Appendix C

Yerington Pit Lake Investigation Reports

(Compact Disk)

GROUNDWATER AT THE YERINGTON MINE

Lyon County, Nevada

INTRODUCTION

A study has been made to determine as closely as possible the quantity of groundwater to be encountered in an open pit operation at the Yerington Mine. The nature of the problem and the incomplete data available preclude the possibility of obtaining exact quantitative answers. The probability of encountering large flows of water into the pit has been eliminated with the important exception of a flow from the Walker River to the east end of the pit along the predominant structural zones associated with the orebody. It is suggested that this possibility should be either eliminated or confirmed by drilling and test pumping a hole at coordinates D-3.

DATA AVAILABLE

The rate at which water was pumped from the No. 1 shaft and adjacent drill holes was reported by Mr. McDonald in his progress reports. Although no detailed records were found showing the rates of pumping or shut down periods, it is assumed that pumping was nearly continuous and that the average rates reported are close enough for the purpose of this study. Pumping rates are given between April 14, 1943 and January 8, 1945. The exact date that pumping was terminated was not found. Drill hole water level measurements and records of the underground mine work indicate that pumping stopped on about February 10, 1945.

The water level in some diamond drill and churn drill holes has been measured and recorded since May, 1943. In all, the water level has been measured in 32 holes. Due in part to caved holes, the data during and immediately after the pumping period are incomplete for many of the holes. The water level data are most complete for the period from before the termination of pumping to several months after pumping ceased. Thus the rate of rise caused by water flowing into the draw-down basin is fairly well recorded. A tabulation of the water level measurements is included with this report.

An important factor in calculating the rates of flow to be expected is the amount of water that will drain from the saturated bedrock and the gravel as the water table is lowered. This factor, which will be referred to as specific yield, will be less than the total porosity of the rocks by the amount of water left in the rocks after they have been drained but before they have been dried. As no data were available on such ~~effective porosities~~ specific yields, two rough experiments were conducted to get some idea of the magnitude of the factor for gravel. Five gallon milk cans were filled with gravel from a shaft west of the mine area. This material was water packed and settled into place by shaking. Enough additional water was added to saturate the gravel. The cans were then turned upside down in metal trays and water was allowed to drain for about 18 hours. The quantity of water thus freely drained was measured and used to calculate a value of specific yield. A portion of the drained gravel from one of the tests was weighed, dried, and reweighed to calculate the percentage of moisture remaining. These tests indicated that the specific yield of the gravel used was about 7% and that 7.25% by volume of water remained after draining. The total porosity of 14.25% thus indicated appears to be low.

DEVELOPMENT OF DATA

The data on pumping rates were plotted against time to form a graph. From this the total quantity of water pumped from the mine and the average rate of pumping were computed.

Graphs were drawn for each drill hole in which the water level was measured. Water elevations were plotted against time for readings between May, 1943 and December, 1947. These graphs show the rates of draw-down pumping and of recovery after pumping ceased. A typical graph would show a rapid lowering of the water table during the early stages of pumping, a gradual decrease in the rate of lowering of the water table until pumping was terminated, a rapid recovery of the water level after pumping ceased, and a final gradual recovery to the permanent water table. The flattening of the draw-down curves during the final stages of pumping and the rapid rise of the water table when pumping ceased indicate that much of the water was flowing in from outside the draw-down basin.

One hundred scale maps with ten-foot contour intervals were prepared to show the water surface on February 1, 1945 and on April 1, 1945. These show the water level at approximate maximum draw-down and at about two months after the water level began to rise with the termination of pumping. Although the data for these maps are limited, it is thought that a fair representation of the water surfaces was obtained for these two dates.

The water levels at maximum draw-down on February 1, 1945, after partial recovery on April 1, 1945, and the premanent water table were plotted on 100-scale north south sections covering the area effected by pumping. From these sections the volumes of bedrock and of gravel drained by pumping to February 1, 1945 and the volumes resaturated to April 1, 1945 were calculated. The amount of water obtained by draining the volume of rock effected at maximum draw-down and the amount of water required to resaturate the rocks were then calculated by using a specific yield of 12% for gravel and 2% for bedrock.

It has been assumed that water was returned to the draw-down basin immediately after pumping ceased at the rate that water flowed in from outside the draw-down basin during the final stages of pumping. It is realized that some water was derived from a further enlargement of the draw-down basin at its upper outlying edges to help in the resaturation of the lower part of the basin. At the time pumping ceased this flow from within the basin would be considerably below the 185 G.P.M. average rate of basin extraction and would decrease as the water level in the basin rose. The gradual decrease in the rate of flow from outside the basin as the water level rose would probably more than offset the flow from within the basin. The amount by which these factors fail to balance each other is not known but could not be large enough to materially influence the general conclusion drawn.

The average rate at which water was extracted during the pumping period must equal the average rate at which water was depleted from the draw-down basin plus the average rate at which water flowed in from outside the draw-down basin. The values of specific yield for gravel and for bedrock were adjusted to satisfy this requirement.

CONCLUSIONS DRAWN

The following is a summary of the results calculated:

Total water pumped 4-14-43 to 2-10-45	164,241,000 Cu. ft.
Average Pumping rate 4-14-43 to 2-10-45	1,273 G.P.M.
Maximum Volume Drained by Pumping to 2-1-45	
Bedrock drained	271,300,000 Cu. ft.
Gravel drained	153,200,000 Cu. ft.
Maximum Volume of water from drained area	
From bedrock at 2% Specific Yield	2,426,000 Cu. ft.
From gravel at 12% Specific Yield	18,384,000 Cu. ft.
Total volume of water from drained area	23,810,000 Cu. ft.
Volume of rock resaturated from 2-1-45 to 4-1-45	
Bedrock	157,200,000 Cu. ft.
Gravel	78,300,000 Cu. ft.
Volume of water in rock resaturated 2-1-45 to 4-1-45	
Water returned to bedrock at 2% Specific Yield	3,144,000 Cu. ft.
Water returned to gravel at 12% Specific Yield	9,396,000 Cu. ft.
Total volume of water returned 2-1-45 to 4-1-45	12,540,000 Cu. ft.
Assume volume of water returned = Inflow from out of basin.	
Inflow rate from outside basin	1,092 G.P.M.
Average rate to drain water in basin	185 G.P.M.
Inflow rate plus average basin drainage	1,277 G.P.M.

Due to the rough and incomplete nature of the primary data and to the broad assumptions that have been made in making the calculations, further refinement of the results is hardly justified. However, the following factors have been considered. During the later stages of pumping the inflow from outside the drainage basin was probably higher than the 1,092 G.P.M. calculated. This is due to the fact that the pumping rate for the ten months prior to February 1, 1945 was 1,400 G.P.M. rather than the 1,273 G.P.M. calculated as the average rate. Also the average rate of water obtained from draining the basin is greater than the rate of flow derived from basin drainage at the time pumping terminated. This is due to the fact that all water is derived from basin drainage at the start of pumping and no water would be derived from basin drainage after an infinite pumping time. In view of these considerations a better estimate of the amount of water flowing in from outside the drainage basin would be 1,200 G.P.M.

The slope of the water surface at the end of the pumping period was steeper on the south and east sides of the drainage basin than on the north and west sides. If similar rock conditions are assumed for the north, east and south sides, more water was flowing into the drainage basin from the south and east than from the north. The west slope of the basin is in gravel and could be expected to have a flatter slope due to higher permeability. Two months after pumping ceased the water level had risen more on the south flank than on the north and west flanks of the drainage basin. This indicates again that the major outside source of water was from the south rather than the north and suggests that there was little water flowing in from the west. The draw-down basin was filled first at its east end as shown by the westward shift of the basin two months after pumping ceased.

In excavating the mine pit as it is now contemplated the flow of water derived from draining the rock within the draw-down basin will not be a large factor. If the water table at the pit is lowered fifty feet per year, the water derived from within the drainage basin should account for an average flow of about 200 G.P.M.

The amount of water to be expected in the pit from sources outside the drainage basin is much harder to estimate. In comparison with the underground workings which tapped water during the pumping period, the proposed pit will cover a much larger area, will reach lower elevations and will be much closer to outside water sources to the east and south. It is reasonable to expect that the pit will develop a much larger flow from outside sources than the estimated 1,200 G.P.M. developed by the mine workings in 1945.

The effectiveness of fissures or broken zones in the bedrock as water channels has not been adequately determined, but large flows of water were encountered in fissures at the 200 level mine workings. The main sources of inflowing water were from the south and east flowing through bedrock and not from the west flowing through gravel. The proposed Yerington Mine pit is bounded, below the static water table at the 4380 foot elevation, by bedrock on the east, on the north except for the northwest corner, and on the south as far west as Section Q.

The Walker River is the only active source of water in the area. There is a water channel through gravel between the river and the south west corner of the pit. A gravel channel connecting the west end of the pit with the river in a northerly direction probably exists, but the effect of such a channel to the north would be insignificant because it would be separated from the river for several miles by a bedrock ridge running north from the mine area. An important possible source of inflowing water will be from the southeast entering the southwest corner of the pit above bedrock. The possibility of effecting a saving in pumping costs and a reduction of interference with mining operations by catching a large part of this water at a bench immediately below the gravel-bedrock contact should be considered.

An estimate of the water expected to flow into the pit from outside the drainage basin depends almost entirely upon the permeability of the bedrock, about which few data are available. If the bedrock permeability is low, the water from outside sources would not greatly exceed the estimated 1,200 G.P.M. developed by February, 1945. At that time the draw-down basin had cut the main gravel channel between the river and the pit almost as effectively as it will be cut by the pit.

The probability of encountering highly permeable zones in the bedrock is indicated by the data available. Large concentrated flows of water from fissures were encountered in driving the 200 level mine workings. On the 300 level much less water was encountered and some evidence of impermeability between the two levels was obtained. The diamond drilling near the proposed west end of the pit indicates that the bedrock in that area is permeable. In drilling hole 80 at coordinates D-0 the water return was lost five times; hole 86 at D-2 lost water ten times; hole 79 at D-4 lost water fourteen times; hole 81 at D-6 lost water six times; hole 83 at C-4 lost water four times. In some of these cases the use of sawdust in addition to cementing was not successful in sealing the holes.

If a highly permeable zone does exist, as along the northwest southeast structure zone of the mine area, a channel connects the Walker River and the east end of the pit. Such a channel could tap the gravel of the river valley at a distance of 1,000 feet from the pit bottom and the river itself would only be 500 feet farther. The effective head or elevation difference would be 250 feet. Such a condition could conceivably allow the inflow of enough water to make it inadvisable to extend the pit as far east as is now contemplated.

An indication of the water to be encountered at the east end of the pit could be obtained by drilling a hole at coordinates D-3 and making pumping tests. A 400-foot hole cased to 300 feet with 12" perforated pipe would be sufficient for pumping tests and would also be valuable as a check on the ore values at this location. Recordings should be made of the water levels of all open drill holes in the effected area as a part of the pumping tests.

Such a test would determine whether or not great quantities of water are to be expected to flow through the bedrock. It would help in determining whether the larger flows are to be expected from the gravel channel to the west end of the pit or from possible bedrock channels to the east end and thus would influence the sequence in which the pit is to be excavated.

CONCLUSIONS

1) Some eighty-five percent of the water pumped from April, 1943 to February, 1945 was derived from outside the drainage basin established by the pumping.

2) Water derived from draining rock within the drainage basin caused by the pit should not exceed 200 G.P.M. if the bottom of the pit is lowered fifty feet per year.

3) Sufficient information is not available concerning the permeability of the bedrock, especially near the east end of the pit.

4) If the bedrock is of low permeability, it will form a barrier against water flowage for all but the west end of the pit. In this case the main flow from outside the drainage basin will be from the southeast entering the southwest corner of the pit above bedrock. The amount of this flow would not greatly exceed 1,400 G.P.M.

5) If highly permeable zones exist in the bedrock at the east end of the pit, large flows of water are to be expected to come directly from the Walker River.

RECOMMENDATIONS

It is recommended that a hole be drilled and that pumping tests be made at coordinates D-3 to help in determining whether or not excessive flows of water will be encountered from the Walker River to the east end of the pit.

Respectfully submitted,

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March 1951

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SLOPE STABILITY AFFECTS OF PIT WATER STORAGE

Yerington Mine
Lyon County, Nevada

PREPARED FOR

The Anaconda Company
Denver, Colorado

By

Dr. Ben L. Seegmiller

June 1979

Approved: Ben L. Seegmiller, P.E. 6/29/79
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SUMMARY OF CONCLUSIONS

The most pertinent conclusions of this report are summarized as follows:

1. *Slope Failure Mode* - Predominately circular soil type failures, as have been observed in the past at Yerington, will likely occur.

2. *Slope Failure Initiation* - Instability will likely begin to occur prior to filling the pit to the 4120 elevation.

3. *Slope Failure Rate* - The rate will be directly related to the rate of filling the pit with water, but it is not expected that catastrophic failure will be likely on a large scale.

4. *Slope Failure Extent* - The probable maximum extent of surface damage is on the order of 1200 - 1300 ft beyond the present pit crest.

5. *Recreation Usage: Pit Area* - No recreational or other usage of the pit area involving the general public should be implemented until it is demonstrated over a 3 to 5 year period that no obvious or probable hazard exists relative to pit slope instability.

INTRODUCTION

The slope stability affects of pit water storage at the Yerington Mine, Lyon County, Nevada is the subject of this report. It was authorized by Mr. William C. Norem, General Manager, The Anaconda Company.

Mining in the Yerington Pit was terminated in June of 1978. Since that time, little or no activity related to mining has taken place in the pit and it has been allowed to partially fill by natural seepage with about 80 ft of water. Owing to the fact that the waters from the Yerington Pit have historically been potable and have been used as culinary water in the adjacent Weed Heights townsite, the possibility of using the pit for water storage and/or recreational purposes has recently been raised by local officals. Water from the nearby Walker River would be diverted during flood stage through a specially cut channel and enter the east end of the pit. The water would fill the pit approximately to the 4360 ft elevation at its maximum level. Because the Yerington Pit had been plagued by slope instability problems during its life and the fact that water can induce slope failures, the question of potential slope subsidence has been raised. To help shed some light on this subject, Seegmiller Associates were retained to study the problem. The present report is the culmination of that study.

The purpose of the study has been to render an opinion on the following: (1) What would the mode of the potential slope failures be? (2) When would they likely occur relative to the rising level of the water in the pit? and (3) What would the extent of the slope failure be relative to the present pit rim? This report and the resulting opinions are limited to the accuracy and reliability of the input data. No liability is assumed or implied for damages to life, limb or property that may result by anyone using the opinions of this report.

Sources of information used for this study include the data supplied by The Anaconda Company and the data collected during two site visits by Seegmiller Associates. This report begins with a review of applicable data relative to past mining, geological discontinuities, groundwater and mechanical properties. A rock mechanics analysis of the pit slopes is then undertaken and some pertinent conclusions and recommendations complete the report.

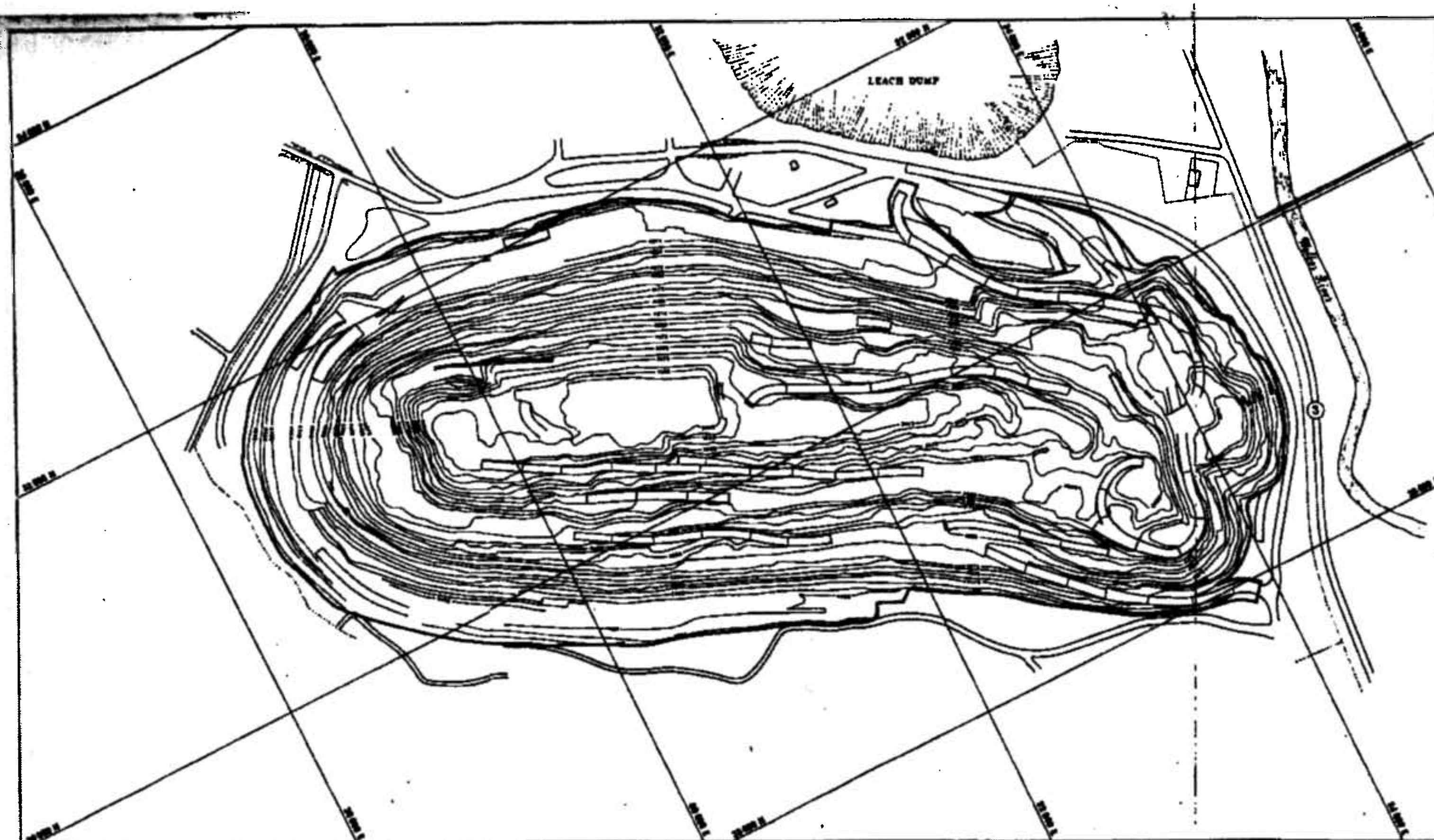
PAST MINING AND SLOPE FAILURES

General

Mining began at Yerington in 1951 and continued until June of 1978. Conventional drilling, blasting, loading and haulage methods were used to mine the waste rock and ore. The alluvial overburden materials were mined, for the most part, by direct digging with power shovels. Pushback techniques were used to gradually increase the area of the mine to its present size, which is approximately 3000 ft wide, 6800 ft long and a maximum of 800 ft deep. The present configuration of the Yerington Pit is approximately as shown in Figure 1.

Failure Modes and Rates

Slope failure in the alluvial materials had normally never occurred as a direct result of oversteepening the allüvial slopes. Failures which did occur and those evident in the present pit are a result of instability in the underlying rocks. These underlying rock materials tended to become unstable as mining progressed deeper and deeper. When the rock materials failed, they caused a loss of foundation support in the overlying alluvium. This resulted in both direct shear and tensional alluvial failures which reached to the surface in the form of tension cracks. Owing to the unusually high number of geologic discontinuities in the rock mass, it tends to act much like a soil mass. It normally does not store energy as the disequilibrium conditons of mining affect it. Rather it reacts almost continuously and directly as mining proceeds. Thus, catastrophic slope failures do not occur, but rather massive slow slope instability in many areas is a common and continuous occurrence. At times a major discontinuity such as a fault has caused local zones to fail more rapidly, but rarely in a catastropic manner. A high groundwater table, which has been in the so-called normal drawdown condition, has also been a factor in the past and present slope instability as has the lower than usual rock mass shear strength. At the present time slope failures of various sizes may be observed in the south, southwest, northwest and north central portions of the pit.



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YERINGTON OPEN PIT MINE

LYON COUNTY - NEVADA

FIGURE 1

GENERAL YERINGTON MINE PLAN

GEOLOGICAL DISCONTINUITIES

General Geology

The Yerington Mine is situated on the western edge of the Basin and Range Province. It is part of a quartz monzonite intrusive mass emplaced during the mid-Mesozoic. The intrusion has locally experienced intensive hydrothermal alteration. An uneven blanket of partially consolidated Pleistocene alluvial sands and gravels overlies the bedrock. These sands and gravels range in thickness from more than 300 ft in the west end of the pit to less than 10 ft in the east end.

Major Discontinuities and Tension Cracks

Geologic discontinuities that are of a major nature are limited to faults in the Yerington Pit. Further, only one known fault, the Sericite Fault, could be classified as being a major fault. Moderate and minor faults of up to 1200 ft in strike length are quite common within the pit. Most of these faults tend to strike northeast-southwest, but their dips may range from about 5^{o} up to 70^{o} and be either east or west in direction. Tension cracks are commonly found along the northwest and north central portions of the pit for distances up to 600 ft beyond the crest. A few prominent tension cracks occur in the south central part of the pit, but are limited to distances of about 250 ft beyond the crest. Locations of some of the fault discontinuities and known tension cracks are presented in Figure 2.

Joint Sets

Visual observations in the present pit reveal that there are usually up to three major joint discontinuity sets at any given location. Further, there are normally an additional one or two moderate and up to three minor joint sets visible. These numerous sets tend to break up the rock such that, in many places, the average block of rock is only 4 to 6 inches in its longest dimension. The small size of the blocks tends to create a rock mass which may equivalently be modeled as a very course gravel or soil material.

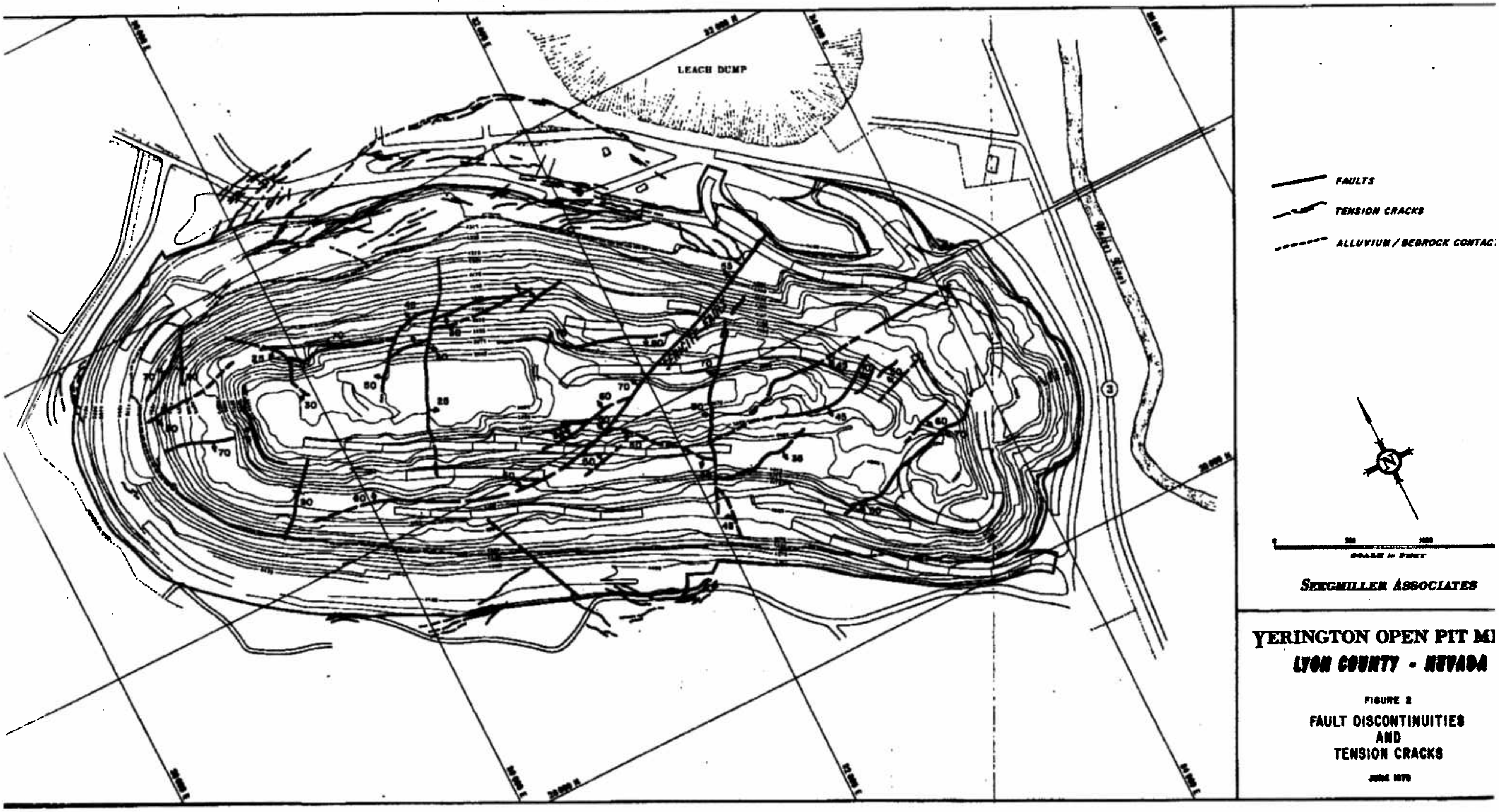
LEACH DUMP
FAULTS
TENSION CRACKS
ALLUVIUM / BEDROCK CONTAC
SPEGMILLER ASSOCIATES
YERINGTON OPEN PIT MI
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FIGURE 2
FAULT DISCONTINUITIES
AND
TENSION CRACKS

GROUNDWATER

General Environment

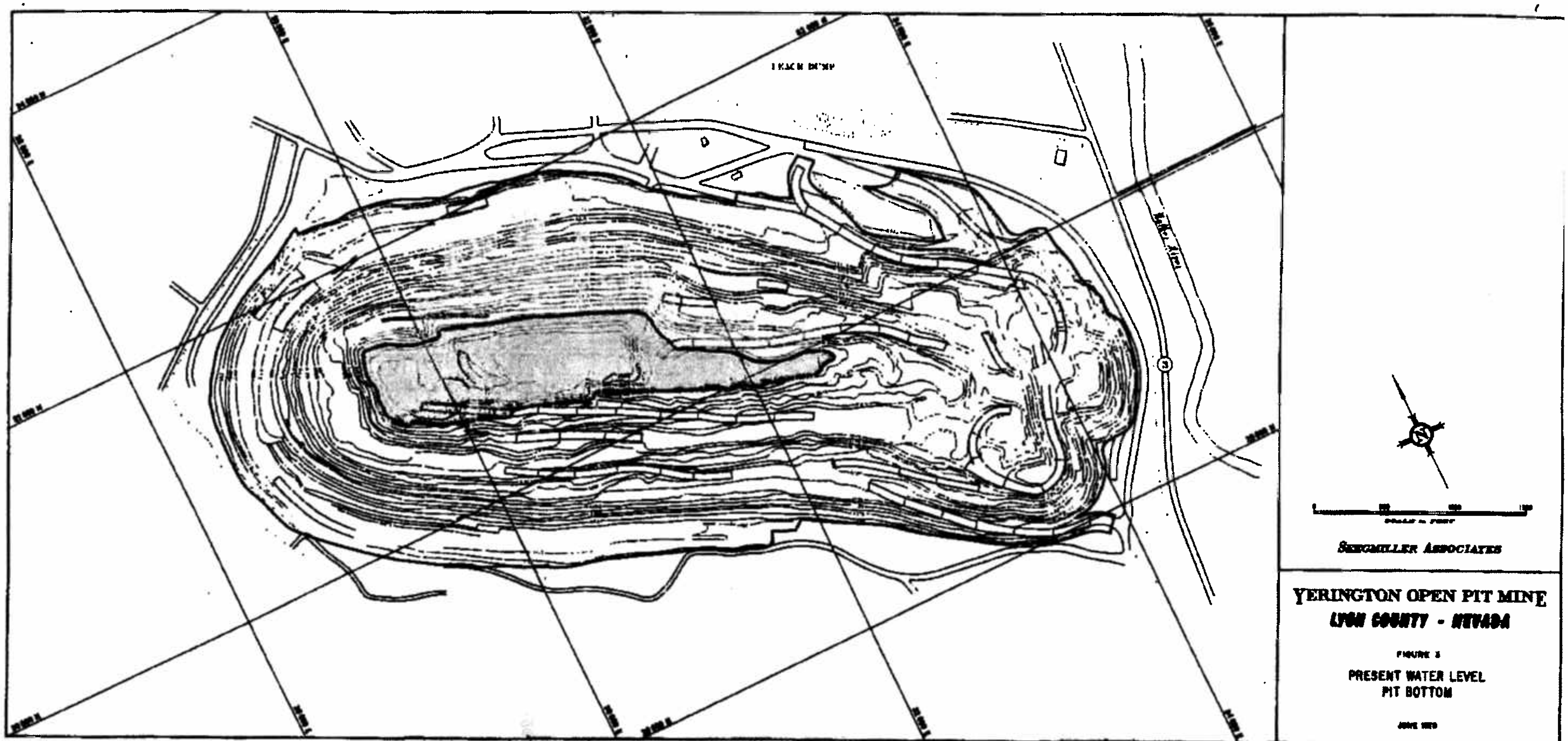
The Yerington area, in general, constitutes a semi-arid environment. Average precipitation during a given year is estimated to be on the order of about 6 inches. Springs and water seeps are not common in the general area. However, the Mason Valley, adjacent to the pit on the east end, has a relatively high groundwater table creating swampy areas in numerous parts.

Water Tables: Pit Area

Prior to mining, the general pit water table was at an elevation of 4350 to 4360 feet. As mining began and progressed, the water table was lowered in the normal draw-down manner by vertical wells located both within and around the periphery of the pit. The Walker River, which is located within several hundreds of feet of the east end of the pit, has been a major source of water in the eastern end of the pit. The elevation of the Walker River is about 4388 ft at its nearest approach to the pit. Water in the west end of the pit was normally encountered during mining at the bed-rock-alluvium contact. The source of this water was presumed to be in part natural drainage from the west mountains and in part from the adjacent townsite which had numerous lawns and other surface dispensing of water. Bedrock groundwater is found at various depths below the alluvium-bedrock contact depending on the area in question. Perched groundwater tables are very common in most of the pit slopes. For analysis purposes it must be assumed that groundwater exists in all the present pit slopes. Further, it will be assumed that it follows a normal drawdown path to the present pit water level elevation of approximately 3880 ft as shown in Figure 3. Due to drainage into the pit along the drawdown path, the water level in the pit bottom is rising at the rate of approximately 1 inch per day.

Maximum Pit Water Level

Water to be stored in the Yerington Pit would be collected at flood stage and channeled into the pit near the southeast end. At flood stage the elevation of the Walker River where it would leave the river would be about 4390 feet. The maximum elevation level that the water in the pit would reach is estimated to be about 4360 ft before stabilizing.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YERINGTON OPEN PIT MINE
LYON COUNTY - NEVADA
PRESENT WATER LEVEL
PIT BOTTOM

MECHANICAL PROPERTIES

General

In order to conduct any type of pit slope stability analysis it is necessary to have an understanding of the mechanical properties of the rock and soil masses. Normally these properties, of which the shear strength is the most important, are determined in part by field and/or laboratory testing. However, for the present study, testing is beyond the scope of the investigation; hense, other methods must be used. These other methods include (1) estimating, using similar studies and other forms of knowledge and (2) back-analysis of existing conditions.

Rock Mass Characteristics

Generally speaking, the Yerington Pit has similarities to other copper operations in the southwestern USA. The alluvial gravels should have shear strengths which will range from 40^{o} to 44^{o} for the angle of sliding friction. and 500 psf to 1000 psf for the cohesion. The unit weight may be assumed to be approximately 125 pcf. For the rock materials the range of friction angles may be on the order of 28^{o} to 34^{o} and the cohesions on the order of 1500 psf to 3000 psf. The average unit weight of the rock may be assumed at 165 psf. Specific magnitudes for the shear strength of any particular slope are best determined by a sensitivity back-analysis of the existing conditions in the slope in question.

ROCK MECHANICS ANALYSIS

Analysis Methods

Pit Zonation. For analysis purposes the Yerington Pit has been divided into a series of zones. These zones each have their own characteristics in terms of geometry, groundwater, mechanical properties and existing factor of safety against slope failure. The north side of the pit has been divided into two zones, the northwest and north central. The east end comprises one zone as does the entire south side and west end. The reason for dividing the pit into two zones along the north side is that it represents the most critical part of the pit in terms of stability. Definite tension cracks exist along much of the north side, past history shows that this side of the pit has had the most stability problems and there is a leach dump, which represents a potential pollutant for the pit water, located approximately 600 ft beyond the present pit crest. Each of the zones is represented in a typical analysis section through the zone. The location of each analysis section is shown in Figure 4.

Failure Mode. Owing to the fact that the discontinuities in the pit slopes create a mass of small blocks, the most probable future failure mode will be circular. Some small wedge, planar and even toppling modes may exist within a localized area. However, overall stability of the pit slopes is the major factor of concern in this study and it is believed that, as in the past, the rock mass will continue to most accurately be modeled using circular failure analyses techniques.

Circular Failure Analyses. Basically these techniques involve examination of the ratio of shearing strength to shearing stress along a circular or curved failure path. The ratio of shearing strength to shearing stress is defined as the safety factor and may be stated mathematically as

$$S.F. = \frac{\text{Shearing Strength}}{\text{Shearing Stress}}$$

Whenever this ratio is greater than 1.00, there will be stability along the failure path examined. When the ratio

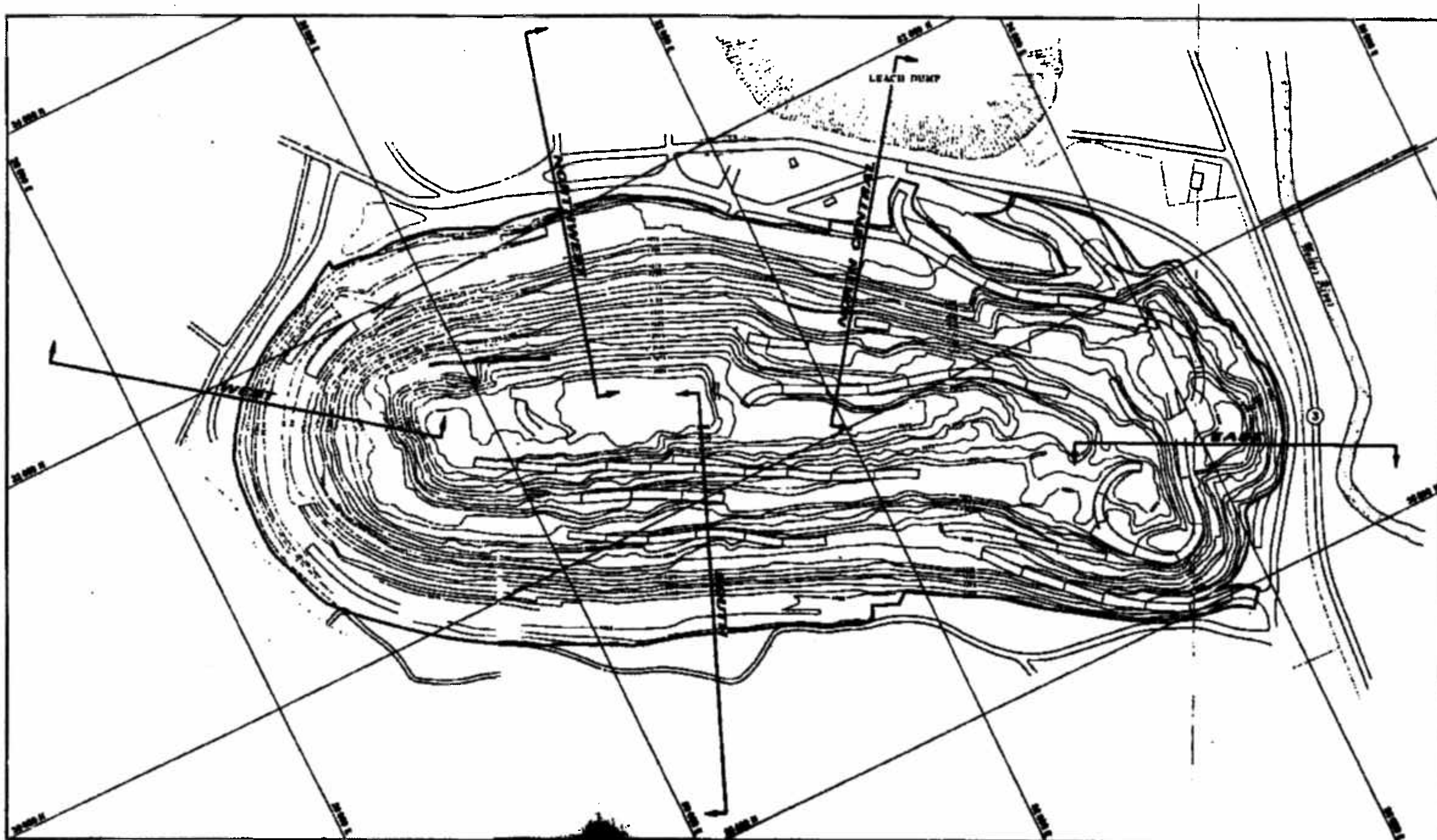

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FIGURE 4

ANALYSIS SECTIONS

is less than 1.00, failure is or will be taking place. When the ratio is equal to 1.00, the rock mass is said to be in a state of limiting equilibrium. Owing to the fact that many of the circular failure analyses involve the investigation of a great number of potential failure surfaces, it is common practice to have the analytical procedure computerized. Using computerized techniques allows a great number of different cases to be rapidly examined using a wide variety of input parameters including differing slope geometries, shear strength and groundwater conditions. An extension of the method can be used to include the variabilities of input parameters, particularly the shear strength. Using such techniques allows an estimation of the probabiltiy of failure of a particual slope to be made.

Procedural Methods. The basic procedure used in the present analysis has been to first model the existing slope as close as possible. A sensitivity analyses is then conducted on the slope model to determine the most likely shear strength parameter and existing safety factor. Once the existing conditions have been reasonably approximated, the effects of the water level in the pit may be examined. The most probable condition may be determined for a given water level and then the potential conditions may be determined when the shear strength parameters are lowered. In the present study the affects of a half-full condition (water level at elevation 4120 ft) and a full condition (water level at elevation 4360 ft) are examined under (1) existing shear strength conditions, (2) shear strength conditions which are believed to exist only 5% of the time and (3) shear strength conditions which are believed to exist only 1% of the time. The safety factor, resulting slope angle and projected limit of adverse effects are then determined for each condition in each analysis section. The points along the pit crest representing the 50%, 5% and 1% estimated probabilities of failure may then be contoured to show the extent of failure as a function of distance from the pit crest.

Stability Back-Analysis

Northwest Zone. The analysis section for this zone is presented in Figure 5. A sensitivity back-analysis was conducted and the results are presented in Figure 6. It is believed that the most likely existing equivalent shear strength is represented when $\phi=31.5^{o}$ and C=2000psf yielding a safety factor of 1.02.

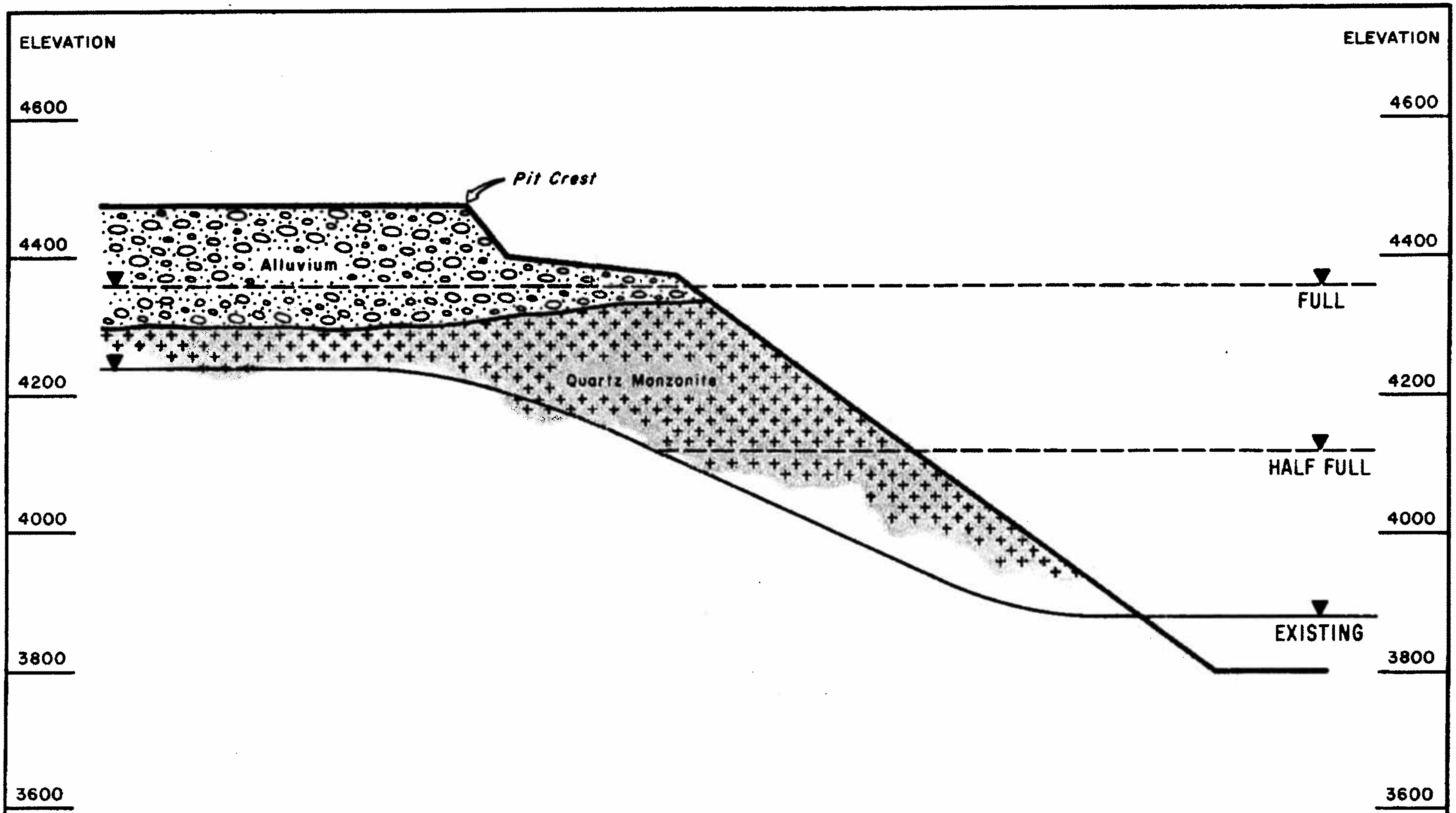


FIGURE 5

YERINGTON OPEN PIT MINE
NORTHWEST ANALYSIS SECTION

SEEGMILLER ASSOCIATES

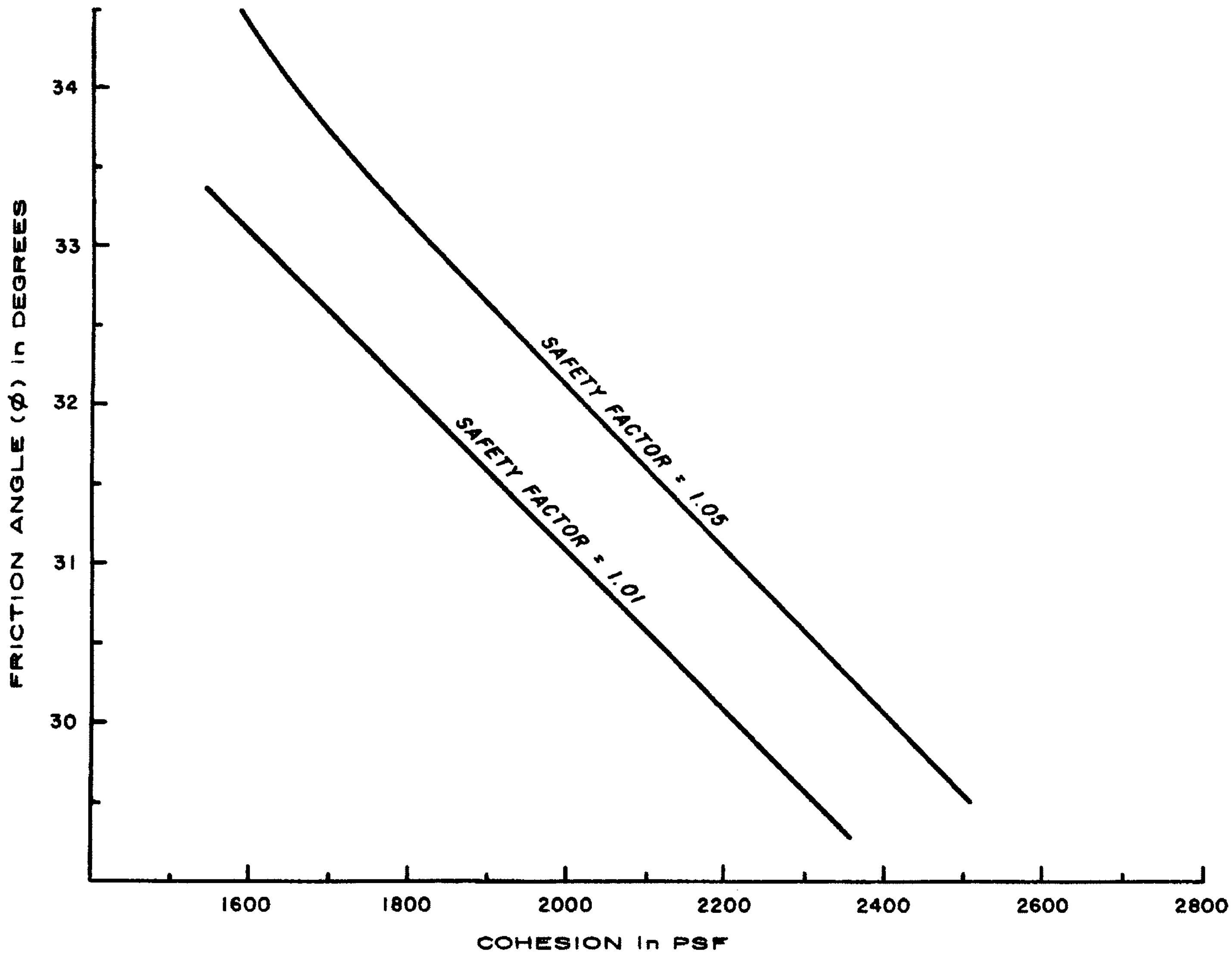


FIGURE 6

SENSITIVITY BACK-ANALYSIS
NORTHWEST SECTION

North Central Zone. This zone is represented in the analysis section presented in Figure 7. The sensitivity back-analysis is shown in Figure 8. The most likely equivalent shear strength parameters are believed to be $\phi=30.0^{\circ}$ and C=1500psf yielding a safety factor of 1.02.

East Zone. This zone very likely represents the most stable portion of the pit because it has little or no alluvium and does not have a history of instability. The analysis section is presented in Figure 9 and the sensitivity back-analysis is depicted in Figure 10. It is believed that the most likely equivalent shear strength parameters are $\phi=32.0^{\circ}$ and C=2500psf resulting in a safety factor of 1.25.

South Zone. The analysis section for this zone is presented in Figure 11 and the sensitivity back-analysis is presented in Figure 12. It is believed that the most likely equivalent shear strength parameters are $\phi=30.0^{\circ}$ and C=2500psf yielding a safety factor of 1.16.

West Zone. The analysis section and sensitivity back-analysis for this zone is presented in Figures 13 and 14, respectively. The most likely equivalent shear strength parameters are believed to be $\phi=33.0^{\circ}$ and C=2000psf resulting in a safety factor of 1.06.

Stability: Half-Full and Full Conditions

The resulting safety factors for each zone under half-full and full water conditions are presented in Table I. The approximate failure probability which is considered the most probable for each zone is presented in Table II for the half-full condition. In addition, the failure distance beyond the slope crest and the ultimate slope angle for various probabilities of failure are also presented in the table. A similar set of probabilities, distances and ultimate slope angles are presented in Table III for the full condition. The distances to which slope instability may affect objects behind the pit crest have been translated into probability of failure contours. The probability of failure contours for the half-full condition are presented in Figure 15 and those for the full condition are presented in Figure 16.

