferable.

4.3.2 Other Geometries

Several variations on the standard geometries were also simulated. Reclaimed mines, in the shape of right angles, are shown in Figs. 4.14 and 4.15, respectively, "pointed" toward and away from the ambient flow. The flow fields produced are mirror images. The prominent geometrical features of these geometries independently influence the flow field. For example, the flow in Fig. 4.14 appears to be approaching a single rectangle parallel to the flow, and the exit from the mine is similar to that of a rectangle normal to the flow.

Fig. 4.16 shows rectangular mine oriented an angle to the uniform flow field, and Fig. 4.17 is a view of the equipotential lines for flow through a mine composed of contiguous offset squares. The flow tends to channelize itself through the more permeable spoil, taking the path of least resistance. Fig. 4.17 also reaffirms the tendency of flow to approach or leave a mine site following a pattern set up by the nearest prominent geometric feature. In this case, the squares.

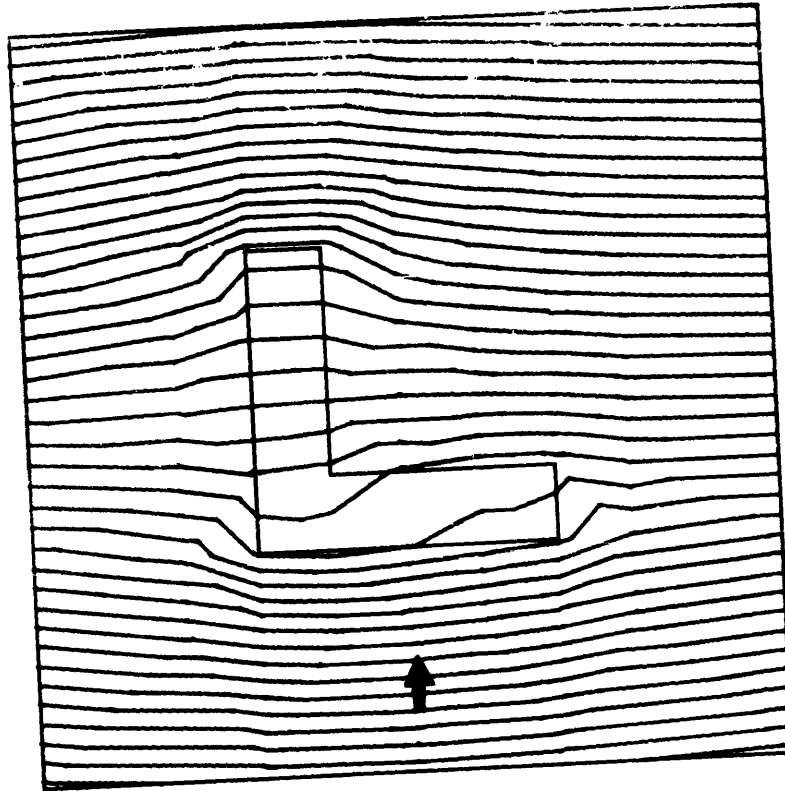


Figure 4.15 Right Angle Mine Pointed Away from Ambient Flow.

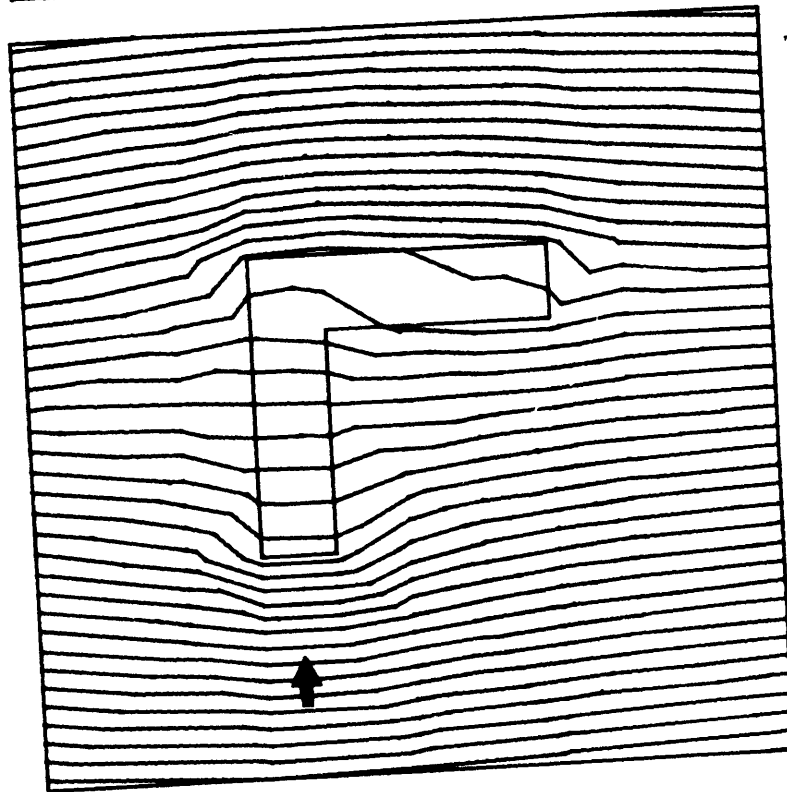


Figure 4.14 Right Angle Mine Pointed Toward Ambient Flow.

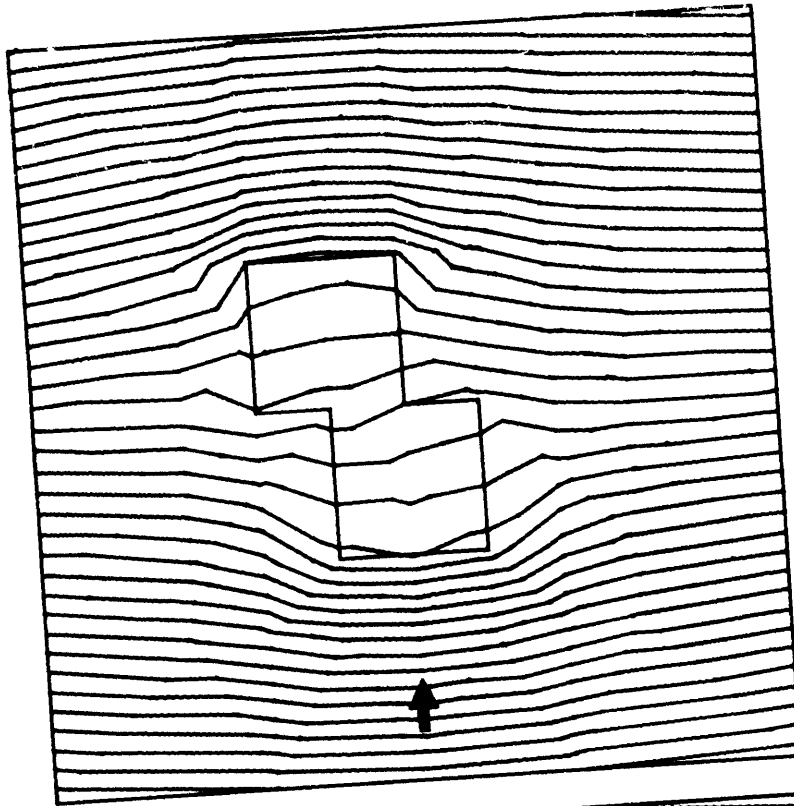


Figure 4.17 Two Contiguous Offset Square Mines.

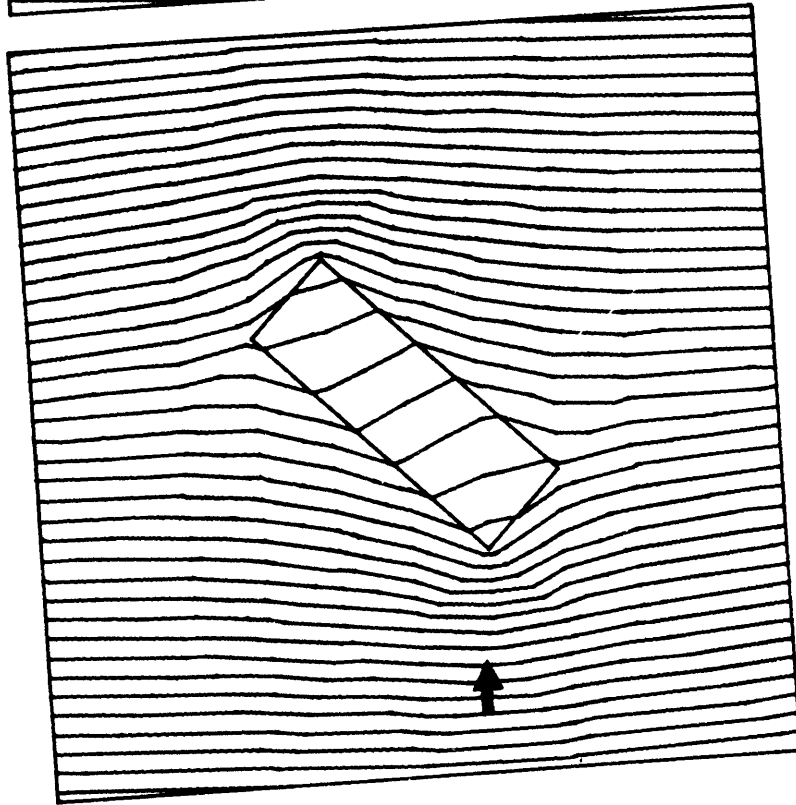


Figure 4.16 Rectangular Mine Oriented at an Angle.

4.4 Influence of Anisotropy

Mining operators impart directional properties to spoil transmissivity and hydraulic conductivity through their method of spoil placement. For local hydrology, gravity sorting and the presence of coal wedges are the two most important features affecting anisotropy.

A series of simulations were performed to evaluate the influence of different levels of spoil anisotropy, on the flow field and the amount of water intercepted by the spoil. The simulations assumed principal directions of anisotropy. That is, they assumed that the ambient uniform flow was oriented either parallel or normal to the preferred directions of flow in the spoil. Since the preferred direction is probably along a trench, a square geometry represents mining with trenches parallel or normal to the upstream side of the mine, a diamond represents mining with trenches parallel to the diagonal, and so on. In the following description the symbol x represents a direction parallel to the ambient flow and y the direction normal to it. The coal bed transmissivity in the flow direction, T_{xc} , was held constant for all tests and used to normalize all other values. The results are presented in Table 4.3 for flow through a square mine. The coal bed aquifer is isotropic in all cases but the last.

The first case represents an isotropic square mine with a transmissivity ratio, $T_s/T_c = 1/1$, which does not disturb the uniform flow field. In the second case, the spoil y direction transmissivity, T_{sy} , has been increased. The flow field, measured in terms of flux

TABLE 4.3

Influence of Anisotropy on a Square Mine

$T_{cx} = 1$ for all tests below (normalized).

Case	Transmissivity Ratio	Transmissivity Ratio	Transmissivity	Transmissivity	Transmissivity	Flux Concentration	Relative Contact Time
	T_x/T_y Coal Bed Aquifer	T_x/T_y Spoil Aquifer	T_x Spoil	T_x Spoil	T_y Spoil	Q_S/Q_A	t_s/t_a
1	1/1	1/1	1	1	1	1.00	1.00
2	1/1	1/6	1	1	6	1.00	1.00
3	1/1	1/1	6	6	6	1.87	0.59
4	1/1	6/1	6	6	1	1.90	0.65
5	1/1	60/1	6	6	0.1	1.93	0.70
6	10/1	1/1	6	6	6	1.43	0.74

concentration and relative contact time, has not been changed, because there is no flow component in the preferred flow direction, y . The flow is still moving uniformly in the x -direction.

The third case represents an isotropic square mine with a transmissivity ratio, $T_s/T_c = 6/1$, which was discussed in the previous two sections. It is presented for comparative purposes and shown in Fig. 4.6.

In the fourth case, only the x -direction transmissivity, T_{sx} , has been increased to the 6/1 level. T_{sy} remains at ambient level so that $T_{sx}/Y_{sy} = 6$ in the spoil. The flow field, shown in Fig. 4.18, is similar to the isotropic, fourth case.

Intuitively, the flux concentration should actually decrease slightly because lateral inflow is restricted. But the simulation results indicate a slight flux increase, which is even more obvious when the spoil anisotropy ratio (T_{sx}/T_{sy}) is raised to 60 as shown in case five. There is a further paradox. As the anisotropy ratio increases, the relative contact time also increases, indicating a reduction of hydraulic gradient and specific discharge near the centerline of the mine. However, this reduction in centerline gradient is more than compensated for by an increase in gradient and flow near the upper and lower mine boundaries, leading to increased total flux. Without further investigation, designed to specifically deal with this phenomenon, it is difficult to establish whether these results represent an actual physical result of anisotropy or numerical error.

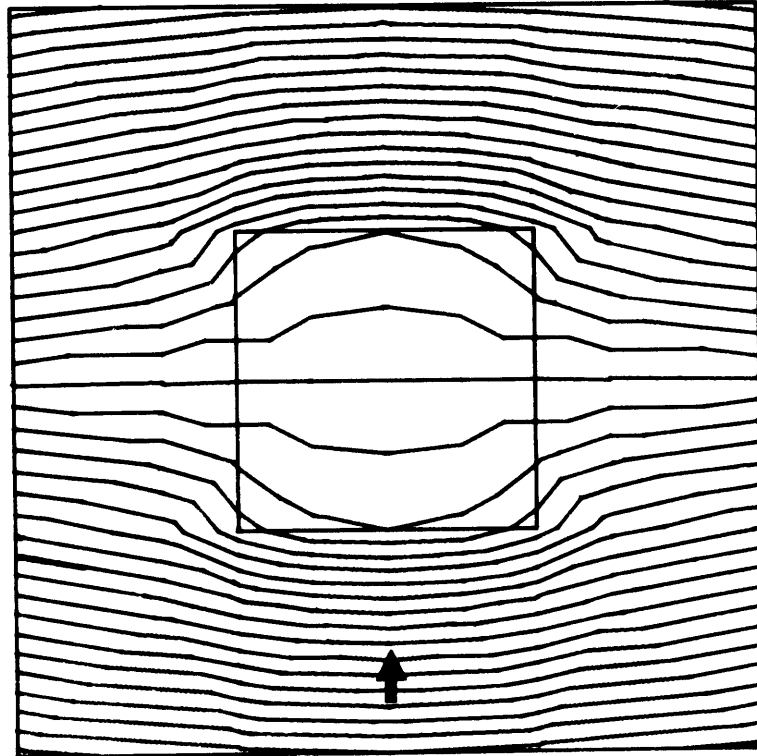


Figure 4.18 Square Mine with Anisotropy,
 $T^s_x/T^s_y = 6$. The corresponding
 isotropic mine is in Figure 4.6.

