Dames & Moore Job No. 8837-102-06
Salt Lake City, Utah
September 8, 1980

HYDROLOGIC EVALUATION
PIT 5 LAKE RECLAMATION
HIGHLAND URANIUM MINE
CONVERSE COUNTY, WYOMING
FOR EXXON MINERALS COMPANY, U.S.A.

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Exxon Minerals Company, U.S.A.
P. O. Box 3020
Casper, Wyoming 82602

Attention: Mr. Donald E. Moe

Gentlemen:

Transmitted herewith are ten copies of our report, "Hydrologic Evaluation, Pit 5 Lake Reclamation, Highland Uranium Mine, Converse County, Wyoming, for Exxon Minerals Company, U.S.A."

This work was authorized by Exxon Contract For Feasibility and Technical Studies No. 11563, dated May 14, 1980.

We appreciate the opportunity to work with you on this project. Please contact us with questions or comments on the report.

Yours very truly,

DAMES & MOORE

A. D. Pernichele
Partner

ADP:11

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INTRODUCTION

This report presents the results of our evaluation of hydrologic conditions which will occur as a result of not backfilling Pit 5 at the end of operations at the Highland surface operations. The Exxon Highland mine and mill are located in Converse County, Wyoming as shown on Plate 1, Location Map. Open pit mining operations began in 1970 and are currently scheduled to end in 1987.

Mining began in the SE 1/4 of Section 28 Range 72 W Township 36 N and has progressed in a northwesterly direction, and will eventually finish near the center of Section 20 as shown on Plate 2, Final Reclamation Plan. As part of the final reclamation plan, the last pit, Pit 5, will be left open and allowed to fill with ground water and surface runoff to form a lake.

PURPOSE AND SCOPE

The purpose of this study was to assess the hydrologic conditions which will exist in the depression left by Pit 5 following reclamation. Specific objectives of the study were to evaluate:

1. The source of water, both surface and subsurface, and the expected quantities and qualities.
2. The quality of water in the lake after equilibrium is reached, with emphasis on salinity and radionuclide concentrations.

3. The water outflow, both evaporation and subsurface flows, and effects on ground water quality in the vicinity.
4. The expected shoreline elevation.
5. Recommended end use of lake.

The scope of our studies has included the evaluation of available geologic, climatologic, and hydrologic data applicable to the site region; evaluation of the surface water balance and quality for the Pit 5 lake; computer modeling of ground water flows to the lake; evaluation of ground water quality data for the site area; assessment of the resulting water quality conditions in the Pit 5 lake using a mass balance approach; and preparation of this summary report.

RECLAMATION PLAN

The open pit mine is progressively backfilled during operations. At the end of mining, a small part of the pit, the Pit 5 lake area, will not be completely backfilled, as shown on Plate 2, Final Reclamation Plan. The pit will be about 400 feet deep. The northern half of Pit 5 will be left at the original mined slope and will be relatively undisturbed natural rock. The southeastern wall of the reclaimed pit will be backfill composed of mixed overburden. The bottom of the pit will be at an approximate elevation of 4,910 feet. The estimated pre-mining water table elevation lies between 5,200 and 5,225 feet.

Riprapped channels will be constructed on the pit sideslopes to convey runoff from the major drainages into the lake. Riprapped channel locations are shown on Plate 2.

SITE CONDITIONS

TOPOGRAPHY

The topography surrounding the site is characterized by gently rolling upland areas and broad stream valleys that are dissected by numerous draws with relatively steep slopes and rounded ridge crests (see Plate 6). Headward erosion of streams since late Tertiary time has resulted in the present-day pattern of uplands and dissected stream valleys. The Highland Flats, an upland area, is a remnant of the Tertiary erosional/depositional surface (Hagmaier, 1971). Shallow depressions provide natural impoundments for surface water in upland areas such as Highland Flats.

The principal drainage of the site area is North Fork Box Creek, an intermittent stream which drains easterly into the Lightning-Lance Creek system eventually reaching the Cheyenne River.

Elevations range from a maximum of approximately 5,700 feet in the Highland Flats area 8 miles west of the site to 5,000 feet on the North Fork Box Creek approximately 2 miles east of the site.

GENERAL GEOLOGY

STRUCTURE

The Exxon uranium mine is located near the southern margin of the Powder River structural basin of northeast Wyoming. The basin is expressed as both a topographic and structural low, bounded on three sides by structural highs. The basin is flanked on the east by the Black Hills Uplift, on the west by the Bighorn Mountains and on the south by the Laramie Mountains and Hartville Uplift.

The basin morphology can be described as an asymetric syncline which gradually opens and broadens to the north-northwest. The axis of the basin trends N.30°W. Measured dips on the Wasatch Formation in the central portion of the basin range from less than one degree to two and one-half degrees. At the margin of the basin, dips steepen to as much as 20 degrees. Dips are usually low to the north and east and reach maximums at the south and southwest fringes of the basin.

STRATIGRAPHY

The Fort Union and Wasatch Formations are the principal units of interest to this study contained in the Powder River Basin. These units are Tertiary continental deposits of semi-consolidated sandstones, siltstones, claystones and coal.

The Paleocene Fort Union Formation reaches a maximum thickness of approximately 3,500 feet and generally is in the range of 2,200 to 2,500 feet when not eroded.

The Wasatch Formation, of early Eocene age, overlies the Fort Union Formation and occupies the central portion of the Powder River Basin. The Wasatch Formation is generally between 1,000 and 3,000 feet thick when not eroded and contains lenses of coarse, crossbedded, arkosic sandstone.

Deeper formations and other aspects of the regional geology are discussed by Hagmaier (1971) and Hodson, et al (1973).

SITE GEOLOGY

STRUCTURE

The Fort Union and Wasatch Formations are essentially horizontal in the site vicinity with slight dips (1° or less) to the northwest toward the basin center. No faulting or evidence of faulting has been detected in the area, either by surface studies or drilling.

STRATIGRAPHY

The site is underlain by interlayered sandstone, siltstone and claystones of the Wasatch and Fort Union Formations. Plate 3 presents a stratigraphic column for the site vicinity.

The uppermost sandstone is referred to as the tailings dam sandstone and is about 50 feet thick. The top of the stratum lies at about elevation 5,180 feet. This sandstone is underlain by a shale, referred to as the tailings dam shale, which is about 40 feet thick.

The ore zone, referred to as the Highland sandstone member, underlies the tailings dam shale and typically consists of three sandstone strata separated by shale. The sandstone strata are typically 30 to 50 feet thick. The shales which separate the sandstone are generally 20 to 40 feet thick and are relatively continuous. Mining generally ends at or near the base of the Highland sandstone above a shale layer at elevation 4,900 to 5,000 feet. Plate 4 displays stratigraphic cross sections with individual sandstone and claystone beds interpreted from drilling data by Exxon personnel.

Plate 5 displays an isopach map of sandstone beds within and above the Highland sandstone but below the original water table. The isopach map overlies the Highland Uranium Operations base map. The cross sections and information used in constituting the isopach map were obtained from an environmental report prepared by Exxon (1977).

GROUND WATER

REGIONAL

A relatively detailed study of the regional ground water regime and its significance to deposition of economically recoverable quantities of uranium is presented in an unpublished Ph.D. thesis (Hagmaier, 1971). Portions of the thesis which are particularly relevant to this study are:

1. A well inventory of the Powder River Basin. There are five wells listed within a five-mile radius of the Exxon site. The reported water levels in the wells should be indicative of pre-mining conditions.
2. Estimates of vertical and horizontal gradients and corresponding regional flow patterns. Near the site area, the Highland Flats area is interpreted as a major regional recharge area, while the North Platte and Dry Fork Cheyenne Rivers are considered major discharge areas.
3. Background ground water chemistry data.

Typical gradients for ground water flow in the Dry Fork Cheyenne River drainage basin, according to Hagmaier (1971) are 0.001 to 0.004 horizontally and 0.2 to 0.4 vertically. Horizontal flow quantities are much larger than vertical flow quantities, however, because of the very large horizontal to vertical permeability ratio which is on the order of 1,000 to 10,000.

Based on the above data presented in Hagmaier (1971), ground water potentials are at maximums in the Highland Flats and decrease in all directions away from Highland Flats. In addition, there is some vertical movement of ground water in the vicinity of the Highland Flats recharge area.

Ground water quality analyses presented in the thesis for shallow wells in the vicinity of Exxon indicate water of the calcium-sodium-sulfate-bicarbonate type with total dissolved solids in the range of 300 to 700 milligrams per liter (mg/l) and pH in the range of 7.5 to 8.5.

ESTIMATION OF PRE-MINING REGIONAL GRADIENTS

Estimated pre-mining ground water levels are displayed on Plate 6. The contours shown on Plate 6 indicate the top of the saturated zone. Data from which this map was constructed were obtained from the Hagmaier thesis well inventory, a Dames & Moore dewatering study performed for Exxon in 1971, a Dames & Moore dewatering study performed for United Nuclear Corporation in 1975, the existing topographic surface, and elevations of natural springs recorded on USGS 15-minute quadrangle maps.

It should be noted that the North Fork Box Creek shows as a perennial stream on the Highland Flats, Wyoming USGS quadrangle, as shown on Plate 6.

It should also be emphasized that the very limited data from which the pre-mining regional gradients were estimated put limitations on their accuracy. Contour intervals are presented in 100-foot increments and it is intended that this contour interval reflect the accuracy with which ground water levels can be determined from Plate 6.

Horizontal gradients interpreted from Plate 6 indicate a range of 0.01 to 0.006 which are somewhat higher than the general regional gradients cited by Hagmaier (1971). The higher gradients are likely due to the local influence of the Highland Flats recharge area. Pre-mining ground water flow directions in the vicinity of the existing pit are southeasterly to easterly.

GROUND WATER HYDRAULIC PARAMETERS

In order to model flow patterns quantitatively in the vicinity of Pit 5 it is necessary to estimate the following hydraulic parameters:

1. Horizontal hydraulic conductivity.
2. Estimated thicknesses of aquifer materials.
3. Porosity.

The above parameters are required for steady-state analysis. Transient analyses require, in addition to the above parameters, an evaluation of the storage coefficient and/or specific yield.

The thickness of aquifer materials has been discussed previously and is presented on Plate 5, along with the finite difference grid used in the model. The hydraulic conductivity values have been reported in several studies for Exxon and neighboring United Nuclear Corporation operations.

The specific sources of data are:

Type of Investigation	Location	By	Date	Average Permeability (ft/yr)
Dewatering	Pit 1	Dames & Moore	1971	2230
Dewatering	Pit 3	Golder & Assoc.	1979	560
Dewatering	North Morton Underground	Dames & Moore	1975	1060
Dewatering	South Morton Mine	Dames & Moore	1977	4600
Solution Mine Pilot	Pit 5	Exxon	1978	1030
Seepage from Buried Tailings	Morton Ranch	Battelle - Pacific NW Labs	1980	7760
Water Balance	Exxon Highland Mill	Dames & Moore	1978	1680
Average for all studies				2700

A summary listing of the previously obtained data is presented in Table 1.

It is our opinion that the average hydraulic conductivity obtained by averaging the results presented in the above listed studies is most likely on the low end of the range of values. The average contains values obtained from tests designed to give order of magnitude estimates of permeability such as air-lift capacity. In addition, coarse sand seams within the geologic section transmit a majority of the flow and may not have been intercepted in many of the tests.

We have selected a value of 1,000 feet per year (approximately 1 x 10^{-3} cm/sec) as a conservative estimate of sand permeability for our modeling purposes. This value should represent "worst case" conditions in the prediction of Pit 5 lake

TABLE 1

SUMMARY OF HYDRAULIC CONDUCTIVITY VALUES

Area	Type Test	Hydraulic Conductivity (cm/sec)	Source of Information
Pit 1	Pumping Tests		Dames & Moore (1971)
D&M T.W.		3.1×10^{-3}	
D&M 3A		5.2×10^{-3}	
D&M 5A		6.6×10^{-3}	
Dewatering #4		3.5×10^{-4}	
Dewatering #10		3.1×10^{-4}	
TW #1		2.9×10^{-4}	
TW #2		9.0×10^{-4}	
Pit 3	Pumping Tests		Golder & Assoc. (1979)
Well #1		4.0×10^{-4}	
Well #2		6.8×10^{-4}	
Solution Mine Pilot	Lab Permeability on Core		Exxon Minerals (1977)
1		9.7×10^{-4}	
2		7.5×10^{-4}	
3		1.2×10^{-3}	
4		7.4×10^{-4}	
5		6.8×10^{-4}	
6		1.2×10^{-3}	
Inj Well		1.2×10^{-3}	
A		5.3×10^{-4}	
B		9.8×10^{-4}	
C		1.1×10^{-3}	
D		8.7×10^{-4}	
E		8.0×10^{-4}	
F		1.1×10^{-3}	

TABLE 1 (Continued)
SUMMARY OF HYDRAULIC CONDUCTIVITY VALUES

Area	Type Test	Hydraulic Conductivity (cm/sec)	Source of Information
Solution Mine Pilot	Well Injection Tests		Exxon Minerals (1977)
Inj-1		8.7×10^{-4}	
Inj-2		1.1×10^{-3}	
Inj-3		8.7×10^{-4}	
Inj-4		1.2×10^{-3}	
Inj-5		1.5×10^{-3}	
Inj-6		1.2×10^{-3}	
North Morton Mine	Air Lift Pumping Tests		Dames & Moore (1975)
DM-1		4.6×10^{-4} - 1.6×10^{-3}	
DM-4		5.4×10^{-4} - 9.4×10^{-3}	
DM-5		6.7×10^{-4} - 4.3×10^{-3}	
DM-6		2.7×10^{-3} - 3.4×10^{-3}	
DM-8		4.0×10^{-4} - 1.6×10^{-3}	
DM-1A		1.9×10^{-3}	
DM-4A		2.3×10^{-4}	
DM-5A		-	
DM-8A		1.8×10^{-4}	
MX 2684A		-	
MX 2685A		-	
MX 2686A		-	
MX 2687A		-	
DM-1B		3.7×10^{-4}	
DM-4B		6.5×10^{-5}	
DM-5B		1.4×10^{-4}	
DM-6B		8.9×10^{-5}	

TABLE 1 (Continued)

SUMMARY OF HYDRAULIC CONDUCTIVITY VALUES

Area	Type Test	Hydraulic Conductivity (cm/sec)	Source of Information
MX 2684B		-	
MX 2685B		-	
MX 2686B		-	
MX 2687B		-	
DM-SP1		1.0×10^{-3}	
DM-SP2		-	
DM-1P		1.0×10^{-3}	
DM-2P		9.1×10^{-4}	
DM-3P		7.8×10^{-4}	
DM-4P		1.0×10^{-3}	
DM-5P		1.6×10^{-3}	
DM-5P2		1.6×10^{-3}	
DM-6P		7.6×10^{-4}	
DM-7P		9.5×10^{-4}	
DM-8P		9.1×10^{-4}	
DM-9P		4.2×10^{-4}	
MX 2684		-	
MX 2685		-	
MX 2686		-	
MX 2687		-	
South Morton Mine	Pumping Test		Dames & Moore (1977)
Water Well		2.8×10^{-3} - 6.1×10^{-3}	
South Morton Mine	Lab Permeability		Battelle (1980)
Tailings From Exxon Tailings Impoundment		2.2×10^{-4}	
Clay Liner-Exxon Tailings Impoundment		2.5×10^{-8}	
Overburden Morton Ranch Area		1.3×10^{-6}	
Sandstone Morton Ranch Area		7.5×10^{-3}	

elevations. Estimates of the lake surface elevation have also been made using a value of 2,000 feet per year ($2x10^{-3}$ cm/sec) for comparison purposes.

Porosity of the sands was estimated at 0.3 on the basis of test data from core samples (Exxon Minerals Co. U.S.A., 1977).

Although the storage coefficient is required only for transient analyses, the value is indicative of confined or unconfined conditions. Only one value of storage coefficient was reported from field testing data presented in Table 1. A storage coefficient value of 1×10^{-5} was obtained from pump test data during the 1971 dewatering investigation by Dames & Moore. This is representative of confined conditions.

Because of the large drawdowns in the vicinity of the current mining operations, unconfined conditions are present in many of the sand seams near the pit. For the purposes of steady state modeling, we have assumed that confined conditions are present in the aquifer. This does not result in significant error provided drawdown is small in comparison to the aquifer's saturated thickness.