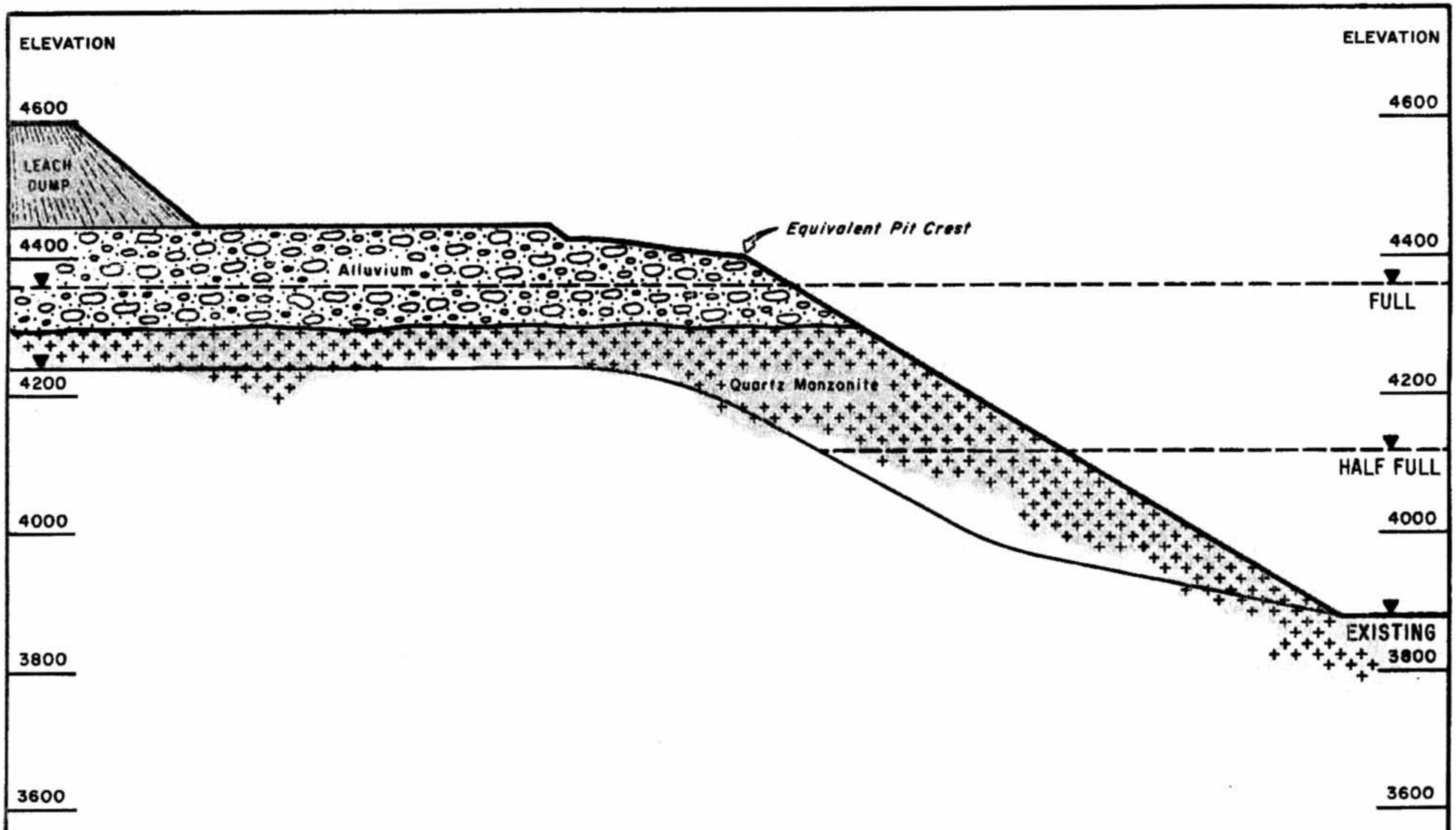


FIGURE 7

YERINGTON OPEN PIT MINE
NORTH CENTRAL ANALYSIS SECTION

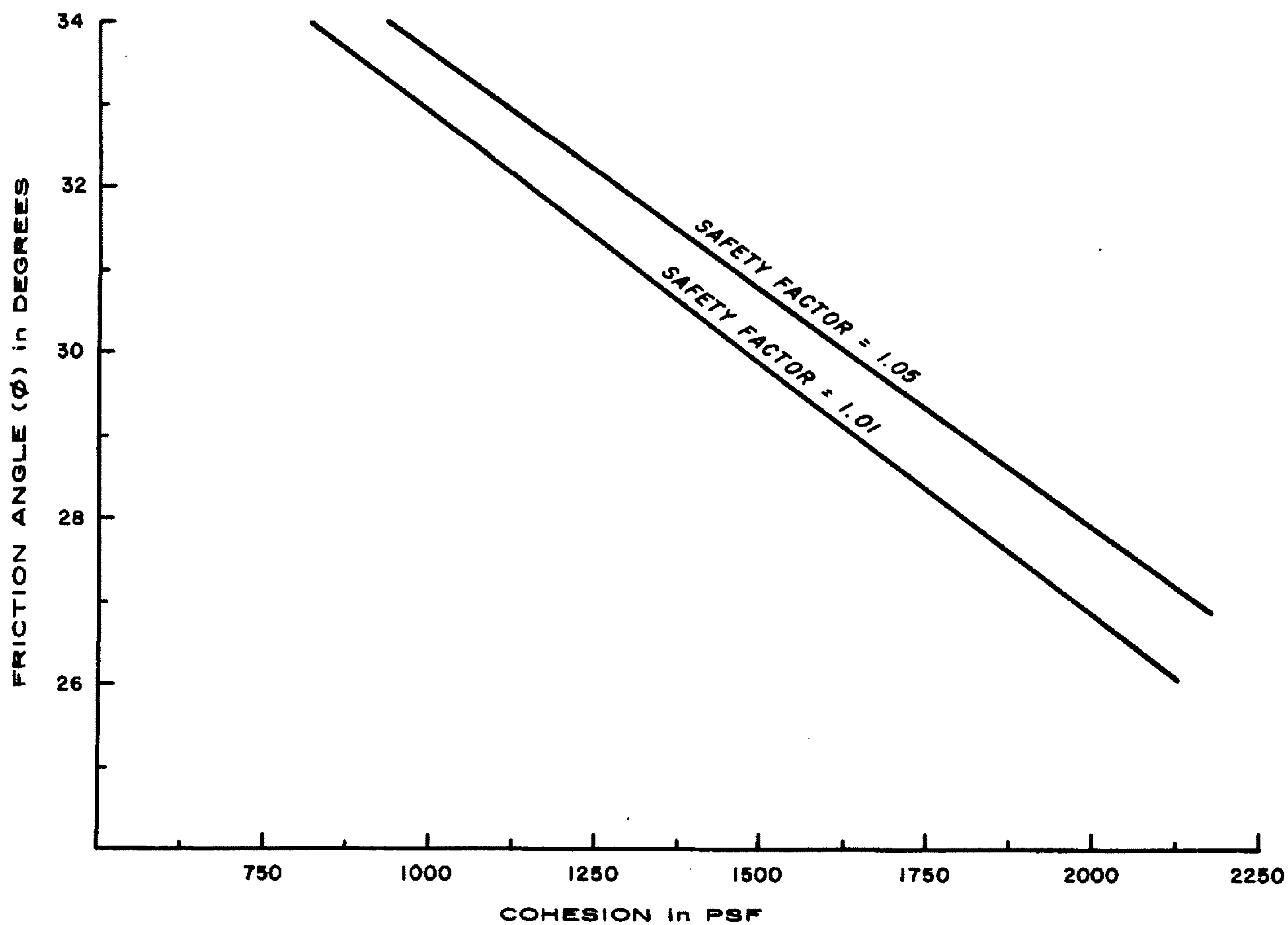


FIGURE 8

SENSITIVITY BACK-ANALYSIS
NORTH CENTRAL SECTION

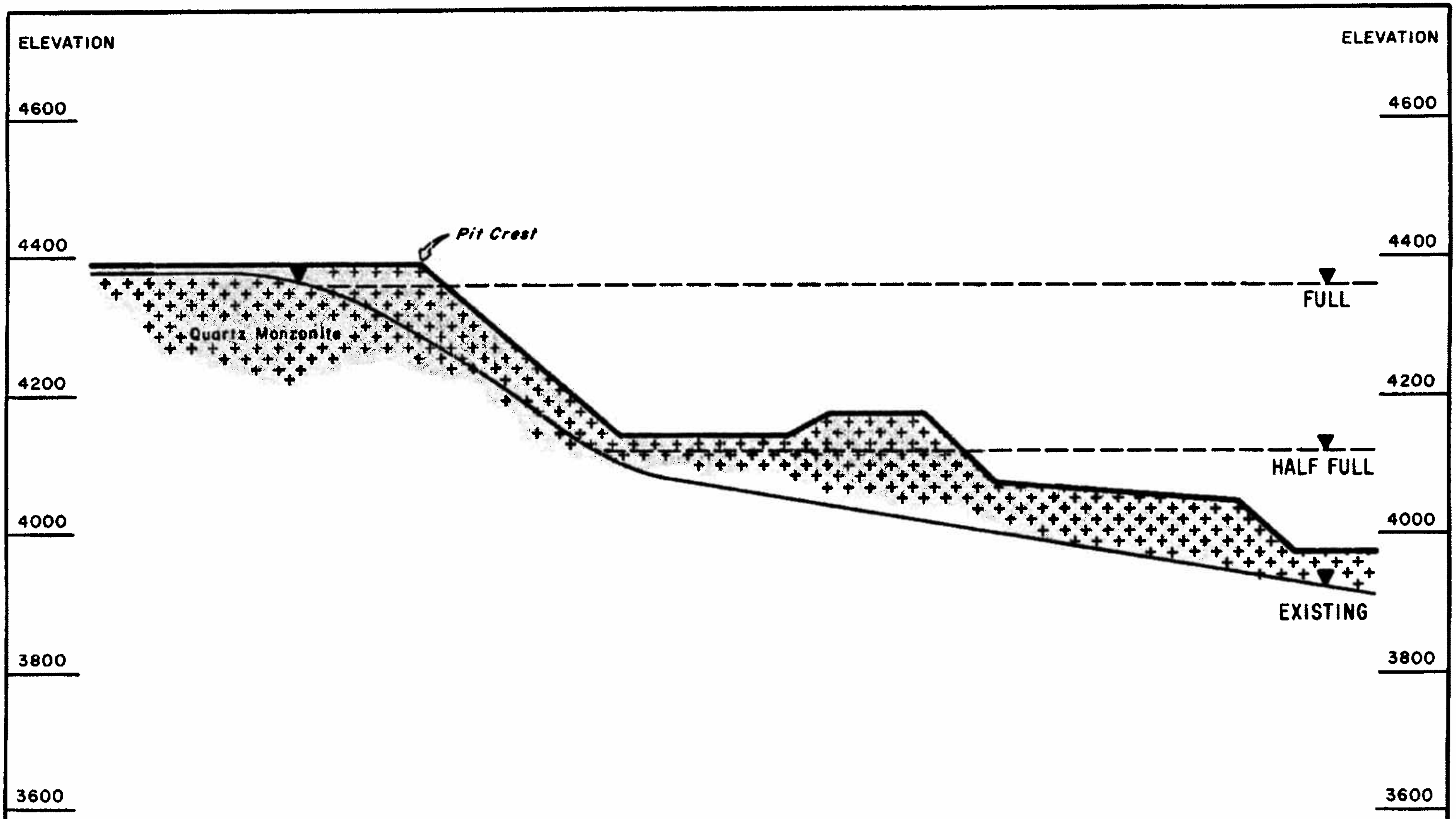


FIGURE 9

YERINGTON OPEN PIT MINE
EAST ANALYSIS SECTION

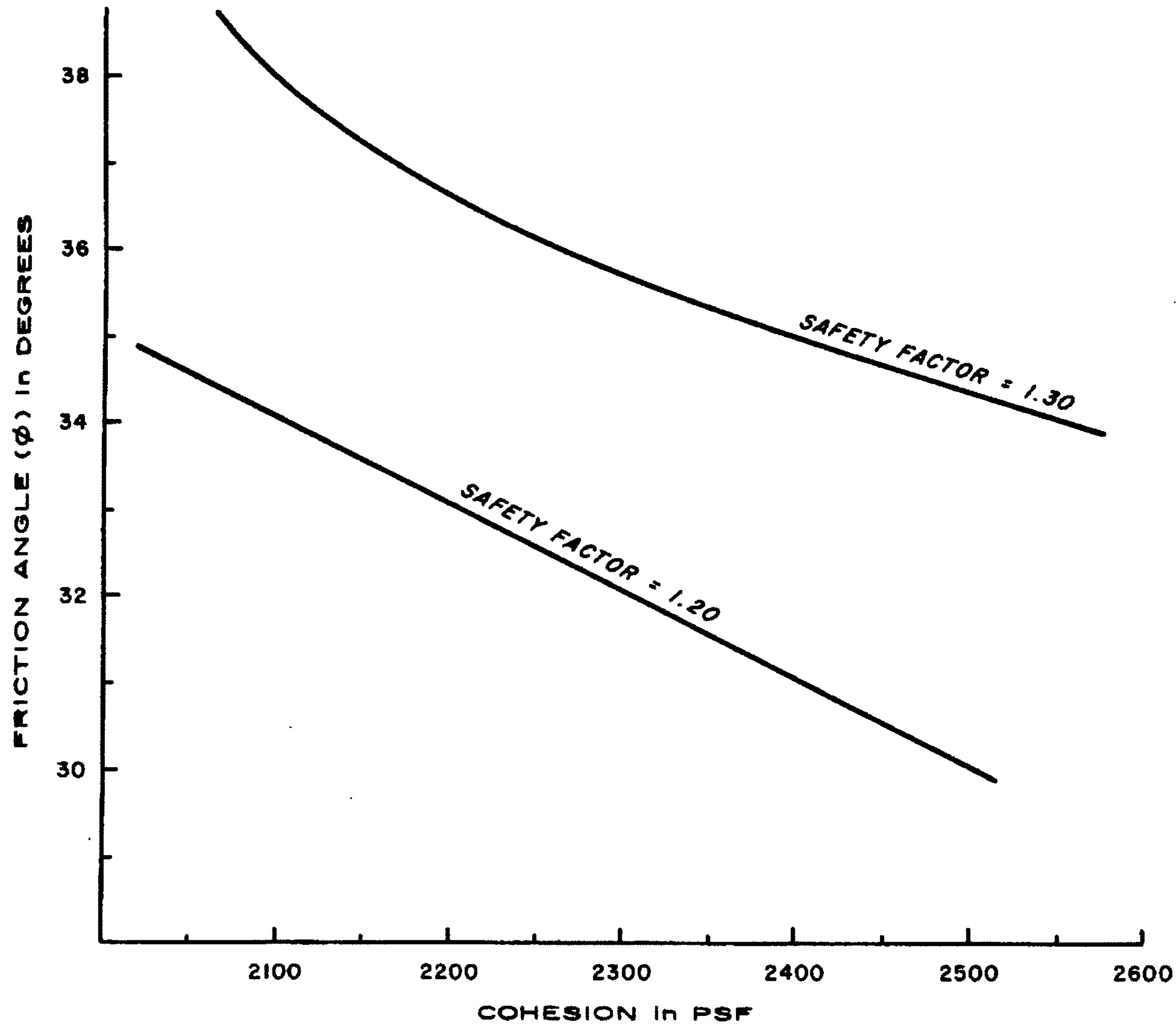


FIGURE 10

SENSITIVITY BACK-ANALYSIS
EAST SECTION

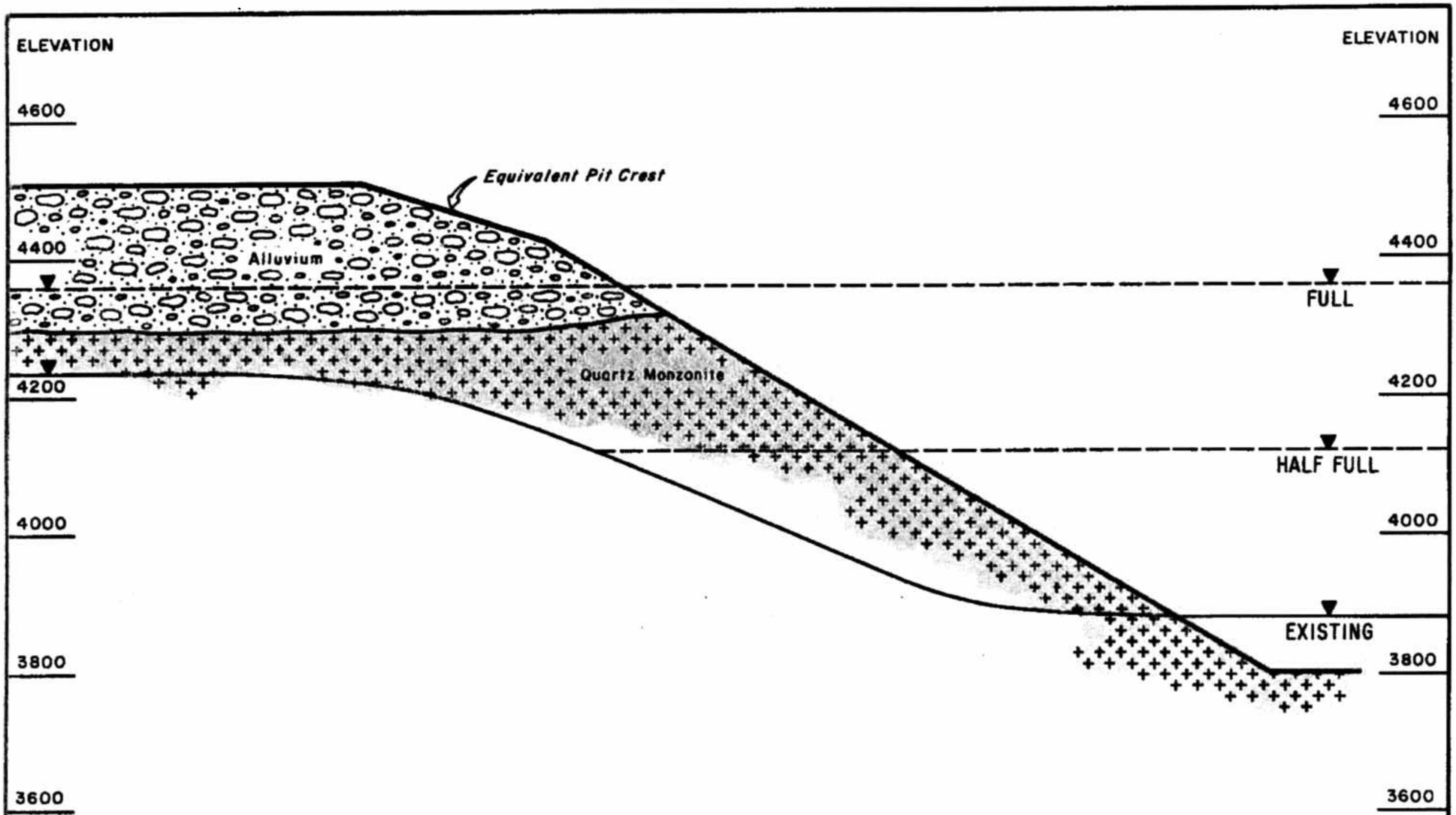


FIGURE 11

YERINGTON OPEN PIT MINE
SOUTH ANALYSIS SECTION

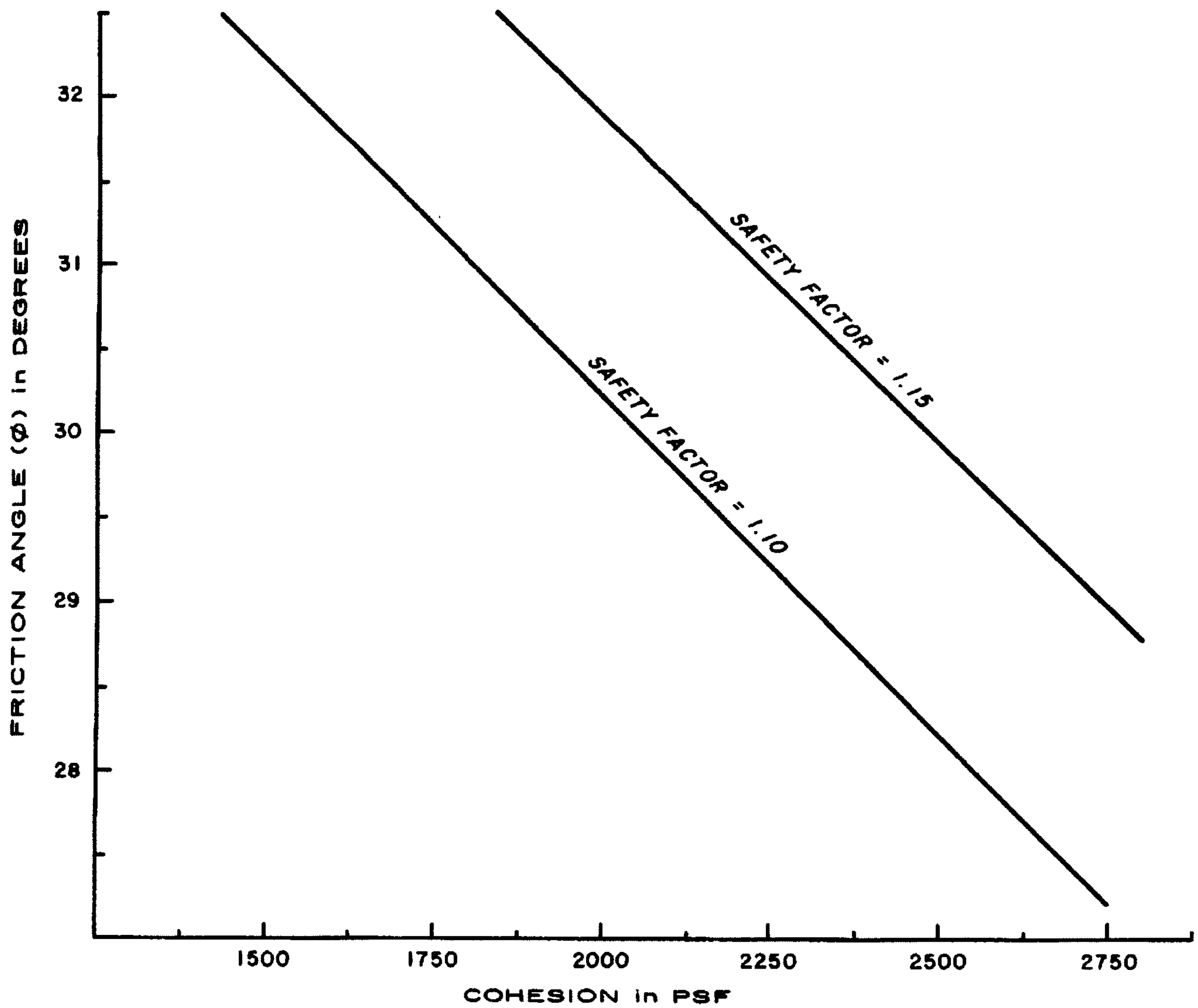


FIGURE 12

SENSITIVITY BACK-ANALYSIS
SOUTH SECTION

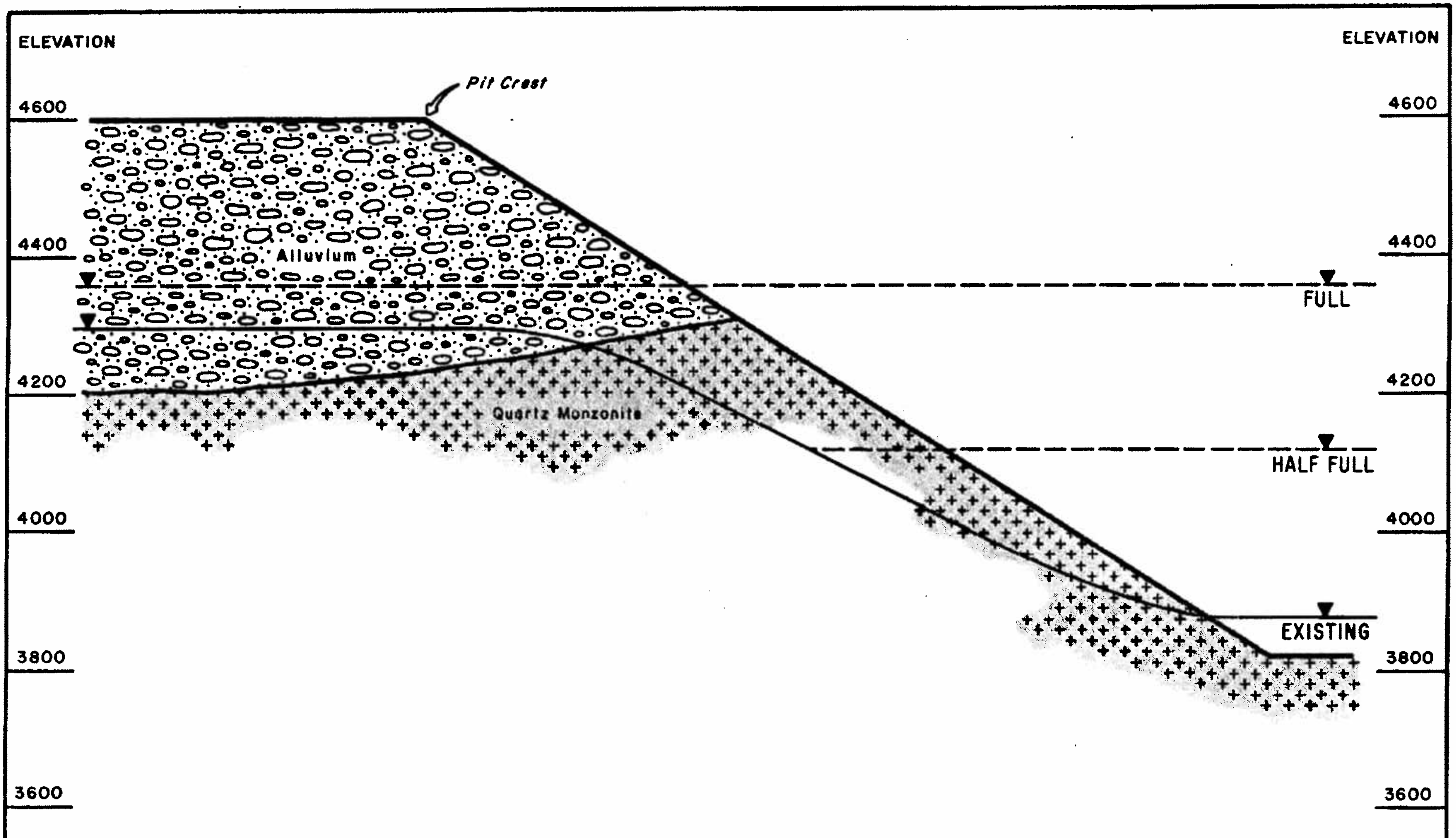


FIGURE 13

YERINGTON OPEN PIT MINE
WEST ANALYSIS SECTION

SEEGMILLER ASSOCIATES

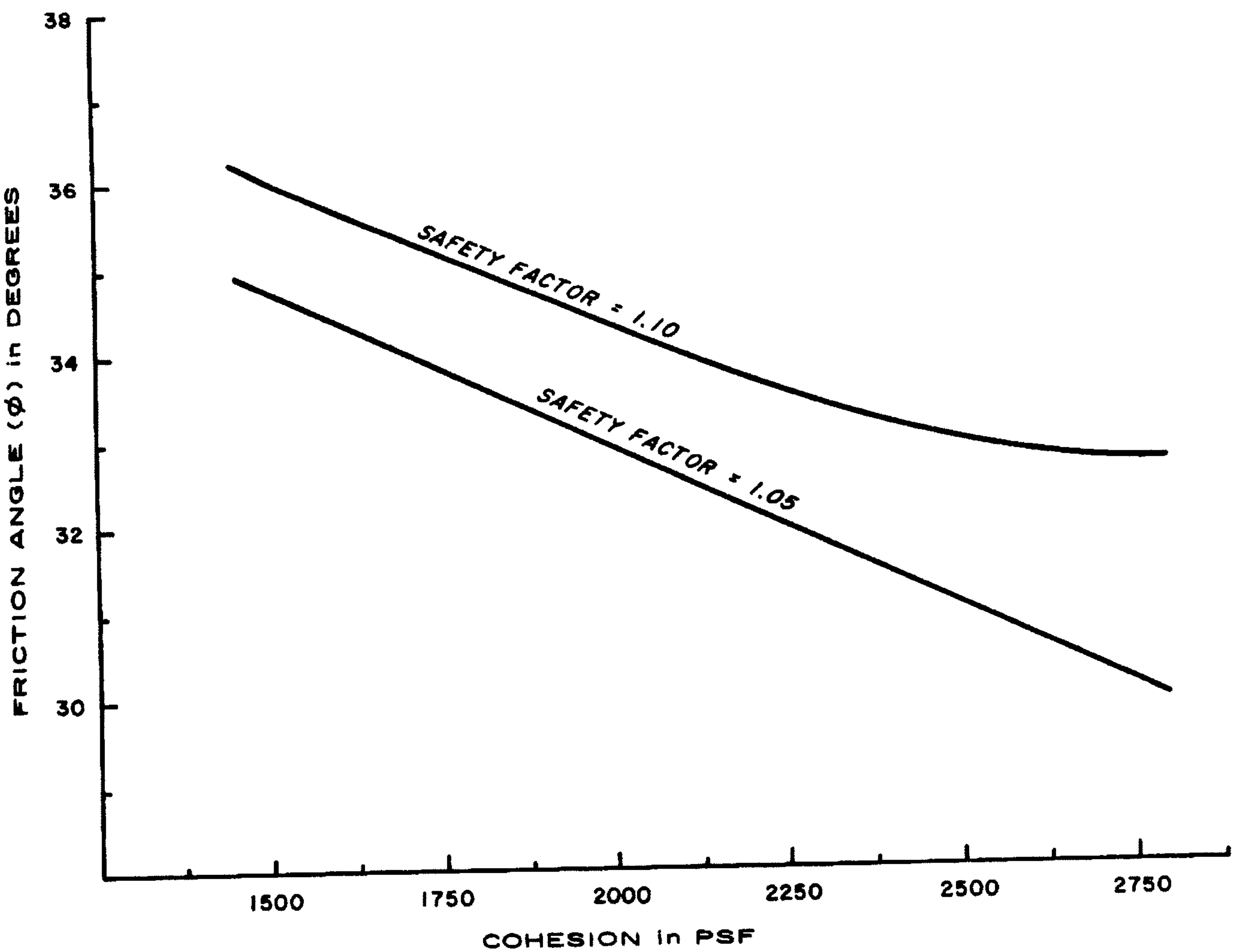


FIGURE 14

SENSITIVITY BACK-ANALYSIS
WEST SECTION

TABLE I

FACTORS OF SAFETY AGAINST CIRCULAR FAILURE

Analysis Section	Water Condition: Half-Full			Water Condition: Full		
	Most Probable Condition	5% Probability	1% Probability	Most Probable Condition	5% Probability	1% Probability
Northwest	0.96	0.84	0.73	0.82	0.70	0.66
North Central	0.96	0.83	0.75	0.80	0.71	0.66
East	1.25	0.98	0.69	1.11	0.89	0.58
South	1.08	0.93	0.80	0.95	0.84	0.74
West	1.00	0.88	0.76	0.88	0.79	0.70

TABLE II

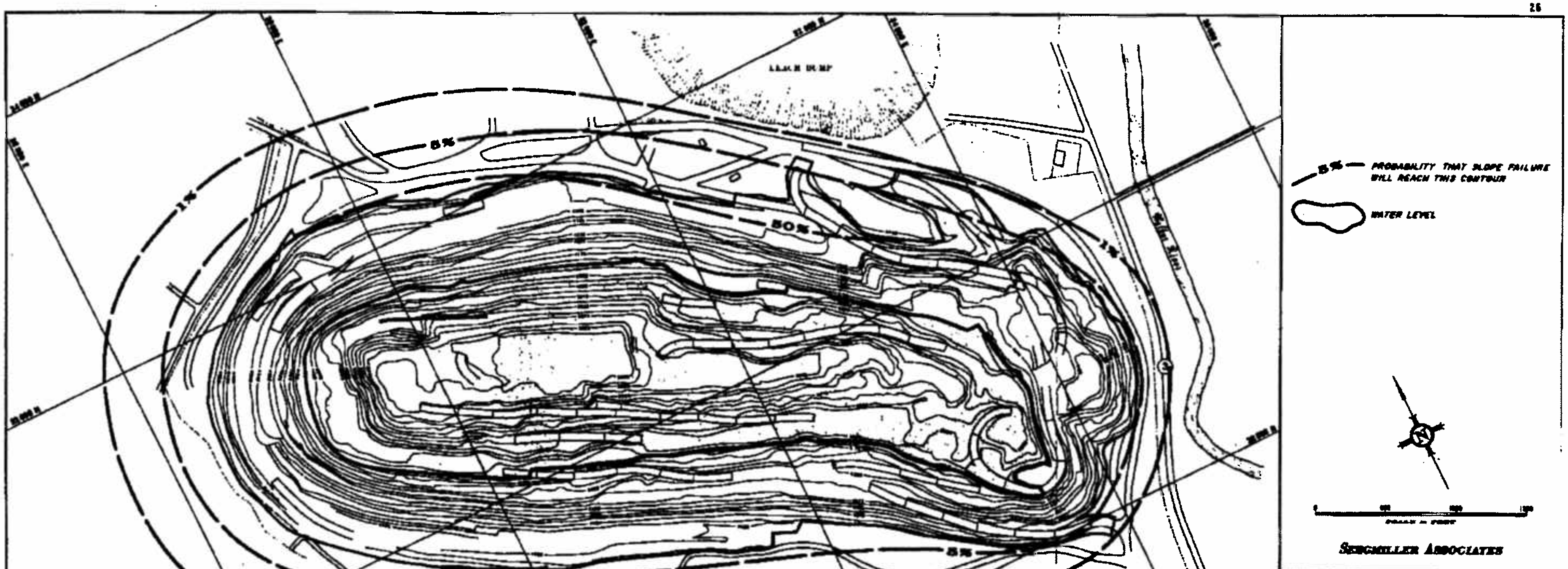
POTENTIAL SLOPE CONDITIONS: HALF-FULL OF WATER

Analysis Section	Existing Slope Angle	Most Probable Condition			5% Chance of Failure		1% Chance of Failure	
		Approximate Failure Probability	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle
Northwest	33.0°	50%	45ft	30.5°	340ft	25.0°	665ft	21.0°
North Central	31.0°	50%	100ft	29.0°	515ft	22.5°	745ft	19.5°
East	40.0°	10%	0ft	40.0°	20ft	38.5°	220ft	26.0°
South	30.0°	35%	0ft	30.0°	210ft	26.5°	650ft	21.0°
West	32.5°	50%	0ft	32.5°	350ft	26.5°	770ft	21.5°

TABLE III

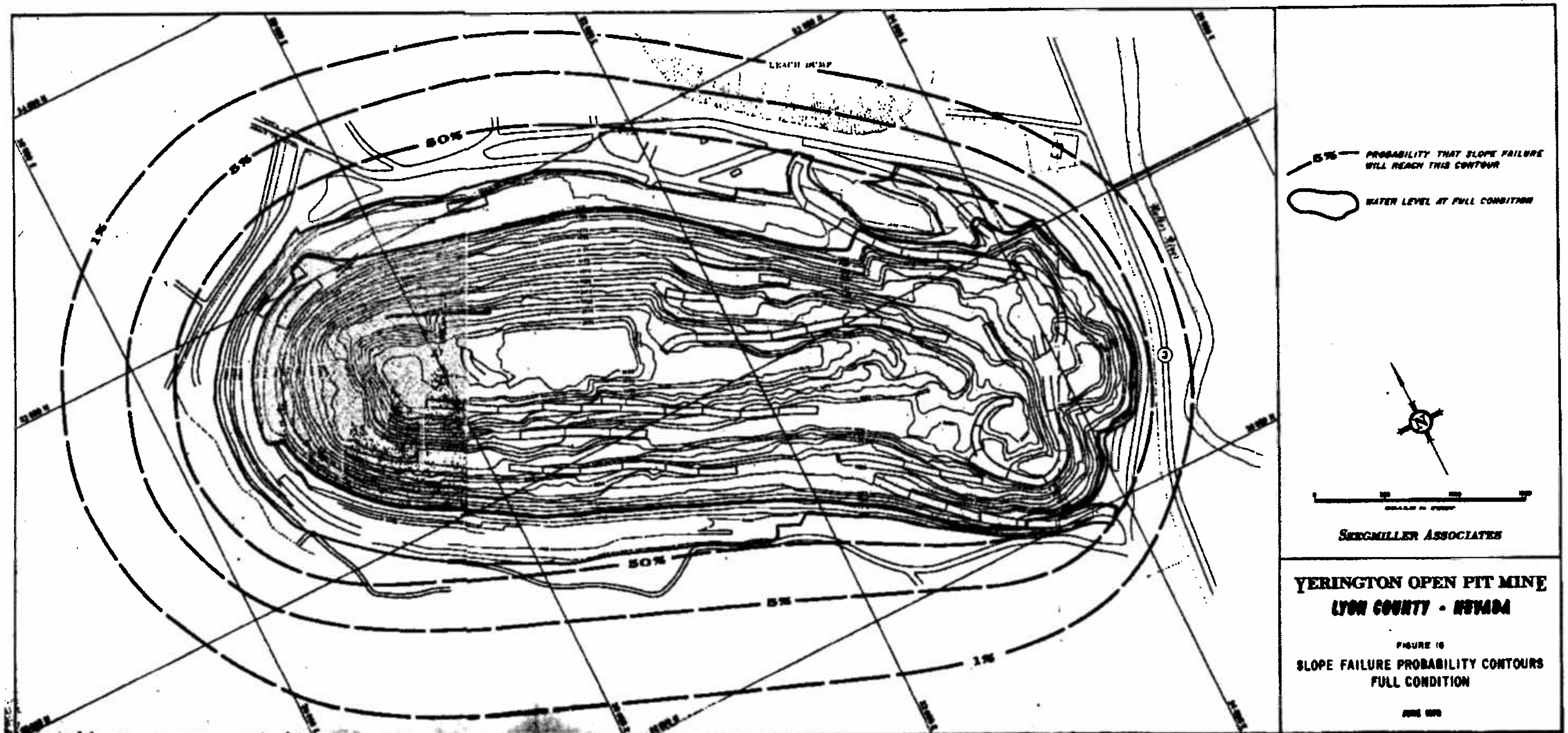
POTENTIAL SLOPE CONDITIONS: FULL OF WATER

Analysis Section	Existing Slope Angle	Most Probable Condition			5% Chance of Failure		1% Chance of Failure	
		Approximate Failure Probability	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle	Failure Distance Limit Beyond Pit Crest	Ultimate Slope Angle
Northwest	33.0°	50%	380ft	24.5°	775ft	19.5°	1075ft	17.0°
North Central	31.0°	50%	585ft	21.5°	930ft	17.5°	1215ft	15.0°
East	40.0°	30%	0ft	40.0°	85ft	33.5°	370ft	20.5°
South	30.0°	50%	170ft	27.5°	555ft	22.0°	1180ft	16.5°
West	32.5°	50%	320ft	27.0°	665ft	22.5°	1110ft	18.5°



YERINGTON OPEN PIT MINE
LYON COUNTY · NEVADA

FIGURE 15
SLOPE FAILURE PROBABILITY CONTOURS
HALF-FULL CONDITION


LEACH DUMP
50%
5%
1%
5% PROBABILITY THAT SLOPE FAILURE WILL REACH THIS CONTOUR
WATER LEVEL AT FULL CONDITION
SEEGMILLER ASSOCIATES
YERINGTON OPEN PIT MINE
LYON COUNTY - NEVADA
FIGURE 16
SLOPE FAILURE PROBABILITY CONTOURS
FULL CONDITION

SUMMARY AND CONCLUSIONS

In summary it is the opinion of Seegmiller Associates that if the Yerington Pit is used for water storage, the following conclusions are valid relative to pit slope instability:

1. *Slope Failure Mode* - The failure mode, or type of slope failure, will predominately be the circular soil type which has historically occurred at Yerington. Such slope failures will include headwall tension cracks at distances of several hundreds of feet beyond the actual slope failure. There will be slumping and subsidence between the pit and the outermost tension cracks. Both vertical and horizontal movement will take place.

2. *Slope Failure Initiation* - Signs of instability will probably become evident prior to the water level reaching the half-full condition at elevation 4120. Such instability is most likely to occur along the north slope of the pit.

3. *Slope Failure Rate* - The rate of slope failure will be directly related to the rate at which water enters the pit. At the half-full water condition, the safety factors are most probable at values slightly less than 1.00 or the theoretical beginning point of failure. In other words a major disequilibrium does not exist, only a minor disequilibrium. Therefore, at the half-full water condition the failure rate should be relatively slow as it has historically been. At the full water condition the safety factor drops to a magnitude of 0.80 in the north central zone which would indicate a higher failure rate than at the half-full water condition. The failure rate would probably still be relatively slow, but it would probably be faster than observed historically. In summary it is believed that catastrophic slope failure would occur with less than a 5% probability

unless the pit is filled with water over a very short period of time such as two months or less.

4. *Slope Failure Extent* - The extent of potential slope failure has been examined in terms of the probability of its occurrence. In general, the practical limit of slope instability and related surface disruption is on the order of 1200-1300 feet beyond the present pit crest. Related problems beyond that distance are believed to have less than a 1% probability of occurrence. The worst case is in the north central zone of the pit and the best case is in the east end of the pit, where any instability affects should be limited to within 400 feet of the crest. The leach dumps in back of the north central portion of the pit appear to have about a 20% probability of being involved in a slope instability at the full water condition. Such instabilities in the leach dump should, from a practical standpoint, not be so great that if their occurrence appears imminent, effective remedial action could be implimented to alleviate or minimize the problem.

RECOMMENDATIONS

Should it be decided that water storage in the Yerington Pit will be undertaken in spite of the potential adverse slope instabilities, the following are recommended:

1. *Water Entry Rate* - The rate of entry of water into the pit should not be rapid. That is, it is not recommended that the pit be filled, if it is ever possible, over a matter of weeks or even several months. Rather it is recommended that the filling rate be over a period of 6 to 12 months or more. The longer the period of time, the better it will be because the rock mass will have longer to adjust to the disequilibrium conditions imposed on it. Catastropic failure probability will be greatly diminished with a low water filling rate.

2. *Displacement Monitoring* - Irregardless of what water filling rate is used, the displacements of the pit slopes should be monitored. This could be accomplished with a simple survey net using a light ranging instrument such as a Hewlett Packard 3800 or similar surveying device. The instrument would measure changes in distances to specific monitoring points and the three-dimensional location of points could be closely monitored using the methods described in Appendix I. Such displacement monitoring would serve a dual purpose in that (1) the inception of catastropic failure may be discerned days or even weeks in advance and (2) the limits of slope movement beyond the pit crest could be accurately measured as a function of pit water level.

3. *Leach Dump Remedial Action* - In the event that slope instability reaches back to the leach dump beyond the north pit crest, several remedial action methods may be employed. First of all, if it appears that slope instability will ultimately reach the dump, as determined by the above

displacement monitoring recommendations, the water level in the pit should not be increased. Secondly, the dump, or at least a portion of it, may be moved to a location beyond the projected limits of slope failure. If that is not possible, then non-leach material could be piled in front of the dump to contain and prevent any of it sliding into the pit contaminating the water.

4. *Recreational Usage of Pit Area* - Prior to usage of the pit area as a recreational site for boating or other activities involving the general public, a 3 to 5 year waiting period should be implimented. During that period of time the water level in the pit should be raised and lowered several times during which displacement monitoring of the pit slopes should be undertaken. Only when it has been determined by an engineering authority that the pit area is safe, should the general public be allowed to have access to it for recreational or other purposes.

APPENDIX I

SLOPE MOVEMENT DETECTION: Computerized Method Using A Light Ranging Instrument

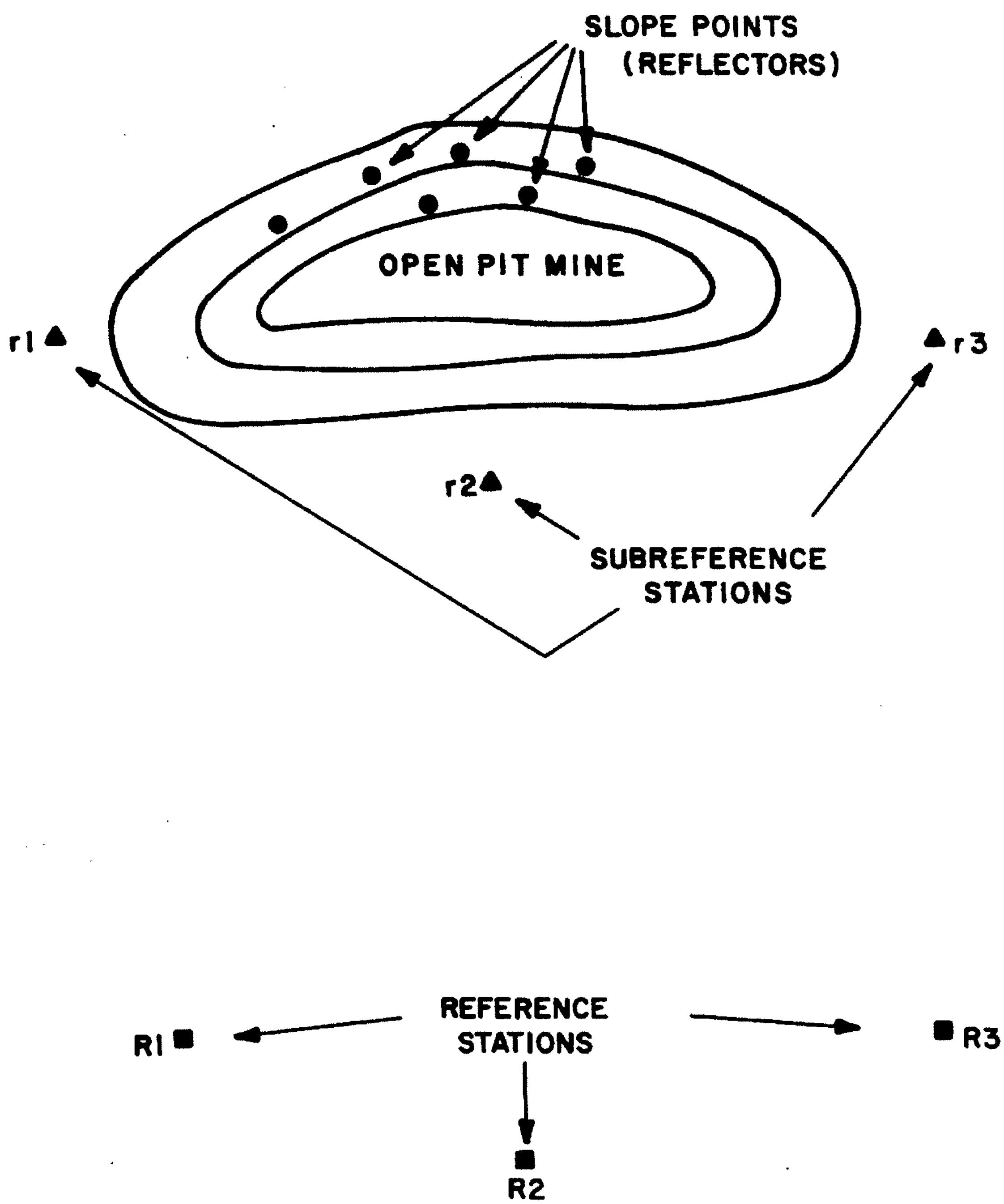


FIGURE I-1

REFERENCE LAYOUT FOR 'SURVEY' MONITORING SYSTEM

The problem can be visualized as a series of interconnected tetrahedra with the reference stations forming the base and the edges to the fourth vertex being the distances measured. Figure I-2 illustrates this basic tetrahedra for one of the subreference points. Considering this basic tetrahedra, the coordinates of the three reference points are known and the distance from each reference point to the subreference point is measured. The solution to the problem will be the coordinates of the subreference station. This solution is given by a set of non-linear simultaneous equations having eight real and imaginary solutions. The number of solutions can be reduced to two by transforming the reference points, both rotationally and translationally, so that one point is at the origin, another on the positive x-axis and the third in the x-y plane. Through application of this porcedure three times the coordinates of the three subreference points can be determined with respect to the three reference points.

By using the determined coordinates for the subreference points as the known vertices of three additional tetrahedra the coordinates of a slope point can be calculated in the same manner. Using the transpose of the transformations used to orient the system, results in the coordinates of the slope point being given in terms of the original fixed reference system.

Problem Example

The following sample problem is presented to illustrate the program input and output. Figure I-3 illustrates the layout of a hypothetical problem showing three reference points, three subreference points and one slope point. The lines represent the distances which are measured. It should be noted that although a total of four distances need to be measured from each subreference point for one slope point there is only one additional measurement necessary from each subreference point for each additional slope point. The following coordinates and distances are required as input data:

I. Reference Stations coordinates:

	North	East	Elevation
R1	0.0000	700.0000	950.0000
R2	750.0000	1850.0000	1038.0000
R3	1600.0000	300.0000	1014.0000

II. Distance from reference to subreference stations:

Reference Stations

	R1	R2	R3
r1	721.2660	1558.9510	1001.2000
r2	651.9200	852.4930	1503.6940
r3	1107.0570	861.7100	934.2080

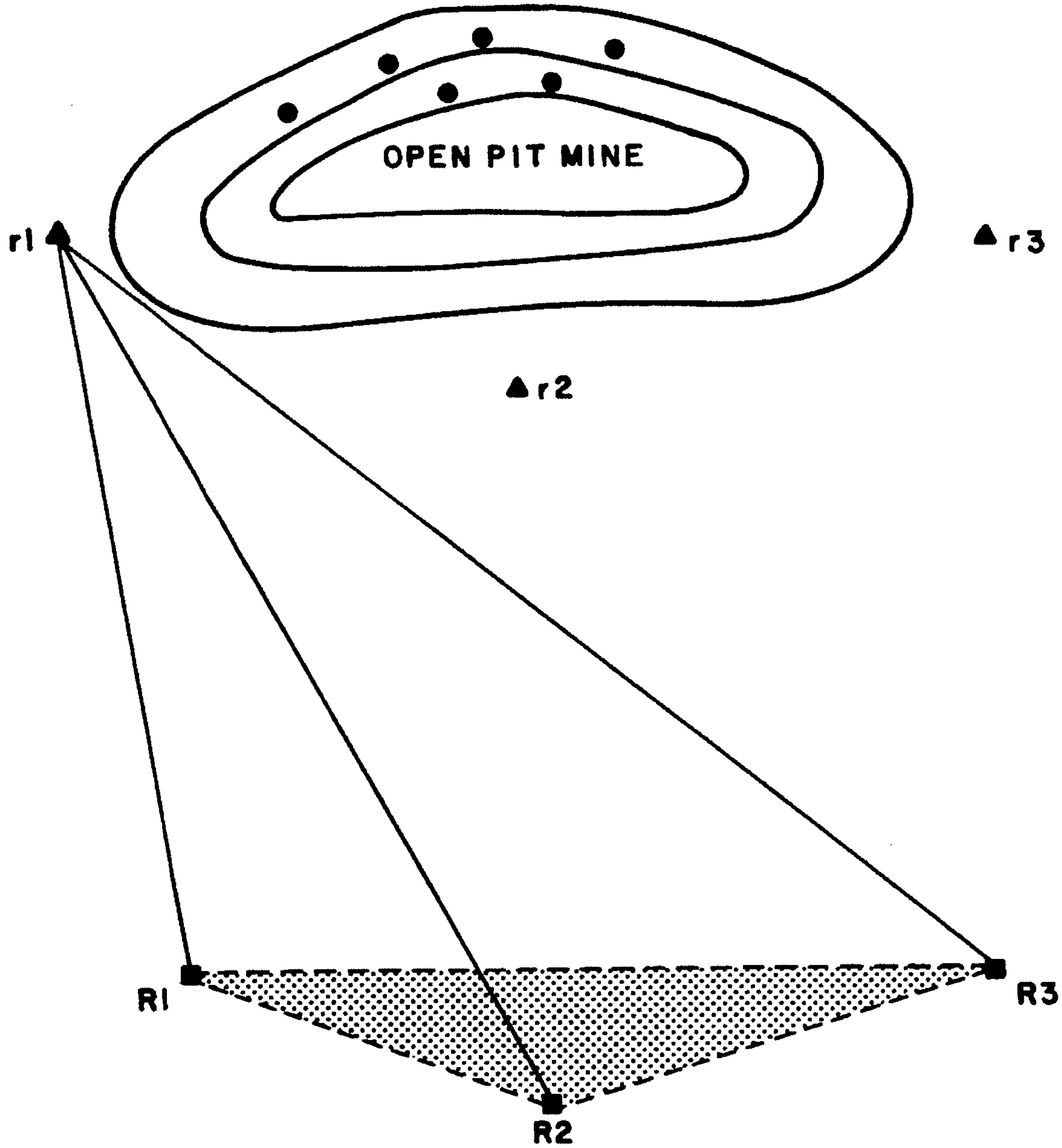


FIGURE I-2

BASIC TETRAHEDRA

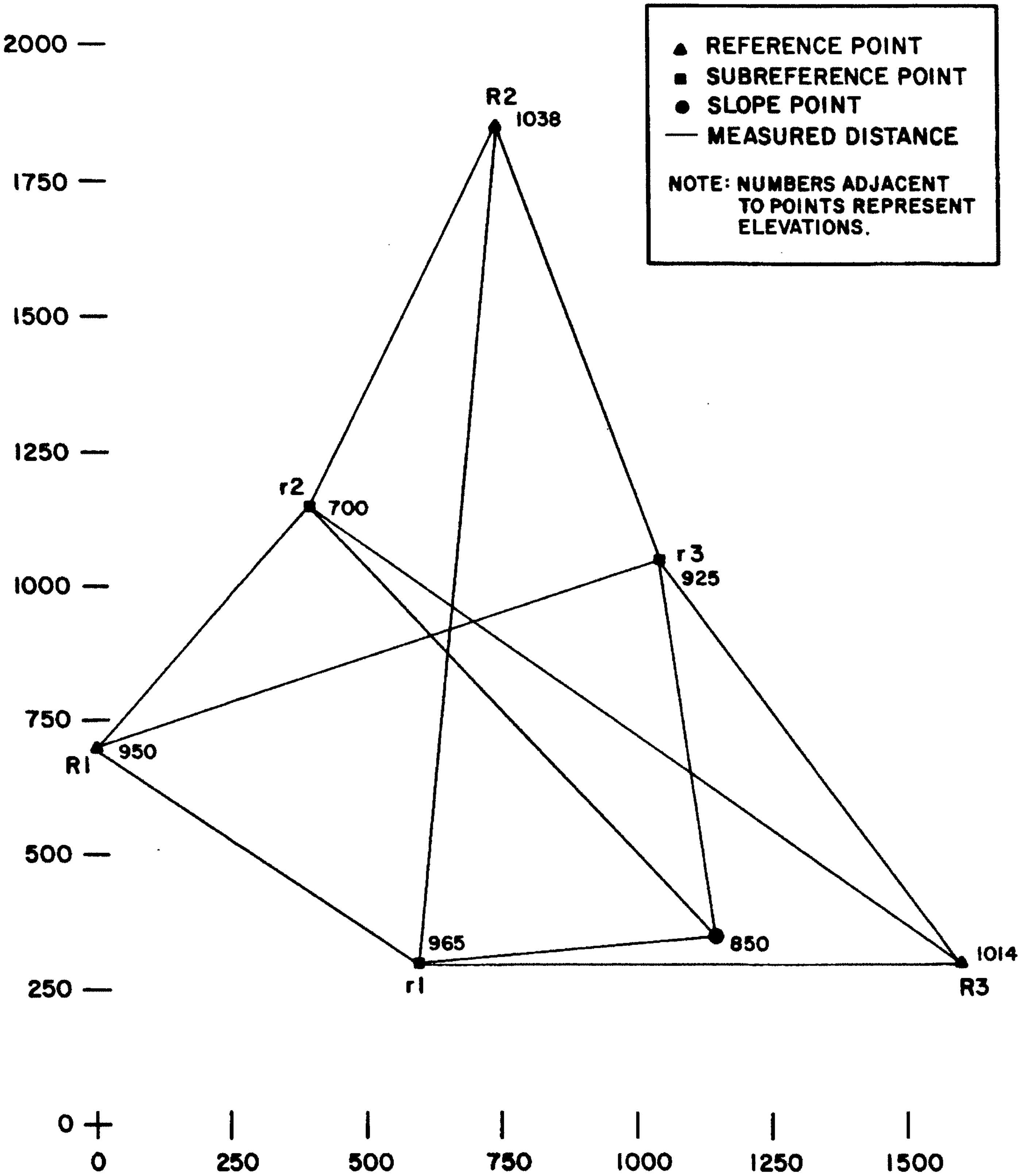


FIGURE I-3

'SURVEY' SAMPLE PROBLEM LAYOUT

III. Original Distance from subreference stations to the slope point:

r1	564.1120
r2	1106.7957
r3	711.1787

IV. Present Distance from subreference stations to the slope point:

r1	564.1135
r2	1106.7976
r3	711.1795

The output data from the computer program includes the following data:

I. Reference Station coordinates:

	North	East	Elevation
R1	0.0000	700.0000	950.0000
R2	750.0000	1850.0000	1038.0000
R3	1600.0000	300.0000	1014.0000

II. Distances from reference to subreference stations:

Reference Stations

	R1	R2	R3
r1	721.2660	1558.9510	1001.2000
r2	651.9200	852.4930	1503.6940
r3	1107.0570	861.7100	934.2080

III. The calculated subreference station coordinates:

	North	East	Elevation
r1	599.9986	299.9992	965.0244
r2	399.9999	1149.9998	700.0001
r3	1049.9996	1050.0000	925.9987

IV. The original coordinates of the slope point:

North	East	Elevation
1149.9957	349.9983	850.0120

V. The present coordinates of the slope point:

North	East	Elevation
1149.9956	349.9976	850.0135

VI. The change in coordinates of the slope point, indicating the three dimensional movement:

North	East	Elevation
-0.0001	-0.0007	0.0015

Water Quality and Limnologic Conditions in Three Existing Pit Lakes, Winter 1996

Prepared for:

Santa Fe Pacific Gold Corporation
Golconda, Nevada

June 1996

PTI

1. ANACONDA PIT LAKE

1.1 ANACONDA FIELD PARAMETERS

During the winter sampling event (early March), the Anaconda pit lake was isothermal, with a water temperature of 6.5° to 7.5 °C throughout the maximum depth of measurement (321 ft, Figure 1-1). The isothermal conditions and uniform density profile indicate that the lake was completely mixed. Specific conductance tended to increase slightly with depth, (850 µs/cm at the surface and 880 µs/cm at 321 ft). The dissolved oxygen (DO) profile indicates that hypolimnion oxygen was replenished during turnover (Figure 1-2). DO concentrations from the surface to a depth of 125 ft (38 m) were 10–11 mg/L. Beyond 150 ft (46 m), the DO concentration decreased to ~7 mg/L, suggesting that the lake was beginning to re-stratify. The winter pH profile was not significantly different from that of the summer, although the pH was generally ~0.5 units lower. The Eh of the lake was fairly constant (~500 mV) with depth, and 50–100 mV greater than that observed during the summer sampling event.

1.2 AQUEOUS CHEMISTRY

Water samples were collected at two depths, and the major ion and nutrient contents (Table 1-1) of the two samples were not significantly different from those observed during the summer sampling, with minimal depth dependency. Calcium (~95 mg/L) and sodium (~79 mg/L) remained the dominant cations, while sulfate (~290 mg/L) remained the dominant anion.

The total dissolved phosphorus concentration was 3.9 µg/L in the shallow sample, and 5.8 µg/L in the deep sample. Total particulate phosphorus in these samples was 5 µg/L and 3 μg/L, respectively, indicating that the lake-total phosphorus concentrations (total dissolved + total particulate) had increased from <5 μg/L in the summer samples, to approximately 9 μg/L in the winter samples. Similarly, ammonia, which was not detected in the summer samples (<0.01 mg/L), was at a concentration of 0.015 mg/L and 0.011 mg/L in the shallow and deep winter samples, respectively. Furthermore, nitrate concentrations, 0.1005 mg/L and 0.1250 mg/L in the shallow and deep samples, were slightly higher than the summer sample concentrations (0.08 mg/L).

Trace metal concentrations (Table 1-2) were similar at the two depths. Antimony, arsenic, barium, boron, copper, manganese, nickel, selenium, and zinc were detected at concentrations that were not significantly different from those measured in samples collected during the summer, with one exception. The dissolved copper concentration in the shallow sample was 77 μg/L, but no copper was detected in the summer epilimnion sample.

Arsenic and mercury concentrations were similar to those measured during the summer. Total arsenic concentrations were ~3.5 μg/L, and more than 90 percent of the total arsenic was present as As^{+5}. Dimethylarsenic acid in the deep sample (0.15 μg/L) was the only methylated arsenic species detected at either depth. Mercury methylation was minimal in both samples (~2 ng/L total mercury and ~0.5 ng/L methyl mercury at both depths).

1.3 PHYTOPLANKTON AND ZOOPLANKTON

The phytoplankton population shifted from predominantly green to predominantly blue-green algae from summer to winter. Species identified included six genera of green algae (which made up 7 to 33 percent of the total phytoplankton density in the two samples) and three genera of blue-green algae (67 to 93 percent of the total phytoplankton density) (Table 1-3). *Chlorella sp.* and *choricystis sp.* were the predominant species of green algae in the two samples, and *Jaaginema subtilissiumum* was the predominant blue-green algae. The dominance of blue-green algae in the winter samples is a significant change from what was observed in the summer samples, which were made up of 66 to 88 percent green algae.

Zooplankton species identified during winter sampling included one species of adult copepod (Class Copepoda), immature copepod larvae (nauplii), and four species of rotifers (Table 1-4). Copepods made up 6 and 18 percent of the total zooplankton in the two samples, while rotifers made up 82 and 94 percent of the total. Cyclopoid nauplius was the predominant copepod, and a species of the Order Bdelloidea was the predominant rotifer. Although the lake exhibited no shift in zooplankton speciation between summer and winter, the total number of zooplankton was nearly ten times smaller than that observed during the summer sampling event.

TABLE 1-1. ANACONDA LAKE WATER COLUMN MAJOR ION AND NUTRIENT ANALYTICAL RESULTS

(All units mg/L)

Analyte	Shallow Sample (Depth = 4.6 m)	Deep Sample (Depth = 61 m)
Ammonia as N	0.0145 [a]	0.011
Nitrate as N	0.1005 [a]	0.125
Total Dissolved Phosphorus	0.0039 [a]	0.0058
Total Particulate Phosphorus	0.005 [a]	0.003
Silica	32.3 [a]	31.5
Chlorophyll a	0 [a]	0
Turbidity	0.578	0.588
TDS	552	576
TOC	1.0 U	1.0 U
DOC	1.4	1.0 U
Chloride	37.6	37.4
Fluoride	1.3	1.3
Sulfate	284	293
Calcium (total)	86.9	91.8
Calcium (dissolved)	91.5	97.7
Magnesium (total)	15.3	15.4
Magnesium (dissolved)	16.3	16.6
Potassium (total)	4.33	5.13
Potassium (dissolved)	5.36	5.47
SiO_2 (total)	32.9	31.4
SiO_2 (dissolved)	34.7	33.4
Sodium (total)	74.2	73.0
Sodium (dissolved)	77.8	79.8

[a] Average of duplicate samples.
U = Not detected; value represents detection limit.

TABLE 1-2. ANACONDA LAKE WATER COLUMN TRACE ELEMENT ANALYTICAL RESULTS

(All units μg/L)

Analyte	Shallow Sample (Depth = 4.6 m)	Deep Sample (Depth = 61 m)
Antimony (total)	6	9
Antimony (dissolved)	7	8
Arsenic (total)	3.66 [a]	3.03
Arsenic (dissolved)	3	2
As^{+3}	0.17 [a]	0.007 U
As^{+5}	3.1 [a]	2.66
Monomethyl arsonic acid	0.045 U[a]	0.045 U
Dimethyl arsenic acid	0.15 [a]	0.040 U
Aluminum (total)	21 U	43
Aluminum (dissolved)	21 U	21 U
Barium (total)	33	30
Barium (dissolved)	33	32
Beryllium (total)	1 U	1 U
Beryllium (dissolved)	1 U	1 U
Boron (total)	402	387
Boron (dissolved)	412	396
Cadmium (total)	2.4 U	2.4 U
Cadmium (dissolved)	2.4 U	2.4 U
Chromium (total)	5 U	5 U
Chromium (dissolved)	5 U	5 U
Copper (total)	81	148
Copper (dissolved)	77	153
Iron (total)	24 U	32
Iron (dissolved)	24 U	24 U
Lead (total)	1 U	2
Lead (dissolved)	1 U	1 U
Manganese (total)	22	59
Manganese (dissolved)	23	64
Mercury (total)[b]	0.0019 [a]	0.00224 [c]
Mercury (dissolved)[b]	0.2 U	0.2 U
Methyl Mercury[b]	0.000045 (U)[a]	0.000041 [c]
Nickel (total)	17 U	17 U
Nickel (dissolved)	17	17 U
Selenium (total)	109	95
Selenium (dissolved)	122	97
Silver (total)	3 U	3 U
Silver (dissolved)	3 U	3 U
Thallium (total)	1 U	1 U
Thallium (dissolved)	1 U	1 U
Zinc (total)	4	6
Zinc (dissolved)	3	4

[a] Average of duplicate samples.

[b] For mercury analyses, total mercury and methyl mercury were analyzed using ultra-clean sampling techniques. Dissolved mercury was analyzed by ICP and thus has a higher detection limit.

[c] Sample taken at a depth of 100 ft.

U = Not detected; value represents detection limit.

(U) = Value is the average of two results, one of which was a non-detect.

TABLE 1-3. ANACONDA PIT LAKE PHYTOPLANKTON ANALYSES

(All units cells/mL)

Sample Depth Interval	0-15 m	0-15 m
Chlorophyta (Green algae)		
Chlamydomonas snowii	63	281
Chlamydomonas sp.	0	63
Chlamydomonas sp.	156	63
Chlorella ellipsoidea	16	0
Chlorella sp.	1625	500
Choricystis sp.	625	13000
Oocystis solitaria	531	594
Percent contribution to tow	10%	33%
Cyanophyta (Blue-green algae)		
Aphanocapsa delicatissima	16	0
Jaaginema subtilissimum	28000	29000
Synechococcus sp.		0
Percent contribution to tow	90%	67%
Total	31032	43501

TABLE 1-4. ANACONDA PIT LAKE ZOOPLANKTON ANALYSES

(All units number/sample)

Sample Depth Interval	0-30 m	0-30 m
Number of tows	4	4
Copepoda		
Paracyclops fimbriatus poppei (female)	2	1
Cyclopoid nauplius	75	45
Percent contribution to tow	18%	6%
Rotifera		
Bdelloid rotifer	226	690
Cephalodella sp.	1	2
Colurella sp.	30	0
Lepadella sp.	91	60
Percent contribution to tow	82%	94%
Total Density	425	798

LIMNOLOGIC CONDITIONS IN THREE EXISTING NEVADA PIT LAKES: OBSERVATIONS AND MODELING USING CE-QUAL-W2

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Golconda, Nevada 89414

ABSTRACT

Limnologic processes that influence the evolution of mine pit lakes include the production of biomass and hydrodynamic mixing. Biological productivity may influence wildlife use, and when combined with lake hydrodynamics, affects the dissolved oxygen distribution and the corresponding chemical reactions within the lake.

Limnologic parameters (temperature and dissolved oxygen profiles, plankton speciation and abundance, and nutrient concentrations) were measured in three existing pit lakes in Nevada to develop a database to support predictions of limnologic conditions in future mine pit lakes. Two of the lakes were thermally stratified during summer sampling and completely vertically mixed during winter, whereas the third lake was completely mixed in summer and winter. The first lake formed when an open-pit copper mine was flooded by rebounding groundwater; it has a maximum depth of 110 m, and is seasonally stratified, well oxygenated, and oligotrophic. The second lake formed in an open-pit gold mine, has a maximum depth of 17 m, and is a seasonally stratified, mesotrophic lake that develops an anoxic hypolimnion at the end of the summer stratified period. The third lake also formed in an open-pit gold mine, has a maximum depth of 7 m, and is an isothermal, saline, well-oxygenated, oligotrophic lake.

Data from the field study were used to develop limnological models of the lakes using the U.S. Army Corps of Engineers hydrodynamic and water quality model CE-QUAL-W2. The model sufficiently describes major limnologic processes, including seasonal variations in temperature and dissolved oxygen concentration, supporting the use of this model to simulate hydrodynamic conditions and biological productivity in mine pit lakes. Information from the field and modeling study is being used to simulate future limnologic conditions in lakes such as the Twin Creeks mine pit lake, which have not yet formed.

Keywords: Pit lake, limnology, hydrodynamics, biological productivity, turnover, geochemical stability, models

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INTRODUCTION

Many current and historical open-pit mine excavations in the United States extend below the regional groundwater table. Following cessation of dewatering activities at these mines, the water table rebounds, forming lakes in the open pits. To date, 17 mine pit lakes have formed in the state of Nevada (where much of the current U.S. metal mining is conducted), and 19 additional lakes are likely to form in the future (Nevada Bureau of Mines and Geology 1995).

Although these lakes are significant long-term features that may be used by humans and wildlife, very little site-specific data have been collected on their limnology. Consequently, recent pit-lake ecological risk assessments have relied on data collected from natural lakes and reservoirs, which may not accurately represent pit lakes. We studied three existing mine pit lakes in Nevada, generating data that can be compared to natural lakes, and will be useful in validating the hydrogeochemical models that are used to predict the limnology and chemical composition of these lakes.

.IMNOLOGIC PROCESSES

The important limnologic processes that influence water quality in pit lakes are hydrodynamic mixing and biological productivity (Wetzel 1983). Hydrodynamic mixing is influenced by wind speed and direction, morphology of the pit lake, length of the lake surface (fetch), and water density, which is a function of thermal and chemical gradients in the water column. Depending on site-specific conditions, these gradients may induce either relatively complete vertical mixing of the water column (e.g., the annual "turnover" of water that occurs in most lakes in temperate climates, termed holomixis), or relatively stable stratification of lake waters in which vertical mixing processes are strongly suppressed.

In some environments, lakes develop a salinity gradient at depth (a chemocline), which permanently inhibits mixing of the entire water column (meromixis). Meromixis can occur when large salinity differences exist between inflowing water and lake water (e.g., freshwater surface inflow into a saltwater lake, or saltwater intrusion into a freshwater lake) or when sediments release dissolved constituents from organic matter. Nevada pit lakes typically do not exhibit the conditions necessary to develop a chemocline. The primary source of inflow is groundwater that is uniformly distributed throughout the lake. Outflow from the lake is dominated by evaporation, which concentrates salts at the surface. These salts mix completely with the water column as the heavier surface water sinks. In addition, biological inputs to the lakes are typically low, which precludes buildup of organic matter in bottom sediments.