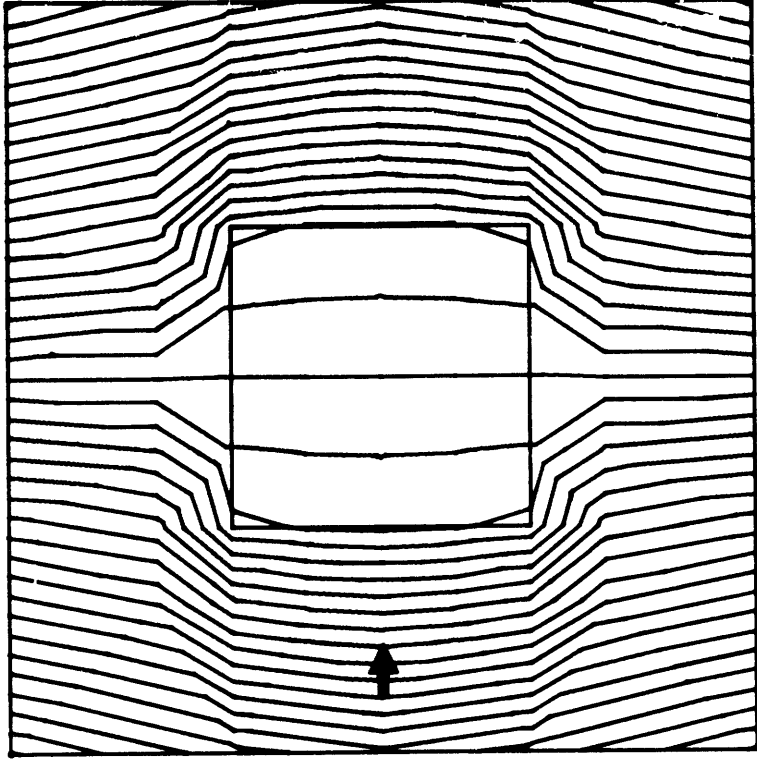


Figure 4.19 Isotropic Square Mine in an
 Anisotropic Flow Field. The
 anisotropy ratio in the coal bed
 aquifer is $T^{cs}_x/T^{cs}_y = 10$, and
 $T^s_x/T^{cs}_x = 6$.

There may also be anisotropy in the surrounding coal bed aquifer because of its fracture flow system. To simulate this effect the coal bed anisotropy ratio, T_{cx}/T_{cy} , was assumed to be 10/1, with flow into an isotropic reclaimed mine such that $T_{sx}/T_{cx} = 6$. The result is shown in Fig. 4.19 and given as case six of Table 4.3. The reduction of T_{cy} makes it more difficult for water to move laterally into the mine, leading to less flux through the mine.

4.5 An Operational Mine

Intercepted aquifers are dewatered during a mining operation, a phenomenon which is well recognized, if not easily predictable. A generic study of this problem would disclose little new information. Therefore, only a simple simulation was performed to show the significant effect an operating mine has on the flow field and to compare to the previous results for post mining conditions. In the simulation, piezometric heads along the mine periphery were set equal to the elevation of the bottom of the pit, and the steady state head distribution was found.

The dramatic changes in the flowfield are shown in Fig. 4.20. Flow is drawn into the site from all directions and piezometric heads are lowered around the mine. As expected, an operational mine totally disrupts local groundwater flow. The effects are, however, temporary, whereas the reclaimed mine simulations represent long-term changes in flow patterns which are related to future water quality.

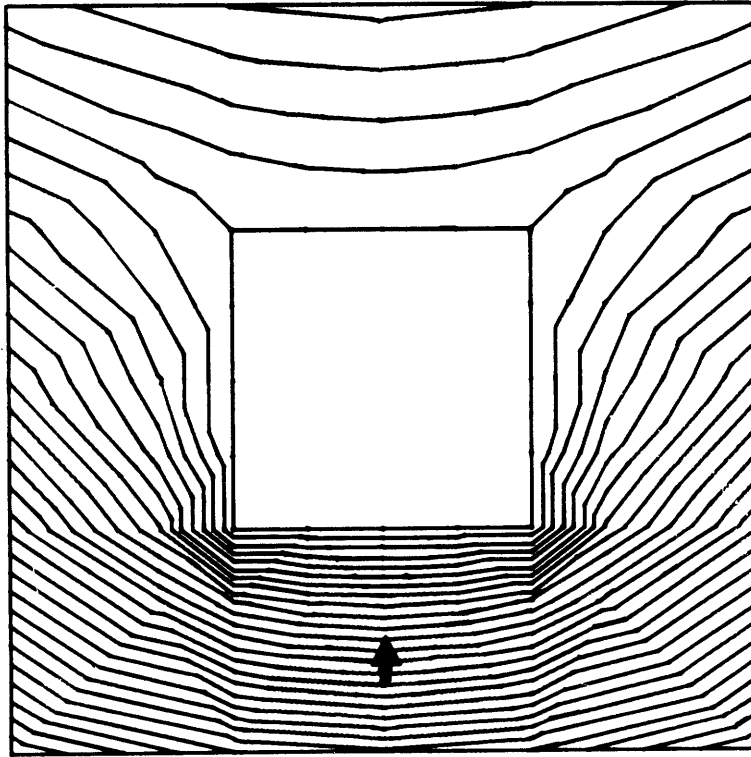


Figure 4.20 Effect of an Operational Mine on the Local Flow Field.

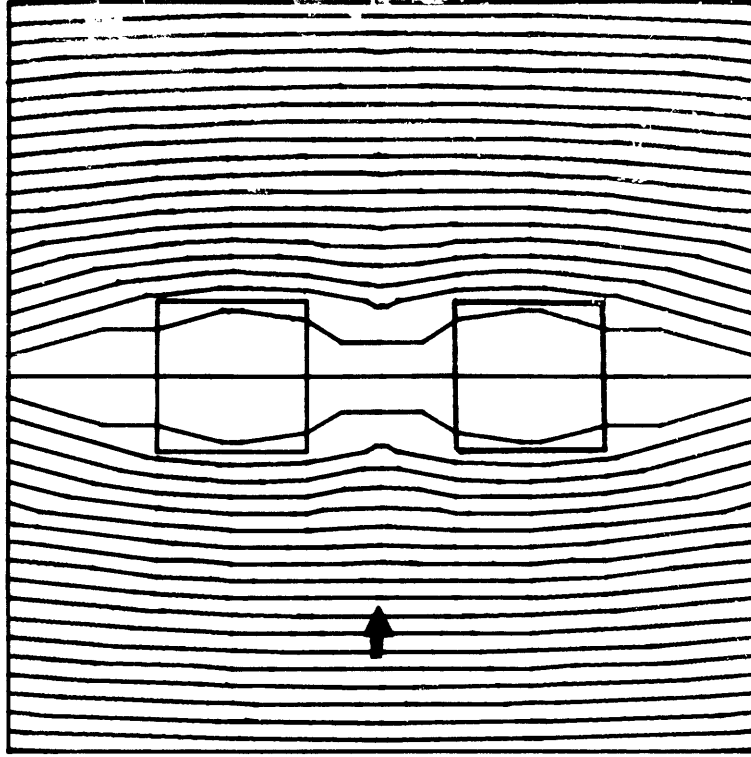


Figure 4.21 Two Square Mines in Line Normal to Ambient Flow.

4.6 Two Reclaimed Mine Sites in Close Proximity

Mines are frequently clustered in rather small areas. To begin to understand how closely spaced mines influence one another, three rather simple situations involving two reclaimed mines were simulated. The results are presented in Table 4.4.

Two square mines were placed in line, normal to the ambient flow, one mine width apart, as shown in Fig. 4.21. The groundwater flows symmetrically around and through the two mines. This configuration assumes approximately the same characteristics as a rectangle oriented normal to the flow. There is a slightly higher flux concentration than for the rectangle because of the additional water drawn laterally into the mines, along the sides between them.

Two square mines were then simulated in line, parallel with the ambient flow, and again one mine width apart, as shown in Fig. 4.22. The results are symmetrical within the mines, with flux concentrations that indicate that the mines act like two independent squares, rather than a continuous rectangle.

Finally, two rectangles, parallel to each other and the flow, were simulated, spaced two mine widths apart as shown in Fig. 4.23. Again the flow patterns are symmetrical around and through the mines. The general influence on the flow field is similar to that of a square, because much of the water flowing between the mines is drawn into them.

TABLE 4.4
Influence of Two Close Mine Sites

<u>Mine Orientation</u>	$\frac{T_s}{T_c}$	$\frac{Q_s}{Q_A}$
Two square mines in line normal to flow, one mine width apart	6/1	1.59
Two square mines in line parallel to flow, one mine width apart	6/1	1.79
Two rectangular mines oriented parallel to the flow	6/1	2.40

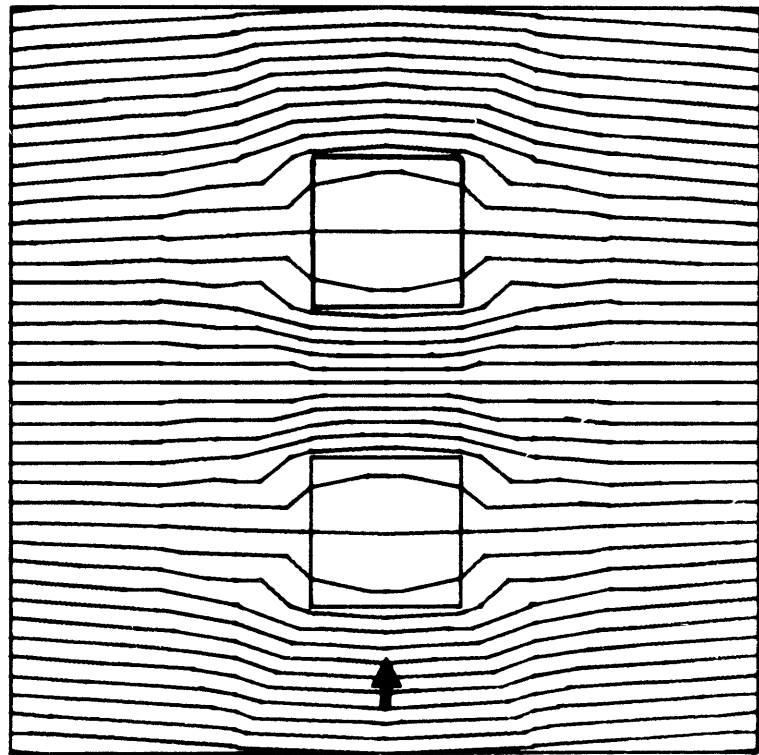


Figure 4.22 Two Square Mines in Line Parallel to Ambient Flow.

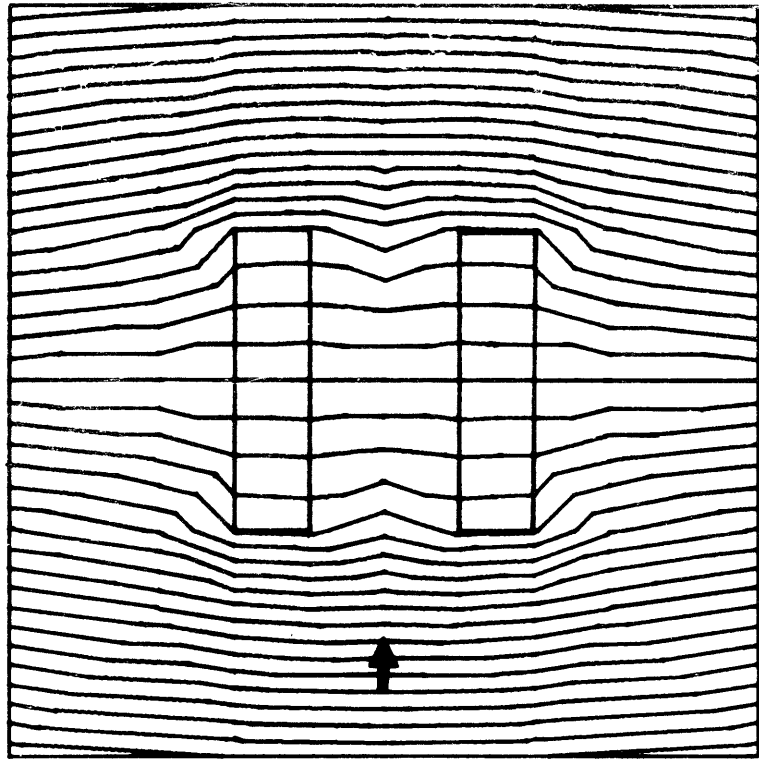


Figure 4.23 Two Parallel Rectangular Mines.

4.7 Summary of Results

The influence of strip mining features on local hydrology is briefly summarized by the following points:

1. Flow tends to concentrate and channelize in and through the more permeable mine spoils.
2. Relative transmissivity has a significant effect on the amount of flow through the mine spoils, for $T_s/T_c \leq 6$. There is a limit to this effect, which is rapidly approached for high transmissivity ratios.
3. Geometry has significant influence on the distortion of the flow field, but decidedly less influence on water quality degradation.
4. Equidimensional mine geometries have less impact than elongated shapes, primarily because they induce the least amount of flow through the spoil per unit extracted coal. The square shape is apparently the best.
5. The most prominent geometric features of complex geometries control the flow field in their vicinity.
6. Spoil anisotropy does not seem to have an important effect on groundwater flow. Instead, T_{sx} , the directional hydraulic property parallel to the ambient flow, determines the flow field, with essentially identical flux concentrations and equipotential patterns for a wide range of T_{sy} . Therefore, anisotropy can probably be neglected, with attention focused on T_{sx} instead.

7. A group of mines in close proximity tend to influence the flow field independently, but in a way that their combined effect is similar to having a single, much larger mine.
8. An operational mine has a more dramatic effect on the equipotential pattern and flow field, than a reclaimed mine. However, it's only temporary, while a reclaimed mine is permanent and has more significant effects on water quality.

CHAPTER 5

FLOW THROUGH A RECLAIMED MINE

As groundwater flows into a reclaimed mine site, it enters an artificial aquifer system shaped by mining procedures.

The two dominant features examined in this chapter are the gravity sorted rubble layer at the bottom of the spoil, and coal wedges left in between trench cuts. Both features are small in scale compared with the total reclaimed mine, but their position at the base of the aquifer influences groundwater flow patterns.

