

Mathematical Modelling of the Konkola Mine Dewatering

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ABSTRACT

Mathematical modelling of ground water flows in the general vicinity of the Konkola Mine was undertaken to simulate the response of complex water-bearing formations at the mine site to drainage and dewatering stresses. Six calibration procedures were devised and tested before a satisfactory selection was made and implemented for hydrologic conditions from 1964 to 1988. The calibrated model was used to simulate the complex three-dimensional character of flows at the site. Predictions of dewatering operations were made with the model for the period from 1989 to 2020, using estimated dewatering rates, locations and schedules.

This paper briefly discusses the adaptation, calibration, and application of the mathematical model MODFLOW, to the complex geologic and hydrogeologic conditions at the Konkola Mine, along with the predicted results. A companion paper entitled "Konkola Mine DeWatering Study" by the same authors presents relevant geologic, hydrologic and mining activity information.

INTRODUCTION

The purpose of this paper is to present the adaptation and application of a mathematical model to obtain hydrological predictions for the Konkola Mine. The model chosen was MODFLOW, developed by the United States Geological Survey (Macdonald & Harbaugh⁽¹⁾). This model has been substantially enhanced and successfully applied by Principia Mathematica Inc. to several major projects.

The technical approach to modelling, its framework, the procedures devised to calibrate the model to the complex site conditions, the sequence of obtaining predicted results as well as the conclusions drawn from them, all form the subject of this paper. Hydrologic modelling of water flows in the general vicinity of the Konkola Mine was intended to simulate the response of the complex water-bearing formations, or aquifers, at the mine site to drainage

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and dewatering stresses. The objectives of model applications in simulating the responses of water-bearing formations may be summarized as follows.

- (1) To *adapt* MODFLOW to the specific three-dimensional hydrologic conditions known to occur in and around the vicinity of the Konkola Mine.
- (2) To *calibrate* the model to hydrologic conditions representing historical operations of mine dewatering practices starting from the pre-mining situation and ending in 1988. The purpose of model calibration was to achieve, as far as is possible, reliable predictions of known, i.e. based upon historical measurements, hydrologic behavior.
- (3) To *apply* the calibrated model to predict changes in water levels, i.e. water pressures expressed as potentiometric heads, in and around the mine which are caused by projected dewatering rates. The purpose of such applications was to devise a rational design for a dewatering system, involving drainage borehole locations, discharge rates of pumps and schedules of dewatering, which will enable water levels to decline within mine areas at rates which permit safe mining operations.

MATHEMATICAL MODEL SELECTION

The selection of a mathematical model as the most suitable means of predicting the consequences of drainage to dewater the Konkola Mine vicinity was made for a number of reasons. Foremost amongst these are: the three-dimensional, and strongly transient, character of subsurface water flows, and corresponding water pressures, in the vicinity of the mine; the presence of surface features, such as streams, swamp areas, etc. which may serve to recharge the subsurface formations in the vicinity of the mine, which in turn might influence the rate of drawdowns; the complex nature of local stratigraphy, the anticlinal structure, the position of the orebody, the mining method adopted as well as changes to it with time and alternatives desired to be investigated; the substantial spatial variability of material properties within water bearing formations as well as within formations that act as their immediate neighbors; the possibility that fracture systems located in certain areas, which possess substantially different hydrologic properties from those of native formations, might exert considerable influences upon the rates and directions of ground water flows; and, the need for a public-domain model that was readily available for close scrutiny by review bodies.

TECHNICAL APPROACH TO MODELLING

The technical approach to hydrologic modelling at the Konkola Mine has consisted of fulfilling eight important tasks as described below.

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The first task was to assemble site specific data concerning: geologic horizons as functions of vertical position; stratigraphic descriptions of water bearing formations; parameter values and ranges for hydrogeologic variables; measurements of potentiometric heads at different locations within the mine and as a function of time; pre-mining hydrologic conditions in as much spatial detail as is possible; historic mine dewatering operations and mine water inflow rates; and, future projections in mine dewatering plans. The lack of data in sufficient amounts concerning pre-mining conditions and early operations of the mine has limited the success with which the model could be calibrated to early operating periods.

Second, selection of a suitable framework for representing site conditions, both those involved in historic dewatering operations and future projections was made. A model domain and a framework of five successive layers were selected. These layers, selected to be truly horizontal, included geologic components from each major formation known to occur within the site. They also included zones of known surface recharge, fracture zones, higher permeability zones in the vicinity of anticlines, composite zones of water bearing formations, etc. The orientation of the model domain, its vertical extent and boundaries were selected such that they represented known conditions as completely as possible.

Third, selection of a numerical grid cell system suitable for predicting flow rates and dewatering scenarios in the vicinity of the mine and to suit the general character of the site was made. The vertical extent of the five layers were selected to accommodate the known mining sequences adopted during the period from 1955 to 1988. The numerical grid cell system consists of variably-spaced rectangular cells; fifty cells were chosen in the north-south direction and thirty-four in the east-west direction. The widths of these cells ranged from a minimum of 200m to a maximum of 800m. Very few of the cells were sized at this maximum. Most of the cells within the mine area were square in shape with 200m sides. While these cell sizes have provided results that are reliable and match historical measurements reasonably well, the known steep gradients in potentiometric heads in the immediate vicinity of the mine can be better represented with finer grid cells involving spacings perhaps in the 10m to 25m range.

Fourth, the well data package of MODFLOW was employed for simulations of dewatering operations during both the calibration and application stages of the study. Thus, pumping discharge rates were assigned to grid cells in a distributed way which reflect the observed responses of aquifers to drainage boreholes.

Fifth, reviews and selections of time spans for model simulations were made based upon assembly of historical data concerning dewatering rates and water level declines. Time span selections were made to accommodate changes to drainage locations, rates and durations which are known to have occurred. In a general sense, the time span simulated in each computer run was chosen to be approximately five years. The results of each such run was then used as starting conditions for the subsequent run covering the next five-year span. The duration of a stress period, defined as a time period during which dewatering rates were held

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constant, was selected to be one year for each run. Each stress period was traversed by twelve uniformly sized time steps, representing approximately one month duration each.

Sixth, data for purposes of model calibration were selected. Two categories of such data were involved: in the first, hydrologic property values lying within suitable ranges were selected for each material type along with dewatering data for each layer in the three-dimensional framework; in the second, measured values of potentiometric head were carefully selected as the basis for evaluating the success of model calibrations.

