MINE WATER. GRANADA, SPAIN. 1985.

DEVELOPMENT OF AN OPEN PIT COAL MINE DEWATERING PLAN IN CESAR DEPARTMENT, COLOMBIA, S.A.

Phillip E. Brown[1], Robert G. Smith[1], and Louis Lombardo[2]
[1]Independent Consultants, Denver, CO., [2]J.T. Byrd Co., Pittsburgh, PA.

ABSTRACT

To design a mine dewatering plan for a proposed multiseam open pit coal mine in Cesar Department, Colombia, S.A., a four-month hydrogeological investigation took place in the Boqueron Syncline Reserve area. The purpose of the study was to predict pit inflows for preliminary design and costing of ground water and precipitation control measures. Finite difference and analytical modeling were used to predict ground water pit inflow. The design and costing of an effective dewatering and depressurization system was developed.

1.0 INTRODUCTION

This paper presents results and interpretation of a four-month hydrogeological investigation of the Boqueron Syncline Coal Reserve Area near the town of La Loma in Cesar Province, Colombia, S.A. (Figure 1). The objectives of the study included:

- delineation of the groundwater flow regime in the vicinity of the Boqueron Syncline Reserve Area in terms of flow direction and hydraulics;
- predictions of inflows into a proposed open-pit coal mine; and
- preliminary design and costing of ground water and precipitation runoff control measures.

The investigation consisted of installation of sixteen piezometers; response and air-lift pump testing; and design and interpretation of computer and analytical procedures to predict ground water inflow into the pit. As illustrated in Figure 2, the study concentrated on the northern portion of Boqueron Syncline, which corresponds with the area designated for the first ten years of mining. From data gathered in the study, extrapolations were made to encompass the entire prospective mine area. Based on the results of the field studies, computer models were developed to predict pit inflow. Finally, water