GROUND WATER QUALITY

The quality of ground water in the vicinity of Pit 5 is generally good and of the calcium bicarbonate type. Table 2 presents water quality data for several selected wells in the area. Wells at sample locations #1 and #2 are located four miles

TABLE 2

GROUND WATER QUALITY DATA

Average Measured Concentration and Variation *

Sample Location And Name	U-Natural (pCi/l)	Ra-226 (pCi/l)	Th-230 (pCi/l)	Na (Mg/l)	Ca (Mg/l)	SO_4 (Mg/l)	Cl (Mg/l)	HCO_3 (Mg/l)	Total Dissolved Solids (Mg/l)
#1 Vollman Ranch-Yard Well	19.1±20.4/37	1.4 ± 1.9/37	2.8 ± 3.7/36	53±19/10	70±6/10	113±18/10	13±13/10	225±16/10	436±64/10
#2 Fowler Ranch Well	9.0±21.4/24	.75±.91/23	1.00±1.05/24	140±31/10	44±13/10	270±48/10	9±1/10	191±19/10	603±56/10
#9 TDM #A (West) Well	19 ±31/23	1.16±1.38/23	1.75±2.08/23	109±24/9	15±8/9	114±12/9	18±20/9	141±71/9	387±79/9
#44 UDG #15 Well	304±795/12	90±176/12	4.2 ± 7.9/7	54/1	43/1	81/1	4/1	207/1	297/1
#49 UDG #11 Well	9.1±11.8/14	2.4 ±1.2/15	1.14±.93/5	74±2/3	37±2/3	118±11/3	5±1/3	179±18/3	359±15/3
#51 UDG #21 Well	24.0±26.5/16	3.47±1.70/16	.84±1.03/7	47±3/3	58±2/3	107±18/3	6±2/3	212±14/3	381±37/3
#52 UDG #22 Well	11.2±18.7/14	1.26±1.37/14	.81±.88/5	83±9/3	29±9/3	127±13/3	5±1/3	165±6/3	361±35/3

* Key:

19.1 ± 20.4/37

Mean concentration ± standard deviation/number of measurements

Source of data: Exxon Minerals Co., U.S.A.

west and two miles northeast, respectively, of Pit 5 on Highland Flats. The remaining wells are located around the pit area as shown on Plate 6. In general, total dissolved solids range from 300 to 400 mg/l; chlorides range from 5 to 18 mg/l; and sulfates range from 80 to 270 mg/l. Radionuclides are generally below MPC and meet EPA drinking water standards except for radium -226 from the mine dewatering well UDG #15 (sample location #44). This well is probably drawing from a mineralized zone. Little information is available for trace constituents. Ground water quality standards are sumarized on Table 3.

SURFACE WATER

GENERAL

This section describes the surface water conditions applicable to the water balance for the Pit 5 lake at the Highland Mine. The undisturbed natural drainage area northwest of Pit 5 and the disturbed area to the south of the lake that would contribute runoff to the lake are considered. The undisturbed natural area consists of about 0.76 square miles, while the disturbed area consists of about 1.37 square miles, making a total drainage area of about 2.13 square miles (see Plate 7) at a lake elevation of 5,180 feet.

PRECIPITATION ESTIMATES

The average annual precipitation at Casper, Wyoming is 11.4 inches based on 36 years of records. The average snowfall

TABLE 3

WATER QUALITY STANDARDS
(In Mg/L Except as Noted)

Species	EPA Drinking Water Standards			WY DEQ PROPOSED GROUND WATER STANDARDS			U.S. NRC MPC (Unrestricted) (Areas)
	Primary	Secondary	Livestock	Domestic	Agricultural	Livestock	
Aluminum (Al)	-	-	5.0	-	5.0	5.0	-
Ammonia (NH_3)	-	-	-	0.5	-	-	-
Arsenic (As)	0.05	-	0.2	0.05	0.1	0.2	-
Barium (Ba)	1.0	-	-	1.0	-	-	-
Beryllium (Be)	-	-	-	-	0.1	-	-
Boron (B)	-	1.0	5.0	0.75	0.75	5.0	-
Cadmium (Cd)	0.01	-	0.05	0.01	0.01	0.05	-
Chromium (Cr)	0.05	-	1.0	0.05	0.10	0.05	-
Cobalt (Co)	-	-	-	-	0.05	1.0	-
Copper (Cu)	-	1.0	0.5	1.0	0.20	0.50	-
Cyanide (CN)	0.05	-	-	0.2	-	-	-
Fluoride (F)	1.4-2.4	-	2.0	1.4-2.4	-	-	-
Hydrogen Sulfide (H_2S	-	-	-	0.05	-	-	-
Lithium (Li)	-	-	-	-	2.5	-	-
Lead (Pb)	0.05	-	0.1	0.05	5.0	0.10	-
Mercury (Hg)	0.002	-	0.01	0.002	-	-	-
Molybdenum (Mo)	-	-	-	-	-	-	-
Nickel (Ni)	-	-	-	-	0.2	-	-
Nitrate (as N)	10.0	-	-	10.1	-	-	-
Nitrate (as N)	-	-	-	1.0	-	10.1	-
Selenium (Se)	0.01	-	0.05	0.01	0.02	0.05	-
Silver (Ag)	0.05	-	-	0.05	-	-	-
Vanadium (V)	-	-	-	-	0.1	0.1	-
Zinc (Zn)	-	5.0	25.0	5.0	2.0	25.0	-
Chloride (Cl)	-	250.0	2000.0	250.0	100.0	2000.0	-
Iron (Fe)	-	0.3	-	0.3	5.0	-	-
Manganese (Mn)	-	0.05	-	0.05	0.2	-	-
Ph	-	6.5-8.5	-	6.5-8.5	4.5-9.0	6.5-8.5	-
Sulfate (SO_4)	-	250.0	3000.0	250.0	200.0	3000.0	-
TDS	-	500.0	-	500.0	2000.0	5000.0	-
Uranium (U)	-	-	-	5.0 mg/l	5.0 mg/l	5.0 mg/l	30,000
Ra-226, 228	5.0 pCi/l	-	-	5.0 pCi/l	5.0 pCi/l	5.0 pCi/l	30.0 pCi/l
Gross α	15.0 pCi/l	-	-	15.0 pCi/l	15.0 pCi/l	15.0 pCi/l	-
Thorium-230	-	-	-	-	-	-	2000.0 pCi/l
Gross β	30.0 pCi/l	-	-	-	-	-	-

contributing to precipitation is about 50 to 55 inches. It is assumed that the average annual precipitation at the Exxon Highland site is the same as at Casper, Wyoming. The records indicate a variation in rainfall at Casper from 7.3 inches to 16.2 inches per year with a standard deviation of about 2.4 inches. This represents a variation from the average of about 64 percent to 142 percent. For this area, the National Climatic Atlas (U.S. Geological Survey, 1970) indicates a variation in runoff from snowmelt and rainfall of about 20 percent to 210 percent with a coefficient of variation of 48 percent. Therefore, for a preliminary estimate, it is assumed that the total yearly precipitation could vary from about 2.3 inches to about 23.9 inches with a mean of 11.4 inches.

RUNOFF ESTIMATES

Several methods have been used to evaluate average annual runoff for the site. The runoff records of various small (i.e., less than 50 square miles) drainage basins on the plains of eastern Wyoming (from U.S. Geological Survey stream gaging stations) indicated mean annual flows varying from about 15 to about 450 acre-feet per square mile. In some mountainous areas, mean annual flows exceeded 1,000 acre-feet per square mile.

The paper "Techniques for Estimating Flow Characteristics of Wyoming Streams" (U.S. Geological Survey, 1976) was also consulted. According to this publication, the Exxon Highland site lies in Region 3 of eastern Wyoming which includes plains areas especially prone to intense thunderstorm activity. An equation developed for mean annual flows for this region is:

$$Q_a = 0.518\ A^{0.53}$$

where Q_a = mean annual flow in cfs

A = drainage area in square miles

Using this equation, mean annual flows for various size drainage basins were estimated. Table 4 indicates the results of this estimate.

TABLE 4

RUNOFF ESTIMATE USING USGS 1976 PAPER

Drainage Area	Mean Annual Runoff	Unit Runoff
1 sq mi	375 ac-ft/yr	375.0 ac-ft/mi^2/yr
10 sq mi	1,270 ac-ft/yr	127.0 ac-ft/mi^2/yr
100 sq mi	4,305 ac-ft/yr	43.1 ac-ft/mi^2/yr
1,000 sq mi	14,590 ac-ft/yr	14.6 ac-ft/mi^2/yr

This analysis indicates that the unit runoff decreases with increasing drainage area. For the drainage area of 2.13 square miles contributing to the Pit 5 lake, this would indicate a mean annual runoff of about 560 acre-feet with a corresponding unit runoff of about 260 acre-feet per square mile per year.

Another source of information investigated was "Hydrologic Effects of Water Spreading in Box Creek Basin, Wyoming" (U.S. Geological Survey, 1961). This report gave storm runoff values for 15 small drainage basins of less than 3 square miles in the Box Creek Basin during the years of 1956 and 1957. The average runoff for these basins based on 2 to 5 storm events per year during the months of May through September was about 22 acre-feet per square mile per year. Assuming that about 50 percent of the runoff results from these storms, while the other 50 percent occurs from snowmelt, a mean runoff of about 45 acre-feet per square mile per year from these basins is indicated.

Potential flood runoff (peak flow and volume) estimates for the area in question were also estimated using "Analysis of Small Drainage Basins in Wyoming" (USGS, 1978). The following data were used in the analysis:

Natural Drainage: Area = 0.76 sq mi
Basin Slope = 118 ft per mi (2.2%)
Max. Relief = 145 ft

Disturbed Drainage: Area = 1.37 sq mi
Basin Slope varies from 39 ft per mi (0.74%) to 264 ft per mi (5%)
Max. Relief - 150 ft

Table 5 gives the results of these estimates.

A methodology is presented in Water Supply Paper 1531-B which relates drainage density to annual runoff. Drainage density is defined by the length of channel divided by the area of the basin. During a previous study (Dames & Moore, 1978), an average density of 5.4 miles per square mile was used and an annual runoff of about 11.5 acre-feet per square mile was

TABLE 5

POTENTIAL FLOOD RUNOFF

Flood Recurrence	Estimated Peak Flow	Estimated Flood Volume
2 yrs	150 cfs	20 ac-ft
5 yrs	310 cfs	38 ac-ft
10 yrs	400 cfs	47 ac-ft
25 yrs	580 cfs	64 ac-ft
50 yrs	1,000 cfs	90 ac-ft
100 yrs	1,200 cfs	105 ac-ft

determined using the methodology presented in WSP 1531-B. The drainage density was obtained by evaluating USGS topographic maps during our previous study. However, the natural drainage northwest of Pit 5 has a density of about 1.6 miles per square mile, while the disturbed area does not have a defined channel. A lower drainage density would indicate an even lower runoff quantity.

Storm runoff estimates were also made using the curve numbers developed by the U.S. Soil Conservation Service from soil and ground cover data (U.S. Dept. of Agriculture, 1974). For the high plains rangeland type of soil and ground cover encountered at the Highland site, the curve numbers would range from 50 to 75, depending on the antecedent moisture conditions and percentage of ground cover. It is assumed that about 5.7 inches of the yearly precipitation of 11.4 inches falls during storms. This would be about 1.0 to 3.0 inches, or 53 to 160 acre-feet/square mile of runoff from these storms and does not include annual runoff from snowmelt.

The low, mean and high annual runoff per square mile of drainage area at the Highland site estimated by the methods described on the previous page are abstracted in Table 6.

The following values of unit runoff have been selected for use in this study: Average annual = 50 acre-feet/square mile; low annual = 10 acre-feet/square mile; high annual = 105 acre-feet/square mile. These values have been selected by our hydrologists as their best estimates based upon review of their runoff evaluations described previously and their engineering judgment and experience.

EVAPORATION ESTIMATES

Lake evaporation is generally the result of a number of factors including solar radiation, cloud cover, humidity, wind speed and duration, elevation and surrounding ground cover. The estimated mean annual lake evaporation for the Highland site, as given in the U.S. Water Atlas (Water Resources Information Center, 1973) is 43.5 inches. The mean annual evaporation from water bodies varies from year to year; however, it does not vary as widely as does precipitation. Based on information obtained from the National Climatic Atlas, it is assumed that the low and

TABLE 6

SUMMARY OF RUNOFF ESTIMATES

Low	Mean	High	Parameter	Method
123.0	608.0	1,214.0	Annual Precipitation (ac-ft/sq mi)	National Climatic Atlas, 1970
15.0	214.0*	450.0	Annual Runoff (ac-ft/sq mi)	Analysis of Available Records
9.0*	45.0	94.0*	Annual Runoff (ac-ft/sq mi)	USGS, 1961 "Box Creek Basin"
25.0*	124.0*	260.0	Annual Runoff (ac-ft/sq mi)	USGS, 1961 "Techniques"
2.4*	11.5	24.2	Annual Runoff (ac-ft/sq mi)	USGS, 1961 "Cheyenne R. Basin"
53.0	76.0*	160.0	Annual Runoff (ac-ft/sq mi)	USDA, 1974

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*Extrapolated in the ratio of low, mean and high annual precipitation high evaporation years vary approximately 8 percent from the mean year. Therefore, the range of probable evaporation from the Pit 5 lake will be 40 to 47 inches per year.

SURFACE WATER QUALITY

Surface water quality appears to vary considerably from natural areas and areas disturbed by the mining operation. In the long term, runoff water quality from disturbed areas should approach that of the undisturbed areas. Table 7 summarizes water quality data for selected sampling sites in the vicinity. Sample locations #33 and #35, which represent undisturbed conditions, show concentrations of uranium and major dissolved species which are three to ten times lower than for the disturbed areas. In evaluation of the quality of runoff waters to Pit 5, it has been assumed that these differences in water quality by area will occur.

EVALUATIONS AND DISCUSSIONS

METHODOLOGY AND APPROACH

This section discusses the approach to our evaluation of the hydrologic conditions which will result at the Pit 5 lake. In order to evaluate the physical and chemical characteristics of the proposed lake, it was necessary to quantitatively evaluate the discharge of surface water and ground water to the lake from both undisturbed and mined areas as well as the quality of the various inflow components.

TABLE 7

SURFACE WATER QUALITY DATA

Average Measured Concentration and Variation *

Sample Location And Name	U-Natural (pCi/l)	Ra-226 (pCi/l)	Th-230 (pCi/l)	Na (Mg/l)	Ca (Mg/l)	SO_4 (Mg/l)	Cl (Mg/l)	HCO_3 (Mg/l)	Total Dissolved Solids (Mg/l)
#33 Fowler Draw Stock Pond	11±26/11	.85±.68/11	50±56/6	18±23/8	24±11/8	38±45/8	6±2/8	82±45/8	149±100/8
#35 Antelope Reservoir	16±16/10	1.83±2.10/10	5±3/2	20±23/9	28±20/9	54±89/9	6±2/9	92±75/9	188±177/9
#5 Creek SE of Highland Fenced Area	144±312/25	6.06±9.27/25	4.1±6.5/25	176±78/11	82±37/11	284±148/11	15±5/11	476±190/11	927±383/11
#36 Reservoir 2A	73±90/12	1.3±1.0/11	3.1±.64/5	139±93/9	49±31/9	324±100/9	15±14/9	220±121/9	749±443/9
#38 Buck Reservoir	80±48/11	5.5±8.3/10	6.0±6.9/3	129±54/9	33±17/9	203±95/9	19±7/9	205±77/9	584±267/9
#71 Oxbow Below Dump 2A	408±280/6	6.1±7.5/6	25±34/2	253±110/8	69±30/8	326±183/8	21±10/7	517±234/7	1151±571/7

* Key:

11 ± 26/11

Mean concentration ± standard deviation/number of measurements

Source of data: Exxon Minerals Co., U.S.A.

HYDROLOGIC BALANCE

A hydrograph for ground water inflow as a function of lake elevation was developed through the use of an integrated finite difference mathematical model. Details of the model are described in Appendix A.

Surface water inflows were compared to evaporation at several hypothetical lake elevations to develop a net surface water discharge hydrograph as a function of lake elevation. Equilibrium between the net surface water discharge and ground water inflow is based upon satisfying the following simple mass balance equation:

$$RO + P - E + GI = 0$$

where

RO = Runoff

P = Direct precipitation

E = Evaporation

GI = Ground water inflow

Lake elevations for average hydrologic conditions, a sustained dry cycle and a sustained wet cycle were estimated on the basis of the above equation, assuming that each condition would last for a time sufficient to reach steady state. These analyses, therefore, truly represent the extremes which can be anticipated for the Pit 5 lake.

WATER QUALITY ESTIMATES

After calculation of the surface and ground water flow contributions were completed, an evaluation of water quality was performed. Several water quality monitoring stations maintained by Exxon around the existing mine were selected as representative of each of the water quality "types." Surface water runoff from undisturbed areas, surface water from reclaimed areas, ground water from undisturbed areas and direct precipitation values for various water quality parameters were developed. The results of our ground water model indicate that ground water contributions from mined areas will be negligible. Water quality in the lake was estimated by volumetrically averaging the contributions of the four inflow "types" assuming complete mixing of the inflows.