Seventh, model calibrations were undertaken for the span of time representing historical dewatering operations undertaken at the mine. Due to the inherent complexities involved, five separate procedures for calibrating MODFLOW to the Konkola Mine were devised, tested and discarded before the sixth was successfully used to calibrate the model to the entire period from 1955 to 1988. Only limited success had been attained with each of the five discarded procedures.

Eighth and last, a scenario was selected to represent the dewatering locations, rates and schedules which would provide desired rates of reduction in water levels which were presumed to be suitable for mining operations planned for the time period from 1989 to the year 2020. The calibrated model was applied to this scenario and predictions for this period were obtained. The six runs of the model to achieve just this aim were undertaken in approximately five-year spans of time per computer run.

MODELLING ASSUMPTIONS

The implementation of the technical approach as summarized above was based upon a set of assumptions which were made to overcome deficiencies in the detailed knowledge about spatial and temporal variations in regional hydrology at the site. The important ones among these assumptions are presented below.

That the geologic units, and especially their stratigraphic representation in the model, are hydrologically connected to each other. This implies that perched water tables, even if they occurred in the early stages of dewatering operations, do not influence sub-surface water flow patterns in any significant way. The Konkola site is indeed traversed by three important water-bearing formations which are generally, and loosely, referred to as the three "aquifers": Hangingwall Aquifer (HWA), Footwall Aquifer (FWA); and, Footwall Quartzite Aquifer (FQA). The water pressures within these three aquifers has indeed been recorded, during stages of mining activity at appropriate elevations, at different levels. However, the geologic units separating the three aquifers, possessed generally of much lower permeability values, play a quantitatively minor but hydrologically an important role. These units are not normally water-bearing in any substantial sense, but water pressures must obey a pressure-continuity

principle within these units. Hence, some connection is made between such aquifers through the relatively impermeable intervening unit which acts as a conduit for flows. The conduits might be fracture systems, both those which exist naturally as well as those which might be induced by mining activities. Consequently, although the intervening units might be loosely described as being "dry" to begin with, they can indeed serve as pathways for subsurface flows. It is these pathways which have been represented in the model through a numerical grid system which accommodates several different material types including those which form the intervening units. What is very important to note is that these units are characterized by very low values of both permeability and storage coefficient; thus, they are **not** themselves water-bearing. Furthermore, the connections between adjacent aquifers through certain segments of these units, in the model, is thus simply a representation of the fracture zones which serve as conduits.

That potentiometric heads in each of the five layers are, at the start of dewatering operations, located at one identical equilibrium surface whose spatial variations are represented in the model.

That fractured zones within specific geologic units may be represented by an equivalent porous media approach. This implies that locally enhanced values of hydraulic conductivity and storage coefficient are sufficient to represent these zones and that conduits of substantial open cross-sectional sizes are generally absent.

That boundary conditions on model boundaries for the four layers which lie beneath the top may be supplied as identical to those adopted for Layer 1. This implies that patterns of recharge and discharge through boundaries of the model domain are unaltered with vertical depth.

That vertical recharge rates, obtained by estimating the influences of recharge zones such as surface streams, may be applied as fluxes to each grid cell of Layer 1. Such fluxes moreover are constant in time but spatially quite variable in order to account for the distribution of material types.

CALIBRATION OF THE MODEL

The complexity of site features required six separate procedures for model calibration to be devised by Principia for the study. Each of the first five were tested and discarded before the sixth was adopted as the most suitable one.

This procedure selected for model calibration makes use of a multi-layer approach, but restricts the *number* of such layers during each simulation time span to only those within which simulated dewatering operations are current. Thus, during the first time span which ended 4th International Mineral Water Association Congress, Ljubljana (Slovenia)-Pörtschach (Austria), September 1991

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in the year 1974 only Layer 1 was simulated. During the second time span which ended in 1981, Layers 1 and 2 were simulated; likewise, the third time span which ended in 1988, Layers 1, 2 and 3 were represented. Future projections beyond the year 1989 did not form part of the calibration procedure. The important features of the satisfactory calibration procedure may be summarized as follows.

- (1) The selected model domain size, shape and the grid system are illustrated in Figure 1. This figure also illustrates several important site features, such as the 3150 foot level development and the three shafts, in relation to the grid system.
- (2) The model layers themselves correspond to the mining levels as follows:
 - Layer 1 - 0 to 660 metres (0 to 2200 feet);
 - Layer 2 - 660 to 875 metres (2200 to 2900 feet);
 - Layer 3 - 875 to 950 metres (2900 to 3150 feet);
 - Layer 4 - 950 to 1180 metres (3150 to 3900 feet);
 - Layer 5 - 1180 to 1405 metres (3900 to 4650 feet).

Apart from Layer 1, each of the others were treated as initially confined but becoming locally unconfined as a result of dewatering operations. Within each layer, a large number of material property zones were defined and modelled.

- (3) Distinctly different hydrologic property values were assigned, within each layer, for each such property zone, comprising several grid-cell clusters. A set of eighty-seven computer runs were made with the calibration procedure in order to derive the different hydrologic property values. It is important to recognize that these values, and indeed the locations of the corresponding property zones themselves, were derived by successive applications of the calibration procedure. It is also worth noting the progressive decreases in the property values with depth; a feature that was anticipated and clearly demonstrated through calibration.
- (4) The satisfactoriness of model calibration was assessed by comparisons of predicted reductions in potentiometric heads, at different locations and different instants of time, caused by the estimated dewatering rates. These estimates are illustrated in Figure 2, which depict discharge rates in cubic metres per day for each year during the period from 1964 to 2020. When the distribution of potentiometric heads, at any instant of time as well as its local value, compared favorably with measured values, the calibration run was deemed to be successful.
- (5) Calibration success was quantitatively assessed for point measurements when the difference between calculated and observed values was in the range of $\pm 20\text{m}$. While this range might appear to be large, it was dictated simply by the shape of the dewatered zone and the steep gradients in potentiometric heads at its outer edges.

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The size of the smallest grid cells adopted was 200m by 200m. It is thus easy to see that with grid cells of this size, it would be very difficult to achieve a closer match without adopting implausible distributions of hydrologic properties especially for those grid cells that were affected by dewatering stresses.