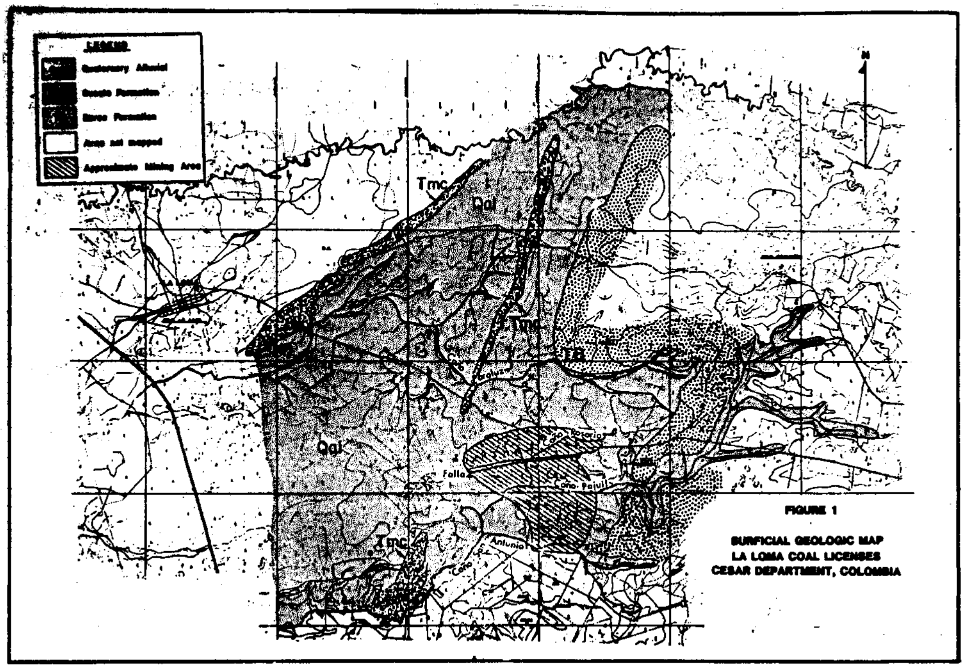

FIGURE 1

SURFICIAL GEOLOGIC MAP
LA LOMA COAL LICENSES
CESAR DEPARTMENT, COLOMBIA

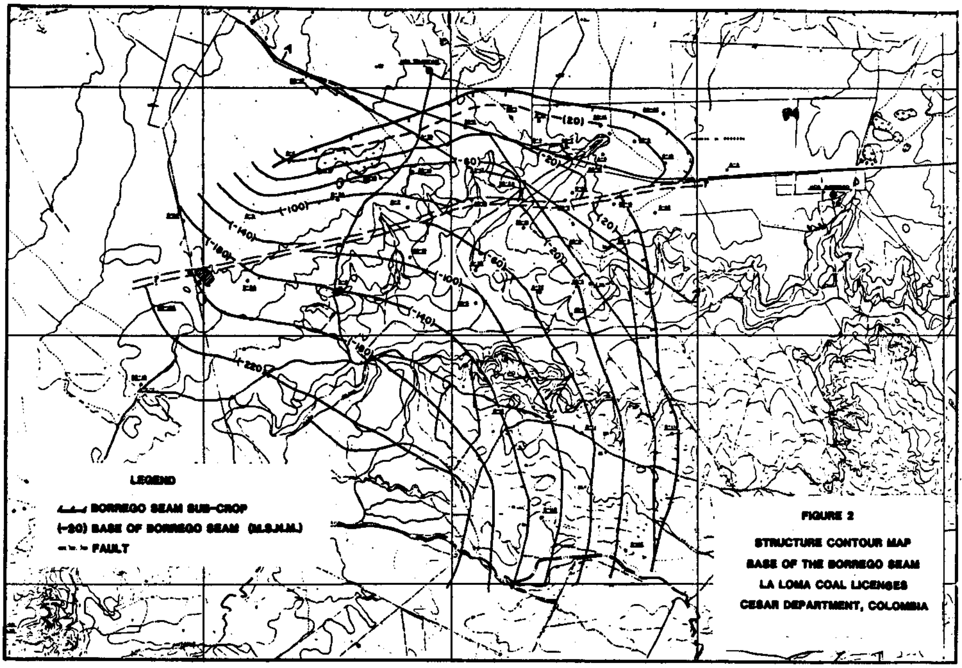

FIGURE 2

STRUCTURE CONTOUR MAP
BASE OF THE BORREGO SEAM
LA LOMA COAL LICENSES
CESAR DEPARTMENT, COLOMBIA

handling procedures were designed to be economical and effective in handling both ground water and surface water inflow into the pit.

2.0 STUDY METHODOLOGIES

Basic geohydrologic data for the project area were gathered in the field using the following methodologies:

Geohydrologic Mapping. The geohydrologic mapping of the study area corresponded with the coal exploration and geologic evaluation of the site. In this phase, the extent of the alluvium and location of bedrock outcrops were determined. Rock core was examined for the degree of fracturing, lithologic nature and continuity of the various lithologic units. Geophysical logs (i.e. resistivity, gamma, gamma-gamma, and caliper) gave additional insight into the hydraulic character of the strata.

Piezometer Installation. To delineate the geohydrology of the Boqueron Syncline Area, sixteen piezometers were completed in either rotary or core holes. These piezometers were used for hydraulic testing, water quality determination and water level sounding of various geohydrologic units. All bore holes, whenever possible, were drilled/cored with water for a lubricant. However, because the nature of the alluvium, bentonite mud and/or surface casing was used to prevent caving. After drilling, the holes were washed with water and developed with air. For piezometers completed in the alluvium, 0.10 meter i.d. casing was used in a 0.22 meter rotary borehole. Piezometers completed in bedrock utilized 0.04 meter i.d. casing for 0.13 meter boreholes. All piezometers were completed in a specific zone determined by the examination of the core and/or geophysical logs using slotted casing, clean gravel pack and a bentonite seal. Piezometers were completed in coal, alluvium and sedimentary units between the various coal seams.

Hydraulic Testing. To obtain quantitative values for the hydraulic character of the strata, a series of aquifer pump tests and laboratory permeability tests were performed. On each piezometer, one of two types of test were performed. One type of test is known as a response test or slug test. This method involved either the instantaneous removal or addition of water and measurement of recovery. The data was then analyzed using Hvorslev's (1951) method for the determination of hydraulic conductivity.

The second method used was airlift pump testing. The duration of the pump tests for each piezometer was quite variable and dependent on the amount of drawdown obtained. The most dependable results came from recovery test analysis.

