SIMULATION OF GROUNDWATER FLUXES DURING OPEN-PIT FILLING AND UNDER STEADY STATE PIT LAKE CONDITIONS

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ABSTRACT

A critical component in determining post-mining pit water quality is knowledge of groundwater fluxes, both as the pit fills and after steady state conditions have been reached. Simulations of the filling of an open pit in Crescent Valley, Nevada, were made to generate inputs for pit lake chemistry predictions. The simulations show that the water table recovery is most rapid immediately after pumping stops, when the hydraulic gradients are steepest. The maximum lateral extent of water table drawdown occurs several years after pumping stops because water continues to be derived from storage as the pit fills. Under steady state conditions, the lake stage is lower than the elevation of the water table in the pit area prior to mining, and groundwater flow is directed toward the pit lake, because evaporation from the lake surface causes it to act as a groundwater sink.

Key words: *groundwater flux, pit filling, pit lake formation, modeling*

INTRODUCTION

The South Pipeline Project is a proposed expansion of Cortez Gold Mine's open-pit mining operations in the southern part of Crescent Valley, which is located in north central Nevada (Figure 1). This proposed expansion would create a second pit adjacent to the permitted pipeline pit. To obtain approval for the project, a number of federal, state, and local permits need to be secured. One of the elements of the permitting process is an assessment of the potential environmental impacts to groundwater resources. To perform this assessment, a numerical groundwater flow model was developed to integrate regional hydrogeologic conditions, recharge from infiltration, evapotranspiration, and stresses induced by the mine dewatering operations. The numerical code used to simulate groundwater flow was an enhanced version of the U.S. Geological Survey's three-dimensional, finite-difference groundwater flow code MODFLOW (McDonald and Harbaugh, 1988).

A critical component in determining post-mining pit water quality is predicting groundwater inflows into the pit over time. The standard version of MODFLOW is limited in its ability to simulate pit lake formation. The new LAK2 package for MODFLOW was used in this study to overcome these limitations. The LAK2 package was selected because it can calculate the transient stage of a pit lake as it fills, as well as accounting for precipitation and evaporation at the lake surface and groundwater inflows or outflows across multiple model layers (Council, 1997).

This study is thought to be unique because it includes the simulation of initial pit lake formation in the adjacent pipeline pit concurrent with large-scale, open-pit dewatering, as well as the ultimate development of a pit lake in both pits after dewatering ceases.

GROUNDWATER FLOW MODEL SETUP AND CALIBRATION

The regional model domain and grid used in this study are shown in Figure 1. The model domain includes all of Crescent Valley, which is roughly 50 miles long by 20 miles wide and has a drainage area of approximately 700 square miles. The model is bounded by mountain ranges to the south, west, and east and by the Humboldt River to the north. To represent the steep gradients due to dewatering, a cell size of 200 x 200 x 200 ft was used near the mine. Cell sizes increase toward the model boundaries to a maximum size of 10,000 ft horizontally and 3,000 ft vertically. The boundaries are, for the most part, defined as no-flow along the crests of the mountain ranges. Constant head boundaries were specified along the Humboldt River and at one location along the western edge of the model domain where a limited amount of groundwater enters the basin due to inflow from an adjacent valley. Basin-wide groundwater recharge was estimated following the method reported by Maxey and Eakin (1949). Evapotranspiration was defined on the basis of available data and was correlated with the distribution of phreatophytes in the center of the valley. Groundwater withdrawals for domestic, municipal, and agricultural usage were also included in the groundwater flow model.

The model was divided into 12 horizontal layers to represent the vertical domain, extending from 9,000 ft above mean sea level to an elevation of 5,000 ft below mean sea level. This extent was necessary to simulate flow in bedrock below the basin-fill deposits, which are thought to attain a maximum thickness of approximately 10,000 ft.