- (6) Results predicted upon completion of model calibration may be observed in the first four frames of Figure 3 which represent contour-fill plots at different instants of time. Each of these plots represents potentiometric heads in the Hangingwall Aquifer. The first frame illustrates the predicted potentiometric head distribution in Layer 1 at the end of the year 1964; the second illustrates heads in Layer 1 at the end of 1974. The third frame depicts heads in Layer 2, where the dominant fraction of dewatering occurs at the end of 1981. Likewise, the fourth frame illustrates heads in Layer 3 at the end of 1988 which represents the end of the calibration period.

The calibrated model was then readied for applications during which no further adjustments to model parameters were permitted. It should be noted that parameter values for Layers 4 and 5 could not be calibrated with respect to historical data because none were available. Hence, these values show decreases with depth similar to those which were required to calibrate the hydrologic behavior of Layers 1 to 3.

APPLICATIONS OF THE CALIBRATED MODEL

Projections of dewatering operations, predicted with the model calibrated from 1964 to 1988, were then made for the total time period between the years 1989 and 2020. This period was divided into two simulation time spans. The first of these, involving operations of Layers 1, 2 and 3, began in 1989 and ended in 1998. The second span, involving operations of Layers 3, 4 and 5, continued to the end of the year 2020. The pattern of discharge is illustrative of operations which begin with increasing discharge from a layer within which dewatering activity just begins, followed by progressive decreases during the subsequent mining from that layer.

The procedure for model applications may be summarized in the following four steps: the results previously predicted for the year 1988 were used as starting conditions for Layers 3, 4 and 5; then, material property flags were assigned to Layers 4 and 5 essentially similar to those derived, through the use of the calibration procedure, for Layer 3 and small adjustments were made to hydrologic property values assigned to each of these flag types to reflect decreases of permeability and storage capacity with depth; revised dewatering rates, estimated for a number of grid cells lying within each of these layers, were used once again to prepare the so-called well package data file for MODFLOW; predictions of the calibrated model to the revised well pumping scenario were then made in several MODFLOW runs, first for the period from 1989 to 1995, thence to 2000 and thereafter to the years 2010 and 2020. The

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predicted potentiometric heads for each of these years are presented as the last four frames of Figure 3.

In order to provide assistance in interpreting predicted results, additional figures are included below. Figure 1 has presented plan view representations of the model domain which identify the locations of two geologic cross-sections, as well as the 950m level drainage drift, at which predicted results have been extracted for separate illustrations. Figures 4 and 5 present geological cross-sections along with corresponding predicted (HWA) potentiometric head distributions for selected years during the span of time that was simulated. Figure 6 illustrates the progressive changes to predicted HWA potentiometric head levels along the main drainage drift.

CONCLUSIONS

Based upon the experiences of model calibrations and applications to the Konkola mine site, a set of conclusions have been drawn and are presented below.

- (1) The model itself and the framework of its application to the Konkola Mine have been correctly chosen. However the domain size may require adjustments to reflect future plans. Specifically, areas in the vicinity of Shaft-3 that were included in the model domain have proved to be somewhat unnecessary to simulate historical dewatering operations. Likewise, to the east of the present model domain, additional areas could be added with benefit. The selected model domain size coupled with the sizes and shapes of grid cells employed has led to computational inefficiencies in certain zones and, unfortunately in some cases, numerical inaccuracies.
- (2) Results predicted through future model applications will benefit, as a result of greater computational accuracy, from a minor revision to the model framework. A revised domain size encompassing reductions to the north and increases to the east could be profitably chosen. Furthermore, grid cells sizes within the mine area could be reduced to values in the range of 10m to 25m. The revised model domain moreover could be oriented such that one coordinate axis could be aligned with the approximate axis of the drainage drift at the 950m (3150 ft) level. The result would be more precise predictions of the potentiometric head distribution at locations where steep gradients have been currently predicted to occur. Smoother temporal variations in declines of such heads will then be predicted. As a consequence, the locations, spacings and expected discharge rates of desired drainage boreholes can be predicted with much greater precision than was achieved with the current model framework.

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- (3) The multi-layer representation with five layers has proved to be satisfactory. The vertical thickness of Layers 3, 4 and 5 could however be revised such that rather than simply reflect proposed mining operations, they could represent the hydrodynamic patterns of dewatering in a more physically appropriate fashion.
- (4) The values of hydrologic properties, for each property zone within each of the five layers represented in the model, which have been derived through extensive applications of the calibration procedure are both realistic and plausible. It will be a very valuable addition to the present understanding of the site to corroborate some of these property values with careful designed measurements made at chosen locations in the vicinity of the mine.
- (5) The general pattern of subsurface flows in and around the Konkola Mine have been correctly predicted by the model. Hence, the predicted results may be satisfactorily used to implement future dewatering plans.
- (6) The predictions undertaken to simulate dewatering operations between the years 1964 and 2020 have demonstrated that most of the water entering the mine system has come out of storage within the mass of water-bearing formations represented in the model domain. Recharge from the boundaries of this domain as well from the ground surface are, relatively speaking, very minor contributors.

ACKNOWLEDGEMENT

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Chapter A1, Book-6, Modelling Techniques, United States Geological Survey.