5.1 Simulation Formulation

Flow through the reclaimed mine interior was studied using an idealized cross sectional view. The coal bed aquifer, rubble layer and saturated finer spoil above the rubble layer were each assumed to have a uniform thickness and uniform hydraulic properties. The rubble layer thickness b_R , was chosen to be 1/7 the coal seam thickness, b_C . This idealization is presented schematically in Fig. 5.1. A trench width L , the distance between coal wedges, is typically 30-50 meters.

Since the area of interest in this study is the lower spoil region, near the rubble layer and coal wedges, the spoil and coal bed aquifer saturated thicknesses were assumed equal, a reasonable assumption at this stage of investigation. Spoil aquifers studied in Montana are reported to behave as confined aquifers (Van Voast et al.,

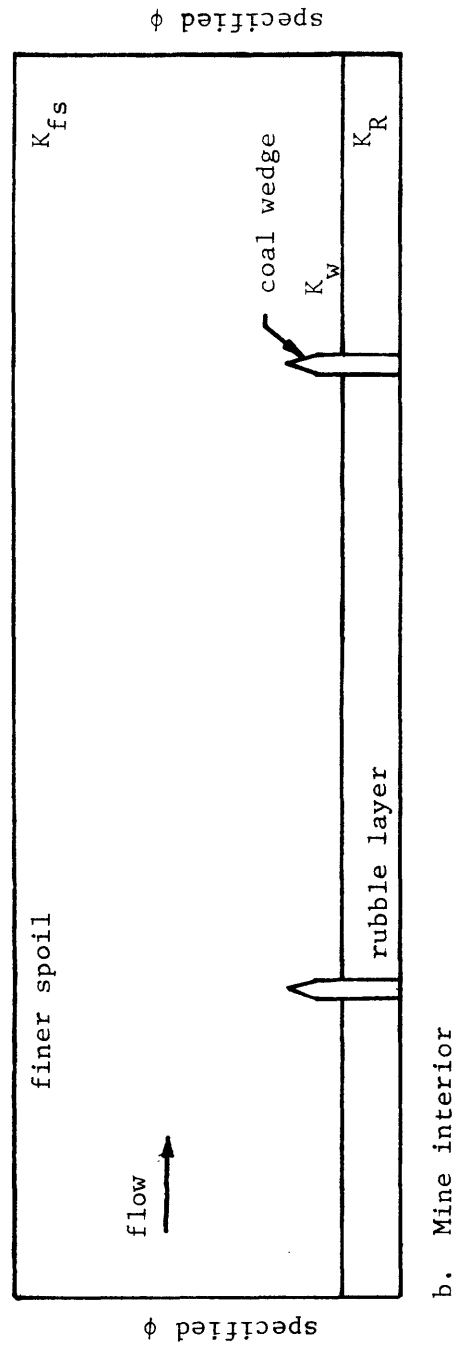
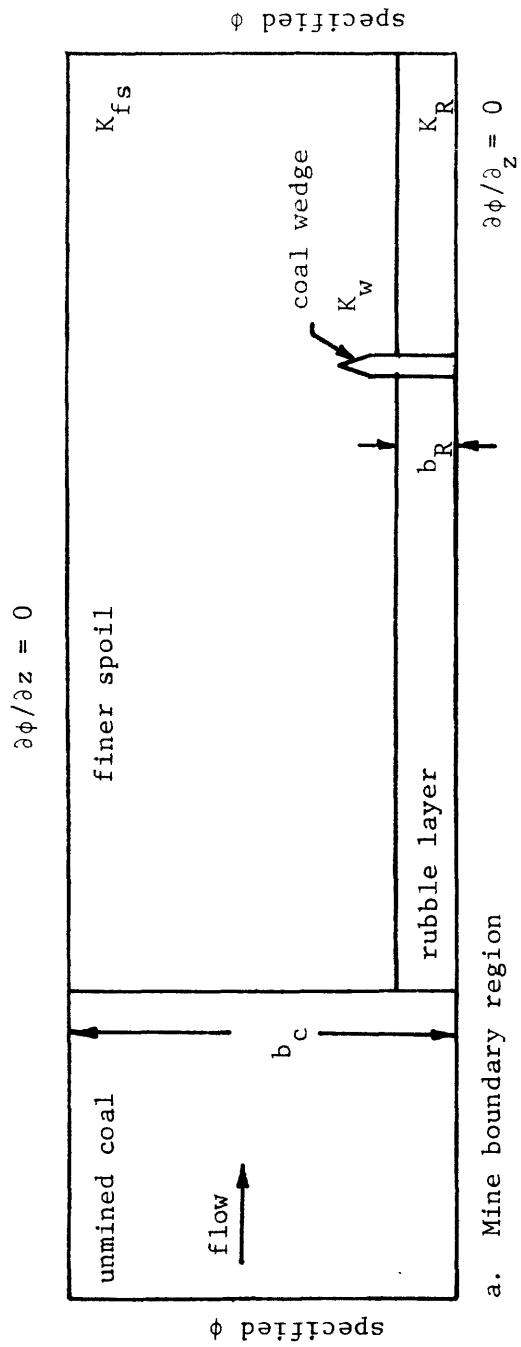


Figure 5.1 Idealized Cross Sectional View of the Mine Aquifer. The vertical scale is exaggerated.

1976b), and Van Voast, in a personal communication (1977), indicates that the saturated thickness in spoil and adjacent coal bed aquifers is about the same for the mines he is studying. Davis (1976b) presents field data that shows the peizometric surface may either be over or below the top of the coal seam. For this study, the saturated thickness was assumed to equal coal seam thickness such that the aquifer is only mildly confined.

Assumptions of relative size and idealizations regarding the aquifer features were incorporated into a finite element grid, containing 311 elements and 184 nodes (Fig. 5.2). The grid is shown with the vertical scale exaggerated by a factor of four. Within the model this vertical exaggeration was eliminated through geometric distortion and later plots of the results are in true scale and isotropic.

Aquifer properties were assigned to element groups to simulate various mine features. For example, the rubble layer was simulated by assigning high hydraulic conductivity to the bottom two element layers. Comparing the idealized aquifers of Fig. 5.1 with the finite element grid structure in Fig. 5.2, reveals how changing properties in other elements allows either the mine boundary region, or the mine interior to be simulated. The grid has greater nodal density near the mine boundary and coal wedges to provide detailed piezometric head information in the areas where flow pattern alteration was expected.

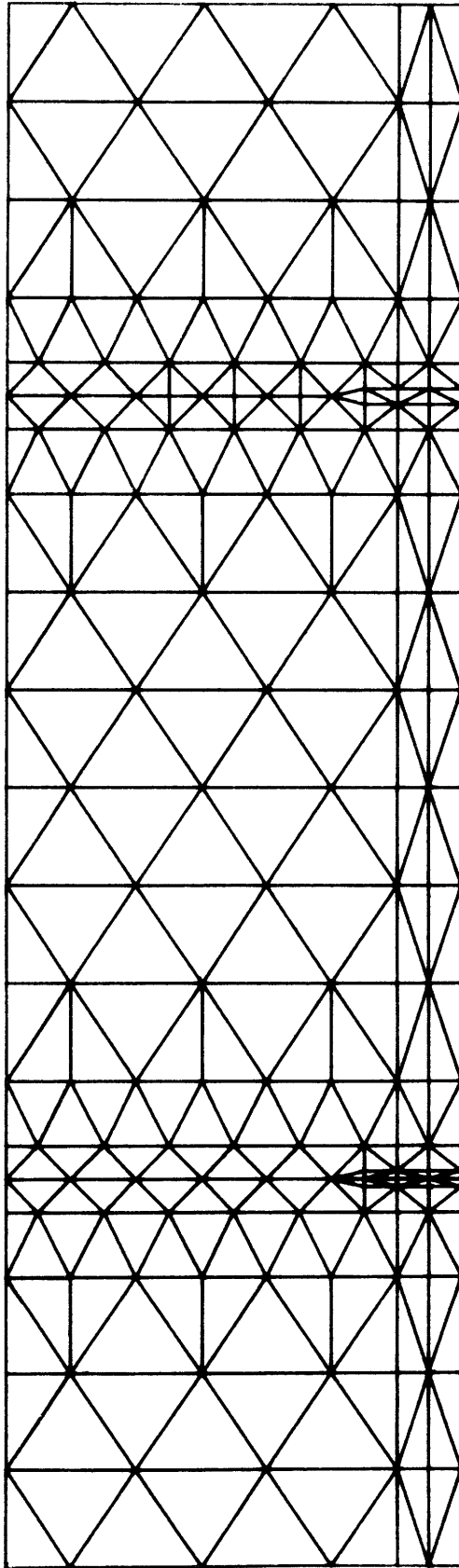


Figure 5.2 Interior Flow Finite Element Grid. It may be used to simulate flow at either the mine boundary or flow between trenches.

The boundary conditions around the grid were entirely specified. No flux conditions were assigned to the top and bottom of the grid which represent the water table and impermeable rock, respectively. Piezometric heads were specified for the two vertical boundaries. The head distribution at these boundaries was assumed to be hydrostatic and matched with the piezometric head gradient found for the square mine in the local hydrology simulation discussed in Chapter 4.

The internal flowfield and local hydrology simulations were also linked through the transmissivity ratio T_s/T_c . The standard ratio of $T_s/T_c = 6/1$ was used for most of the simulations. Since the saturated thickness $b = b_c = b_s$ is constant, the transmissivity and hydraulic conductivity ratios are equal, so $T_s/T_c = K_s/K_c = 6$, where K_s represents the effective hydraulic conductivity for the spoil aquifer over its entire saturated thickness. The hydraulic conductivity ratios between the rubble layer and fine spoil, K_R/K_{fs} , and the fine spoil and the coal, K_{fs}/K_c , were varied to analyze their effects on the amount of flux passing through the rubble layer, Q_R , relative to the total Q . With K_s established, relative to K_c , the relationship between the other hydraulic conductivity ratios was defined using the horizontal flow approximation to maintain a constant total flux, Q , through the system (see Appendix D).

The horizontal flow approximation was used as an analytical check for the simulation of mine interiors without coal wedges, in which the finer spoil and rubble layers act as a simple two layer system (see Fig. D.1). The analytical and simulation results are within 1%

of each other, based on simulated fluxes calculated from element specific discharges. Since the flow is uniform in each layer in this system, the nodal and elemental velocities are equal everywhere, except at the boundary between the rubble layer and finer spoil. Along that boundary the nodal specific discharge represents an average of the specific discharges in the two layers, whereas the elemental specific discharge more accurately represents the abrupt change in specific discharges at the boundary.

5.2 Influence of the Rubble Layer and Coal Wedges

When flow is parallel to the coal wedges, or when the coal wedges are absent, the rubble layer and saturated finer spoil act as a simple two layer horizontal flow system. The amount of flow through either layer is regulated by their relative transmissivities, as demonstrated in Eq. D.2 and Fig. 5.3. The flow through the rubble layer increases with increasing T_R/T_{fs} .

The horizontal flow approximation works well because the flowfield responds rapidly to changes in transmissivity. For example, at the mine boundary, flow quickly concentrates into the highly permeable, rubble zone, as shown in Fig. 5.4, resulting in essentially vertical equipotential lines only a distance $L/8$ into the first spoil trench. Since water flowing in the rubble layer does not contact the finer spoil, which contains most of the leachable material, the rubble layer helps minimize water quality degradation.

When flow is orthogonal to the coal wedges, the flowfield is

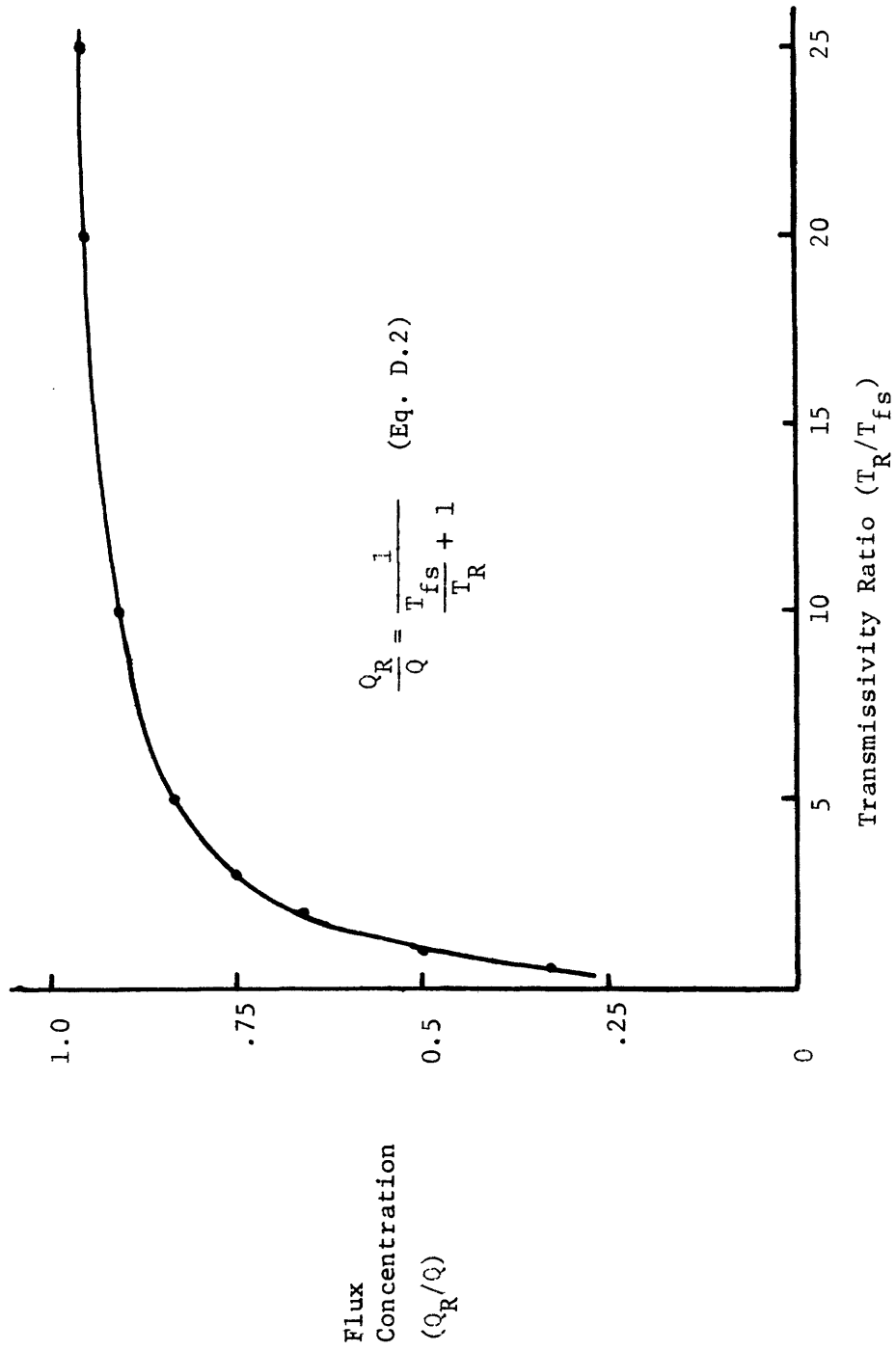


Figure 5.3 Relation Between Transmissivity Ratio, T_R/T_{fs} and the Flux Concentration, Q_R/Q .