Modeled bedrock units include carbonate, siliceous, volcanic, and intrusive rocks. Basin-fill deposits were divided into younger and older basin-fill units. The younger basin-fill units include alluvial fans, landslides, stream flood plains, and playas. The older basin-fill units consist of semiconsolidated deposits of conglomerate, sandstone, siltstone, freshwater limestone, evaporite, and interbedded volcanic rocks. Altogether, 22 separate hydrolithologic units were assigned in the model.

Extensive faulting in the mountain ranges surrounding Crescent Valley plays an important role in the groundwater flow system. Regional faults, and a number of smaller faults that were interpreted to act as partial barriers to groundwater flow in the immediate vicinity of the mine, were simulated in the model by using the Horizontal-Flow Barrier (HFB) package for MODFLOW.

The model was calibrated to both historical water-level measurements and to data collected during the first two years of dewatering the pipeline pit. The calibration also included matching estimated groundwater fluxes at appropriate points along the model boundary.

SIMULATION OF PIT LAKE FILLING

Methodology

A three-dimensional representation of the ultimate pit lake was developed on the basis of the 200 x 200 x 200 ft discretization of the model grid in the area of the pits. Model grid cells adjacent to the exterior of the lake were designated as “lake cells,” and were assigned hydrogeologic properties corresponding to the rock types that will ultimately be exposed in the pit walls. The deepest part of the lake is approximately 700 feet below the static pre-mining water table elevation. Overall, the pit lake spans five layers in the model (Figure 2).

Interactions between groundwater, the pit lake, and the atmosphere were simulated with the new LAK2 package for MODFLOW. The LAK2 package (1) takes into account precipitation into and evaporation out of the pit lake; (2) provides both horizontal and vertical groundwater flux components through the lake cells, which are used as inputs to the geochemical models; (3) keeps track of lake stage and components of the volumetric budget through time; and (4) simulates interactions with surface streams, although this feature was not used in the present study.

Output of groundwater flux through each 200 x 200 ft area of the ultimate pit surface was generated on a monthly basis during the first few years of pit filling, when flow rates into the pit were the greatest. The times between outputs were increased during the later part of the simulation as the fluxes diminished.

RESULTS

Four different pit configurations were simulated to analyze the potential effects of different mining options. Figure 3a shows Scenario 1, where the South Pipeline pit is continuous with the deeper pipeline pit. In Scenario 2 (Figure 3b), a portion of the waste rock removed from the South Pipeline pit is placed in the pipeline pit, yielding a lake of a smaller volume. Under Scenario 3 (Figure 3c), the South Pipeline pit does not exist, and the lake forms only in the pipeline pit. Finally, in Scenario 4 (Figure 3d), the entire pipeline pit is backfilled with waste rock, and the lake forms only in the South Pipeline pit.

In the case of Scenario 1 (Figure 3a), pit lake filling was initiated during the latter stages of dewatering when mining operations are focused on shallower deposits in the South Pipeline pit. Figure 4 shows (1) the excavation schedule for both the pipeline and South Pipeline pits, (2) the predicted dewatering rates, and (3) the calculated lake stage during the final period of dewatering. The lake initially forms in the deepest part of the pipeline pit and then gradually enters the South Pipeline pit during the last two years of dewatering. This simulation is thought to be unique in that large-scale, open-pit dewatering and pit lake filling were simulated concurrently.

Figure 5 shows the water level in the pit for each configuration after dewatering ceases. Water level recovery is most rapid immediately after pumping stops, when hydraulic gradients are the steepest. The differences in lake stage recovery between the various scenarios are due to the fact that the simulated lakes have different volumes and different dewatering and filling histories.

During dewatering, excess produced water will be returned to the groundwater basin via a series of infiltration galleries. Simulation results show that the drawdown at the end of dewatering will be effectively constrained to the north and to the south by the planned infiltration (Figure 6).