Nevada is in a temperate zone, where lakes generally exhibit isothermal conditions in the winter, followed by stratification in the spring and summer, with a corresponding peak in productivity. During the period of stratification, the warmer, less dense water near the surface defines the epilimnion, and the cold, more dense water near the bottom defines the hypolimnion (usually with a temperature 1–2° above 4 °C, the maximum density for pure water). The depth interval over which the water temperature changes from the epilimnion temperature to the hypolimnion temperature is termed the metalimnion, and the depth of the maximum rate of temperature change is termed the thermocline.

The surface water cools in the fall, and when its temperature reaches 4°C, the lake may dergo complete vertical mixing, or turnover, returning hypolimnetic nutrients to surface waters, uich receive enough light to support biological productivity (the euphotic zone). Lakes that mix mpletely are termed holomictic, whereas lakes that exhibit a permanent chemical density gradi-t (chemocline) do not mix completely and are termed meromictic. Temperate-zone lakes may velop ice cover in mid-winter, and when this ice cover breaks up in the spring, the lake may rn over again. Lakes that turn over once per year, in the fall, are termed monomictic, and lakes at turn over in the fall and spring are termed dimictic.

Biological productivity is determined by light intensity, nutrient availability, and types of ankton present, and temperate-zone lake productivity is most dependent on nutrient availability. most lakes, the level of productivity corresponds to the total phosphorus loading rate and corre-onding water-column concentration. Highly productive (eutrophic) lakes generally have total ater-column phosphorus concentrations greater than 0.03 mg/L, while lakes that exhibit low oductivity (oligotrophic) generally have total water-column phosphorus concentrations below 01 mg/L (Wetzel 1983). Productivity of an individual lake, however, also depends on lake orphometry, chemistry, and local climate, leading to a relatively large range in trophic status for given total phosphorus concentration, as is evidenced by the study lakes.

Together, the processes of hydrodynamic mixing and biomass production will influence e distribution of oxygen in the water column. Hence, a thorough understanding of these rocesses is necessary for predicting chemical interactions and attenuation mechanisms that are ıfluenced by the dissolved oxygen concentration and corresponding oxidation state of iron (e.g., ırption of metals to amorphous ferrous hydroxides) in the pit lake.

ESCRIPTION OF THE STUDY AREA

Nevada mine pit lakes exhibit unique morphology and hydrology, which distinguish them om natural lakes and reservoirs. These characteristics also have a profound effect on eochemistry and limnology:

- The lakes lie in highly mineralized zones, so their geochemical characteristics are highly site specific, and metals and acid loading from pit walls can influence the chemistry and toxicity of lake water.
- The hydrology is dominated by groundwater inflow, so organic carbon inputs are primarily autochthonous.
- Lake outflow often occurs primarily through evaporation, and the lakes can be highly alkaline and/or saline.
- The lakes have large relative depths (large depth-to-surface-area ratios), which can affect lake hydrodynamics.
- The steep pit walls allow only minimal shoreline development of poor-quality sediment, so the lakes exhibit little littoral-zone habitat and shore-zone vegetation (typically <1% of shore zone).

The three Nevada lakes studied represent a range of size and biological productivity. The Anaconda lake, near Yerington, began filling in an open-pit copper mine in 1977 and currently has a surface area of 175 hectares and a maximum depth of 100 m; it is a seasonally stratified, well-oxygenated, oligotrophic lake. The Aurora lake, near Hawthorne, began forming in an open-pit gold mine in 1993 and has a surface area of 1 hectare and a maximum depth of 20 m; it is a seasonally stratified lake, seasonally anoxic at depth, and mesotrophic. The Boss lake, near Tonopah, began forming in an open-pit gold mine in 1989 and has a surface area of 0.25 hectares and a maximum depth of 7 m; it is an isothermal, saline (TDS=12,000 mg/L), well-oxygenated, low-productivity lake.

METHODS

Physical parameters were measured *in situ* throughout the water column using a calibrated Hydrolab multiparameter water quality instrument. At each sampling location, the instrument was lowered through the water column, measuring temperature, specific conductivity (SC), dissolved oxygen (DO), pH, and Eh approximately every 2 m depth. The data were used to identify temperature zones (e.g., the thermocline, epilimnion, and hypolimnion) and distinct geochemical zones (e.g., anoxic zones and chemically stratified zones).

Water samples for chemical analyses from each distinct zone were collected using weighted Tygon tubing and a peristaltic pump. Samples were collected for total and dissolved (<0.45 μm) silica. In addition, water was passed through a 1-μm glass fiber filter, and the filter was collected for determination of total particulate phosphorus. The filtrate was collected and frozen for determination of total dissolved phosphorus, nitrate, and ammonia. This process was repeated, and the filter was collected, placed in ethanol, and submitted for determination of chlorophyll-a content.

The extent of the photic zone (the zone with sufficient light for photosynthesis to occur) was measured by lowering a Secchi disk until it was no longer visible (i.e., the Secchi depth). Phytoplankton samples were collected at both discrete and composite depth intervals. Bulk water samples were collected from discrete sampling points using the peristaltic pump, and composite samples were collected using a weighted 1/8th-inch Tygon tube lowered to the desired depth, pinched at the top, and withdrawn from the water column. Zooplankton samples were collected by lowering a 37-μm plankton net to a specific depth and pulling the net up through the water column to the surface. All plankton samples were placed in amber glass jars and preserved with Lugol's solution (buffered iodine; 2% for phytoplankton and 4% for zooplankton).

Nutrient samples were submitted to the Center for Limnology at the University of Colorado (CU) for analysis of silica, total dissolved phosphorus, and ammonia (spectrophotometric techniques) and nitrate (ICP). Filter material also was submitted to CU for analysis of total particulate phosphorus (pyrolosis technique) and chlorophyll-a by hot ethanol extraction correcting for phaeophyton.

The phytoplankton and zooplankton samples were analyzed using standard limnological analytical techniques (Wetzel and Likens 1991). The samples were placed in a sedimentation chamber fitted with a slip cover at the bottom and placed in an inverted microscope. The iodine in the Lugol's preservative stained the cells and organisms and increased their weight to enhance sedimentation. Following settling, the number of cells and/or organisms, size of cells, and species were determined visually using an inverted optical microscope.

FIELD SAMPLING RESULTS

The Anaconda and Aurora lakes are seasonally stratified, and the Boss lake is isothermal year-round (Figure 1). None of the three lakes exhibits a salinity gradient (chemocline), which would inhibit complete mixing at turnover. The seasonal DO profiles of the Anaconda lake are typical of low-productivity lakes with large relative depths, while the DO profile for the Aurora lake reflects the seasonal variation that occurs in shallow, productive lakes (Wetzel 1983). The Boss lake is well oxygenated year-round, because of its low productivity and small size, which allow complete mixing year-round. The increase in DO at depth in winter in all three lakes, together with the uniform density profile, indicate that the lakes are holomictic. All three lakes are near neutral (pH=7 to 8.5) and moderately alkaline (80–140 mg/L as $CaCO_3$).

Phytoplankton concentrations correlate well with nutrient concentrations (total phosphorus <10 μg/L; Table 1) in the Anaconda pit lake, and the population shifted from predominantly green algae in summer to predominantly blue-green algae in winter and spring (Figure 2; Table 2). The positive heterograde DO profile (peak in DO at the thermocline) in the spring can be explained by the large population of blue-green algae at this depth (Figure 3). Zooplankton were limited in number and in species diversity, with Bdelloid rotifers making up nearly 100% of the samples in each season. Chlorophyll-a concentrations (~ 0.1μg/L) indicate that total pelagic-zone biomass is low.

The Aurora lake also showed seasonal population shifts in phytoplankton, with a large bloom of green algae in summer, and low concentrations of all species in winter and spring (Figure 2; Table 2). In lakes with nitrogen-to-phosphorus ratios greater than 10, phosphorus controls productivity (Thomann and Mueller 1987). Aurora lake nutrient concentrations indicate severe phosphorus limitation (total P ~20 μg/L; NO_3-N ~5,000 μg/L) and that the lake should be mesotrophic. The lower phytoplankton concentration in this lake vs. Anaconda is probably due to the sample depth interval. The Secchi depth in this lake is 1–2 m, whereas integrated samples were collected to a depth of 8 m, beyond which phytoplankton are unlikely to grow. In addition, the chlorophyll-a concentration is five times higher than that measured in the Anaconda lake, indicating that the lake is more productive. The summer dissolved oxygen profile indicates that the large bloom of green algae in summer is causing a large oxygen demand in deep water during the stratified period. The Aurora lake zooplankton concentration is 20 times larger than those measured in the Anaconda lake and 100 times larger than those measured in the Boss lake. Species diversity was also much higher.

Boss lake nutrient concentrations are extremely high (total P ~500 μg/L; NO_3-N ~25,000 μg/L) (Table 1), but phytoplankton and zooplankton concentration and diversity do not indicate that the lake is productive (Tables 2 and 3). Productivity in this lake is probably limited by water chemistry and potential metals toxicity (TDS = 12,000 mg/L; dissolved arsenic = 1 mg/L).

LIMNOLOGICAL MODELING

Mine pit-lake permitting investigations often require predictions of the composition and behavior of lakes that have not yet formed. To evaluate the ability of models to predict limnologic conditions in pit lakes, the U.S. Army Corps of Engineers limnological model CE-QUAL-W2 (Cole and Buchak 1995) was configured to replicate temperature and DO conditions in the Anaconda and Aurora lakes. The Boss lake was not included in this study, because it appears to exhibit chemical effects that inhibit phytoplankton productivity, which limnological models cannot simulate.

CE-QUAL-W2 simulates mixing that occurs within a water body because of wind, density gradients within the water column, and biological productivity (e.g., plankton population, nutrient utilization, photosynthesis, and respiration). The bathymetric profile of each lake, meteorological data, and measured nutrient concentrations were incorporated into models of the two lakes. Physical constants are used in the model to simulate the hydrodynamic mixing that results from density gradients and chemical coefficients. These constants, used to simulate organic matter decay and nutrient transformations, were set to default values (Cole and Buchak 1995; Environmental Laboratory 1986). Biological coefficients are used to predict growth of the phytoplankton community, and values for these coefficients were selected based on literature values (Cole and Buchak 1995; Environmental Laboratory 1986; Environmental Research Lab 1985).

Model results indicated that CE-QUAL-W2 is able to describe hydrodynamic conditions (e.g., thermal stratification and turnover) and DO conditions (e.g., peaks in DO due to phytoplankton photosynthesis, and reduction in DO due to phytoplankton decay; Figures 4 and 5) in both lakes.

CONCLUSION

Although the lakes studied are morphologically very different from natural lakes and reservoirs, temperature, specific conductivity, pH, and dissolved oxygen profiles indicate that the physical and biological characteristics of the lakes are consistent with those of natural lakes. For example:

- Temperature, specific conductivity, and DO profiles indicate that the lakes mix completely at turnover.
- DO profiles are consistent with those measured in lakes containing pelagic-zone phytoplankton.

Consequently, the unique setting of the lakes does not appear to greatly affect pelagic-zone behavior, and model results indicate that pit-lake limnology can be simulated provided geochemical conditions do not limit biological productivity.

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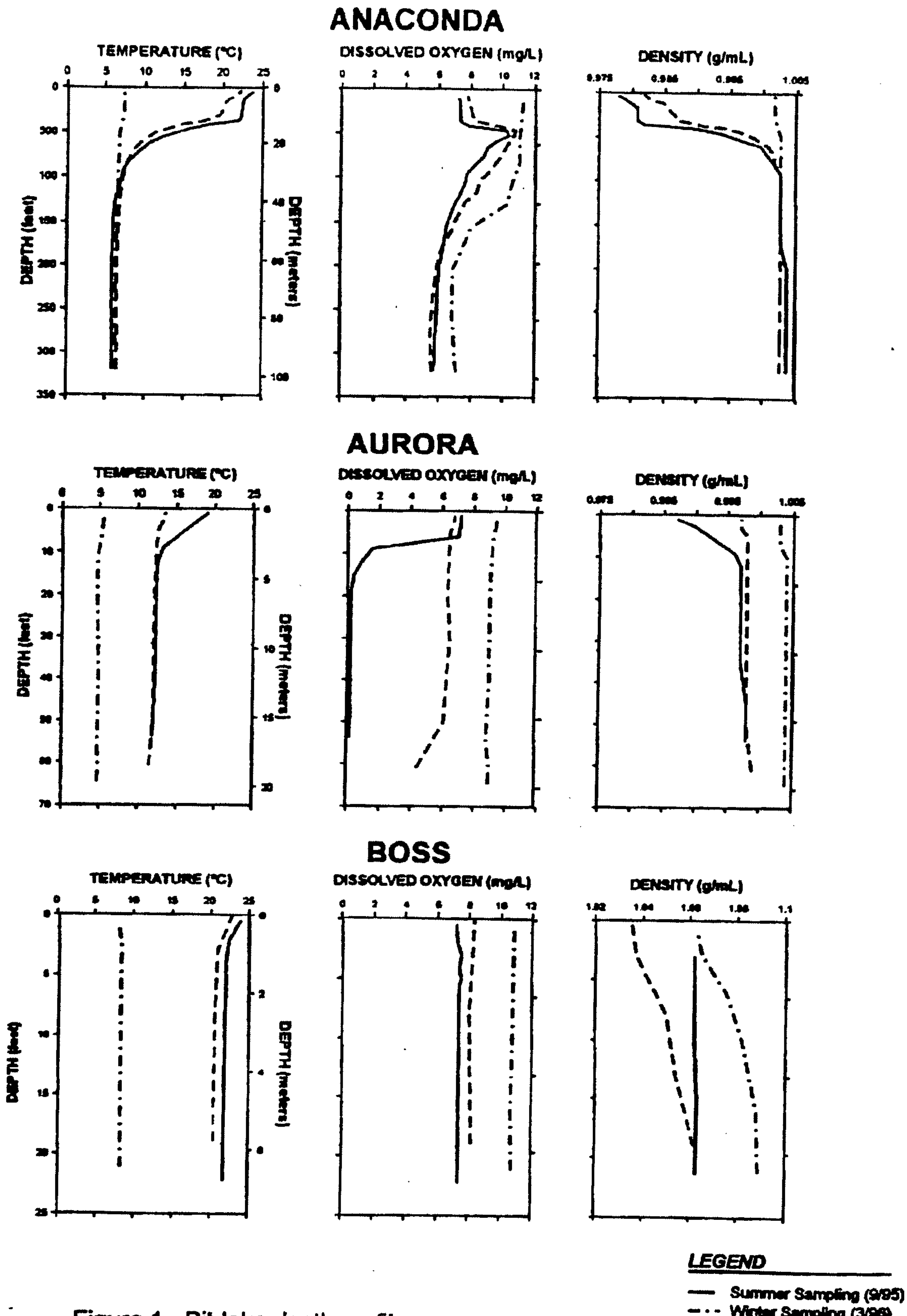

Figure 1. Pit-lake depth profiles.

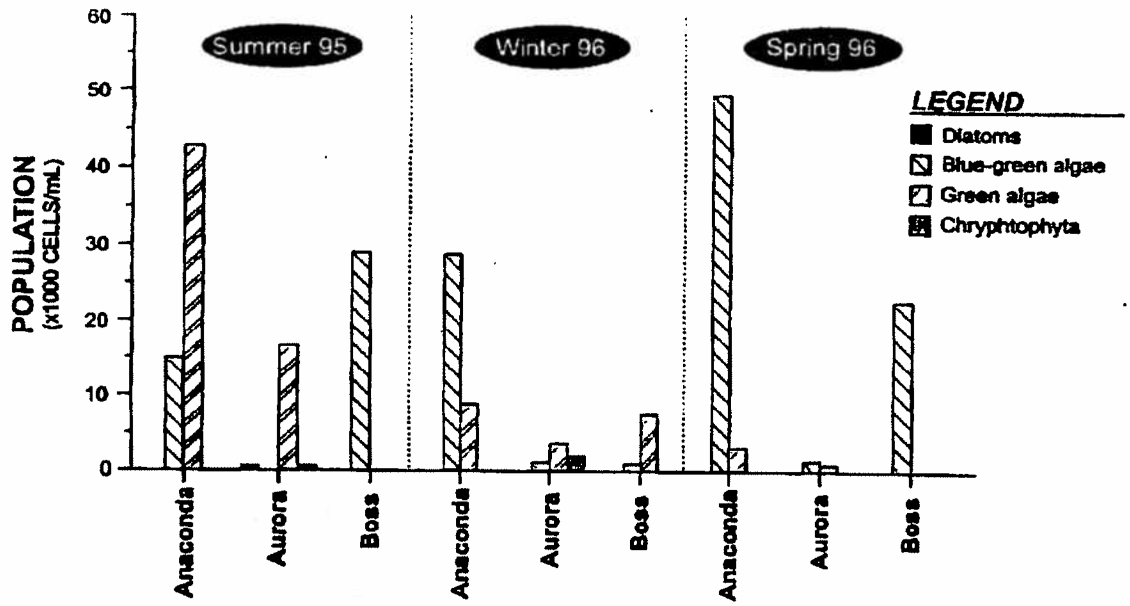

Figure 2. Seasonal phytoplankton concentrations.

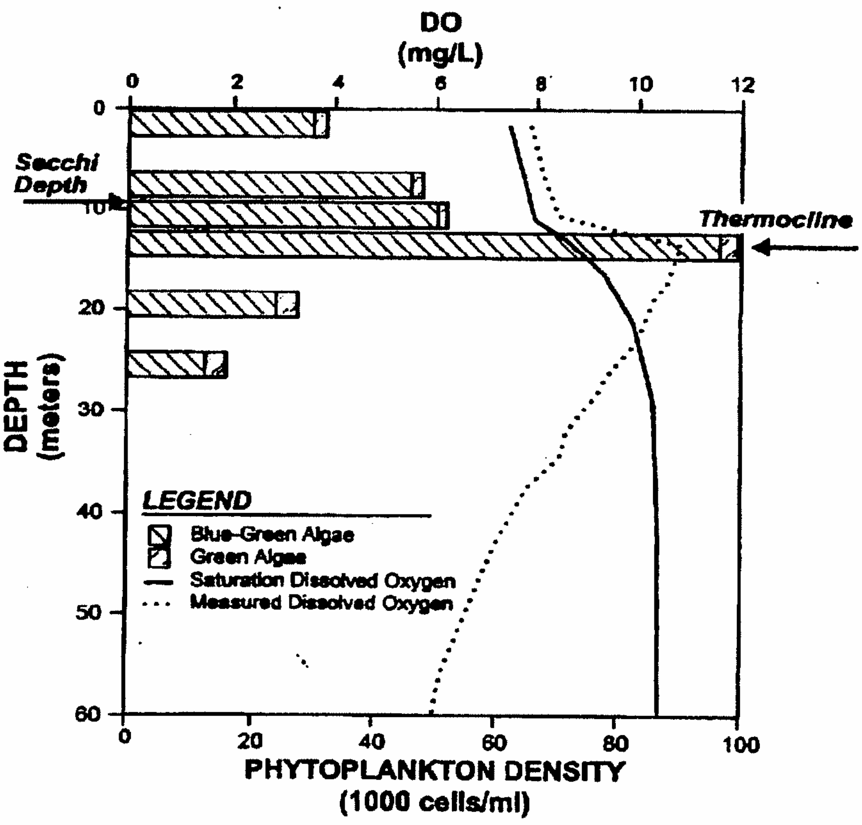

Figure 3. Anaconda pit lake phytoplankton and dissolved oxygen profile.

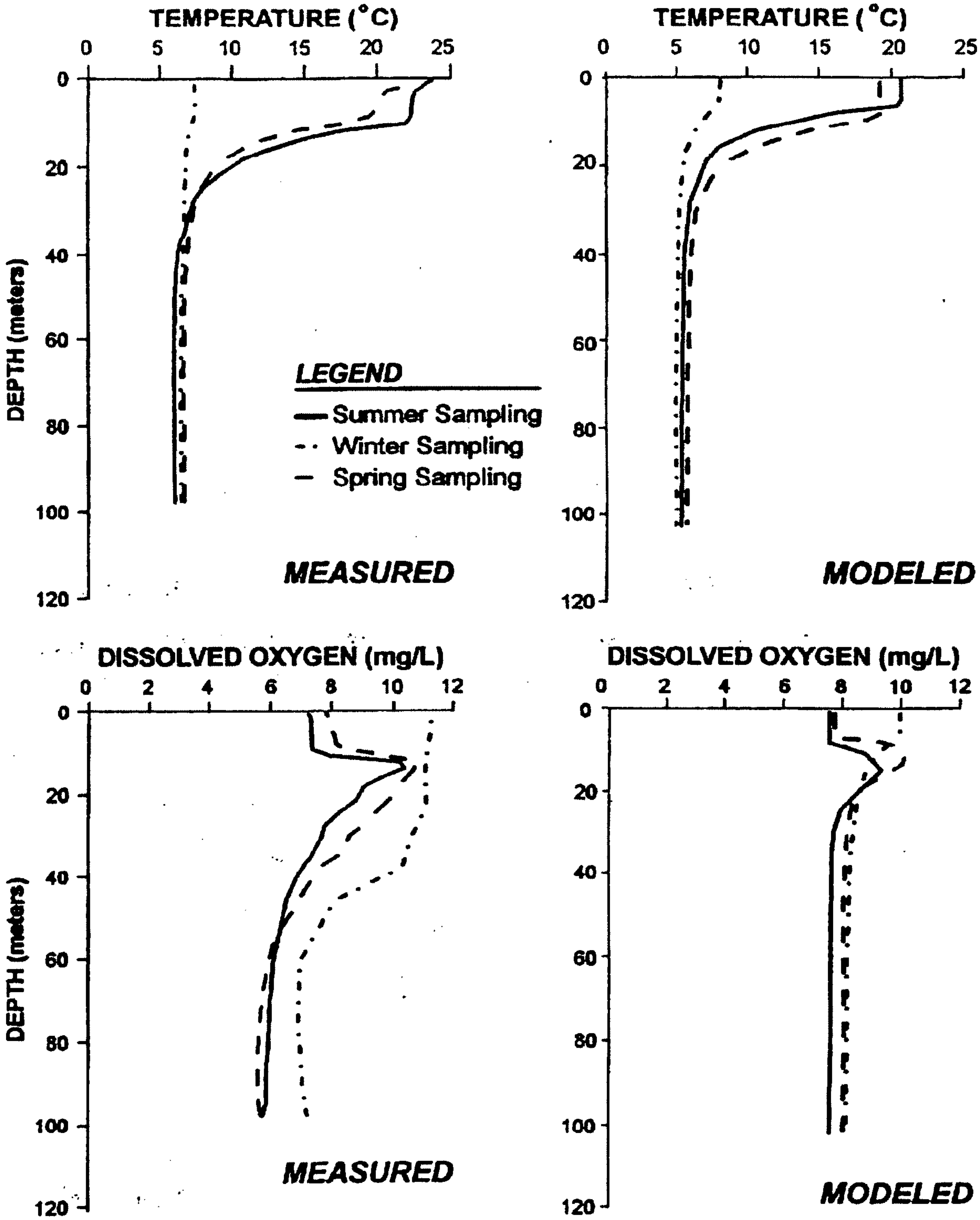

Figure 4. Anaconda lake measured and modeled results.

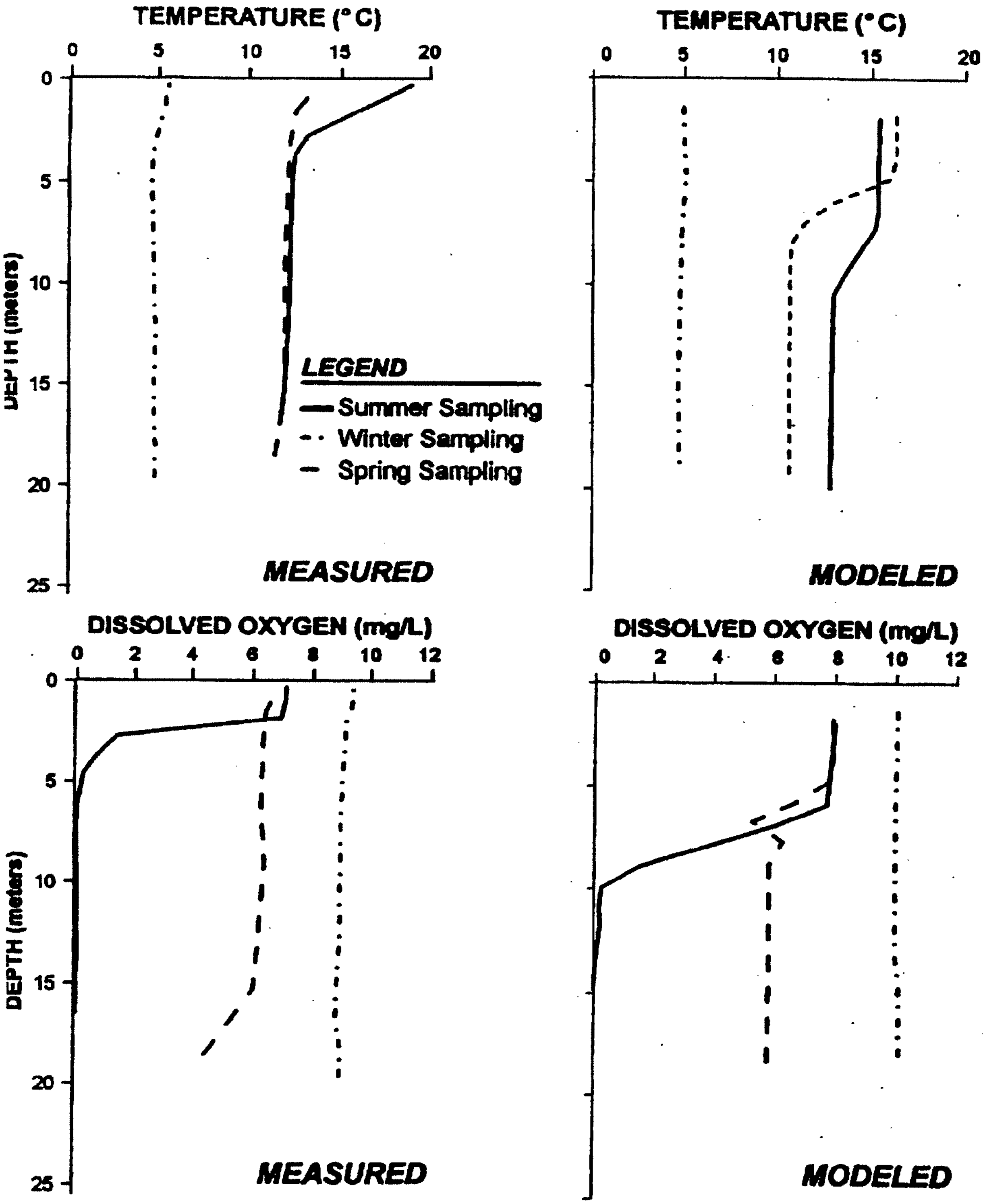

Figure 5. Aurora lake measured and modeled results.

TABLE 1. NUTRIENT CONCENTRATIONS

	Total Phosphorus (µg/L)	Particulate Phosphorus (µg/L)	NO_3 (µg/L)	NH_3 (µg/L)	SiO_2 (mg/L)
ANACONDA PIT LAKE					
EPILIMNION					
Summer (9/95)	<5	–	80	<10	35.6
Winter (3/96)	8.9	5.0	100.5	14.5	32.3
Spring (6/96)	7.4	1.4	98	8.0	40.2
HYPOLIMNION					
Summer (9/95)	<5	–	80	10	33.4
Winter (3/96)	8.8	3.0	125	11	31.5
Spring (6/96)	6.6	1.2	122	6.0	35.7
AURORA PIT LAKE					
EPILIMNION					
Summer (9/95)	20	–	3,860	<10	19.6
Winter (3/96)	15.1	6.1	5,148	14	16.3
Spring (6/96)	22.6	8.3	3,978	16	15.3
HYPOLIMNION					
Summer (9/95)	30	–	4,640	<100	17.4
Winter (3/96)	46.4	15	5,290	21	16.7
Spring (6/96)	29.2	12.8	4,110	16	15.5
BOSS PIT LAKE					
Summer (9/95)	520	–	24,800	15	17.9
Winter (3/96)	440	3.0	25,676	11	17.8
Spring (6/96)	472	1.2	20,823	5	18.9

TABLE 2. PHYTOPLANKTON

(All units cells/mL)

	Summer 95	Winter 96	Spring 96
ANACONDA PIT LAKE (0–15 m)			
Chlorophyta (green algae)			
Chlamydomonas globosa	–	–	188
Chlamydomonas snowii	–	172	–
Chlamydomonas sp. 1	94	32	–
Chlamydomonas sp. 2	31	110	–
Chlorella ellipsoidea	–	8	–
Chlorella minutissima	41,551	–	–
Chlorella sp.	–	1,063	875
Choricystis minor	–	–	16
Choricystis sp.	–	6,813	–
Cylindrocystis brebissonii	–	–	656
Mesotaenium sp.	–	–	1,250
Oocystis lacustris	1,009	–	–
Oocystis solitaria	–	563	–
Scenedesmus ecornis	–	–	8
Percent of total	74%	22%	6%
Cyanophyta (blue-green algae)			
Aphanothece delicatissima	–	8	–
Aphanothece nidulans	–	–	813
Aphanothece sp.	376	–	–
Jaaginema geminatum	149	–	28,500
Jaaginema subtilissimum	14,304	28,600	20,000
Percent of total	26%	79%	94%
Total density	57,513	37,267	52,306
AURORA PIT LAKE (0–8 m)			
Bacillariophyta (diatoms)			
Cyclotella sp.	–	16	–
Fragilaria tenera	438	–	–
Nitzschia palea	31	–	–
Percent of total	3%	0.27%	–
Chlorophyta (green algae)			
Chlamydomonas angulosa	–	125	–
Chlamydomonas globosa	–	–	156
Chlorella minutissima	15,875	–	–
Chlorella sp.	–	3,188	16
Chloricystis minor	–	–	375
Monoraphidium convolutum	–	63	–
Oocystis solitaria	–	31	–
Percent of total	95%	58%	34%
Cryphtophyta			
Chroomonas acuta	–	1,625	–
Cryptomona marsonii	–	125	–
Cryptomonas sp.	438	–	–
Percent of total	3%	30%	–

TABLE 2. (cont.)
(All units cells/mL)

	Summer 95	Winter 96	Spring 96
AURORA PIT LAKE (cont.)			
Cyanophyta (blue-green algae)			
Aphanothece nidulans	–	–	1,000
Synechococcus sp.	–	750	–
Percent of total	–	13%	63%
Euglenophyta			
Euglena sp.	–	–	47
Percent of total	–	–	3%
Total density	16,782	5,923	1,594
BOSS PIT LAKE (0–6 m)			
Bacillariophyta (diatoms)			
Achnanthes minutissima	1.5	–	–
Cymbella cesatii	49.5	–	–
Cymbella gracilis	–	–	6
Percent of total	0.2%	–	0%
Chlorophyta (green algae)			
Chlamydomonas snowii	–	6,875	–
Chlamydomonas sp. 3	188	–	–
Chlorococcum sp.	1.5	–	–
Monoraphidinium minutum	2.5	–	–
Percent of total	0.2%	93%	–
Cyanophyta (blue-green algae)			
Aphanothece sp.	3,750	–	26,875
Jaaginema subtilissimum	–	500	–
Rhabdoglosa sp.	25,469	–	–
Synechococcus sp.	125	–	–
Percent of total	98.8%	6.8%	100%
Pyrrophyta (dynoflagellate)			
Gymnodinium palustre	8	–	–
Percent of total	0.02%	–	–
Total density	29,595	7,375	26,881

TABLE 3. ZOOPLANKTON

(All units organisms/m^3)

	Summer 95	Winter 96	Spring 96
ANACONDA PIT LAKE (0–30 m)			
Copepoda			
Eucyclops agilis (male)	0.038	--	--
Paracyclops fimbriatus poppei (female)	0.23	0.17	--
Paracyclops fimbriatus poppei (male)	0.04	--	--
Cyclopoid nauplius	1.7	6.8	0.91
Percent of total	0.3%	12%	0.3%
Rotifera			
Bdelloid rotifer	547	52	144
Cephalodella sp.	0.45	0.17	0.91
Colurella sp.	62	1.7	96
Lecane (L.) sp.	0.076	--	--
Lecane (M.) sp.	0.72	--	1.6
Lepadella sp.	70	8.6	92
Unknown rotifer sp. 1	--	--	14
Unknown rotifer sp. 2	--	--	0.91
Percent of total	100%	88%	100%
Total Density	682	69	340
AURORA PIT LAKE (0–9 m)			
Cladocera			
Alona sp.	--	0.29	--
Daphnia pulex (female)	2,736	385	767
Daphnia pulex (male)	--	1.5	--
Daphnia schodleri (female)	921	2,761	1,008
Daphnia schodleri (male)	--	5.3	--
Daphnia spp. (male)	118	--	--
Cladoceran juvenile	--	102	149
Percent of total	33%	98%	20%
Copepoda			
Acanthocyclops vernalis (female)	4.1	1.8	1.5
Acanthocyclops vernalis (male)	12	0.59	--
Eucyclops agilis (female)	1.5	4.4	3.8
Eucyclops agilis (male)	--	0.59	2.3
Cyclopoid juvenile	1,618	13	2,050
Cyclopoid nauplius	489	35	5,817
Percent of total	20%	2%	80%
Rotifera			
Asplanchna sp.	--	--	22
Bdelloid rotifer	--	1.2	0.76
Epiphanes senta	0.37	--	--
Filinia longiseta	6,809	--	--
Polyarthra vulgaris	208	--	--
Percent of total	47%	0.04%	0.01%
Total Density	12,917	3,312	9,821
BOSS PIT LAKE (0–6 m)			
Copepoda			
Eucyclops agilis (female)	--	--	0.57
Cyclopoid juvenile	--	--	9.7
Cyclopoid nauplius	--	--	34
Percent of total	--	--	25%
Rotifera			
Bdelloid rotifer	--	4.7	0.57
Brachionus urceolaris	4.1	1.6	6.9
Hexarthra sp.	--	--	--
Lecane (M.) sp.	82	--	86
Lepadella sp.	--	--	1.1
Unknown rotifer sp. 1	2.3	--	43
Percent of total	100%	100%	75%
Total Density	89	6.2	182

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PTI
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May 17, 1996

Pat Maley
Santa Fe Pacific Gold Corporation
Twin Creeks Mine
P.O. Box 69
Golconda, NV 89414

Subject: Interim results from a study of the chemical composition, limnology, and ecology of three existing Nevada pit lakes
PTI Project No. CA1Q0601

Dear Pat:

Attached are the interim results from observation, sampling, and analysis of three existing open-pit mine lakes in Nevada. These data were collected in August and September 1995 by scientists from PTI Environmental Services (PTI), Boulder, Colorado, and Resource Concepts, Inc. (RCI), Carson City, Nevada. The attached tables summarize the chemical composition, limnology, and ecology of the Anaconda, Aurora Partnership, and Boss pit lakes.

RCI provided descriptions of the wildlife habitat and near-shore zone of each lake (i.e., identified plant and insect species and abundance), recorded wildlife observations during the sampling event, and sampled the lake sediment and plants for trace-metal analysis. PTI characterized the physical and chemical composition of the lakes by measuring vertical profiles of field parameters (Eh, pH, temperature, dissolved oxygen, specific conductivity, and turbidity), and collected water samples for chemical composition and metals speciation analysis. PTI also collected phytoplankton and zooplankton samples for species identification and population density analyses, and insect samples for trace metal and speciation analysis.

The attached tables present the data in three sections, one for each lake. A table containing the sample location, sample depth, and analyte list is provided for each section, and is correlated to a figure displaying the sample locations. Data summaries include phytoplankton and zooplankton number and species, littoral zone characteristics, and a list of wildlife species observed during the sampling event. In addition, analytical results are presented for major ion, nutrient, and trace element concentrations in the water column, as well as trace element contents of plant tissue, insect tissue, and sediment samples. Finally, figures are provided showing vertical profiles of temperature, dissolved oxygen concentration, pH, specific conductance, Eh, and turbidity in each lake.

Results from winter sampling of the analog pit lakes in March 1996 will be provided after all of the analytical results are received. As always, if you have any questions, please feel free to call me or David Atkins at (303) 444-7270.

Sincerely,

Houston Kempton
Senior Geochemist

cc: John Young (SFPGC)
Sheila Anderson (RCI)
David Atkins (PTI)
Valerie Randall (RTi) (2 copies)
Jerry Moritz (BLM, Winnemucca)
Tom Olsen (BLM, Reno)
Rick Cardwell (Parametrix)
David Gaskin (NDEP)
Doug Zimmerman (NDEP)
Russ Fields (NDOM)
Linda Schevenell, Ph.D. (NBM&G)
Doug Hunt (NDOW)

Section 1

Anaconda Lake

TABLE 1-1. ANACONDA LAKE SAMPLE DESCRIPTIONS AND ANALYTE LIST

Sample Locations	Interval (meters)	Sample Description	Analytes
A,B,C	23, 46[a]	Hypolimnion composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[b]
A,B,C	4.6	Epilimnion composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[b]
A	23	Hypolimnion water	Mercury speciation, Hg
A	4.6	Epilimnion water	Mercury speciation, Hg
A	23	Hypolimnion water	Sulfide
A	4.6	Epilimnion water	Sulfide
A	0-15	Phytoplankton	Number and speciation
A	0-30	Zooplankton	Number and speciation
B	23	Hypolimnion water	Mercury speciation, Hg
B	4.6	Epilimnion water	Mercury speciation, Hg
B	0-15	Phytoplankton	Number and speciation
B	0-30	Zooplankton	Number and speciation
C	0-15	Phytoplankton	Number and speciation
C	0-30	Zooplankton	Number and speciation
ANLZA, ANLZB	NA	Plant tissue	Mercury speciation, arsenic speciation, As, Ag, Cd, Cu, Hg, Pb, Sb, Se, Zn
ANLZA, ANLZB	NA	Sediment	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, TOC, Zn
ANLZA	NA	Sediment	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, TOC, Zn
ANLZA	NA	Insect tissue	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, Zn

[a] Depth at 23 meters was sampled at Location C. Locations A and B were sampled at 46 meters in depth.

[b] Total and dissolved metals include antimony, arsenic, aluminum, barium, beryllium, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, mercury, nickel, potassium, silica, selenium, silver, sodium, thallium, zinc.

TABLE 1-2. SUMMARY OF PHYTOPLANKTON SPECIES IDENTIFIED FROM THE EPILIMNION OF THE ANACONDA PIT LAKE
(Organisms/mL)

SPECIES LIST	PHYTOPLANKTON TOW ZONE			
	SITE A	SITE B	SITE B (dupicate)	SITE C
Sample depth interval (m)	0-15	0-15	0-15	0-15
Chlorophyta				
Chlamydomonas sp. 1	168	94	94	0
Chlamydomonas sp. 2	31	31	31	31
Chlorella minutissima	52,396	43,789	36,370	33,648
Oocystis lacustris	1,000	689	1,127	1,220
Percent contribution to tow	**76**	**88**	**67**	**66**
Cyanophyta				
Aphanothece sp	532	0	970	0
Jaaginema[1] *geminatum*	0	94	0	500
Jaaginema subtilissimum	16,370	5,728	17,278	17,840
Percent contribution to tow	**24**	**12**	**33**	**34**
Total density	70,517	50,425	55,870	53,239

[1] *Jaaginema (=Ocillatoria)*

TABLE 1-3. SUMMARY OF ZOOPLANKTON SPECIES IDENTIFIED FROM THE EPILIMNION OF THE ANACONDA PIT LAKE
(Total number of organisms)

SPECIES LIST	ZOOPLANKTON TOW ZONE		
	SITE A	SITE B	SITE C
Sample depth interval (m)	0-30	0-30	0-30
Number of tows	4	4	4
Copepoda			
Eucyclops agilis (male)	0	0	1
Paracyclops fimbriatus poppei (female)	4	2	0
Paracyclops fimbriatus poppei (male)	0	0	1
Cyclopoid nauplius	7	15	23
Percent contribution to tow	**0.3**	**0.2**	**0.4**
Rotifera			
bdelloid rotifer	2,685	7,200	4,560
Cephalodella sp.	0	4	8
Colurella sp.	210	525	900
Lepadella sp.	555	780	510
Lecane (L.) sp.	0	1	1
Lecane (M.) sp.	2	14	3
Percent contribution to tow	**99.7**	**99.8**	**99.6**
Total density	3,462	8,541	6,007

TABLE 1-4. SUMMARY OF LITTORAL ZONE SAMPLE AREA CHARACTERISTICS FOR THE ANACONDA PIT LAKE

PARAMETER	LITTORAL ZONE SAMPLE AREAS	
	ANLZA	ANLZB
Location	At point where access road enters pit lake at southeast shore	At point where access road enters pit lake (eastern exposure) on northeast shore
Approximate Area (ac)	1.41	0.31
Sediment Development		
Texture	• fractured rock and fines	• fines over fractured rock
Depth	• 0.0-0.6 cm	• 25-30 cm
Color	• light brown	• black with white cover over organic layers
Biological Structure	• detritus	• Macrophytes, detritus
Presence of Debris	• none	• Leaf litter
Oily Sheen	• none	• none
Odor	• none	• organic
Macrophytes	none	*Typha* sp. (cattails) *Ludwigia* sp. Salt Cedar (inundated)
Invertebrates	Chironomids Aquatic Beetles Aquatic True Bugs	Chironomid
Periphyton	Epilithic algae Epipelic algae	Epilithic algae Epipelic algae Epiphytic algae

TABLE 1-5. WILDLIFE SPECIES LIST FOR ANACONDA PIT LAKE

Scientific Name	Common Name
BIRDS	
Actitis macularia	Spotted Sandpiper
Larus californicus	California Gull
Podiceps auritus	Horned Grebe
Podiceps nigricollis	Eared Grebe
Salponctes obsoletus	Rock Wren
Cathartes aura	Turkey Vulture
Riparia riparia	Bank Swallow
MAMMALS	
Unidentified	Bat
REPTILES	
Unidentified	Lizard

Observation Dates: 8/23–8/25, and 8/28/95

TABLE 1-6. ANACONDA LAKE WATER COLUMN MAJOR ION AND NUTRIENT ANALYTICAL RESULTS

Analyte	Epilimnion (mg/L)	Hypolimnion (mg/L)
Chlorophyll (μg/L)	0 J	0 J
pH (s.u.)	7.15	7.17
Alkalinity ($CaCO_3$)	120	124
TDS	600	707
TOC	1.3	1.1
DOC	1.7 UJ	1.6 UJ
NH_4	0.01 U	0.01 U
NO_2 + NO_3	0.08	0.08
Phosphorus (total)	0.005 U	0.005 U
Chloride	41.1	37.8
Fluoride	1.3	1.4
Sulfate	292	291
Calcium (total)	90.6	92.8
Calcium (dissolved)	96.4	104
Magnesium (total)	15.7	15.1
Magnesium (dissolved)	17.0	17.2
Potassium (total)	5.59	5.25
Potassium (dissolved)	5.86	5.72
SiO_2 (total)	32.5	28.4
SiO_2 (dissolved)	35.6	33.4
Sodium (total)	78.6	73.8
Sodium (dissolved)	85.3	83.5

U = Not detected; value represents detection limit.
J = Estimated

TABLE 1-7. ANACONDA LAKE WATER COLUMNS TRACE ELEMENT ANALYTICAL RESULTS

Analyte	Epilimnion (µg/L)	Hypolimnion (µg/L)
WAD CN-	10 U	10 U
Sulfide	50 R	50 R
Antimony (total)	6.0	7.0
Antimony (dissolved)	6.0	7.0
Arsenic (total)	4.73	2.82
Arsenic (dissolved)	2.0 J	1.0 J
As^{-3}	0.29	0.24 U
As^{-5}	4.44	2.82
Monomethyl arsonic acid	0.24 U	0.24 U[a]
Dimethyl arsonic acid	0.24 U	0.24 U[a]
Aluminum (total)	33 UJ	36 UJ
Aluminum (dissolved)	17	21
Barium (total)	34	29
Barium (dissolved)	34	33
Beryllium (total)	1.0 U	1.0 U
Beryllium (dissolved)	1.0 U	1.0 U
Cadmium (total)	2.0 U	2.0 U
Cadmium (dissolved)	2.0 U	2.0 U
Chromium (total)	6.0 UJ	3.0 U
Chromium (dissolved)	3.0 U	3.0 U
Copper (total)	25 UJ	131
Copper (dissolved)	20 UJ	131
Iron (total)	17 U	20 UJ
Iron (dissolved)	17 U	17 U
Lead (total)	1.0 U	1.0 U
Lead (dissolved)	1.0 U	1.0 U
Manganese (total)	14	42
Manganese (dissolved)	13	46
Mercury (total)[b]	0.00252 [a]	0.00212 [a]
Mercury (dissolved)[b]	0.2 U	0.2 U
Methyl mercury[b]	0.0000335 U	0.0000335 U
Nickel (total)	21 U	21 U
Nickel (dissolved)	21 U	21 U
Selenium (total)	107 J	123 J
Selenium (dissolved)	92 J	112 J
Silver (total)	2.0 U	2.0 U
Silver (dissolved)	2.0 U	2.0 U
Thallium (total)	1.0 U	1.0 U
Thallium (dissolved)	1.0 U	1.0 U
Zinc (total)	4.0 UJ	9.0 UJ
Zinc (dissolved)	2.0 U	6.0 UJ

[a] Average of duplicate samples.

[b] For mercury analyses, total mercury and methyl mercury were analyzed using ultra-clean sampling techniques. Dissolved mercury was analyzed by ICP and thus has a higher detection limit.

U = Not detected; value represents detection limit.

J = Estimated.

R = Result was rejected.

TABLE 1-8. ANACONDA LAKE - METALS IN SEDIMENT, PLANT, AND MACROINVERTEBRATE TISSUE SAMPLES

Analyte	Epilimnion Water Concentration (µg/L)	Sediment[a] Site D (µg/g)	Sediment[a] Site E (µg/g)	Plant[b] Tissue *(Typha sp)* (µg/g)	Plant[b] Tissue *(Ludwigia sp)* (µg/g)	Macroinvertebrate[b] Tissue (Insect Composite) (µg/g)
%Moisture		62	39	95	97	81
Antimony (total)	6.0	5.73	6.33	0.00315 U	0.01914	0.08018
Arsenic (total)	4.73	8.73 J	22.6 J	0.0219	0.1527	0.0437 J
As^{+3}	0.29	0.005 U	0.005 U			
As^{+5}	4.44	3.1	2.5			
Monomethylarsonic acid	0.24 U	0.057 U	0.057 U	0.00025 U	0.00183	0.00551
Dimethylarsenic acid	0.24 U	0.052 U	0.052 U	0.00025 U	0.00015 U	0.00874
Cadmium (total)	2.0 U	0.122 J	0.181 J	0.0016 U	0.00672	0.05738 J
Copper (total)	25 UJ	1510 J	1280 J	2.57	34.2	110.58
Lead (total)	1.0 U	5.87 J	8.26 J	0.016	0.0456	0.3325 J
Mercury (total)	0.00252 [c]	0.319	0.196	0.000185	0.00432	0.3743
Methyl mercury	0.0000338 U[c]	0.00389	0.000151	0.000083	0.00039	0.3515
Selenium (total)	107 J	21.6 J	7.15 J	0.485	0.933	1.938 J
Silver (total)	2.0 U	0.298 J	0.451 J	0.00309 U	0.001854 U	0.011742 U
Zinc (total)	4.0 UJ	33	56.3	0.74 J	0.762 J	20.52

[a] Dry weight values.
[b] Wet weight values.
[c] Average of duplicate samples.
U = Not detected; value represents detection limit.
J = Estimated.
Note: Blank space indicates no analysis performed.

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Section 2

Aurora Lake

TABLE 2-1. AURORA LAKE SAMPLE DESCRIPTIONS AND ANALYTE LIST

Sample Locations	Interval (meters)	Sample Description	Analyte
A,B,C	6.1	Hypolimnion composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[a]
A,B,C	1.1	Epilimnion composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[a]
A,B,C	NA	Composite zooplankton tissue	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, Zn
A	6.1	Hypolimnion water	Mercury speciation, Hg
A	6.1	Hypolimnion water	Sulfide
A	1.1	Epilimnion water	Mercury speciation, Hg
A	1.1	Epilimnion water	Sulfide
A	0-15	Phytoplankton	Number and speciation
A	0-15	Zooplankton	Number and speciation
B	0-7.6	Phytoplankton	Number and speciation
B	0-7.6	Zooplankton	Number and speciation
C	0-4.6	Phytoplankton	Number and speciation
C	0-4.6	Zooplankton	Number and speciation
AULZA	NA	Sediment	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, TOC, Zn
AULZA	NA	Insect tissue	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, Zn

[a] Total and dissolved metals include antimony, arsenic, aluminum, barium, beryllium, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, mercury, nickel, potassium, silica, selenium, silver, sodium, thallium, zinc.

TABLE 2-2. SUMMARY OF PELAGIC PHYTOPLANKTON SPECIES IDENTIFIED FROM THE AURORA PIT LAKE
(Organisms/mL)

SPECIES LIST	PLANKTON TOW ZONE			
	Site A	Site A (duplicate)	Site B	Site C
Sample depth interval (m)	0-15	0-15	0-7.6	0-4.6
Bacillariophyta (Diatoms)				
Fragilaria delicatissima	16	0	0	16
Fragilaria tenera	63	313	438	688
Nitzschia palea	16	0	31	250
Percent contribution to tow	**1**	**1**	**3**	**5**
Chlorophyta (Green algae)				
Chlamydomonas globosa	31	0	0	0
Chlorella minutissima	13,688	25,313	15,875	15,813
Chlorella sp.	63	0	0	0
Percent contribution to tow	**92**	**98**	**95**	**88**
Chryptophyta				
Chryptomonas sp.	438	63	438	250
Percent contribution to tow	**3**	**0.2**	**3**	**1**
Cyanophyta (Blue-green algae)				
Aphanothece sp	625	0	0	0
Jaaginema geminatum	0	0	0	938
Percent contribution to tow	**4**	**0**	**0**	**5**
Euglenophyta				
Euglena mubabillis	0	63	0	63
Percent contribution to tow	**0**	**0.2**	**0**	**0.3**
Total density	14,940	25,752	16,782	18,018

TABLE 2-3 SUMMARY OF PELAGIC ZOOPLANKTON SPECIES IDENTIFIED FROM THE AURORA PIT LAKE
(Total number of organisms)

SPECIES LIST	PLANKTON TOW ZONE		
	Site A	Site B	Site C
Sample depth interval (m)	0-15	0-7.6	0-4.6
Number of tows	1	1	1
Cladocera			
Daphnia pulex (female)	3,000	4,020	285
Daphnia schodleri (female)	465	990	1,005
Daphnia spp. *(male)*	165	60	90
Percent contribution to tow	**19**	**43**	36
Copepoda			
Eucyclops agilis (female)	0	3	1
Acanthocyclops vernalis (female)	4	6	1
Acanthocyclops vernalis (male)	12	6	14
Cyclopoid juvenile	1,755	2,175	390
Cyclopoid nauplius	345	225	735
Percent contribution to tow	**11**	**21**	**29**
Rotifera			
Epiphanes senta	1	0	0
Filinia longiseta	13,035	4,080	1,065
Polyarthra vulgaris	195	60	300
Percent contribution to tow	**70**	**36**	**35**
Total density	18,977	11,625	3,886

TABLE 2-4. SUMMARY OF LITTORAL ZONE SAMPLE AREA CHARACTERISTICS FOR THE AURORA PIT LAKE

PARAMETER	LITTORAL ZONE SAMPLE AREA
	AULZA
Location	Shallow area at west end of pit lake
Approximate Area (ac)	2.31
Sediment Development	
Texture	• fractured rock and sand with some fines
Depth	• 0.5–1.0 cm
Color	• light brown
Biological Structure	• none
Presence of Debris	• none
Oily Sheen	• none
Odor	• none
Macrophytes	none
Invertebrates	Backswimmers
	Aquatic Mites
	Water Boatsman
	Aquatic Wasps
	White flies
	Ephippia
	Chironomid larvae
	Nematodes
Periphyton	Blue-green algae (*Jaaginema)*
	Diatoms

TABLE 2-5. SPECIES LIST FOR AURORA PIT LAKE

Scientific Name	Common Name
BIRDS	
Actitis macularia	Spotted Sandpiper
Salponctes obsoletus	Rock Wren
Riparia riparia	Bank Swallow
Accipiter cooperii	Cooper's Hawk
MAMMALS	
Spermophilus townsendii	Townsend's Ground Squirrel
Unidentified	Bat

Observation Dates: 8/29/95–8/31/95

TABLE 2-6. AURORA LAKE WATER COLUMN MAJOR ION AND NUTRIENT ANALYTICAL RESULTS

Analyte	Epilimnion (mg/L)	Hypolimnion (mg/L)
Chlorophyll (μg/L)	0.85 J	0.5 J
pH (s.u.)	7.59	7.68
Alkalinity ($CaCO_3$)	89.1	106
TDS	478	524
TOC	1.9	1.6
DOC	3.0 UJ	1.9 UJ
NH_4	0.01 U	0.1 U
$NO_2 + NO_3$	3.86	4.64
Phosphorus (total)	0.02	0.03
Chloride	11.4	11.7
Fluoride	0.6	0.4
Sulfate	266	266
Calcium (total)	80.6	82.5
Calcium (dissolved)	86.1	84.3
Magnesium (total)	20.1	19
Magnesium (dissolved)	21.6	19.5
Potassium (total)	5.42 UJ	5.90 UJ
Potassium (dissolved)	6.45 UJ	5.33 UJ
SiO_2 (total)	18.8	18.1
SiO_2 (dissolved)	19.6	17.4
Sodium (total)	37.6	35.4
Sodium (dissolved)	40.3	36.2

U = Not detected; value represents detection limit.
J = Estimated

TABLE 2-7. AURORA LAKE WATER COLUMN
TRACE ELEMENT ANALYTICAL RESULTS

Analyte	Epilimnion (μg/L)	Hypolimnion (μg/L)
WAD CN-	10 U	10 U
Sulfide	50 R	50 R
Antimony (total)	3.0	4.0
Antimony (dissolved)	3.0	4.0
Arsenic (total)	8.95	8.98
Arsenic (dissolved)	7.0 J	4.0 J
As^{+3}	0.24 U	0.24 U
As^{+5}	9.2	8.98
Monomethyl arsonic acid	0.24 U[a]	0.24 U
Dimethyl arsenic acid	0.365 [a]	0.24 U
Aluminum (total)	245	271
Aluminum (dissolved)	26 UJ	8.0 U
Barium (total)	78	71
Barium (dissolved)	76	68
Beryllium (total)	1.0 U	1.0 U
Beryllium (dissolved	1.0 U	1.0 U
Cadmium (total)	2.0 U	2.0 U
Cadmium (dissolved)	2.0 U	2.0 U
Chromium (total)	3.0 U	3.0 U
Chromium (dissolved)	4.0 UJ	3.0 U
Copper (total)	5.0 UJ	3.0 UJ
Copper (dissolved)	3.0 UJ	3.0 U
Iron (total)	839	174
Iron (dissolved)	17 U	17 U
Lead (total)	3.0 UJ	1.0 U
Lead (dissolved)	1.0 UJ	1.0 U
Manganese (total)	43	70
Manganese (dissolved)	1.0 U	57
Mercury (total)[b]	0.01585 [a]	0.0334
Mercury (dissolved)[b]	0.2 U	0.2 U
Methyl mercury[b]	0.000041	0.0000336 U
Nickel (total)	21 U	21 U
Nickel (dissolved)	21 U	21 U
Selenium (total)	11 J	11 J
Selenium (dissolved)	11 J	10 J
Silver (total)	2.0 U	2.0 U
Silver (dissolved)	2.0 U	2.0 U
Thallium (total)	1.0 UJ	1.0 U
Thallium (dissolved)	1.0 UJ	1.0 U
Zinc (total)	4.0 UJ	4.0 UJ
Zinc (dissolved)	2.0 UJ	7.0 UJ

[a]Average of duplicate samples.

[b]For mercury analyses, total mercury and methyl mercury were analyzed using ultra-clean sampling techniques. Dissolved mercury was analyzed by ICP and thus has a higher detection limit.

U = Not detected; value represents detection limit.

J = Estimated.

R = Result was rejected.

TABLE 2-8. AURORA LAKE - METALS IN SEDIMENT AND MACROINVERTEBRATE SAMPLES

Analyte	Epilimnion Water Concentration (µg/L)	Sediment[a] (µg/g)	Duplicate[a] Sediment (µg/g)	Macroinvertebrate[b] Tissue (Black Flies) (µg/g)	Zooplankton[b] Tissue *(Daphnia)* (µg/g)
% Moisture		48	30	95	96
Antimony (total)	3.0	12.2	16.5	0.01225	0.00252 U
Arsenic (total)	8.95	63.7 J	102 J	0.215 J	0.608 J
As^{+3}	0.24 U	0.005	0.009		
As^{+5}	9.2 [c]	8.6	9.5		
Monomethylarsonic acid	0.24 U[c]	0.057 U	0.057 U	0.034	0.0156
Dimethylarsenic acid	0.365 [c]	0.052 U	0.052 U	0.0018	0.232
Cadmium (total)	2.0 U	0.276 J	0.752 J	0.00515 J	0.772 J
Copper (total)	5.0 UJ	38.3 J	48.1 J	1.385	0.936
Lead (total)	3.0 UJ	6.81 J	9.59 J	0.0468 J	0.00728 J
Mercury (total)	0.01585 [c]	0.209	0.206	0.00695	0.0868
Methyl mercury	0.000041	0.000063 U	0.00006 U	0.000068	0.001332
Selenium (total)	11 J	0.52 J	0.71 J	0.0445 J	0.2552 J
Silver (total)	2.0 U	1.4 J	2.01 J	0.0147	0.02308
Zinc (total)	4.0 UJ	97.4	95.8	4.515	14.56

[a] Dry weight values.

[b] Wet weight values.

[c] Average of duplicate samples.

U = Not detected; value represents detection limit.

J = Estimated.

Section 3

Boss Lake

TABLE 3-1. BOSS LAKE SAMPLE DESCRIPTIONS AND ANALYTE LIST

Sample Locations	Interval (meters)	Sample Description	Analyte
A,B	2.8, 4.0[a]	Deep composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[b]
A,B	0.46	Shallow composite water	Arsenic speciation, chlorophyll, WAD CN^-, NH_4, NO_2+NO_3, total P, alkalinity, pH, Cl, F, SO_4, TDS, TOC, DOC, total and dissolved metals[b]
A	0-6	Phytoplankton	Number and speciation
A	0-6	Zooplankton	Number and speciation
A	4.0	Deep water	Mercury speciation, Hg
A	4.0	Deep water	Sulfide
A	0.46	Shallow water	Mercury speciation, Hg
A	0.46	Shallow water	Sulfide
B	0-3	Phytoplankton	Number and speciation
B	0-3	Zooplankton	Number and speciation
BOLZA	NA	Sediment	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, TOC, Zn
B	NA	Insect tissue	Mercury speciation, arsenic speciation, Ag, As, Cd, Cu, Hg, Pb, Sb, Se, Zn
C	NA	Precipitate	Arsenic speciation, NO_2+NO_3, Cl, F, SO_4, total metals[c]
C	NA	Host-rock	Arsenic speciation, NO_2+NO_3, Cl, F, SO_4, total metals[c]

[a] Depth at 2.8 meters was sampled at Location B.

[b] Total and dissolved metals include antimony, arsenic, aluminum, barium, beryllium, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, mercury, nickel, potassium, silica, selenium, silver, sodium, thallium, zinc.