Laboratory testing on samples of the sedimentary units between the coal seams also was performed. From these tests, dry densities, void ratios, porosity and rock permeability were determined.

Water Quality. Ground water extracted from the various piezometers was tested for pH, conductivity and temperature. To obtain the samples, the piezometers were air-lifted.

Water Level Sounding. To determine monthly water level variations, a routine program was initiated.

3.0 RESULTS

The procedures used to investigate the Boqueron Syncline Coal Reserve Area gave insight into the geohydrologic nature of the area. The results of this study are briefly described as follows:

Geohydrologic Mapping. In general, the coal reserve area occupies the axial portion of the Boqueron Syncline, which is modified by an east-west trending slip fault. The strata that contains the coal is part of the Tertiary Age Los Cuervos Formation, which is overlain by a veneer of Quaternary alluvium. Figure 1 is a surficial geologic map of the area.

As would be expected, the ground water of the area is profoundly affected by the lithology and structure of the bedrock and the topography of the area. Figure 3 is a generalized columnar section describing the lithology and hydraulic character of the shallow bedrock and alluvium. Figure 4 is a geologic cross section across the syncline.

Hydraulic Testing. The results indicate the hydraulic conductivities and transmissivities of the alluvium, coal seams and sedimentary strata between the coal seams are quite variable. Response test results from the alluvium yielded yielded a range between 2.9 x 10E-4 to 2.0 x 10E-6 cm/sec. In the sedimentary strata between the coal seams hydraulic conductivities ranged between 1.4 x 10E-4 to 7.8 x 10E-6 cm/sec. Air-lift pump tests on the coal seams yielded transmissivities, which ranged between 8.9 to 79.3 m squared/day; for the alluvium hydraulic conductivities, it ranged between 1.4 x 10E-2 and 7.3 x 10E-4 cm/sec. Laboratory analyses of sedimentary bedrock core showed a range of porosity between 0.2% and 3.2%. Bulk densities ranged between 2.17 and 2.75 g/cc with permeabilities on the order of 10E-7 cm/sec.

Water Quality Testing. Temperature was relatively consistent, ranging between 29.5 and 34.0 degrees C. The pH of water samples ranged between 6.98 to 8.62 with specific conductivity ranging 61 - 590 umhos/cm.

Water Level Soundings. Water levels will be discussed in detail in Section 4.0 of this paper.

4.0 DISCUSSION OF RESULTS

The data gathered thus far indicates that the ground water regime at the mine site can be divided into two hydrogeologic systems: the alluvium and the bedrock. Each system behaves differently, but they are connected via vertical leakage. The following discussion presents a conceptual method of these two systems and develops a mathematical model for predicting pit inflows and impacts of mining.

Conceptual Ground Water Flow Model. Overlying the bedrock of the Boqueron Syncline Reserve Area is a veneer of alluvium that averages 20 meters in thickness. In the northern part of the reserve area, the