However, the drawdown cone will continue to expand laterally for some period after dewatering ceases, because water continues to be derived from storage in the basin-fill aquifer as the pit lake fills. Figure 6 shows 10- and 100-foot drawdown contours at the end of dewatering and at the time of maximum lateral extent of the drawdown cone, which occurs approximately 20 years after dewatering ceases.

Figure 7 shows a profile of the water table along the axis of Crescent Valley at various times during its recovery to equilibrium. The low, flat portions of the curves correspond to the pit lake surface, which grows with time until the lake becomes full. Model simulations indicate that the final lake stage will be approximately 15 feet lower than the elevation of the water table in the pit area prior to mining, because the lake acts as a localized evaporative sink for groundwater. Furthermore, as the lake reaches equilibrium, all of the water flowing into the lake is removed by evaporation, so there is no flow out of the lake to groundwater.

DISCUSSION

Overall, the LAK2 package was found to be extremely useful, robust, and relatively straightforward to apply to simulations of pit lake filling. However, proper use of the LAK2 package for this type of application requires careful setup of individual lake cells: e.g., using too coarse of a grid can adversely impact the calculation of the transient lake stage, and a missing lake cell can lead to errors in the volumetric budget. Vertical discretization is also important, especially at later times when the rate of change of the lake stage is relatively slow. For the purpose of geochemical modeling, finer temporal discretization of output is required early on when fluxes into the pit are changing rapidly, to better characterize the volume of water flushing oxidized wall rock.

SUMMARY AND CONCLUSIONS

The LAK2 package for MODFLOW was used to simulate pit lake filling under four different pit configurations, corresponding to different mining options. This study is believed to be one of the only ones to simulate large-scale, open-pit dewatering and pit filling at the same time. Results of the simulations show that the transient pit lake stage is impacted by the configuration of the pit and the previous dewatering and filling history.

The methodology described in this paper for simulating pit filling is generally applicable to any MODFLOW-based model of open-pit dewatering and post-mining pit filling. The generated groundwater fluxes and lake-stage outputs are critical components for geochemical modeling of post-mining pit water quality.

ACKNOWLEDGEMENTS

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Figure 1. Regional groundwater flow model grid and domain.