GROUND WATER FLOW MODEL

GENERAL

This section of the report describes the ground water models used to predict the effects of the Pit 5 lake on the ground water system. Of particular interest in the modeling effort are identification of regions from which flow will enter the pit, quantity of seepage entering the pit, expected areas of influence and an estimate of time required after mining operations cease to reach an equilibrium condition.

A mathematical model developed by Dames & Moore (Sharma, 1979) which is of the integrated finite difference variety was used to predict steady-state effects of the Pit 5 lake on the ground water system. The model, which is capable of analyzing heat and mass transport in conjuction with fluid flow in porous media, was used solely for determining ground water flow directions and quantities. The model was utilized in two-dimensional plan view, which allows for variations in material properties areally but not vertically. The two dimensional plan view model also necessarily assumes no vertical component of flow. A detailed description of the model is presented in Appendix A.

Initially, the model was calibrated to the estimated pre-mining conditions. Plate 6 shows the estimated pre-miming water levels in comparison with the water levels obtained from the calibration. After calibration was achieved the model was modified to represent post-mining conditions by introducing the backfilled portions of the previously mined areas and the Pit 5 lake.

INPUT PARAMETERS FOR THE STEADY STATE MODEL

Input parameters required for the model are the finite difference mesh, aquifer transmissivity and boundary conditions. Since this model was used to approximate steady state conditions, the storage coefficient was not a necessary input parameter.

Plate 5 displays the finite difference mesh, and corresponding aquifer thickness used for this investigation. The mesh was made finer in the vicinity of the Pit 5 lake and backfill areas where it was anticipated that the largest head differentials would occur. The mesh outer boundaries were assigned constant head values obtained from the estimated pre-mining ground water levels.

Transmissivity values were input on the basis of sand thickness as determined from Plate 5 and assuming a uniform permeability of 1 x 10^{-3} cm/sec for the sands. Recharge rates to the aquifer were finally estimated at an average rate of 0.4 inch/year below elevation 5,400 feet and 0.8 inch/year above elevation 5,400 feet. These values were selected based upon information presented in U.S. Department of Interior (1974) and higher than average recharge expected in the Highland Flats area.

CALIBRATION

Calibration was achieved by adjusting the recharge rate, the hydraulic conductivity of the sand and thickness of the sands within reasonable limits to values which would permit a reasonably close match to the estimated pre-mining ground water levels. It must be re-emphasized at this point, that the estimates of pre-mining ground water elevations are probably only accurate at best to within 25 feet. The calibration, therefore, is also an approximation to actual pre-mining conditions.

Plate 6 displays the results of the simulation of the premining ground water levels. The best calibration was achieved by assuming an infiltration rate of 0.8 inches per year in the Highland Flats area above elevation 5,400 feet and 0.4 inches per year in the remaining area, a hydraulic conductivity of 1 x 10^{-3} cm/sec, and sand thicknesses estimated from geologic information as shown on Plate 5. Calculation of flow passing through the area which is currently being mined indicates a flow rate of approximately 500 gpm. This is in good agreement with Exxon's current estimated dewatering rate from the pit of 600 to 800 gpm.

SIMULATION OF PIT 5 LAKE

After calibration had been achieved, input parameters to the mesh were modified to model the effects of areas disturbed from the mining operation and the Pit 5 lake. Parameters outside of these areas were maintained identical to the parameters used during the calibration run.

Recent studies performed for the United Nuclear Corporation Morton Ranch property immediately to the south of the Exxon site (Nelson and others, 1980) estimated the permeability of overburden backfill materials at 10^{-6} cm/sec. For the purposes of our investigation, we have conservatively assumed that the backfill has a permeability of 10^{-5} cm/sec.

The rectangular grid was segmented to approximate the outline of the Pit 5 lake and was assigned constant head values for the simulation. Several constant head values were assigned to the Pit 5 lake to simulate different lake elevations and the resulting ground water inflows calculated as an example. Plate 8 shows ground water contours resulting from a steady-state lake level of 5,175 feet. These calculations allowed the development of a hydrograph for ground water inflow versus lake elevation as presented on Plate 9.

SURFACE WATER MODEL

GENERAL

This section discusses the surface water balance for the Pit 5 lake. It is based on surface water runoff, direct precipitation or snowfall and evaporation estimates from the lake during high, average and low precipitation years. The water balance estimates have been broken down into monthly increments based on available information on the runoff distribution for the area. No difference in runoff quantities from the reclaimed disturbed area and the undisturbed area were believed appropriate. Total tributary area to the lake at elevation 5,180 feet is 2.13 square miles.

YEARLY SURFACE WATER BALANCE

The net water balance for the Pit 5 lake was determined for several potential lake elevations. Three water balance situations were evaluated for each elevation: 1) average precipitation, runoff and evaporation; 2) low precipitation and runoff with high evaporation; and, 3) high precipitation and runoff with low evaporation. High evaporation was used conjunctively with low precipitation/runoff because low precipitation years would be expected to have the least number of days with cloud cover resulting in higher evaporation. Likewise, low evaporation was used with high precipitation/runoff years.

The following relationship was used to determine the net surface water balance of the lake:

direct precipitation + runoff - evaporation = net balance
(on lake) (from lake)

Plate 9 summarizes the results of the annual surface water balance as well as ground water inflow. As may be seen from Plate 9 and Tables 8A, 8B, and 8C, a net evaporative loss of 328 gpm (530 acre-feet per year) occurs at a lake elevation of 5,180 for the low precipitation, high evaporation year. A net surface water gain of 15 gpm (25 acre-feet per year) is estimated for the lake at elevation 5,180 during the high precipitation, low evaporation year. During low and average precipitation years, the lake at elevation 5,180 would tend to have a net yearly water loss; during the high precipitation, low evaporation year, there would be a small yearly water gain.

TABLE 8A

SURFACE WATER BALANCE IN ACRE-FEET
AVERAGE PRECIPITATION AND EVAPORATION YEAR*

Month	Runoff	+	Direct Precipitation	-	Evaporation	=	Net
January	4.7		6.2		32.2		-21.3
February	4.7		6.2		32.2		-21.3
March	7.6		10.0		37.6		-20.0
April	15.0		19.8		42.9		- 8.1
May	18.7		24.7		42.9		+ .5
June	12.1		16.0		53.7		-25.6
July	9.4		12.4		75.1		-53.3
August	6.1		8.0		59.0		-44.9
September	7.6		10.0		48.3		-30.7
October	9.4		12.4		42.9		-21.1
November	6.6		8.7		37.6		-22.3
December	4.7		6.2		32.2		-21.3
Yearly Totals	106.5	+	140.6	-	536.5	=	-289.4 ac-f

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*For lake elevation of 5,180 feet

lake area = 148 ac

tributary area = 2.13 mi^2

TABLE 8B

SURFACE WATER BALANCE IN ACRE-FEET
LOW PRECIPITATION AND HIGH EVAPORATION YEAR*

Month	Runoff	+	Direct Precipitation	-	Evaporation	=	Net
January	0.9		1.3		34.8		-32.6
February	0.9		1.3		34.8		-32.6
March	1.5		2.0		40.6		-37.1
April	3.0		4.0		46.4		-39.4
May	3.7		5.0		46.4		-37.7
June	2.4		3.2		58.0		-52.4
July	1.9		2.5		81.2		-76.8
August	1.2		1.6		63.8		-61.0
September	1.5		2.0		52.2		-48.7
October	1.9		2.5		46.4		-42.0
November	1.3		1.8		40.6		-37.5
December	0.9		1.3		34.8		-32.6
Yearly Totals	21.1	+	28.5	-	580	=	-530.4 ac-f

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*For lake at elevation 5,180 feet

TABLE 8C

SURFACE WATER BALANCE IN ACRE-FEET
HIGH PRECIPITATION AND LOW EVAPORATION YEAR*

Month	Runoff	+	Direct Precipitation	-	Evaporation	=	Net
January	9.8		13.0		29.6		- 6.8
February	9.8		13.0		29.6		- 6.8
March	15.9		20.9		34.5		+ 2.3
April	31.5		41.6		39.5		+33.6
May	39.4		51.9		39.5		+51.8
June	25.5		33.6		49.3		+ 9.8
July	19.7		25.9		69.1		-23.5
August	12.7		16.8		54.3		-24.8
September	15.9		20.9		44.4		- 7.6
October	19.7		25.9		39.5		+ 6.1
November	13.9		18.3		34.5		- 2.3
December	9.8		13.0		29.6		- 6.8
Yearly Totals	223.6	+	294.8	-	493.4	=	+ 25.0 ac-f

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*For lake at elevation 5,180 feet

MONTHLY DISTRIBUTION OF YEARLY SURFACE WATER BALANCE

Monthly distributions for the average, low and high precipitation years were determined for the higher lake elevation of 5,180 feet MSL. The monthly precipitation distribution as determined from Water Supply Paper 1531-B (U.S. Geological Survey, 1961) was used. Although the runoff would not have exactly the same monthly distribution as the precipitation due to winter snowpack that would not create direct runoff, it is assumed that the monthly distributions are approximately the same for both precipitation and runoff. The monthly distributions of total yearly precipitation, runoff and evaporation are given on Table 9 as percentages of the yearly total and as unit value for an average year. In general, the highest precipitation and runoff occur in the spring while the highest evaporation occurs during the summer months.

Tables 8A, 8B, and 8C display the monthly distributions of surface water balance for the lake at elevation 5,180 feet. As may be seen, the highest monthly net water loss is 76.8 acre-feet and occurs during July of the low precipitation, high evaporation year. The highest net monthly gain of 51.8 acre-feet occurs during May of the high precipitation, low evaporation year. The highest seasonal variations occur from May through July. During these months the net surface water balance has the greatest change. This occurs because the late spring month of May

TABLE 9

MONTHLY DISTRIBUTION OF PRECIPITATION AND RUNOFF

	Runoff		Precipitation		Evaporation	
Month	(% of annual)	(ac-ft/mi^2)*	(% of annual)	(ac-ft/mi^2)*	(% of annual)	(ac-ft/mi^2)*
January	4.4%	2.2	4.4%	26.8	6%	139.2
February	4.4%	2.2	4.4%	26.8	6%	139.2
March	7.1%	3.6	7.1%	43.2	7%	162.4
April	14.1%	7.1	14.1%	85.7	8%	185.6
May	17.6%	8.8	17.6%	107.0	8%	185.6
June	11.4%	5.7	11.4%	69.3	10%	232.0
July	8.8%	4.4	8.8%	53.5	14%	324.8
August	5.7%	2.9	5.7%	34.7	11%	255.2
September	7.1%	3.6	7.1%	43.2	9%	208.8
October	8.8%	4.4	8.8%	53.5	8%	185.6
November	6.2%	3.1	6.2%	37.7	7%	162.4
December	4.4%	2.2	4.4%	26.8	6%	139.2
	100%	50.	100%	608.	100%	2320.

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*For average year and lake elevation of 5,180 generally has high precipitation and runoff coupled with low evaporation, while the summer month of July generally has low precipitation and runoff coupled with high evaporation. The winter months have net water losses for all the three cases analyzed.

ESTIMATED SEASONAL LAKE LEVEL FLUCTUATIONS

An area-capacity curve of the proposed Pit 5 lake at the Highland Mine was developed for the purposes of this study, as shown on Plate 10. As may be seen from this curve, the area of the lake would vary from about 58 acres at elevation 5,000 feet to about 148 acres at elevation 5,180 feet, while the total volume would vary from about 4,000 acre-feet at elevation 5,000 feet to about 21,500 acre-feet at elevation 5,180 feet.

At a lake elevation of 5,180 feet and considering both the surface water balance and ground water inflow, the maximum volume fluctuations occur in May and September during an average year. The maximum fluctuation is 58 acre-feet and would correspond to a lake level fluctuation of 0.4 feet.

At lake elevation 5,180 feet, a high precipitation-low evaporation year would produce an excess water volume of 314 acre-feet when combined with ground water inflow. This would cause a lake level rise of 2.1 feet.

Therefore, the maximum anticipated fluctuations in yearly lake water balance would have a small effect on lake elevation.

LAKE SEDIMENTATION

The sediment yield of a watershed is determined from several factors, among which are the following:

1. Rainfall - amount and intensity
2. Ground cover
3. Soil type and geologic formation
4. Land use
5. Topography
6. Density, slope, shape, size and alignment of drainage channels.

For the purposes of this study, an average rainfall and runoff year was assumed. Years with extremely heavy rainfall and snowmelt runoff would be expected to produce more sediment yield than dry years; however, over the long period considered here, average values are believed appropriate.

Estimates for the transport of sediments into the Pit 5 lake were developed by the Universal Soil Loss Equation (USLE) for both the undisturbed area north of the lake, as well as the disturbed area south of the lake. Details of this method are presented in the joint publication by the SCS and EPA entitled "Preliminary Guidance of Estimating Erosion on Areas Disturbed by

Surface Mining Activities in the Interior Western United States" (Environmental Protection Agency, 1977). As stated in this publication: "The Universal Soil Loss Equation (USLE) is an empirically developed formula historically used to estimate soil loss on agricultural lands."

The soil loss equation is A = R K L S C P, where:

A = The computed soil loss expressed in tons/acre/year.

R = The rainfall factor, is the number of erosion index units in a normal year's rain. The erosion index is a measure of the erosive force of specific rainfall.

K = The soil erodibility factor, is the erosion rate per unit of erosion index for a specific soil in cultivated continuous fallow, on a 9 percent slope, 72,6 feet long.

L = The slope length factor, is the ratio of soil loss from the field slope length to that from a 72.6-foot length on the same soil type and gradient.

S = The slope gradient factor, is the ratio of soil loss from the field gradient to that from a 9 percent slope.

C = The cover or cropping management factor, is the ratio of soil loss from a field with specified cropping and management to that from the fallow condition on which the factor K is evaluated.

P = The erosion control practice factor, is the ratio of soil loss under specified soil maangement practices, to that with straight rows, up and down the slope.

Soil loss, as determined by the basic USLE, is only a measure of the quantity of soil eroded from the ground; it is not the quantity of soil delivered beyond the watershed boundaries. Eroded soil may be deposited before leaving the drainage basin and entering the lake. Thus, an additional factor based on the basin size, the delivery ratio (DR), is applied to the basic equation to determine the actual sediment delivery. The DR values listed as follows were estimated from the relationship expressed in the Sedimentation Engineering Technical Manual (Vaoni 1975):

PARAMETERS

Basin	R	K	LS	C	P	DR
Undisturbed Area North of Lake	40	.21	7.4	.175	1	.335
Disturbed Area South of Lake	40	.26	5.51	.175	1	.270

The total sediment delivery values were calculated to be as follows:

Basin	Soil Loss Unit (tons/Ac/Yr)	Soil Loss Total (tons/yr)	Sediment Delivery (tons/yr)
Undisturbed Area North of Lake	10.88	5287	1771
Disturbed Area South of Lake	10.03	8785	2372
			4143 tons/yr

As indicated above, the area south of the Pit 5 lake disturbed by mining operations would produce about 34 percent more sediment than the undisturbed area northwest of Pit 5.

The total of 4,143 tons per year sediment delivery corresponds to about 2.6 acre-feet per year. Over a 40-year period, this would produce only 104 acre-feet. Approximately 90 percent of the surface soils of the basins draining into the lake are either of the Bowbac or Decolney series. Laboratory analysis show them to be clay-loams of very fine particle size suggesting slow settling rates.

The USLE was developed over several decades using observational data from a limited number of specific gaging locations. It is a generalized equation used to qualitatively indicate the erosion potential of a watershed and not to estimate numerically-accurate sediment volumes.

Comparing the value determined by the USLE with results of reservoir sediment surveys compiled by the Water and Power Resources Services (formerly USBR), one finds that the expected sediment yield for an undisturbed drainage area of this size would be in the range of about 2.0 acre-feet per square mile per year,or about 3,180 tons per square mile per year (USDI, 1974). Assuming this more conservative value, the total estimated sediment yield would be about 6,770 tons per year, or about 4.3 acre-feet per year. Over a 40-year period, this would mean about 172 acre-feet.

The sediment values estimated here would probably decrease with time as the disturbed area regains natural vegetation. Therefore, whichever estimate is chosen, the long-term sedimentation of the Pit 5 lake appears to be a minor consideration.

FINDINGS

OVERALL WATER BALANCE FOR LAKE SYSTEM

The overall water balance for the lake system is summarized on Plate 9. It shows the net surface water discharge to the lake as a function of elevation for dry years (low precipitation-high evaporation), normal years (average precipitation and evaporation), and wet years (high precipitation-low evaporation). Net surface water discharge is lake evaporation minus direct precipitation minus runoff. During wet years there is a net surface water inflow (or negative discharge). Also shown are ground water inflows as a function of elevation for the estimated range of permeability (1×10^{-3} cm/sec) and 2×10^{-3} cm/sec) for the aquifer. The intersection of the surface water discharge curve and the ground water inflow curve yields the elevation of the lake for equilibrium conditions.