AGE	THICKNESS (meters)	FORMATION	HYDROGEOLOGIC UNIT	DESCRIPTION
Quaternary	0-80	Alluvium	Alluvium	Light brown to grayish brown, very fine to coarse-grained quartzose sand in a fine grain silty matrix with some clean sand lenses, interbedded with gray to yellow clays, permeabilities are quite variable ranging from 2.0 x 10^{-6} cm/sec to 1.3 x 10^{-2} cm/sec.
Pleistocene	0-50	Terrace	Terrace	Sand with cobbles, unsaturated in vicinity of the Boqueron Syncline reserve area.
Pliocene – Miocene	60-650	Cuesta	Cuesta	Unconformably overlies the Los Cuervos formation. Consists of basal ridge conglomerates with well cemented sandstones and grey claystones. Low primary permeabilities.
Eocene	130-800	Los Cuervos	Interburden	Composed of tight, lenticular sandstones, shales, and mudstones, which have low primary and secondary permeabilities (7.10 x 10^{-5} cm/sec to 1.4 x 10^{-4} cm/sec). Although not highly fractured, the interburden does appear to create a continum of water between the various coal seams.
Paleocene			Aguila Seam	Ranges in thickness between 1.36 to 2.26 meters (4.5 to 7.4 feet). Visible pyrite crystals on cleat surfaces. Very clean indicating relative low permeability.
			Perico Seam	Interbedded with carbonaceous shale. Ranges in thickness from 0.91 to 2.88 meters (3.0 to 9.4 feet). Minor pyrite.
			Monito Seam	Generally clean. 0.30 to 0.91 meters thick (1.0 to 3.0 feet). Very thin and not considered an aquifer.
			Caballero Seam	The thickness of this unit ranges from 0.40 to 1.58 meters (1.3 to 5.2 feet). The seam thins to the south. The core samples indicate some secondary permeability
			Gran Madre Seam	Having an average thickness of 7.90 meters (25.9 feet). the Gran Madre seam is considered to be a major water bearing unit. Permeability ranges between 9.0 x 10^{-3} cm/sec and 9.7 x 10^{-5} cm/sec with the highest values near the subcrop. the coal, in general, is not highly fractured except near the axis of the syncline. the seam splits south of the Arroyo Pajuil.
			Doncella Seam	The seam average thickness, 1.28 meters (4.2 feet) some interbeds of shale. Not considered a major water bearing unit
			Cazador Seam	thickness ranges between 1.40 to 2.21 meters (4.6 to 7.2 feet) and on the average is 1.60 meters (5.2 feet). Like the Doncella, it is not considered a major water bearing unit.
			Babilla Seam	Uppermost seam in the Boqueron Syncline- average thickness .93 m (6.3 ft) no inseam partings. No piezometers were completed in this unit.
			Rouzaud Seam	Averaging 4.27 meters (14.0 feet) thick, the Rouzaud is an extremely clean coal. Geophysical logs and core sample indicate little fracturing and low primary and secondary permeability.
			Borrego Seam	Average thickness is 4.82 meters (15.8 feet). Consistantly the most fractured seam in the reserve area. Transmissivity range between 12.14 m^2/day and 58.44 m^2/day. The groundwater in the seam is also under artesian conditions, however, potentiometric map indicates a continum between this seam and the entire bedrock unit due to fracturing.
			Alanito Seam	Lowermost of the thin unmineable coals. The seam ranges in thickness from 0.24 to 1.19 meters (0.8 to 3.9 feet) and is not considered a major water bearing unit.
			Diablito Seam	Lowermost mineable seam in the area. The seam ranges in thickness from 0.70 to 1.22 meters (2.3 to 4.0 feet) in the northern portion of the syncline to 2.50 to 3.00 meters (8.2 to 9.8 feet) south of Arroyo Pajuil. No piezometers were completed in this unit, however, the degree of the fracturing indicated a moderately high permeability.
	180-300	Barco	Barco	Highly resistant, fine to coarse grained cemented sandstone, low primary permeability.

FIGURE 3
GENERALIZED COLUMNAR SECTION OF THE BOQUERON SYNCLINE AREA WITH HYDRAULIC CHARACTERISTICS LA LOMA COAL LICENSES CESAR DEPARTMENT, COLOMBIA