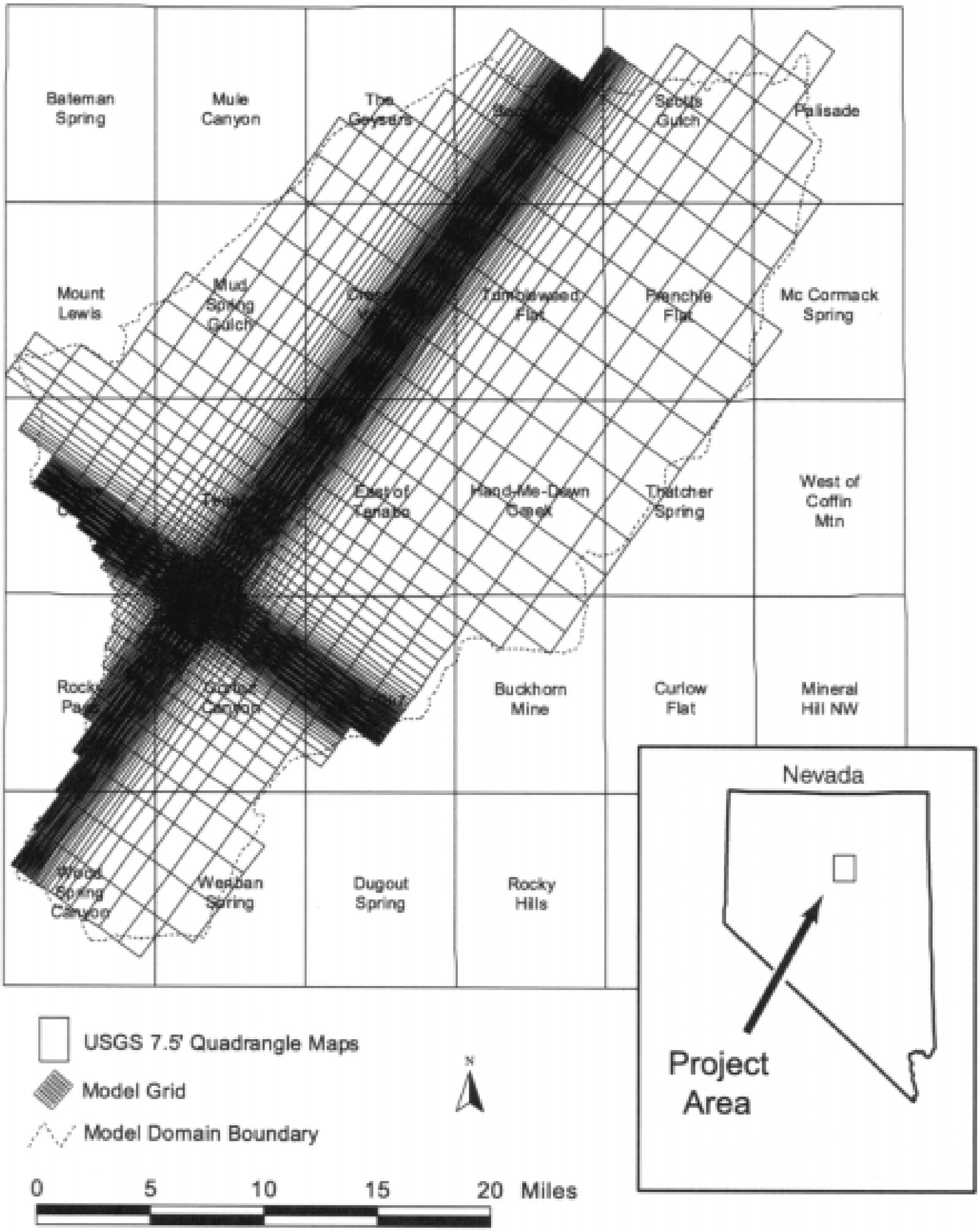

Figure 2. Lake cells by model layer (Scenario 1).