[c] Total metals include aluminum, arsenic, barium, beryllium, cadmium, calcium, chromium, copper, iron, lead, magnesium, manganese, mercury, nickel, potassium, selenium, silver, sodium, thallium, zinc.

TABLE 3-2. SUMMARY OF PELAGIC PHYTOPLANKTON SPECIES IDENTIFIED IN THE BOSS PIT LAKE
(Organisms/mL)

SPECIES LIST	PLANKTON TOW ZONE		
	SITE A	SITE A (duplicate)	SITE B
Sample depth interval (m)	0-6	0-6	0-3
Bacillariophyta (Diatoms)			
Achnanthes minutissima	0	3	0
Cymbella cesatii	85	14	5
Nitzschia fonticola	0	0	11
Percent contribution to tow	**0.2**	**0.1**	**0.2**
Chlorophyta (Green algae)			
Chlamydomonas sp. 3	63	313	438
Chlorococcum sp.	0	3	5
Monoraphidinium minutum	5	0	0
Percent contribution to tow	**0.2**	**2**	**4.7**
Chryptophyta			
Chroomonas sp.	0	0	8
Percent contribution to tow	**0**	**0**	**0.1**
Cyanophyta (Blue-green algae)			
Synechococcus sp.	0	250	0
Aphanothece sp.	0	7,500	7,500
Rhabdoglosa sp.	43,125	7,813	1,438
Percent contribution to tow	**99.6**	**97.9**	**95**
Pyrrophyta (Dynoflagellate)			
Gymnodinium palustre	16	0	0
Percent contribution to tow	**0.04**	**0**	**0**
Total density	43,294	15,896	9,655

TABLE 3-3. SUMMARY OF PELAGIC ZOOPLANKTON SPECIES IDENTIFIED IN THE BOSS PIT LAKE
(Total number of organisms)

SPECIES LIST	PLANKTON TOW ZONE	
	SITE A	SITE B
Sample depth interval (m)	0-6	0-3
Number of tows	5	5
Rotifera		
bdelloid rotifer	0	13
Brachionus urceolaris	9	9
Hexarthra sp.	0	1
Lecane (M.) sp.	180	480
rotifer A	5	41
Percent contribution to tow	100	100
Total density	194	544

TABLE 3-4. SUMMARY OF LITTORAL ZONE SAMPLE AREA CHARACTERISTICS FOR THE BOSS PIT LAKE

PARAMETER	LITTORAL ZONE SAMPLE AREAS (BOLZA)
Location	At point where haul road entered pit lake
Approximate Area (ac)	0.23
Sediment Development	• fractured rock and fines
Texture	• 10.5 cm
Depth	• 0.5 cm light brown silt
Color	10 cm black clayey silt
Biological Structure	• none
Presence of Debris	• none
Oily Sheen	• none
Odor	• organic
Macrophytes	none
Invertebrates	Soil Mites
	Mayflies
	Damselflies
Periphyton (epipelic)	Euglena
	Diatoms
	Bdelloid rotifer
	Nematodes

TABLE 3-5. SPECIES LIST FOR BOSS PIT LAKE AND PONDS

Scientific Name	Common Name
Species present at the Boss Pit Lake	
BIRDS	
Spizella breweri	Brewer's Sparrow
REPTILES	
Callisaurus draconoides	Zebratail Lizard
Species present at the adjacent cyanide heap leach solution collection ponds	
BIRDS	
Actitis macularia	Spotted Sandpiper
Podiceps auritus	Horned Grebe
Anas stepera	Gadwall
Himantopus mexicanus	Black-necked Stilt
Euphagus cyanocephalus	Brewer's Blackbird
Unidentified	Swallow

Observation Dates: 9/11/95–9/13/95

TABLE 3-6. BOSS LAKE WATER COLUMN MAJOR ION AND NUTRIENT ANALYTICAL RESULTS

Analyte	Shallow (mg/L)	Deep (mg/L)
Chlorophyll (μg/L)	0 J	0.2 J
pH (s.u.)	8.29	8.25
Alkalinity ($CaCO_3$)	102	101
TDS	12400	12700
TOC	1 UJ	1.9 J
DOC	1 UJ	1.2 UJ
NH_4	0.01 U	0.02 UJ
NO_2 + NO_3	25.2	24.4
Phosphorus (total)	0.51	0.53
Chloride	3130	3560
Fluoride	2.5 U	2.5 U
Sulfate	5150	5090
Calcium (total)	633	574
Calcium (dissolved)	613	662
Magnesium (total)	256	232
Magnesium (dissolved)	252	270
Potassium (total)	22.7	20.3
Potassium (dissolved)	20	23.7
SiO_2 (total)	18.8	17
SiO_2 (dissolved)	18.7	19.9
Sodium (total)	2490	2780
Sodium (dissolved)	2460	2640

U = Not detected; value represents detection limit.
J = Estimated.

TABLE 3-7. BOSS LAKE WATER COLUMN TRACE ELEMENT ANALYTICAL RESULTS

Analyte	Shallow (µg/L)	Deep (µg/L)
WAD CN-	10 U	10 U
Sulfide	50 R	50 R
Antimony (total)	28	26
Antimony (dissolved)	33	31
Arsenic (total)	1570	1240
Arsenic (dissolved)	1230	1170
As^{+3}	5.6	3.5
As^{+5}	1560	1240
Monomethyl arsonic acid	24.4 U	24.4 U
Dimethyl arsenic acid	24.4 U	24.4 U
Aluminum (total)	57 UJ	57 UJ
Aluminum (dissolved)	11 UJ	92 UJ
Barium (total)	1.0 U	1.0 U
Barium (dissolved)	1.0 U	1.0 U
Beryllium (total)	1.0 U	1.0 U
Beryllium (dissolved	1.0 U	1.0 U
Cadmium (total)	2.0 U	2.0 U
Cadmium (dissolved)	2.0 U	2.0 U
Chromium (total)	3.0 U	716
Chromium (dissolved)	3.0 U	9.0 UJ
Copper (total)	3.0 U	8.0
Copper (dissolved)	3.0 U	4.0 UJ
Iron (total)	18 UJ	2920
Iron (dissolved)	17 U	17 U
Lead (total)	1.0 U	1.0 U
Lead (dissolved)	1.0 U	1.0 U
Manganese (total)	1.0 U	63
Manganese (dissolved)	1.0 U	1.0 U
Mercury (total)[a]	0.0516	0.0496
Mercury (dissolved)[a]	0.2 U	0.2 U
Methyl mercury[a]	0.0000339 U	0.0000341 U
Nickel (total)	21 U	321
Nickel (dissolved)	21 U	21 U
Selenium (total)	50 J	74 J
Selenium (dissolved)	82 J	30 UJ
Silver (total)	2.0 U	2.0 U
Silver (dissolved)	2.0 U	7.0
Thallium (total)	1.0 J	1.0 UJ
Thallium (dissolved)	1.0 J	1.0 J
Zinc (total)	255	8.0
Zinc (dissolved)	2.0 U	3.0 U

[a] For mercury analyses, total mercury and methyl mercury were analyzed using ultra-clean sampling techniques. Dissolved mercury was analyzed by ICP and thus has a higher detection limit.

U = Not detected; value represents detection limit.

J = Estimated.

R = Result was rejected.

TABLE 3-8. BOSS LAKE - METALS IN SEDIMENT AND MACROINVERTEBRATE SAMPLES

Analyte	Shallow Water Concentration (µg/L)	Sediment[a] (µg/g)	Macroinvertebrate[b] Tissue (Insect Composite) (µg/g)
%Moisture		39	93
Antimony (total)	28	58	0.0819
Arsenic (total)	1570	1050 J	2.051 J
As^{+3}	5.6	14.5	
As^{+5}	1560	155	
Monomethylarsonic acid	24.4 U	1.1 U	0.0035 U
Dimethylarsenic acid	24.4 U	1 U	0.0035 U
Cadmium (total)	2.0 U	0.419 J	0.02422 J
Copper (total)	3.0 U	31 J	1.239 J
Lead (total)	1.0 U	14.5 J	0.04466 J
Mercury (total)	0.0516	0.213	0.01113
Methyl mercury	0.0000339 U	0.0003173	0.001645
Selenium (total)	50 J	2.44 J	0.1246 J
Silver (total)	2.0 U	2.12 J	0.05152 J
Zinc (total)	255	114	7

[a] Dry weight values.

[b] Wet weight values.

U = Not detected; value represents detection limit.

J = Estimated.

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TABLE 3-9. BOSS LAKE CHEMICAL SOLID RESULTS

(All units mg/kg)

Analyte	Precipitate	Host Rock
Aluminum (total)	2900	5780
Arsenic (total)	302	998
As^{+3}	2.38	4.56
As^{+5}	300	993
Barium (total)	22.4	8.7
Beryllium (total)	0.2 U	0.2 U
Cadmium (total)	1	3.3
Calcium (total)	66700	4370
Chloride	150000	5430
Chromium (total)	9.5	50.7
Copper (total)	4.1	12.9
Fluoride	66.2	24.9
Iron (total)	6200	25400
Lead (total)	8 U	8 U
Magnesium (total)	12400	4700
Manganese (total)	250	143
Mercury (total)	3.1	1.1
Nickel (total)	7.5	26.5
Nitrate-N	611	37
Nitrite-N	130 U	6.3 U
$NO_2 + NO_3$	611	37
Potassium (total)	595	712
Selenium (total)	16.4	39.7
Silver (total)	15.8	1.2
Sodium (total)	111000	3910
Sulfate	200000	9060
Thallium (total)	8 U	8 U
Zinc (total)	17.5	40.6

U = Not detected; value represents detection limit.

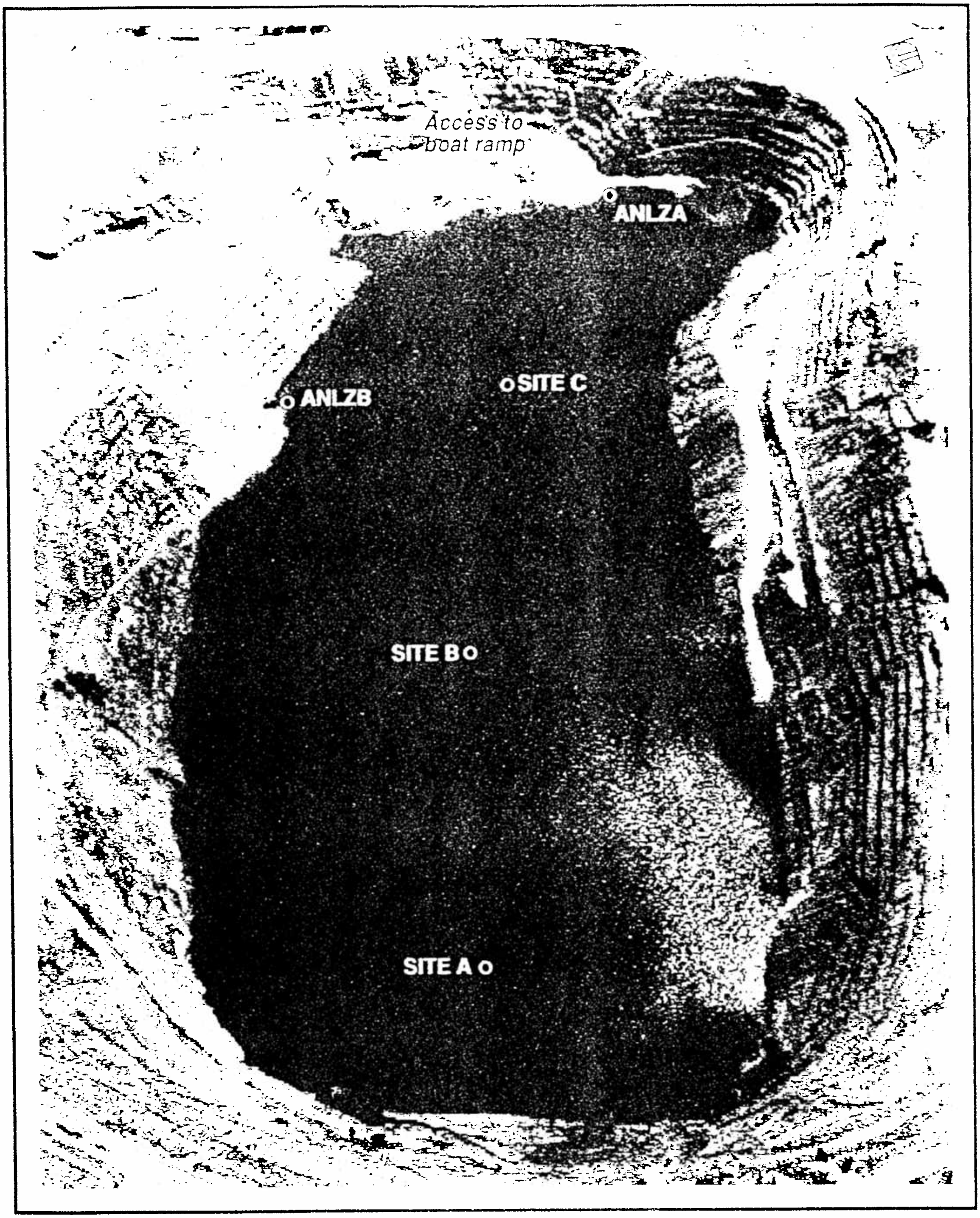

Figure 1-1. Anaconda pit-lake pelagic zone sampling locations (looking east).

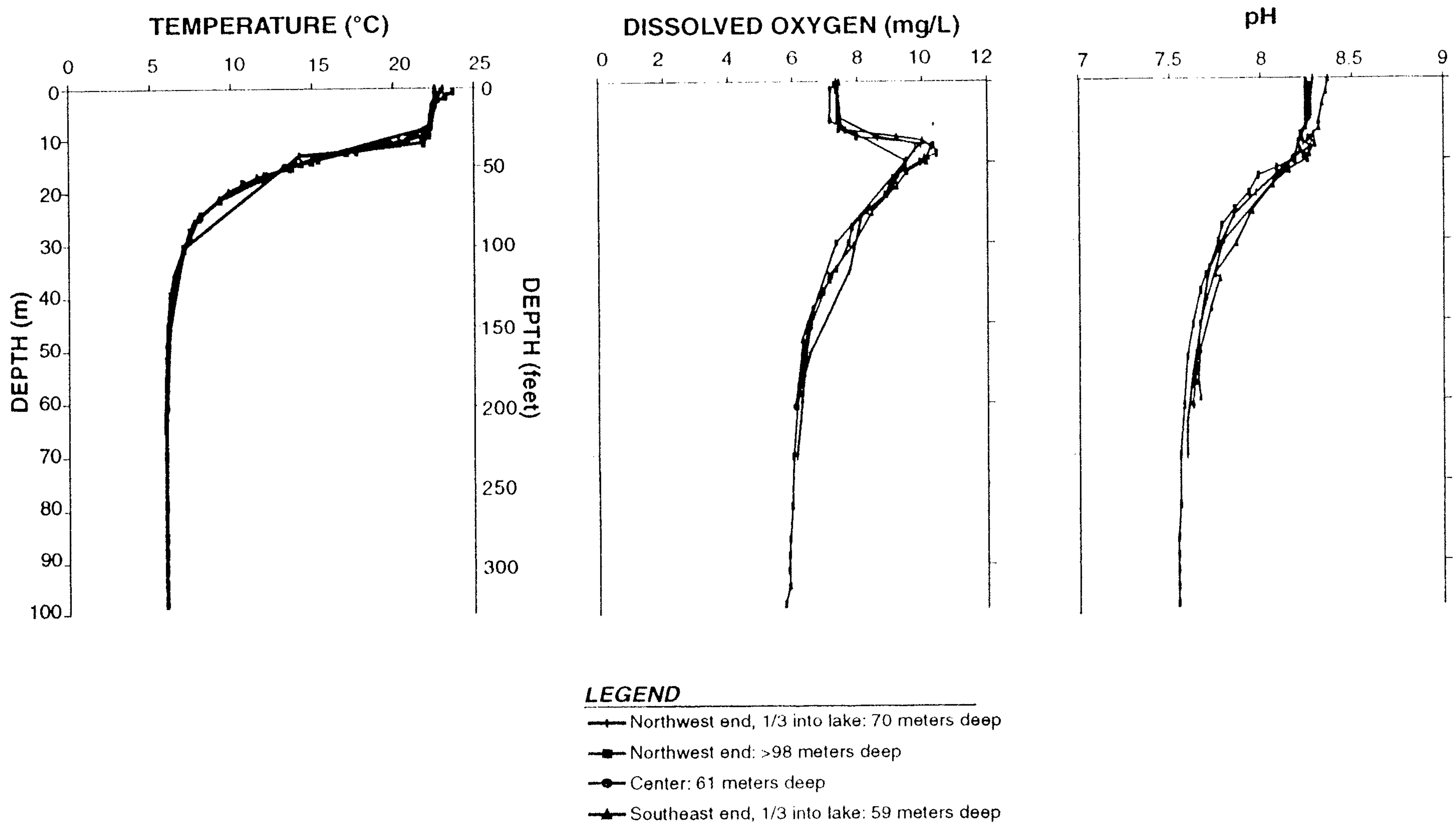

Figure 1-2. Anaconda pit-lake temperature, dissolved oxygen, and pH profiles.

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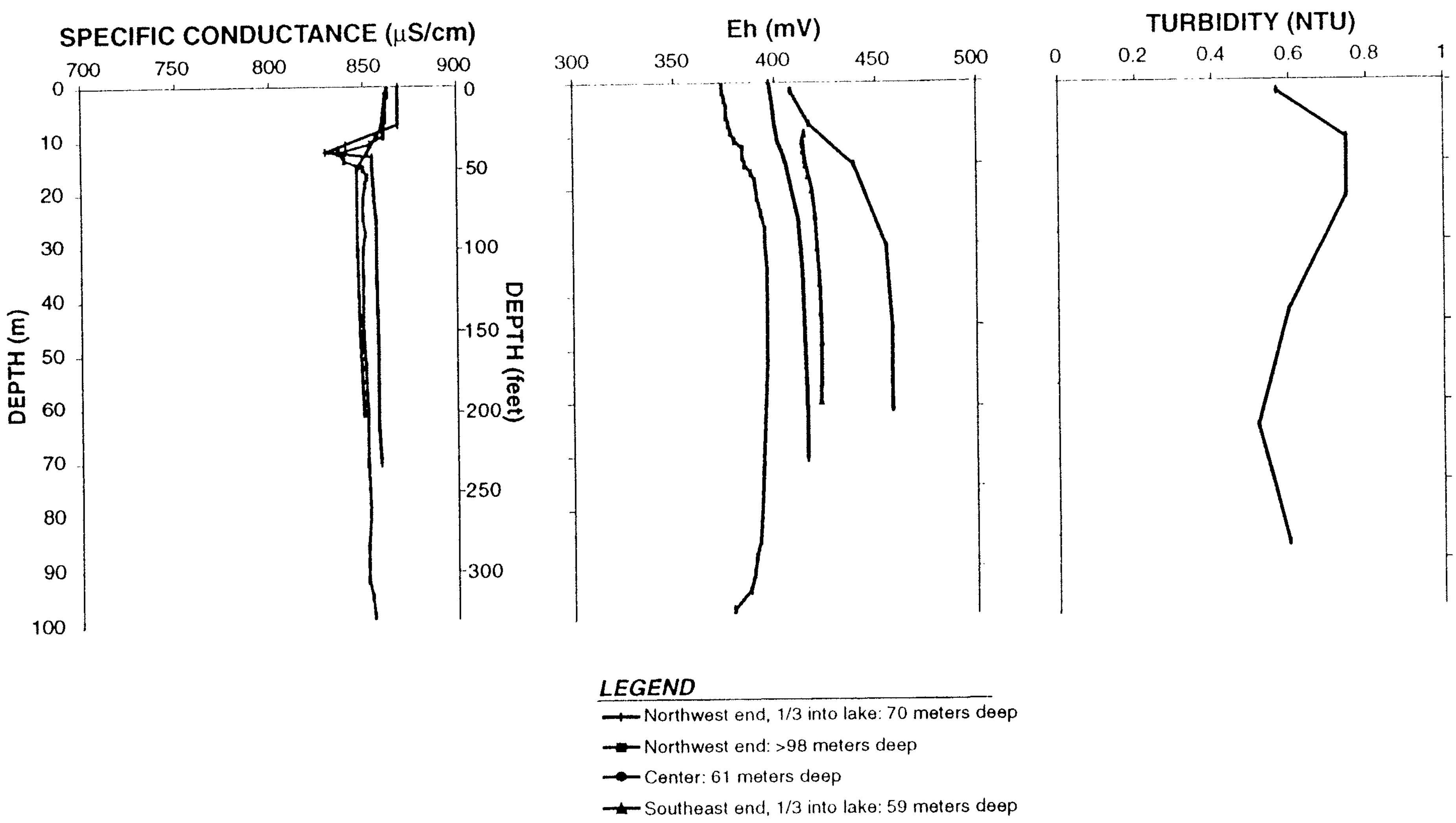

Figure 1-3. Anaconda pit-lake specific conductance, Eh, and turbidity profiles.

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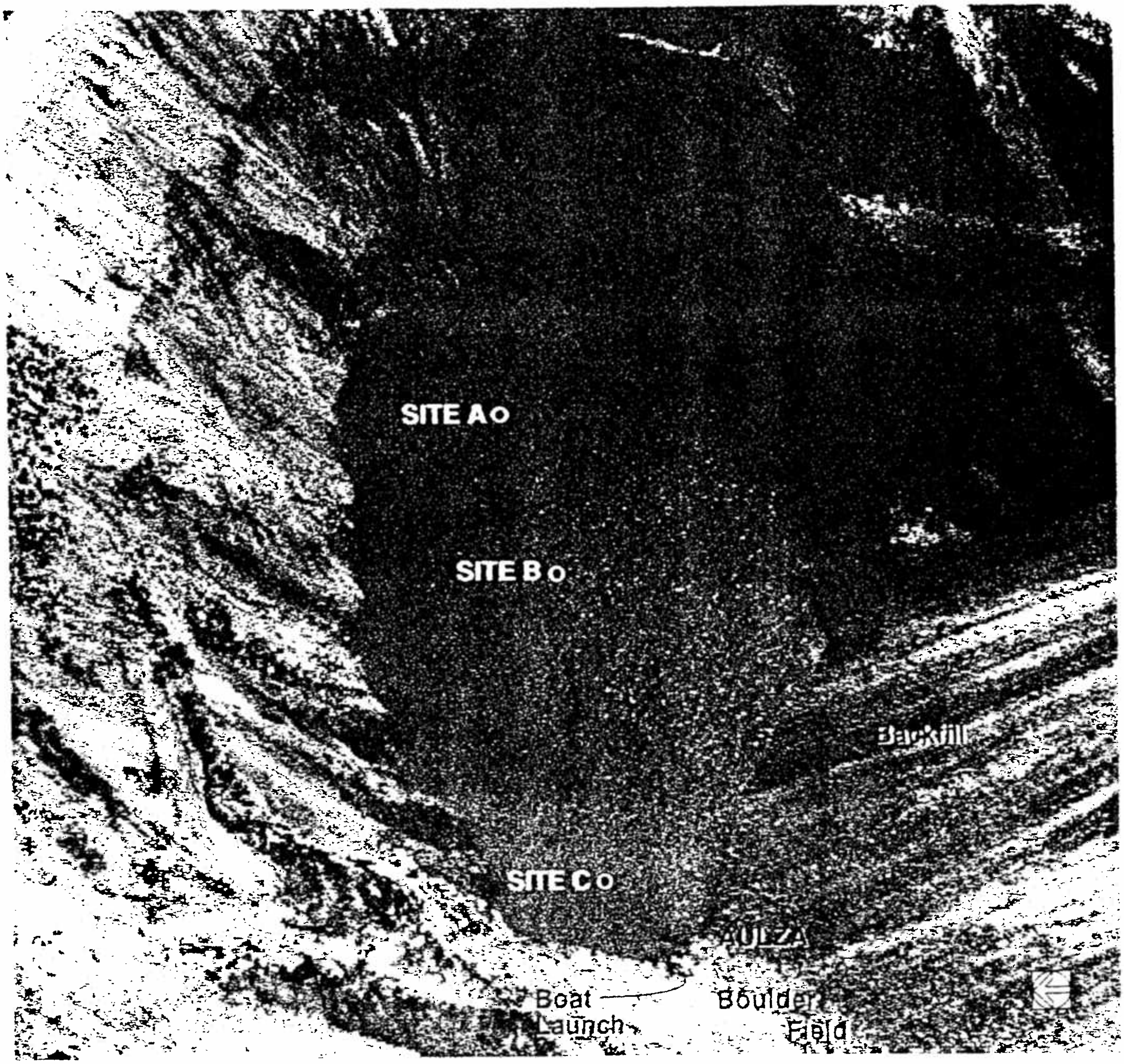

Figure 2-1. Aurora pit-lake pelagic zone sampling locations (looking east).

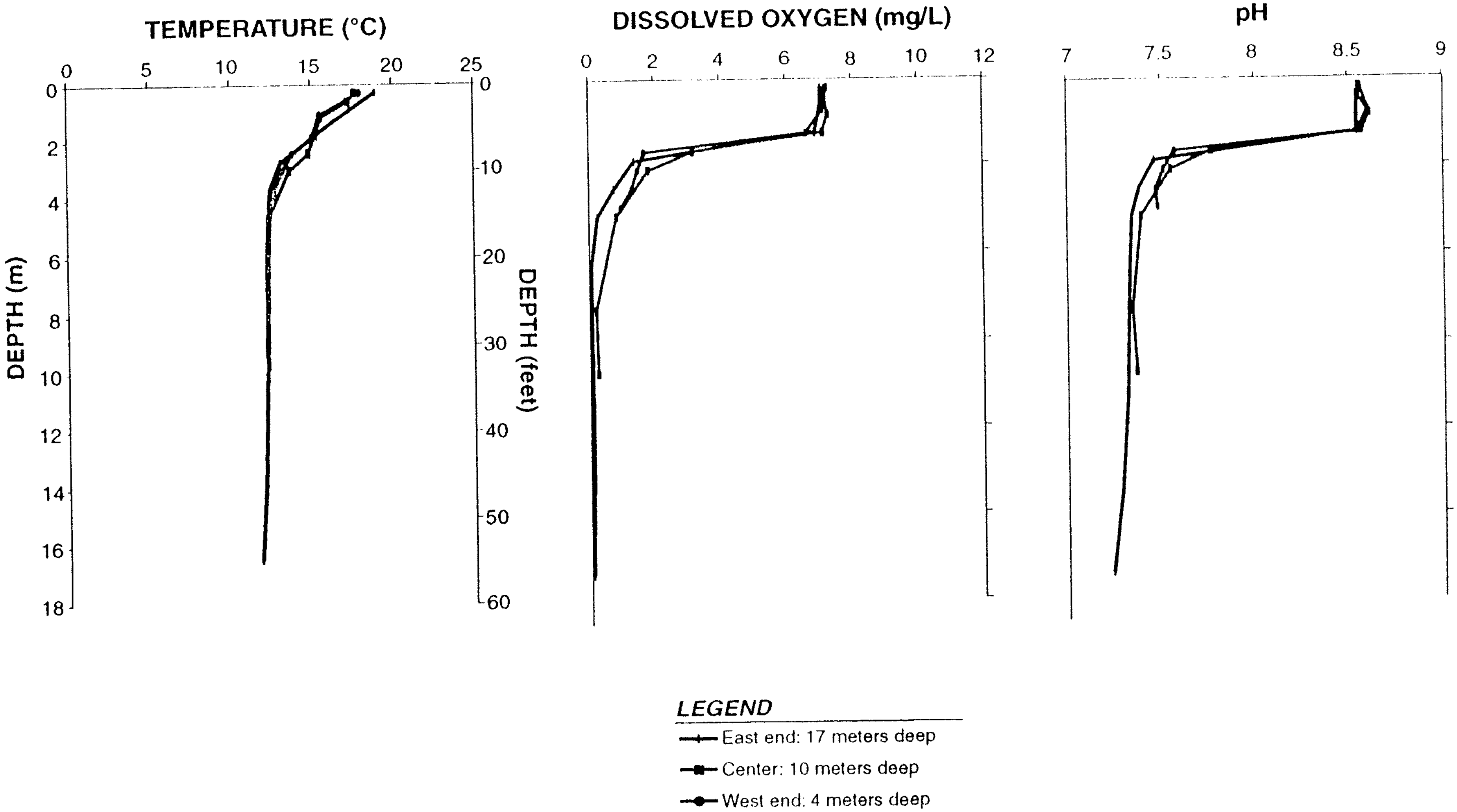

Figure 2-2. Aurora pit-lake temperature, dissolved oxygen, and pH profiles.

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CA1Q0601 040296

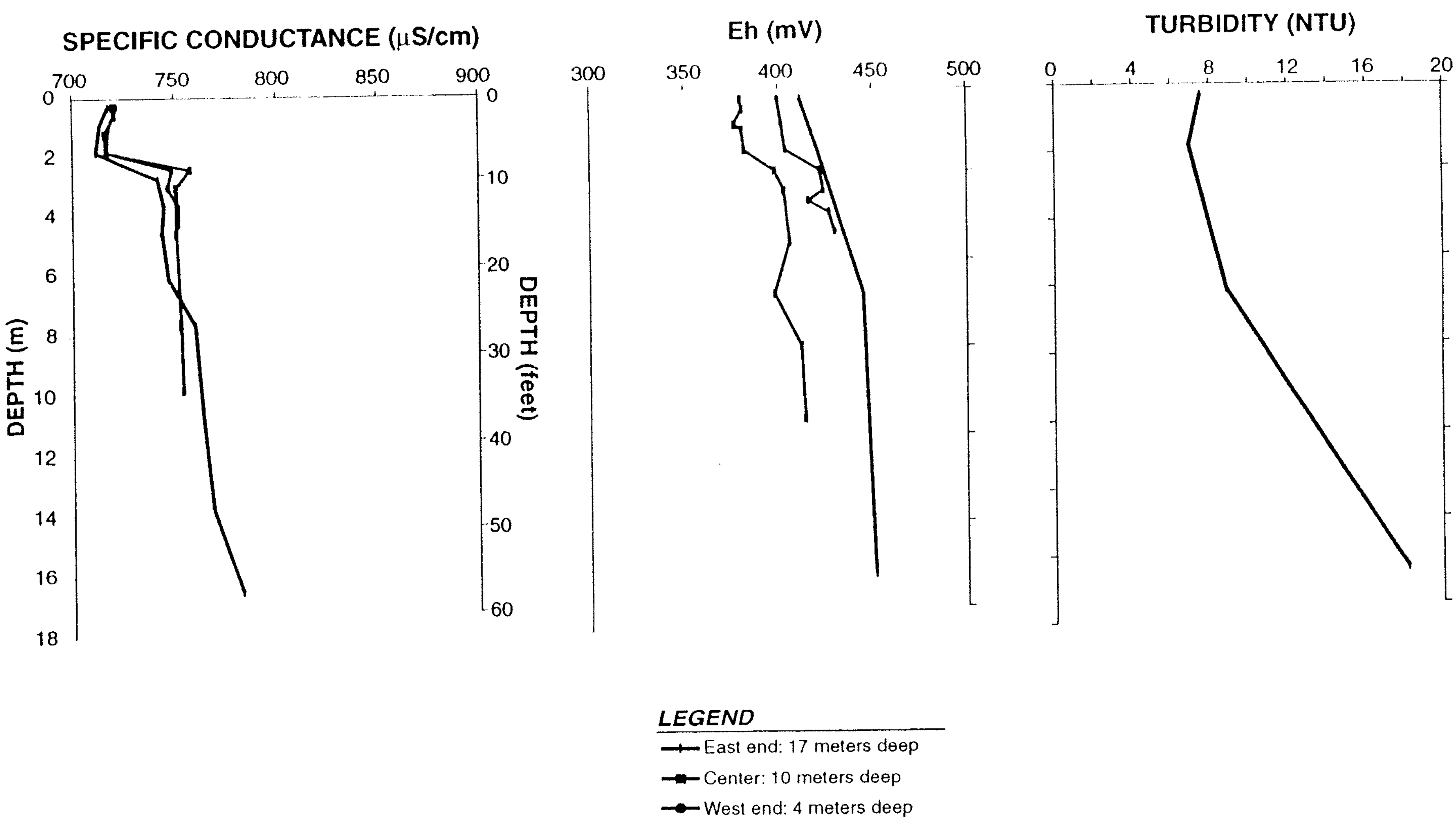

Figure 2-3. Aurora pit-lake specific conductance, Eh, and turbidity profiles.

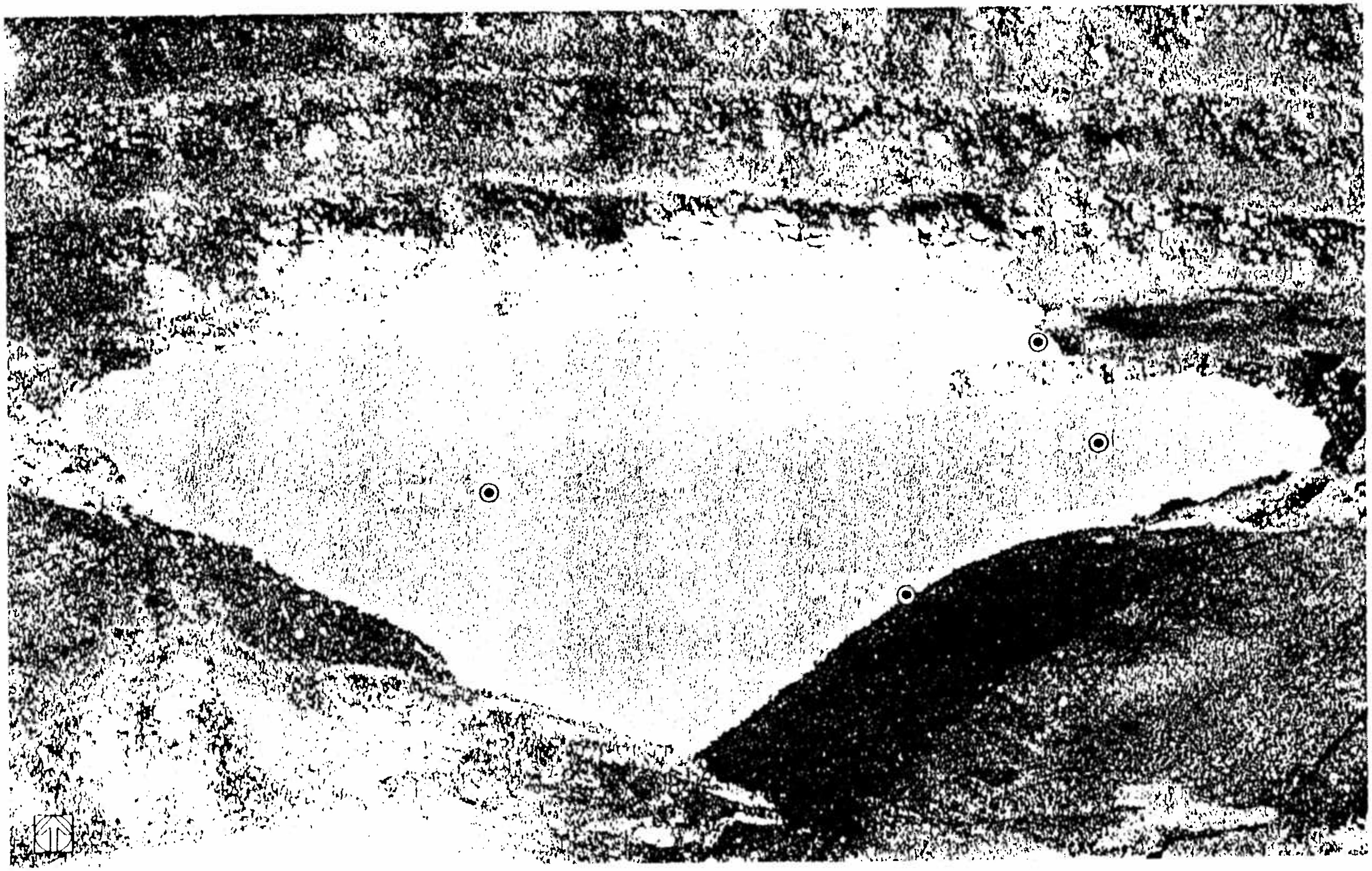

Figure 3-1. Boss pit-lake pelagic zone sampling locations (looking north).

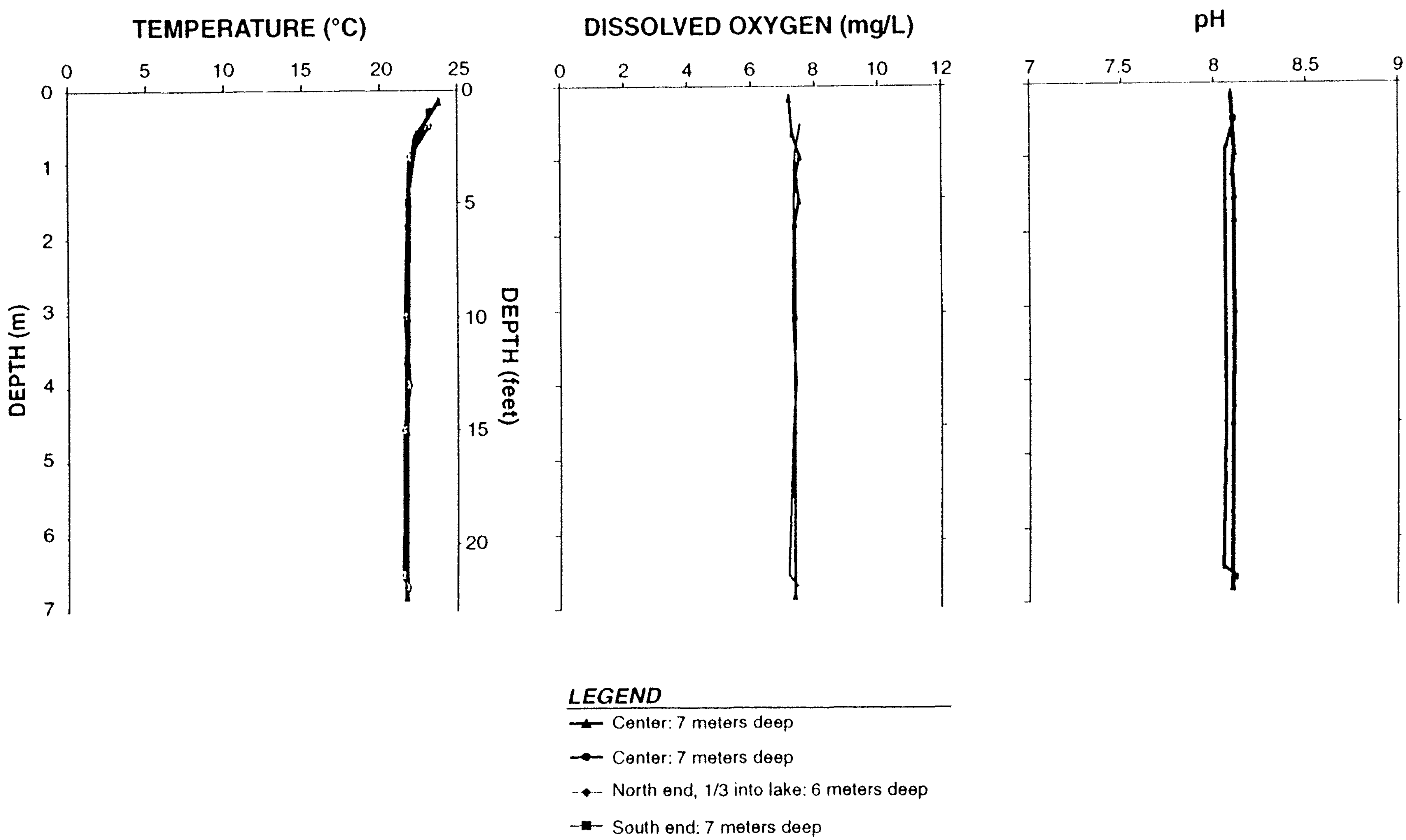

Figure 3-2. Boss pit-lake temperature, dissolved oxygen, and pH profiles.

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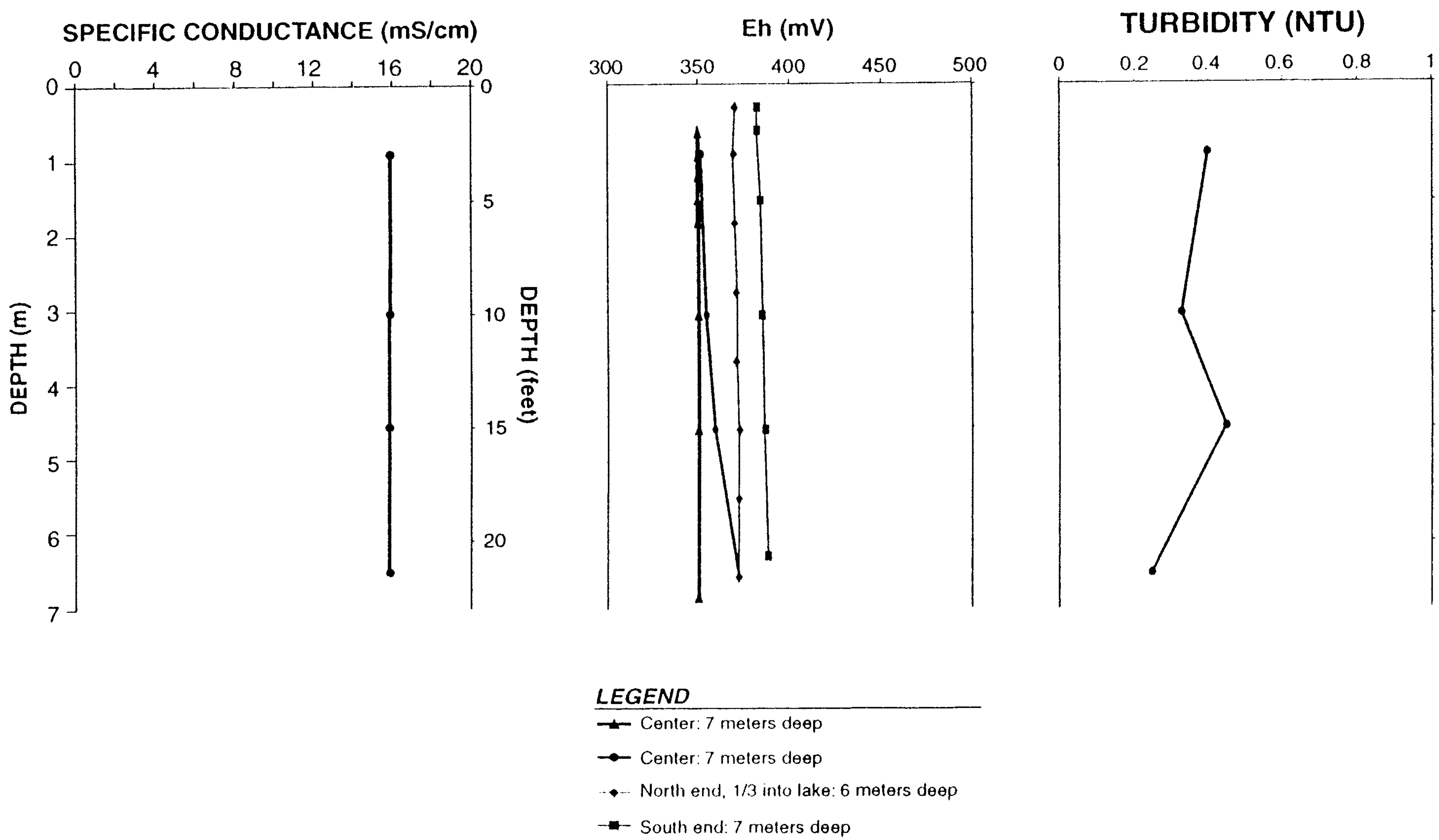

Figure 3-3. Boss pit-lake specific conductance, Eh, and turbidity profiles.

Department of the Interior
U.S. Fish and Wildlife Service
Region 1

Environmental Contaminants Program
Off-Refuge Investigations Sub-Activity

Final Report

NV – Assessment of Wildlife Hazards Associated With Mine Pit Lakes

Project ID: 1F34

By

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July 2004

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Executive Summary

Several open pit mines in Nevada lower groundwater to mine ore below the water table. After mining, the pits partially fill with groundwater to form pit lakes. Water quality in the pit lakes may be affected by a variety of factors including the quality of inflowing groundwater, atmospheric precipitation, sulfide oxidation in surrounding rock, dissolution of metals, precipitation of metals, and evaporative concentration. Oxidation reactions on exposed pit walls may release sulfate, acid, and metals into the pit lake. In some cases, water contained in the pit lakes may be of poor quality and may contain concentrations of metals or other inorganic constituents that greatly exceed water quality standards and published wildlife effect levels. Two types of pit lakes may form. The first type has a circumneutral pH and may develop a complex food web. The second type is highly acidic and will remain relatively sterile. While this second type may be less attractive to wildlife, it is highly toxic if water is consumed. Geochemical modeling to predict water quality in some future pit lakes has predicted long-term degradation of pit lake water quality. Wildlife use and the degree of threat presented by inorganic contaminants in pit lakes are uncertain, although at least limited riparian and aquatic communities will become established in most pit lakes where pH remains circumneutral. In these circumneutral pH pit lakes, wildlife use and fish introductions over the long-term are uncertain. Wildlife exposure to contaminants through drinking water and consumption of contaminated foods in the lakes may occur. Constituents that bioaccumulate or biomagnify in the food chain, such as selenium and mercury, are of greatest concern. Currently, little is known about biological characteristics of mine pit lakes. This investigation was designed to provide information on habitat and community development, habitat quality, wildlife use, inorganic contaminants behavior and partitioning, and the potential for wildlife exposure to inorganic contaminants in mine pit lakes.

Five pit lakes or pit lake complexes, including Yerington, Buena Vista complex, Tuscarora, Clipper, and Aurora, with a variety of mining histories were visited as a part of this study, with emphasis on the lakes at the abandoned copper mine near Yerington, Nevada, and the abandoned gold mine near Tuscarora, Nevada. Habitat, community development, and wildlife use varied among sites. All of these pit lakes maintained a circumneutral pH. Water quality, based on field measurements of specific conductance, was poorest at the Clipper pit lake and the best at the Tuscarora pit lake. Copper and selenium concentrations in water at the Yerington pit lake were elevated; however, copper concentrations were declining. Biological samples, including vegetation, aquatic invertebrates, fish, and bird eggs, were collected from the Yerington and Tuscarora pits for analysis of metals and trace elements.

Residues in vegetation and aquatic invertebrates were evaluated in relation to: avian dietary effect levels; residues in fish were evaluated in relation to effects on fish, avian consumption, and to human consumption; and residues in bird eggs were evaluated in relation to reproductive effects. Copper concentrations in algae and aquatic invertebrates from the Yerington pit lake were elevated; however, birds retain a very small portion of ingested copper. Mercury concentrations in amphipods and bass from

the Tuscarora pit lake were elevated in relation to adverse dietary effect levels for birds, whereas mercury levels in bass were in the range where adverse effects to fish and fish-eating birds may be expected. Mercury levels in the bass also exceeded a human health consumption advisory concentration. Selenium in algae and aquatic invertebrates from the Yerington pit lake was elevated and exceeded a dietary threshold associated with adverse reproductive effects in birds. Residues in swallow eggs from the Yerington pit were below adverse effect concentrations.

The information collected during this study and that of a previous study demonstrated elevated exposure of wildlife to selected inorganic contaminants at three pit lakes. This information points to the need for routine studies at pit lakes from their formation to beyond the completion of filling to determine risks to wildlife, including migratory birds. Without such studies, risks to wildlife will be unknown and uncontrolled.

Introduction

Several open pit mines in Nevada and other western states lower groundwater, typically by aggressive pumping, to mine ore below the water table (Miller et al. 1996). After mining, the remaining pits partially fill with groundwater to form pit lakes. In the foreseeable future, more than 35 such pit lakes will exist in Nevada. Sizes of the pit lakes will vary from less than one hectare to more than 360 hectares. The lakes that are expected to form will contain from less than 100 acre-feet (AF) to about 540,000 AF of water (Miller 2002). For comparative purposes, all existing reservoirs in Nevada, excluding Lake Mead, contain approximately 600,000 AF (Miller 2002). Pit lakes in the Humboldt River basin of Nevada will contain 2.5 times this amount.

Two types of pit lakes may form. The first type has a circumneutral pH and may develop a complex food web. The second type is highly acidic and will remain relatively sterile. While this second type may be less attractive to wildlife, it is highly toxic if water is consumed.

Water quality in the pit lakes is, or will be, affected by a variety of factors, including the quality of inflowing ground water, outflow of groundwater, atmospheric precipitation, sulfide oxidation in surrounding rock, dissolution of metals, precipitation of metals, and evaporative concentration. The interaction of groundwater with the walls and surrounding rock of the pit will be an important factor in the future quality of pit lake water (Miller 2002). Oxidation reactions on the exposed pit walls may release sulfate, acid, and metals into the lake. The host rock is dewatered when a pit is excavated below the water table. If the host rock is sulfide-rich, it will oxidize when exposed to air that is pulled onto the evacuated pore spaces (Miller 2002). Reaction products will be generated on the exposed surfaces, and the oxidation products will be flushed into the pit lake by groundwater as the pit refills. Sulfuric acid is one reaction product of concern which may result in the leaching of metals and trace elements into the pit lake and may lower water pH to hazardous levels.

In some cases, water contained in pits is, or is expected to be, of poor quality and may contain concentrations of metals or other inorganic constituents that greatly exceed water quality standards and published wildlife effect levels. For example, pit lake water in Nevada has been found to contain mercury at concentrations exceeding 80 μg/L (Macdonald 1992), selenium exceeding 100 μg/L (Macdonald 1992; Miller et al. 1996; Miller 2002; Brown and Caldwell 2003) and copper exceeding 30 mg/L (Macdonald 1992; Miller et al. 1996). The current mercury chronic (96 hour) standard for protection of aquatic life is 0.012 μg/L in Nevada (Nevada Administrative Code [NAC] 2000). Mercury strongly accumulates and magnifies in biological systems and low concentrations in water may be concentrated to hazardous levels in higher trophic levels (Zillioux et al. 1993). Waterborne selenium concentrations $\geq$ 2 μg/L are considered hazardous to the health and long-term survival of fish and wildlife (Lemly 1996). The acute and chronic aquatic life standards for copper are hardness dependent and are based on filtered samples. Although the copper concentrations reported above were for unfiltered samples, the concentrations were alarming in relation to effects on aquatic life as well as for irrigation and the watering of livestock where the Nevada standards are 200 and 500 μg/L, respectively (NAC 2000).

Geochemical modeling efforts to determine water quality at some future pit lakes have predicted long-term degradation of pit lake water quality. In some cases, water quality continued to deteriorate for the time period that the model was run (as long as 230 years) (U.S. Bureau of Land Management 1996). This may be due in part to evapoconcentration where the concentration factor may be 10 to 40 times the concentration in the ground water inflow (Atkinson 2002). Evapoconcentration is a major consideration for constituents such as arsenic, selenium, and other elements. However, modeling can be rather complex due to various uncertainties in the process (Moreno and Sinton 2002).

Wildlife use and the degree of threat presented by inorganic contaminants in pit lakes are uncertain. It is assumed that riparian and aquatic communities will become established in most pit lakes at circumneutral pH. However, the nature of these communities is questionable. Water contained in mine pits may be nutrient-poor or may contain elevated concentrations of contaminants which may restrict productivity. Mine pit lakes will typically be deep and steep sided, thereby limiting riparian and shallow lentic habitat. However, benches and ramps in the mine pit, along with erosion of pit walls, may provide limited areas where shallow lentic or riparian communities may become established, especially following the completion of lake filling. Similarly, wildlife use and fish introductions over the long-term are uncertain. Wildlife using pit lakes may be exposed to hazardous levels of environmental contaminants in pit lakes. In an extreme case (Berkeley Pit near Butte, Montana) a large-scale avian die-off was attributed to poor quality pit lake water. In this incident, the death of 342 snow geese (*Chen caerulescens*) was attributed to acute metal toxicosis and sulfuric acid exposure resulting from exposure to and consumption of poor quality pit water (Hagler Bailly Consulting, Inc. 1996). Under less extreme conditions, exposure to inorganic contaminants may occur through exposure to water and consumption of contaminated foods from the pit lake. In other cases bioaccumulation and biomagnification become important factors affecting contaminant uptake.

Currently, little is known about biological and chemical characteristics of mine pit lakes. As a result, the ultimate hazards of these lakes are poorly understood. This investigation was designed to provide information on habitat and community development, habitat quality, wildlife use, inorganic contaminant behavior and partitioning, and the potential for wildlife exposure to inorganic contaminants in mine pit lakes.

Study Sites

Yerington

The Yerington Mine pit lake is located in Lyon County, Nevada, approximately 1.6 kilometers (km) west of the city of Yerington, in Mason Valley (Table 1; Figure 1). The pit was mined for copper ore from 1953 to 1978 (Brown and Caldwell 2003). The east-south-east end of the pit is within 0.4 km of the Walker River. Flows in the river were temporarily diverted into the pit during the flood of January 1997 to relieve flooding in the Yerington area, which increased the level of water in the pit lake (Brown and Caldwell 2003). This pit lake was visited on June 12 and 13, 2000. The pit lake was approximately 110 meters (m) deep at the time of this study and its surface was approximately 70 to 110 m below the pit rim. The estimated volume of the lake at the time of this study was about 30,000 AF (Brown and Caldwell 2003). Pit walls are relatively steep sided, but three ramps are present running below the lake level where water levels are relatively shallow in limited areas. Pit lake water quality is dominated by elevated concentrations of copper and selenium.

Buena Vista Complex

This pit lake complex is located in Pershing County, Nevada, approximately 25 km southeast of Lovelock and north of the Carson Sink (Table 1; Figure 1). This iron mining district was active from 1943 until at least the early 1960s (Reeves 1964). Four abandoned mines in this complex were visited on May 31, 2000. Buena Vista 1 is located on the north side of the Buena Vista Hills. This pit is about 15 m deep and contained a small (0.1 hectare), shallow (< 20 cm deep) pit lake of likely meteoric water which may go dry. The Buena Vista 2 pit is < 30 to 45 m deep and contained a lake estimated to be more than 15 m deep and about 1.2 hectares in surface area. The lake was inaccessible. The Buena Vista 3 pit was approximately 30 to 45 m deep and contained a lake with a surface area of about 0.4 hectare that was estimated to be 30 m deep. The lake had a deep center and a shallow shelf. The Buena Vista 4 pit was long and narrow on a north to south axis, deep, with a lake < 10 m deep, and about 1.2 hectares in size, which was shallow at the south end.

Tuscarora

This pit lake is located in northwestern Elko County, Nevada (Table 1; Figure 1). This mining district had a long history of gold and silver production which primarily occurred in the 1870s to 1890s (http://www.nvghosttowns.topcities.com/pastpro/tuscaror.htm). The use of mercury amalgamation for the recovery of precious metals from ores was common during this era. Horizon Gold Shares Inc. began open pit gold mining operations in July 1987 and ceased in August 1989 (Nevada Division of Environmental Protection 1998). The site was visited on June 20-21, 2000 and July 16, 2001. The spring-fed lake is approximately 2 hectares in size, with an outflow. Pit walls are 0 to 10 m high in alluvium.

Clipper

This pit lake is located approximately 30 km southwest of Crescent Valley, Lander County, Nevada (Table 1; Figure 1). The site was visited on June 19, 2000 and July 17, 2001. The pit is steep-walled with the lake being about 90 m below the rim. One small bench is submerged on a haul road. The pit wall on the west side was sloughing. The site is an abandoned barite mine.

Aurora

This pit is located in southwestern Mineral County, Nevada (Table 1; Figure 1). The site was visited on June 13, 2000. The pit is about 40 m deep with a lake of about 4 hectares. Pit walls are relatively steep. The site is an abandoned gold mine.

Methods

Biological characteristics were assessed at least once at each pit lake that was visited. Data on aquatic and riparian vegetation occurrence and abundance and migratory bird and resident wildlife use were collected by direct observation. Aquatic macroinvertebrate occurrence and relative abundance data were collected with the use of kick nets, plankton nets, and light traps. Field measurements of water quality were obtained with use of a Hydrolab (Hydrolab Corporation, Austin, Texas) which was calibrated daily using reference standards. Measurements included water depth, temperature, dissolved oxygen, specific conductance, pH, and in some cases turbidity and salinity. Measurements were normally conducted at 10 m intervals in depth, and in larger lakes at up to four sites in the lake.

Composites of aquatic vegetation and macroinvertebrates were collected at the Yerington and Tuscarora pit lakes. Vegetation samples were collected with gloved hand, placed in chemically clean jars, placed on ice in the field, and frozen upon return to the laboratory. Aquatic macroinvertebrates were collected with a kicknet, sorted from debris, placed in chemically clean jars, placed on ice in the field, and frozen upon return to the laboratory. Three individual largemouth bass (*Micropterus salmoides*) were collected from the Tuscarora pit lake with nets, placed in individual clean containers, placed on ice in the field, and frozen upon return to the laboratory. Three pooled sets of bank swallow (*Riparia riparia*) eggs, each consisting of two to three eggs, all of which had failed to hatch, were collected from nests at the south wall of the Yerington pit. Egg contents were emptied into chemically clean glass jars, placed on ice in the field, and frozen upon return to the laboratory.

All collection gear used for sample collection for chemical analysis was thoroughly washed with Citranox (Alconox, Inc., White Plains, New York) prior to use in each pit lake. The gear was then washed with site water and a brush between collection sites in each pit lake and finally rinsed with deionized water before each use.

Samples were submitted to Laboratory and Environmental Testing, Inc., Columbia, Missouri, a contract laboratory under the Patuxent Analytical Control Facility (PACF), Laurel, Maryland, of the U.S. Fish and Wildlife Service, for metal and trace element analysis. Samples were homogenized, freeze dried to determine percent moisture, and digested in preparation for analysis. Mercury was analyzed by cold vapor atomic absorption (AA), arsenic and selenium by hydride generation AA, lead and cadmium by graphite furnace AA, and the remainder by inductively coupled plasma (ICP). Quality control/quality assurance (QA/QC) included the analysis of two procedural blanks (one each for animal and plant tissue), two duplicates (one each for an invertebrate and vegetation sample), two reference materials (apple leaves and lobster hepatopancreas), and two spike recoveries (one each for an invertebrate and vegetation sample). Recovery of arsenic from the spiked vegetation sample was low; therefore, the vegetation arsenic values may be biased low. QA/QC and analytical results were approved by PACF. All concentrations reported herein, including those from the literature, are expressed on a dry weight basis, unless noted otherwise.

Results

Biological Observations

Yerington

Vegetation around the pit lake was limited to small areas of cottonwoods (*Populus* sp.), willow (*Salix* sp.), tamarisk (*Tamarix* sp.), cattails (*Typha* sp.), and shrubs that were concentrated in areas of spring inflows. Four samples of algae (*Cladophora*) were collected from the lake for analysis; sample weights ranged from 20 to 50 g. Fish were absent from the lake, as confirmed by gill netting for 2 days.

Bird observations conducted during this study recorded the following species and maximum numbers or relative abundance during the period of June 12-14, 2000: bank swallow, abundant, nesting on pit walls and foraging over the lake (three pooled egg samples were collected for analysis; sample weights ranged from 1.1 to 2.5 g); western grebe (*Aechmophorus occidentalis*), one foraging in shallow water along the east side of the lake; eared grebe (*Podiceps nigricollis*), three; killdeer (*Charadrius vociferous*), one; unidentified passerines, eight along the south side uplands; unidentified duck, two; unidentified cormorant, one; Canada goose (*Branta canadensis*), one. Two mule deer (*Odocoileus hemionus*) were also seen, along with several lizards. Mule deer were seen coming to the lake to drink during later observations. Bird observations made at later dates, outside the time-frame of this study, found larger total numbers (up to about 300) during the winter, with Canada geese, several species of ducks, and grebes being predominant.