Ground water inflow during average climatic conditions is expected to range from 180 to 195 gpm. This would be balanced by a net surface water discharge: a 180 gpm discharge, for example, consists of 332 gpm evaporation, 66 gpm runoff, and 86 gpm direct precipitation. During dry years the equilibrium ground water inflow is estimated to range from 300 to 330 gpm. During a long series of wet years the lake level would return to approximately the pre-mining elevation, resulting in nearly zero ground water inflow.

EXPECTED SHORELINE ELEVATION

The expected shoreline elevation for the lake is also shown on Plate 9 for the various ranges in climatic conditions and assumed range in aquifer permeability. Under average climatic conditions, the lake elevation is expected to range from 5,180 to 5,195 feet under equilibrium conditions. Plate 9 also shows the equilibrium lake levels for wet and dry climatic cycles. Lake elevations are expected to be 15 to 30 feet higher for a sustained wet cycle compared to an average year and are 10 to 20 feet lower for the dry cycle. The lake will generally vary less than one foot seasonally throughout an average year.

ESTIMATED TIME TO EQUILIBRIUM

The time required for the lake to fill and reach an approximate equilibrium level is controlled by the rate of ground water inflow, runoff, direct precipitation and evaporation, all of which are a function of lake elevation. For the purposes of making a preliminary estimate of time to reach equilibrium the following assumptions were made:

1. Average ground water inflow is approximately 800 gpm from the time dewatering ceases until elevation 5,080 feet is reached.
2. Changes in lake level are sufficiently slow to use the previously developed ground water inflow hydrograph above elevation 5,080 feet.
3. Average hydrologic conditions exist during lake filling.
4. The stage-volume relationship for the lake is approximately that shown on Plate 10.

Using the above assumptions, the rate of filling is calculated interactively on an average annual basis by solving the following equation:

$$RO + P - E + GI = S$$

where the parameters on the right hand side of the equation have been defined previously (p 27) and S is the storage volume change.

The results of the calculations are presented graphically on Plate 11. The lake will rise approximately 190 feet during the first 10 years of filling but will take over 30 years to rise the remaining 80 feet to equilibrium level at elevation 5,180 feet.

LAKE WATER QUALITY

The Pit 5 lake will have no surface outlet and will discharge by evaporation only. Therefore, in the long term the lake will assume a character similar to other internally drained lakes in the region, such as Soda Lake, Pratts Soda Lake and Nine-Mile Lake. Existing internally drained lakes on Highland Flats are expected to have higher water quality since these lakes are perched above the ground water table and are drained to some degree by seepage.

Estimates of water quality have been made using a mass balance approach and assuming that there is no precipitation of dissolved constituents. The water quality data presented in Tables 2 and 7 were used to obtain typical water quality values for runoff from disturbed and undisturbed areas, from ground water inflow and from direct precipitation. Water quality values for rain were taken from Lerman (1978). Ground water inflow from the backfill area will be about 3 percent of the total ground water inflow due to its much lower permeability. Therefore, the effects of disturbance of the backfill material upon water quality have been assumed negligible. Values used to estimate the future lake water quality are shown on Table 10. These values are the weighted averages of the average values shown previously on Tables 2 and 7, except that median values were used for radionuclide values for Sample Locations #44 and #5. The radionuclide data for these sites contain several spurious values which grossly bias the average values, as indicated by the standard deviation values which are twice the average values. Median values for uranium, radium, and thorium for Sample Location #44 were 15, 22 and 0.5 pCi/l, respectively; and were 55, 3.3, and 2.0, respectively, for Sample Location #5.

A mass balance approach was used to estimate the concentrations with time in the lake. This was done by calculating the inflow rates for ground water for direct precipitation, for disturbed area runoff, and for undisturbed area runoff for

TABLE 10

WATER QUALITY VALUES USED TO ESTIMATE LAKE WATER QUALITY

Constituent	Direct Precipitation	Disturbed Area Runoff	Undisturbed Area Runoff	Ground Water
Chloride	0.3	20.	6.	11.
Sulfate	2.4	283.	46.	114.
TDS	10.	840.	170.	448.
Uranium-Nat	0.	103.	14.	15.
Radium-226	0.	3.6	1.4	6.5
Thorium-230	0.	3.8	30.	.79

increments of time during the initial lake filling period of 42 years. Expressed in mathematical form:

$$((P)(Cp) + (GI)(Cg) + (DRO)(Cd) + (URO)(Cu))\ (T)/V = C_l$$

where

P = Rate of precipitation inflow
Cp = Constituent concentration in precipitation
GI = Rate of ground water inflow
Cg = Constituent concentration in ground water
DRO = Disturbed area runoff inflow rate
Cd = Constituent concentration in disturbed area runoff
URO = Undisturbed area runoff inflow rate
Cu = Constituent concentration in undisturbed area runoff
T = Time
V = Volume of lake water
C_l = Constituent concentration in lake

After the lake comes to equilibrium, the relative proportions of flow from the three sources remain constant. Table 11 summarizes flow rates and calculated constituent concentrations using the strict mass balance method.

Constituent concentrations are relatively constant through the first 30 years when evaporation is relatively small in comparison with inflows and the increasing volume of water in the lake. The water quality during this period strongly reflects that of ground water which represents 60 to 90 percent of the

TABLE 11

FLOW RATES INTO LAKE AND LAKE WATER QUALITY

Time From Start Of Filling (Years)	Direct Precipitation (Ac-ft/yr)	Ground Water (Ac-ft/yr)	Disturbed Area Runoff (Ac-ft/yr)	Undisturbed Area Runoff (Ac-ft/yr)	Chloride (ppm)	Sulfate (ppm)	Total Dissolved Solids (ppm)	Uranium-Natural (pCi/l)	Radium-226 (pCi/l)	Thorium-230 (pCi/l)
3.6	27.5	1,290	77.5	38.0	14	154	585	25	7.8	2.2
6.4	62.5	1,290	74.5	38.0	13	140	533	23	7.2	2.0
8.3	75.	1,290	73.5	38.0	13	141	538	23	7.2	2.0
10	86.5	1,153	72.5	38.0	13	143	546	23	7.3	2.1
13	102	887	71.0	38.0	14	146	555	24	7.4	2.2
17	116	677	70.0	38.0	14	148	560	25	7.4	2.3
22	124.5	520	69.5	38.0	14	153	577	26	7.6	2.5
28	131	395	69.0	38.0	15	162	610	28	7.9	2.9
42	137	318	68.5	38.0	17	187	703	34	8.8	3.8
100	141	289	68.0	38.0	30	335	1,227	65	14.8	8.1
150	141	289	68.0	38.0	42	461	1,680	94	19.8	11.8
200	141	289	68.0	38.0	53	587	2,132	122	24.9	15.7
300	141	289	68.0	38.0	75	840	3,036	177	35.0	23.3
500	141	289	68.0	38.0	120	1,345	4,845	287	55.3	38.4

inflow. Chloride, sulfate, and total dissolved solids are approximately 14, 150 and 600 ppm, respectively, at the end of this initial period. These concentrations are similar to those of the North Plate River and fresh water reservoirs in the region. With time these concentrations will increase and are estimated to reach 120, 1,345 and 4,845 mg/l for chloride, sulfate and total dissolved solids, respectively, after 500 years. Chloride concentration would be within secondary drinking water standards. Sulfates would exceed secondary drinking water standards (250 ppm) after 70 years, but would be similar to other internally drained lakes in the region. The lake would reach a level defined as slightly saline, as defined in Hem (1970) (1,000 to 3,000 ppm) after 100 years and would reach a level defined as moderately saline (3,000 to 10,000 ppm) after 300 years. Total dissolved solids will undoubtedly be lower than the levels estimated from the mass balance, since a number of precipitation reactions will affect concentration such as gypsum and carbonate precipitation. In addition, utilization of dissolved minerals by photosynthesis will also reduce concentrations below those calculated.

Natural-uranium concentrations during the lake filling period are expected to be on the order of 23 pCi/l which is equivalent ot 0.034 mg/l based upon an activity of $6.77\text{x}10^{-7}$ Ci/gm. After 500 years the uranium is estimated to concentrate to 287 pCi/l (0.42 mg/l). These levels are well below MPC and DEQ standards.

Radium -226 is expected to be on the order of 7 pCi/l during the initial filling period and to increase to 55 pCi/l after 500 years assuming no precipitation of radium. In actuality, the radium concentration may be controlled by ion exchange upon clay particles which settle out of suspension. Radium, however, will likely exceed the EPA drinking water standard of 5 pCi/l.

Thorium -230 is expected to range from 2 pCi/l initially to 38 pCi/l after 500 years. This will be well below MPC.

Trace metals are expected to be low due to ion exchange reactions and the unfavorable pH environment for solubility which will be slightly alkaline.

The lake will be relatively deep, and stratification within the lake will likely result in higher quality water at the surface where direct precipitation will have a significant influence.

Sedimetation in the lake is expected to be on the order of 2.5 acre-feet/year. About 6 percent of the lake's original volume would be filled by sediment after 500 years.

RECOMMENDED END USE OF THE LAKE

End uses of the lake are dependent upon many factors including location, probable future activities in the general area, water levels and water quality. Due to its remote location, potential recreational use of the lake would likely be minimal.

No significant areas of tillage have or likely will occur in the Pit 5 vicinity. Long-term potential for industrial water use appears small for the area.

Stockwatering and wildlife watering appear to be the main potential uses for the lake. From a salinity and sulfate standpoint, the lake should be of acceptable quality for livestock. However, radium is estimated to exceed the 5 pCi/l standard for livestock and other consumptive uses by plants and animals. Therefore, radium removal treatment will probably be necessary for stockwatering use.

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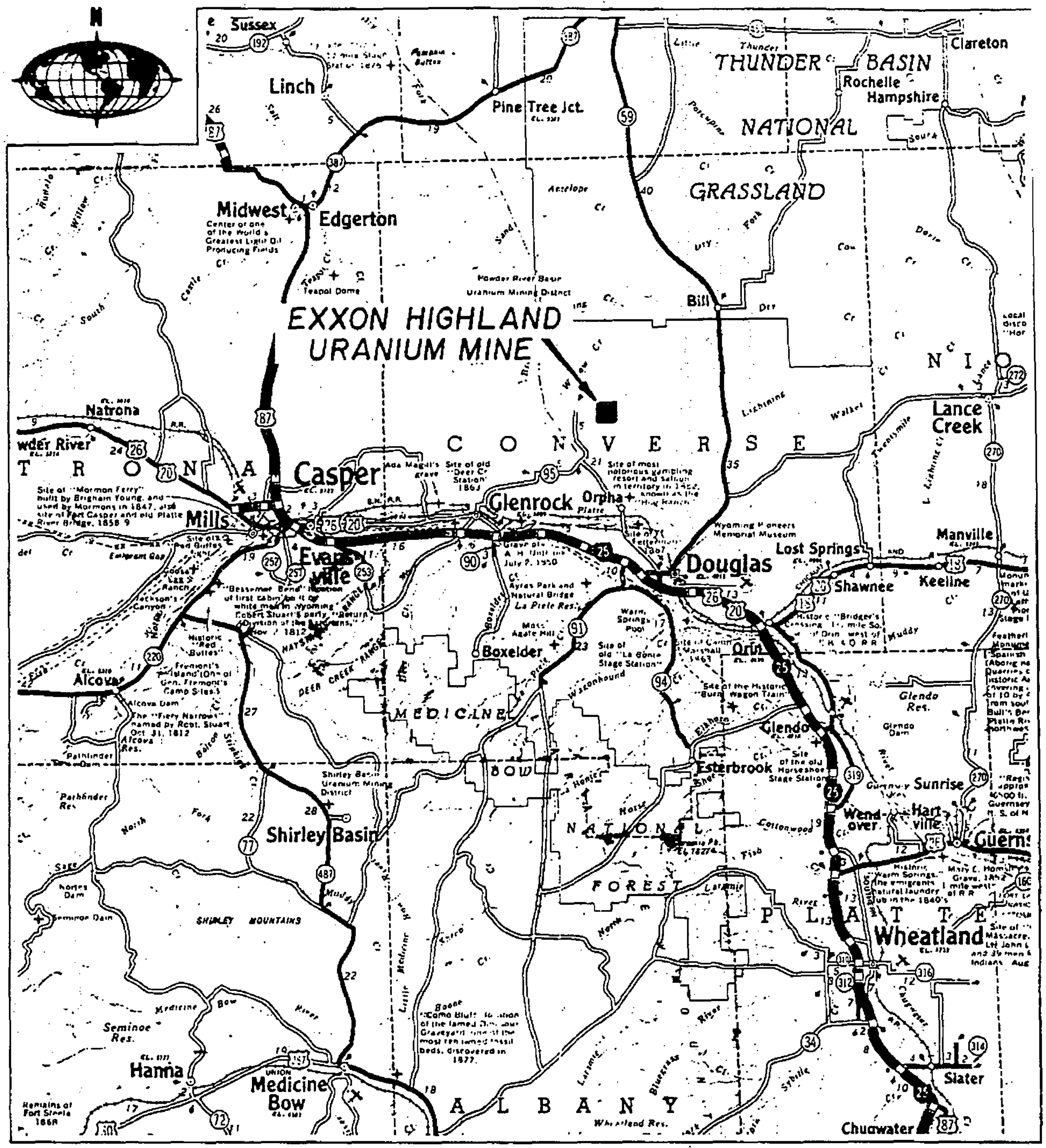
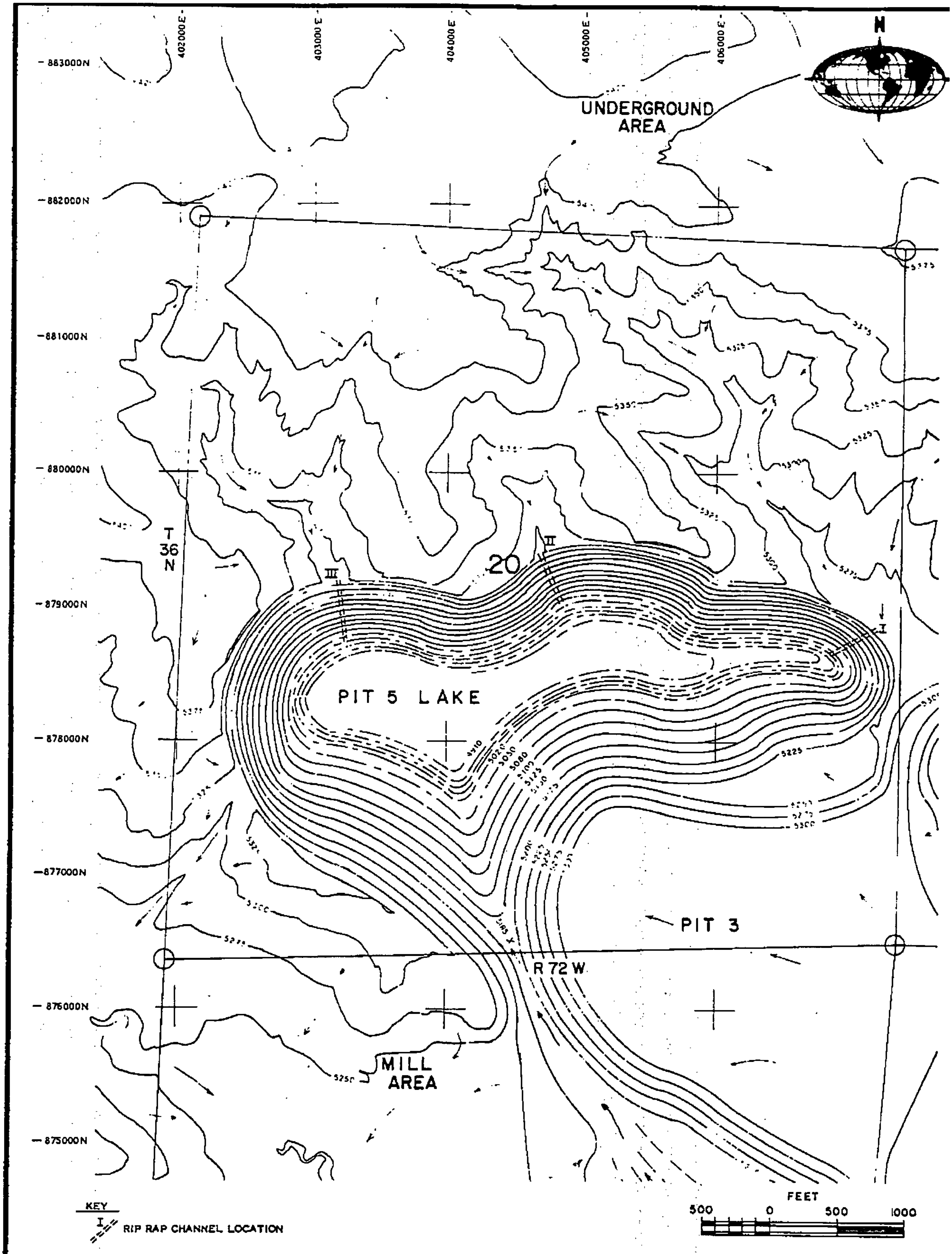


LOCATION MAP

REFERENCE :
OFFICIAL HIGHWAY MAP ENTITLED "WYOMING 1979 - 1980"
BY WYOMING STATE HIGHWAY COMMISSION CHEYENNE, WYOMING.