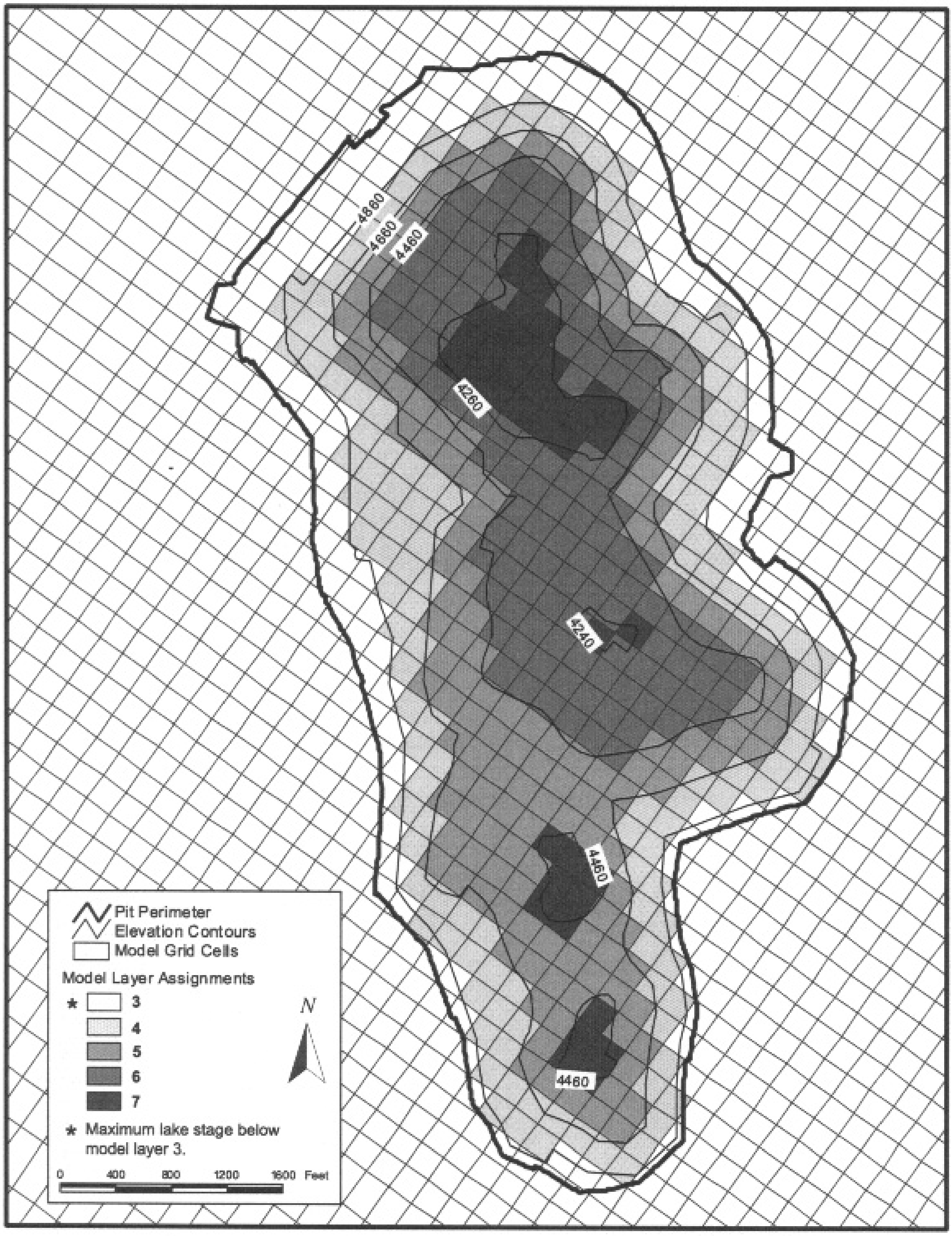

Figure 3. Pipeline - South Pipeline pit cross-sections.