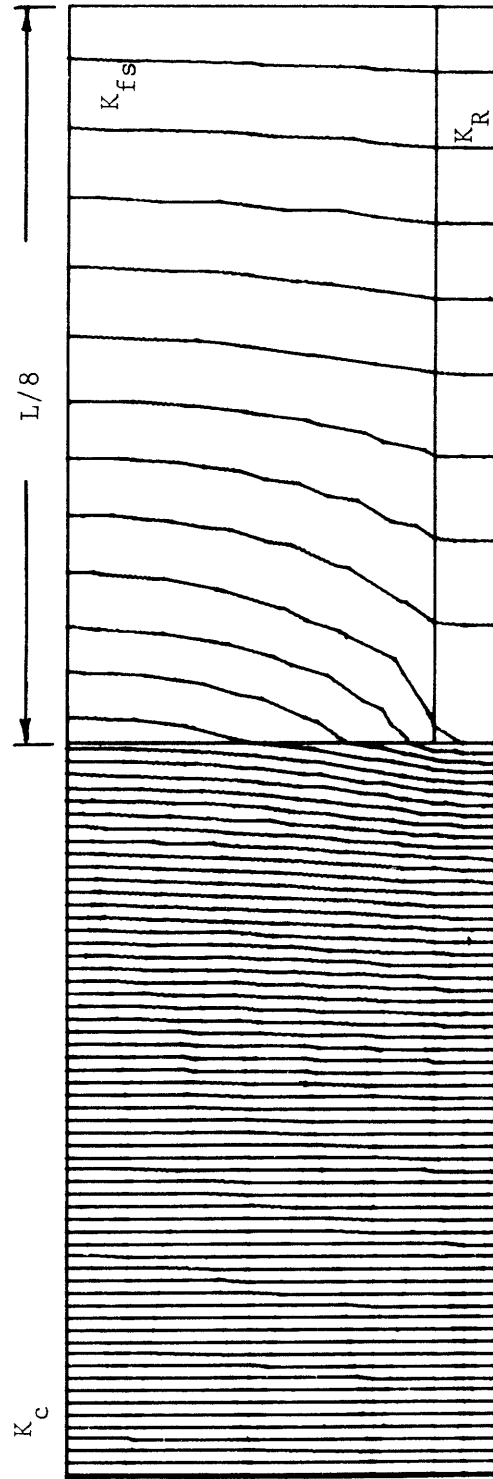
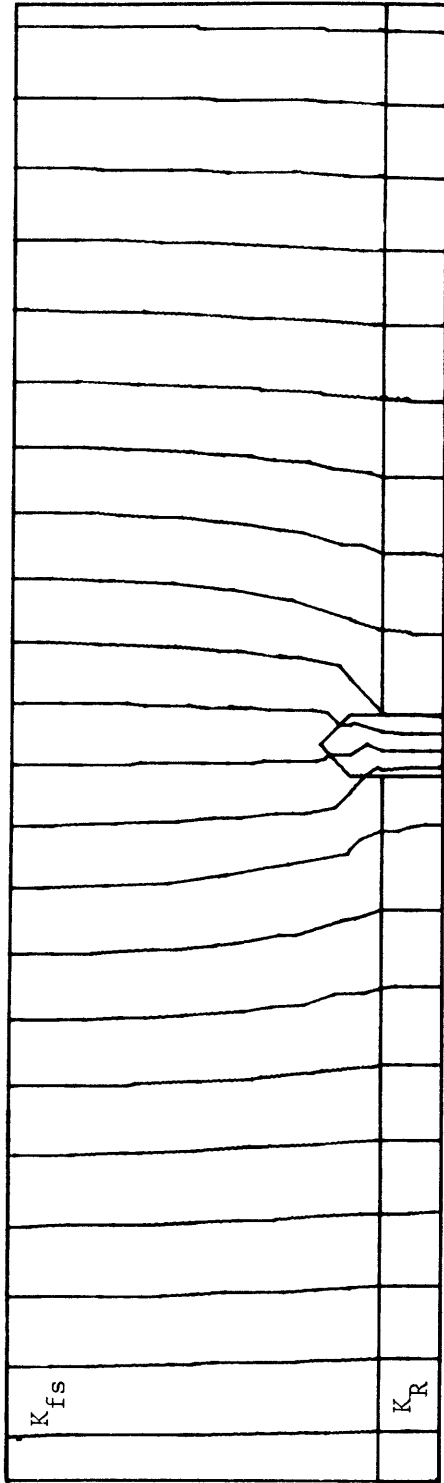


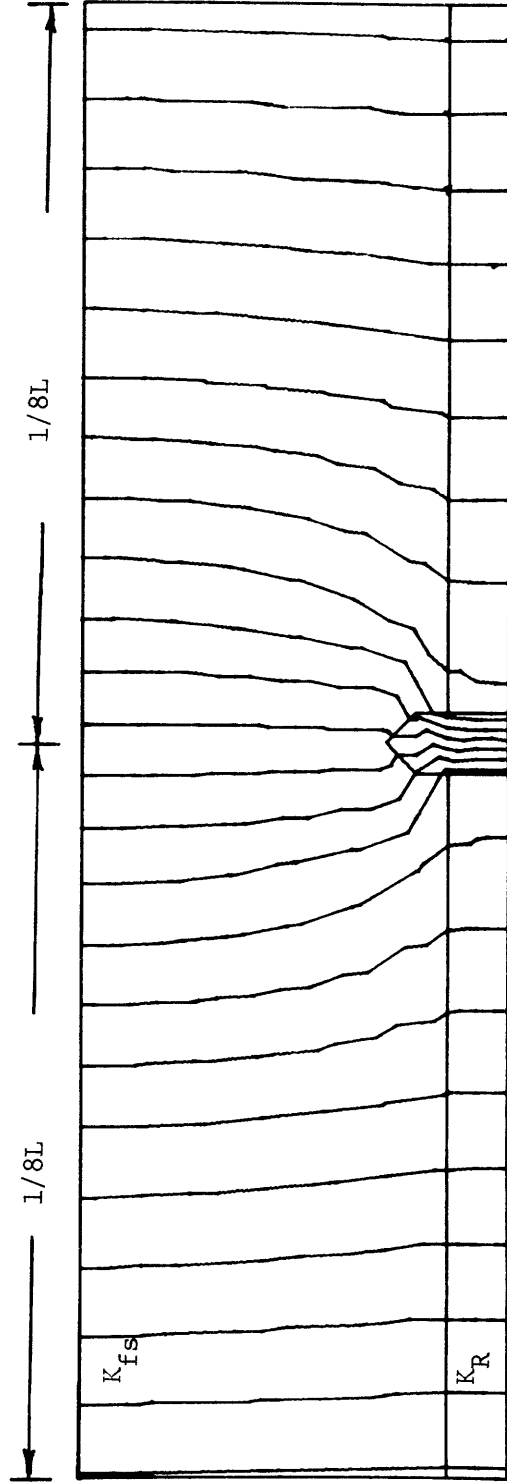
Figure 5.4 Flow Entering the Reclaimed Mine. The flux rapidly concentrates in the highly permeable rubble layer.

distorted near the wedges due to their different hydraulic properties, as shown in Fig. 5.5. Since wedge properties vary over a narrow range, relative to the surrounding material, their influence on the flowfield is limited. Wedge hydraulic conductivity is probably greater than the coal bed hydraulic conductivity because of the additional fracturing caused by blasting, but less than the finer spoil hydraulic conductivity because it has not actually been broken and disaggregated. The influence of the coal wedge largely depends on the ratio K_R/K_{fs} . If the ratio is unity, and if $K_w = K_{fs}$, then there is no effect on the flowfield; it is entirely uniform. But as the ratio increases, more flux concentrates in the rubble layer, and the presence of a less permeable coal wedge causes the flow to distort near the wedge.

The coal wedge has less effect on the flowfield when its hydraulic conductivity is equal to the finer spoil, than when it equals that of the less permeable coal (see Fig. 5.5). This is shown quantitatively by cases A and B in Table 5.1 for a spoil non-homogeneity ratio $K_R/K_{fs} = 8$. Fifty-three percent of Q_R remains within the rubble layer thickness, b_R , at the wedge when $K_w = K_{fs}$, but only 34% of Q_R remains when $K_w = K_c$. Most of the water is forced into brief contact with the finer spoil. Therefore, to provide the maximum coal wedge influence in the remaining simulations, the wedge hydraulic conductivity was set at its minimum, $K_w = K_c$, and flow was simulated perpendicular to the wedges.



a. $K_w = K_{fs}$ (minimum expected)



b. $K_w = K_c$ (maximum expected)

Figure 5.5 Influence of Coal Wedges on Flow Field.

TABLE 5.1

Simulation results from the interior flow simulation.

Case	K_s/K_c	K_{fs}/K_c	K_R/K_{fs}	K_w^*	Q_R/Q^* w/o wedges	Q_R/Q^{**} w/wedges	Q_{bR}/Q at wedge
A	6	3	8	K_{fs}	0.57	0.57	0.30
B	6	3	8	K_c	0.57	0.58	0.20
C	9	3	15	K_c	0.71	0.71	0.24
D	3	1.5	8	K_c	0.57	0.56	0.27
E	6	0.5	72	K_c	0.93	0.93	0.92

K_s = effective hydraulic conductivity of the saturated spoil

K_c = hydraulic conductivity of coal

K_{fs} = hydraulic conductivity of finer spoil

K_R = hydraulic conductivity of rubble layer

K_w = hydraulic conductivity of coal wedge

Q_R = flux through rubble layer

Q = total flux through system

Q_{bR} = flux within rubble layer thickness, b_R , at the coal wedge

*Theoretical calculation based on horizontal flow approximation (Appendix D), also equal to simulation without wedges.

**Based on simulation results including wedges.

Even under these extreme values of K_w , the coal wedge has little effect on the net flow through the reclaimed mine. Total flux through the spoil aquifer is decreased by less than 5% of what it is in the absence of the wedge. This is evident in Table 5.1 in the small variation of Q_R/Q determined with and without the coal wedges. The wedges are not significant factors in inducing anisotropy. The difference in net transmissivity orthogonal to or parallel to the wedges is negligible. Because of the small wedge influence, the horizontal flow approximation accurately estimates the ratio of flux through the rubble layer to the total flux through the aquifer.

The flux distribution is distorted only in the immediate wedge vicinity. For more than 90% of the trench width between wedges, the flux distribution is accurately predicted by the horizontal flow approximation. Fig. 5.6 shows the velocity profiles at several points along the trench.

5.3 Summary

The simulation results may be summarized as follows:

- 1) The rubble layer is the dominant spoil hydraulic feature,
- 2) When its properties are known for the rubble layer and finer spoil, the horizontal flow approximation accurately predicts the flux through the rubble layer,
- 3) The maximum expected wedge influence is limited to the immediate wedge vicinity,

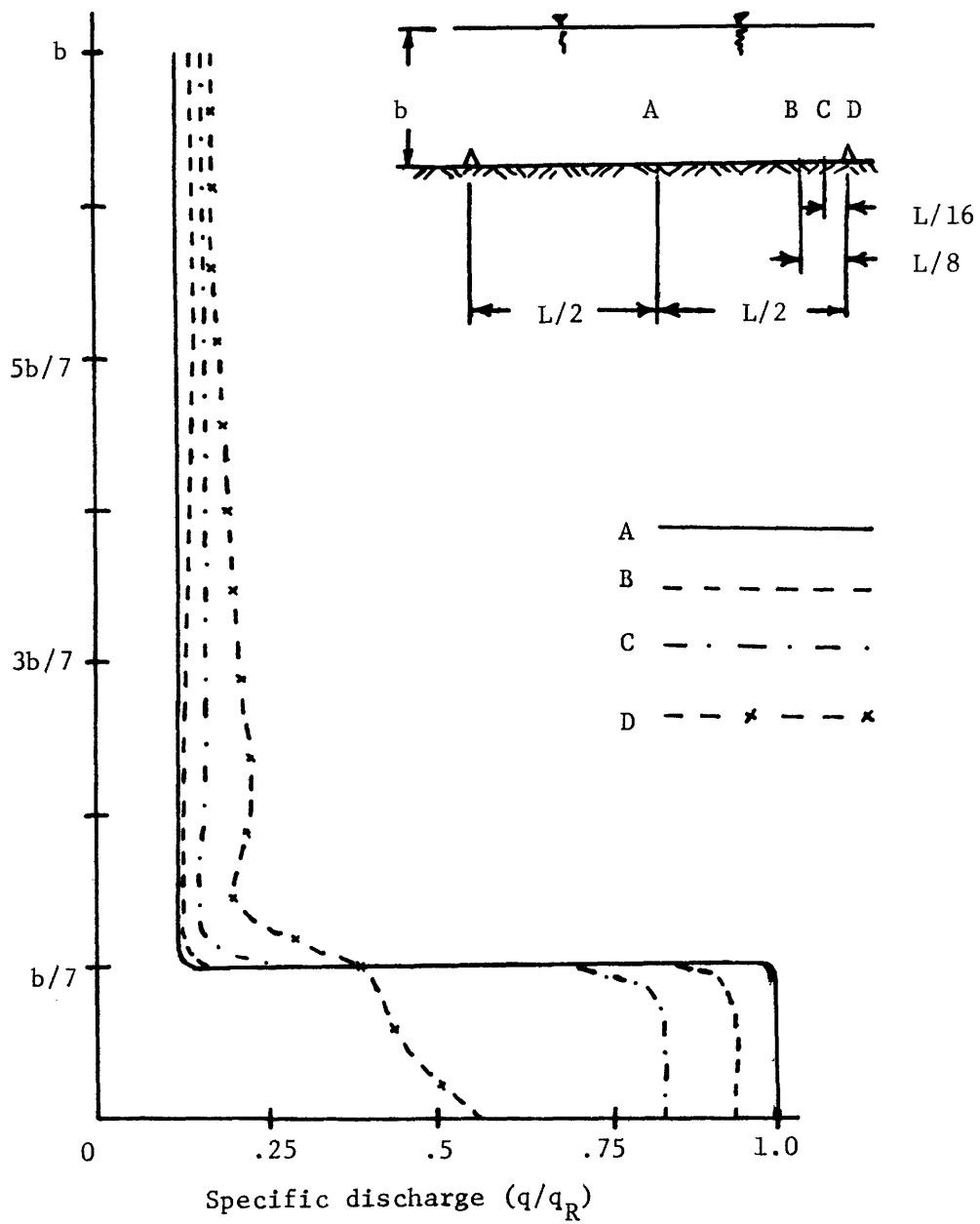


Figure 5.6 Velocity Distribution Along the Trench.