DAMES & MOORE

PLATE 1



FINAL RECLAMATION PLAN

REFERENCE
DRAWING ENTITLED " LIFE OF PROJECT FINAL RECLAMATION PLAN (PIT 5 INCLUDED AS LAKE)" BY EXXON MINERALS COMPANY, U.S.A., HIGHLAND URANIUM OPERATIONS. DRAWING DATED 4-15-80.

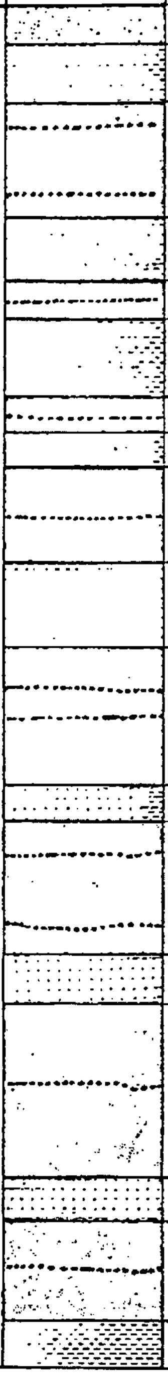
DAMES & MOORE

PLATE 2

REVISIONS
BY ___ DATE ___
BY ___ DATE ___
PLATE ___ OF ___

FILE ___
BY ___
CHECKED BY ___ DATE ___

GENERALIZED STRATIGRAPHIC COLUMN
HIGHLAND AREA
CONVERSE COUNTY, WYOMING



SYSTEM	SERIES	FORMATION	LITHOLOGY	
TERTIARY	PALEOCENE	FORT UNION		Soil & Weathered Zone
				Siltstone and claystone (shale): Color varies from olive orange to gray green.
				Sandstone: Thickness varies from 0-35; color varies from shades of gray to yellow-olive to red; grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts; beds vary from loose friable sand to well cemented (carbonate) sandstone; does not contain uranium mineralization.
				Siltstone and claystone (shale): Generally gray green, may contain thin interbedded sandstone and lignite beds, thickness varies from locality to locality.
				Sandstone: Same as above.
				Siltstone and claystone (shale). Generally gray green; may contain thin interbedded sandstone and lignitic beds thickness varies from locality to locality.
				Sandstone. Same as above.
				Siltstone and claystone (shale) Same as above.
				Sandstone: Thickness varies from 0-50 feet, color varies from shades of gray to yellow-olive to red; grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts; beds vary from loose friable sand to well cemented (carbonate) sandstone. does not contain uranium mineralization in Highland area.
				Siltstone and claystone (tailings dam shale): Thickness varies from 5-40 feet thick; generally gray green with thin beds of sandstone.
				Sandstone (upper Highland sandstone): Thickness ranges from 0-50 feet; color varies from shades of gray to yellow-olive to red, grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts, beds vary from loose friable sand to well cemented (carbonate) sandstone; no economic uranium in solution mine area.
				Siltstone & claystone: Thickness varies from 5-30 feet; generally gray green.
				Sandstone (middle Highland sandstone); Thickness varies from 5-50 feet thick, color varies from shades of gray to yellow-olive to red; grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts; beds vary from loose friable sand to well cemented (carbonate) sandstone; major ore bearing unit in Highland area
				Siltstone and claystone: Thickness varies from 0-50 feet; generally gray green, may contain thinbedded sandstone units.
				Sandstone (lower Highland sandstone): Thickness varies from 0-50 feet thick, color varies from shades of gray to yellow-olive to red; grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts; beds vary from loose friable sand to well cemented (carbonate) sandstone; major ore bearing unit in Highland area.
				Siltstone and claystone: Thickness varies from 5-80 feet; color generally gray green.
				Sandstone: Thickness varies from 0-60 feet; color varies from shades of gray to yellow-olive to red; grain size varies from medium-grained sand to gravel, most commonly medium to very coarse-grained sand; scattered conglomerate and siltstone beds less than 2 feet thick; sandstone contains varying amounts of shale and siltstone clasts; beds vary from loose friable sand to well cemented (carbonate) sandstone; does not contain economic amounts of uranium in Highland area.
				Siltstone & claystone (shale): Same as above.

NOTE: The stratigraphic section above ore sands varies in thickness relative to the elevation of the surface. As the surface elevation rises, the thickness of the sequence of beds increases. The lithological units are similar to those described in this columnar section; however, the number of units and their thickness will vary from locality to locality.

STRATIGRAPHIC COLUMN

DAMES & MOORE

PLATE 3

REVISIONS
BY ______ DATE ______

FILE 08837-102, Exxon Minerals

CHECKED BY ______ DATE 11-6

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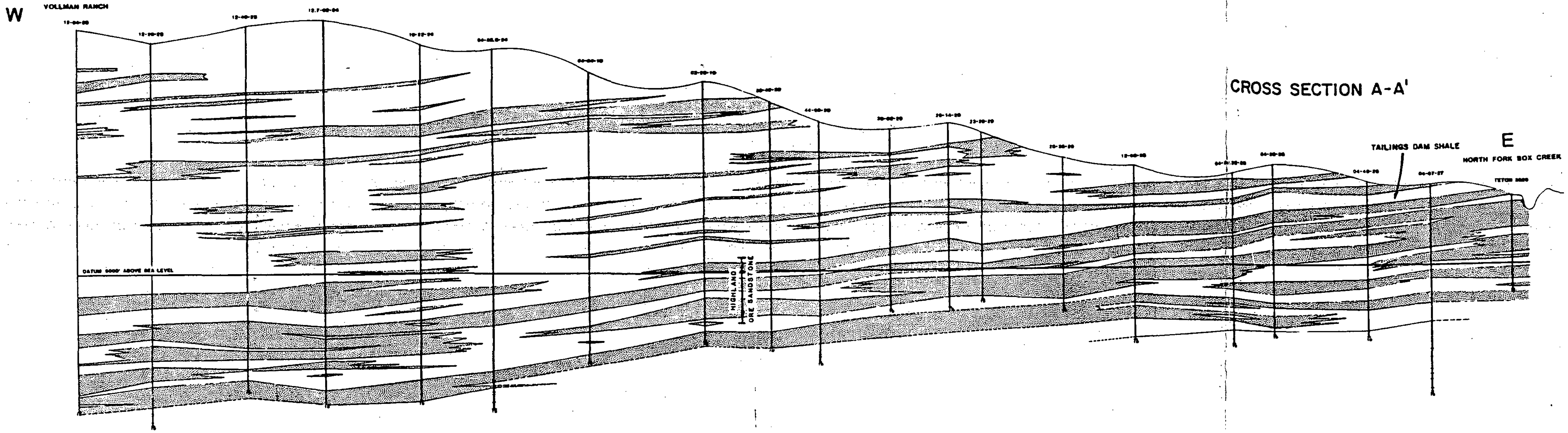
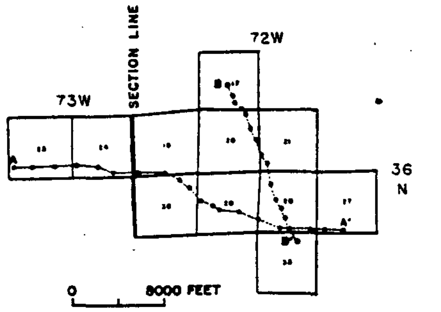
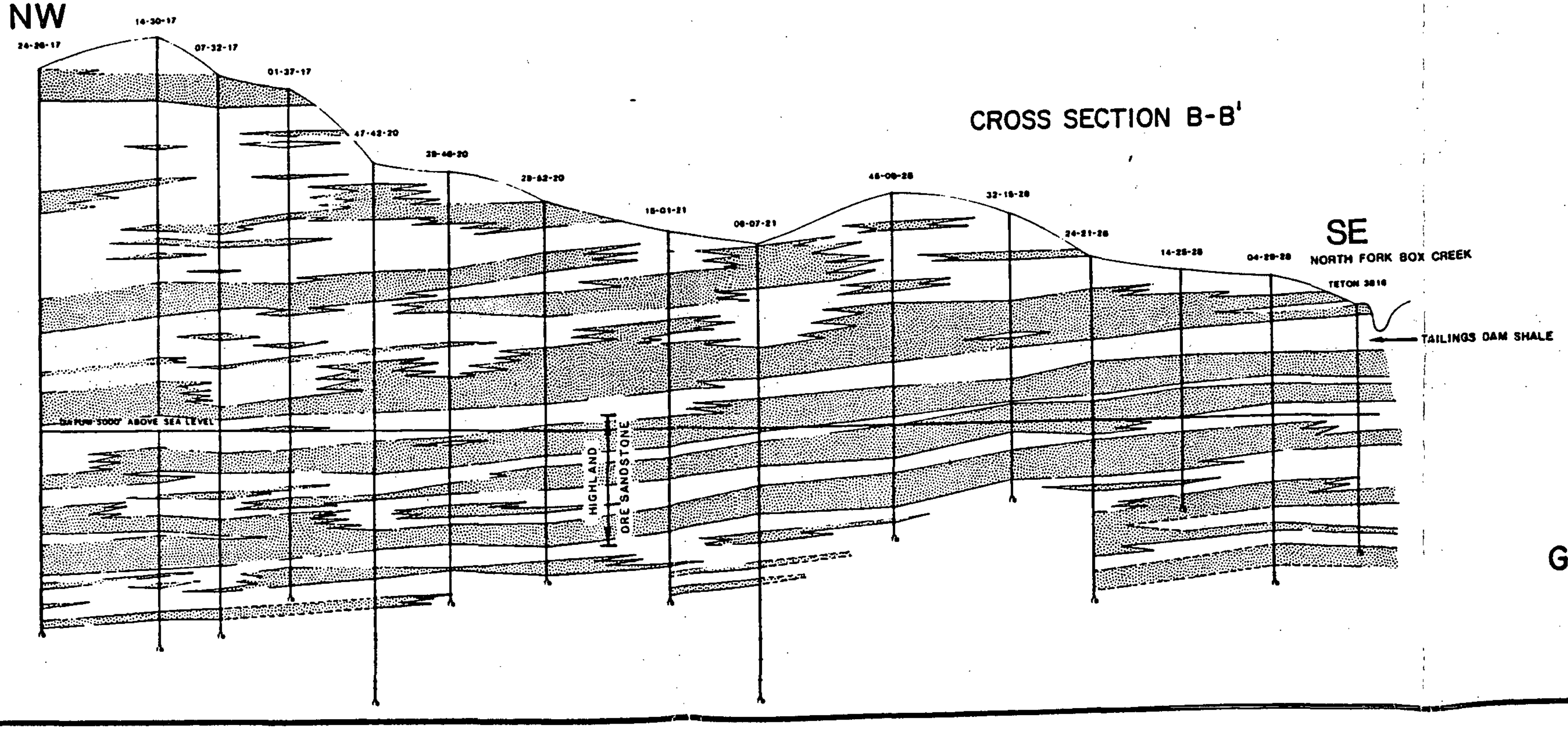


CROSS SECTION A-A'





CROSS SECTION B-B'

KEY

30-02-29 | EXXON EXPLORATION DRILL HOLE AND NUMBER

VERTICAL SCALE IN FEET
80 0 160 240

HORIZONTAL SCALE IN FEET
800 0 1600 2400

REFERENCE
PLATES ENTITLED "X-SECTION A-A', HIGHLAND AREA, CONVERSE COUNTY, WYOMING" AND "X-SECTION B-B', HIGHLAND AREA, CONVERSE COUNTY, WYOMING" FROM EXXON COMPANY, U.S.A. SUPPLEMENTAL ENVIRONMENTAL REPORT DATED AUGUST 1977.

GEOLOGIC CROSS-SECTIONS

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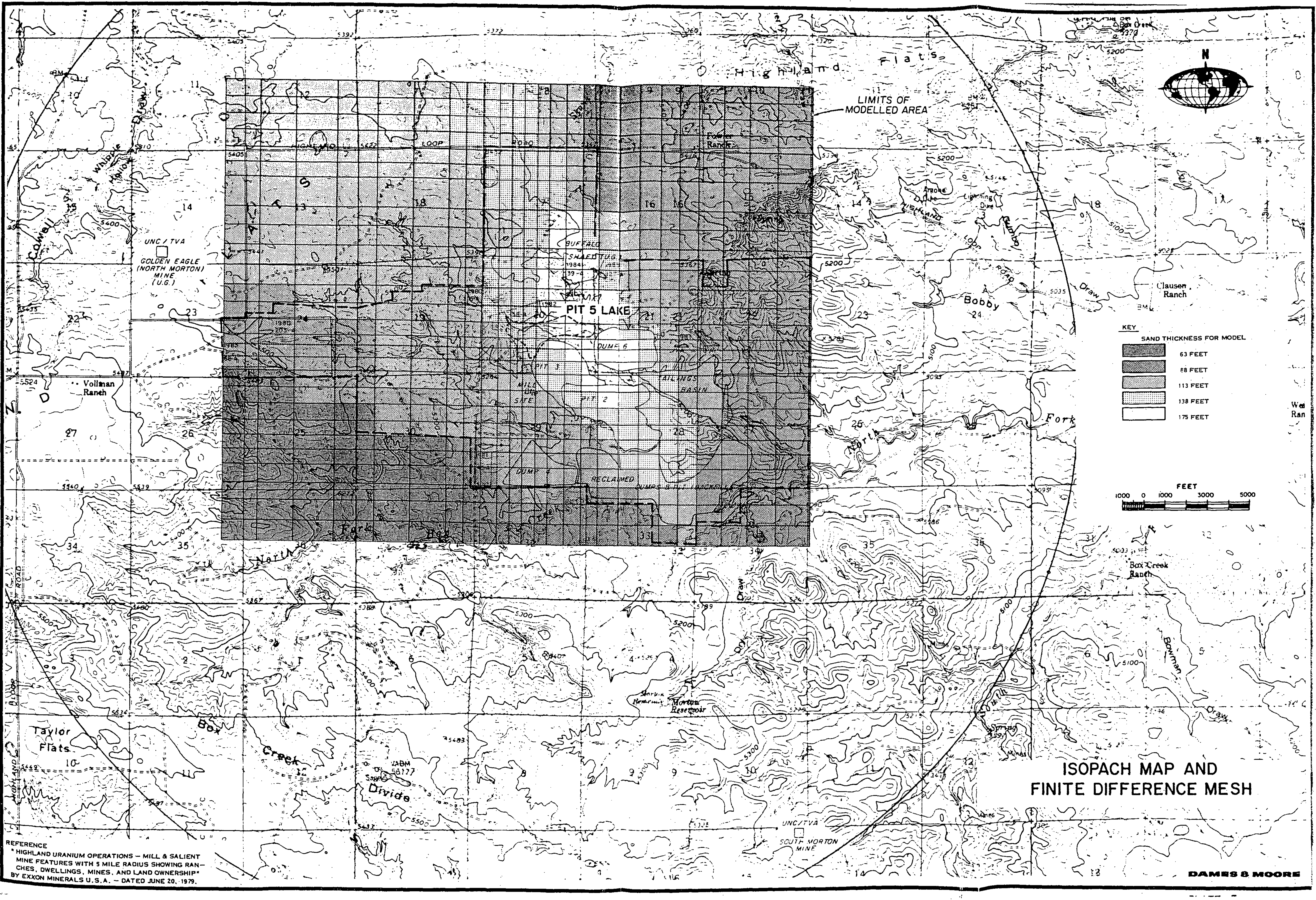
PLATE 4