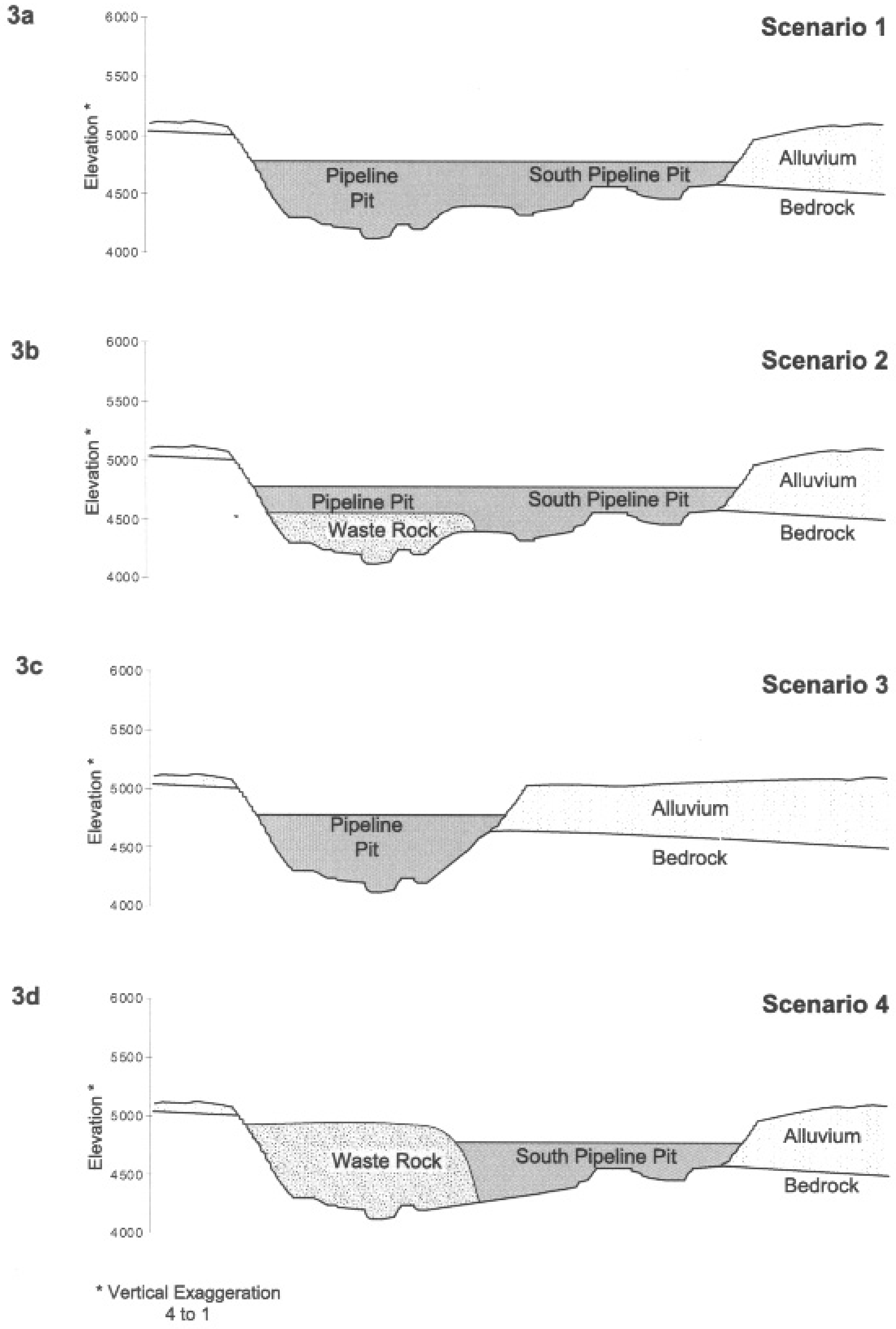

Figure 4. Mine dewatering schedule, dewatering rates, and pit lake stage during dewatering.