- 4) At the wedge most of the water flowing through the aquifer, 70-90%, is forced into brief contact with the finer spoil,
- 5) Wedge induced anisotropy is not significant,
- 6) The relative transmissivity of the rubble layer to finer spoil determines the relative amount of flow in each.

The flow is essentially horizontal.

Flow in the rubble layer is preferred because it avoids contact with the more leachable finer spoil.

CHAPTER 6

REGIONAL GROUNDWATER FLOW

Regional groundwater flow simulations were designed to evaluate the influence of an operational strip mine on the regional flow field. Mine size, mine location, and water table configuration affect the system through its upper boundary, while aquifer non-homogeneity affects it through internal hydraulic properties. Various combinations of these characteristics were simulated using a two dimensional cross sectional model to obtain the regional equipotential lines.

6.1 Assumptions

The following assumptions were made for this study:

1. The system modeled is regional in scale, including a major recharge area at the regional topographic high and a major discharge area at the topographic low. The upper boundary is the water table, or phreatic surface. Its elevation is controlled by local topography, and the piezometric heads are specified along it. No flux boundaries are assigned to the remaining boundaries, which represent a horizontal impervious basement, and two imaginary vertical boundaries at the groundwater divide and regional discharge area. These boundaries are shown in Fig. 6.1.

2. The water table configuration represents a steady state between natural recharge and discharge, and the operational mine drawdown.

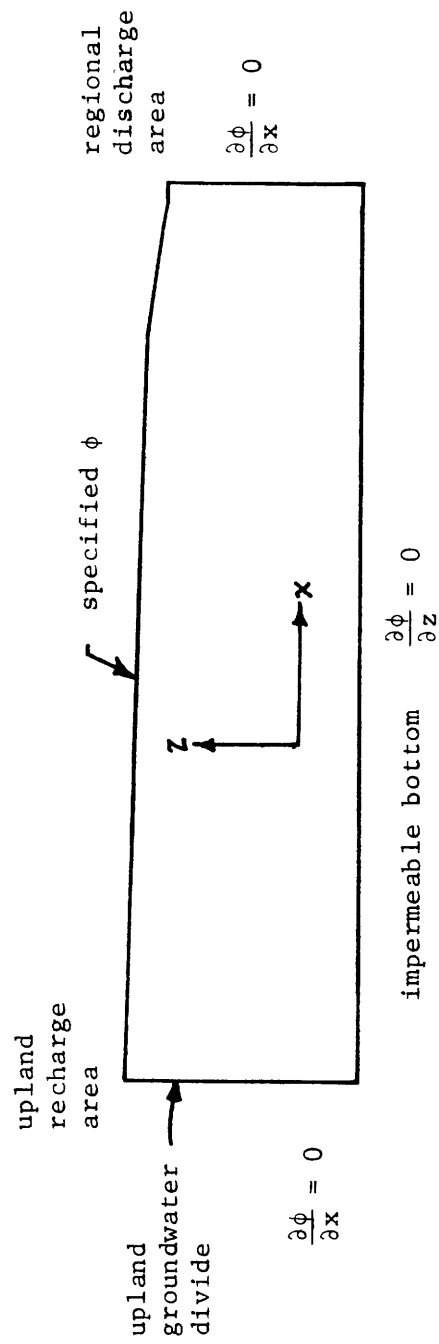


Figure 6.1 Boundary Conditions for Regional Cross Sectional Simulation.

3. At the mine site, the water table is drawdown to the bottom of the mine excavation. Away from the mine the drawdown decreases exponentially, until it reaches zero, and the water table reaches the ambient level.

4. The regional aquifer system is isotropic. Freeze and Witherspoon (1966, 67) and Toth (1962) used similar assumptions for boundary conditions and discuss their appropriateness.

That the phreatic surface is controlled by the local topography is confirmed by observations of the U.S. Geological Survey (1974) in the Fort Union Coal region (Montana, Wyoming and the Dakotas). They report that "...groundwater movement in the shallow aquifers is determined largely by the topography and structural configurations of the basin," confirming that the theoretical work done by Freeze and Witherspoon (1967) applies to the Northern Great Plains region.

Field data is available to demonstrate that a steady state is reached during mining operations. After only three years of mining at Decker, Montana, the rate of piezometric head decline markedly slowed, and an equilibrium is being approached (Van Voast and Hedges, 1975). Since a given site may be mined for 30-50 years, and since within a relatively small coal bearing area mining may continue for several hundred years, the steady state assumption is reasonable.

The exponential drawdown around a mine excavation is predicted by the Dupuit solution, which assumes essentially horizontal flow (Bear, 1972). Although significant vertical flow is involved in mine

interception of regional flow, the fundamental exponential character of the drawdown is still appropriate. This is shown by Van Schiff-gaarde,Engelund et al. (1957) for an analogous drainage problem involving vertical flow.

The aquifer was assumed isotropic in order to concentrate on the effects of the mine relative to other aquifer characteristics. In many natural systems, the horizontal hydraulic conductivity tends to be greater than the vertical, which would tend to lessen the mine effect.

6.2 Model

A finite element grid was designed to give maximum nodal density along the phreatic surface for easy introduction of mining operations and topography variation, and to give detailed piezometric head information around these features. The grid contains 372 elements and 215 nodes and is shown in Fig. 6.2 with a constant regional slope.

The basin was arbitrarily chosen to have a depth to lateral extent ratio of 1:12, where depth is measured at the shallowest point, i.e., the discharge area on the right hand side of the grid. The grid and all other illustrations in this chapter, are presented at that aspect ratio, and are in true scale and isotropic. The grid was actually drawn with a 1:4.6 aspect ratio and geometrically distorted using the transformed sections (Bear, 1972; Freeze and Witherspoon, 1967):

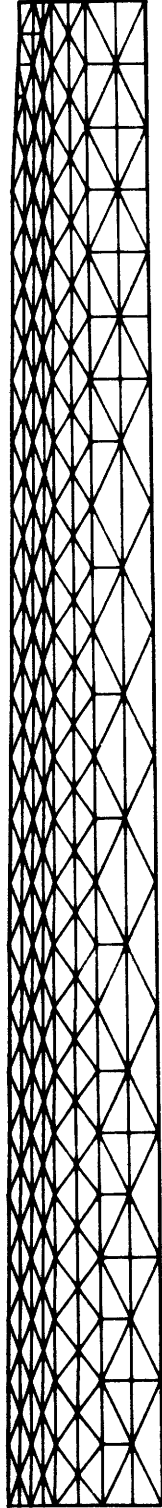


Figure 6.2 Regional Finite Element Grid.

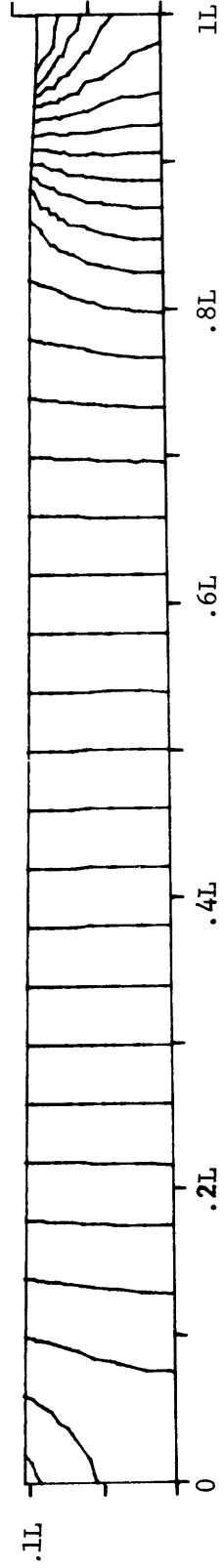


Figure 6.3 Ambient Regional System. The system is homogeneous and isotropic with a 1:12 depth to lateral extent aspect ratio.

$$X = \sqrt{\frac{K_o}{K_x}} x$$

$$Y = \sqrt{\frac{K_o}{K_y}} y$$

where X, Y = length in prototype scale; x, y = distorted scale in the model; K_o = hydraulic conductivity in real scale, under isotropic conditions; and K_x, K_y = hydraulic conductivities used in the model. The model was run with $K_y = K_o$ and $K_x = K_o/6.8$ to achieve the 1:12 aspect ratio.

Total relief was arbitrarily set at 1/5 the basin depth. Piezometric heads were set equal to the water table elevation, and nodes were moved to represent mine drawdown and topographic variation. The results are presented by equipotential lines, plotted using a constant contour interval equal to 1/33 of the total available head.

The simulation assumption and conditions are similar to those used by Freeze and Witherspoon (1967) in their theoretical analysis of the effect of water-table configuration and subsurface permeability variation on regional groundwater flow. Their study should be used in conjunction with the results presented here.

The following effects were simulated and qualitatively analyzed:

1. Mine location - recharge area, mid-region, and discharge area.
2. Mine size - mine depth equal to 5, 10 and 20% of the regional depth, located mid-region.

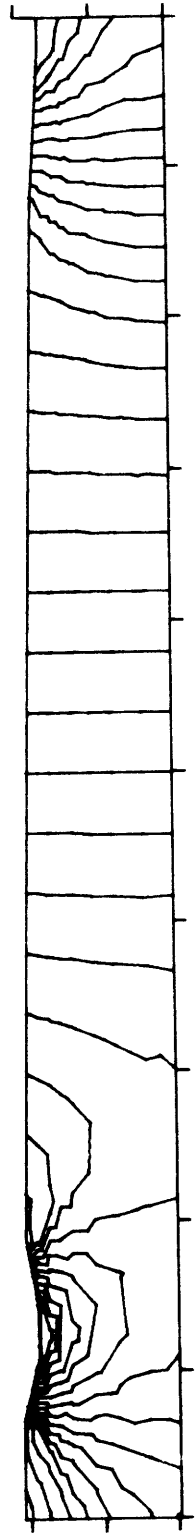
3. Topographic influences.
4. Subsurface layering.

6.3 Regional Mine Location

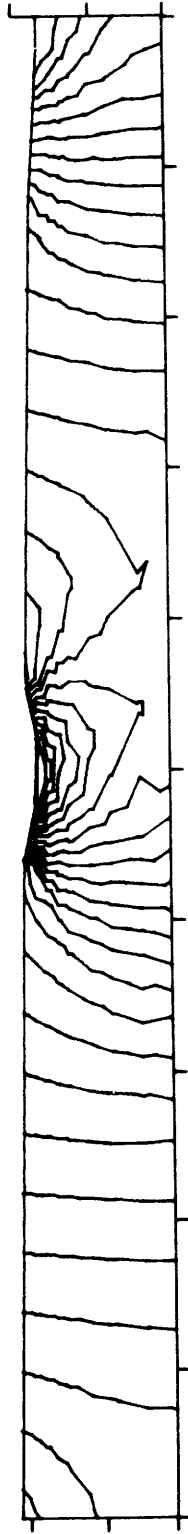
The ambient regional flow system, with a major stream valley is presented in Fig. 6.3. The media is homogeneous and isotropic. Equipotential lines intercept the phreatic surface at intervals where the change in elevation along the surface equals the head drop in the contour interval. Closely spaced equipotential lines indicate a steep hydraulic gradient, and steep water table slope. This is observable near the discharge area of Fig. 6.3. Discharge is concentrated in a relatively small area at the downstream end of discharge area, and recharge, at the upstream end of the recharge area. Most of the flow field is dominated by essentially horizontal flow (Toth, 1962 and Freeze and Witherspoon, 1967).

A mine penetrating approximately 10% of the regional depth was located in the upper recharge area as shown in Fig. 6.4a. This creates a local flow system, or sub basin, with the mine, the local discharge area, at its center. Recharge in the mine area and upstream is effectively cut off from the regional system, reducing total regional discharge.

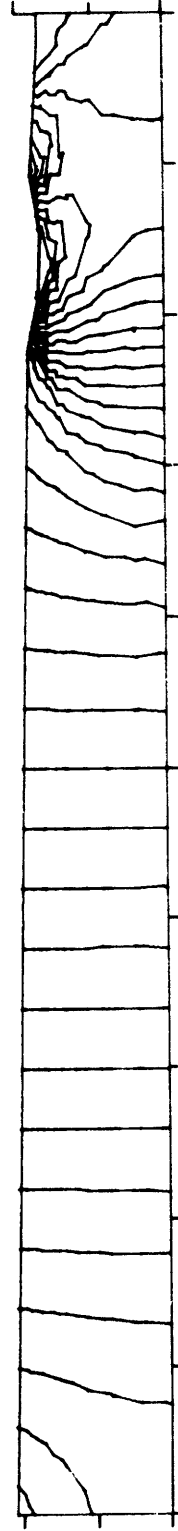
The same mine located mid-region, effectively cuts off most of the regional recharge area as shown in Fig. 6.4b. Two sub basins are formed, above and below the mine. Most of the water entering the up-



a. Mine located in upper recharge area.



b. Mine located mid-region.



c. Mine located near major discharge area.

Figure 6.4 Influence of Regional Mine Location. The mine penetrates 10% of the regional depth.