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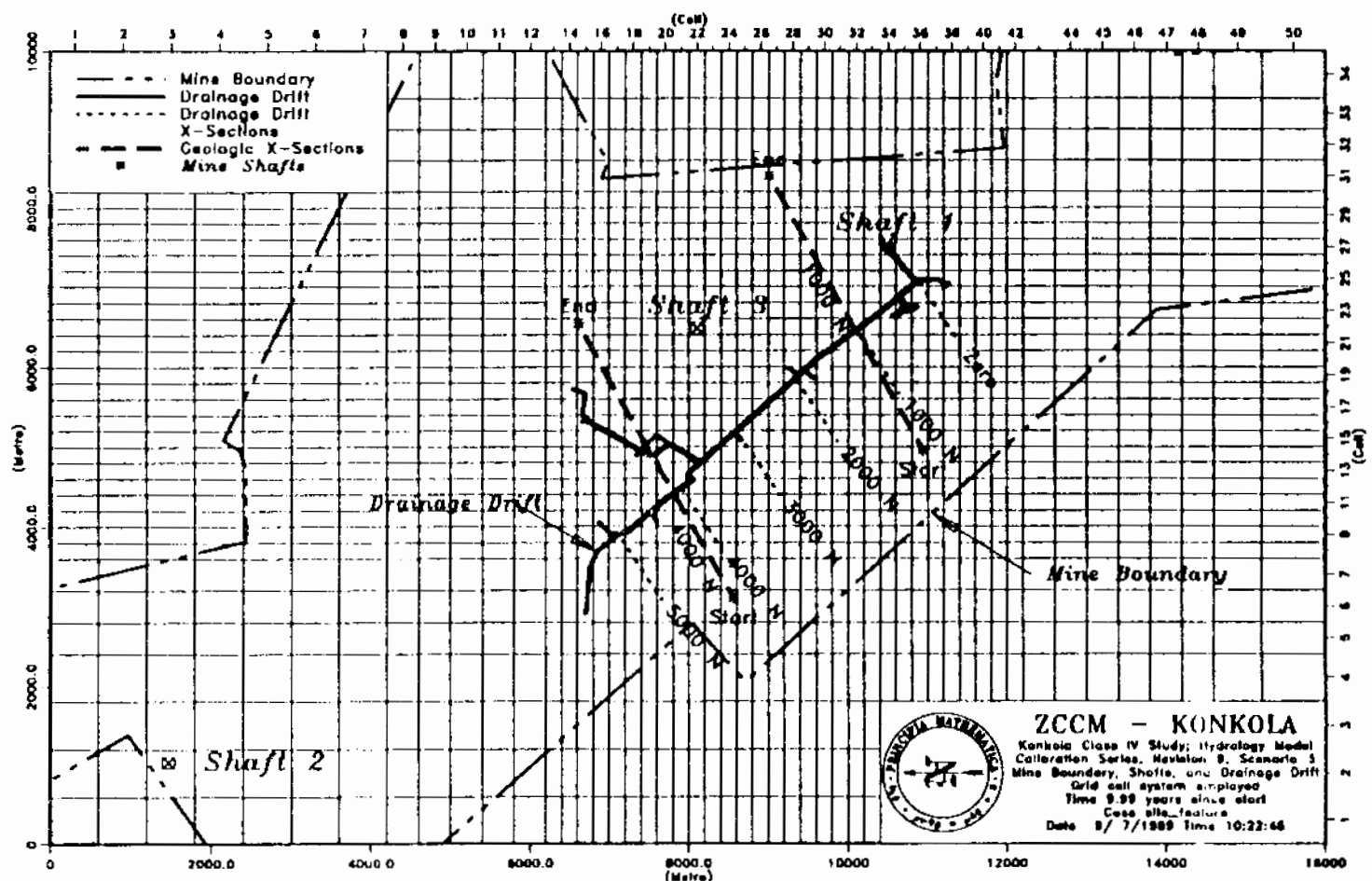


Figure 1. Mine Boundary, Drainage Drift, Geologic Cross-Sections, and Drainage Drift Cross-Sections



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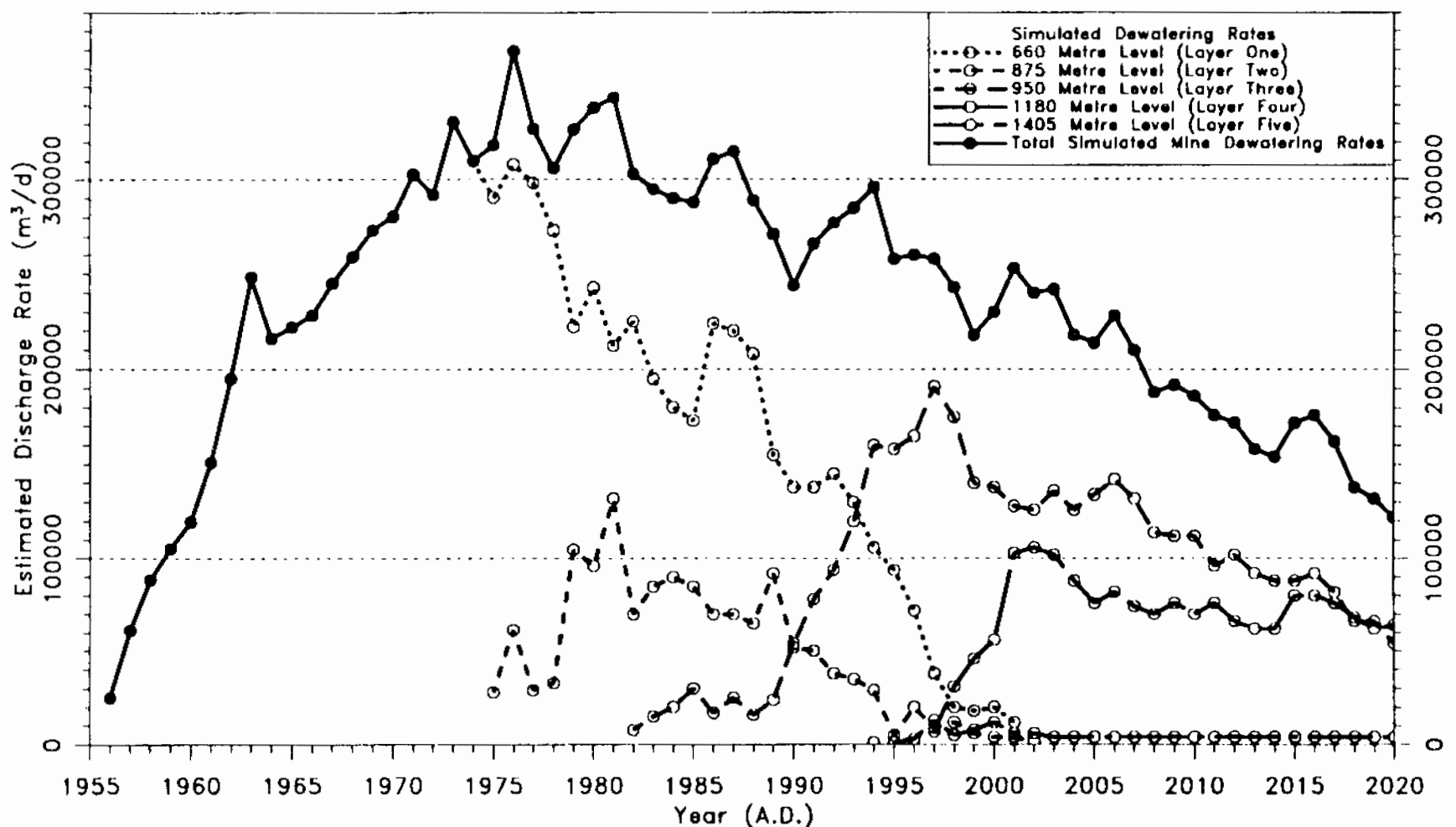
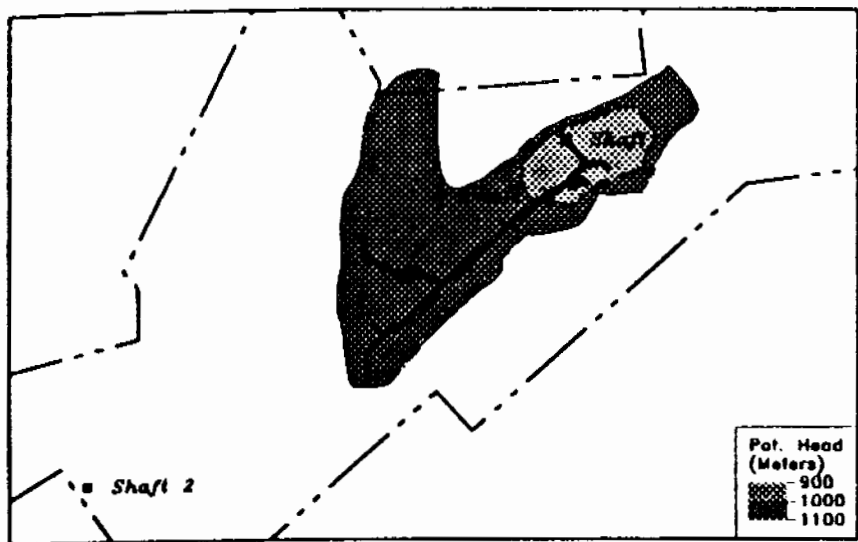