KEY

SAND THICKNESS FOR MODEL

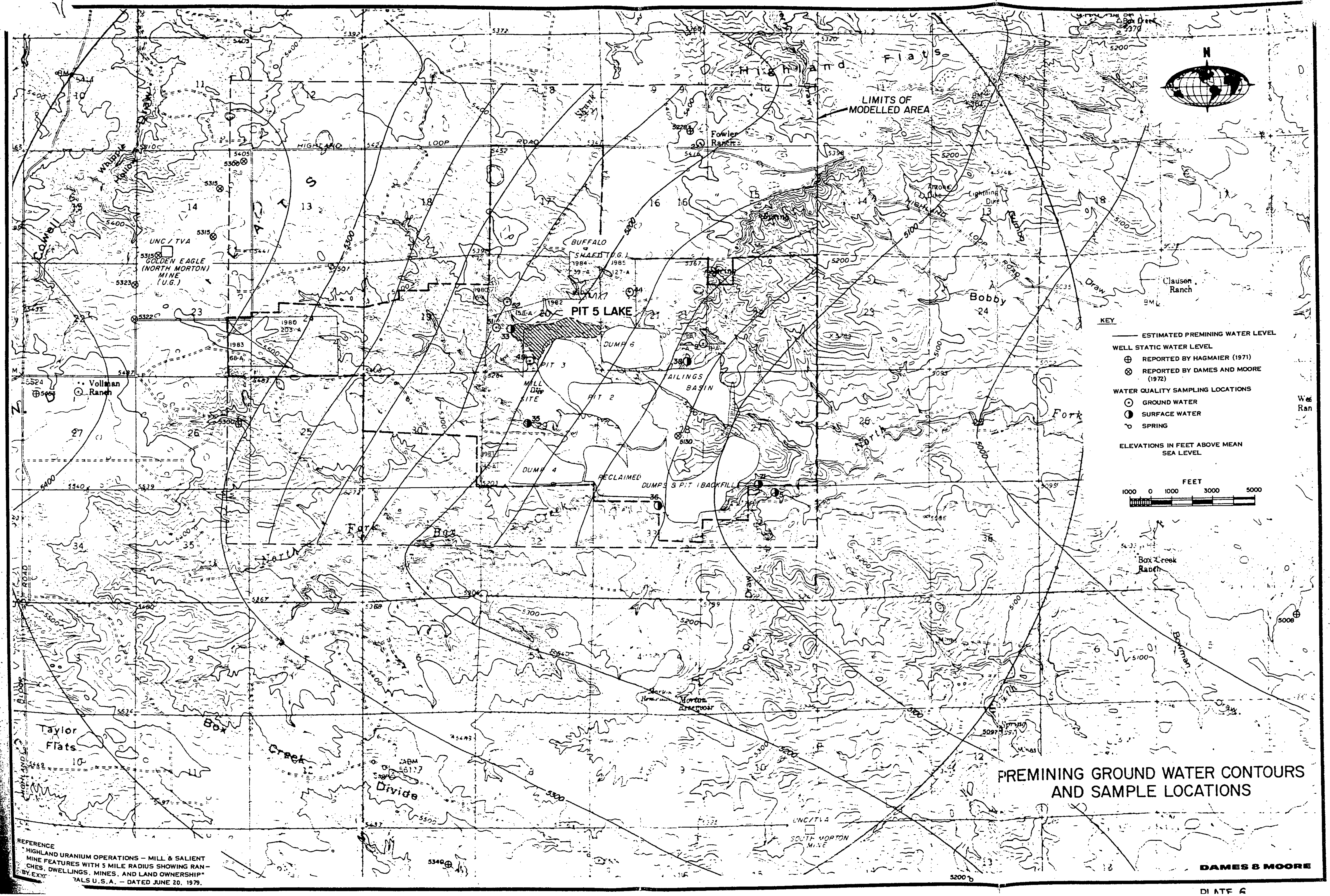
▩	63 FEET
▩	88 FEET
▨	113 FEET
░	138 FEET
☐	175 FEET

FEET
1000 0 1000 3000 5000

ISOPACH MAP AND FINITE DIFFERENCE MESH

REFERENCE
"HIGHLAND URANIUM OPERATIONS — MILL & SALIENT MINE FEATURES WITH 5 MILE RADIUS SHOWING RANCHES, DWELLINGS, MINES, AND LAND OWNERSHIP" BY EXXON MINERALS U.S.A. — DATED JUNE 20, 1979.

DAMES & MOORE

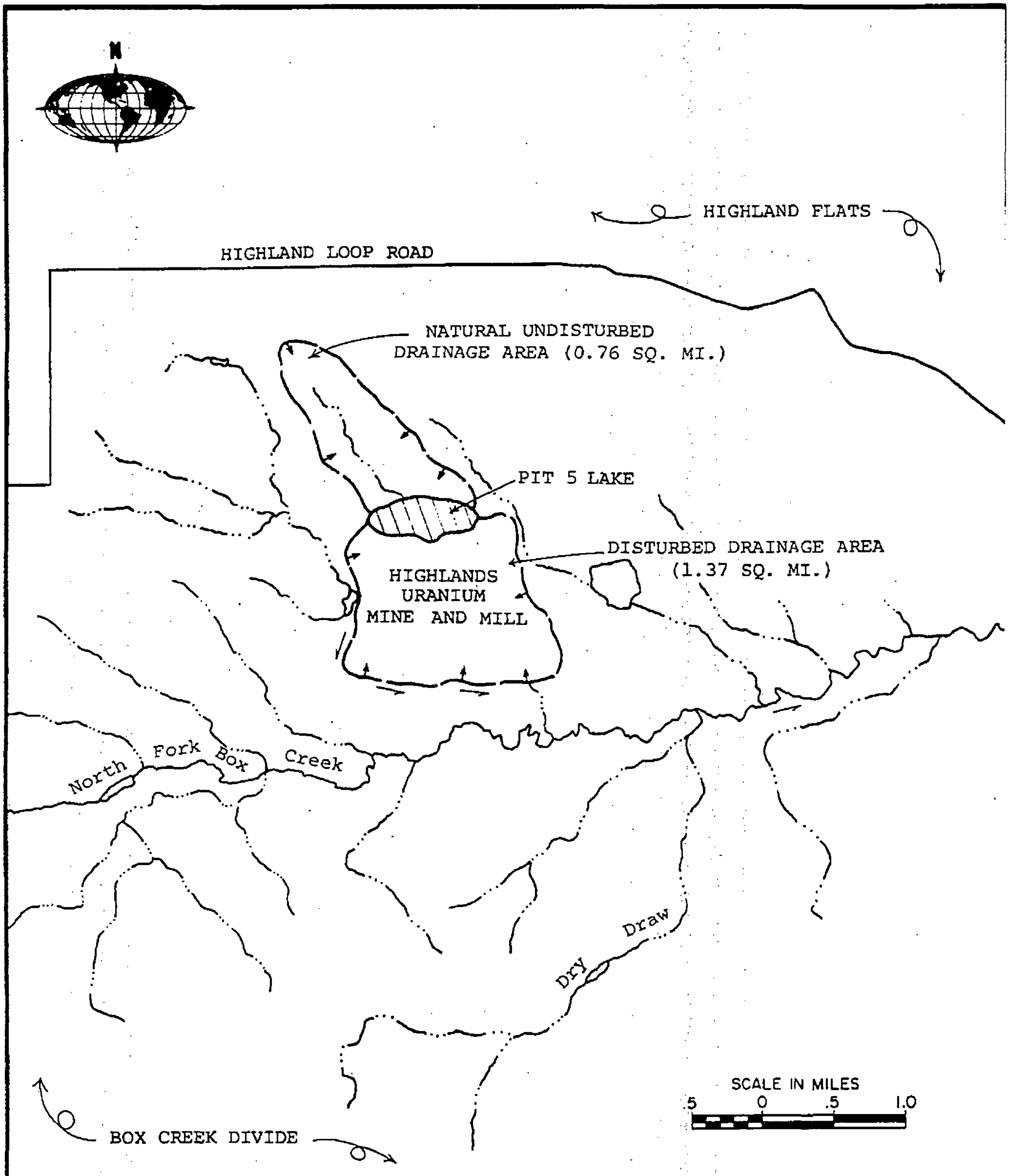


PREMINING GROUND WATER CONTOURS AND SAMPLE LOCATIONS

REFERENCE
"HIGHLAND URANIUM OPERATIONS – MILL & SALIENT MINE FEATURES WITH 5 MILE RADIUS SHOWING RANCHES, DWELLINGS, MINES, AND LAND OWNERSHIP"
BY EXXC RALS U.S.A. – DATED JUNE 20, 1979.

DAMES & MOORE

PLATE 6

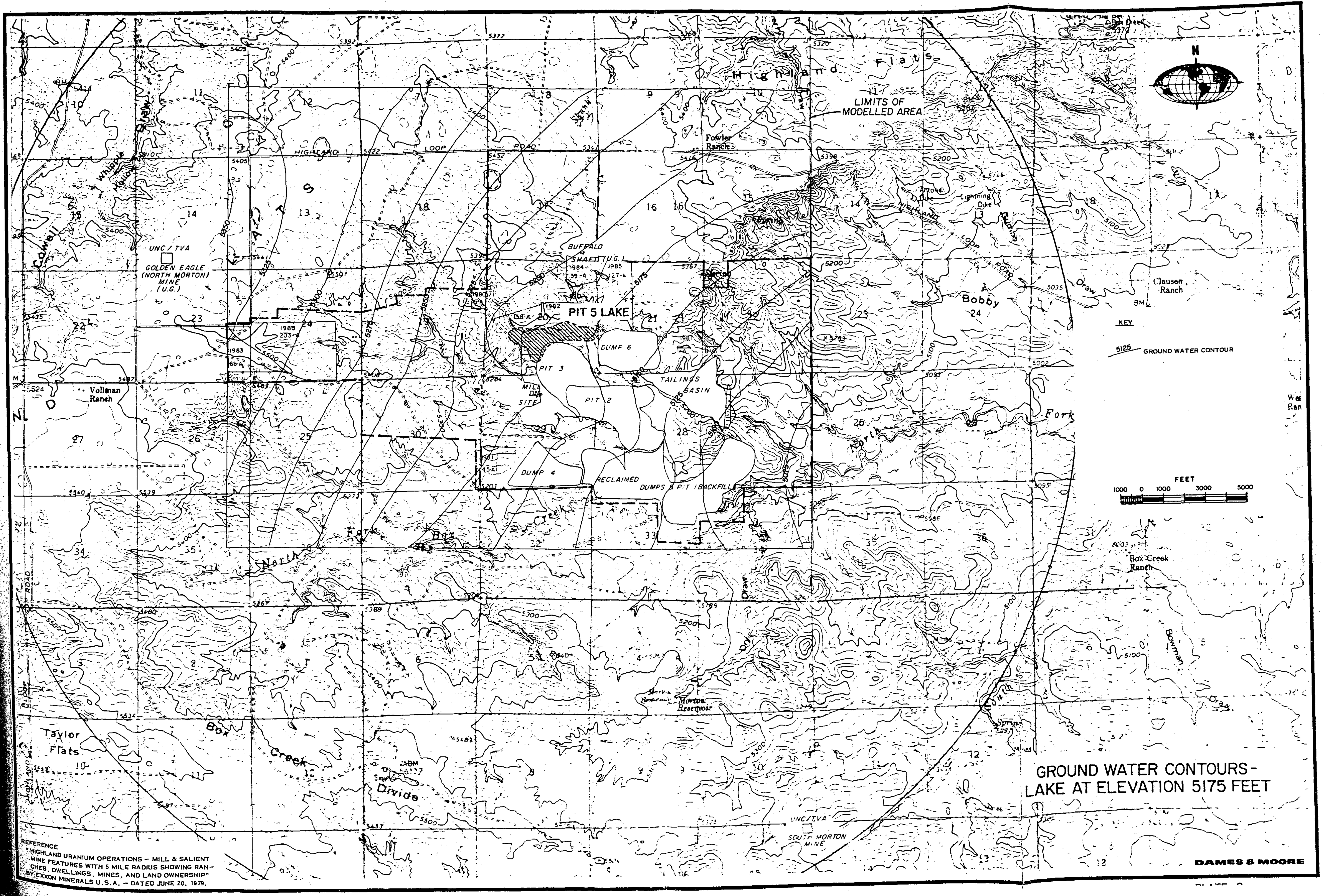


DRAINAGE AREA

REFERENCE
U.S.G.S. QUADRANGLES ENTITLED "BILL, WYOMING" AND "HIGHLAND FLATS WYOMING" – BOTH SHEETS DATED 1959.

DAMES & MOORE

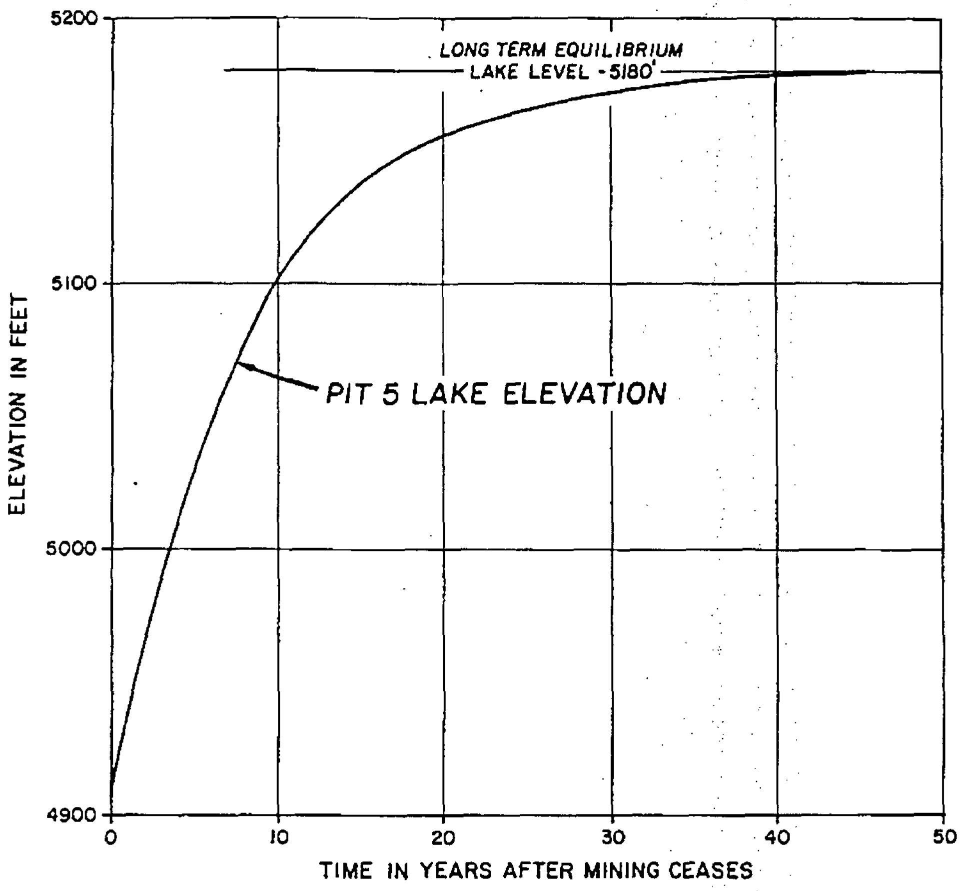
PLATE 7



GROUND WATER CONTOURS - LAKE AT ELEVATION 5175 FEET

REFERENCE
"HIGHLAND URANIUM OPERATIONS – MILL & SALIENT MINE FEATURES WITH 5 MILE RADIUS SHOWING RANCHES, DWELLINGS, MINES, AND LAND OWNERSHIP" BY EXXON MINERALS U.S.A. – DATED JUNE 20, 1979.