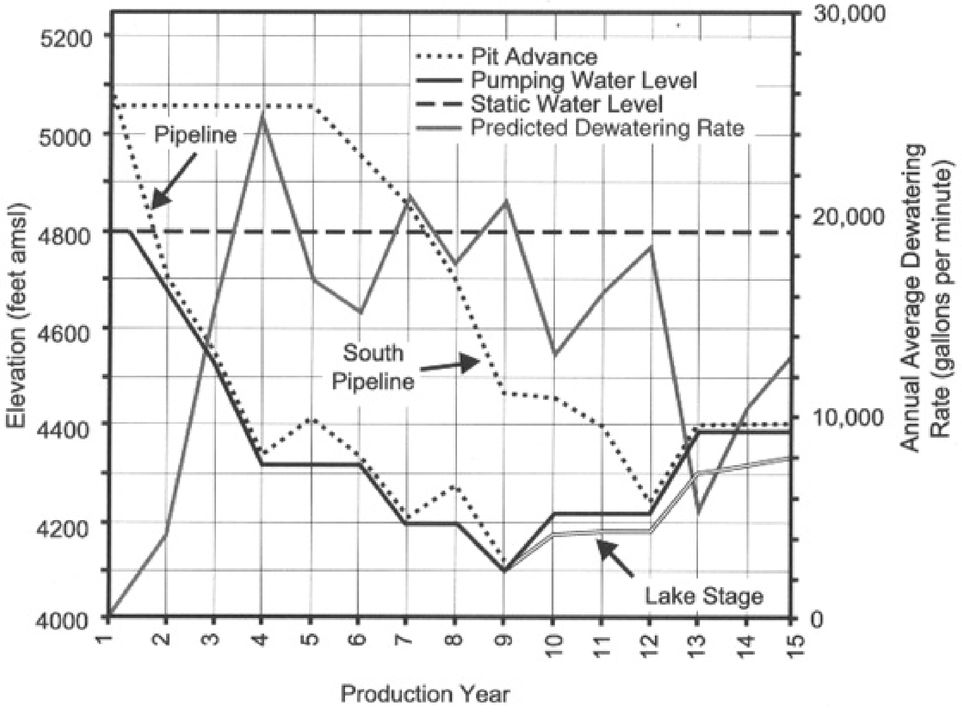

Figure 5. Hydrographs of lake stage during recovery.

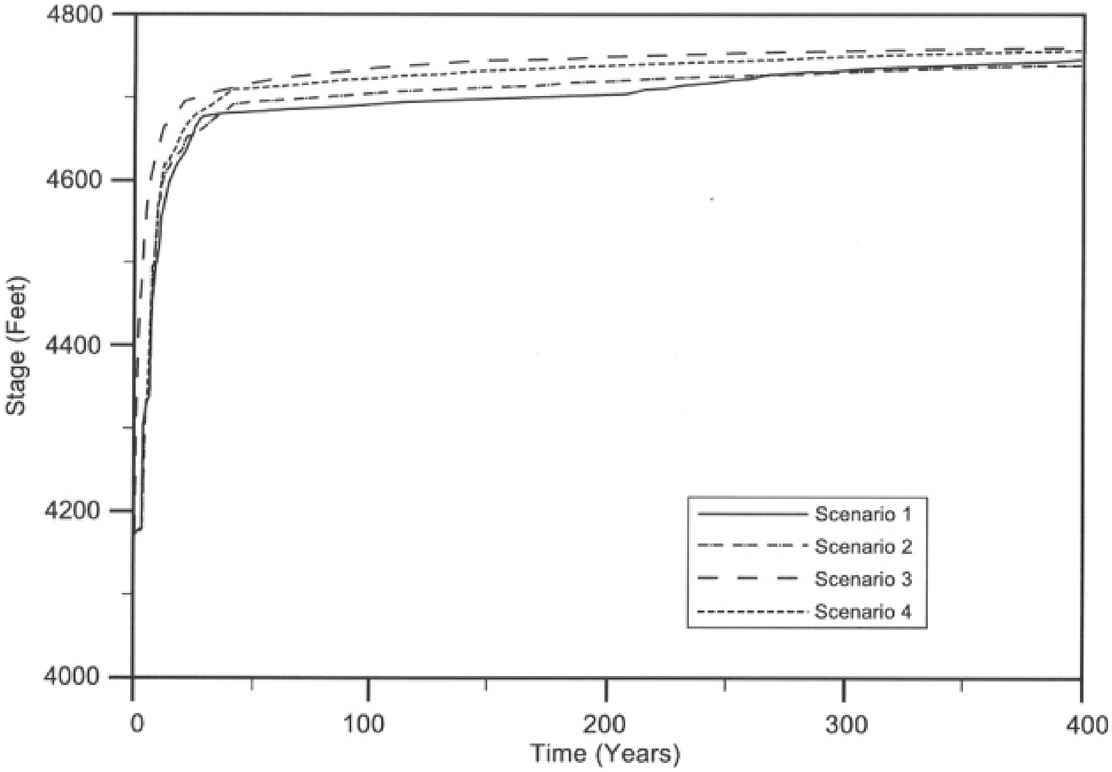

Figure 6. Predicted water table drawdown in basin-fill deposits.