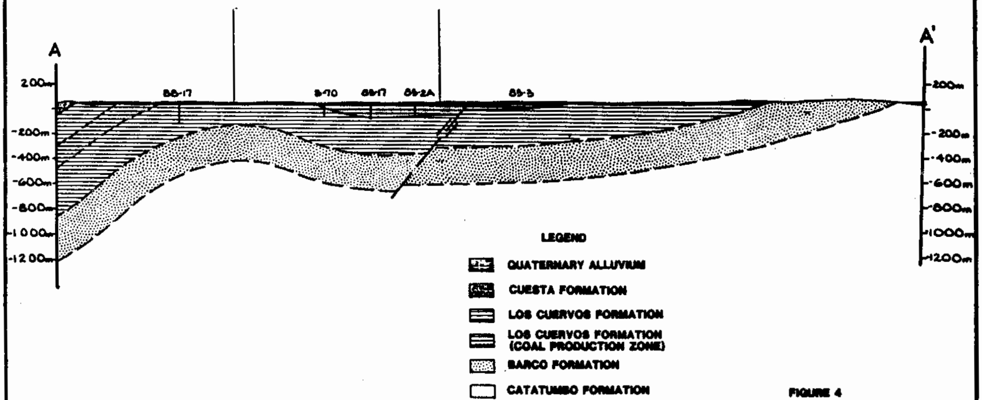

FIGURE 4

GENERALIZED GEOLOGIC CROSS SECTION PROFILE A-A'
LA LOMA COAL LICENSES
CESAR DEPARTMENT, COLOMBIA

alluvium thins toward the drainages. Farther south, along the Caño Rosario, there is thickening of the alluvium reflected by the axis of the Boqueron Syncline. The alluvium is composed of fine to coarse sand that ranges from clean to a mixture with silt and clay. Within the alluvium, there are lenses of clay that limit infiltration. In areas where the surficial soil has a high clay content, ponding occurs after precipitation. The alluvial ground water system is for the most part under water table conditions, although discontinuous clay lenses may confine the ground water in some areas. The alluvium water table map (Figure 5) shows the ground water is controlled by the topography with recharge occurring along topographic highs and discharge along drainages. The hydraulic gradient ranges from 0.005 m/m to 0.007 m/m and is quite variable. Aquifer tests performed substantiated this variability of the flow system.

Hydraulic conductivities for the alluvium vary from 2.0 x 10E-6 cm/sec to 1.4 x 10E-2 cm/sec. Low values were associated with the lenticular clay and silt lenses; whereas, the higher values were related to paleochannels of clean fluvial sands that have finite limits in the alluvium. The ground water quality of the alluvial ground water also was variable with specific conductivity ranging from 61 umhos/cm to 1300 umhos/cm and pH ranging from 7.07 to 7.91. Temperatures ranged from 29.5 to 33.5 C.

The bedrock ground water system is more complex than the alluvial system. It can be divided into two components; the coal, and the sandstone/shale interburden which separates the various coal units. Each of these has different hydraulic properties. However, a continuum exists because of fracturing, which creates one ground water flow component.

The various coal seams are the principal water bearing bedrock units. Of the twelve seams encountered in exploration activities, two seams were chosen for geohydrologic investigation; the Gran Madre, which is the thickest seam (averaging 7.9 m), and the Borrego, which was the most continuous. Both seams show a decrease in hydraulic conductivity down dip. Hydraulic conductivities for the Gran Madre ranged from 1.3 x 10E-2 cm/sec near the subcrop to 9.7 x 10E-5 down dip. The Borrego seam which is somewhat more fractured, ranges in hydraulic conductivity from 1.4 x 10E-3 cm/sec near the subcrop to 3.5 x 10E-3 cm/sec down dip. The siltstones and shales, although saturated, have lower hydraulic conductivities (on the order 10E-6 cm/sec) and act as aquitards.

The potentiometric surface map (Figure 6) of the bedrock ground water system shows a consistent flow pattern. The bedrock ground water levels are controlled by the structure of the Boqueron Syncline. This consistency indicates a continuum exists between the coal seams and sedimentary interbeds. It is uncertain what role the east-west trending fault plays on the ground water system. However, it is believed that bedrock ground water flow is confined to the limits of the syncline.

Bedrock ground water quality indicates that the water quality for both coal seams is very similar to that of the alluvium indicating recharge along the subcrops. Higher specific conductivities in the