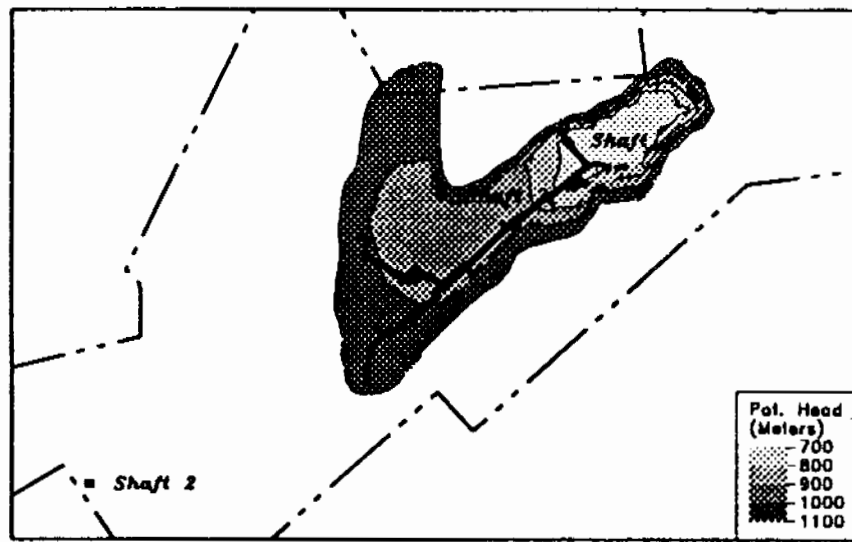
Figure 2. Model Simulated Mine Dewatering Rates (Layers 1-5) and Total



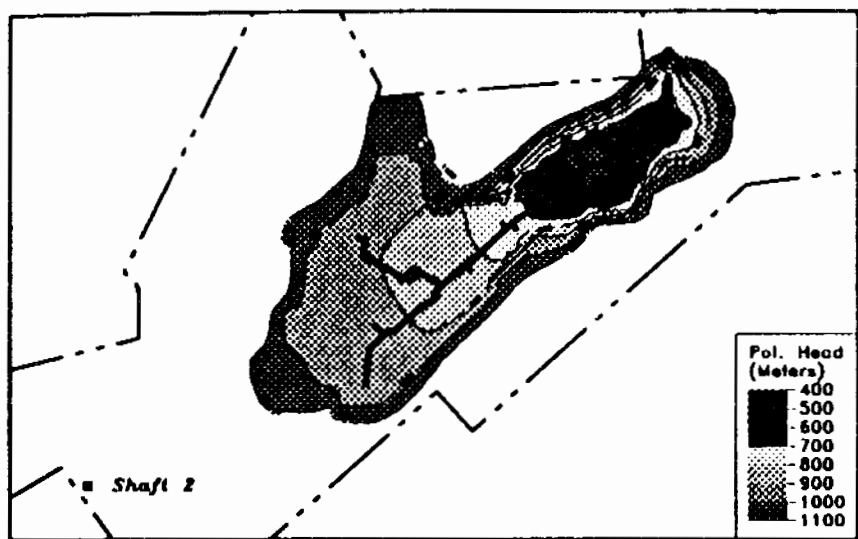
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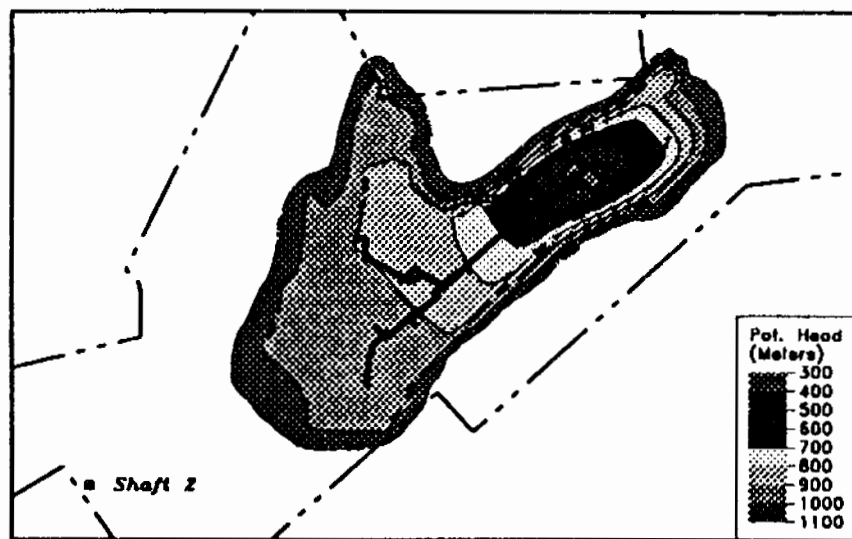
1964 Predicted Potentiometric Heads