Daphnia (Cladocera) and copepods (Order Calanoida) were found in plankton hauls from the lake conducted on June 13, 2000. The contents of a light trap recovered on June 14, 2000 included abundant numbers of *Daphnia* of at least two species, one *Ceriodaphnia* (Cladocera), copepods (Copepoda) of two orders (Calanoida and Cyclopoida), as well as one unidentified insect. Three samples of dragonfly larvae (Odonata, *Libellula* sp.) and one sample of naucorids (Hemiptera, Naucoridae, *Ambrysus* sp.) were collected by kicknet for analysis. Sample weights of invertebrates ranged from 21 to 33 g.

Buena Vista Complex

The Buena Vista 1 lake had a fringe of tamarisk trees. Wildlife was not noted at this site. Algae were present in the Buena Vista 2 lake and a sparse fringe of shrubs was present around the lake. The only wildlife noted at this site was approximately 10 unidentified passerines. A fringe of tamarisk and small shrubs was present at Buena Vista 3. Unidentified blackbirds and wrens were present at this site as well as one common crow (*Corvus brachyrhynchos*) and one Say's phoebe (*Sayornis saya*). Aquatic invertebrates that were present included: corixids (Corixidae) and copepods, which were abundant; mayflies (Ephemeroptera) which were common; and stoneflies (Plecoptera). Algae and pondweed (presumably *Potamogeton* sp.), the latter on a shelf, were also present in the lake. Vegetation at Buena Vista 4 included a sparse fringe of shrubs and tamarisk, with algae being abundant in the water. Birds observed at this site included an unidentified wren, one red-tailed hawk (*Buteo jamaicensis*), and one great horned owl

(*Bubo virginianus*). Hemiptera were abundant in the lake, whereas dragonflies and mayflies were ranked as sparse.

Tuscarora

A few willows were present on the east-north-east shore; submergent vegetation was sparse. Three samples of submergent vegetation, later identified as golden dock (*Rumex maritimus*), were collected for analysis; sample weights ranged from 17 to 22 g. Wildlife observations in June 2000 included the following (maximums): Brewer's blackbird (*Euphagus cyanocephalus*), seven; unidentified swallows, 15 nesting on west pit wall; killdeer, four, nesting; American robin (*Turdus migratorius*), one; common nighthawk (*Chordeiles minor*), one; black-necked stilt (*Himantopus mexicanus*), one; unidentified shorebird, two; unidentified duck, one, and unidentified ground squirrel, three. Three largemouth bass (350 to 365 mm total length and 688 to 805 g total weight) and three samples of amphipods (Amphipoda; sample weights ranged from 9 to 20 g) were collected for analysis. *Daphnia* and amphipods were abundant, whereas corixids and beetles (Coloeptera) were common in captures from light traps. Copepods (Orders Cyclopoida and Calanoida) were also captured in a plankton net.

Wildlife observations in July 2001 included the following maximum numbers during two observation periods: unidentified swallow, > 30; common raven (*Corvus corax*), three, one with a nest; mourning dove (*Zenaida macroura*), two; common nighthawk, one; Swainson's hawk (*Buteo swainsoni*), three; killdeer, one; red-tailed hawk, two; red-shafted flicker (*Colaptes auratus*), one; coyote (*Canus latrans*), six; and black-tailed hare (*Lepus californicus*), one. The following aquatic invertebrates were also found: amphipods, abundant; two types of Coleoptera, one common and one sparse; corixids, abundant; naucorids, common; and *Daphnia*, common. More than three largemouth bass were seen in the lake.

Clipper

Observations in June 2000 reported that sparse amounts of algae were present in the lake, with sparse amounts of tamarisk present around the edges of the lake, and sparse vegetation on the benches of the pit walls. Wildlife observations in June 2000 reported the following: great horned owl, three; raven, two; unidentified swallow, > six; and American coot (*Fulica americana*), one. Speckled dace (*Rhinichthys osculus*) were common in the lake. Aquatic invertebrates that were found, all recorded as sparse, included: notonectid (Hemiptera, Notonectidae), damselflies (Odonata, adults and juveniles), corixids, Hymenoptera (adult), chironomid (Chironomidae) larvae, and Coleoptera (Georyssidae). Observations conducted in July 2001 reported an unidentified type of aquatic vegetation to be common and cattails to be sparse. Wildlife observations included: olive-sided flycatcher (*Contopus borealis*); dusky flycatcher (*Empidonax oberholseri*); common nighthawk; and an unidentified bat.

Aurora

Wildlife observations made during the June 2000 visit recorded the following: unidentified swallows, 20-30 nesting on the pit high walls; starling (*Sturnus vulgaris*); unidentified hawk; upland birds in the vicinity; and deer sign.

Field Measurements of Water Quality

Data on field measurements of water quality are provided in Table 2. At the Yerington pit lake, water temperature declined rapidly with depth from the surface to approximately 30 m and then was relatively constant. Dissolved oxygen increased from the surface to about 20 meters in depth and declined with increasing depth. Specific conductance increased slightly with depth, whereas pH tended to decline with depth. At the Tuscarora pit lake, water temperature was the highest at the surface, dissolved oxygen was somewhat variable in relation to depth depending on the location, specific conductance increased slightly with increasing depth, and pH generally declined with increasing depth. In addition to the data presented in Table 2, turbidity measurements ranged from 14.5 to 24.7 nephelometric turbidity units (NTU) at the Tuscarora pit lake in July 2001. At the Clipper pit lake, water temperature declined with depth, dissolved oxygen was somewhat variable, specific conductance was relatively stable, and pH declined slightly with increasing depth. Turbidity was also measured at the Clipper pit lake in July 2001 and ranged from 15.0 to 28.9 NTU. Salinity measurements at the same site ranged from 1.28 to 1.34 parts per thousand. Surface water quality data for Buena Vista 1, 3, and 4 and Aurora are also provided in Table 2.

Metals and Trace Elements in Water

Concentrations of metals and trace elements have been reported for the Yerington, Tuscarora, and Aurora pit lakes by other investigators. Selected data are provided here (Table 3) in an effort to relate water quality to residues of various constituents in biological samples that were collected.

The recent data (1991-2001) for the Yerington pit lake were compiled by Brown and Caldwell (2003). However, the data presented in Table 3 are limited to samples that were specifically designated as being total (i.e., not filtered) or dissolved (i.e., filtered), which eliminated the bulk of the data and narrowed the data set to the years 1995-1998. Ranges of concentrations of various constituents in both filtered (dissolved) and unfiltered (total) samples did not appear to be biased by collection location due to avoidance of samples collected near surface water inputs. Data from a variety of depths in the lake are included. The depth-averaged dissolved copper concentration in 1995 was 136 µg/L; however in 2000 and 2001 the concentration had declined to only about 20 µg/L (R. Hershey, pers. comm.). Selenium concentrations for the same period, on the other hand, have been relatively stable and have remained within the range of 100 to 130 µg/L.

Water quality in the Tuscarora pit lake was provided by L. Stillings (pers. comm.). All data were for dissolved constituents. Samples were collected in January, April, July, and November 2000 from five variable depths during each sampling event (Table 3). Specific conductance ranged from 246.6 to 364.7 µS/cm, and generally increased with depth. No other consistent trends in water quality parameters were noted in relation to season or depth.

Water quality data in the Aurora pit lake were measured by Kempton (1996) in 1995. The data provided in Table 3 are for dissolved constituents in one sample each from the epilimnion and hypolimnion. Total dissolved solids concentrations were 478 and 524 mg/L, whereas pH was 7.59 and 7.68 for the epilimnion and hypolimnion, respectively.

Metals and Trace Elements in Biological Samples

Geometric means and ranges of concentrations of metals and trace elements for samples from the Yerington and the Tuscarora pit lakes that were collected during this study are provided in Tables 4 and 5, respectively. At the Yerington pit lake, naucorids usually had similar or lower concentrations of all elements than dragonfly larvae, with the exception of zinc where the concentration was twice as high, and especially for cadmium where the concentration was an order of magnitude higher in naucorids. However, caution should be used in comparisons due to the small number of samples analyzed. Ranges of concentrations within a given sample type were highly variable for chromium and manganese in algae, and mercury in swallow eggs. For the samples from the Tuscarora pit lake, ranges of concentrations within a given sample type were highly variable for aluminum and iron in amphipods.

Discussion

Water Quality

Overall, water quality, as indicated by specific conductance, was poorest (i.e., high conductivity) at the Clipper pit lake and the best (i.e., low conductivity) at the Tuscarora pit lake. Water pH was similarly circumneutral among all sites sampled.

Concentrations of metals and trace elements in pit lake water (Table 3) were compared to Nevada water quality standards for aquatic life, irrigation, and watering of livestock (Nevada Administrative Code 2000). However, standards for aquatic life are often hardness-related. A hardness of 275 mg/L for the Yerington pit lake, based on data from R. Hershey (pers. comm.) was used in calculations. For the Yerington pit lake, standards for irrigation and watering livestock were not exceeded, with the exception of selenium which exceeded both standards (i.e., 20 and 50 μg/L, respectively). Copper concentrations in earlier samples exceeded the acute (i.e., 39 μg/L) and chronic (i.e., 24 μg/L) aquatic life standards; however, samples collected in 2000 and 2001 had concentrations lower than these standards. The single reported dissolved molybdenum concentration exceeded the aquatic life standard of 19 μg/L. Total selenium concentrations in water greatly exceeded the acute (i.e., 20 μg/L) and chronic (i.e., 5 μg/L) aquatic life standards. No other elements exceeded the Nevada standards. The elevated copper and selenium concentrations in water are in agreement with the elevated concentrations that were found in algae and macroinvertebrates. It should be noted that the State of Nevada does not apply water quality standards to pit lakes.

Water quality in the Tuscarora pit lake was generally good, with no dissolved concentrations exceeding aquatic life standards for Nevada. However, no data for mercury were available. Water quality in the Aurora pit lake was generally good except for selenium, where the concentration was approximately two times the chronic aquatic life standard for Nevada.

Relation of Element Concentrations to Avian Dietary Effects

Concentrations of metals and trace elements in biological samples were evaluated as potential food sources to migratory birds. However, it should be noted that algae and the portions of golden dock that were collected may not be commonly consumed by migratory birds. Effect concentrations for barium, beryllium, iron, magnesium, manganese, and strontium are not known and these constituents are not discussed further.

Aluminum

An aluminum concentration of 5,000 µg/g was considered an adverse dietary effect level in waterfowl (Sparling 1990), with diets less than 1,000 µg/g considered to be not harmful (Sparling and Lowe 1996). However, interactions with calcium and phosphorus are likely important. The higher concentration above was exceeded in all algae samples and in two of three samples of dragonfly larvae from the Yerington pit lake and in one of three samples of golden dock from the Tuscarora pit lake.

Arsenic

The dietary no-observed-adverse effect-level (NOAEL) for two aquatic avian species were 19-22 µg/g (wet weight) when based on sodium arsenite in the diet and 3.4-3.9 µg/g (wet weight) when based on copper acetoarsenite (U.S. Department of the Interior 1998). An arsenic concentration of 30 µg/g in the diet of mallard (*Anas platyrhynchos*) ducklings was associated with reduced weight gain (Camardese et al. 1990). Arsenic concentrations in algae, aquatic invertebrates, and fish from both pit lakes did not exceed the latter concentration.

Boron

Weight gain of mallard ducklings whose parents received a diet containing 30 µg/g boron was significantly reduced, whereas the reproductive success of adult mallards that received a diet containing 1,000 µg/g was significantly reduced (Smith and Anders 1989). Only one of four algae samples from the Yerington pit lake contained more than 30 µg/g, with the geometric mean being lower. No other samples exceeded this concentration.

Cadmium

All cadmium concentrations in algae, aquatic invertebrates, and fish from both pit lakes were more than an order of magnitude below a level of concern in mallard ducklings of 20 µg/g (Cain et al. 1983).

Chromium

Potential adverse effects on health and reproduction of wildlife would be expected when chromium in the diet exceeds 10 µg/g (Eisler 2000a). Three of four algae samples and one of three dragonfly samples from the Yerington pit lake equaled or exceeded this threshold, with concentrations in biological samples from the Tuscarora pit lake being much lower.

Copper

Eisler (2000a) considered poultry diets containing < 200 µg/g of copper to be safe. Copper concentrations in all samples of both algae and aquatic invertebrates from the Yerington pit lake exceeded this level, with three algae samples exceeding it by more than an order of magnitude. However, birds retain a very small portion of ingested copper (Eisler 2000a). Copper concentrations in biological samples from the Tuscarora pit lake were all less than 65 µg/g.

Mercury

Adverse reproductive effects in mallards were associated with a dietary concentration of 0.5 µg/g (Heinz 1979). All mercury concentrations in algae and aquatic invertebrates from the Yerington pit lake were well below this concentration. However, mercury concentrations in amphipods and especially largemouth bass from the Tuscarora pit lake were much higher, with concentrations in amphipods ranging from 0.74 to 2.5 µg/g and concentrations in bass ranging from 14 to 20 µg/g (dry weight). The mercury concentrations in bass on a wet weight basis ranged from 3.8 to 5.6 µg/g. These concentrations, especially those found in fish, may have significant adverse effects to some migratory birds. Nearly all mercury in fish is in the more toxic methyl form (Wiener and Spry 1996). Barr (1986) found adverse effects to common loon (*Gavia immer*) reproduction and behavior when their diet contained 0.3 µg/g (wet weight). However, at least some fish-eating birds are able to demethylate methyl mercury, thereby providing protection from toxic effects (Henny et al. 2002).

Molybdenum

Growth reduction in birds was associated with a lower dietary concentration of molybdenum of 200 µg/g (Eisler 2000b). All molybdenum concentrations in biological samples from both pit lakes were one to two orders of magnitude lower than this concentration.

Nickel

A dietary concentration of 800 µg/g (fresh weight) of nickel has been associated with adverse effects to adult mallards (Eisler 2000a). All nickel concentrations in biological samples from the both pit lakes were far below this level.

Lead

An avian dietary concentration of < 5 µg/g of lead was proposed to be protective (Eisler 2000a). All lead concentrations in biological samples from both pit lakes were below this level.

Selenium

The lower threshold of dietary exposure associated with adverse reproductive effects in birds is 3 µg/g (U.S. Department of the Interior 1998). Three of four algae samples from the Yerington pit lake had selenium concentrations that exceeded this threshold and all samples of aquatic invertebrates had far higher concentrations, with two of four exceeding it by more than an order of magnitude. Selenium concentrations in biological samples from the Tuscarora pit lake were much lower, with only the concentrations in amphipods approaching this threshold concentration.

Vanadium

The avian dietary concern level for vanadium is 100 µg/g (White and Dieter 1978). Vanadium concentrations in aquatic invertebrates and algae from both pit lakes were well below the concern level.

Zinc

The dietary effect levels proposed for birds are < 178 µg/g to prevent marginal sublethal effects and < 2000 µg/g to prevent the death of chicks and ducklings (Eisler 2000a). Zinc concentrations in aquatic invertebrates and algae from both pit lakes were well below these levels.

Summary

In general, residues of mercury in amphipods and bass from the Tuscarora pit lake and selenium in algae and aquatic invertebrates from the Yerington pit lake were of greatest concern in relation to fish and/or wildlife effect levels. Although aluminum, chromium, and copper concentrations in algae and aquatic invertebrates from the Yerington pit lake were elevated, their potential effects are less clear.

Residues in Eggs in Relation to Effects

Concentrations of metals and trace elements in bank swallow eggs from the Yerington pit were evaluated in relation to published effect levels. The no observed effect level of inorganic arsenic in avian eggs is 1.8 µg/g, whereas the corresponding level for boron is 22 µg/g (Seiler et al. 2003). Arsenic and boron concentrations in bank swallow eggs were well below these levels. The background level of cadmium in eggs was listed as 0.15 µg/g (Seiler et al. 2003), with no information being provided on a no observed effect level. One of three bank swallow eggs had a cadmium concentration exceeding this level. Copper concentrations in bank swallow eggs were below the listed background level of 5.5 µg/g (Seiler et al. 2003). The no observed effect level and the dose-response threshold in avian eggs for mercury were both listed as 3.0 µg/g by Seiler et al. (2003), with the background level being 0.1 µg/g. Mercury concentrations exceeded the background level, but not the no observed effect level. The background level, no observed effect level, and lowest observed effect level for molybdenum in avian eggs were 0.25 µg/g, 23 µg/g, and 23 µg/g, respectively (Seiler et al. 2003). Molybdenum was not detected in bank swallow eggs at a detection limit of 2 µg/g. The background level for selenium in avian eggs was listed as 1.9 µg/g, with the dose response threshold for toxic effects being 6.0 µg/g (Seiler et al. 2003). Selenium concentrations in bank swallow eggs were only slightly above the listed background level. The background level for zinc in avian eggs was listed at 50 µg/g; no information was provided on concentrations related to toxic thresholds (Seiler et al. 2003). Zinc concentrations in all bank swallow egg samples exceeded the background concentration.

Bank swallows that nest on the southern cliff face of the Yerington pit may forage, in part, over riparian areas and adjacent fields along the Walker River as well as over the pit lake. Therefore, their accumulation of metals and trace elements from sources in the pit lake may be limited. Their assumed foraging behavior may explain the low concentrations of many constituents in their eggs. The presence of moderate mercury concentrations in bank swallow eggs may be due to mercury contamination of the Walker River from historic mining (Wiemeyer 2002). Overall, the metal and trace element concentrations in bank swallow eggs from the Yerington pit were not high enough to be of concern. Information is needed on selenium concentrations in tissues of aquatic birds, such as grebes, that have been observed foraging on the Yerington pit lake.

Effects Levels in Fish

Elevated concentrations of metals and trace elements in fish tissues may cause adverse effects to fish. Concentrations of selected elements were evaluated in relation to concentrations found in bass from the Tuscarora pit lake. Decreased growth and survival of juvenile bluegill (*Lepomis macrochirus*) was related to a concentration of 2.1 µg/g arsenic (wet weight; Gilderhus 1966); arsenic concentrations in bass were far lower. Eisler (2000a) suggested that a chromium concentration > 4.0 µg/g indicated probable exposure; the chromium concentration in one bass (i.e., 3.2 µg/g) approached this level. Whole body concentrations of mercury that were associated with sublethal or lethal toxic effects were about 5 µg/g (wet weight) for brook trout (*Salvelinus fontinalis*) and about 10 µg/g (wet weight) for rainbow trout (*Oncorhynchus mykiss*) (Wiener and Spry 1996). Mercury concentrations in bass from the Tuscarora pit lake ranged from 3.8 to 5.6 µg/g (wet weight), which overlaps the lower range of effect concentrations for trout. However, the comparative sensitivity of largemouth bass is unknown. Predator avoidance behavior in fish may be adversely affected at lower concentrations. For example, avoidance behavior of golden shiners (*Notemigonus crysoleucas*) with a whole body concentration of 5.18 µg/g (wet weight) mercury was adversely affected (Webber and Haines 2003). Selenium concentrations of 4 µg/g in whole bodies of fish have been associated with mortality of juveniles and reproductive failure (Lemly 1996). This concentration has also been proposed as a national tissue-based criterion for the protection of aquatic life in the United States (Hamilton 2002). Selenium concentrations in bass from the Tuscarora pit lake were somewhat lower. The elevated mercury concentrations may be due in part to its use in recovery of precious metals at the Tuscarora mining district in the late 1800s.

Previous Biological Data

Kempton (1996) previously collected biological samples and conducted limited wildlife observations at the Yerington pit lake in August and September 1995. He found four species of Chlorphyta and three species of Cyanophyta (phytoplankton) as well as four species of Copepoda and several species of Rotifera (zooplankton) from tows in the epilimnion of the lake. He also reported the following from the littoral zone: macrophytes - cattails, *Ludwigia* sp., and tamarisk; periphyton, algae; and invertebrates - chironomids, aquatic beetles, and aquatic true bugs. The following wildlife species were observed: spotted sandpiper (*Actitis macularia*), California gull (*Larus californicus*), horned grebe (*Podiceps auritus*), eared grebe, rock wren (*Salpinctes obsoletus*), turkey vulture (*Cathartes aura*), bank swallow, unidentified bat, and unidentified lizard. Cattail, *Ludwigia* sp., and an insect composite were collected for analysis of selected metals and trace elements (Table 6). Copper concentrations in *Ludwigia* and the insect composite were above the level reported to be safe (Eisler 2000a). Mercury in the insect composite exceeded the avian dietary effect concentration (Heinz 1979). Selenium concentrations in all biological samples exceeded the lower threshold dietary exposure associated with adverse effects to reproduction (U.S. Department of the Interior 1998).

Bass were said to have been introduced to the Yerington pit lake 10 or more years ago (J. Sawyer, pers. comm.) and fish could have been introduced when Walker River water was diverted into the pit lake in January 1997. The current absence of fish may be due to the toxicity of elevated concentrations of selected metals and trace elements in the water, with selenium and copper being the prime suspects.

Kempton (1996) also collected biological samples and conducted limited wildlife observations at the Aurora pit lake in August 1995. He found three species of Bacillariophyta (diatoms), three species of Chlorophyta (green algae), one species of Chryptophyta, two species of Cyanophyta (blue-green algae), and one species of Euglenophyta, all phytoplankton, in plankton tows. He also found three species of Cladophera (*Daphnia*), five species of Copepoda, and three species of Rotifera, all zooplankton, in plankton tows. He reported the following from the littoral zone: no macrophytes; the following invertebrates - backswimmers, aquatic mites, water boatmen, aquatic wasps, white flies, ephippia, chironomid larvae, and nematodes; and the following periphyton – blue-green algae (*Jaaginema*), and diatoms. Wildlife observations included spotted sandpiper, rock wren, bank swallow, Cooper's hawk (*Accipiter cooperii*), Townsend's ground squirrel (*Spermophilus townsendii*), and an unidentified bat. Black flies and *Daphnia* were collected for analysis of selected metals and trace elements (Table 7). Concentrations of four elements in the *Daphnia* sample approached or exceeded dietary concentrations associated with adverse effects in birds (see discussion above). The estimated cadmium concentration approached the concern level for mallard ducklings (Cain et al. 1983). The mercury concentration was four times the dietary concentration associated with adverse reproductive effects in mallards (Heinz 1979). The estimated selenium concentration was twice the lower threshold of dietary exposure associated with adverse reproductive effects in birds (U.S. Department of the Interior 1998). The zinc concentration was twice the proposed dietary effect level in birds to prevent sublethal effects (Eisler 2000a).

Recommendations

General

This report is only the first step in providing biological information on habitat and community development, habitat quality, wildlife use, including migratory birds, and the potential for wildlife exposure to inorganic contaminants in mine pit lakes in Nevada. The number of pit lakes that was visited was small and the number where contaminants data were collected was even more limited. However, the information that was obtained, demonstrating elevated exposure of wildlife to selected contaminants at two pit lakes and reinforced by the previous findings at a third pit lake, clearly points to the need for routine studies at pit lakes from their formation, through the period of filling, and continued beyond the time of lake level stabilization. Such studies should be required by state and federal regulatory agencies as part of the mine permitting process. Without such studies, the risks to wildlife will be unknown and uncontrolled. Such studies may also eventually aid in understanding risks at future pit lakes prior to their filling, which might lead to management actions that could reduce risks to wildlife.

Human Health Concerns

The U.S. Environmental Protection Agency (2004) has provided monthly fish consumption limits for humans in relation to various concentrations of mercury in fish. The concentrations are for methylmercury in fish fillets; therefore, they cannot be directly related to mercury concentrations in whole fish. However, nearly all mercury in fish is in the methylmercury form, with concentrations in muscle tending to be higher than in whole body, at least for trout (Wiener and Spry 1996). No fish consumption was advised when methylmercury concentrations were > 1.9 µg/g (wet weight). Total mercury concentrations in largemouth bass from the Tuscarora pit lake ranged from 3.8 to 5.6 µg/g (wet weight), which are two to three times higher than the no consumption advisory. Therefore, it is recommended that no largemouth bass from this site be consumed by humans.

Acknowledgements

We thank Erik Orsak, Jesse Rivera, Margie Evans, and Cody Short for assistance with field work. Ron Hershey of the Desert Research Institute provided water quality data for the Yerington pit lake. Lisa Stillings of the U.S. Geological Survey provided water quality data for the Tuscarora pit lake. Joe Sawyer provided information on the Yerington pit lake. Russ Mac Rae and Julie Campbell provided critical reviews of a draft of this report.

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Table 1. Locations and elevations of mine pit lakes in Nevada visited during the study, 2000-2001.

Pit lake	UTM's North	UTM's East	Elevation (meters)
Yerington	4316962	310036	1276
Tuscarora	4573575	564994	~1850
Buena Vista 1	4433199	401215	not recorded
Buena Vista 2	4433204	402125	1299
Buena Vista 3	4436234	397314	1247
Buena Vista 4	4438073	398620	1277
Clipper	4455332	514231	1654
Aurora	4240047	335245	2176

Table 2. Field measurements of water quality[a] at mine pit lakes in Nevada, 2000-2001.

Pit lake	Date	Depth (m)	Temp. (°C)	DO (mg/L)	SpC (µS/cm)	pH (SU)
Yerington	6/13/00					
West end		0	20.43	7.52	830	8.41
		10	16.98	8.98	834	8.35
		20	8.69	9.95	867	8.35
		30	6.99	8.11	912	8.23
		40	6.61	7.66	863	8.12
		50	6.40	6.73	868	8.02
		60	6.33	6.34	869	7.95
		70	6.33	6.21	869	7.92
		80	6.33	5.92	870	7.88
East end		0	20.44	7.30	829	8.30
		10	18.25	9.13	834	8.36
		20	8.64	10.69	855	8.36
		30	7.32	9.22	857	8.28
		40	6.61	8.67	866	8.17
		50	6.66	7.20	869	8.13
		60	6.70	6.54	869	8.10
		70	6.71	6.10	867	8.08
		80	6.75	5.92	868	8.05
		90	6.73	5.41	870	8.04
		100	6.73	5.22	872	8.02
Middle		0	20.34	7.30	831	8.34
		10	16.02	8.50	835	8.35
		20	8.47	10.00	852	8.36
		30	7.14	9.60	860	8.30
		40	6.68	8.50	8.65	8.18
		50	6.48	7.26	8.69	8.08
		60	6.32	6.51	868	8.00
		70	6.35	6.30	869	7.97
		80	6.35	6.07	870	7.93
		90	6.33	5.94	867	7.90
		100	6.42	5.41	869	7.87
Tuscarora	7/16/01					
West end		0	18.99	8.58	306	8.87
		10	9.82	8.95	317	8.36
East end		0	19.07	8.07	307	8.90
		10	10.34	9.67	312	8.48
Middle		0	19.08	8.30	307	8.90
		10	9.43	11.08	314	8.40
		20	6.81	3.56	329	7.80
#1[b]	6/20/00	0	17.67	7.28	260	8.07
		10	10.20	8.05	283	8.03

Table 2. *continued*

Pit lake	Date	Depth (m)	Temp. (°C)	DO (mg/L)	SpC (μS/cm)	pH (SU)
		~15	7.4	6.24	309	7.85
#2[c]	6/20/00	0	17.28	7.26	258	8.02
		10	10.46	7.90	275	7.99
#3[d]	6/20/00	0	17.23	7.50	260	8.03
		10	10.20	7.98	276	8.00
		~18	6.00	4.16	318	7.73
#4[e]	6/20/00	0	17.50	7.40	255	7.98
		10	10.23	8.40	277	8.03
		~15	6.37	7.33	316	7.85
Buena Vista 1	5/31/00	0	19.0	9.7	1080	7.3
Buena Vista 2	5/31/00	N.S.[f]				
Buena Vista 3	5/31/00	0	22.0	8.9	1940	7.8
Buena Vista 4	5/31/00	0	19.8	8.3	1070	7.8
Clipper	7/17/01					
West end		0	21.08	8.97	2493	8.37
		10	5.42	14.06	2383	7.39
		25	4.28	9.39	2392	7.12
East end		0	20.43	7.80	2484	8.47
		10	5.08	10.53	2383	7.78
		14	4.33	11.72	2386	7.54
Middle		0	20.42	8.65	2482	8.48
		10	5.07	10.80	2386	7.84
		20	4.17	9.01	2417	7.45
		23	4.28	7.65	2425	7.27
Aurora	6/13/00	0	17.00	8.1	1180	8.4

[a] DO = dissolved oxygen; SpC = specific conductance.
[b] 20 meters from west shore.
[c] About 50 meters east of site #1.
[d] About 50 meters east of site #2.
[e] About 50 meters east of site #3.
[f] N.S. = not sampled; inaccessible.

Table 3. Ranges of concentrations of selected metals and trace elements in water (total = unfiltered; dissolved = filtered) from the Yerington[a], Tuscarora[b], and Aurora[c] pit lakes.

Constituent	Yerington Total µg/L	Yerington Dissolved µg/L	Tuscarora Dissolved µg/L	Aurora Dissolved µg/L
Aluminum	21-43 (4)[d]	<0.99-21 (5)	3.4-38 (20)	<8.0-<26 (2)
Arsenic	2.82-4.73 (4)	<5.3-3 (5)	3.9-6.0 (20)	4.0-7.0 (2)
Barium	29-34 (4)	32-34 (5)	26-35 (20)	68-76 (2)
Beryllium	1 (4)	<4.8-1 (5)	<0.05-<0.06 (20)	<1.0 (2)
Boron	387-402 (2)	396-412 (2)	32.5-42.3 (20)	No data
Cadmium	2.0-2.4 (4)	2.0-2.4 (4)	<0.02 (20)	<2.0 (2)
Chromium	2.4-6.0 (4)	<0.51-5 (5)	<1-2 (20)	<3.0-<4.0 (2)
Copper	25-148 (4)	20-153 (5)	<0.5-0.8 (20)	<3.0 (2)
Iron	2-32 (4)	17-24 (4)	22-49 (20)	17 (2)
Lead	1-2 (4)	<3.1-1 (5)	<0.05-0.08 (20)	<1.0 (2)
Magnesium	No data	No data	6150-9000 (20)	19500-21600 (2)
Manganese	14-59 (4)	13-64 (5)	1.1-74 (20)	<1.0-57 (2)
Mercury	0.0019-0.00252 (4)	0.2[e] (4)	No data	<0.2 (2)
Molybdenum	No data	49 (1)	2.0-2.4 (20)	No data
Nickel	17-21 (4)	12-21 (5)	<0.1-0.1 (20)	<21 (2)
Selenium	95-123 (4)	92-122 (5)	<0.2-1.0 (20)	10-11 (2)
Strontium	No data	>0.40 (1)	220-330 (20)	No data
Vanadium	No data	7.2 (1)	0.49-1.4 (20)	No data
Zinc	4-9 (4)	<3.3-6 (5)	<0.5-21[f] (20)	<2.0-<7.0 (2)

[a] Data from Brown and Caldwell (2003). Data were collected in 1995-98.
[b] Data from L. Stillings (pers. comm.). Samples were collected in January, April, July and November 2000.
[c] Data from Kempton (1996). Data were collected in 1995. Some concentrations were estimated.
[d] Number of samples given in parentheses.
[e] Dissolved mercury data are highly questionable as they are much higher than data for total.
[f] Outlier; next highest concentration was 2.0 µg/L.

Table 4. Geometric mean (extremes) metal and trace element concentrations (µg/g dry weight) in biological samples collected in June 2000 from the Yerington Pit and pit lake.

Constituent	Algae (*Cladophora*) (n = 4)	Odonata dragonfly larvae (n = 3)	Naucorids creeping water bugs (n = 1)	Bank Swallow eggs (n = 3)
Aluminum	10947. (8830-12800)	4732. (3200-5780)	2440.	6.9 (3-11)
Arsenic	12.6 (9.5-16)	5.9 (5-7)	2.4	nd[1] (<0.4-<0.5)
Boron	25.7 (20-41)	7.6 (7.0-9.1)	5.0	nd (<2.0)
Barium	84.1 (55.9-103)	24.7 (16.0-39.7)	13.	7.7 (7.2-8.1)
Beryllium	0.35 (0.20-0.51)	0.16 (0.1-0.2)	<0.10	nd (<0.10)
Cadmium	0.29 (0.20-0.35)	0.79 (0.51-0.98)	7.8	nd (<0.1-1.2)
Chromium	20.8 (9.3-51.6)	8.0 (5.6-10)	4.8	nd (<0.50)
Copper	1995. (1250-3000)	1199. (911-1480)	634.	3.2 (2.8-4.1)
Iron	10678. (6900-14300)	4515. (2950-6000)	2100.	167. (160-170)
Mercury	0.25 (0.20-0.31)	0.20 (0.20)	0.30	0.55 (0.20-0.96)
Magnesium	7386. (6200-9030)	2958. (2210-3790)	2450.	478. (465-489)
Manganese	201. (84.6-521)	166. (93-258)	70.	2.5 (1.8-3.9)
Molybdenum	3.5 (3-4)	nd (<2.0-3.0)	<2.0	nd (<2.0)
Nickel	16.6 (9.3-26)	8.9 (7.3-10)	4.5	nd (<0.5-1.0)
Lead	2.5 (1.3-3.9)	1.5 (1.0-2.0)	0.74	nd (<0.20)
Selenium	6.1 (2.4-13)	34.7 (27-42)	14.	2.5 (2.1-2.9)
Strontium	177. (112-278)	63.0 (48.2-74.0)	54.7	27.4 (20.9-33.0)
Vanadium	27.7 (19-39)	10.1 (6.6-14)	4.3	nd (<0.50)
Zinc	38.2 (28.0-55.8)	93.8 (83.8-114)	229.	75.0 (64.9-86.9)

[1] nd = not detected or > 50% of samples with non-detectable concentrations.

Table 5. Geometric mean (extremes) metal and trace element concentrations (μg/g dry weight) in biological samples collected in June 2000 from the Tuscarora pit lake.

Constituent	Golden dock *Rumex maritimus* (n = 3)	Amphipoda *Gammarus* (n = 3)	Largemouth bass *Micropterus salmoides* (n = 3)
Aluminum	2061. (1340-3170)	2449. (893-5110)	58. (33-80)
Arsenic	2.2 (1.4-3.0)	7.3 (4.8-10)	nd[1] (<0.2-0.2)
Boron	23. (22-24)	2.9 (2-4)	nd (<2.0)
Barium	56. (49.6-61.4)	183. (163-231)	7.8 (6.9-8.8)
Beryllium	nd (<0.10-0.10)	0.08 (<0.10-0.10)	nd (<0.10)
Cadmium	0.16 (0.1-0.2)	0.50 (0.46-0.57)	nd (<0.10)
Chromium	1.5 (1.0-2.0)	1.2 (0.9-2.0)	1.4 (0.8-3.2)
Copper	11. (10-13)	58. (56.1-62.5)	2.7 (1.7-4.1)
Iron	1465. (918-2210)	1526. (419-3060)	73. (71-75)
Mercury	nd (<0.10)	1.3 (0.74-2.5)	17. (14-20)
Magnesium	5240. (4890-5920)	2786. (2640-2990)	1719. (1670-1790)
Manganese	354. (267-485)	58. (32.0-91.3)	4.1 (3.2-6.5)
Molybdenum	nd (<2.0)	nd (<2.0)	nd (<2.0)
Nickel	1.9 (1.5-2.3)	1.5 (1.0-3.2)	nd (<0.50)
Lead	1.4 (1.0-2.0)	1.9 (0.5-3.6)	nd (<0.20)
Selenium	0.36 (0.3-0.4)	2.4 (2.1-2.7)	1.7 (1.6-1.9)
Strontium	112. (100-133)	607. (565-676)	128. (114-138)
Vanadium	4.2 (3.0-5.8)	3.2 (1.0-8.4)	nd (<0.50)
Zinc	36. (35-37)	74. (70.5-77.5)	69. (59.4-82.6)

[1] nd = not detected or > 50% of samples with non-detectable concentrations.

Table 6. Residues of metals and trace elements (µg/g dry weight) in biota collected in 1995 from the Yerington pit lake reported by Kempton (1996). Concentrations were converted to a dry weight basis based on percent moisture values.

Constituent	Plant tissue *Typha* sp.	Plant tissue *Ludwigia* sp.	Macroinvertebrates Insect Composite
Antimony	<0.063	0.64	0.42
Arsenic	0.438	5.09	0.23*
Cadmium	<0.032	0.22	0.30*
Copper	51.4	1140.	582.
Lead	0.32	1.52	1.75*
Mercury	0.0037	0.14	1.97
Methylmercury	0.0017	0.013	1.85
Selenium	9.7	31.1	10.2*
Silver	<0.062	<0.062	<0.062
Zinc	14.8	25.4	108.

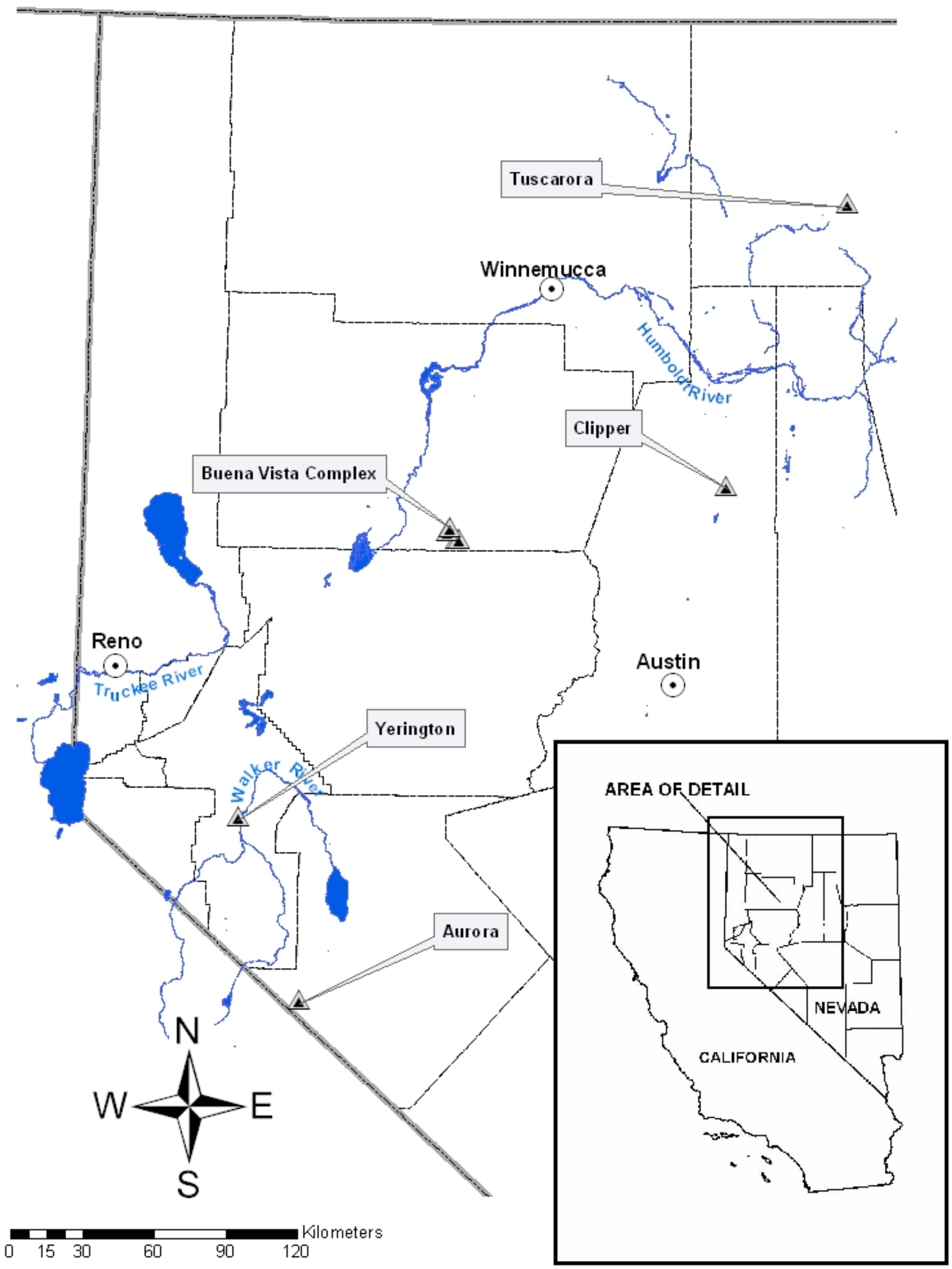
* Estimated values.

Table 7. Residues of metals and trace elements (µg/g dry weight) in biota collected in 1995 from the Aurora pit lake reported by Kempton (1996). Concentrations were converted to a dry weight basis based on percent moisture values.

Constituent	Simuliidae Black flies	Zooplankton *Daphnia*
Antimony	0.25	<0.063
Arsenic	4.3*	15.2*
Cadmium	0.10*	19.3*
Copper	27.7	23.4
Lead	0.94*	0.18*
Mercury	0.14	2.17
Methylmercury	0.001	0.03
Selenium	0.89*	6.38
Silver	0.29	0.58
Zinc	90.3	364.

* Estimated values.

Figure 1. Location of mine pit lakes in Nevada included as part of this study, 2000-2001.



Stratification and Geochemical Trends in the Yerington Pit Mine Lake, Lyon County, Nevada

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Executive Summary

The pit lake at the Yerington porphyry copper mine was monitored for nearly a year with a portable meteorological station, a self contained water column probe, and standard geochemical analyses. Additional geochemical analyses from wells adjacent to the lake were provided by Arimetco, Inc., the current operator at Yerington. These data as well as those from previous studies at Yerington and climate data from public domain sources were used to construct simple hydrodynamic and geochemical models of the lake which in turn allow general long term predictions of water stratification and redox conditions of the water column. This study suggests that:

(1). The lake will not permanently stratify in any plausible future climate scenario and thus will remain oxygenated over the next several decades. Long term stratification is precluded by relatively low concentrations of dissolved solids in ground water and the small amount of surface water entering the lake. This scenario could conceivably change if large amounts of water from the Walker River were to enter the lake in the very latest stages of filling.

(2). Waters in the lake appear to be losing sodium, potassium, magnesium, and bicarbonate while gaining sulfate and calcium. The addition of sulfate is no doubt the result of sulfide weathering and could increase in the future. Behavior of other major elements is difficult to model in terms of a simple carbonate system but could be the result of silicate weathering or cation exchange of clays.

(3). The lake contains elevated concentrations of selenium which will increase over time due to the oxygenated nature of the water and the character of the Yerington ores. Se concentrations in sulfides of the Yerington district appear to be high relative to sulfides from other porphyry copper deposits and are the source of the selenium in the lake. Copper is also present in elevated concentrations in lake water and is also the result of sulfide dissolution. The lack of long term anoxic conditions should prevent accumulation of other base metals in lake water.

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INTRODUCTION

The Yerington mining district of western Nevada is one of the most famous and long-lived in the western United States (Knopf, 1918). Vein style mineralization was discovered in 1800s and eventually three porphyry and numerous skarn copper deposits were developed. Mining has continued at varying activity until the present and produced more than 6 million tons of copper (Einaudi, 1982). After World War II, large scale open pit mining by the Anaconda Company began to exploit the low grade copper reserves in the eastern portion of the district. The result was an open pit mine approximately 1990 m (6200 ft) long with a maximum width of 750 m (2500 ft). Mining from the open pit ceased in 1978 and the pit subsequently filled with water. Like all mines in which mining extends to depths below the pre-mining water table, water inflow is dominated by groundwater. In 1998, the lake had a maximum depth of approximately 110 m and is still in the process of filling. The Yerington pit lake is among the deepest in North America.

A number of environmental concerns surround pit mine lakes. Perhaps the most important is chemical evolution of water within the pit. During initial stages of filling, the pit is considered to be terminal whereby ground water flows into the lake, but not out. As the lake level begins to approach that of the surround potentiometric water surface, the lake takes on a "flow through" character in which groundwater upgradient of the lake flows in and evolved pit lake water becomes a source of dissolved constituents for water flowing down the hydraulic gradient and away from the lake. The nature of pit lake water as a function of time is therefore of considerable concern with respect to groundwater quality in the surrounding area. Additional concerns come from the pit lake itself which despite efforts to the contrary, is often used as habitat and drinking water by wildlife and birds.

The hydrology of any lake can be described within the context of a simple model in which water enters by groundwater or surface water inflow and leaves by groundwater or evaporation (Figure 1). Chemical constituents enter or leave the lake in the same manner with additional sources and sinks from dissolution of minerals due to water-rock interactions in the pit lake walls; adsorption/desorption onto clays, Fe-oxides, and organic matter; and the formation of solid phases which become sequestered in sediment at the pit lake bottom. The formation of many solid mineral phases can be enhanced or retarded by the redox state of the water column.

Understanding residence times (which allows enhanced wallrock-water interaction) and stratification of the water column (which determines the redox state) are important keys to predicting the geochemistry of a lake. If the lake is in a terminal phase (the early stage of filling) water residence times can be expected to be relatively long and extended rock-water interactions will probably ensue. If the lake is in its latter, flow through stage than residence times would be shorter although the precise value depends on the hydraulic conductivity and gradient of the regional groundwater flow system.

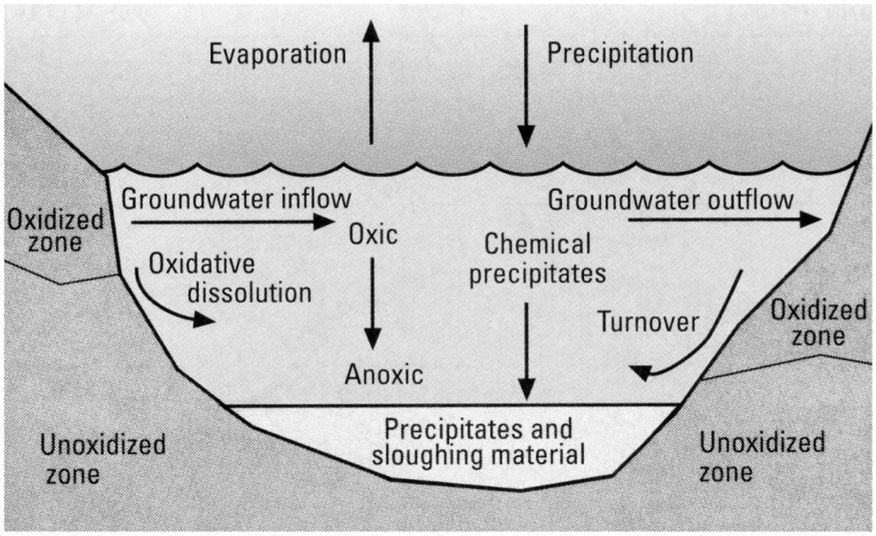


Figure 1. Diagrammatic representation of the physical and chemical processes in a large pit mine lake (from Miller et al., 1996)

The ability to predict the redox state of pit waters is crucial to any prognostic model of lake water quality. The solubility of many metals and colloidal iron is strongly redox dependent. For instance, it has long been recognized that most sulfide minerals are insoluble in low redox state waters (Stumm and Morgan, 1996) meaning that the dissolution of sulfides in these environments is minimal. On the other hand, colloidal iron strongly absorbs selenium and arsenic in oxygenated environments and will dissolve and release these elements in anoxic waters (Davis and Eary, 1997). Redox conditions in the water column therefore play a critical role in determining which suite of trace metals may end up in solution when ground water interacts with ore-bearing rocks.

Surface waters of lakes tend to be oxygenated due to the exchange of gases with the atmosphere. In the deeper portion of lakes, oxygen is consumed by organic matter produced by photosynthesis at the surface or the oxidation of sulfide minerals at depth. The replenishment of oxygen to these deep waters is dependent on (1) solar heat flux which warms the upper water and tends to stratify the water column, (2) vertical solute gradients which also stratify the water, and (3) wind shear stress which tends to mix the water column. The redox state of the deep water of lakes is dependent on the two counteracting effects of density and velocity shear. In the past, it has been believed that lakes with large depth/area ratios such as pit lakes are less prone to deep water mixing due the more limited effects of wind-induced currents (Lyons et al., 1994). While this ratio is a useful general measure of the tendency of lakes to mix and remain oxygenated, this approach neglects the complex development of vertical density gradients which prevent deep hypolimnonic water from mixing with the overlying epilimnion. In addition to pit lake geometry, the presence of high walls tends to shelter the lake surface from winds and thus is a potentially important factor for inhibiting water column mixing.

BACKGROUND

Previous research

Concerns of the water quality associated with the large increase in open pit gold mining operations in the Great Basin and elsewhere in the world has prompted a number of studies of existing pit lakes. These studies have considered the water balances of the lakes, the hydrodynamic behavior of lake waters, water-wall rock interaction, and long term geochemical behavior of pit lake waters. Specific pit lake studies include the Spenceville Mine, California (Levy et al., 1996) and the Butte Mine, Montana (Davis and Ashenberg, 1989; Robins et al., 1997). Studies which compare the chemistry of existing pit lakes and make efforts to lay out the methodology for the future chemistry of pit lakes include Miller et al. (1996), Pillard et al. (1996), and Davis and Eary (1997). Studies which have focused specifically on lake limnology include Lyons et al. (1994), Vandersluis et al. (1995), Doyle and Runnels (1997), and Atkins et al. (1997). The latter paper is based on a larger unpublished data set (Kempton, 1996).

The lake of the Yerington mine is a particularly useful analog for future large open pit gold mines because of its great depth (~110 m) and relatively large areal size. The lake was sampled in 1994 and 1995 by research groups from PTI Environmental Services and the Desert Research Institute. Using these data, Hershey et al. (1996) speculated that the lake did not completely turn over on a seasonal basis.

Present study

In February, 1998, the University of Utah entered into a contract with Arimetco, Inc., the current owner and operator of the Yerington mine, to study the pit mine lake for a period of one year. The primary objective was to provide long term predictions of oxygen levels in the water column from which general long term predictions of lake water quality could be made. In order to achieve this objective several analytical systems were deployed at the lake: (1) a portable meteorological station which could measure the input of kinetic energy via winds to the lake surface, (2) an internally recording current and water temperature meter deployed at 10 m depth in the center of the lake, and (3) quarterly sampling of water chemistry. Data from all of these endeavors were to be integrated with existing data to produce the conclusion presented here.

Geology of the Yerington district

A number of excellent studies of the geology of the Yerington district have been published (Knopf, 1918; Profett, 1977; Profett and Dilles, 1984; Carten, 1986). The geology near the Yerington open pit mine is dominated by a variety of felsic volcanic and shallow plutonic rocks. These igneous rocks are the product of a Jurassic age magmatic system which was subsequently tilted nearly 90 degrees to reveal excellent exposures of the fossilized hydrothermal system which formed the ore deposits of the Yerington district. Published geologic maps of the Yerington mine show only silicic igneous rocks in the mine pit (Profett and Dilles, 1984; Carten, 1986) (Figure 2) although carbonate rocks and mineralized skarns associated with the igneous rocks are a well known feature of the Yerington district as a whole. Implications of this observation are discussed in more detail below.

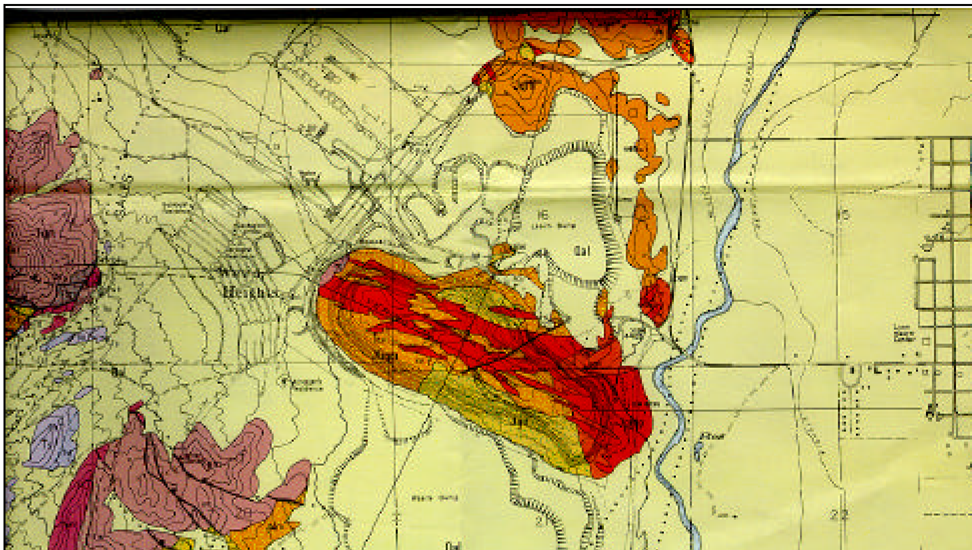


Figure 2. Geologic map of the area surrounding the Yerington mine (from Profett and Dilles, 1984). Map symbols: J_{qmp} (granite), J_{bqm} (quartz monzonite), and J_{gd} (quartz monzodiorite) represent various lithologies of the Jurassic Yerington batholith. T_{gm}, T_{ei}, T_{ru}, T_{wh} are various Tertiary silicic volcanic units and Q_{al} is quaternary alluvium.

Methodologies

Data on the hydrology, climatology, and geochemistry of the Yerington mine were collected between May, 1998 and May, 1999. Some technical problems with data collection were encountered over the course of the year, although the amount of data collected was more than sufficient to complete the goals of the project. Data collected during this project were incorporated with existing data from previous studies of the lake. The combined data sets were then used to construct simple hydrodynamic and geochemical models of the lake waters.

Climatology. A portable meteorological station was deployed near the lake surface on the southern access road to the lake. The station sampled wind direction and speed and air temperature every hour. The data were stored internally and downloaded during visits to the lake which took place at intervals of 6-7 weeks. A continuous meteorological record was collected for the times periods of May 2 to September 18, 1998 and from December 12, 1998 to May 12, 1999. The gap in the meteorological record toward the end of 1998 was the result of a breakage of a portable computer enroute to Reno on one of the sampling trips.

Surface heat flux and hence evaporation rates from a body of water are functions of surface air temperature, wind speed, net longwave and shortwave radiation (which is largely a function of cloud cover), relative humidity, and atmospheric pressure. Since only wind and temperature data were recorded by the meteorological station, additional climate data were determined from hourly weather measurements for Fallon, Nevada obtained through EarthInfo, Inc.'s collation of weather data from the National Climate Data Center (NCDC).

Hydrology. Data on water velocity and temperature were collected with an S-4 current meter manufactured by Applied Microsystems. The S-4 is an electromagnetic current meter which produces a small electrical field during operation. Moving water disturbs the field and generates the measurement. This type of current meter is capable of measuring very low velocities (~1 cm/s) of the type expected in pit mine lakes. For this project, the probe was retrofitted with thermistor with an accuracy of $\underline{+}0.01^{o}1C$ in order to test the validity of numerical models of temperature.

The probe was deployed at a 10 m depth in the middle of the lake and programmed to sample the water over a 10 minute period which was then recorded at a variety of time intervals. The 10 m depth was intended to correspond to the approximate depth of the thermocline (zone of greatest temperature gradient). The probe was recovered and the data downloaded at the same time as the portable meteorological station. At the time of these visits, the probe was reprogrammed to significantly decrease the sampling interval (to the order of seconds) and an *in situ* profile of water column temperature was determined. Considerable technical difficulties were encountered with probe deployment and operation and thus the record obtained extends only from May 2 through July 6 and September 18 through October 30, 1998.

Chemistry. Samples from the water column of the Yerington pit lake were collected quarterly between May, 1998 and January, 1999 at the same location in the western side as the current meter. Samples were collected at 10 m intervals from 0-50 m depth and at 15 m intervals below that. A total of 10 samples in the water column were collected. Water was pumped from depth through polyurethane tubing with a peristaltic pump. The sample tube was flushed with three volumes of water between samples. Dissolved oxygen of the pumped water was measured with a Yellow Springs Model 50B meter by taking as much care as possible to avoid exposure of sample water to the atmosphere during measurements. Malfunction of the meter prevented measurement of dissolved oxygen during the August, 1998 sampling trip. pH was determined for all samples with a Beckman model 12 pH meter. Three types of samples were collected: unfiltered for measurement of alkalinity, filtered unacidified for anion analysis, and filtered acidified for cation analysis. During the 1/29/99 lake sampling, the filter holder broke, meaning that both cation and anion analysis of this suite of samples were unfiltered. The anion and alkalinity samples were transported back to the University of Utah while the anion samples were shipped to a commercial laboratory for analysis by inductively coupled mass spectrometry (ICP). Samples of ground water at two locations near the pit lake were collected and analyzed by Arimetco personnel at various times (Figure 3).

The first set of lake samples (collected 5/5/98) were analyzed for cations by Western Analysis, Inc. of Salt Lake City while subsequent lake samples and all ground water samples were analyzed by Col-Tech EnviroLabs of Reno. Anion analysis was conducted on a Dionex ion chromatograph at the University of Utah.

Initial results of water analysis revealed detectable concentrations of two trace metals substantially above the 50% concentration drinking water standards established for the project: copper and selenium. While the source of the copper is obvious, the source of the selenium is more problematic. A geologist with extensive research experience in the Yerington district (John Dilles of Oregon State University) indicated that the selenium was probably present in sulfide phases (a logical conclusion given the chemical similarities of sulfur and selenium), specifically the chalcopyrite-bornite mineral assemblage. For this reason, an auxiliary project was begun by Melissa Mitchell, an undergraduate at the University of Utah, to determine the source of the selenium at Yerington. Unfortunately, flooding of the Yerington mine and the loss of documented core from the deposit since closing of the mine in 1978 made it difficult to locate sulfide samples from the deposit. A single pyrite-chalcopyrite sample from Yerington was found in the University of Utah's ore deposits collection and additional samples from the nearby Ann-Mason porphyry system were provided by Dilles. Polished mounts of these samples as well as a suite of samples from the geologically similar Bingham Canyon copper deposit in Utah were prepared and analyzed with the Department of Geology and Geophysics electron microprobe.

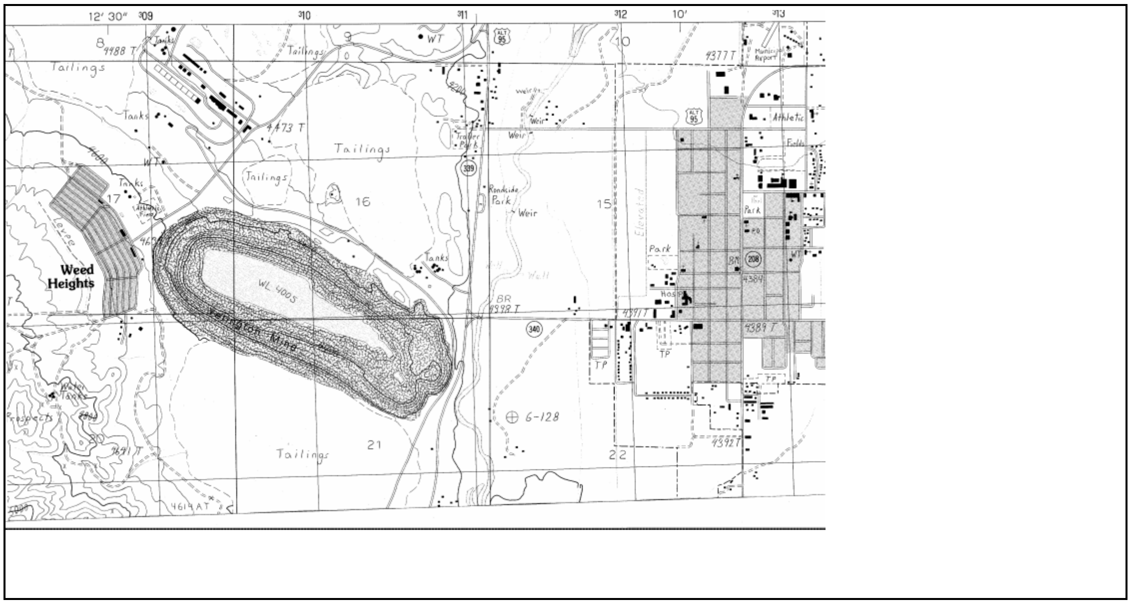


Figure 3. Simplified topography from the Yerington area showing the location of the sampling location in the middle of the lake (star) and groundwater wells (circles). From the U.S .Geological Survey Yerington 7.5' quadrangle.