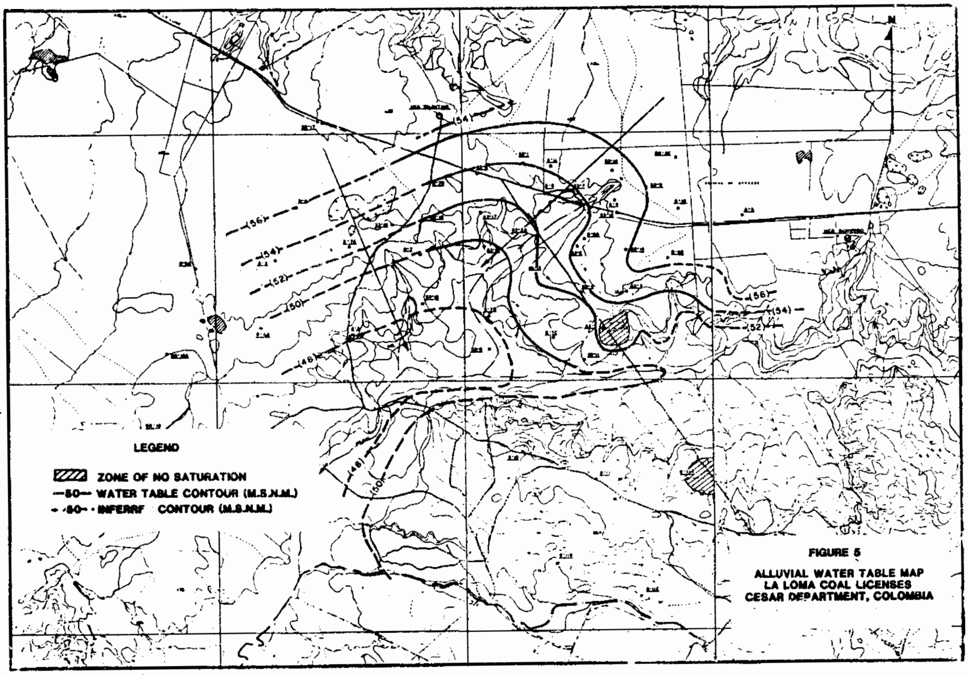

FIGURE 5

ALLUVIAL WATER TABLE MAP
LA LOMA COAL LICENSES
CESAR DEPARTMENT, COLOMBIA

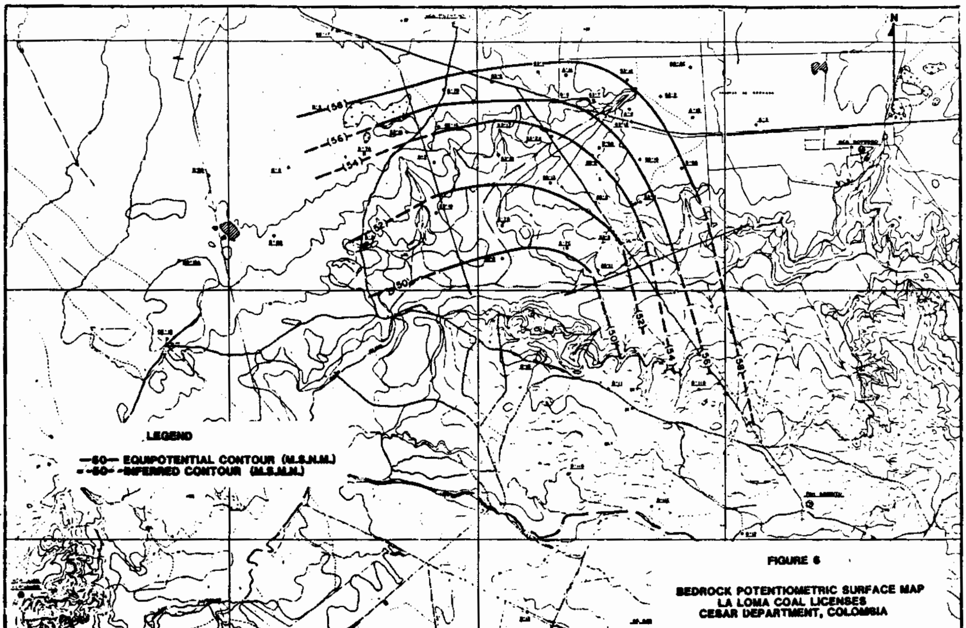

FIGURE 6

BEDROCK POTENTIOMETRIC SURFACE MAP
LA LOMA COAL LICENSES
CESAR DEPARTMENT, COLOMBIA

sedimentary interbeds indicate a slower moving ground water system.

Mathematical Ground Water Model. To calculate the inflow into the proposed open coal mine in the Boqueron Syncline area, two different modeling approaches were taken. One approach, a finite difference model, was used to simulate the flow from the alluvial aquifer. Another approach, an analytical model, was used to depict flow from the bedrock aquifer.

The Prickett-Lonquist finite difference method was used to simulate the impact of the mine on the alluvial aquifer. The San Antonio River is a constant head boundary to the south; to the north and west, the bedrock outcrops and subsequent thinning of the alluvium are no flow boundaries; and no boundaries were specified to the east. The model was written in the Basic programming language and implemented on a TRS-80 Model III micro computer. A 15 (east-west) x 16 (north-south) grid was set up with a 500 meter grid spacing in the vicinity of the mine and 2000 meter spacing at the edges.