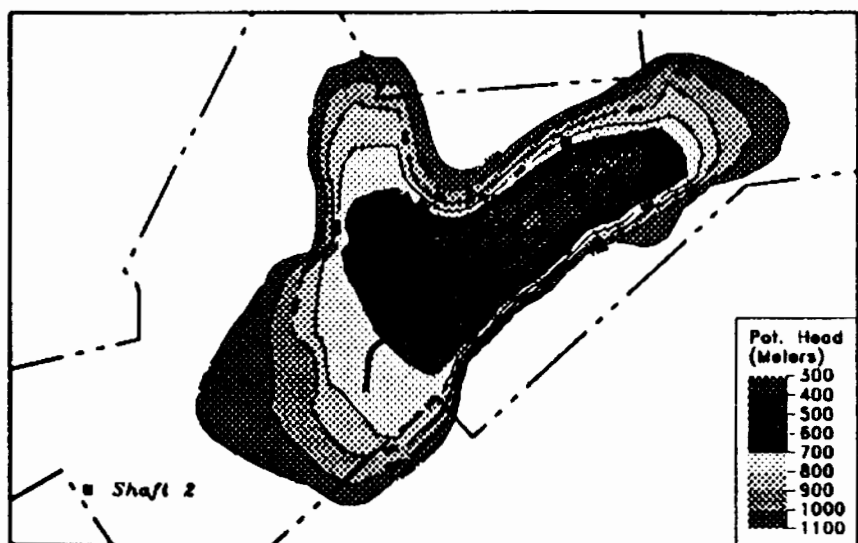
1974 Predicted Potentiometric Heads



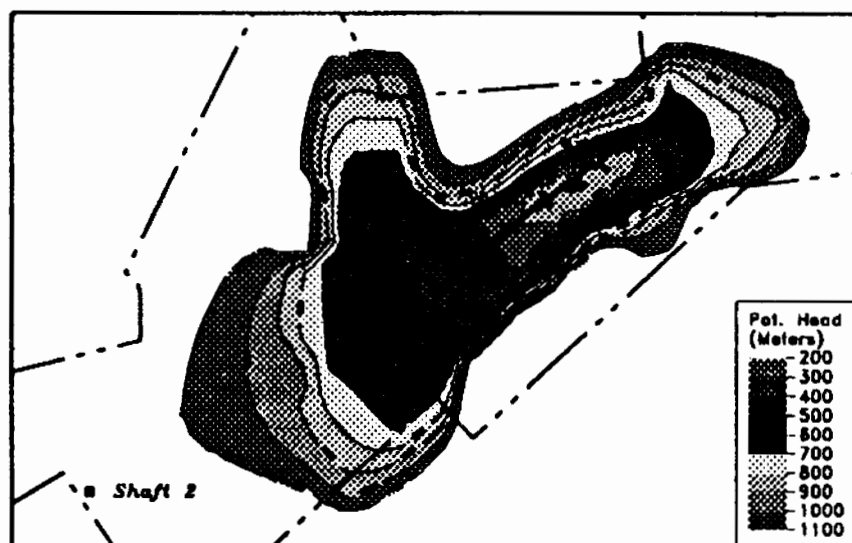
1981 Predicted Potentiometric Heads



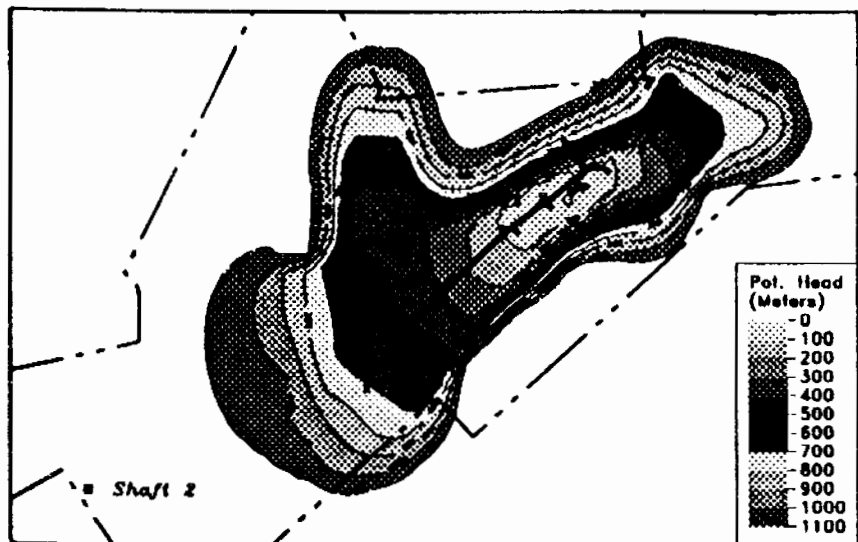
1988 Predicted Potentiometric Heads



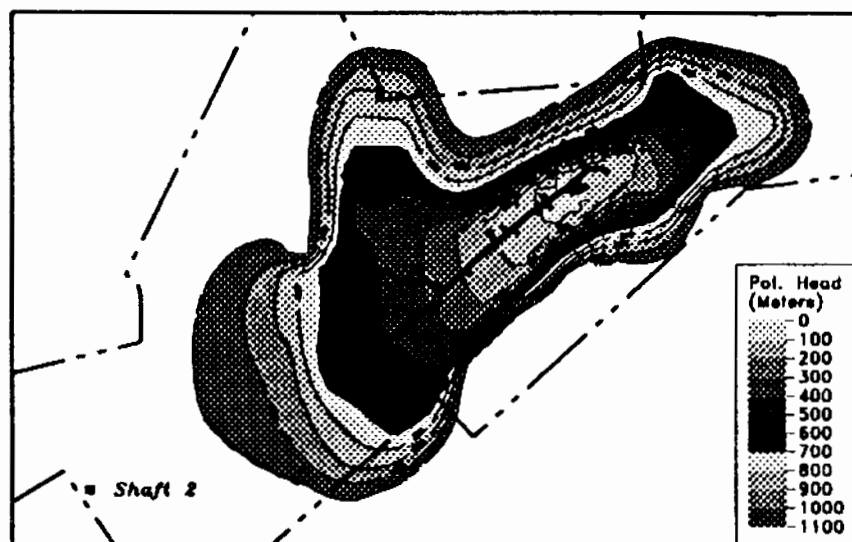
1995 Predicted Potentiometric Heads



2000 Predicted Potentiometric Heads



2010 Predicted Potentiometric Heads



2020 Predicted Potentiometric Heads

Figure 3. Multiple Frame Depicting Progressive Dewatering in the Hanging Wall Aquifer