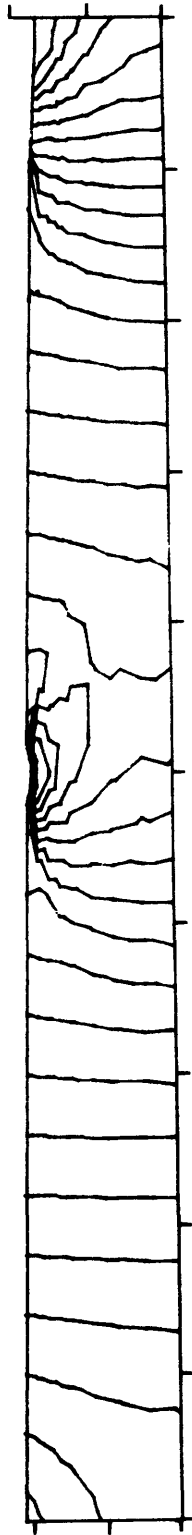
stream subsystem discharges into the mine, while the lower subsystem primarily discharges to the regional discharge area at the topographic low. Some flow passes through the regional system from the upstream recharge area, along the bottom of the system. This mine intercepts a larger portion of the total available recharge than the one further upstream.

In Fig. 6.4c the mine is located in the middle of the ambient system discharge area, creating two major discharge sites for the regional system: the mine and the natural area downslope. Much of the regional flow is discharged into the operating mine.

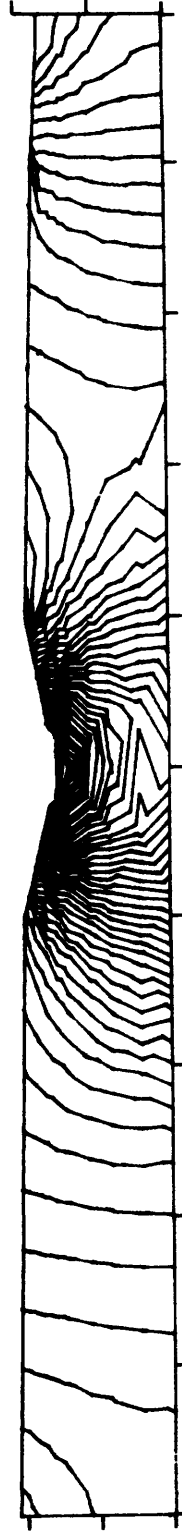
A mine located in regional discharge areas has a significant effect on the regional flow system. It becomes a major discharge site for the regional system, limiting the amount of water discharging via the natural area and exposing the water to possible contamination by contact with the spoil. If large quantities of water are intercepted by the mine, they may create a disposal problem.

6.4 Operational Mine Size

The effects of a mine penetrating 10% of the regional depth in Fig. 6.4b are compared with mines penetrating 5 and 20% in Figs. 6.5a and 6.5b, respectively. Located in mid-region, each of the mines create a new local sub basin. The 5% mine creates the smallest system and has the least effect on the regional system, although its effect is surprisingly large for its size. There is still significant regional along the bottom of the aquifer.



a. Mine penetrates 5% of the regional depth.



b. Mine penetrates 20% of the regional depth, no regional flow passes beneath it, so it may be considered fully penetrating.

Figure 6.5 Influence of Mine Depth. The mines are located mid-region.

The influence of the 10% mine extends over a greater width and depth than the smaller mine. It creates a larger local sub basin and intercepts most of the regional flow.

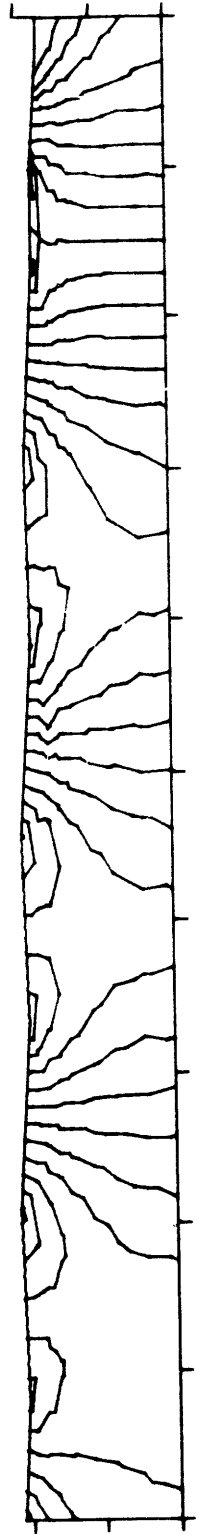
The 20% mine intercepts all upstream flow and effectively cuts most of the recharge area off from the regional discharge creating two sub basins with no regional flow. This mine and any larger ones, may be considered to fully penetrate the regional flow system.

As mine size increases, more water is intercepted, and sub basin flow, rather than regional flow becomes predominate. With more water intercepted potential dewatering and water quality problems increase.

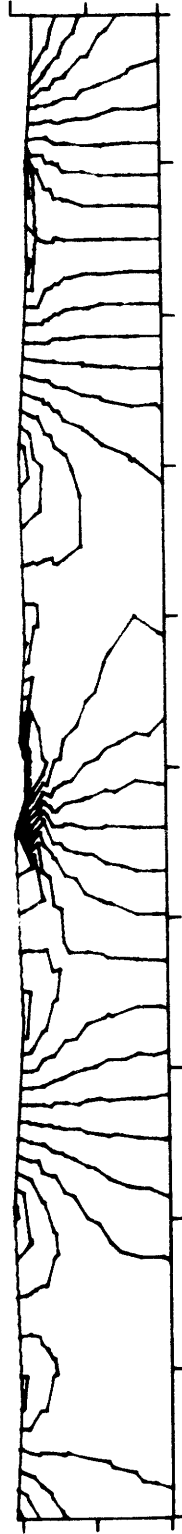
6.5 Topographic Variation

Natural regional phreatic surfaces seldom have a constant slope. They normally include local recharge and discharge areas, representative of hummocky terrain which is typical for large areas of the Northern Great Plains. Fig. 6.6a depicts such a setting before mining has started. The total relief in the local systems is approximately 7% of the regional depth, and it has a relatively minor effect on the regional system. Cases with a greater degree of hummockiness may effectively divide what would otherwise be a regional system into a series of local systems. Toth (1962) and Freeze and Witherspoon (1967) further discuss the influence of hummocky terrain.

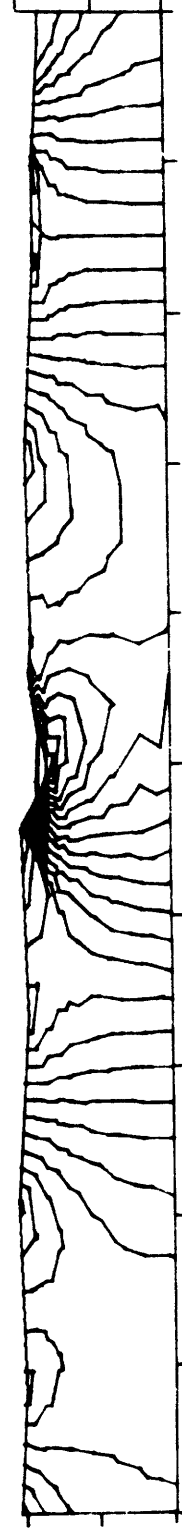
A mine which penetrates about 5% of the regional depth and located on a hillside at mid-region only slightly distorts the flow field (Fig. 6.6b). The mine is on the same scale as the topography



a. Ambient regional system. Total local relief equals approximately 7% of the regional depth.



b. Mine penetrates 5% of the regional depth, less than the scale of topographic variation.



c. Mine penetrates 10% of the regional depth, greater than the scale of topographic variation.

Figure 6.6 Mine Located in Hummocky Topography. The mines are located on a hillside at mid-region. The dark area to the left of the mine is where many equipotential lines come together.

variation of the local systems and merely extends the influence of the local system. But Fig. 6.6c shows that a mine penetrating 10% of the regional depth has a more pronounced effect because it is larger than the scale of topographic variation. This mine creates an intermediate flow system, significantly limiting the regional flow. An even larger mine would intercept all the regional flow as discussed in the previous section.

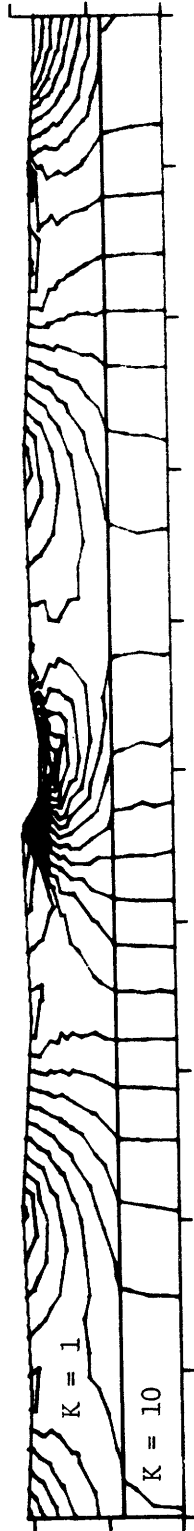
For a mine to be felt beyond the local system, it must be on a larger scale than that of the local topographic variation.

6.6 Subsurface Layering

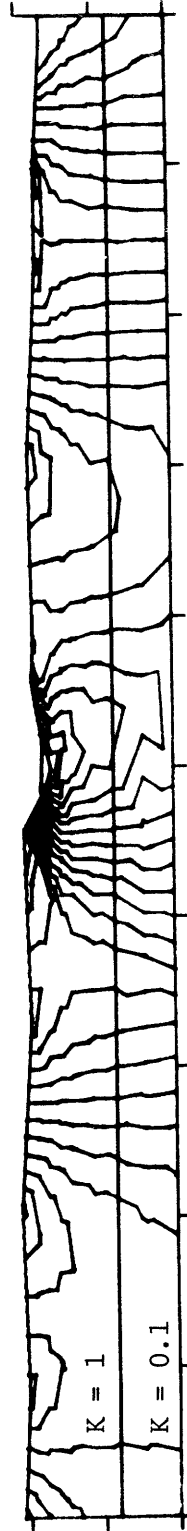
Regional aquifer systems can seldom be considered completely homogeneous. There are often distinct layers of high and low permeability. For purposes of illustration, a simple two layer system is considered here. When the lower layer is more permeable than the upper, the lower formation is, in effect, an aquifer with essentially horizontal flow being recharged from above. And when the lower or basal layer is less permeable, the regional system is effectively restricted to the upper formation. These general characteristics are discussed in greater detail in Freeze and Witherspoon (1967).

When a mine penetrates an upper layer which has only one tenth the permeability of the basal layer, the effects on the flow field are minimal (Fig. 6.7a). Most of the regional flow is concentrated in the more permeable layer and unaffected by the mine.

However, if the upper layer is ten times more permeable than the



a. The mine is located in the less permeable layer, it does not affect the regional flow concentrated in the more permeable lower layer.



b. The mine is located in the more permeable upper layer. The regional system is effectively only the upper layer, and the mine which penetrates almost 20% of this depth may be considered fully penetrating.

Figure 6.7 Two Layered Regional System. The mines penetrate 10% of the regional depth and are located mid-region.

lower, most of the flow concentrates in the upper layer and the regional system is effectively shallower. This is shown in Fig. 6.7b where a mine penetrating 10% of the total basin depth intercepts all the regional flow and may be considered fully penetrating. This example reaffirms that the bottom of the regional system need not be impermeable. In this example, an order of magnitude permeability difference effectively eliminated the basal layer from the regional system.

6.7 Summary

The regional simulation results confirm the basic groundwater flow principles established by Toth (1962) and Freeze and Witherspoon (1967) and extend them to regional groundwater systems influenced by strip mining operations. One surprising aspect is the potentially large effects of relatively small mines. Mines only penetrating 5 to 10% of the regional depth may induce vertical leakage from deep within the system.

The results may be summarized as follows:

1. Mines placed in or near the regional discharge area have a greater effect on the regional system, than those placed elsewhere in the recharge area.
2. Mines penetrating more than 20% of the depth in a homogeneous system may be considered fully penetrating.
3. Topographic variation masks the effects of very small mines, but mines larger than the scale of topographic variation

still exert a significant influence on the regional flow system.

4. In layered regional systems the greatest regional impact occurs when the principal water transmitting layers are intercepted by the mine dewatering scheme.

These observations refer to operating mines, but what about the influence of reclaimed mines on regional flow? This was not simulated, because the answer is obvious. The effect of a reclaimed mine on the flowfield is due to changes in hydraulic properties and infiltration patterns. These are often too small on a regional scale to be significant.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This study generically investigated the influence of strip mining features on the groundwater system. A finite element model, AQUIFEM-1, was used to simulate the effects of a mining operation from three frames of reference: a plan view of the local hydrology, cross sectional view of the interior flowfield through a reclaimed mine, and a cross sectional view of the regional flow system. Each system was carefully schematized into a finite element grid and boundary conditions.

The simulation model solved for the steady state piezometric head distribution. For each simulation the piezometric head contours were plotted and, in some cases, flux concentration, induced by the mine properties, and the contact time of water passing through the reclaimed spoil were calculated. Although only the flow of water through the spoil was modeled, water quality effects were inferred through a set of indices dealing with the reclaimed mine size and amount of water passing through it. The effects of a reclaimed mine were studied in the local and interior flow simulations. The influence of an operational mine was examined in the regional simulation.

The effects of relative transmissivity between the spoil and surrounding coal bed aquifer were examined in the local hydrology

simulation. A wide range of transmissivity ratios were simulated for a square mine and analytically determined for a circular one, with the following results:

1. Flow concentrates and channelizes in the more permeable mine spoil,
2. Flux concentration is significantly influenced by the transmissivity ratio for values of $T_s/T_c \leq 6$.

Mine geometry effects were also investigated in the local hydrology simulation. Five simple standard geometries, and several complex geometries were examined with these results:

1. Geometry significantly influences flowfield distortion, but has less effect on water quality degradation,
2. Equidimensional mines induce the least amount of flow through the spoil per unit of coal extracted. The rectangular mine oriented normal to the ambient flow was found to be the least desirable, and the square mine apparently the best,
3. The most prominent geometric features of mines with complex geometries control the flowfield in their vicinity,
4. Mines in close proximity tend to independently influence the flow field, but often in a way that their combined effect is similar to having a single, much larger mine.

The local hydrology simulations regarding anisotropy found that spoil anisotropy does not seem to have an important effect on ground-

water flow and can probably be neglected. T_{sx} , the directional hydraulic property parallel to ambient flow, primarily determines the flowfield.

Internal mine features, the rubble layer and coal wedges, were examined in the interior flow simulation. The coal wedge was found to have a negligible influence on the flowfield, considering the limited range of wedge hydraulic conductivity, and does not induce significant spoil anisotropy. Flow through the spoil aquifer is essentially horizontal, thus the horizontal flow approximation accurately predicts the flux distribution between the rubble layer and saturated finer spoil above it. The highly permeable rubble layer is the dominant hydraulic feature. Its influence is beneficial because flow in the rubble layer avoids contact with the more leachable finer spoil.