The model was run on the impact mode. An impact mode model uses the theory for superposition to simplify the modeling process. Rather than using the initial position of the potentiometric surface and the actual elevations of the mine pit and the boundaries as the starting point for the simulations, the initial potentiometric surface is assumed to be the datum and all other elevations (bottoms of the aquifer and pit) are input to the model in terms of their relation to the initial potentiometric surface. The theory of superposition implies that the results of the impact mode model are equivalent to the results of the model using actual elevations.

The alluvial aquifer was assumed to be unconfined. Input to the model consisted of the saturated thickness of the alluvium in each grid node and the aquifer characteristics. Saturated thickness of the aquifer ranged between 0 and 25 m with a geometric mean hydraulic conductivity of 0.75 m/day. No specific yield were available so a conservative value of 0.1 was used.

The results of the finite difference model run on six month time steps indicated that peak inflow for design was on the order of 10 l/sec and occurs at the commencement of the second five-year mining period. Drawdowns caused by the mine pit are less than a meter within 2000 meters of the pit.

Due to the uncertainties regarding the ground water flow in the bedrock aquifer, an analytical model was used to simulate pit inflow. The primary water bearing units in the bedrock are the coal seams, although the shale and sandstone interbeds do transmit water. A three dimensional model would more accurately simulate the flow through this stratigraphy, however, due to the preliminary nature of this study and lack of data, this was not done. A preliminary estimate of pit inflow was made by assuming a composite transmissivity for an average cross section of the bedrock and using analytical equations to predict the inflow into the mine. The analytical model used was a two dimensional successive steady state model which utilizes an equation describing the steady state flow to a finite line sink.

The equation for steady state flow to a finite line sink predicts inflow to the sink (or mine pit) given the drawdown, aquifer characteristic, length of sink, and radius of influence. The finite line sink is assumed to represent a wall of the mine pit. Nonsteady inflow is approximated using s, a semi-empirical expression for the radius of influence. The radius of influence is a function of time and aquifer characteristics. Varying mine pit configurations are simulated using superposition. Multiple finite line sinks are used to represent the mine pit. Image finite line sinks are used to represent no flow boundaries. The model is based on work done by Muskat (1937) and software is available from Koch and Associates, Denver, Colorado.

The hydraulic conductivity of the bedrock was determined by averaging the hydraulic conductivity of the coals and interbeds, computing a composite transmissivity for some typical cross section, then computing a theoretical hydraulic conductivity based on the model aquifer thickness (150 m). Based on the aquifer tests of the Gran Madre and Borrego coal seams, a geometric mean hydraulic conductivity of the interbed was 0.062 m/day. Composite transmissivities were determined for a variety of well sites yielding an arithmetic average of 46.7 m sq/day. The average thickness of the aquifer was about 100 meters, therefore, the hydraulic conductivity in the model was 0.50 m/day. A storage coefficient was assumed to be 0.05 for conservative results.

The pit was represented in the model by a series of constant head finite line sinks for the five years of mining. The length of each constant head finite line sink represented the width of the working face at each year. The elevation represented the elevation of the bottom of the pit. The pits were assumed to be excavated north to south progressing downdip.

Pit inflow increases during each five year mining phase as the pit is deepened and enlarged. The peak inflow occurs at the end of the ten-year period and is equal to 337 l/sec. The impact of the pit on the potentiometric surface will be limited to 4000 meters of the pit.

5.0 MINE INFLOW MANAGEMENT

Based on the results from the field study and modeling effort, a preliminary internal mine drainage plan was developed. The plan was designed to be flexible and cost effective. Ground water into the pit is to be eliminated by a series of pumps located in sumps. Precipitation accumulation in the pit will be stored on benches to the extent possible, evaporated and/or pumped out of the pit.

The following discussion outlines the ground water and drainage handling procedures for the life of the mine which can be divided into three stages. Stage one includes the initial pit opening and the first five years of mining. Stage two represented the second five years and stage three is the mining beyond year ten.