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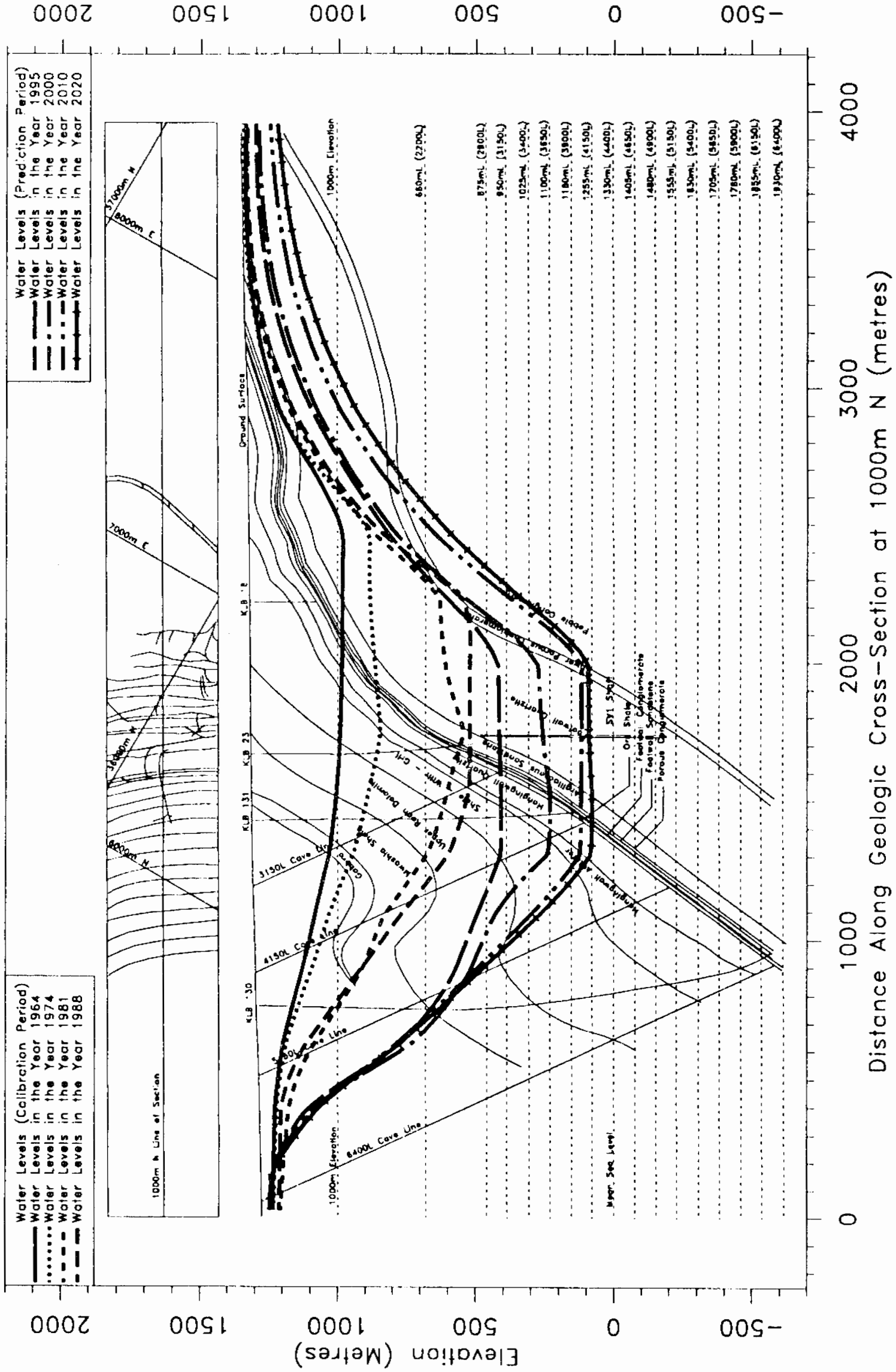