The effects of operational mine size and location in the regional flowfield were evaluated for cases with a gently sloping water table, with topography variation and with a layered aquifer system:

1. Mines located in the regional discharge area have the greatest effect on the regional system,
2. Mines penetrating more than 20% of the effective regional depth may be considered fully penetrating,
3. Topographic variation masks the effects of very small mines. To significantly influence the regional flow system,

a mine must be larger than the scale of topographic variation,

4. Regional flow concentrates in the more permeable layers, which a mine must penetrate to significantly influence the regional flow system.

7.2 Conclusions

Regional location is the most important factor in the influence of an operational mine on groundwater resources. Mines located in the upland recharge areas contact the least amount of water and are therefore more desirable. Relative transmissivity is the most important factor in determining the influence of a reclaimed mine.

Equidimensional mine geometries are preferred to elongated geometries. Rectangular mines oriented perpendicular to the ambient flow are particularly inefficient because a great deal of water is exposed to possible contamination for the amount of coal extracted.

The formation of rubble layers should be encouraged as a means to limit water contact with the more leachable spoil material. The formation of coal wedges, which are apparently of little hydrologic consequence, should be governed by economic considerations, as they are now.

Although the simulation technique in this study used was applied to simple mine geometries and situations in this study, it is even more appropriate for the complex situations encountered in the field. In these cases, existing finite element or finite

difference groundwater flow models can accommodate both natural and mine induced variation of aquifer properties, as well as complicated boundary conditions. The primary problem of application is not the modeling technique itself, but rather the collection of an adequate data base.

This study has established a preliminary ranking of the relative importance of several strip mining features and their influence on the groundwater flow system. The results may be used as a basis for more detailed investigations, both in the field and theoretically.

7.3 Recommendations

Much more research is needed to establish a good understanding of the spoil chemistry and dissolved solids loading of groundwater. Both laboratory and field results are needed. This type of information may then be used to model the mass transport and chemical reactions in order to predict long-term groundwater quality.

A groundwater model should be linked with surface water models to simulate surface infiltration and percolation through the spoil to the spoil aquifer. This would involve a two-dimensional, cross sectional view of the reclaimed mine site. This is of interest for studying the possible groundwater quality effects of a reclaimed strip mine located in a recharge area and for studying the effects of a stream passing through the reclaimed site. Many mines divert streams around the site during operation and plan to redivert them back over the reclaimed spoil, when reclamation is completed. Although the

streams are typically ephemeral in the Northern Great Plains, a re-diverted stream is a potential recharge source for the groundwater system after storms and during snowmelt. This recharge water may be degraded through contact with the spoil. The model could predict the system's response under different conditions and be used as a design and management tool for determining the most environmentally sound alternatives.

More simulation work should investigate the effects of locating many mines in a very small area. An actual site where intensive mining is likely, such as in the Powder River Basin, can be modeled for the groundwater system's response to various numbers and locations of mines. A generic three-dimensional regional model can also be used to examine the regional multiple mine influence, as well as examine the lateral extent of a mine's influence.

An intense groundwater observation program should be prepared for several proposed mine sites to establish the dynamic response of an actual hydrologic system to strip mining and the changes in hydrologic properties at the reclaimed mine. The pre-mining hydrologic conditions should be well documented for comparison with the post mining situation. Observation wells should be placed in the spoil as soon as possible to monitor the re-establishment of the flowfield. And observation wells should be maintained at different depths to monitor the effects on the regional system. During the mining operation the wells may be used to establish hydraulic gradients, both

laterally from the mine and with depth. After reclamation the wells would monitor the establishment of flow in the spoil aquifer, but they could not observe the effects of the rubble layer because of the horizontal flow conditions found in Chapter 5.

The hydraulic properties of the rubble layer and other finer spoil may be determined through pumping tests. The pumping wells should be screened at a different depth for each set of tests. Observation wells should also monitor the water level at different depths. This will give an indication of the variations in hydraulic properties.

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APPENDIX A

GLOSSARY

Anisotropy - The condition in which hydraulic conductivity or transmissivity are directionally dependent.

Aquifer - A formation, group of formations, or part of a formation that is water bearing, and permits significant amounts of water to move through it under ordinary field conditions.

Coal Wedge - A small rib of coal left between trench cuts in some mining operations.

Dragline - A type of excavating equipment which casts a rope-hung bucket a considerable distance and digs by pulling the bucket toward itself.

Effective Porosity - The void volume between particles of a porous media which are available for fluid flow, relative to total volume.

Equipotential - Set of points with equal piezometric heads.

Flux - Volumetric discharge per unit area [L/T].

Groundwater - Water present in the saturated zone of an aquifer.

Homogeneity - Properties are uniform throughout the media.

Hydraulic Conductivity - Rate of water flow through a unit area under a unit hydraulic gradient [L/T]; or more simply, the ability of the aquifer material to conduct water through it under hydraulic gradients.

Hydraulic Gradient - Piezometric head loss per unit length [L/L].

Leachate - Liquid that has percolated through a medium and has extracted dissolved or suspended solids from it.

Overburden - The earth, rock and other minerals lying in the natural state above coal deposits before excavation.

Piezometric head - The level to which water will rise in a piezometer or observation well which is screened over some depth.

Piezometric surface - The imaginary surface formed by all the piezometric heads in an aquifer.

Reclamation - Backfilling, grading, top soiling, planting, revegetation and other work to restore an area of land affected by strip mining.

Rubble Layer - A highly permeable region sometimes formed at the base of the spoil by gravity sorting of the large spoil fragments.

Scraper - An excavating machine which loads by lowering a blade, forcing material into a compartment as it drives forward.

Shovel - An excavating and loading machine consisting of a digging bucket at the end of an arm suspended from a boom. When digging the bucket moves forward and upward. The machine usually excavates at the level at which it stands.

Specific Discharge - Volume of water flowing through a cross sectional area [L/T].

Spoil - All overburden material removed, disturbed or displaced by excavating equipment, blasting, or any other means. Spoil is the soil and rock that has been removed from its original location.

Streamline - In steady flow only, the path that a water parcel follows. More generally, it is an instantaneous curve that is, at every point, tangent to the direction of the fluid velocity.

Strip Mining - Refers to the procedure of mining that entails the complete removal of all material from over the coal to be mined in a series of rows or strips; also referred to as open-cut, open-pit or surface mining.

Transmissivity - Rate of water flow through a vertical strip of aquifer one unit wide, extending the full saturated thickness of the aquifer, under a unit hydraulic gradient [L^2/T]; or more simply, the ability of the aquifer to transmit water through its entire saturated thickness.



APPENDIX B

LISTING OF CONTOUR

CONTOUR was written by Pedro Restrepo, a Research Assistant at the Ralph M. Parsons Laboratory at MIT. The program linearly interpolates the piezometric heads at the nodes, over the triangular finite element. The input requires the number of elements, NEL, number of nodes, NNOD, number of functions to be plotted, NFUN, the normalizing factors for the x and y coordinates, DELX and DELY, the contour interval, DELZ, and the plot size, XPLOT. Then the reference datums are read for each plot. This is followed by the nodal coordinates, nodes connecting each element, and the piezometric heads for each node. Finally the number of nodes needed to connect the boundary outline, NNCON, and the node numbers used for the outline.

```

CONT0001
CONT0002
CONT0003
CONT0004
CONT0005
CONT0006
CONT0007
CONT0008
CONT0009
CONT0010
CONT0011
CONT0012
CONT0013
CONT0014
CONT0015
CONT0016
CONT0017
CONT0018
CONT0019
CONT0020
CONT0021
CONT0022
CONT0023
CONT0024
CONT0025
CONT0026
CONT0027
CONT0028
CONT0029
CONT0030
CONT0031
CONT0032
CONT0033
CONT0034
CONT0035
CONT0036

IMPLICIT INTEGER*2 (I-N)
DIMENSION X(400), Y(400), U(260, 14), NINT(460), N1(460), N2(460),
1 N3(460), NODIN(400), DATUM(14), NODCON(30, 14), NNCON(14)
NI=1
1310 FORMAT(16I5)
IN=8
IO=5
READ(IN, 1000) NEL, NNOD, NFUN, DELX, DELY, DELZ, XPLOT
WRITE(IO, 1000) NEL, NNOD, NFUN, DELX, DELY, DELZ, XPLOT
1000 FORMAT(4I5, 5F10.0)
READ(IN, 1300) (DATUM(I), I=1, NFUN)
WRITE(IO, 1300) (DATUM(I), I=1, NFUN)
XMIN=1.E10
YMIN=1.E10
XMAX=-1.E10
YMAX=-1.E10
DO 10 I=1, NNOD
READ(IN, 1100) NEXT, X(I), Y(I)
NINT(NEXT)=I
1300 FORMAT(8F10.0)
1100 FORMAT(I10, 2F10.0)
IF(XMIN.GT.X(I)) XMIN=X(I)
IF(XMAX.LT.X(I)) XMAX=X(I)
IF(YMIN.GT.Y(I)) YMIN=Y(I)
IF(YMAX.LT.Y(I)) YMAX=Y(I)
1150 FORMAT(I10, 2F10.2)
10 CONTINUE
DO 20 I=1, NEL
READ(IN, 1200) IEL, N1(I), N2(I), N3(I)
1200 FORMAT(4I10)
20 CONTINUE
DO 24 J=1, NFUN
READ(IN, 1300) (U(I, J), I=1, NNOD)
READ(IN, 1010) (NNCON(J), J=1, NFUN)
1010 FORMAT(8I10)
DO 701 J= 1, NFUN

```

CONT0037
 CONT0038
 CONT0039
 CONT0040
 CONT0041
 CONT0042
 CONT0043
 CONT0044
 CONT0045
 CONT0046
 CONT0047
 CONT0048
 CONT0049
 CONT0050
 CONT0051
 CONT0052
 CONT0053
 CONT0054
 CONT0055
 CONT0056
 CONT0057
 CONT0058
 CONT0059
 CONT0060
 CONT0061
 CONT0062
 CONT0063
 CONT0064
 CONT0065
 CONT0066
 CONT0067
 CONT0068
 CONT0069
 CONT0070
 CONT0071
 CONT0072

```

NCON= NCON(J)
READ(IN,1310) (NODCON(I,J),I=1, NCON)
WRITE(IO,1310) (NODCON(I,J),I=1, NCON)
CONTINUE
XMIN=FLOAT(IFIX(XMIN/DELX))*DELX
XMAX=FLOAT(IFIX(XMAX/DELX)+1)*DELX
YMIN=FLOAT(IFIX(YMIN/DELY))*DELY
YMAX=FLOAT(IFIX(YMAX/DELY)+1)*DELY
RX=XPLOT/(XMAX-XMIN)
RY=XPLOT/(YMAX-YMIN)
CALL GERBER(16,70)
CALL PLOT(32)
CALL SCALE(100.,100.,0.,0.)
CALL WINDOW(0.0,0.0,XPLOT,XPLOT)
CALL SPLOT(0.,0.,0)
CALL TCHAR(15.,15.,0.)
NTKX=IFIX((XMAX-XMIN)/DELX)
NTKY=IFIX((YMAX-YMIN)/DELY)
RX=XPLOT/(XMAX-XMIN)
RY=XPLOT/(YMAX-YMIN)
IF(RY-RX)25,30,30
25 R=RY
GO TO 32
30 R=RX
32 DO 110 J=1,NPUN
33 DO 100 I=1,NPL
CALL ORDER(N1,N2,N3,NINT,U,I,J,I1,I2,I3)
U1=U(I1,J)-DATUM(J)
U2=U(I2,J)-DATUM(J)
U3=U(I3,J)-DATUM(J)
Z1=FLOAT(IFIX(U1/DELZ)+1)*DELZ
Z2=FLOAT(IFIX(U2/DELZ))*DELZ
Z3=FLOAT(IFIX(U3/DELZ))*DELZ
IF(U1.LE.0.0)Z1=Z1-DELZ
IF(Z2.LE.0.0.AND.U2.LT.0.0)Z2=Z2-DELZ
IF(Z3.LE.0.0.AND.U3.LT.0.0)Z3=Z3-DELZ
  
```

701

CONT0073
CONT0074
CONT0075
CONT0076
CONT0077
CONT0078
CONT0079
CONT0080
CONT0081
CONT0082
CONT0083
CONT0084
CONT0085
CONT0086
CONT0087
CONT0088
CONT0089
CONT0090
CONT0091

```
Z=Z1
95 IF (Z.GT.Z2) GO TO 40
   CALL INTER(X,Y,J,I1,I2,U,Z,XP1,YP1,DATUM)
   GO TO 42
40 IF (Z.GT.Z3) GO TO 100
   CALL INTER(X,Y,J,I2,I3,U,Z,XP1,YP1,DATUM)
42 CONTINUE
   CALL INTER(X,Y,J,I1,I3,U,Z,XP2,YP2,DATUM)
   WRITE (6,700) XP1,YP1,XP2,YP2
700 FORMAT (4F10.3)
   CALL PLTC(XP1,YP1,XP2,YP2,R,XMIN,YMIN)
   Z=Z+DELZ
   GO TO 95
100 CONTINUE
   CALL BORDER(NODCON,NNCON,R,XMIN,YMIN,X,Y,NINT,J)
   PAUSE
110 CONTINUE
   CALL EXIT
   END
```



```

SUBROUTINE BORDER(NODCON,NNCON,R,XMIN,YMIN,X,Y,NINT,J)
IMPLICIT INTEGER*2(I-N)
DIMENSION NODCON(30,14),X(400),Y(400),NINT(400),NNCON(14)
FX(Z) = (Z-XMIN)*R
FY(Z) = (Z-YMIN)*R
N1= NODCON(1,J)
N1= NINT(N1)
X2= FX(X(N1))
Y2= FY(Y(N1))
CALL SPLOT(X2,Y2,0)
NCON= NNCON(J)
DO 20 I=2, NCON
N1= NODCON(I,J)
N1= NINT(N1)
X1= FX(X(N1))
Y1= FY(Y(N1))
CALL SPLOT(X1,Y1,1)
CONTINUE
CALL SPLOT(X2,Y2,1)
RETURN
END

```

20

144

```

BORD0001
BORD0002
BORD0003
BORD0004
BORD0005
BORD0006
BORD0007
BORD0008
BORD0009
BORD0010
BORD0011
BORD0012
BORD0013
BORD0014
BORD0015
BORD0016
BORD0017
BORD0018
BORD0019
BORD0020
BORD0021