Stage I, Dewatering. In this phase of the operation, the dewatering program will be extremely flexible. Initially, an excavation will be made down to bedrock, thus creating a sump. The sump will be dewatered using a small diesel driven, barge mounted recessed impeller pump capable of pumping 63 l/sec at 15 meters of head. This will dewater the alluvium sufficiently enough to begin the stripping operation. Before opening the pit into the bedrock, a ditch along the base of the alluvium will be dug capable of handling 9.8 l/sec of ground water discharge and the runoff from a 25 year, 6 hour precipitation event. The ditch will transport the water to a sump, which will be equipped with a pump capable of pumping 13 l/sec at 18 meters of head. Areas will be provided for storage of precipitation with auxilliary pump(s) available for additional pumpage.

As the pit progresses down dip, a series of benches will be constructed. Each bench will be sloped so that ground water and rainfall runoff will be directed toward storage areas. The water levels in these storage areas will be controlled by evaporation, downdrains equipped with check values and/or portable pumps.

Dewatering of the pit will take place in a series of fifteen meter lifts using recessed impeller pumps mounted on skids, wheels or barges. It is anticipated that by the end of year five, a series of nine pumps discharging at 63 l/sec will be required to pump ground water from the pit. An additional six pumps will be used for handling runoff from storm events.

Stage II, Dewatering. At the end of year five, electrical pump(s) capable of 340 l/sec at 60 meters of total dynamic head will be mounted on a barge at the bottom of the pit in a sump. The pumps installed in Stage I will be removed from the benches and drainage will be regulated by check valves and downdrains toward the main sump. If necessary, the smaller pumps will be employed for dewatering after storm events. The discharges from the main sump will be routed toward the peripheral ditch.

As mining progresses, the drainage from the benches will be directed toward water storage areas, where the water will be evaporated or directed via downdrains toward the bottom of the fifth-year pit. If a large storm occurs, the portable pumps will be moved to the active bench(es) and the runoff will be pumped to higher benches as quickly as possible.

Stage II, year eight, angle depressurization wells will be employed. These wells will be drilled at 45 degree angles from the lowest active bench to at least twenty five meters below the next bench to be mined. The spacing of these wells has not been determined at this time.

Stage III, Dewatering. At the end of year ten, the large sump pump will be moved from the year five position to the lowest point in the year ten pit. As mining progresses down dip, additional pumps will be added as necessary.

6.0 CONCLUSIONS

This study was completed with relatively few piezometers and limited aquifer test data. Due to the isolated nature of the site, numerous problems with drilling rig breakdown, shortage of supplies and equipment, and inclement weather conditions were encountered while conducting the field investigation. Additional work will be required prior to final design; however the following conclusions were reached from the preliminary investigation.

With proper water management procedures, ground water and precipitation entering the pit could be handled economically.

The ground water in the vicinity of the Boqueron Syncline Reserve Area can be divided into two basic aquifers: the alluvium and the bedrock. The alluvium consists of fine to coarse grained sand, silt and clay. The water levels and flow of the alluvial ground water are controlled by the topography of the site. The bedrock aquifer, which is under artesian pressure, is composed of coal seams and shales, mudstones, and sandstones. The coal seams are the most permeable, however, fractures in the other strata contain water.

Predictive models indicate, by using conservative assumptions, that at the end of year ten approximately 350 l/sec of ground water will be entering the pit from the bedrock aquifer and 9.8 l/sec of ground water will be entering the pit from the alluvium.

Ground water control in the first five years of mining will be controlled by relatively small, portable diesel powered pumps in series. In the second ten years, when electric power becomes available, two 500 horsepower turbine pumps will be employed in sumps at the bottom of the pit. The smaller pumps will be used for spot dewatering.

Due to the nature of the climate, precipitation could cause problems in the mining operation. For control of runoff, large storage areas on the benched were designed. Downdrains and gate valves for gravity feed to the lower pump sumps will be provided. The small diesel pumps also will be used on the active bench to provide a dry working surface.

For depressurization, angle holes will be drilled on each bench as the mine progresses down dip and allowed to drain.

References

Hvorslev, M.J., 1951, "Time Lag and Soil Permeability in Groundwater Observations", U.S. Army Corps of Engineers Waterways Experiment Station, Bulletin 36.

Muskat, M., 1937. Flow of Homogeneous Fluids through Porous Media, McGraw-Hill Publ.