Figure 4. Hanging Wall Aquifer Potentiometric Heads; 1000 N X-Section



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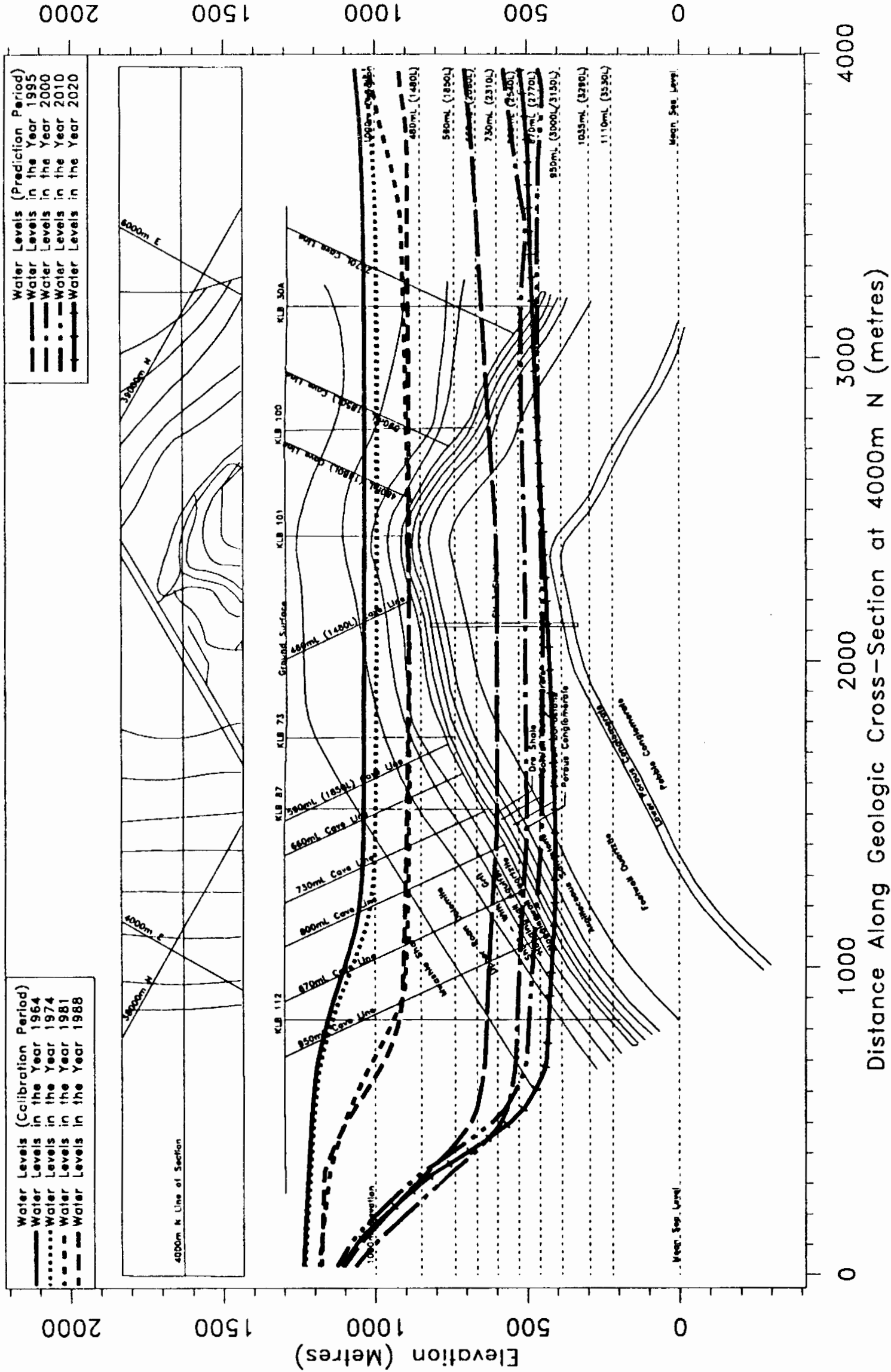


Figure 5. Hanging Wall Aquifer Potentiometric Heads; 4000 N X-Section

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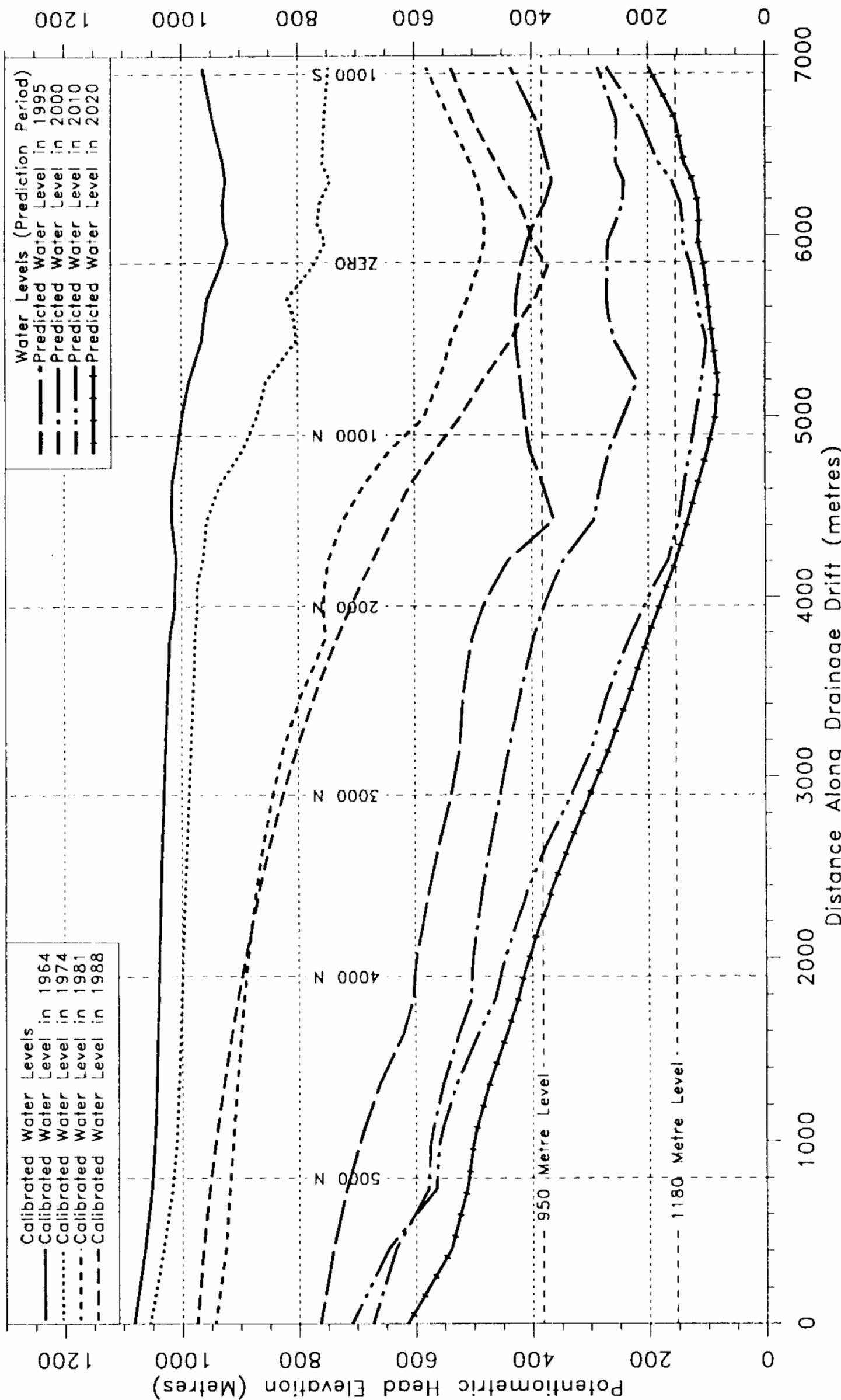


Figure 6. Potentiometric Head in the Hanging Wall Aquifer; Along the Drainage Drift