```

OPDR0001
 ORDR0002
 ORDR0003
 ORDR0004
 ORDR0005
 ORDR0006
 ORDR0007
 ORDR0008
 ORDR0009
 ORDR0010
 ORDR0011
 ORDR0012
 ORDR0013
 ORDR0014
 ORDR0015
 ORDR0016
 ORDR0017
 ORDR0018
 ORDR0019
 ORDR0020
 ORDR0021
 ORDR0022
 ORDR0023
 ORDR0024
 ORDR0025
 ORDR0026
 ORDR0027
 ORDR0028
 ORDR0029
 ORDR0030
 ORDR0031
 ORDR0032
 ORDR0033
 ORDR0034
 ORDR0035
 ORDR0036

```

SUBROUTINE ORDER(N1,N2,N3,NINT,U,I,J,I1,I2,I3)
IMPLICIT INTEGER*2(I-N)
DIMENSION N1(460),N2(460),N3(460),NINT(460),D(260,14)
NEXT=N1(I)
1200 FORMAT(4I10)
NI1=NINT(NEXT)
U1=U(NI1,J)
NEXT=N2(I)
NI2=NINT(NEXT)
U2=U(NI2,J)
NEXT=N3(I)
NI3=NINT(NEXT)
U3=U(NI3,J)
IF(U1-U2)10,20,20
10 IF(U2-U3)30,40,40
30 I3=NI3
I2=NI2
I1=NI1
GO TO 110
40 IF(U1-U3)50,60,60
50 I3=NI2
I2=NI3
I1=NI1
GO TO 110
20 IF(U2-U3)70,80,80
80 I3=NI1
I2=NI2
I1=NI3
GO TO 110
70 IF(U1-U3)90,100,100
90 I3=NI3
I2=NI1
I1=NI2
GO TO 110
60 I3=NI2
I2=NI1
  
```

ORDR0037
ORDR0038
ORDR0039
ORDR0040
ORDR0041
ORDR0042
ORDR0043

I1=NI3
GO TO 110
100 I3=NI1
I2=NI3
I1=NI2
110 RETURN
END

```

SUBROUTINE INTER(X,Y,J,I1,I2,U,Z,XP1,YP1,DATUM)
IMPLICIT INTEGER*2(I-N)
DIMENSION X(400),Y(400),U(260,14),DATUM(14)
U1=U(I1,J) -DATUM(J)
U2=U(I2,J) -DATUM(J)
X1=X(I1)
Y1=Y(I1)
X2=X(I2)
Y2=Y(I2)
IF(X1.EQ.X2)GO TO 10
XP1=X1+(X2-X1)/(U2-U1)*(Z-U1)
YP1=Y1+(Y2-Y1)/(X2-X1)*(XP1-X1)
RETURN
10 YP1=Y1+(Y2-Y1)/(U2-U1)*(Z-U1)
XP1=X1+(X2-X1)/(Y2-Y1)*(YP1-Y1)
RETURN
END

```

```

INTR0001
INTR0002
INTR0003
INTR0004
INTR0005
INTR0006
INTR0007
INTR0008
INTR0009
INTR0010
INTR0011
INTR0012
INTR0013
INTR0014
INTR0015
INTR0016
INTR0017

```

```

SUBROUTINE PLTC (XP1, YP1, XP2, YP2, R, XMIN, YMIN)
IMPLICIT INTEGER*2 (I-N)
FX (X) = (X - XMIN) * R
FY (Y) = (Y - YMIN) * R
DATA IC/2/
IC=3-IC
X1=FX (XP1)
Y1=FY (YP1)
X2=FX (XP2)
Y2=FY (YP2)
GO TO (1,2), IC
1 CALL SPLOT (X1, Y1, 0)
  CALL SPLOT (X2, Y2, 1)
  RETURN
2 CALL SPLOT (X2, Y2, 0)
  CALL SPLOT (X1, Y1, 1)
  RETURN
END

```

```

PLTC0001
PLTC0002
PLTC0003
PLTC0004
PLTC0005
PLTC0006
PLTC0007
PLTC0008
PLTC0009
PLTC0010
PLTC0011
PLTC0012
PLTC0013
PLTC0014
PLTC0015
PLTC0016
PLTC0017
PLTC0018

```



APPENDIX C

ANALYTICAL SOLUTION FOR A CIRCULAR MINE IN A UNIFORM FLOW FIELD

The analytical solution for a circular mine in a two-dimensional, uniform, steady flow field is readily found through the separation of variables technique. The aquifer is divided into two homogeneous, isotropic regions: the circular mine with spoil hydraulic conductivity, K_s ; and the exterior flow region with coal bed hydraulic conductivity, K_c ; which are shown in Figure C.1. The ratio K_s/K_c is an important parameter relating the spoil and coal hydraulic properties, and is frequently used for evaluation purposes. For the linear system studied in Chapters 4 and 5, this ratio is equivalent to T_s/T_c .

The uniform flow field is described by the horizontal hydraulic gradient $\vec{J} = -\partial\phi/\partial x \vec{i}$, where \vec{i} is the unit vector in the direction of flow, x , and ϕ is the aquifer piezometric head. The well-known relationships between specific discharge, q , the velocity potential, Φ , and the peizometric head, ϕ are:

$$\vec{q} = -\nabla\Phi$$

$$\vec{q} = -K\nabla\phi$$

and $\Phi = K\phi$.

For steady flow the governing equation in each region is the Laplace equation, $\nabla \cdot \vec{q} = 0$, or

$$\nabla^2\phi_s = 0 \tag{C.1}$$

$$\nabla^2\phi_c = 0 \tag{C.2}$$

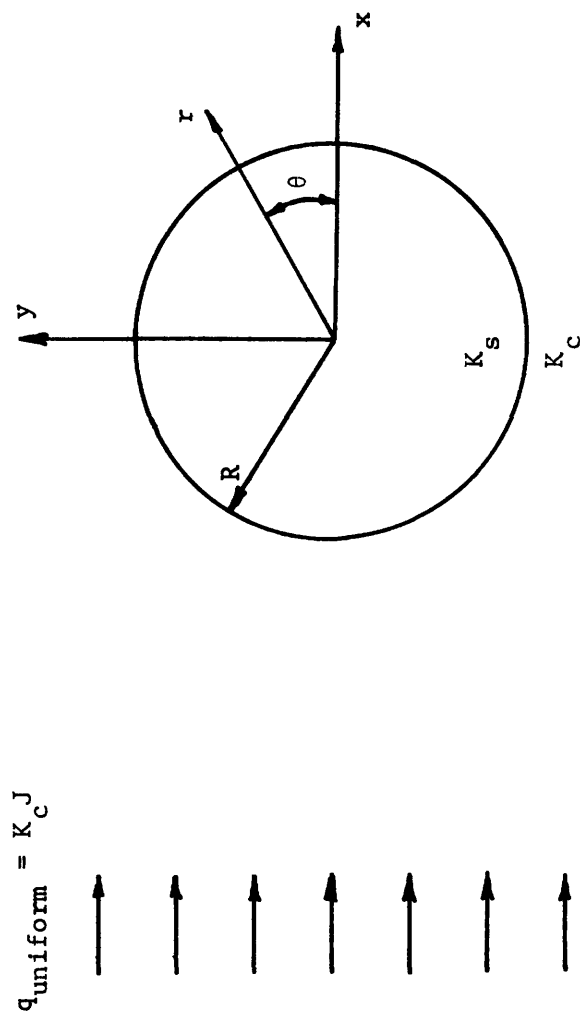


Figure C.1 Circular Mine in a Uniform Flow Field.

with boundary condition

$$\phi_c = -K_c J x = -K_c J r \cos\theta \quad \text{as } x \rightarrow \infty \quad (\text{C.3})$$

and interface matching conditions between regions

$$\phi_s = \phi_c \rightarrow K_c \phi_s = K_s \phi_c \quad , \quad r = R \quad (\text{C.4})$$

$$\left. \frac{\partial \phi_s}{\partial r} \right|_R = \left. \frac{\partial \phi_c}{\partial r} \right|_R \quad (\text{C.5})$$

Using the separation of variables technique:

$$\phi = R(r) \cdot \theta(\theta)$$

where

$$R = \begin{array}{l} Ar^\lambda + Br^{-\lambda}; \lambda \neq 0 \\ A \ln r + B; \lambda = 0 \end{array}$$

$$\theta = \begin{array}{l} C \cos \lambda \theta + D \sin \lambda \theta; \lambda \neq 0 \\ C \theta + D; \lambda = 0 \end{array}$$

Applying boundary condition C.3 to the external region, $\lambda = 1$,

and

$$\phi_c = -K_c J r \cos\theta + B' \frac{\cos\theta}{r} \quad (\text{C.6})$$

where $B' = DB$. In the spoil, the solution is ($A' = AC$)

$$\phi_s = A' r \cos\theta \quad (\text{C.7})$$

which insures matching at the interface (i.e., $\lambda = 0$, $D = 0$) and avoids an unbounded solution at $r = 0$ (i.e., $B = 0$).

The matching conditions along $r = R$ require (Eq. C.5)

$$-K_c J - B'/R^2 = A'$$

and (Eq. C.4)

$$-K_c J + B'/R^2 = A'(K_c/K_s)$$

which can be solved simultaneously to yield

$$A' = -2K_c K_s J / (K_s + K_c)$$

$$B' = JR^2 K_c (K_s - K_c) / (K_s + K_c)$$

When substituted into Eqs. C.6 and C.7 the potential solution is found

$$\phi_c = -K_c J r \cos\theta + K_c J \frac{(K_s - K_c)}{(K_s + K_c)} \frac{R^2}{r} \cos\theta$$

$$\phi_s = -2K_c J \frac{K_s}{(K_s + K_c)} r \cos\theta$$

with piezometric heads,

$$\phi_c = -Jr \cos\theta + J \frac{(K_s - K_c)}{(K_s + K_c)} \frac{R^2}{r} \cos\theta \quad (C.8)$$

$$\phi_s = -2K_c J \frac{1}{(K_s + K_c)} r \cos\theta \quad (C.9)$$

and stream functions,

$$\psi_c = -K_c J r \sin\theta - K_c J \frac{(K_s - K_c)}{(K_s + K_c)} \frac{R^2}{r} \sin\theta \quad (C.10)$$

$$\psi_s = -2K_c J \frac{K_s}{(K_s + K_c)} r \sin\theta \quad (C.11)$$

Eqs. C.9 and C.11 imply that the flow through the mine spoil is uniform and oriented in the x-direction. That is, the equipotential lines in the mine are parallel and evenly spaced, and the gradient in the spoil is identically given by

$$J_s = 2K_c J / (K_s + K_c) = \text{constant} \quad (C.12)$$

The flow field is plotted and shown in Figs. 3.5 and 4.10 for various ratios of $K_s/K_c (= T_s/T_c)$.

The theoretical flux through the mine spoil is given by

$Q_s = K_s J_s A$ where A is the area concerned. Similarly, the flux through an area A of the ambient uniform flow field is $Q_A = K_c J A$. Taking the ratio and applying Eq. C.12,

$$\frac{Q_s}{Q_A} = \frac{K_s J_s}{K_c} = \frac{2K_s}{K_s + K_c} = \frac{2}{1 + (K_c/K_s)} \quad (C.13)$$

This flux concentration ratio reveals that as K_s increases, the maximum flux concentration for a circular area of high permeability is 2.0. Conversely as K_s decreases, the flux concentration goes to zero.

When transmissivity ratio is used Eqs. C.12 and C.13 become

$$J_s = 2T_c J / (T_s + T_c)$$

and

$$\frac{Q_s}{Q_A} = \frac{2}{1 + (T_c/T_s)}$$

McWhorter and Rowe (1976) were the first to apply this well-known analytical solution to a hypothetical circular mine.

APPENDIX D

HORIZONTAL FLOW CALCULATION

The horizontal flow calculation, based on Darcy's Law and the continuity equation, is applied to the interior flow situation idealized in Fig. D.1. Darcy's Law, $Q = KbJ$, where J is the hydraulic gradient, b is the saturated thickness, and Q is the discharge per unit mine width, is combined with continuity, $Q_C = Q_R + Q_{FS} = Q_S$, to yield:

$$Q_C = K_c b_c J_c = (K_{fs} b_{fs} + K_R b_R) J_s = Q_S \quad (D.1)$$

where C, R, fs, and S refer to the coal bed, rubble layer, fine spoil, and total spoil bed, respectively. Since $T = Kb$, and $T_s = T_{fs} + T_R$, this becomes $T_c J_c = T_s J_s$ or $T_s/T_c = J_c/J_s$. The ratio of flux through the rubble layer to the total flux ($Q = Q_C = Q_S$) is expressed as:

$$\frac{Q_R}{Q} = \frac{T_R J_R}{T_c J_c} = \frac{T_R}{T_R + T_{fs}} \quad (D.2)$$

Similarly:

$$\frac{Q_{FS}}{Q} = \frac{T_{FS}}{T_R + T_{FS}} \quad (D.3)$$

The relationship between K_R and K_{fs} is easily found when the transmissivity ratio, T_s/T_c and K_{fs}/K_c are specified. From Eq. D.1

$$\frac{K_R}{K_{fs}} = \frac{K_c}{K_{FS}} \frac{b_c}{b_R} \frac{J_c}{J_s} - \frac{b_{fs}}{b_R} \quad (D.4)$$

If $T_s/T_c = 6/1$, then $J_c/J_s = 6/1$. If as in the finite element grid of Chapter 5, $b_R = b/7$ and $b_{fs} = 6b/7$, and if $K_{FS}/K_c = 3/1$, then by substituting into Eq. D.4, $K_R/K_{fs} = 8/1$. Also note that $b_c = b$ and $J_c = J$, the gradient of the ambient flowfield.

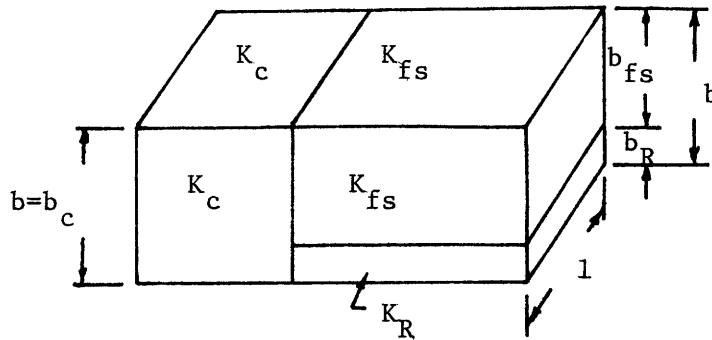


Figure D.1 Idealized Interior Flow Situation.