Hydrodynamic models. In order to understand the hydrodynamic behavior of the water column, a primitive equation numerical models were used to predict the thermal evolution of Yerington pit lake waters. The model is a one-dimensional version of the Princeton Ocean Model (POM) which is widely used to study circulation in lakes, estuaries, and shallow coastal oceans (see reference list at http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/). This model have been used extensively in his research over a number of years (Jewell, 1992, 1995 a, b) and has a long track record in accurately predicting the thermal and bigeochemical characteristics of lakes and shallow marine settings.

Geochemical models. A variety of geochemical speciation and transport computer codes are available to model the geochemical behavior of natural waters. For this project, the PHREEQC geochemical code (Parkhurst et al., 1995) was chosen to study the lake waters. This is an extremely flexible code which has been employed in many previous modeling studies of natural waters. Several thermodynamic data bases are available for use with this code. The MINTEQA2 data base was used in this study because it included selenium mineral phases (Allison et al., 1990)

RESULTS

Meteorological data were used as boundary conditions for the numerical hydrodynamic model. Comparison between model output and the velocity and temperature data were then compared in order to assess the validity of model output. Model and data were then used to predict the hydrodynamic behavior of the water column under different climate scenarios. The model output was then used in conjunction with PHREEQC to evaluate the idealized, long term geochemical of the water column.

Hydrodynamic behavior of the water column.

Observations. The Yerington pit lake shows limnologic behavior very similar to that of natural lakes at mid latitude locations. A seasonal thermocline develops in the spring, increasing to a maximum surface temperature of approximately 25^{o}C in the late summer and fall. Hypolimnitic water was relatively uniform (6.2-6.5^{o}C) below approximately 40 m depth (Table 1). At the winter sampling in January, 1999, the lake had a uniform temperature of approximately 6^{o}C, indicating that turnover probably occurred sometime in late 1998. Since freshwater has a density maximum at 4^{o}C, continued cooling after the January sampling would simply have left the water column completely mixed until surface temperature fell below 4^{o}C at which time the water column could have again become restratified. The fact that the coldest waters measured in the deep portion of the Yerington Lake have been in the range of 5-7^{o}C (Kempton, 1996; Table 1) argues against this and instead suggests instead that the lake is monomictic i.e., it mixes once during the coldest portion of the year.

One of the goals of the project was to determine how much the pit walls adjacent to a large lake such as Yerington isolates surface waters from wind shear. Obviously, wind intensity has very high short term variability. In order to mitigate this variability in collected data, the average of the wind kinetic energy ($E = 0.5*\rho*V^2$) was computed over a 24 hour period for both the meteorological station at the Yerington pit lake and for five years (1986-1990) of NCDC data from Fallon. (1999 meteorological data for Fallon were not available at the time of the writing of this project). While both the Yerington pit lake and Fallon are characterized by the predominance of low energy winds, Yerington has a distinct lack of the winter time high energy winds found at Fallon (Figure 4). The low wind intensities at the Yerington pit lake produced modest currents (< 6 cm/s) at 10 m depth in the lake (Figure 5).

Numerical models. The seasonal behavior the Yerington pit lake water column was studied with the Princeton Ocean Model (POM) described in Jewell (1995a) modified to incorporate real time atmospheric boundary conditions. Surface heat flux was computed using an energy balance model which incorporates short wave radiation, long wave radiation, latent heat flux, and sensible (conductive) heat flux. These variables can be calculated from surface air temperature, wind velocity, relative humidity, atmospheric pressure, and cloudiness. The model is based on similar previously published modeling studies and techniques (Gill, 1982; Mellor and Kantha, 1989). The two most important adjustable parameters in the model are the amount of light penetration and the extinction coefficient. Two scenarios are shown (Figure 6): a high light penetration-low extinction coefficient scenario (most often applied to lakes with low suspend organic and inorganic matter and a low light penetration-high extinction coefficient scenario (probably more appropriate for the Yerington pit lake).

Depth (m)	Temp (C)	DO (mg/L)	Saturated DO (mg/L)	AOU (mg/L)	pH
5/5/1998					
0	14.8	8.8	7.08	-1.72	
10	9.9	7.0	7.91	0.91	8.2
20	6.9	6.8	8.51	1.71	7.3
30	6.3	6.8	8.64	1.84	7.6
40	6.3	7.2	8.64	1.44	6.2
50	6.2	8.3	8.66	0.36	7.5
65	6.2	8.6	8.66	0.06	7.5
80	6.2	8.8	8.66	-0.14	7.3
95	6.2	9.0	8.66	-0.34	7.2
110	6.2	9.0	8.66	-0.34	7.5
6/19/1998					
0	18.5				
10	13.4				
20	7.2				
30	6.5				
40	6.5				
50	6.4				
65	6.3				
80	6.3				
95	6.3				
110	6.3				
8/16/1998					
0	23.1		5.98		7.9
10	14.9		7.06		8.3
20	7.6		8.36		8.1
30	6.7		8.55		7.9
40	6.5		8.59		7.9
50	6.4		8.61		7.9
65	6.3		8.64		7.8
80	6.4		8.61		7.8
95	6.4		8.61		7.8
110	6.4		8.61		7.8
10/30/1998					
0	14.0	9.0	7.20	-1.80	8.5
10	14.2	8.3	7.17	-1.13	8.6
20	12.0	9.6	7.53	-2.07	8.4
30	6.9	7.8			8.2
40	6.5	7.4	8.59	1.19	8.0
50	6.5	7.3	8.59	1.29	7.9
65	6.5	7.7	8.59	0.89	8.0
80	6.5	7.0	8.59	1.59	7.9
95	6.5	7.0	8.59	1.59	7.9
110	6.5	6.9	8.59	1.69	7.9
1/29/1999					
0	5.9	10.4	8.72	-1.68	8.3
10	5.9	12.1	8.72	-3.38	8.0
20	5.9	10.2	8.72	-1.48	8.0
30	5.9	10.8	8.72	-2.08	8.0
40	5.9	10.7	8.72	-1.98	8.0
50	5.9	10.8	8.72	-2.08	8.0
65	5.9	11.2	8.72	-2.48	8.0
80	5.9	11.0	8.72	-2.28	8.0
95	5.9	11.0	8.72	-2.28	8.0
110	5.9	11.2	8.72	-2.48	7.9

Table 1. Temperature, dissolved oxygen, and pH values of the Yerington pit lake. Saturated DO is calculated from Weiss (1970). AOU (Apparent Oxygen Utilization) = DO - DO(saturated).

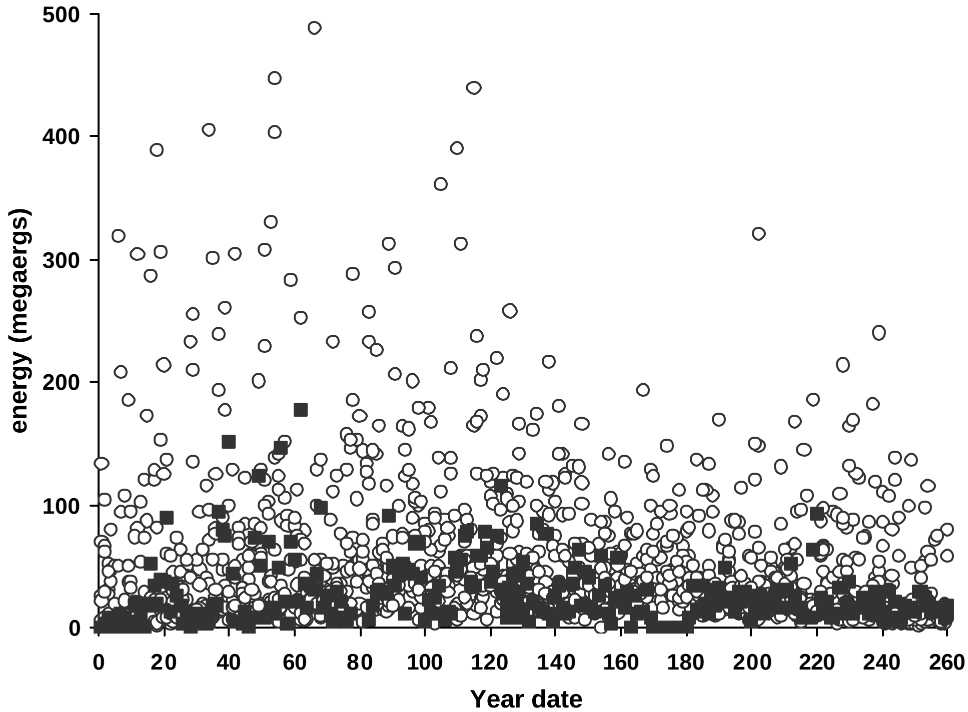


Figure 4. Summary of daily averaged wind kinetic energy (megaergs) for January September, 1998. Open circles are NCDC data for Fallon, Nevada from 1986-1990. Closed squares are meteorological data collected for this project.

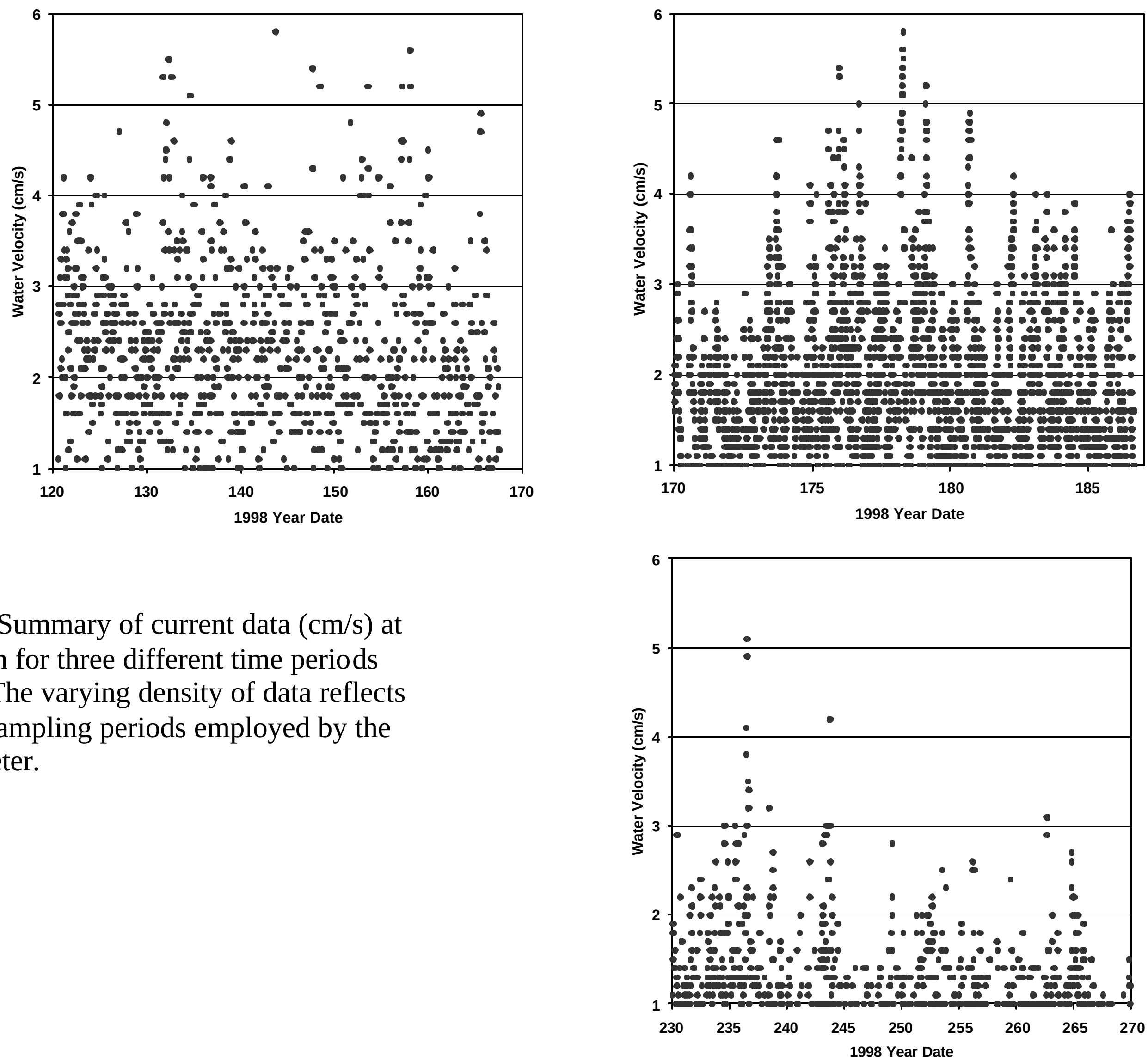
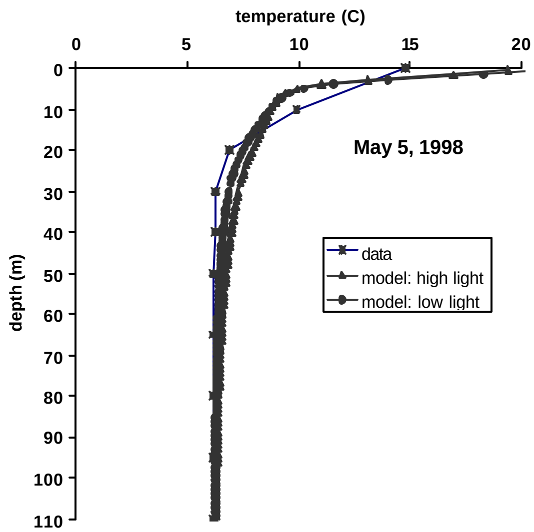


Figure 5. Summary of current data (cm/s) at 10 m depth for three different time periods in 1998. The varying density of data reflects different sampling periods employed by the current meter.



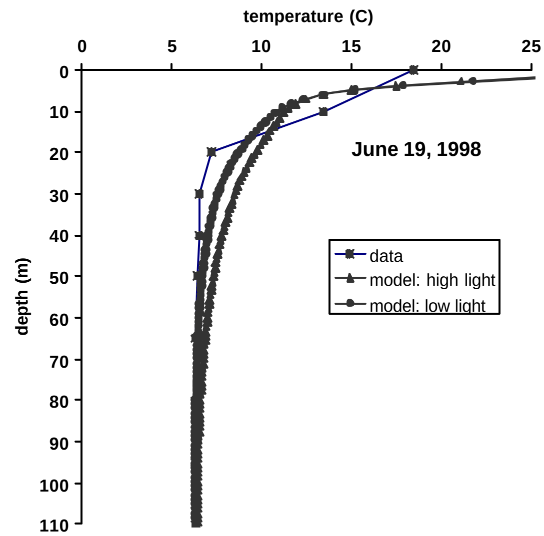
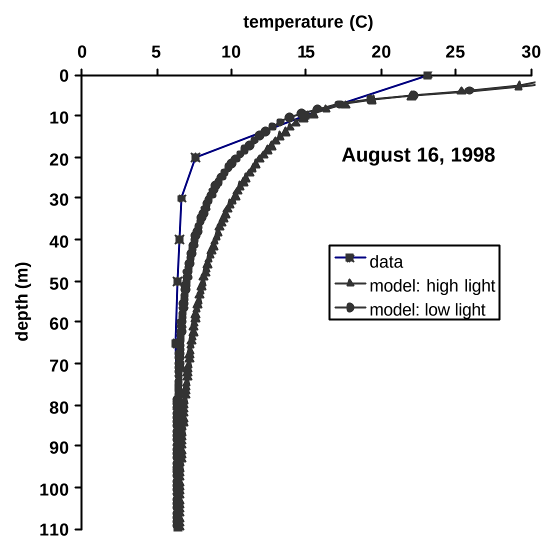


Figure 6. Comparison of temperature data at the Yerington pit lake and output from the numerical model. Model output is shown for high and low light penetration simulations corresponding to 60% and 80% of light penetrating the water column.



Input data for the model was derived from the surface air temperature and wind speed collected during this study. On the whole, results from the model show good correspondence between observed and modeled values (Figure 6). The model shows the poorest correspondence near the thermocline. This is probably due to the inability of the 1-dimensional model to reproduce 3-dimensional effects such as internal waves (Jewell, 1995b). The high and low light model scenarios do not produce significant differences in predicted temperatures.

Geochemical trends.

Major elements. In addition to the samples collected over the course of this project, analyses of lake water collected by Arimetco personnel between 1996 and 1997 and one analysis published in a journal are included in the data set (Miller et al., 1996) (Table 2). Many of the lake samples collected by Arimetco have a significantly different chemistry than the other lake samples. This may be attributable to the fact that these samples were collected in the littoral (shore) zone of the lake which often has a chemistry distinctly different from the bulk of lake water due to surface runoff, interactions with suspended sediment, or much higher biological activity. For this reason, these samples have been excluded from subsequent analysis of lake chemistry.

The accuracy of geochemical analyses is typically established by computing a charge balance for a given sample. This involves converting concentrations of the major cations and anions into equivalents (multiplying the molar concentration of the element by charge of the ion) and determining how close the two come to balancing. For relatively high TDS waters such as those at Yerington, the difference should be less than 5%. Unfortunately, many of the samples in this project exceeded that threshold. Samples analyzed by Western Analysis (the 5/5/98 lake samples) had the best charge balances. The poorest results were recorded in the water well samples. For the purpose of this report, all lake samples in which the charge balance difference exceeded 10% were excluded from subsequent analysis. It should be noted that the particularly poor charge balances for the analyses of 1/29/99 is probably due to their being unfiltered during collection. Since lakes waters exceed calcite saturation (see discussion below), small calcite particles might have dissolved in the acidified cation samples bottles while not dissolving in the unacidified samples analyzed for alkalinity. Even though groundwater samples have very poor charge balances, they have been included in subsequent analyses since these were the only groundwater data available.

The major cation elements (Ca, Mg, Na, K) of the Yerington pit lake do not vary significantly on either a temporal or spatial (depth) basis (Table 2). Likewise, bicarbonate (the dominant component of alkalinity for waters of this pH range), sulfate, and chloride are not significantly changed in the waters.

Perhaps the most important question to be evolved from the major ion analysis: how does the pit lake modify the chemistry of the incoming ground water? This question can be addressed in a general fashion by computing ratios of elements and considering the conservative vs. nonconservative behavior of a chemical component relative to an ion (chloride) which is widely considered to be conservative. This allows the effects of evaporation to be differentiated from chemical reactions involving wall rocks, biology, or other lacustrine processes. The procedure involves predicting the concentration of a specific ion in the lake water on the basis of the ratio between chloride in the lake water and the inflowing groundwater:

	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	HCO3 (ppm)	SO4 (ppm)	Cl (ppm)	NO3 (ppm)	F (ppm)	Sr (ppm)	Ba (ppb)	Fe (ppb)	Mn (ppb)	Li (ppb)	Cu (ppb)	Se (ppb)	Hg (ppb)	Sb (ppb)	Tl (ppb)	pH
7/25/1996 (1)	29	3	33	6	100	38	17	0.2	0.6		30	212	n.d		315	n.d	n.d	n.d	43	8.0
11/21/1996 (1)	33	3	49	7	128	87	21	n.d	0.6		31	190	n.d		183	n.d	n.d	n.d	27	7.2
Miller (2)	76	7	93	15		270	36	0.7	1.4		34	10	320		160	130				
5/5/1998																				
Surface	75	5	70	14	148	258	35	1.9	1.2	0.58	30	n.d	n.d	30	n.d	n.d	n.d	n.d	n.d	
10 m	77	5	69	14	146	244	35	1.6	1.3	0.57	27	14	13	24	n.d	n.d	1	n.d	n.d	8.2
20 m	82	5	79	16	147	259	36	2.1	1.2	0.63	29	n.d	14	35	n.d	n.d	n.d	n.d	n.d	7.3
30 m	82	5	84	17	146	269	36	4.1	1.2	0.71	30	n.d	n.d	43	n.d	n.d	n.d	n.d	n.d	7.6
40 m	83	6	84	18	146	278	37	1.7	1.2	0.72	37	49	20	29	n.d	n.d	n.d	n.d	n.d	6.2
50 m	80	5	80	17	142	279	36	5.4	1.2	0.70	31	n.d	19	41	n.d	n.d	n.d	n.d	n.d	7.5
65m	82	5	85	17	146	265	36	2.1	1.2	0.76	34	n.d	22	33	n.d	n.d	n.d	n.d	n.d	7.5
80 m	78	5	74	16	148	267	36	1.7	1.1	0.76	29	n.d	20	25	n.d	n.d	n.d	n.d	n.d	7.3
95 m	78	5	82	17	146	272	36	1.7	1.2	0.60	31	n.d	17	33	n.d	n.d	n.d	n.d	n.d	7.2
110 m	82	5	86	16	146	272	36	1.7	1.5	0.77	29	28	21	25	n.d	n.d	n.d	n.d	n.d	7.5
7/7/1997 (1)	78	5	94	19	118	315	37	n.d	1.4		n.d	20	10		20	105		7	n.d	
8/16/1998																				
surface	69	4	71	14	124	272	38	0.9	0.9	0.96	43	n.d	n.d	20	n.d	92	n.d	7	n.d	7.9
10 m	61	4	78	14	135	263	36	1.2	1.2	0.95	44	n.d	n.d	19	n.d	92	2	7	n.d	8.3
20 m	63	4	83	14	145	273	39	1.0	1.0	0.97	44	n.d	10	19	54	91	1	8	n.d	8.1
30 m	64	4	83	15	141	277	37	1.4	0.8	0.98	46	n.d	10	19	64	95	1	8	n.d	7.9
40 m	64	4	86	14	143	279	38	1.2	0.9	0.99	36	n.d	20	18	56	96	1	8	n.d	7.9
50 m	67	5	88	15	146	278	37	1.3	1.1	0.97	46	n.d	n.d	18	56	92	1	8	n.d	7.9
65m	66	5	86	15	145	278	37	1.2	0.9	0.99	46	n.d	n.d	18	56	95	n.d	8	n.d	7.8
80 m	69	5	86	15	144	277	37	1.3	0.9	0.99	46	n.d	20	18	56	92	n.d	8	n.d	7.8
95 m	67	4	87	14	143	283	38	1.2	0.9	0.98	47	n.d	20	18	58	103	n.d	8	n.d	7.8
110 m	67	4	86	14	144	277	37	1.2	0.9	0.98	46	n.d	20	18	58	95	n.d	8	n.d	7.8
10/30/1998																				
surface	74	5	74	14	127	271	33	n.d	0.8	0.75	31	n.d	n.d	26	n.d	89	n.d	6	n.d	8.5
10 m	74	5	75	14	129	271	31	n.d	0.8	0.77	32	n.d	n.d	27	11	93	n.d	7	n.d	8.6
20 m	72	5	82	14	144	284	32	2.0	0.8	0.76	31	n.d	n.d	28	32	96	n.d	7	n.d	8.4
30 m	72	5	82	14	144	277	29	2.1	0.7	0.76	30	n.d	n.d	29	46	96	n.d	7	n.d	8.2
40 m	74	5	82	14	146	277	29	2.4	0.7	0.78	31	n.d	n.d	31	42	98	n.d	7	n.d	8.0
50 m	73	5	82	14	146	279	30	2.3	0.7	0.76	31	n.d	n.d	31	43	95	n.d	7	n.d	7.9
65m	72	5	81	14	146	278	30	2.2	0.8	0.76	31	n.d	n.d	34	45	96	n.d	8	n.d	8.0
80 m	71	5	82	14	141	278	31	2.3	0.8	0.76	31	n.d	n.d	36	48	96	n.d	8	n.d	7.9
95 m	74	5	83	14	146	279	30	2.3	0.8	0.76	31	n.d	n.d	37	49	93	n.d	8	n.d	7.9
110 m	72	5	83	14	146	279	30	2.4	0.8	0.72	30	n.d	n.d	25	43	94	n.d	7	n.d	7.9
1/29/1999																				
surface	82	4	91	17	148	286	38			0.85	n.d	41	20	14	44	141	n.d	8	n.d	8.3
10 m	90	4	99	18	154	275	39			0.83	n.d	41	20	12	34	133	n.d	8	n.d	8.0
20 m	86	4	95	17	153	275	35			0.85	n.d	31	20	12	42	136	n.d	8	n.d	8.0
30 m	87	4	96	17	148	270	38			0.79	n.d	177	19	10	40	134	n.d	8	n.d	8.0
40 m	85	4	94	17	147	262	38			0.82	n.d	33	57	11	43	138	n.d	8	n.d	8.0
50 m	96	5	106	19	148	266	38			0.82	n.d	28	23	11	38	135	n.d	8	n.d	8.0
65m	91	5	100	19	145	260	37			0.85	n.d	21	21	10	40	144	n.d	8	n.d	8.0
80 m	82	4	90	17	145	260	38			0.84	n.d	19	20	n.d.	39	135	n.d	8	n.d	8.0
95 m	79	5	87	17	148	266	37			0.87	n.d	15	n.d.	10	40	143	n.d	8	n.d	8.0
110 m	95	4	105	18	145	266	37			0.86	n.d	17	n.d.	10	39	139	n.d	8	n.d	7.9
Well 36 (1)																				
7/17/1996	36	6	30	8	119	32	18	0.3	0.6		32	n.d	n.d		67	n.d	n.d	n.d	1	7.3
7/8/1998	35	4	37	8	132	39	14	n.d	0.5		n.d	n.d	n.d		12	n.d	n.d	n.d	n.d	8.1
3/10/1999	32	2	30	7	130	34	12	n.d	0.4		n.d	307	148		196	n.d	n.d	n.d	n.d	7.2
Well 2B (1)																				
7/1/1998	42	4	37	7	126	273	24	3.1	1.5		n.d	50	n.d		70	7	n.d	n.d	n.d	8.0
10/2/1998	42	4	39	8	128	39	27	2.2	0.6		n.d	80	n.d		n.d	n.d	n.d	n.d	n.d	7.3
11/18/1998	39	4	41	8	124	40	28	0.7	0.9		n.d	80	n.d		n.d	n.d	n.d	n.d	n.d	7.8
4/1/1999	41	3	36	8	128	45	28	0.9	0.4		n.d	62	n.d		n.d	n.d	n.d	n.d	n.d	7.3

n.d.= not
detected

Analyses for Ag, Al, As, Be, Bi, Cd, Cr, Co, Ga, Pb, Mo, Ni P, Sc, Sn, Ti, V, and Zn all below 50% drinking water MCL levels

(1) Analysis from Miller et al. (1996)
(2) Analysis from Arimetco, Inc.

Table 2. Major, minor, and trace element chemistry of the Yerington pit lake and associated groundwater

$$ion^* = ion_{gw} \times (Cl_{lake}/Cl_{gw}) \quad (1)$$

If the predicted concentration (ion*) exceeds the measured ion concentration in the lake, then that particular constituent has been added to the water by some chemical reaction within the lake. Likewise, if ion* is less than the measured concentration, the ion has been removed or there is a net sink in the water column. Average groundwater composition from two wells (36 and 2B) (Table 2) were used for this analysis.

For Well 36 Na^+, K^+, $Mg,^{2+}$ HCO_3^- appear to have been removed from lake water while Ca has been added (Figure 7). For Well 2B, the picture is more ambiguous. K^+ and HCO_3^- appear to be constant and all other elements appear to have been added to lake water (Figure 8). The increase in dissolved sulfate in lake waters relative to groundwater is almost certainly the result of oxidation of sulfide minerals (primarily pyrite) caused by interaction of lake water with the surrounding wall rock. This can be seen with the classic equation chemical equation which partially describes the initial weathering of pyrite acid mine systems (Stumm and Morgan, 1996, p. 691):

$$FeS_2 + H_2O + \frac{15}{4}O_2 = Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (2)$$

Unlike acid mine drainages, hydrogen ion produced as a result of (2) is probably consumed by chemical processes within the lake. A variety of possibilities may account for this. For instance, photosynthesis consumes hydrogen ions while producing algal protoplasm via the classic Redfield equation (Redfield, 1963):

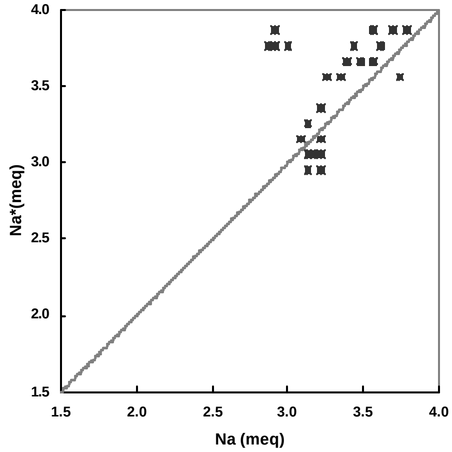
$$106CO_2 + 16NO^- + HPO_4^{2-} + 122H_2 0 + 18H^+ = C_{106}H_{263}O_{110}N_{16}P + 138O_2 \quad (3)$$

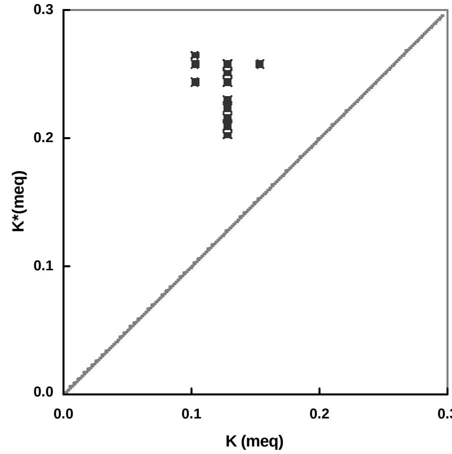
Another possibility might be that despite the lack of mapped carbonate units in the pit lake (Figure 2), calcite is being dissolved

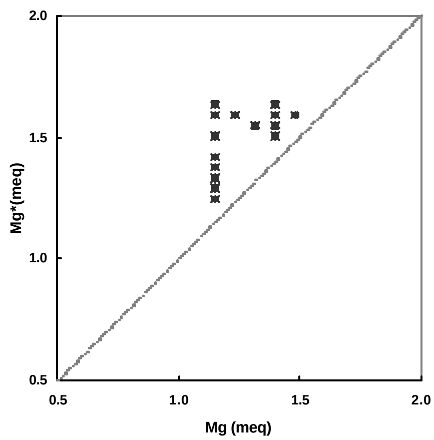
$$CaCO_3 + H^+ = Ca^{2+} + HCO_3^- \quad (4)$$

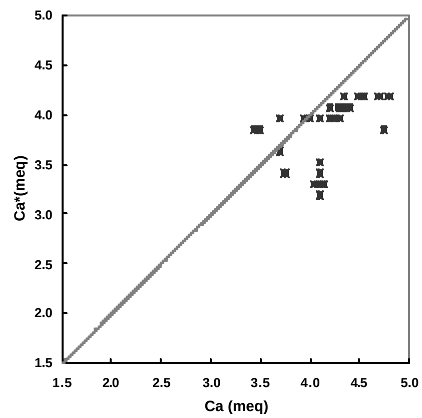
However, this reaction produces both calcium and bicarbonate while the mass balance model suggests that the lake is a sink rather than a source of bicarbonate (Figures 7, 8).

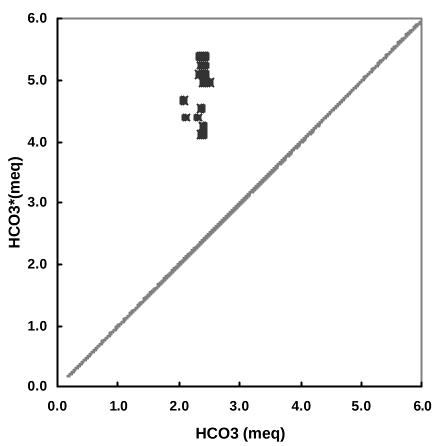
Analysis of both groundwater and lake water with the aqueous speciation model PHREEQC revealed that groundwater is not saturated with any minerals of note. Lakes waters are saturated with respect to calcite and at, the lake surface, aragonite (Figure 9).


Na*(meq)
Na (meq)


K*(meq)
K (meq)


Mg*(meq)
Mg (meq)


Ca*(meq)
Ca (meq)


HCO3*(meq)
HCO3 (meq)

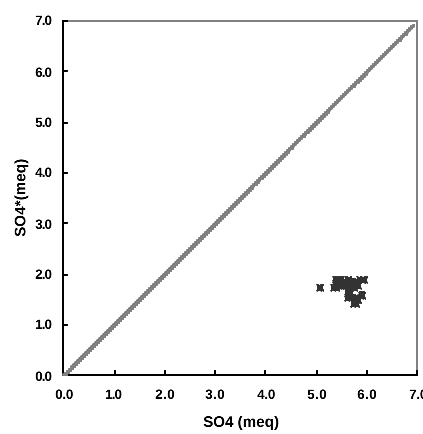

SO4*(meq)
SO4 (meq)

Figure 7. Comparison of observed ion concentrations in the lake and predicted concentrations by evaporation of ground water from Well 36 (designated with an *). Values in the upper right hand side of the graph indicate removal from the lake while those in the lower right indicate addition to the lake.

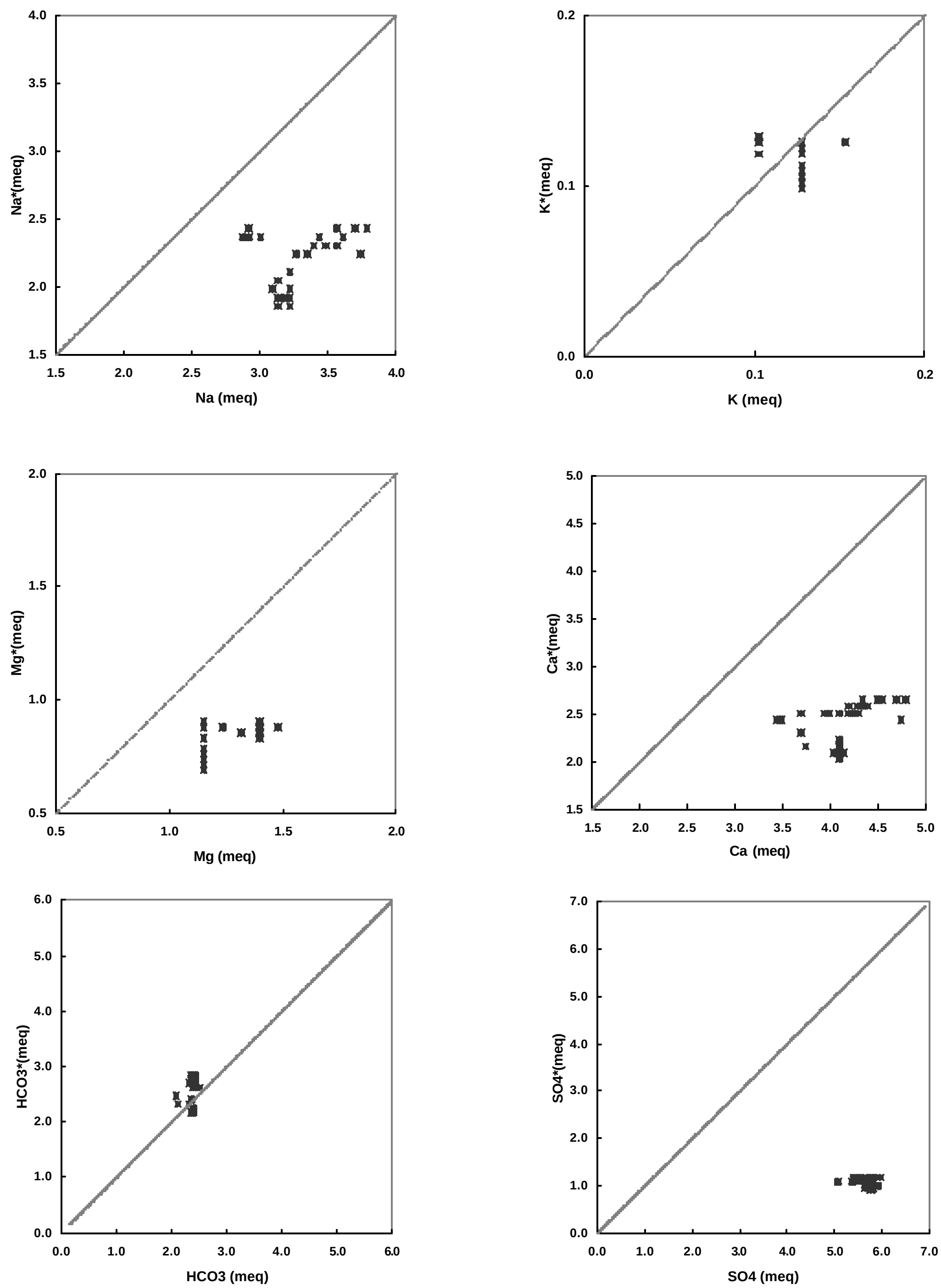


Figure 8. Comparison of observed ion concentrations in the lake and predicted concentrations by evaporation of ground water from Well 2B (designated with an *). Values in the upper right hand side of the graph indicate removal from the lake while those in the lower right indicate addition to the lake.

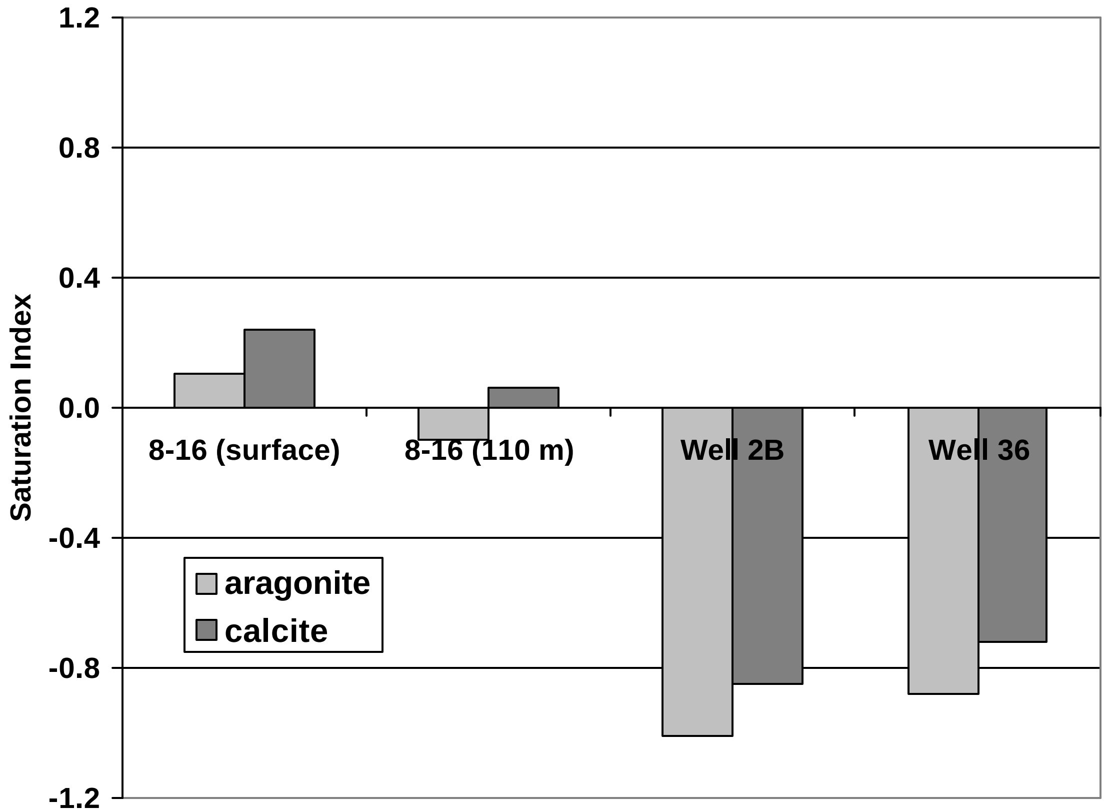


Figure 9. Saturation Index (SI) defined as the ion activity product for a particular mineral divided by the equilibrium constant (Stumm and Morgan, 1997) for lake and groundwater of the Yerington system. A positive SI indicates the mineral is oversaturated while a negative number indicates undersaturation.

Selected trace metals. Most trace metals were below detection limits established for this study. Other important trace elements exhibited considerable variation over the course of the multiple sampling trips. Selenium in concentrations of 89-105 ppb was present in all analyses except that the 5/5/98 and 1/29/99 sampling. The former set of samples was analyzed by Western Analysis and their analytic method may have been faulty for this element. The elevated concentrations of Se as well as Fe in the 1/29/99 samples is probably due to dissolution of colloidal ferric iron hydroxides in the acidified, unfiltered samples from this trip. Se is generally below detection limit in the groundwater samples suggesting that like geochemically similar sulfur, this element is being added by in lake geochemical reactions (equation 2).

The source of selenium is solid substitution of this element in sulfides of the Yerington deposit (Table 4). Pyrite, chalcopyrite, and bornite all show significant amounts of selenium (up to 0.121 weight percent) at Yerington and in the nearby Ann-Mason porphyry copper deposit. Samples from similar porphyry copper deposit (Bingham Canyon) have only minor amounts of Se (Table 4).

Table 4. Concentrations of Se in sulfides of the Yerington, Ann Mason, and Bingham, Canyon, Utah porphyry copper deposits (weight percent). n = number of analyses per sample. n.d. = not detected.

	pyrite	chalcopyrite	bornite
Yerington	0.121 ± 0.045 (n=9)	0.066 ± 0.029 (n=4)	
Ann Mason			
D222-1286.5		0.009 ± 0.013 (n=7)	0.019 ± 0.021 (n=6)
D109-1863		0.027 ± 0.054 (n=6)	0.057 ± 0.069 (n=11)
D114-2616		0.002 ± 0.005 (n=7)	0.016 ± 0.024 (n=6)
Bingham Canyon			
625	n.d. (n=2)	0.004 ± 0.007 (n=7)	
619c	0.004 ± 0.007 (n=6)	n.d. (n=6)	
639	0.001 ± 0.001 (n=6)	0.002 ± 0.004 (n=6)	

Copper concentrations of 1-64 ppb are present in most lake samples with the exception again being the earliest 5/5/98 suite. The lack of detectable copper in the surface waters during the summer and fall in the lake may be due to bioutilization of this element during photosynthesis. Copper in groundwater is present in approximately the same concentrations as the lake, suggesting that dissolution of copper is not an important lacustrine process.

Several other trace elements show variable concentrations. Antimony is present in the 7-8 ppb range in all except the very first lake samples but is absent from groundwater (Table 2). Mercury makes irregular appearances close to the detection limit. Thallium is present in rather large concentrations (27 and 43 ppb) in the 1996 lake samples analyzed by Arimetco. As mentioned previously, the chemistry of these waters is anomalous relative to most other lake samples and the abnormal Tl may be a result of processes which are peculiar to the lakes littoral environment.

Nutrient elements. The development of anoxia in a water body is dependent on the amount of available nutrients (phosphorous, nitrogen, and various trace elements such as iron and copper) as well as the ability to exchange oxygen with the atmosphere. Primary productivity of most lakes is considered to be phosphorous limited (i.e., phosphorous is the first element to be depleted during photosynthesis and thus limits the amount of biological productivity). Most lake eutrophication models are based on phosphorous loading (i.e., the amount of phosphorous added per unit area of the lake per time) (e.g., Vollenweider, 1975). Unfortunately, phosphorous was below the detection limit in all of the water analyses carried out to date at Yerington. In seawater, nitrogen and phosphorous have a ratio of approximately 16:1 and so phosphorous concentrations can often be inferred from nitrogen concentrations. N:P ratios in lakes are much more variable and this method cannot be applied with any confidence. Even if it could be, measured nitrogen concentrations from Yerington are extremely variable with reported values of 0.08 ppm (Kempton, 1996), 0.67 ppm (Miller et al., 1996), or 0-5.4 ppm (Table 1, this study).

pH. Although pH as low as 6.2 is recorded in upper hypolimion of the spring/summer lake waters, the vast majority of pH measurement for both lake and groundwaters in the Yerington area are in the 7.5-8.5 range (Table 2). In general, lake water is approximately one pH unit higher than that measured in the groundwater.

Dissolved oxygen. Dissolved oxygen concentrations are a function of temperature and dissolved salts and are therefore most easily examined within the context of the their relative saturation in water. Gas solubility equations in Weiss (1970) were used to determine oxygen solubility for a given temperature. Measured oxygen concentrations could then be examined within the framework of saturation concentrations (Figure 10). The high temperature (> 10^{o}C) lake samples near the surface are generally saturated or supersaturated with respect to oxygen, a condition that is commonly observed in photosynthetically active lake and ocean waters (e.g., Broecker and Peng, 1982). Hypolimnotic waters are depleted in DO by 1-2 mg/L a feature which can also be explained as the result of oxidation of organic matter sinking from the photic zone. The fact that deep water oxygen depletion was not greater in 1998 than it was in previous sampling years is additional evidence that the lake turns over on an annual basis.

It is interesting to examine the behavior of the Yerington pit lake relative to other pit mine lakes. Although the Yerington lake does not become seasonally anoxic, the much shallower Aurora pit lake does (Kempton, 1996). This is the result of (1) the much higher nitrate and nitrite concentrations at Aurora (4-5 ppm) and (2) the much shallower depth at Aurora (17 m vs. 110 m at Yerington). Lake depth is an important consideration because in lakes which overturn annually, the hypolimnion provides a large dissolved oxygen reservoir capable of oxidizing organic matter from the epilimnion. Since the depth of the photic zone of lakes is less variable than the depth of the epilimnion, deep lakes (> 50 m) have less of a tendency to become anoxic than lakes which are between 20 and 50 m deep (Jewell, 1992).

Long term climatological and geochemical trends

The ability to make long term predictions of water quality in pit lakes involves an extremely large number of meteorological, hydrological, and geochemical factors, only a small number of which can be examined in this study. The most important aspect of the long term behavior of pit lake waters examined here is the tendency of pit lake waters to develop a permanently stratified water column which will subsequently become anoxic, thereby significantly changing water column chemistry.

Modern climatology and water balance. Yerington is located in the rain shadow of the Sierra Nevada mountains in an area of extremely low annual rainfall (5.3" or 13.5 cm per year) (Western Regional Climate Center: http://www.wrcc.dri.edu). Evaporation calculated from the combined Fallon and Yerington data sets according to the methods outlined in Gill (1982) were approximately 0.6-0.7 m/yr. This is considerably less than values from published values of pan evaporation rates of 1.2-1.5 m/yr for this area of Nevada (e.g., Dingman, 1994, Figure 7-6). The difference could be due to the lower wind energy in the Yerington pit (Figure 4) since evaporation is directly proportional to wind velocity (e.g, Gill, 1982, eq. 2.4.5).

If precipitation minus evaporation (P-E) is assumed to be approximately 0.5 m/year, then total P-E since mine closure would be approximately 10 m. This implies a concentration factor in lake waters of approximately 10% which is considerably less than the difference in chloride concentrations (representing a conservative element) observed between lake water and ground water (approximately 100% and 50% for wells 2B and 36 respectively) (Table 2). Similar discrepancies have been noted in other pit lake studies and may be attributable to a certain amount of dissolved salts which accumulate on the floors and wall of open pit mines during mining operations (Castendyk, 1999).

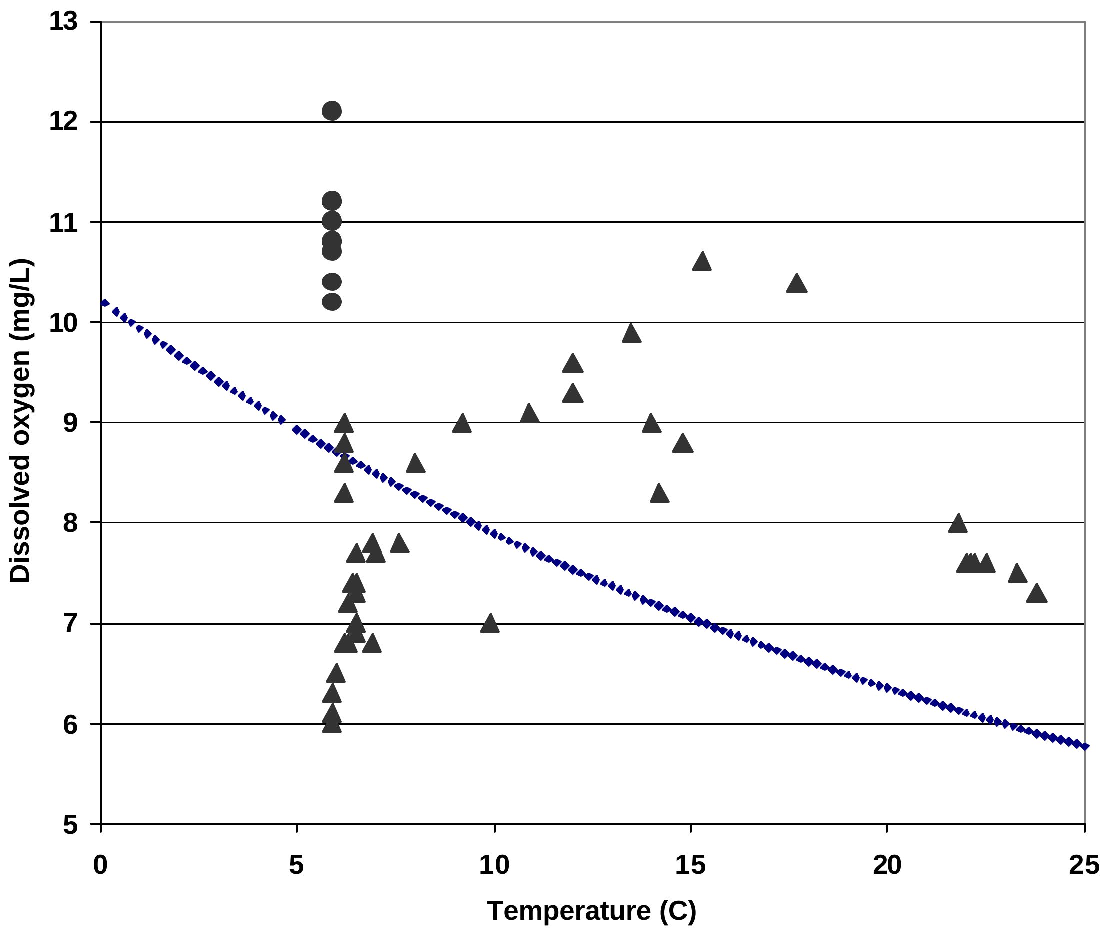


Figure 10. Temperature-dissolved oxygen data from the Yerington pit lake. Triangles represent date from Table 1 and Kempton (1996) during thermal stratification while circles represent samples taken during lake turnover in January, 1999.

During the winter of 1997, flood waters from the Walker River were diverted into the Yerington pit lake. The precise volume of diverted water is not precisely known (J. Sawyer, personal communication). A plot of known lake elevation over time reveals that lake elevation increased 2-3 feet above what might be considered the normal trend of the rising lake level (Figure 11). The change in chemistry in the lake brought about by the water diversion is therefore not believed to be significant.

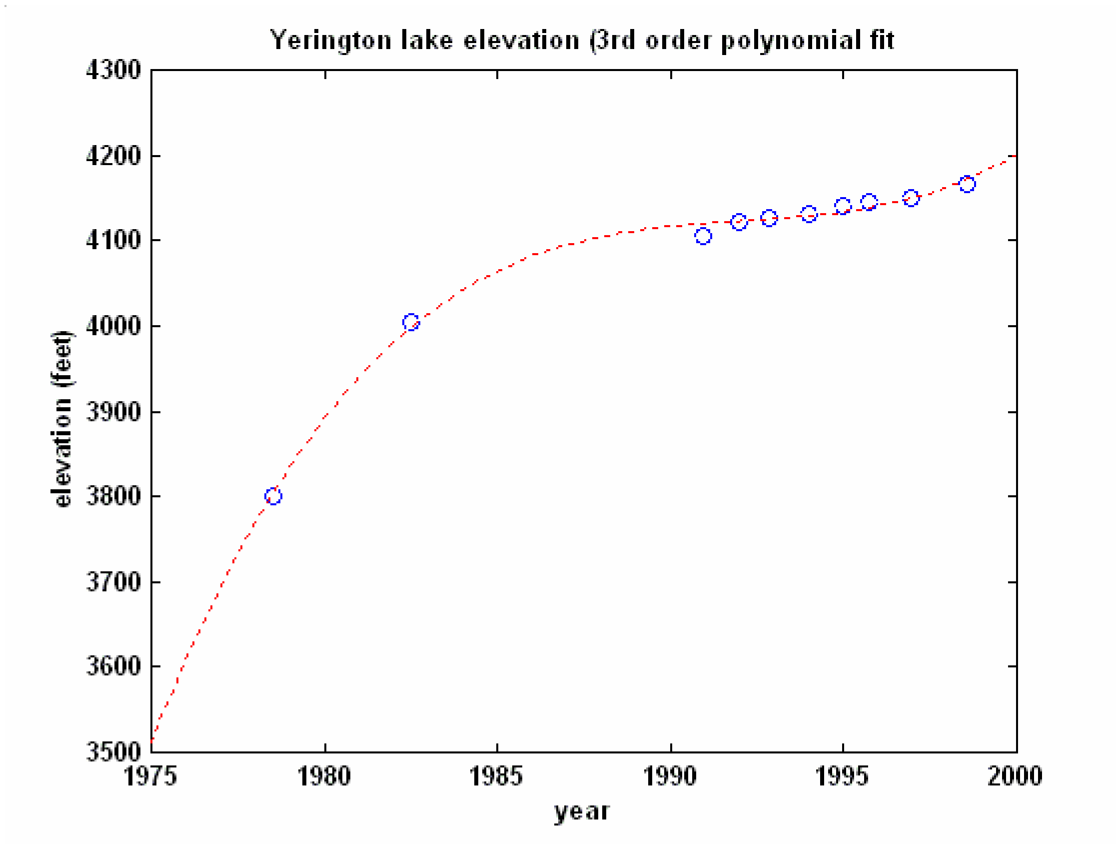


Figure 11. 3rd order polynomial fit of pre-Walker River diversion lake elevation with respect to time. The first two data points represent the cessation of mining (1978) and lake elevation from the Yerington 7.5' topographic map (1982). Post 1990 elevation data were provided by Arimetco. The last circle represents the post river diversion elevation.

Long term climatological trends. The long term stability and hence the redox condition and geochemistry of the water column in the Yerington pit lake needs to be evaluated within the context of climate extremes expected over the next century. Foremost among these, are hypothesized climate trends in the Great Basin as a result of atmospheric warming. Causes of global warming are controversial and both the observed climate changes to date as well as those predicted with atmospheric general circulation models (GCMs) show extreme spatial variability in both temperature and precipitation changes (Houghten et al., 1990).

For the sake of this project, two climate extremes which might increase stratification during the next 50 years were examined: (1) mean temperature was assumed to increase by 6^oC and (2) annual precipitation was increased by 2 mm/day (0.73 m/year). These conditions correspond to the maximum changes predicted by GCM output (Houghton, 1990, figures 5.4-5.6). It should be emphasized that GCM models have very coarse spatial resolution (100s of km) and often are not capable of resolving complex topography such as the rain shadow effect of the Sierra Nevada mountains and so these simulations should simply be taken as the most extreme of many possible climate scenarios.

Water column stability and dissolved oxygen concentrations were studied with the 1-dimensional Princeton Ocean Model (POM) and surface heat flux calculations described above. A baseline, 50-year simulation was run using an annual cycle of five year (1986-1990) averages for pressure, humidity, cloud cover and surface air temperature at Fallon as model input. Wind velocity recorded at the surface of the Yerington pit lake was used where possible for model input. Where wind speed data were missing, wind was set to a constant value of 3.2 m/s (7 mph). This baseline, 50 year simulation was then repeated using the climate extremes mentioned above.

In both the baseline and extreme climate scenarios, the Yerington pit lake overturns on an annual basis (Figure 12). Note surprisingly, the temperature of the deep water is 2-3^o higher in the global warming scenario (Figure 12b). Modeled dissolved oxygen below the thermocline therefore does change more than the 1-2 mg/L observed on an annual basis in the data (Figure 10).

Water column stability. The lack of predicted permanent stratification and therefore long term anoxia in the Yerington pit lake is the result of (1) the relatively low total dissolved solids of the water column and (2) the relatively small amount of surface water which enters the lake on an annual basis. In order for a water body to become permanently stratified, vertical density gradients from freshwater surface inflow during seasonal thermal stratification must be sufficiently strong large that winds will not mix the waters once the lake becomes thermally homogenous in the fall and/or spring. Such conditions simply do not exist at Yerington. In fact, the magnitude of seasonal evaporation is such that the TDS of surface waters is <u>greater</u> than the TDS of deep waters during thermal stratification (Kempton, 1996, Figure 1-3).

Previous studies of water column stability in pit lakes have applied lake surface area/depth ratio (often called the Peterson Scaling Parameter or PSP) as a measure of the tendency of the lake to stratify (Vandersluis et al.., 1995). The underlying assumption of this parameter is that deep lakes are less prone to wind shear forcing and thus more likely to stratify. While this ratio is appropriate for freshwater lakes, others have argued that (1) thermal heat flux (primarily from geothermal waters), (2) evaporation loss, and (3) groundwater outflow are the key variables for understanding pit lake stratification (Lyons et al., 1994). Of these three variables, geothermal heat flow is the most difficult to predict because detailed knowledge of bottom heat flux into a lake is site specific. This variable is probably not important at Yerington

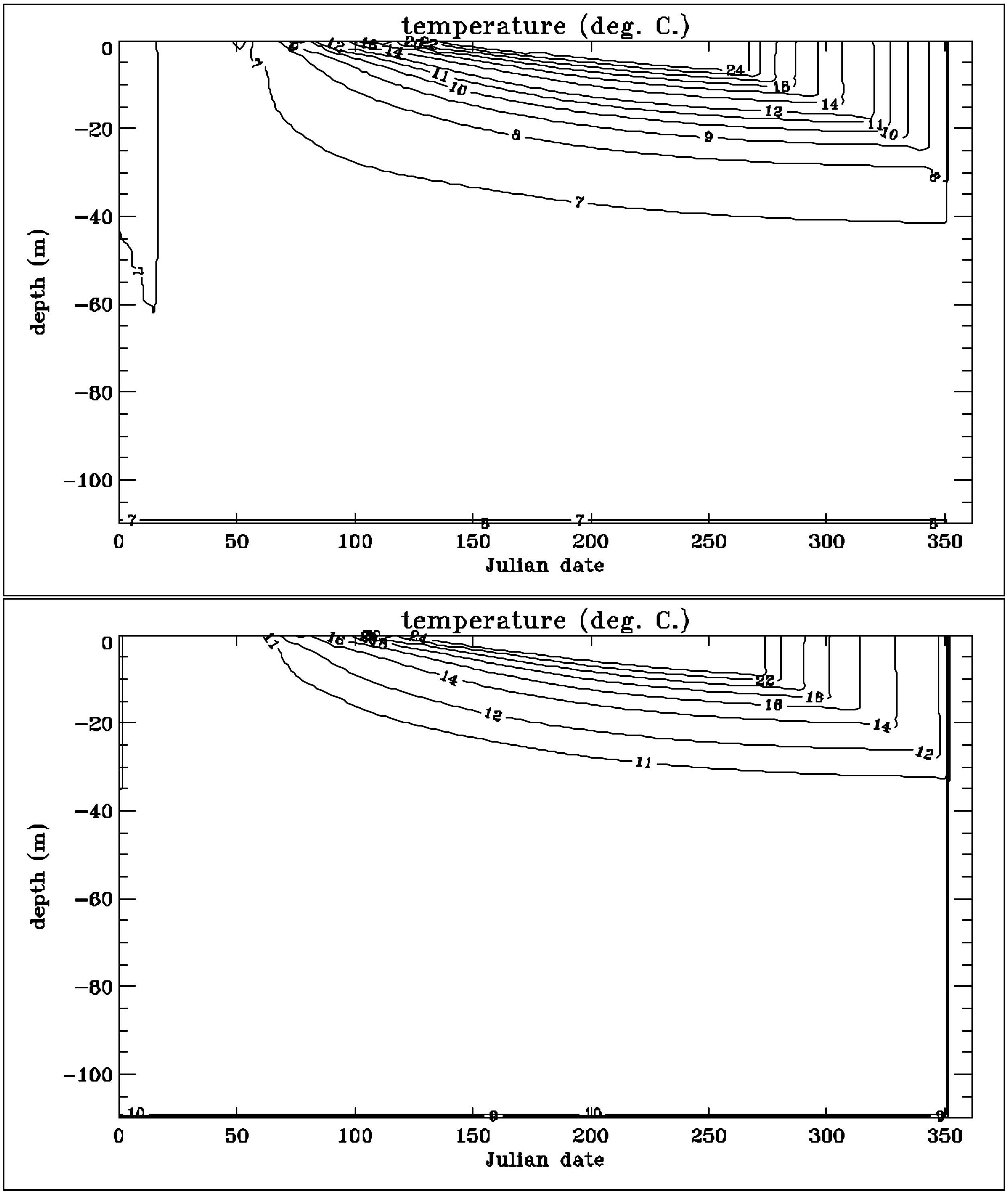


Figure 12. Simulation of seasonal temperature in the Yerington pit lake at the end of 50 years. Top panel used modern climate conditions while the bottom panel shows conditions for elevated temperature and rainfall which might be expected in an extreme example of global warming.

and so will not be considered further here. Likewise, net groundwater flux to a lake is difficult to determine without detailed knowledge of local hydraulic conductivity and head gradients. Even so, the role of groundwater in lake stratification should only be an issue in those cases were the solute concentration of the groundwater is sufficiently greater than surface water flowing into lake so that wind shear will not mix the lake when the vertical thermal gradient reaches zero (during the late fall for temperate latitude lakes). The third variable, high seasonal evaporation, should increase the density of surface waters and thus promote mixing during high wind events.