DAMES & MOORE



TIME VERSUS ELEVATION
FOR RISE OF PIT 5 LAKE

DAMES & MOORE

PLATE 10

REVISIONS
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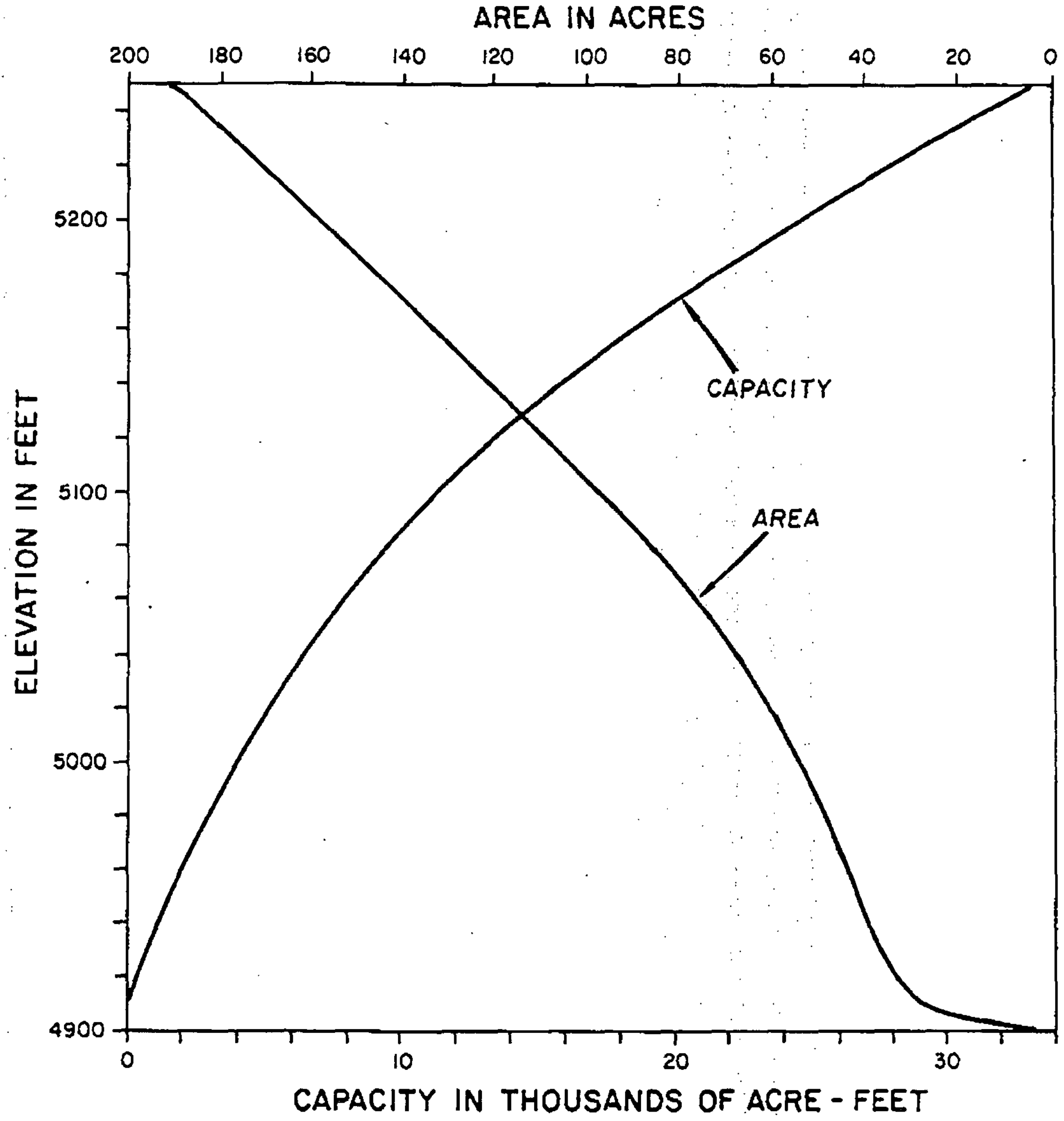
FILE ____

REVISIONS BY ____ DATE ____



PIT 5 LAKE AREA CAPACITY CURVE

DAMES & MOORE

PLATE 11

APPENDIX A

GROUND WATER MATHEMATICAL MODEL DOCUMENTATION

1.0 INTRODUCTION

In this appendix, prior to the description of the present mathematical model recent published literature concerning prediction procedures for flows in porous media coupled with heat and/or mass transfers, is first reviewed. Underground porous media are the primary subjects of concern, and the review is intended to provide an overview of the state-of-the-art. For this reason, it is necessarily brief.

The prediction procedures considered here include both analytical solution techniques for simplified governing equations and mathematical models based upon numerical solution techniques for sets of coupled and uncoupled governing differential equations. Attempts have not been made to prepare here a detailed classification of these procedures based upon vigorous mathematical criteria. The intention rather is to present a coherent summary which highlights the salient features and recent advances.

It is recognized that in preparing this review complete attention may not have been paid to the degree of validation, in respect of reliable field and laboratory data, that each available procedure may have been subjected to. The degree of sophistication and flexibility built into the procedures which permit them to accept such data in some convenient form, will be considered sufficient for purposes of review. This is largely due to the paucity of data, in sufficient quantity and of suitable quality, available for purposes of validation.

In the following sub-sections, reviews are separately presented for hydrodynamic aspects, aspects of chemical-species transport, and heat-transfer aspects respectively. This loose sub-division is maintained purely for reasons of convenience in presentation.

1.1 HYDRODYNAMICS

Analytical techniques for solving simplified equations of groundwater mass balance have been employed now for a number of years. The techniques involve basic assumptions about the geometric configuration of the flow domain and the uniformity of material properties. The employment of these techniques usually results in closed-form expressions for hydraulic head as a function of space and time. The velocity fields are then extracted by the approximate use of Darcy's law.

The deployment of such techniques for the flow distribution in multiple inter-connected aquifers has been reported by Bredehoeft and Pinder (1970). A recent and elegant treatment of leakage flow between aquifers is presented by Dever and Cleary (1979). A principal assumption involved in the above procedures is that the flow field is entirely saturated. The analysis of the more difficult problem of unsaturated flows has received relatively little quantitative attention. Braester et al. (1971) have prepared a comprehensive survey of governing equations for unsaturated flows. Gambolati (1973) has presented a discussion of vertical unsaturated flow analysis. It may be concluded, however, that versatile analytical procedures for saturated-unsaturated flow predictions do not, in general, exist. A simple one-dimensional procedure for predicting purely unsaturated flows has, however, recently been reported by McWhorter and Nelson (1979) who applied it to the prediction of seepage beneath tailings ponds.

Recent years have seen the proliferation of mathematical models based upon numerical schemes for solving the non-linear form of the mass-conservation equation. Narasimhan and Witherspoon (1977) review much of the current literature on the subject and indicate that both finite-difference and finite-element techniques have been employed with varying degrees of success. The premier ones of the former variety are those developed by Bredehoeft and Pinder (1970), Prickett and Lounquist (1971), Cooley (1974), Trescott et al. (1976), and Sharma (1979). Of the latter variety, the works by Narasimhan et al. (1976), Neuman (1973) and Pinder (1973) represent the principal ones. Trescott and Larson (1977) compare the efficacy of iterative methods used to solve sets of algebraic equations resulting from any form of numerical discretization.

Numerical procedures particularly suited to the prediction of saturated/unsaturated flows have also been developed (see for example Freeze, 1971; Narasimhan et al., 1977; Sharma and Hamilton, 1978; etc). The numerical formulation of leakage interactions between elements of a multiple aquifer system are extensively discussed by Frind (1979). The simulation of individual wells as well as the interactions amongst them have been reported by Prickett and Lounquist (1971) and Akbar et al. (1974).

An assessment of these and other similar procedures, in formulation and especially in implementation, has been prepared recently by Weston (1978). In agreement with this assessment, it is agrued here that numerical procedures, of sufficient degrees of comprehensiveness are presently available for application to the range of problems currently encountered. The major area of weakness in this is the prediction of flows in porous media with superposed fracture distributions. The state-of-the-prediction art for such flows has been thoroughly reviewed recently by Gringarten (1979).

1.2 MASS TRANSFER

The use of the term mass transfer here is intended to signify the transport of reacting chemical species within porous media by the complex interaction of several physical and chemical mechanisms. The set of such mechanisms considered here as a basis for review is:

- convection;
- diffusion and dispersion;
- buffering of pH;
- chemical precipitation by reactions with the solid matrix as well as the interstitial water;
- hydrolysis and precipitation;
- oxidation-reduction reactions;
- radioactive decay;
- volatilization;
- mechanical filtration;

- biological degradation; and,
- cation-exchange reactions.

It must be emphasized that specialized knowledge of the in-situ effects of individual mechanisms are understood only to a limited extent. The set of sophisticated measurements necessary to quantify these influences are currently being made in a variety of contexts. It is thus reasonable to suppose that soon the data obtained from these measurements will be available for purposes of refining the available mathematical models.

Analytical solutions to the convective dispersion equation have been developed by a number of authors, each of whom has been interested in specific geometric configurations and specific chemical species. The deployment of these solutions has been governed to a large extent by the requirements of the technical discipline encompassing each problem. For instance, a one-dimensional solution including adsorption effects has been developed by Gupta and Greenkorn (1973) as a tool in soil-chemistry. The work by Aikens et al. (1979) presents a variety of useful analytical solutions which take radioactive decay into account. Such solutions are indeed simple to use, and provide order-of-magnitude results in respect of concentration distributions with a modicum of effort. However, as geometries, material properties or the reactive mechanisms themselves become more complex, it is more convenient to employ mathematical models based upon numerical solution techniques.

One-dimensional models of this type abound in the literature. An interesting work by Selim et al. (1977) is concerned with finite-difference simulations of reactive solute transport through multilayered soils. Davidson et al. (1978) report the extension of this work to the finite-difference treatment of coupled adsorption, convective dispersion as well as biological degradation. This work represents an excellent study of the effects of pesticides in soils. The recent publication by Konikow and Bredehoeft (1978) describes a comprehensive finite-difference procedure for solving the coupled flow and chemical-species transport equations. A similar procedure, employing a sophisticated hybrid differencing scheme, has also been developed by Sharma (1979). These procedures are typical of economical schemes being currently reported, and to be entirely valid must be supplied with reliable physical and chemical data.

In like fashion, finite-element based numerical methods have been developed by researchers for predicting chemical-species transport in porous media. Rubin and James (1973) present one such method which uses the Galerkin approach. Gray and Pinder (1976) discuss the efficacy of this and other finite-element approaches, and in addition compare their relative accuracies. The application of one such approach by Pinder (1973) to groundwater contamination in Long Island is a meticulously-documented study augmented by field measurements. The application of finite-element methods to other types of problems involving transport of chemical species has also been achieved. One such application by Kealy et al. (1974) involves the analysis of seepage from tailings ponds. In this connection the work by Duguid and Reeves (1976) is well known. Weston (1978) presents a comprehensive review of major models of the above types and commends some for routine application. In short, a wide range of models covering a range of applicability is presently available for use in predicting the transport of reacting chemical species. The data requirements for these models are not available in the same level of quality.

1.3 HEAT TRANSFER

The analysis of heat transfer coupled with fluid flow in porous media, has also been conducted using both analytical and numerical techniques. The analytical solutions have, depending on specific boundary conditions, have much in common with those for transport of chemical species. However, the range of application of both analytical and numerical solutions for heat transfer is limited when compared with transport of chemical species.

The work by Harlan (1973) on the prediction of freezing in soils is an excellent early example of the use of a numerical procedure for the analysis of freezing fronts in porous media. Likewise, Holst and Aziz (1972) as well as Rubin and Roth (1979) examine aspects of thermally-induced convection in porous media and the stability of such flows. Special attention has been paid by Runchal et al. (1978) to the problem of heat-transfer effects, resulting from the disposal of high-level radioactive waste, upon groundwater motion. All such procedures depend, of course, on the supply of adequate field data, of sufficient quantities and of sufficient quality for purposes of input and validation. Such data, in respect of heat transfer, is extremely sparse, and hence most heat transfer models must be considered to be in a state of development. A recent example of field measurements of temperature effects in porous-media flows is that by Molz et al (1978). These measurements were specifically made in connection with thermal energy storage in aquifers. The problems involved in such storage have been discussed by Werner and Kley (1977). Theoretical studies of this problem, using both finite-difference and finite-element methods have been reported. Amongst the former is the work by INTERCOMP (1976); examples of the latter are: Mercer et al (1975); and, Papadopulos and Larson (1978).

2.0 MATHEMATICAL FOUNDATIONS

2.1 PREAMBLE

In what follows, a mathematical description is provided of a mathematically general version of the model. Two-dimensional versions of the model have been sucessfully employed in a variety of engineering applications. A simple three-dimensional version of the model has been developed, tested and applied recently by Dames & Moore (Sharma, 1979; and Hamilton and Sharma, 1979). It is economical of computational effort, whilst retaining the sophistry of physical and chemical formulations embedded other models mentioned above.

2.2 GOVERNING EQUATIONS

The symbols in the following equations are described in the Nomenclature list.

a. Piezometric head, h:

It can be shown (Narasimhan, 1975) that the partial differential equation governing the distribution of piezometric head is:

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left\{\Gamma_x^h \frac{\partial h}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{\Gamma_y^h \frac{\partial h}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{\Gamma_z^h \frac{\partial h}{\partial z}\right\} + \not{s}^h \quad . (1)$$

b. Fluid velocity components, U, V, W:

The well known Darcy Hypothesis is used to relate the velocity components to the distribution of piezometric head thus:

$$\begin{aligned} U &= -\Gamma_x^U \frac{\partial h}{\partial x} + \not{s}^U \\ V &= -\Gamma_y^V \frac{\partial h}{\partial y} + \not{s}^V \\ W &= -\Gamma_z^W \frac{\partial h}{\partial z} + \not{s}^W \end{aligned} \qquad (2)$$

c. Concentration of chemical species j, C_j:

It has been shown (Sharma, 1979) that the convective transport equation for the concentration of species is:

$$\frac{\partial}{\partial t}(dC_j) + \frac{\partial}{\partial x}(dUC_j) + \frac{\partial}{\partial y}(dVC_j) + \frac{\partial}{\partial z}(dWC_j)$$

$$= \frac{\partial}{\partial x}\left\{\Gamma_x^{c_j} d \frac{\partial C_j}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{\Gamma_y^{c_j} d \frac{\partial C_j}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{\Gamma_z^{c_j} d \frac{\partial C_j}{\partial z}\right\}$$

$$+ \not{s}^{c_j} \quad . \qquad (3)$$

d. Thermal energy, T:

The equation governing the conservation of thermal energy may be expressed as follows.

$$\frac{\partial}{\partial t}(\bar{C}_v T) + \frac{\partial}{\partial x}(U\bar{C}_p T) + \frac{\partial}{\partial y}(V\bar{C}_p T) + \frac{\partial}{\partial z}(W\bar{C}_p T)$$

$$= \frac{\partial}{\partial x}\left\{\Gamma_x^T \frac{\partial T}{\partial x}\right\} + \frac{\partial}{\partial y}\left\{\Gamma_y^T \frac{\partial T}{\partial y}\right\} + \frac{\partial}{\partial z}\left\{\Gamma_z^T \frac{\partial T}{\partial z}\right\}$$

$$+ s^T \qquad (4)$$

2.3 INITIAL AND BOUNDARY CONDITIONS

Initial and boundary conditions, respectively within and on the boundary of the solution domain, for each of the dependent variables must be supplied in order to complete the mathematical specification of the problem.

Initial conditions designate the distribution of h, C_j and T, over the entire solution domain of interest, at the commencement of the solution. Such conditions may be obtained from the results of a field-measurement program , as for example would be the regional piezometric head distribution. Alternatively, they may be obtained from laboratory-scale experiments, as for example the ambient concentration of chemical species in ground water. They may also be supplied from the results of previous calculations of a similar nature.

Boundary conditions represent variations of the dependent variables, their fluxes or combinations thereof, at the boundaries of the solution domain. Such conditions may also be obtained from the results of a field-measurement program, as would be the case with recharge boundaries. It is important to note that boundary conditions may vary with time, and as a result, influence the accuracy of results obtained with computational solution procedures.

In addition to the above it must be noted that certain man-made as well as natural influences affect the distribution of h, C_j and T

within the solution domain. Such influences include discharging (and recharging) wells; artifical and natural barriers occuring locally to flow (and, heat and mass transfer) within the domain.

3.0 NUMERICAL SOLUTION PROCEDURE

3.1 GENERAL

The numerical procedure adopted in the present model is of the integrated finite-difference (IFD) variety with origins in an earlier work on computational fluid mechanics and heat transfer (Sharma, 1974). Details of the present procedure are available in Sharma (1979). A brief description is provided in this section.

3.2 NUMERICAL GRID AND VARIABLE LOCATIONS

An illustration of the numerical grid adopted in the x-y plane is illustrated in Figure (1). In this figure the faces of control volumes, used in deriving the discretised equations, are indicated as dashed lines. The intersections of grid lines, termed grid nodes, are chosen to lie in the geometric center of the associated control volumes. An exception is made at the boundaries of the domain wehre the nodes lie on the boundaries themselves.

All problem variables, with the exception of the velocity components U, V and W, are presumed to be located at grid nodes. The x-direction velocity components U are presumed to lie on the intersections of the control-volume faces in the y-z plane with the x direction grid lines. Likewise, the y-direction velocity components V are presumed to lie on the intersections of the control-volume faces in the x-z planes with y-direction grid lines. In general, with the possibility of using variable grid spacings in any given direction, it is important to note that velocity components in any given direction do not lie exactly midway between grid nodes in that direction.