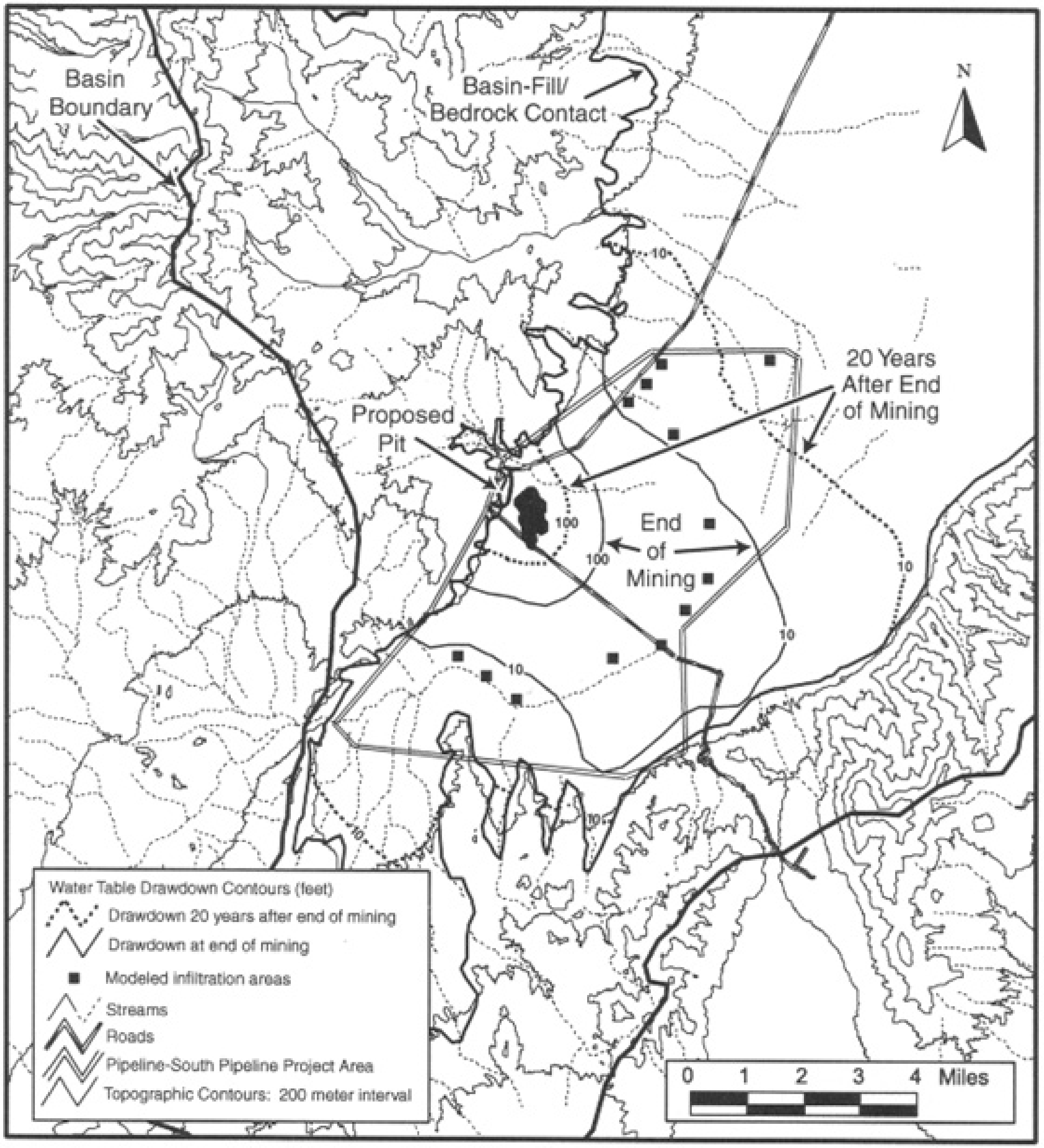

Figure 7. North/south profile of water table recovery after dewatering ceases, Scenario 1.