At the most basic physical level, the tendency of a water mass to become stratified is simply dependent on the vertical density gradient (which encompasses the three variables mentioned by Lyons et al., 1994) as well as water velocity shear brought about by wind forcing (which is implied but not specifically considered in the PSP). All of these variables can be conveniently expressed as the gradient Richardson number, the ratio of the density gradient (which tends to stabilize a water column) and the velocity shear gradient (which tends to destabilize it). If the gradient Richardson number exceeds 0.25, the water column is believed to be stable (Turner, 1973).

$$Ri = \frac{-g\dfrac{\partial r}{\partial z}}{r\left(\dfrac{\partial Vx}{\partial z}\right)^2} \quad (5)$$

In equation (5), ρ is density, u is horizontal velocity, and g is the gravitational constant. The gradient Richardson number can be used to make general determinations of the tendency of Yerington mine to mix or remain permanently stratified. For the sake of this study, the velocity gradient was determined by taking the maximum measured velocity at 10 m (6 cm/s; Figure 5), at which time the water column would be most unstable, over the shortest vertical distance at which the modeled water velocity was probably close to zero (assumed to be the point where the vertical temperature gradient is zero). This depth is approximately 40 m (Figure 6). Under these conditions is ~ 0.06 ms^{-1}/(40 - 10) m = .002 s^{-1}. The denominator of the Richardson number is therefore 0.004 $kgm^{-3}s^{-2}$. In order to maintain a stable water column must be ~ (.004 $kgm^{-3}s^{-2}$)(0.25)/9.8 ms^{-2} = .0001 kg/m^4. The density gradient over this 30 m vertical interval must therefore be 0.003 kg/m^3 = 3 g/ m^3 or 3 mg/L. These density gradients are relatively small and indicate that stratification could occur if (1) the TDS of the lake increases significantly and (2) a larger amount of fresh water (such as Walker River diversion) were to enter the lake over a short period of time.

DISCUSSION

Nearly 20 years after open pit mining operations ceased, the Yerington mine is still in the process of filling. Within the context of overall pit lake evolution, the lake is in its terminal phase, that is, groundwater is entering the lake with little if any water leaving to enter the regional groundwater system. Once lake elevation approximately equals that of the regional groundwater system, the lake will be in its flow through stage and changes in water by the pit lake can have an important influence on groundwater quality downgradient from the lake.

On the basis of this study, it is believed that the Yerington pit lake will not become anoxic either in its short term, terminal phase or in the long term (decades from) once the flow through stage has been achieved. Permanent stratification in a pit mine as well as in natural lakes is brought about by low density surface water flows capping higher density groundwater entering the deeper portions of the lake. Even if seasonal cooling of the relatively fresh surface waters produces an isothermal vertical temperature profile, vertical solute gradients produce a density gradient with a sufficiently high gradient Richardson number (equation 5) to prevent seasonal mixing of the water column.

The total dissolved solids of groundwater entering the Yerington pit lake is relatively low. Even though evaporation has increased the total solutes in lake by 50-100% since mine closure, TDS of the lake remains low. Even if geochemical reactions within the lake were to produce large amounts of solutes, the topographic setting of the lake is such that surface water runoff is minimal (Figure 3).

Water quality in the Yerington pit lake is remarkably good with only a small number of trace elements (Cu, SO_4, Se) present at concentrations greater than the 50% concentration level for groundwater. Clearly, these will have an impact on regional groundwater surrounding once the lake achieves flow through status. The exact nature of these impacts depends on factors (primarily the hydraulic conductivity and regional hydraulic gradients) which are beyond the scope of this report. It can be stated with some certainty, however, that anoxic waters with associated high concentrations of metals will probably not be a factor in the overall environmental impact of the Yerington mine on its surrounding.

ACKNOWLEDGMENTS

Financial support for the project was provided by Arimetco, Inc. Funds for detailed study of the selenium in sulfides was provided by the University of Utah Undergraduate Research Program in a grant to Melissa Mitchell. Field assistance at Yerington was provided by Devin Castendyk, Ben Passey, Gary Robertson, Alfanso Rios, and Melissa Mitchell. A special thanks goes to Dennis Dalton and Joe Sawyer of Arimetco for sharing their knowledge of the Yerington pit lake during the course of this project.

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Hydrology and Water Quality of the Yerington Pit Lake, Yerington, NV

Ronald L. Hershey, Assistant Research Hydrogeologist,
Division of Hydrologic Sciences, Desert Research Institute

INTRODUCTION

Recently, the former Anaconda copper mine in Yerington, NV has been under close regulatory scrutiny because of contaminated ground-water and fugitive dust issues. Because of these environmental problems and the close proximity of residences and tribal lands down gradient and down wind of the mine, the U.S. Environmental Protection Agency has recommended the site be added to the Superfund's National Priority List. However, NPL listing rarely occurs for sites without consent from the state. Nevada has opposed the Superfund listing of the Yerington mine, thus, the mine is now in an "Issues Resolution" phase where EPA, the Nevada Division of Environmental Protection, U.S. Bureau of Land Management, Lyon County, Yerington Paiute Tribe, Walker River Paiute Tribe, and Atlantic Richfield Company (principle responsible party for the mine) are developing work plans to address the environmental problems associated with the mine.

In addition to the ground-water contamination and fugitive dust, other mine units including buildings, heaps, waste-rock piles, and the open pit are being evaluated for environmental problems. The pit was excavated to exploit a porphyry-copper deposit and several large diameter wells were drilled and pumped to de-water the orebody to allow mining below the water table. Since cessation of mining in 1978, ground water has been filling the pit creating a pit lake. The lake is presently almost 400 ft deep and the pit continues to fill at about 5 ft per year. Brief descriptions of the geology, hydrology, limnology, and water quality of the pit lake follow.

GEOLOGY

The Yerington mine is located in the Yerington district, Lyon County, Nevada. The district lies 50 miles east of the Sierra Nevada batholith and within the Great Basin physiographic province. The Yerington district is situated within the Yerington batholith, a composite granitic body of Middle Jurassic age that intruded volcanic and sedimentary rocks of Triassic-Jurassic age. The Yerington batholith is composed of equigranular quartz monzodiorite (McLeod Hill unit) intruded by a lesser volume of equigranular quartz monzonite (Bear unit). Late-stage granite porphyry dike swarms associated with the porphyritic-granitic stocks intruded the central portions of the batholith. The Yerington mine is centered over one of these dike swarms (Carten, 1986).

The mine occupies a position on an alluvial fan two miles east of the Singatse Range which flanks the Mason Valley on the west and rises some 1,900 ft above the valley floor. The present channel of the Walker River passes within 1,200 ft of the eastern edge of the pit. The porphyry copper deposit is entirely within granitic rocks, primarily quartz monzonite. Granitic rocks represent several intrusive phases and are in turn cut by a variety of dikes (Moore, 1969).

The orebody is one of the few porphyries where geologic conditions were optimum for the formation of an important economic concentration of oxide ore and a minimum economic secondary enrichment. The lower limit of oxidation is sharp and distinct and redeposition of oxidized copper products is considered to have occurred for the most part *in-situ*. The principal oxidation product is chrysocolla which occurs irregularly dispersed throughout the rock and as narrow seams along fractures. Locally, clay-altered phenocrysts of the porphyry contain sufficient finely divided chrysocolla to constitute important ore. Cuprite, tenorite, and melaconite all have a wide distribution within the oxide zone while malachite and azurite occur but are not abundant (Wilson, 1963).

Lying between the primary sulfide and the chrysocolla horizon is a transition zone in which chalcocite, cuprite, melaconite, native copper and chrysocolla occur superimposed upon primary mineralization. Immediately underlying the transition zone, the primary sulfide minerals, pyrite and chalcopyrite occur as minute grains in the groundmass of the porphyry, in feldspar and quartz phenocrysts, and as narrow seams. Generally chalcopyrite is slightly more abundant that pyrite. Small amounts of bornite and covellite are present, and primary chalcocite has been detected microscopically.

Sodium-calcium metasomatism has affected more than one-third of the altered granitic rock associated with the ore deposit. This type of alternation is characterized by the conversion of magmatic minerals to more sodium- and/or calcium-rich minerals including K-feldspar to oligoclase and biotite to actinolite. It is distinct from propylitic alteration in which albite is formed principally by the loss of calcium from plagioclase, not by the metasomatic addition of sodium. Except for the presence of this alteration type, alteration and mineralization assemblages at the Yerington mine are similar to those observed at other copper deposits. Potassic alteration dominated the main levels of the deposit and is structurally overlain and crosscut by sericitic alteration (Carten, 1986).

HYDROLOGY

As mentioned previously, the eastern edge of the pit is about 1,200 ft from the Walker River. The Walker River supplies water to the alluvial aquifer in the Mason Valley and ground water in the alluvial aquifer near the mine flows northward, the same direction as the river. However, prior to the flood of January 1, 1997, only minute amounts of water from the alluvial aquifer reached the pit because of an intervening range front fault on the east edge of the pit. The fault juxtaposes relatively impermeable orebody granite against the saturated alluvial aquifer on the river side of the fault, effectively creating a hydraulic barrier between the pit and the river-saturated alluvium. This barrier was breached during the 1997 flood as a channel between the river and the pit was cut with mining equipment to drain off water flooding the town of Yerington. Since then, ground water from the alluvial aquifer is flowing into the pit at about 100-120 gpm (varies seasonally). The initial cut in the barrier was substantially enlarged by the flood waters and the resulting alluvial fan inside the pit is easily seen from the Weed Heights observation area.

On the western side of the pit, the thickness of the overlying alluvium increases substantially due to both an increase in elevation of the alluvial fan surface (4400 ft elevation land surface east edge of the pit vs. 4600 ft west edge) and a decrease in elevation of the alluvium/bedrock contact. Several small springs on the western pit wall issue from the alluvium/bedrock contact. These springs are best observed from the mine boundary fence on the east edge of the pit next to Nevada State Road 339. The springs can be located by the vegetation about halfway down the west face of the pit wall below the Weed Heights observation area. Flow from these springs varies seasonally from 50 to 60 gpm.

Initially, seven large diameter wells, varying between 200 and 300 ft in depth, were drilled in 1952 to de-water the orebody. These wells were drilled in a semi-circle around the soon-to-be eastern edge of the pit. These wells were drilled on the western side of the range-front fault separating the orebody from the Walker River and alluvial aquifer. Depth to ground water in these wells at the time of drilling ranged between 80 and 90 ft. As mining deepened the pit, two additional de-watering wells were drilled inside the pit and the other de-watering wells outside the pit were reamed and deepened. Drilling records of these new de-watering wells and deepening of existing de-watering wells are very limited.

The pit continues to fill with ground water and the lake surface will eventually approach the pre-de-watering water table elevation. However, the final lake elevation will depend on the amount of annual evaporation and ground-water inflow. At the present lake elevation and assuming a constant increase in lake elevation at 5-ft/yr, the pit will reach the pre-de-watering water table elevation in about 40 years. However, annual lake level rise will decrease as the volume of the pit increases with widening pit area and as evaporation increases because of additional lake surface area. From 1991 to the flood of early 1997, the lake increased in volume about 800 acre-ft per year. Post flood volume changes from 1997 to 2001 are now about 1,000 acre-ft per year.

LIMNOLOGY

Lyons *et al.* (1994) noted that pit lakes are different than most natural lakes and man-made reservoirs because pit lakes, in general, have much smaller surface area and much greater depths. Also, pit lakes have virtually no shoreline or shallow water area, limiting development of biological communities in the littoral zone. Because of these distinctive physical characteristics, pit-lake limnology may be very different from that of natural lakes. Vertical profiles and biological sampling have been conducted at the Yerington pit lake to examine this concept more closely.

Figure 1 shows results of several vertical profiles of temperature at the deepest part of the lake during 2000. During the winter, the lake is isothermal, demonstrating that the lake is well mixed this time of year. As the spring and summer progress and the days get longer, thermal energy received by the lake increases and the lake surface temperature rises, causing thermal stratification. In the autumn, with cooling of the lake surface, the epilimnion (warm surface layer) increases in thickness until the lake turns over and becomes isothermal. These data indicate that the lake is monomitic, that is, it turns over once per year. Walker and Pyramid lakes are also monomitic (Lyons *et al.*, 1994; Lebo *et al.*, 1993), suggesting that the Yerington pit lake does not have substantially different physical limnology than other northern Nevada lakes.

Figure 2 shows dissolved oxygen (DO) profiles. These profiles demonstrate two important aspects of the pit lake's limnology. First, the lake contains DO at all depths during all parts of the year. This shows that the hypolimnion (cool bottom layer) does not become anoxic, and so reduced species such as As^{+3} will not be released from the sediments into the water column. Secondly, the increases in DO in the epilimnion indicates algal respiration.. DO profiles also confirm that the pit lake is monomictic.

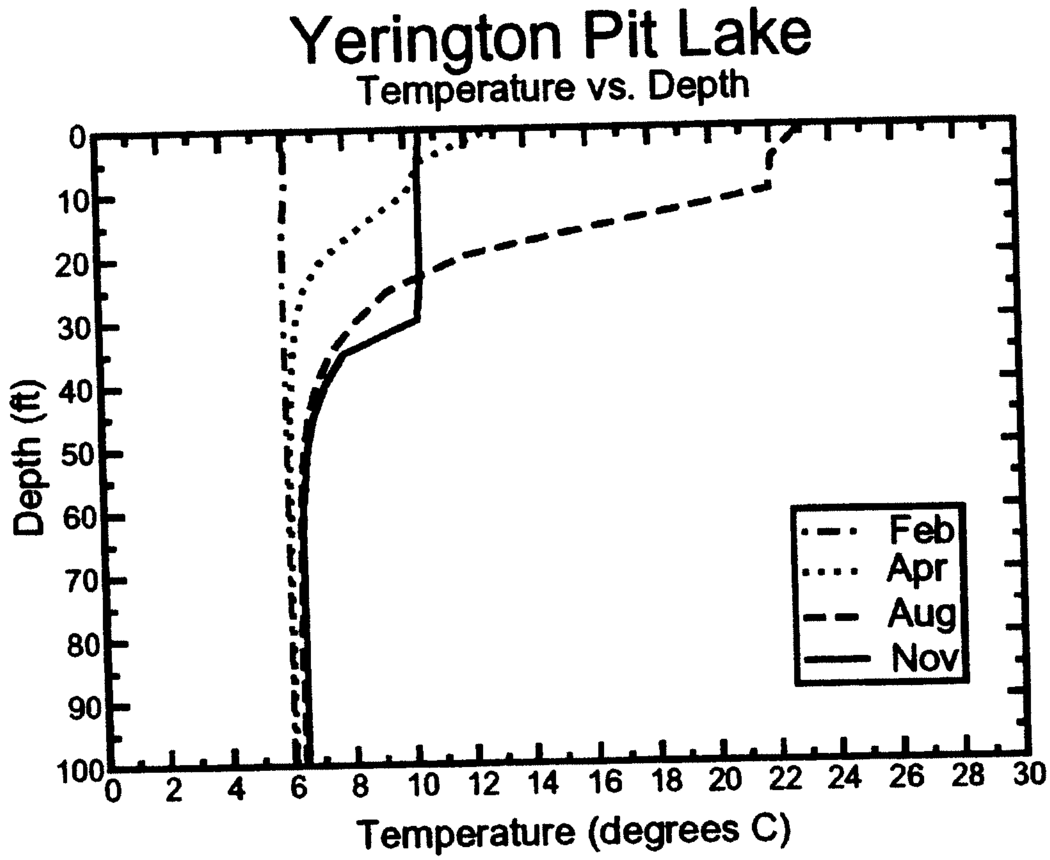

FIGURE 1.

Biological sampling revealed that the pit lake is very poor in biota. The predominant phytoplankton found were green algae and cyanobacteria (blue-green algae). The total primary production is low as shown by cell counts (approximately 4,000 cells/ml) and higher forms of life including zooplankton and macro-invertebrates were absent. Sampling for lake nutrients also revealed them to be in short supply. The combination of low nutrient levels, low primary production, and DO at or near saturation classifies the pit lake as oligotrophic or unproductive.

WATER QUALITY

In general, the Yerington pit lake has good water quality. The pH is alkaline at approximately 8.3 and the total dissolved solids are approximately 650 mg/L. Figure 3, a diagram of the major ions, shows that the pit lake is predominantly calcium, sodium, and sulfate, and that the lake water chemistry is well mixed and unaffected by the annual thermal stratification. However, trace element concentrations of copper and selenium are high.

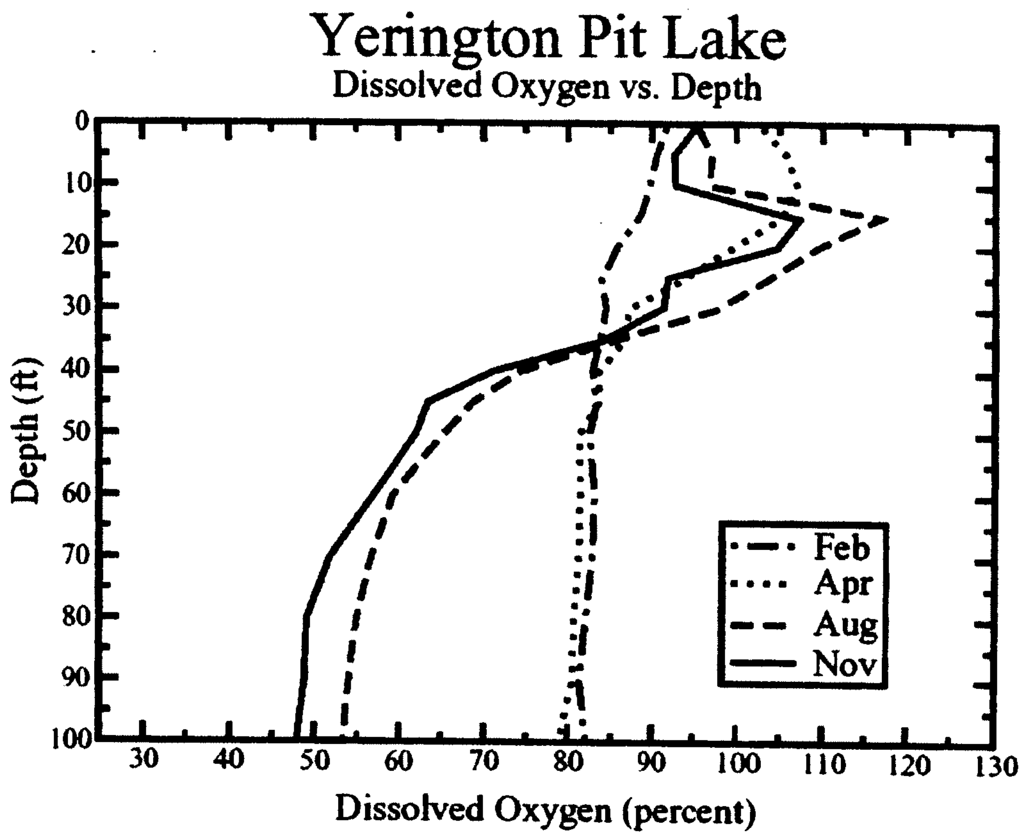

FIGURE 2.

Copper concentrations were, not surprisingly, high, but have been decreasing over the last six years. In 1995, copper concentrations were over 150 ug/L but have decreased to below 50 ug/L in 2000. Possible explanations for the decrease include precipitation of copper minerals and dilution by ground water in flow. However, equilibration calculations show that all important copper oxide minerals are below saturation; therefore, it is unlikely that copper minerals are precipitating in the pit lake. Dilution is also unlikely as there appears to be abundant copper in the pit walls, and because equilibration calculations show under-saturation with respect to copper minerals, copper is probably dissolving from the pit walls into the pit lake. Another mechanism that could remove copper would be uptake by algae. Copper is a trace nutrient for algae and the decrease in dissolved copper may be the result of it being consumed. Also, organic matter has a strong affinity for adsorbing copper. Analysis of copper concentrations and total organic carbon in sediments from the pit lake show a strong correlation between the amount of copper and TOC in the sediments. Dead algae, as well as other organic matter, will settle out of the water column and accumulate in the sediments, sequestering copper from the lake.

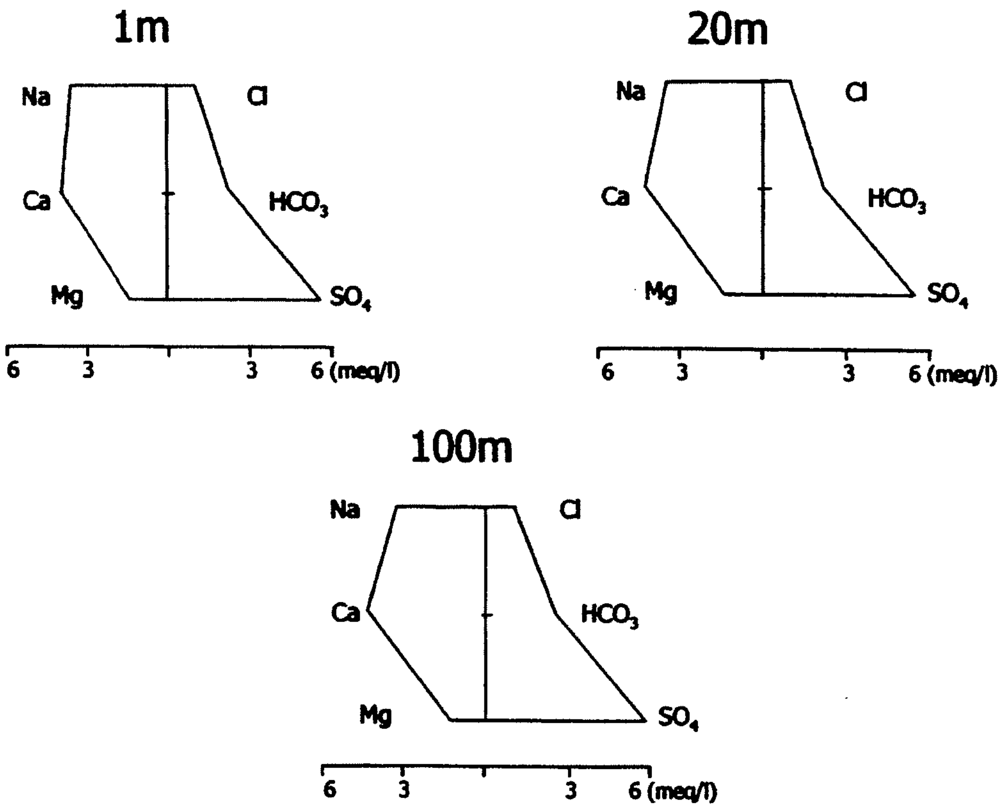

FIGURE 3. Yerington Pit Lake major ions.

The major environmental concern for the pit lake is the high selenium concentrations about 100 ug/L and relatively constant over the last six years. These concentrations are 20 times the Nevada aquatic life standards. At these concentrations, animals such as macro-invertebrates and fish would not survive in the pit lake. Previously, a large number of bass were stocked in the lake to develop a recreational use for the pit lake. However, today, no fish have been observed in the lake. The high selenium concentrations are also a concern for water fowl and deer who periodically frequent the lake.

REFERENCES

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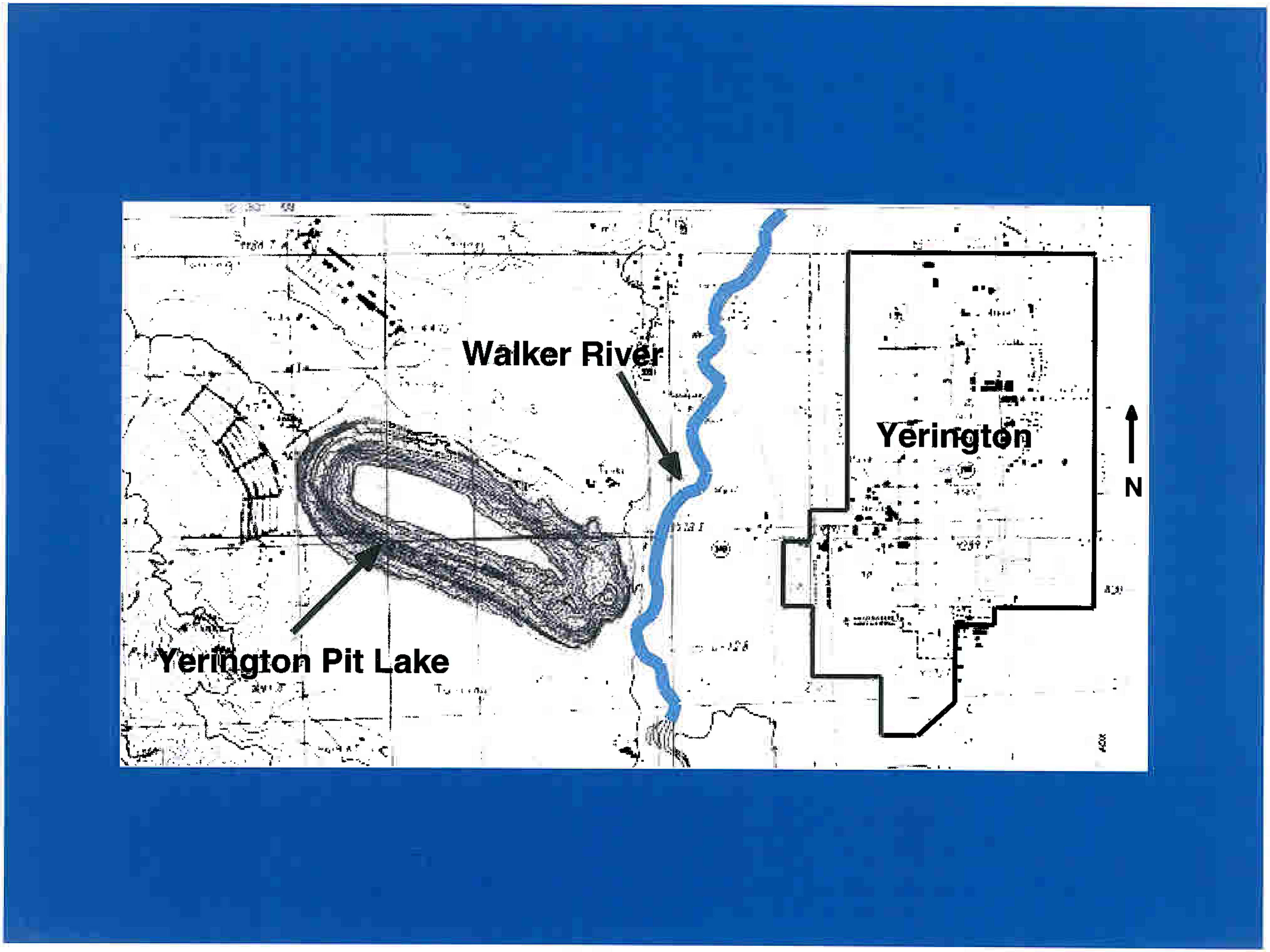
Dynamics of the Yerington Pit Lake

Ronald L. Hershey
Division of Hydrologic Sciences
Desert Research Institute

Introduction

- Geology
- Hydrology
- Limnology
- Water Quality



Walker River
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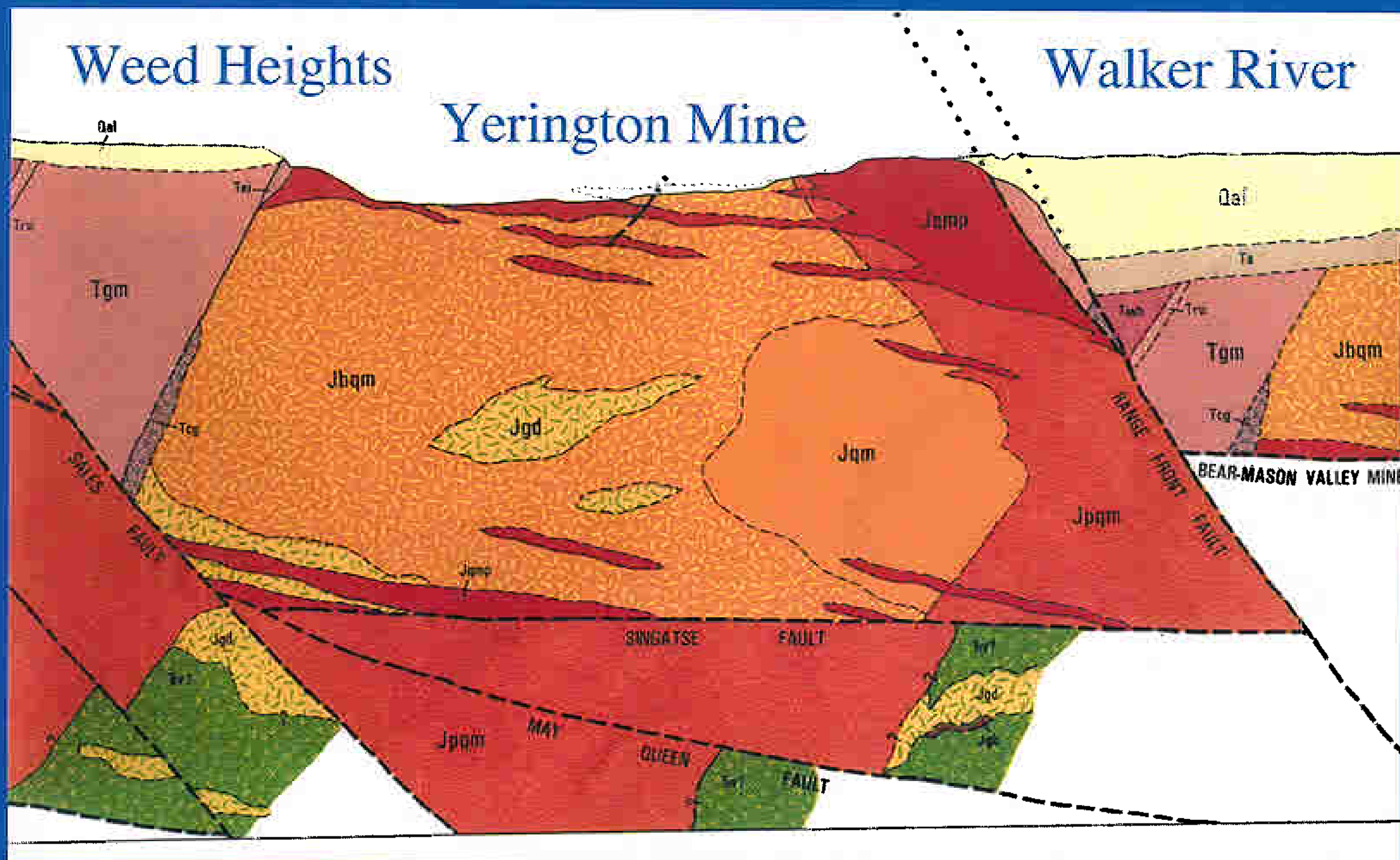
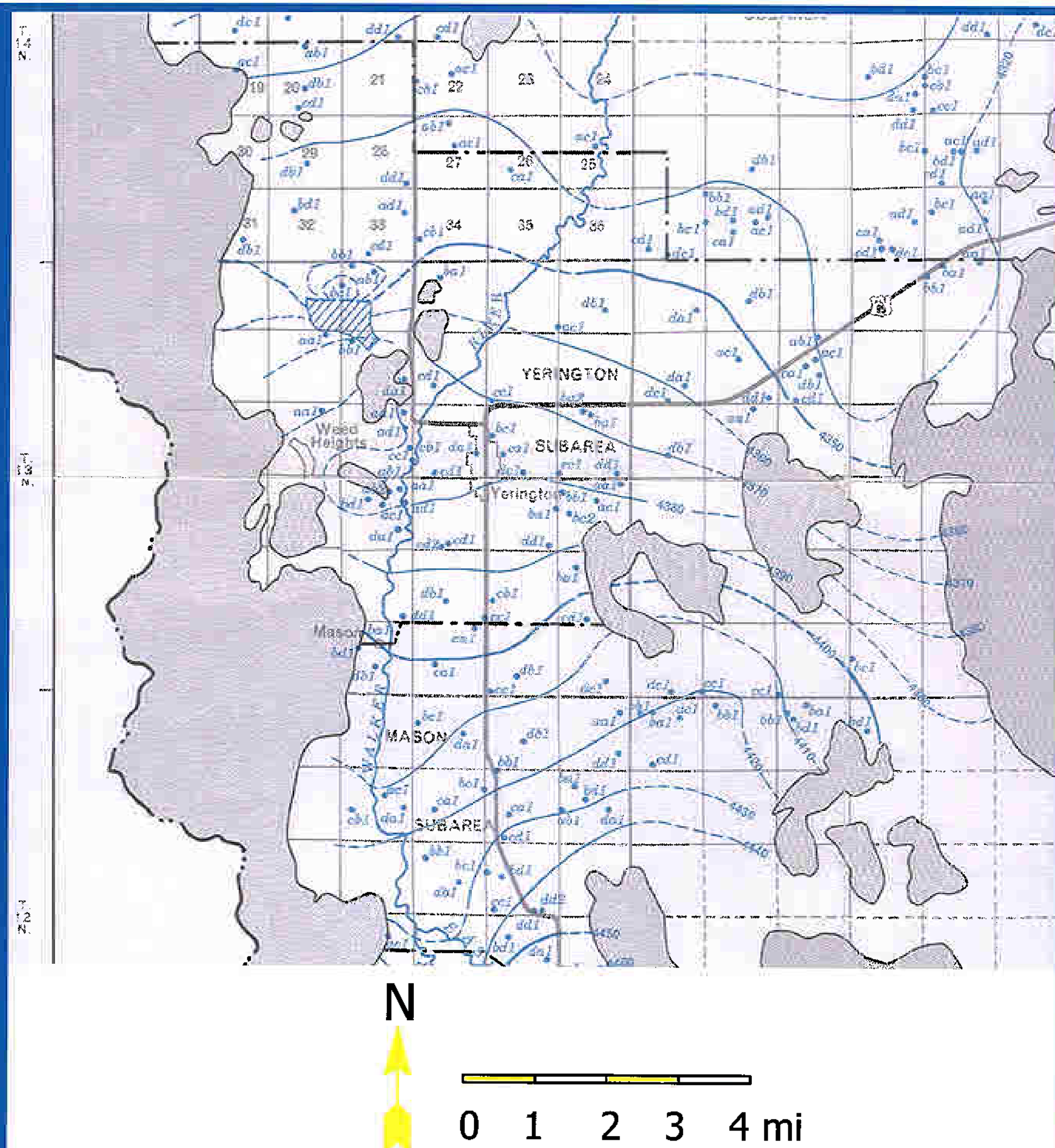
Yerington Pit Lake

Geologic Map Yerington Pit



Geology

- Host: Quartz Monzonite
- Oxide Ore: Chrysocolla
- Sulfide Ore: Chalcopyrite
- Alteration: Na-Ca Metasomatism
Potassic Alteration
Sericitic Alteration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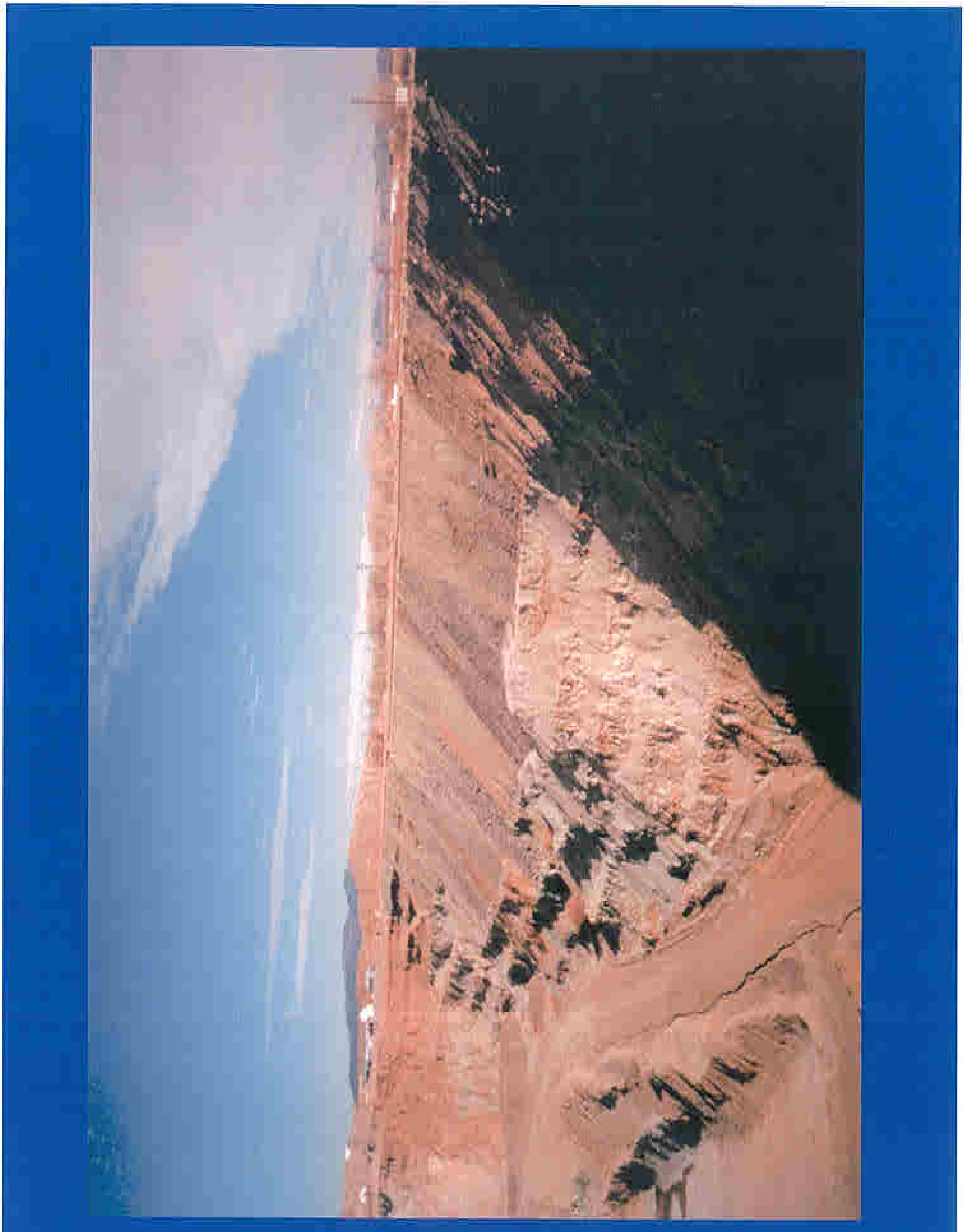
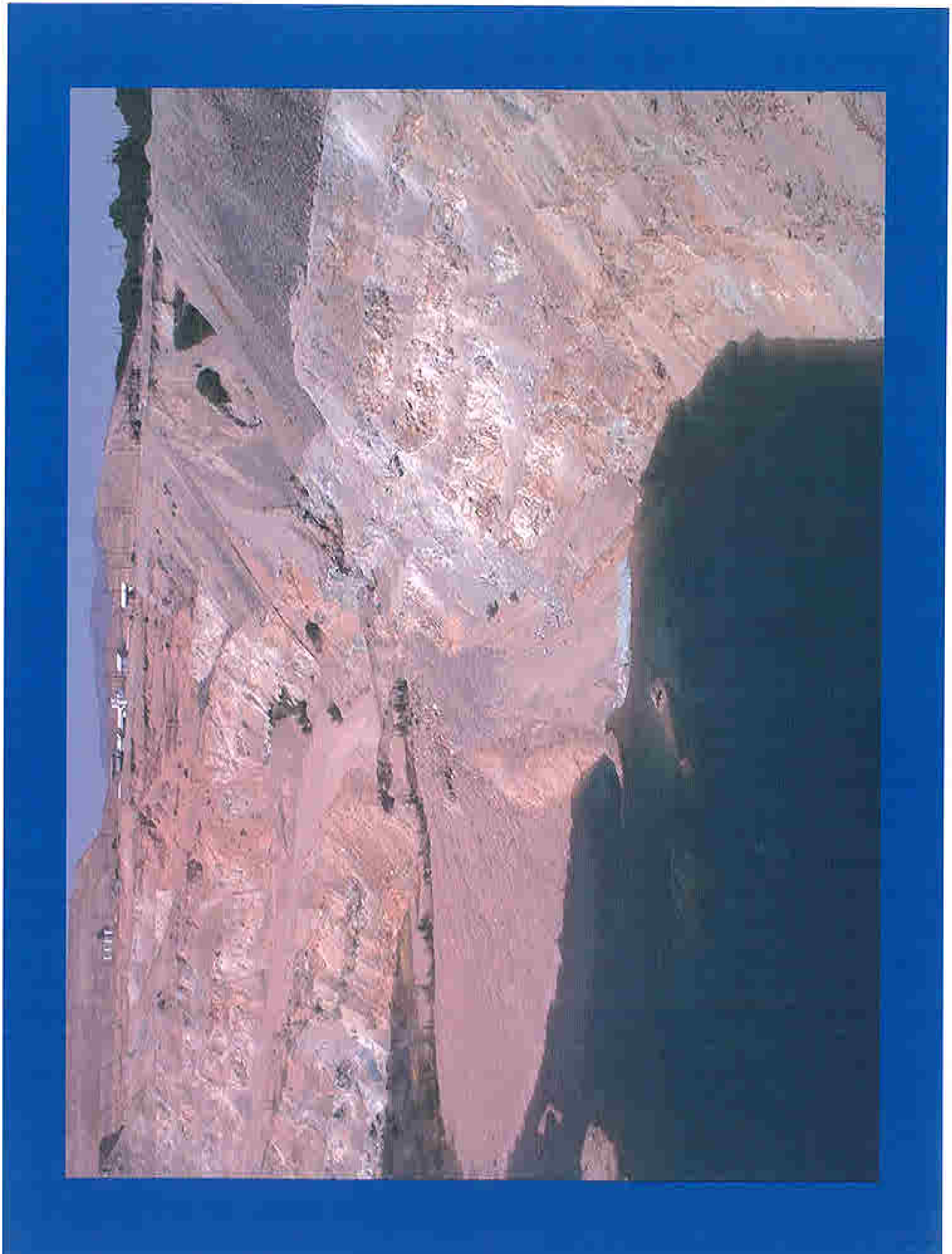
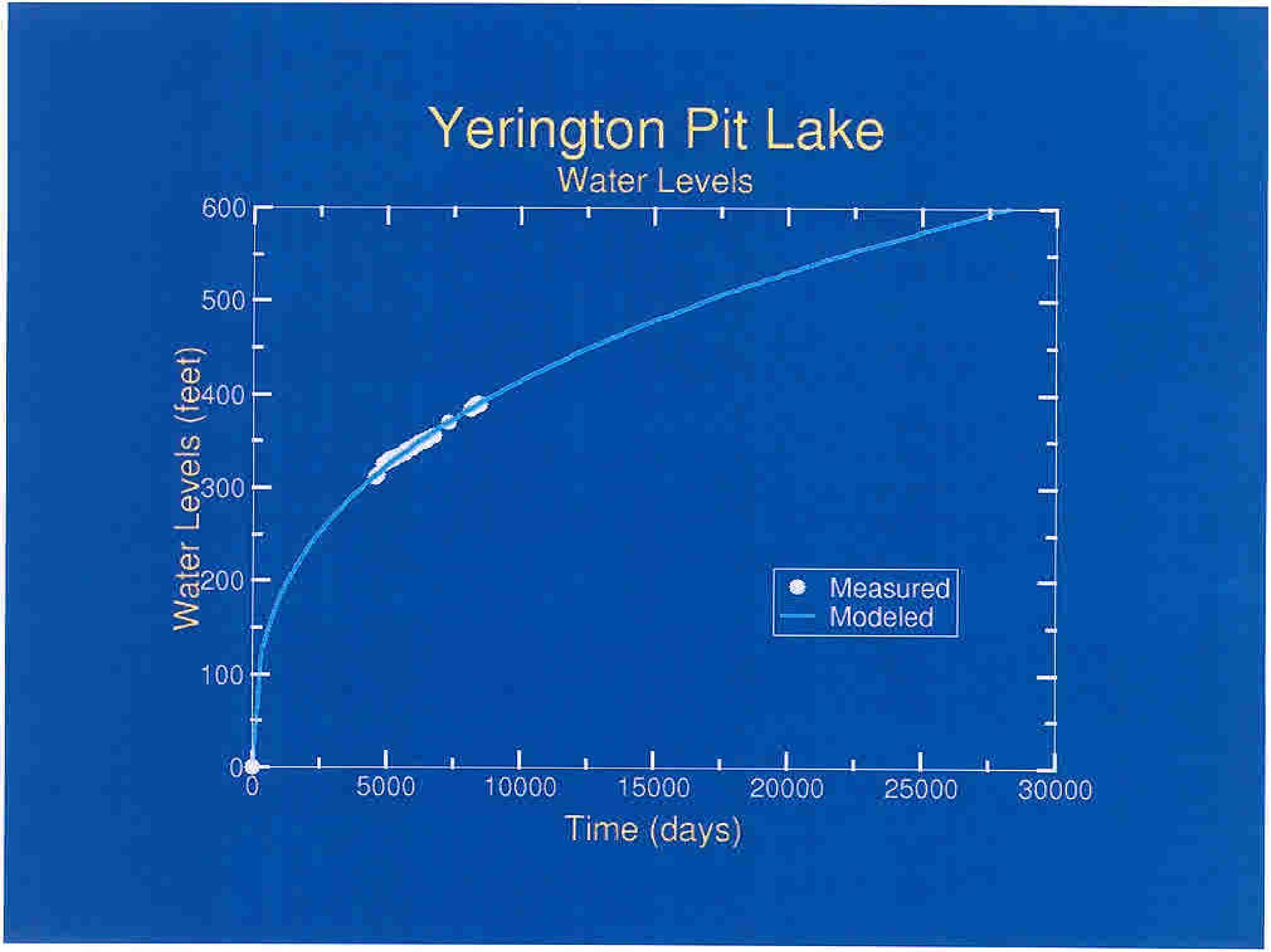
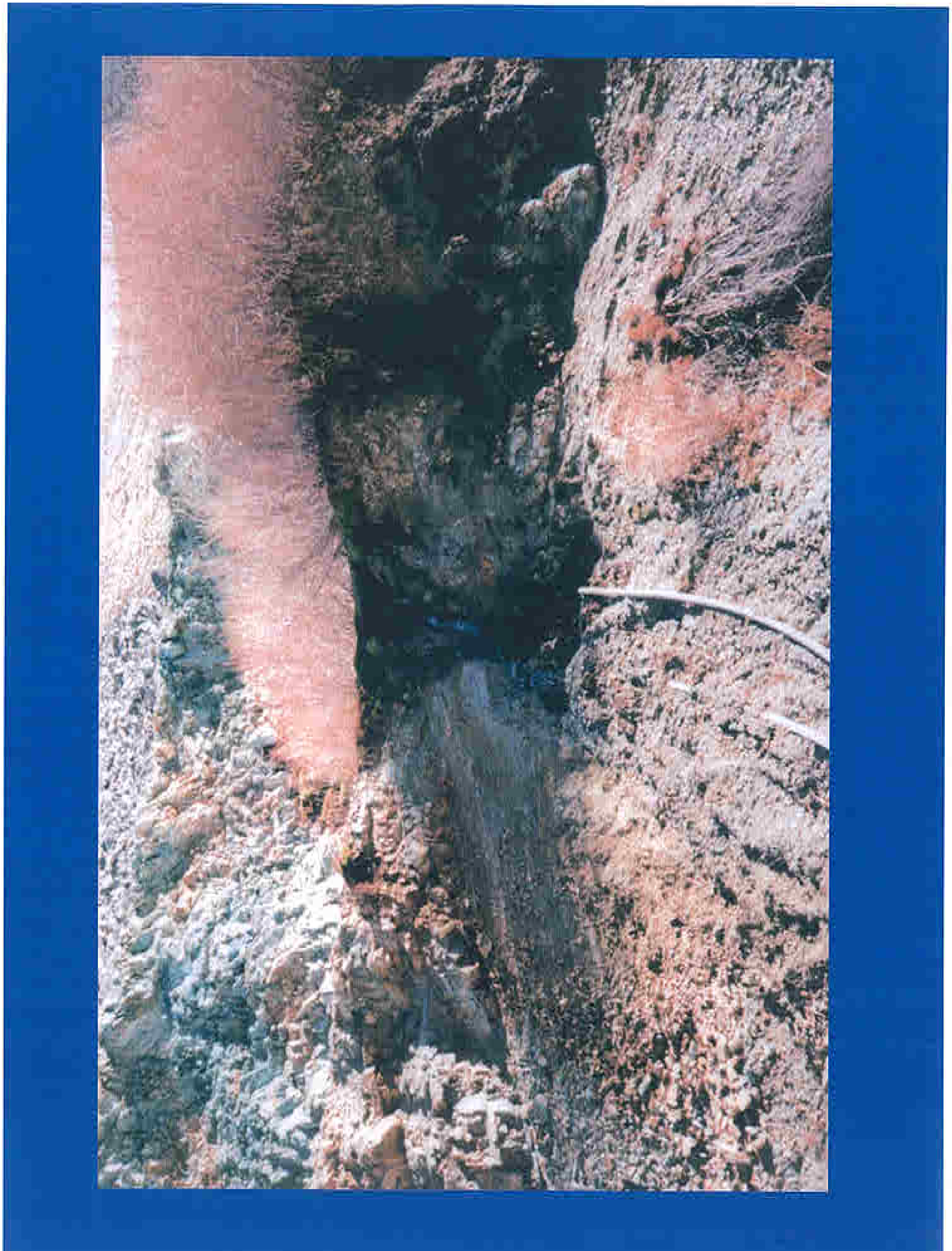
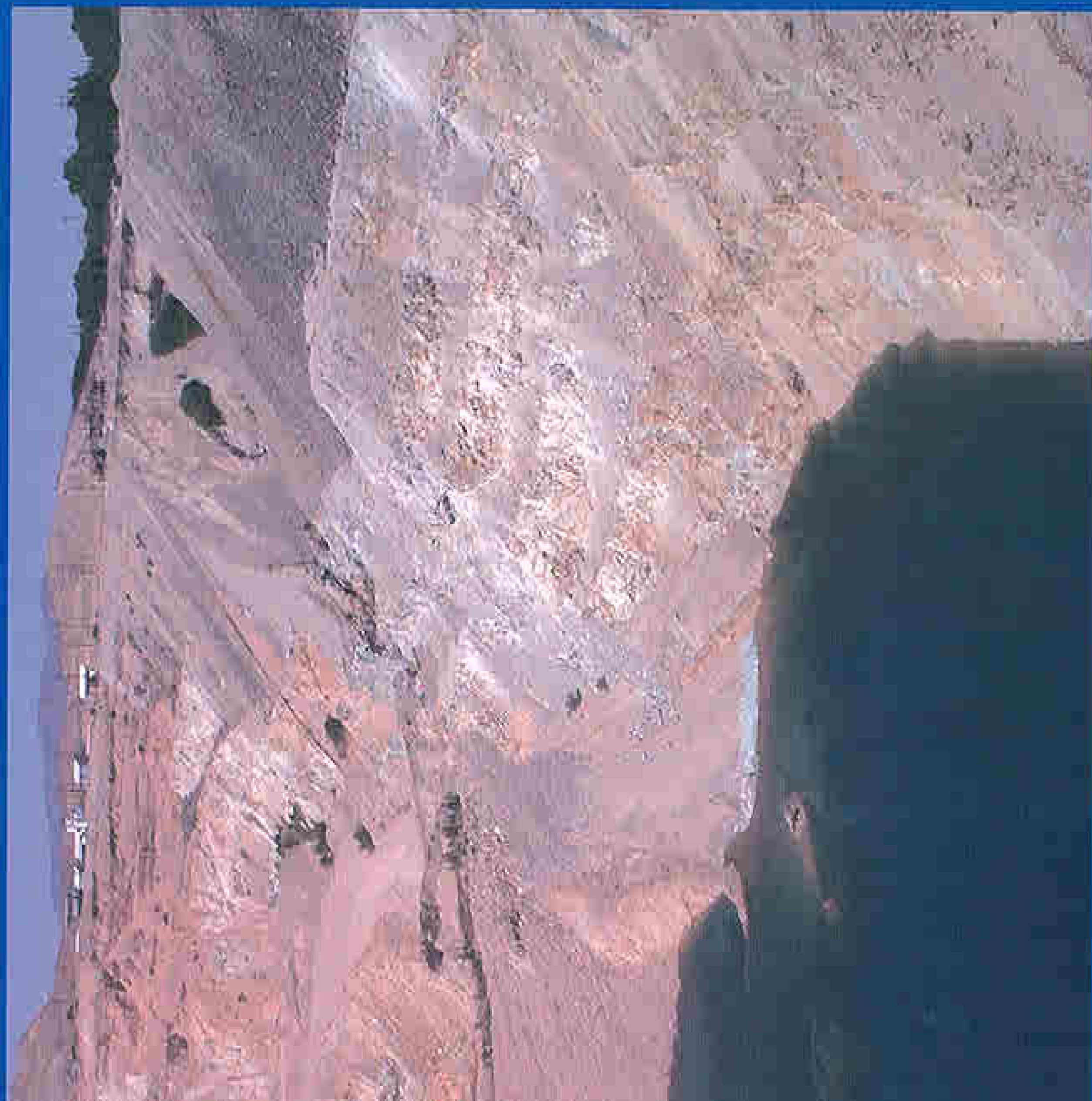
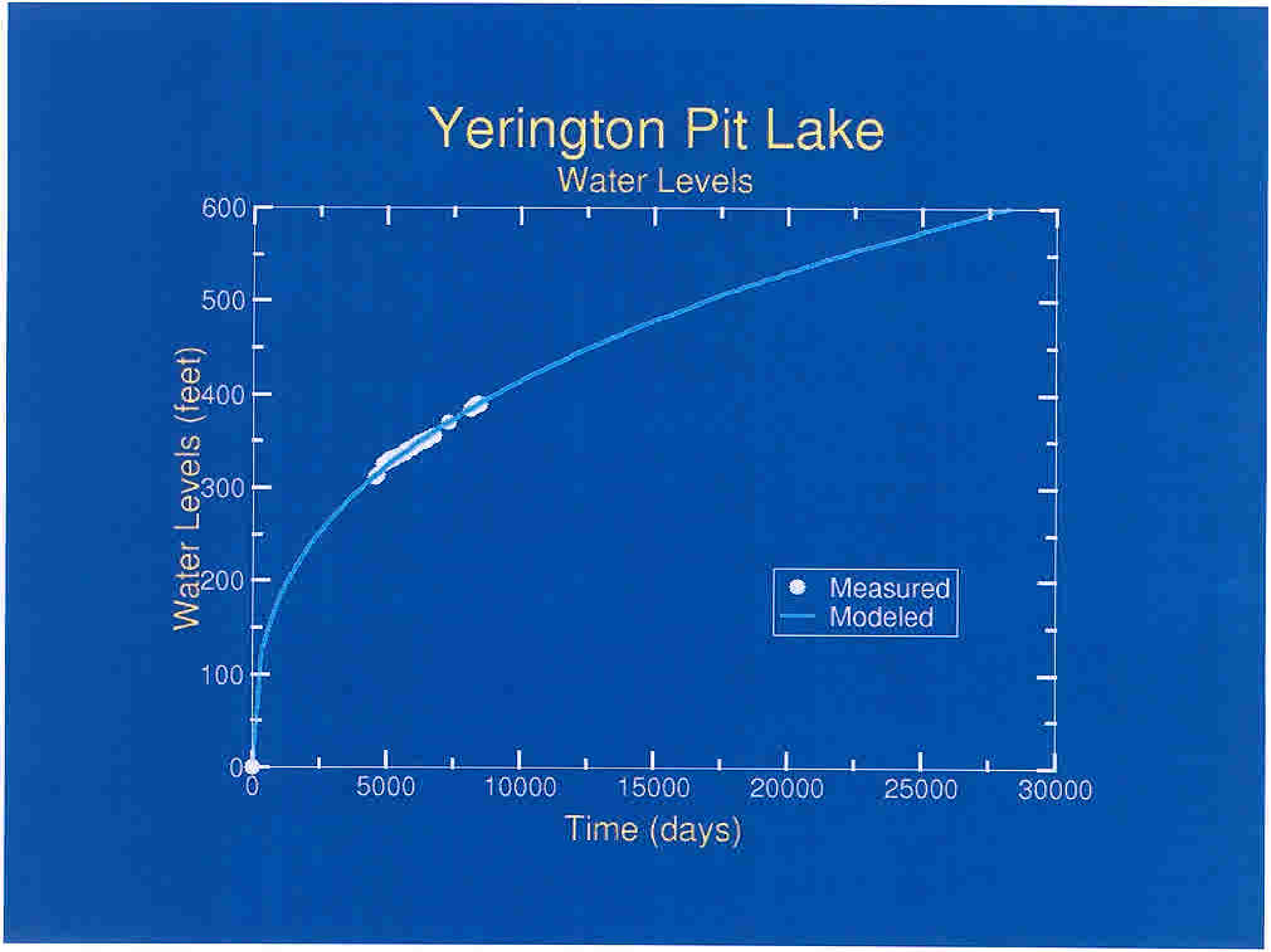





Yerington Pit Lake
Water Levels
Water Levels (feet)
600
500
400
300
200
100
0
0
5000
10000
15000
20000
25000
30000
Time (days)
Measured
Modeled

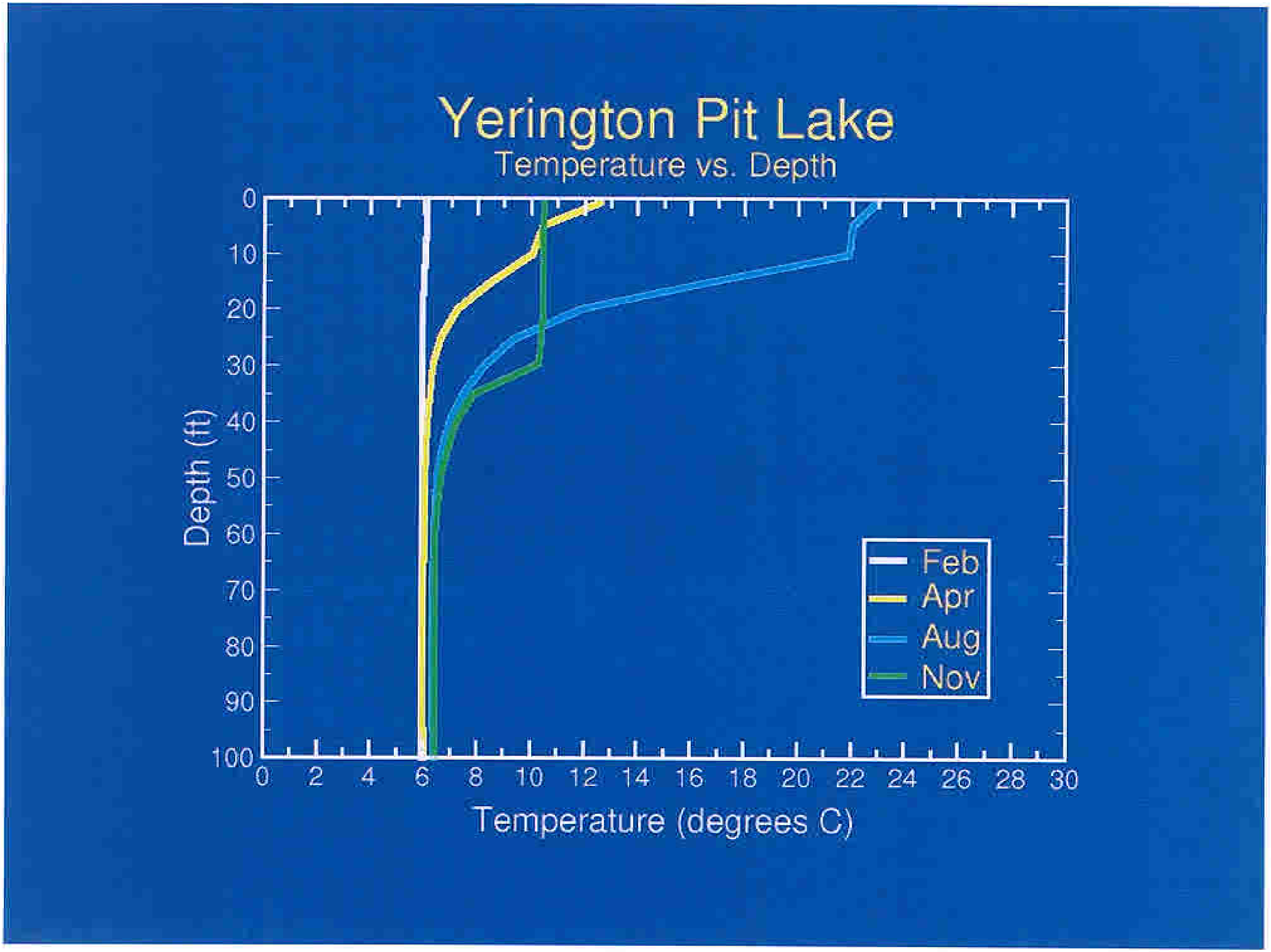





Yerington Pit Lake
Water Levels
Water Levels (feet)
0
100
200
300
400
500
600
0
5000
10000
15000
20000
25000
30000
Time (days)
Measured
Modeled

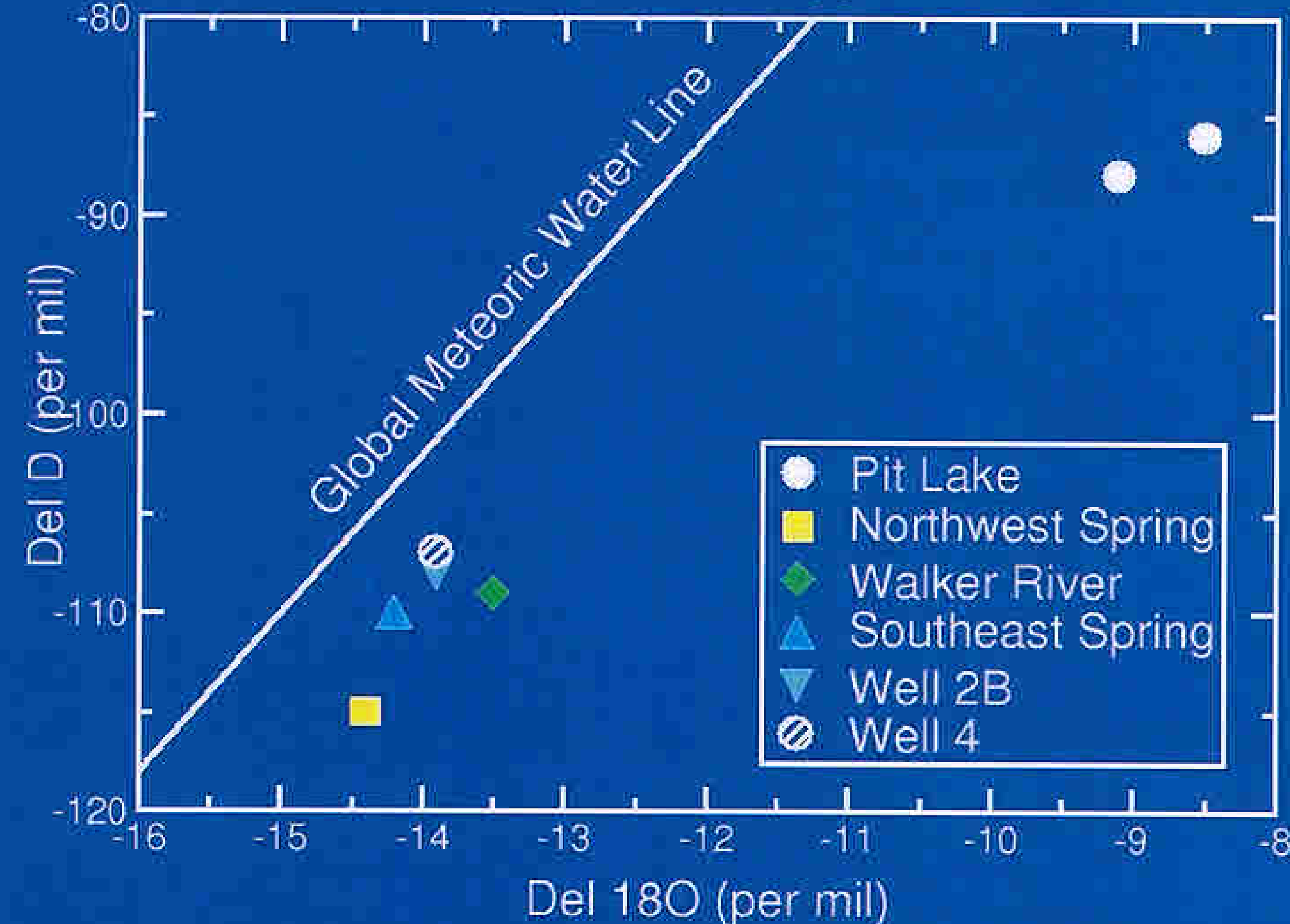
Water Balance

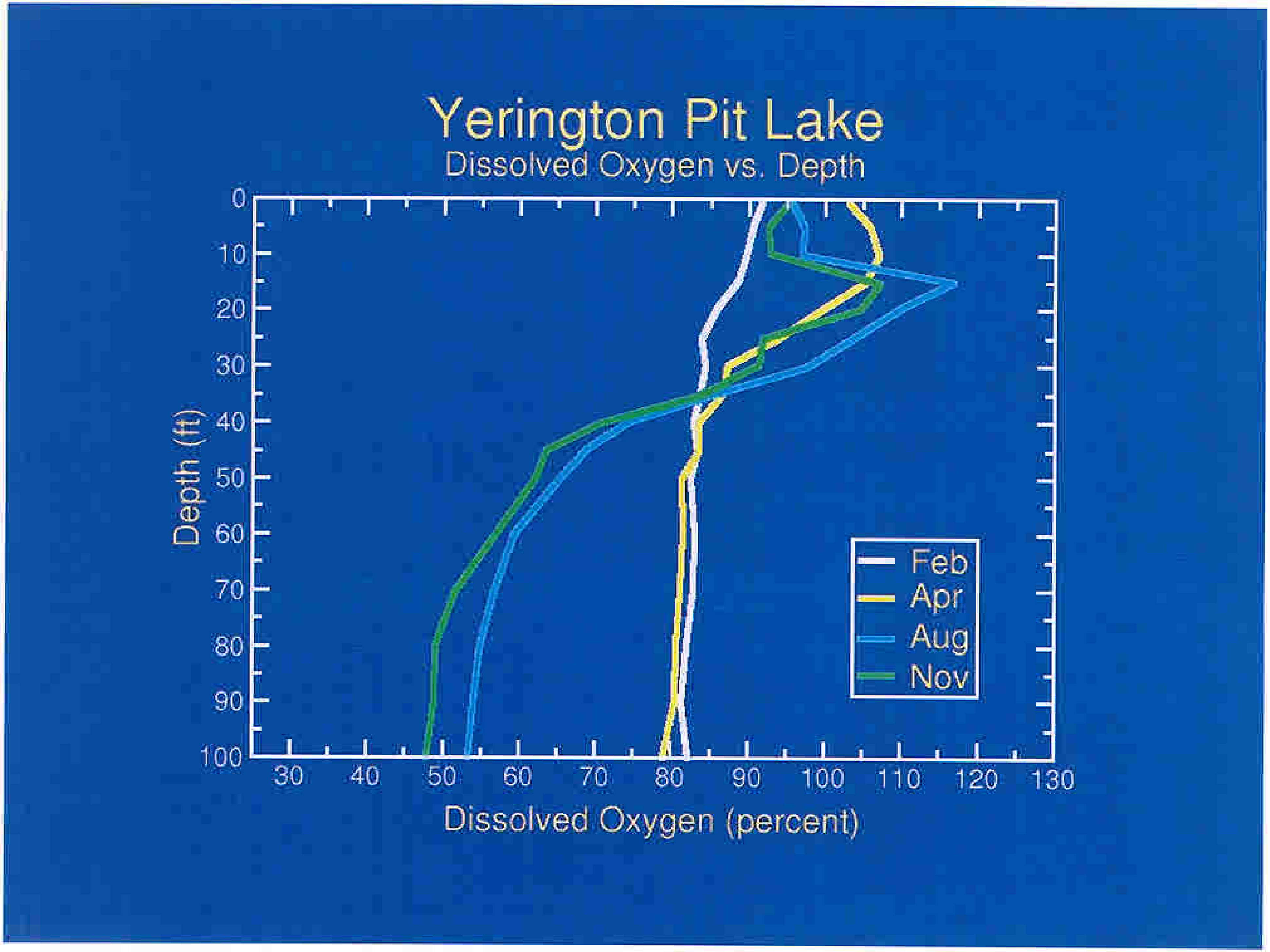
Volume	397 million gallons/yr	
East Spring	60 million gallons/yr	15%
West Spring	32 million gallons/yr	8%
Precipitation	23 million gallons/yr	6%
Evaporation	-39 million gallons/yr	-10%
Groundwater	321 million gallons/yr	81%


Yerington Pit Lake
Temperature vs. Depth
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Temperature (degrees C)
Feb
Apr
Aug
Nov

Yerington Pit Lake

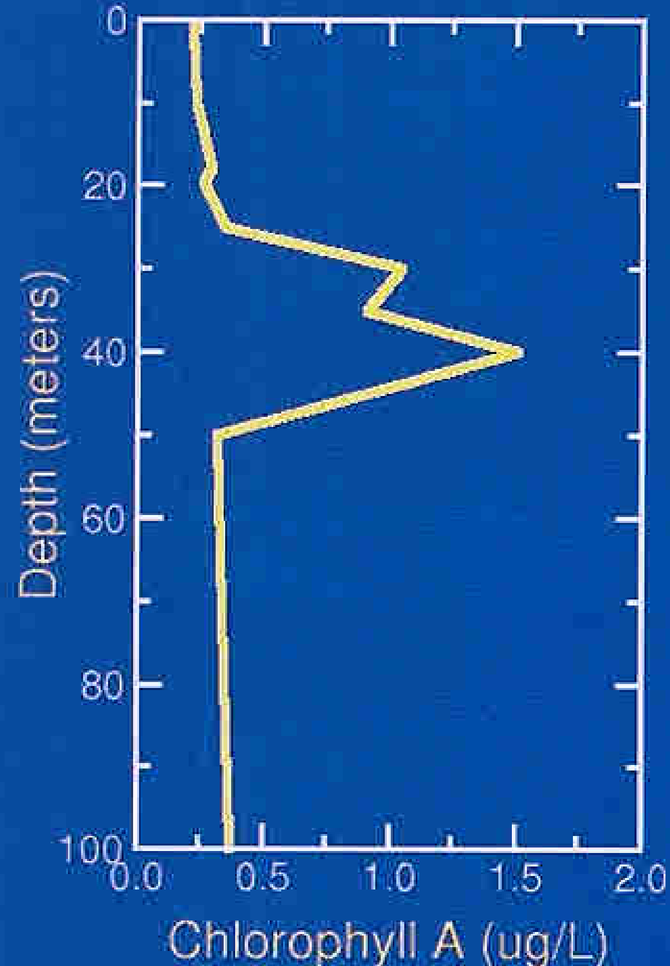
Deuterium vs. Oxygen-18

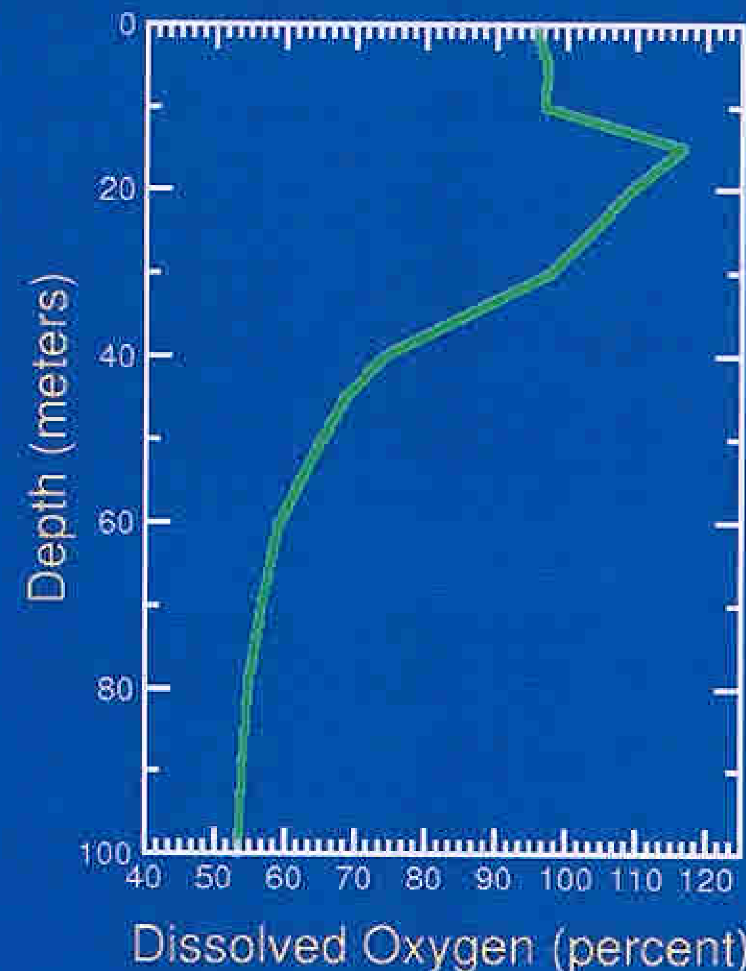




Yerington Pit Lake
Dissolved Oxygen vs. Depth
Depth (ft)
0
10
20
30
40
50
60
70
80
90
100
30
40
50
60
70
80
90
100
110
120
130
Dissolved Oxygen (percent)
Feb
Apr
Aug
Nov

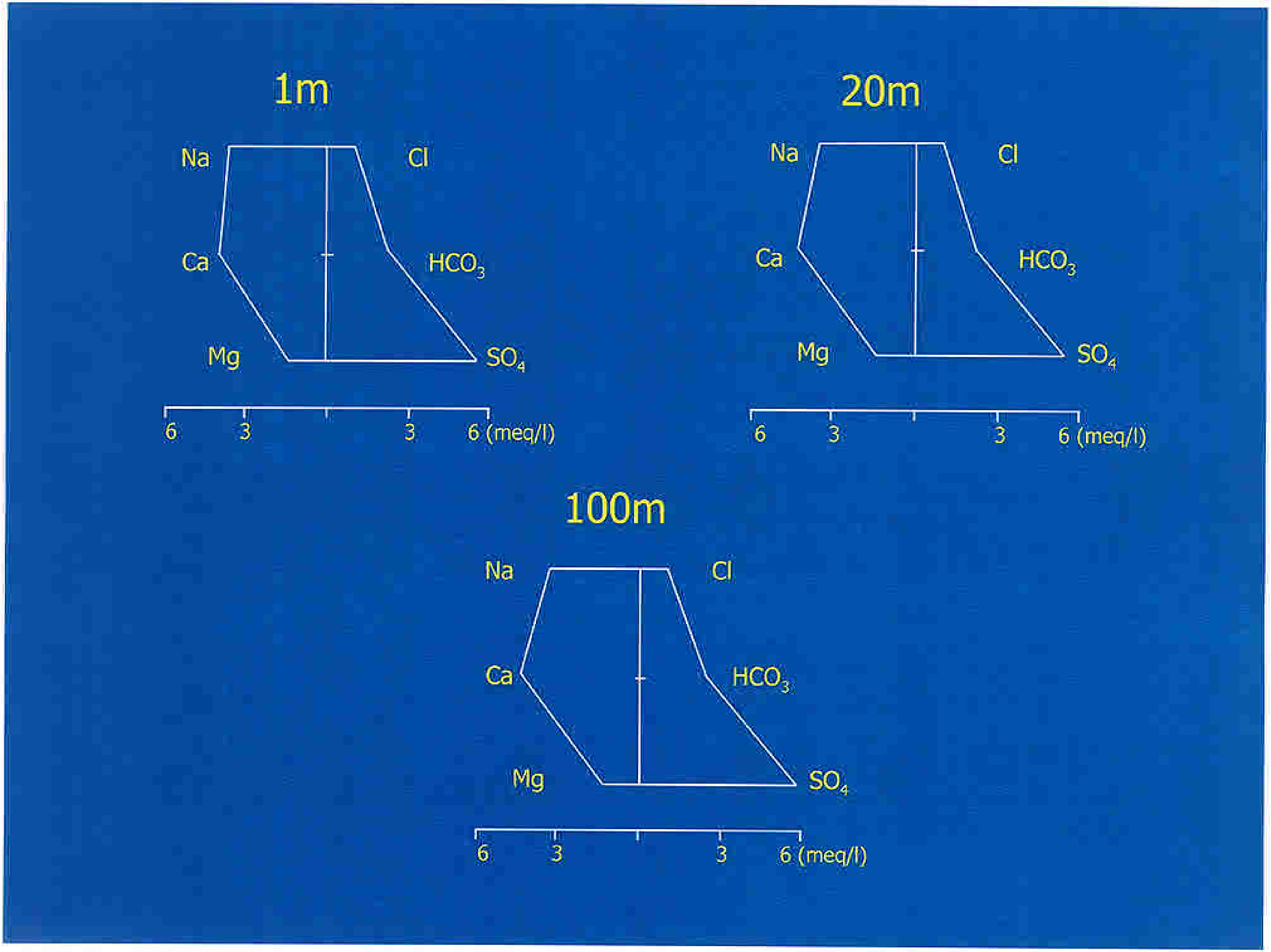
Yerington Pit Lake
August 2000

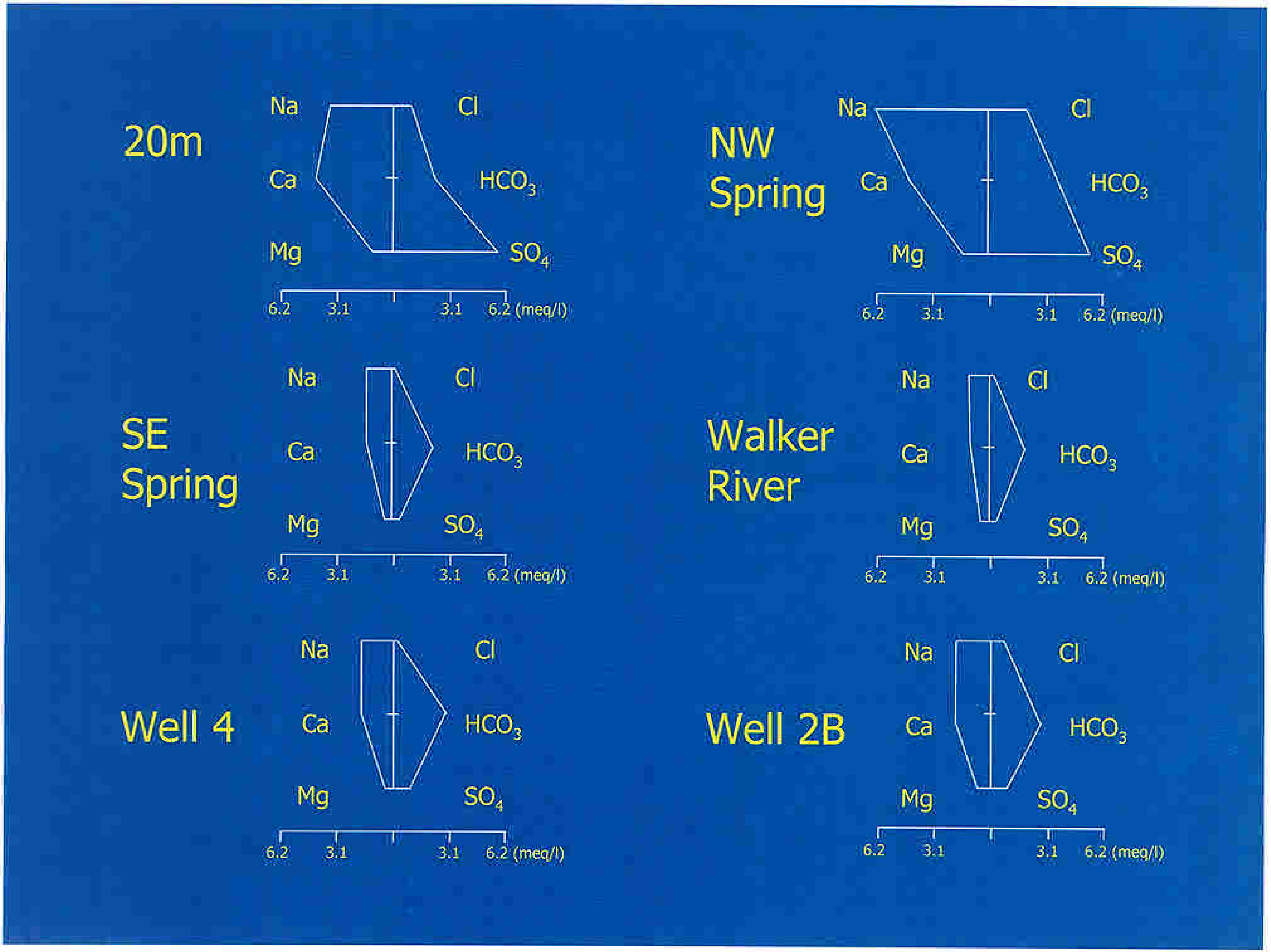


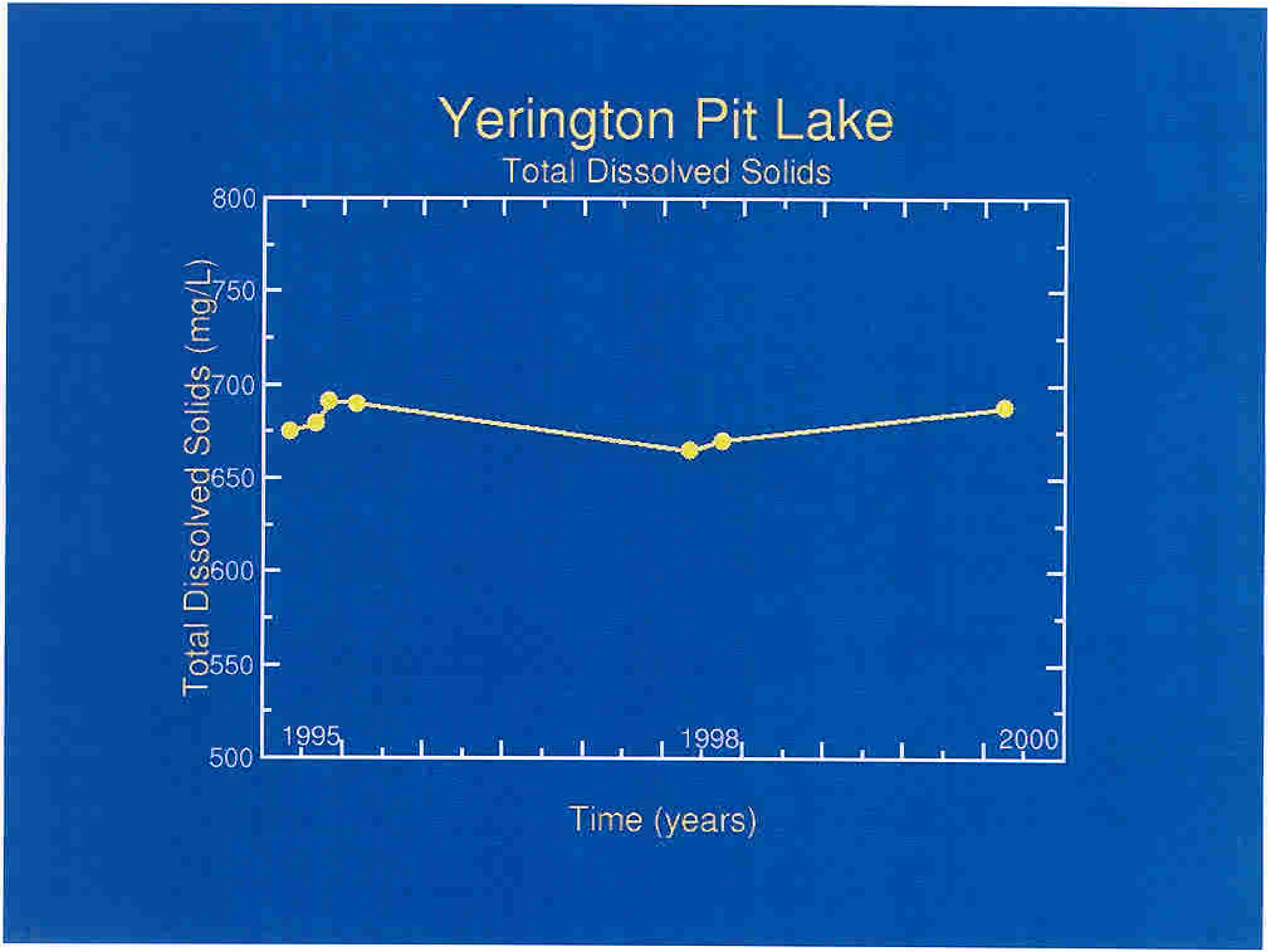


Pit Lake Chemistry

- pH 7.8 to 8.2
- SO_4^{2-} 260 to 280 mg/L
- Cu 7.5 to 158 µg/L
- Se 110 to 130 µg/L
- As 2 to 7 µg/L

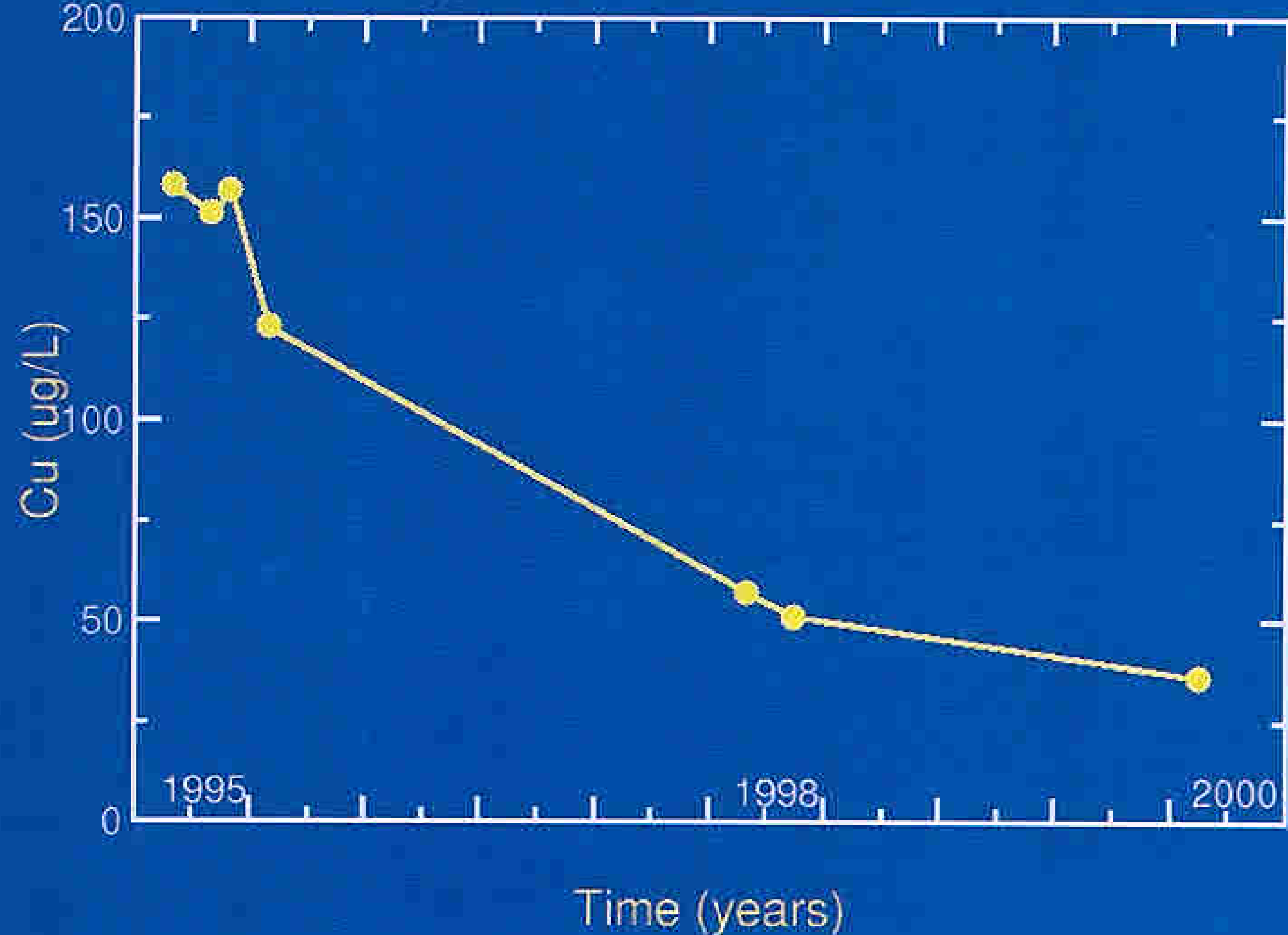

1m
Na
Cl
Ca
HCO3
Mg
SO4
6
3
3
6 (meq/l)
20m
Na
Cl
Ca
HCO3
Mg
SO4
6
3
3
6 (meq/l)
100m
Na
Cl
Ca
HCO3
Mg
SO4
6
3
3
6 (meq/l)


20m
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)
NW Spring
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)
SE Spring
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)
Walker River
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)
Well 4
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)
Well 2B
Na
Cl
Ca
HCO3
Mg
SO4
6.2
3.1
3.1
6.2 (meq/l)


Yerington Pit Lake
Total Dissolved Solids
Total Dissolved Solids (mg/L)
800
750
700
650
600
550
500
1995
1998
2000
Time (years)

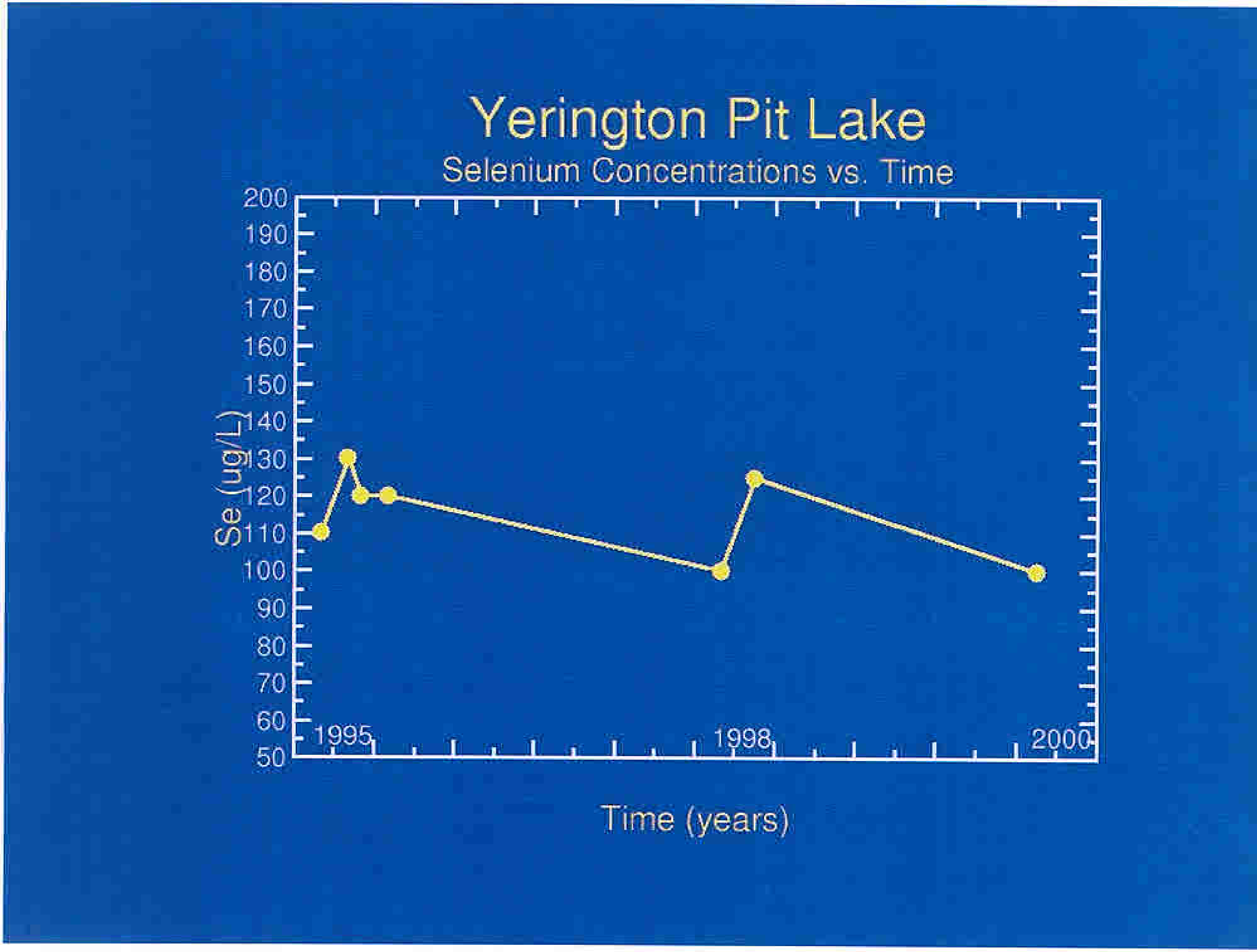
Yerington Pit Lake

Copper Concentrations vs. Time



Cu and Total Organic Carbon in Sediments

Depth (m)	TOC (mg/kg)	Cu (mg/kg)
15	11,000	52,000
37	147,000	119,000
100	80	25,000


Yerington Pit Lake
Selenium Concentrations vs. Time
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
Se (ug/L)
1995
1998
2000
Time (years)

Summary

- 40 years to fill pit to pre-mine water level
- Majority of inflow from deep groundwater
- Limnology typical of other northern Nevada lakes, turns over annually
- Good water quality, TDS 650 mg/L, pH 8.3
- Copper concentrations decreasing with time
- Selenium concentrations are high: 100 μg/L

Predicting the steady-state water quality of pit lakes

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Preprint 98-020, presented at the SME Annual Meeting, March 9-11, 1998, Orlando, FL. Manuscript accepted for publication December 1998. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME prior to Jan. 31, 2000.

Abstract

A simple method for estimating the steady-state water quality of a pit lake is presented. The steady-state concentration of a conservative chemical constituent in a pit lake is shown to be a simple function of the inflow rate, the evaporation rate and the inflow concentration. An analytical method is presented for estimating the equilibrium ground water-inflow rate for use in water-quality predictions. The time required to reach chemical steady state is estimated using an iterative mass-balance model. Mine operators should find the methodology useful for planning and screening regulatory applications where conservative estimates of pit-lake water quality are desirable.

Introduction

In recent years, the prediction of pit-lake water quality has become an increasingly sophisticated task, which is often accomplished by coupling complex numerical models of lake hydrology, geochemistry and limnology. In many practical situations, however, such aggressive (and costly) modeling efforts may not be necessary or desirable. Conservative estimates of pit water quality can be developed using simple analytical methods that are appropriate for many practical applications that require predictions to provide an adequate margin of safety. This paper presents a simple equilibrium-based methodology that can be used to develop conservative estimates of pit-lake water quality.

Steady-state pit water quality

In general, the concentration of a conservative chemical constituent in a pit lake will increase gradually until chemical steady state is approximated. This situation is illustrated in Fig. 1.

During the early stages of pit recovery, pit inflow components are at a maximum (primarily ground water inflow) and evaporation is at a minimum (minimal lake surface area), and the pit water composition closely reflects the inflow composition (Segment A in Fig. 1). As pit filling continues, the inflow gradually decreases and evaporation increases, resulting in a gradual concentration of pit-lake constituents (Segment B in Fig. 1). Finally, upon completion of pit filling and achievement of flow equilibrium, the inflow components are at a minimum and evaporation rates are at a maximum. Pit-lake water quality becomes gradually poorer until, at some point, chemical steady state is achieved and pit water quality remains constant (Segment C in Fig. 1).

In arid regions, it is not uncommon to encounter pit lakes with high evaporation rates and relatively low ground water-inflow rates. Under these conditions, pit inflow may equal the evaporation rate upon pit recovery, with no net ground water or surface-water outflow. The water quality of this type of "closed pit" will continue to become poorer (Segment D in Fig. 1), compared to the water quality of a pit that has some degree of outflow.

The shape and slope of the transient portion of the concentration profile presented in Fig. 1 can vary considerably, depending on the relative degree of reactivity (i.e., oxidation and chemical leaching) of the pit wall rocks. The profile illustrated in Fig. 1 is representative of a pit possessing nonreactive pit wall rocks.

Steady-state mass balance. In its simplest form, the steady-state mass-balance equation for a conservative chemical constituent can be written as:

$$Q_{in}C_{in} = Q_{out}C_{out} \qquad (1)$$

where,

Q_{in} is the equilibrium pit inflow rate,

Q_{out} is the equilibrium pit outflow rate,

C_{in} is the inflow concentration and

C_{out} is the outflow concentration.

The outflow components on the right-hand side of Eq. (1) can be expanded as:

$$Q_{out}C_{out} = Q_{evt}C_{evt} + Q_{gsout}C_{gsout} \qquad (2)$$

where,

Q_{evt} is the evaporation rate,

C_{evt} is the evaporative concentration,

Q_{gsout} is the combined ground

water/surface-water outflow rate and,

C_{gsout} is the combined ground water/surface-water outflow concentration (ground water and surface-water outflow concentrations are assumed to be equal under fully mixed conditions).

Because C_{evt} is zero, Eq. (2) can be reduced to

$$Q_{out}C_{out} = Q_{gsout}C_{gsout} \quad (3)$$

The steady-state flow balance is

$$Q_{gsout} = Q_{in} - Q_{evt} \quad (4)$$

Further, the pit lake concentration (C_{pit}) is equal to the ground water/surface-water outflow concentration at steady-state or

$$C_{pit} = C_{gsout} \quad (5)$$

Substitution of Eqs. (3), (4) and (5) into Eq. (1) and rearranging gives the following expression for steady-state concentration

$$\frac{C_{pit}}{C_{in}} = \frac{Q_{in}}{Q_{in} - Q_{evt}} \quad (6)$$

where,

Q_{in} represents the flow-weighted average concentration of all inflow components or

$$C_{in} = \frac{Q_{gwin}C_{gwin} + Q_{swin}C_{swin} + Q_{run}C_{run} + Q_{precip}C_{precip}}{Q_{in}} \quad (7)$$

where,

the subscripts *win*, *swin*, *run* and *precip* represent ground water, surface-water, runoff and direct precipitation flows and concentrations, respectively; and

Q_{in} represents the total pit-inflow rate or the sum of the four pit inflow components.

Equation (6) simply states that the steady-state concentration is dependent only on the inflow concentration, inflow rate and evaporation rate. Further, the relative concentration (ratio of pit concentration to inflow concentration) is a function of only the inflow and evaporation rates. Equation (6) also indicates that the concentration of a constituent will increase without limit as Q_{gsout} approaches zero (i.e., a closed pit or sink) or when evaporation exactly equals inflow (in practice, the concentration would increase until chemical saturation and precipitation occurs, and the dissolved concentration would then remain constant).

Time required to reach chemical steady state. Upon achieving flow equilibrium (complete filling), a significant period of time will pass before steady-state water quality is approximated. A measure of the time required to reach chemical steady state is needed to improve the utility of water-quality calculations.

The time-dependent, or transient form, of the chemical mass-balance equation is a function of pit lake volume, as well as inflow and evaporation rates. An iterative mass-balance model (PITEQ) was used to determine the time required to reach an approximate chemical steady state over a range of equilibrium flow conditions.

Figure 2 illustrates the time required to reach approximate chemical steady state (95% of the computed steady-state concentration), given various equilibrium inflow and evaporation rates as a function of pit volume. Figure 2 illustrates what is intuitively suspected — the larger the pit lake, the longer it takes to reach chemical steady state.

Equation (6) can be used in conjunction with Fig. 2 to develop an estimate of the steady-state pit water quality and an estimate of the time required to reach equilibrium given the inflow rate, inflow concentration, evaporation rate and pit-lake volume. The following sections describe simple methods that can be used to develop estimates of equilibrium flow rates for use in the water-quality calculations.

Equilibrium pit inflow rates

The equilibrium pit inflow rate is the sum of the four component inflow rates representing ground water, surface-water, runoff and direct precipitation. Methods for estimating each of the component inflows are described in the following sections.

Ground water inflow. Groundwater inflow is typically much greater than other inflow components and, therefore, has the most significant influence on pit water quality. Ground water inflow to a pit or excavation consists of two components: 1) the inflow due to the drawdown of the potentiometric surface caused by dewatering and net evaporation and 2) the passive inflow resulting from an initially sloping potentiometric surface. Upon pit filling and achievement of flow equilibrium, the effects of aquifer dewatering are negligible and passive ground water inflow is dominant. Previous investigators have estimated ground water-inflow rates to open pits and excavations using equations derived from well hydraulics (i.e., Hanna et al., 1992; Vanersluis et al., 1995). A limitation of these and similar methods is the inherent assumption that the potentiometric surface is initially flat (i.e., inflow is zero upon equilibrium recovery). Methods that do not account for passive ground water inflow will underestimate the flux of ground water at equilibrium, often leading to overly pessimistic predic-

FIGURE 1

Evolution of water quality in a typical pit lake.

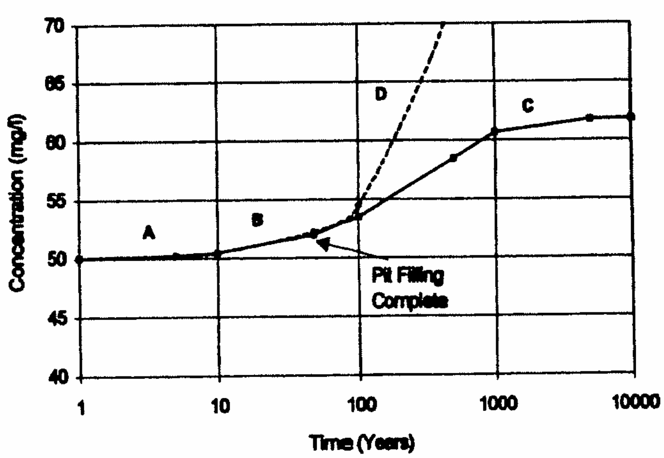
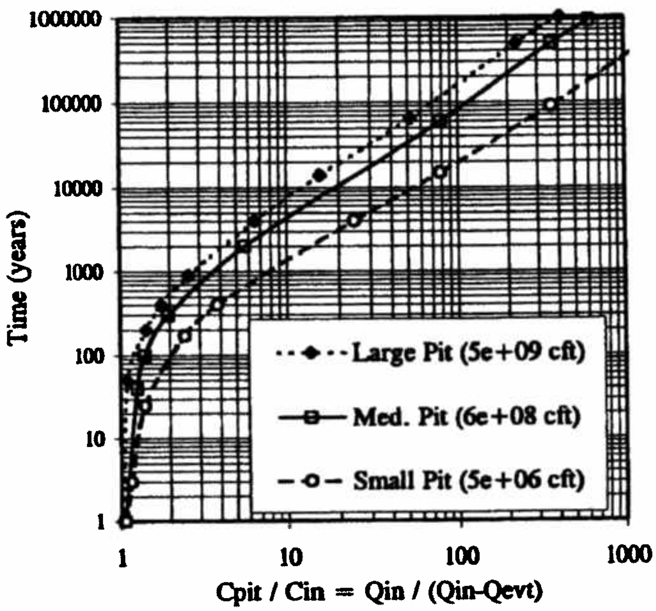


FIGURE 2

Time required to reach chemical steady state (C_{ss}) for various pit volumes, inflow and evaporation rates.



tions of pit water quality.

Passive inflow to a conductive cylinder: In a uniform flow field, the passive groundwater inflow (and outflow) through a fully penetrating cylinder in a homogeneous aquifer can be expressed as a form of Darcy's Law

$$Q_{gwin} = 2KbIr \qquad (8)$$

where,
K is the aquifer hydraulic conductivity,
b is the aquifer thickness,
I is the regional hydraulic gradient and
r is the radius of the cylinder.

This situation is illustrated in Fig. 3(a).

Open structures such as pits, wells and excavations are features of extremely large conductivity providing essentially no resistance to flow. The presence of these features strictly violates the assumption of a homogeneous aquifer on which Eq. (8) is based. The passive inflow to an infinitely conductive cylinder has been determined analytically by previous investigators, including Halevy et al. (1967), Drost et al. (1968) and Strack (1989). The resulting expression for this inflow is

$$Q_{gwin} = 4KbIr \qquad (9)$$

A comparison of Eq. (8) and (9) leads to the simple conclusion that inflow to the infinitely conductive cylinder is twice that of the homogeneous inflow at steady state (Fig. 3(b)). It is evident from an examination of Fig. 3 that inflow to the conductive cylinder is increased due to a doubling of the area (width) of inflow relative to the homogeneous solution. The magnitude of this inflow can usually be neglected for most applications involving small-scale features, including wells and boreholes. However, for large-scale features, including open pits, excavations and lakes, the inflow can be significant and plays an important role in the evolution of pit water quality.

The relationship expressed in Eq. (9) is exact in the case of confined aquifers and is approximate in the case of unconfined aquifers, where the saturated thickness is approximately uniform. The assumption of uniform saturated thickness is usually appropriate for estimating passive inflow when aquifer recovery (filling) is nearly complete.

Passive inflow to an ideal pit (truncated cone): Equation (9) provides insight into the effect of a conductive heterogeneity on ground water flow, but is limited in its applicability to cylindrically shaped structures. An equation can be derived for a more pit-like geometry, such as a truncated cone. This situation is illustrated in Fig. 4.

A first approximation for equilibrium inflow to a pit can be derived using similar logic as that used to derive flow to a cylinder. From Darcy's Law, the homogeneous inflow through a truncated cone can be determined using a trapezoid as the cross-sectional area for inflow (Fig. 4). Doubling the cross-sectional area (width) of inflow to account for the conductive heterogeneity leads to the expression

$$Q_{gwin} = 2KbI(r_b + r_p) \qquad (10)$$

where,
r_b is the radius of the pit base and
r_p is the radius of the pit lake surface.

It is important to note that Eq. (10) is a two-dimensional approximation that assumes flow is horizontal. In actuality, the sloping nature of the pit wall requires upward vertical-flow components upon pit recovery (the pit wall is an equipotential surface). As illustrated in Fig. 4, the upward vertical flow paths are shorter than the horizontal flow paths, resulting in an increase in the local hydraulic gradient. As a result, Eq. (4) should underestimate the groundwater inflow (and outflow) rate.

The additional inflow produced by upward vertical flow is proportional to the decreased length of the flow path (increased gradient). Therefore, the additional inflow resulting from vertical flow can be estimated by comparing the relative lengths of the horizontal and vertical flow paths. From Fig. 4, the horizontal length of flow is related to the vertical length of flow by the following approximation equation

$$\frac{r_p - r_b}{L} = \frac{1}{\cos\beta} \qquad (11)$$

where b is the complement of the pit slope angle (f).

The cosine term in Eq. (11) can be considered a vertical correction factor to the flow gradient (I). It follows from this relationship and Eq. (10) that the corrected inflow is

$$Q_{gwin} \cong \frac{2KbI(r_b + r_p)}{\cos\beta} \qquad (12)$$

The resulting expression is referred to as the "passive pit inflow equation." This equation was tested against a three-dimensional numerical flow model solution with nearly identical results.

Ground water inflow to irregular pits: The methodology presented for estimation of inflow to pits of simple geometry can be expanded to include pits of irregular geometry. Previously developed expressions for pit inflows were simplified as a result of pit symmetry. For irregularly shaped pits, estimates of pit inflow can be developed by summing the inflow to a representative number of horizontal "slices" through the pit using a computer program employing the analytic-element method, i.e., TWODAN (Fists, 1995).

Computer programs that employ the analytic-element method allow heterogeneities of irregular shapes to be simulated, and the effects of pumping, evaporation and recharge (i.e., runoff or other inflows) can be assessed simultaneously. The computed groundwater inflow can be corrected using Eq. (11) to account for vertical flow components, if so desired. Although this method involves slightly more effort than a simple calculation, the method provides a cost-effective alternative to more involved numerical flow modeling for estimation of pit inflow rates.

Equilibrium pit-lake elevation: For many years, ground water practitioners have used analytical solutions derived from well hydraulics to estimate the inflow to an open pit or excavation at various stages of pit dewatering or recovery.

Steady-state solutions are most commonly derived from a form of the Dupuit equation (for unconfined aquifers)

$$Q = \frac{\pi K b \left(H^2 - h^2\right)^2}{ln\left(\frac{R}{r_p}\right)} \qquad (13)$$

where,
H is the premining potentiometric surface elevation,
h is the potentiometric surface elevation at the desired level,
R is the radius of influence and
r_p is the radius of the pit lake at the desired level.

The radius of influence can be estimated from the following expression (Dobranzanski, 1956)

$$R = 575s(HK)^{1/2} \qquad (14)$$

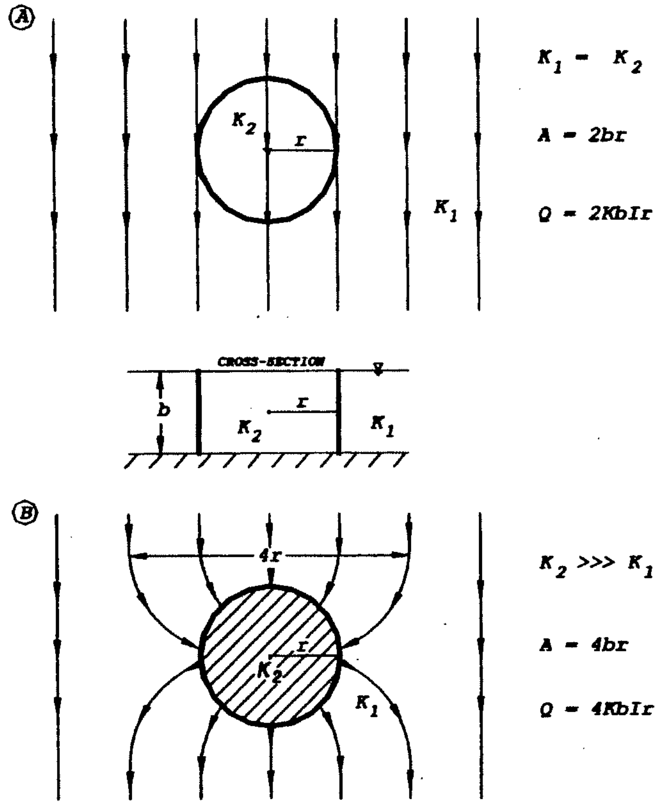
where,
s is the drawdown and
all length units are in meters and all time units are in seconds.

Transient solutions, often based upon large-diameter well theory, have also been applied to pit-filling problems (i.e., Naugel and Atkinson, 1992). These and similar equations can be used to estimate ground water-inflow rates at various stages of pit recovery or dewatering or to estimate the equilibrium elevation of the pit-lake surface. The equilibrium pit-lake elevation can be estimated using the aforementioned equations and solving for drawdown given a known net evaporation (pumping) rate and premining potentiometric surface elevation.

Inflow by surface-water, runoff and direct precipitation. In general, surface-water inflow and pit-slope runoff are small compared to the inflow of groundwater. In some cases, however, these secondary flows can be a significant source of chemical loading due to the oxidation and leaching of constituents from the pit wall rocks. For these reasons, surface-water inflows and runoff are an important consideration of any model of pit-lake filling and chemistry.

FIGURE 3

Passive flow (A) through a cylinder in a homogenous aquifer and (B) through a highly conductive cylinder.



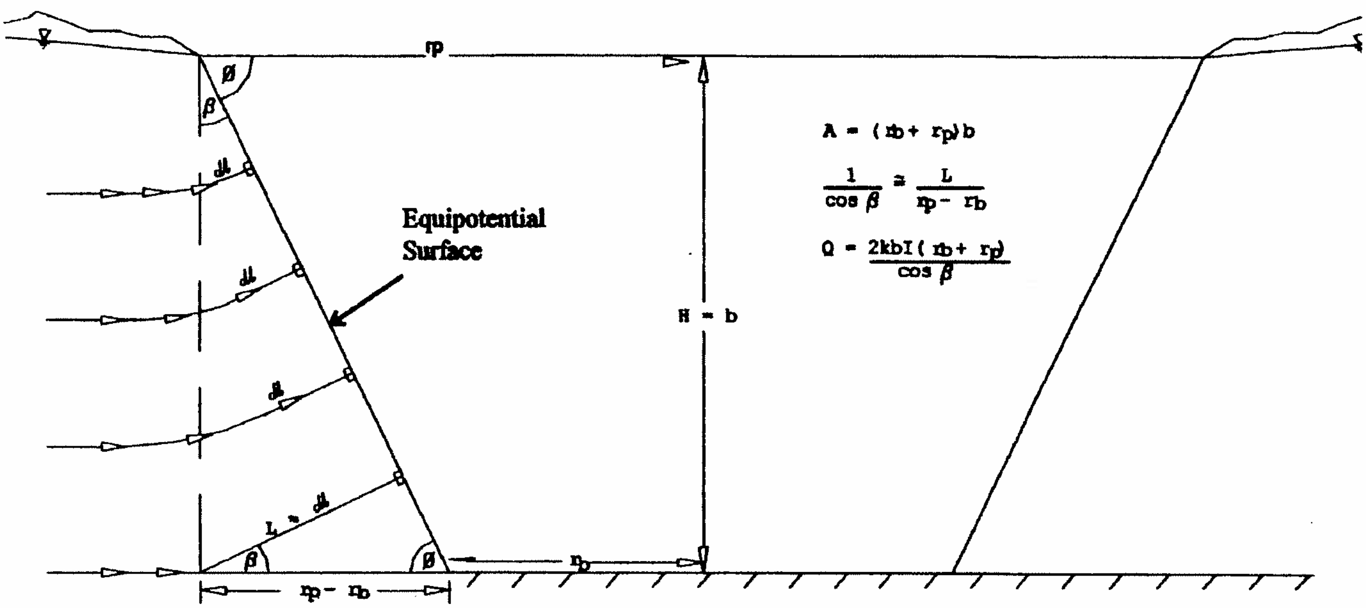
Runoff is overland flow of excess precipitation from the steep slopes of the pit highwall and surrounding pit catchment area. For pit water-quality problems, runoff is often treated as the sum of two components: the runoff from the pit highwall, which often contains elevated concentrations of metals due to oxidation and leaching of constituents from the pit wall rocks, and the runoff from the remaining pit catchment area, which generally contains lower concentrations of dissolved constituents. Commonly employed "rules-of-thumb" assume that runoff from the pit highwall is 50% to 100% of direct precipitation, while runoff from the remaining pit catchment area is 10% to 20% of direct precipitation. If desired, more sophisticated computer programs could be used to develop more reliable estimates of runoff.

Estimates of surface-water inflow and direct precipitation can be developed by direct measurement or otherwise estimated from regional flow data, reclamation plans, permit applications or surface-water flow models.

The proportion of surface-water, runoff and direct precipitation inflow will vary seasonally and as pit recovery progresses. For purposes of this paper, estimates of steady-state water quality should be derived using average annual component inflows upon pit recovery.

FIGURE 4

Cross-section illustrating ground water flow through an ideal pit (truncated cone).



Pit outflow

Pit outflow components include lake surface evaporation, ground water outflow and surface-water outflow. Volumetric evaporation rates can be estimated with a good deal of accuracy from published regional or site-specific pan-evaporation rates and from estimates of the reservoir surface area. The combined ground water/surface-water outflow rate is computed as the difference of all other previously estimated inflow and outflow components (Q_{gout} in Eq. (4)). The quality of surface-water and ground water outflow is assumed to be equal under fully mixed conditions.

In arid regions, it is not unusual to encounter pit lakes with high evaporation rates and relatively low ground water-inflow rates due to the low transmissivity of aquifer materials. In these situations, the sum of pit inflow components may equal the evaporation rate at some point during pit recovery, with no ground water or surface-water outflow from the pit (Q_{gout}). As predicted by Eq. (6), the water quality of this type of closed pit or sink will gradually increase without limit, until chemical saturation and precipitation occurs, at which time the dissolved concentration will remain constant for practical purposes. It is not uncommon for pit lakes in arid regions to act as sinks during the summer months (when evaporation is at a maximum) and to act as water sources during the wetter seasons. Steady-state (or long-term average) water-quality estimates for pit lakes possessing extreme seasonal flow variations should be developed using rates representative of average annual conditions.

A prudent first step of any pit-lake modeling effort should be to determine whether a pit lake will possess net outflow or whether the lake will be a sink and subject to the negative effects of evapoconcentration. Equations for estimating equilibrium pit inflow presented in this paper are ideally suited for this purpose and are amenable to sensitivity analysis over the range of anticipated inflow and evaporation rates.

Conclusions

A simple, equilibrium-based methodology is presented to aid mine planners and operators in predicting the ultimate water quality of pit lakes. Original equations have been developed for estimating the passive ground water-inflow rate to an open pit or excavation. The method also considers the time required to reach chemical steady state given the pit-lake volume, inflow and evaporation rate. The method is amenable to sensitivity analysis, allowing the uncertainty of water-quality predictions to be assessed in a simple and cost-effective manner. ■

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