8.0 FIGURES

3.3 THE DISCRETISED EQUATIONS

Discretised forms of the partial-differential equations (1), (3), and (4) are obtained by integrating them over the above-mentioned control volumes. It is presumed for purposes of integration that the dependent variables vary linearly between successive grid nodes. Furthermore, one such discretised algebraic equation per dependent variable, may be derived thus for each control volume within the solution domain. Such an algebraic equation represents, in finite-difference form, the conservation of mass or of chemical species. The preservation of these conservation principles in the simultaneous solution of the algebraic equations permits an exact accounting of mass and momentum to be made. It is of great importance to note that such precise accounting of chemical species is vital in problems concerning the limited disposal of waste at a given site. Many, otherwise praiseworthy mathematical models, do not ensure that this is the case.

The discretised equations, at an arbitrary grid node , have the following forms:

a. piezometric head:

$$\left\{ \sum_{P} A^{h} - SN_{P}^{h} \right\} h_{P} = \sum_{i = E,W,N,S,F,B,O} A_{i}^{h} h_{i} + SO_{P}^{h} \quad .(5)$$

b. Species concentration:

$$\left\{ \sum_{P} A^{C_j} - SN_{P}^{C_j} \right\} C_{j_P} = \sum_{i = E,W,N,S,F,B,O} A_{i}^{C_j} C_{j_i} + SO_{P}^{C_j} \quad .(6)$$

c. Temperature:

$$\left\{ \sum_{P} A^{T} - SN_{P}^{T} \right\} T_{P} = \sum_{i = E,W,N,S,F,B,O} A_{i}^{T} T_{i} + SO_{P}^{T} \quad . (7)$$

In the above, A's denote coefficients computed from known (or sometimes presumed known temporarily) values of hydraulic conductivity, dispersion coefficients etc.; and SO, SN are components of a linearised source term; i denote respectively the neighbouring grid nodes in space; O denotes the coefficient associated with the previous-time value of the appropriate dependent variable; and F, B denote the forward or backward application of the block correction procedure. Various forms which the source terms may take are shown in Table 1, presented overleaf.

3.4 THE SOLUTION ALGORITHM

The sets of simultaneous algebraic equations noted above are solved by the efficient application of an alternating-direction, heavily-implicit, line-by-line solution algorithm coupled to a plane-by-plane block correction proecedure. Details are provided by Sharma (1979). This algorithm applied iteratively leads to relatively monotonic solutions for most problems with commonly-encountered boundary conditions.

4.0 COMPUTER-PROGRAM DETAILS

The algorithm mentioned above has been incorporated into a set of computer programs written for one-, two- and three- dimensional problems. These programs, called TARGET (for Transient Analyser of Reacting Ground Water Effluent Transport), are written in standard FORTRAN-IV. They are thus capable of being run on most available computers. On a CDC-6600 machine a typical computer run for an unsteady two-dimensional problem requires approximately 60 seconds of central processor time.

5.0 SOME PREDICTED RESULTS

For purposes of testing the computer program TARGET and to demonstrate the accuracy of results predicted thereby, a few test runs were made of a selected problem. The problem posed is that of unsteady convective dispersion in one space dimension.

Grid-dependency tests were first conducted to determine the effect of grid-size upon numerical accuracy. It was observed in that sufficiently accurate results may be obtained with a reasonable number of grid nodes. Further tests investigating the dependence of accuracy upon the chosen time-step were conducted. These are illustrated in Figures 2 and 3, which indicate that for accuracy a sufficiently small timestep must be chosen. Subsequently predictions of a moving solute front were made. For a given set of parameters, the predicted results for this case may be observed in Figure 3 to compare very favourably with the corresponding analytical solutions.

TARGET has undergone numerous other tests, not reported here, to ensure that the program is essentially correct and that the results predicted with it are both plausible and valid. The validation tests are being continued in parallel efforts.

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7.0 NOMENCLATURE

A_i^φ	coefficients representing hydraulic conductivity or dispersion coefficients etc., for variable Ø at position i;
C_j	chemical species concentration of species j;
$C_{j,d}$	concentration, of species j, of discharge;
$\bar{C}_p$	average specific heat capacity at constant pressure;
$C_{p,d}$	specific heat capacity at constant pressure of discharge;
$\bar{C}_v$	average specific heat capacity at constant volume;
h	hydraulic head;
k_z	vertical hydraulic permeability;
$\dot{q}'''$	flow rate;
S	storage coefficient;
s^φ	source term for variable Ø;
SO_p	component of linearized source term for variable Ø at node p;
SN_p	component of linearized source term for variable Ø at node p;
T	temperature;
T_d	temperdatue of discharge;
t	time;
U	x-direction velocity;
V	y-direction velocity;
W	z-direction velocity;
x	horizontal cartesian coordinate direction;
y	horizontal cartesian coordinate direction;
z	vertical cartesian coordinate direction;
Γ_x^φ	effective hydraulic conductivity or dispersion coefficient for variable, in direction x;
ρ	density;
ρ_o	reference density.

SCHEMATIC ILLUSTRATION OF NUMERICAL GRID

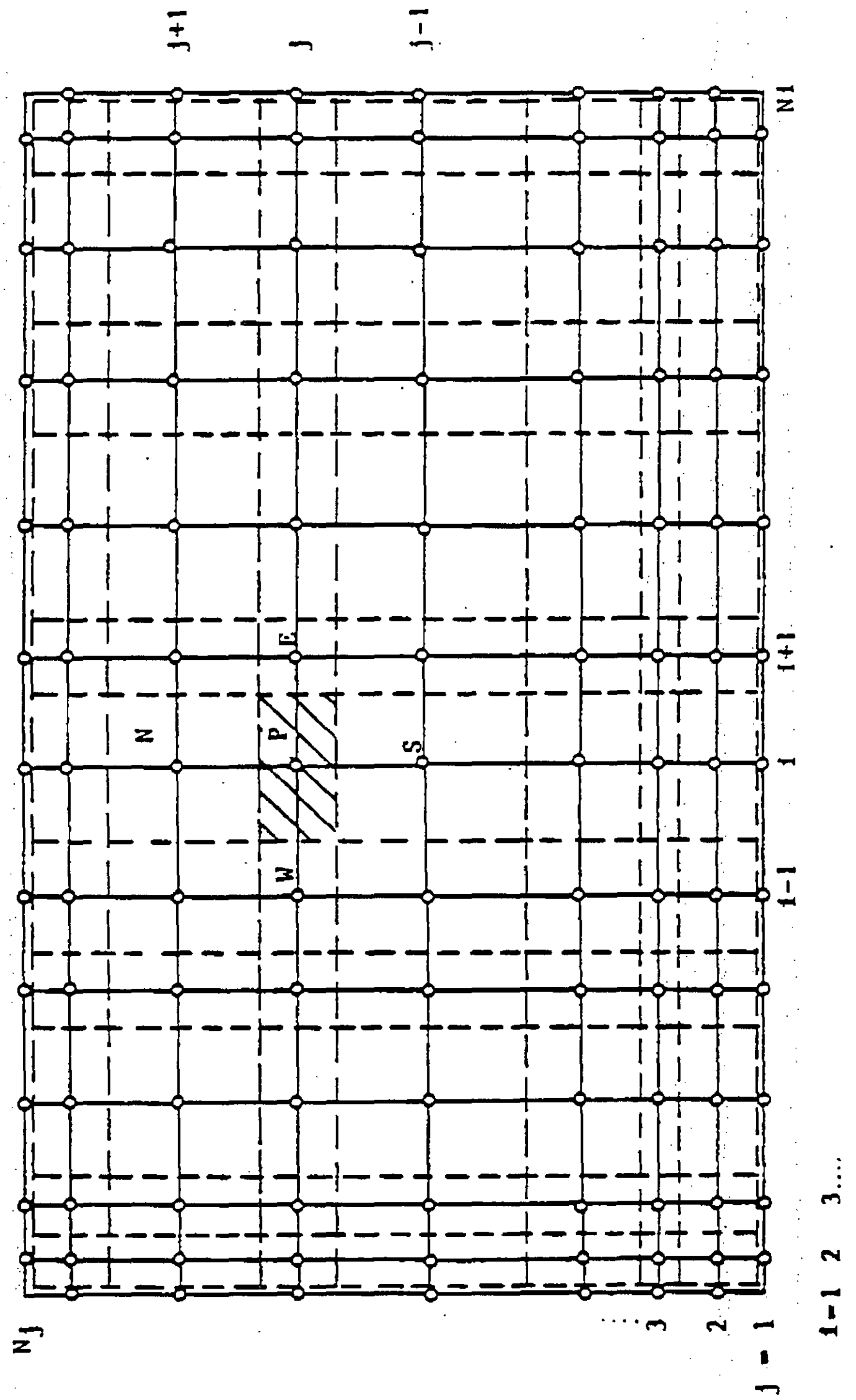


Figure 1

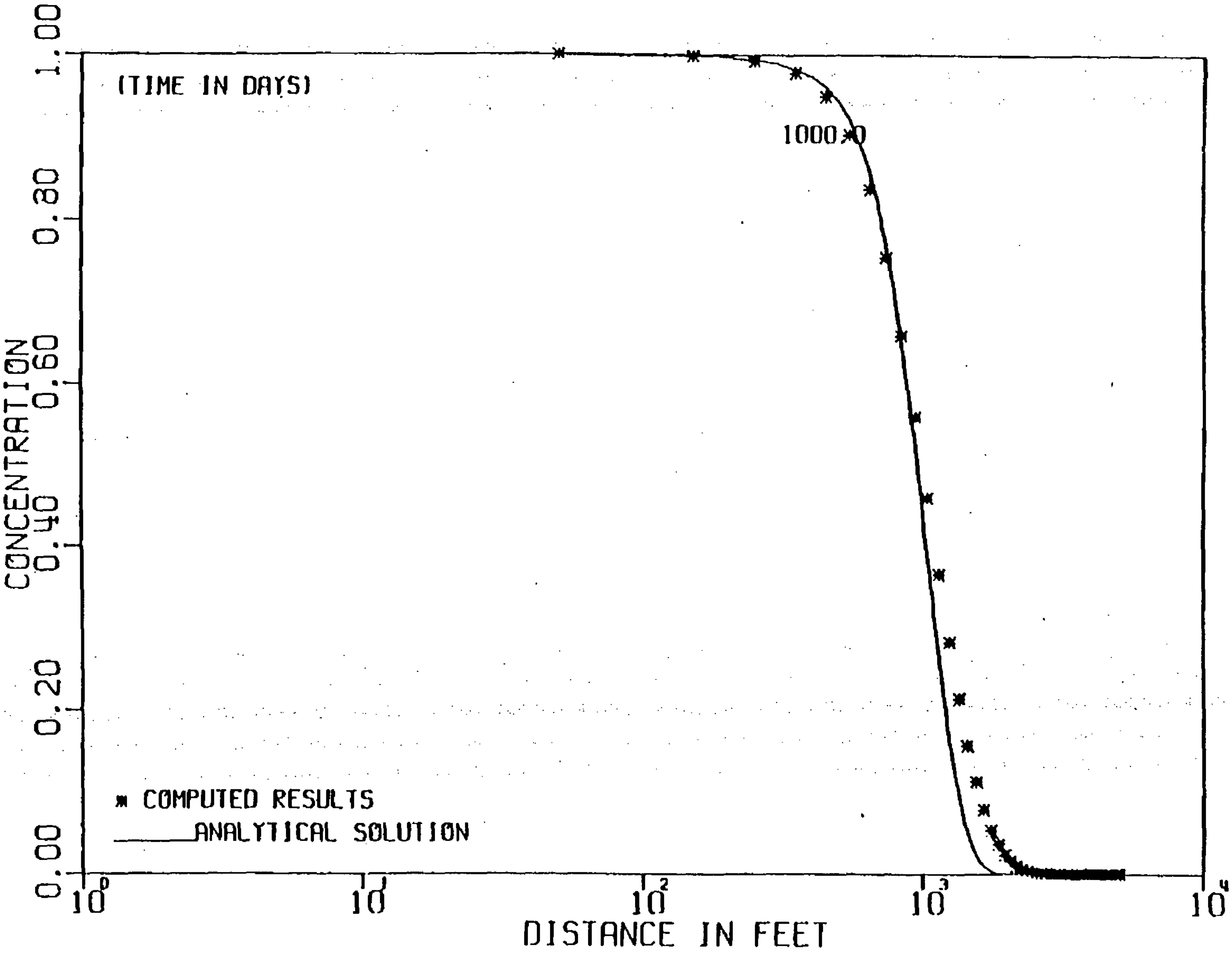
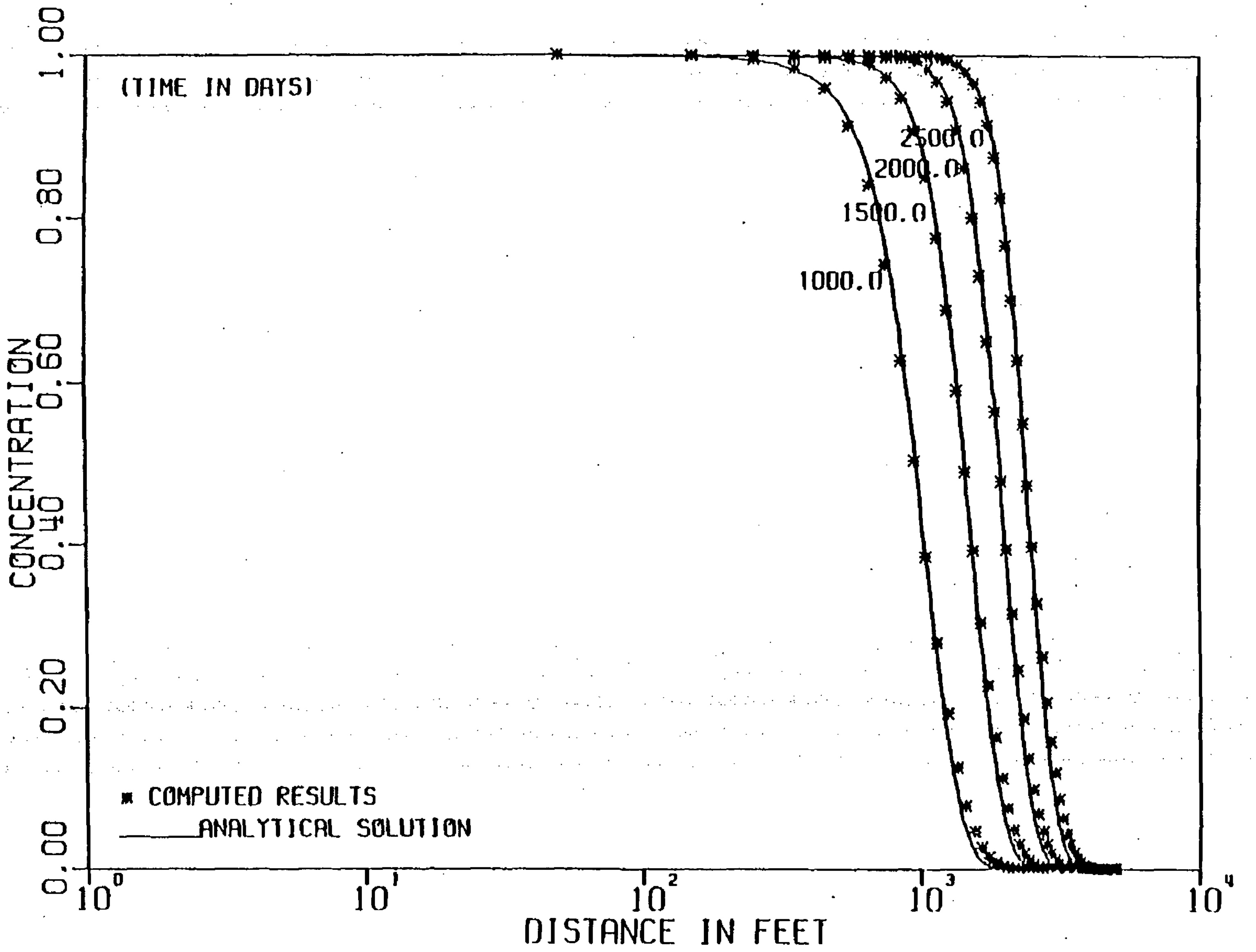


Figure 2

TIME DEPENDENCE OF CONCENTRATION DISTRIBUTIONS

Figure 3



TIME DEPENDENCE OF CONCENTRATION DISTRIBUTIONS

Source Term Description	Algebraic Form
Piezometric heat distribution	
Injection or extraction flow rate	$\pm \dot{q}'''$
Buoyancy	$- \frac{\partial}{\partial z}\left\{k_z \left[1 - \frac{\rho}{\rho_0}\right]\right\}$
Temperature distribution	
Injection or extraction rate	$\dot{q}'''\left\{c_{p,d} T_d - \bar{c}_p T\right\}$
Concentration distribution	
Injection or extraction rate	$\dot{q}'''\left\{c_{j,d} - c_j\right\}$

TABLE 1

DESCRIPTION OF SOURCE TERMS

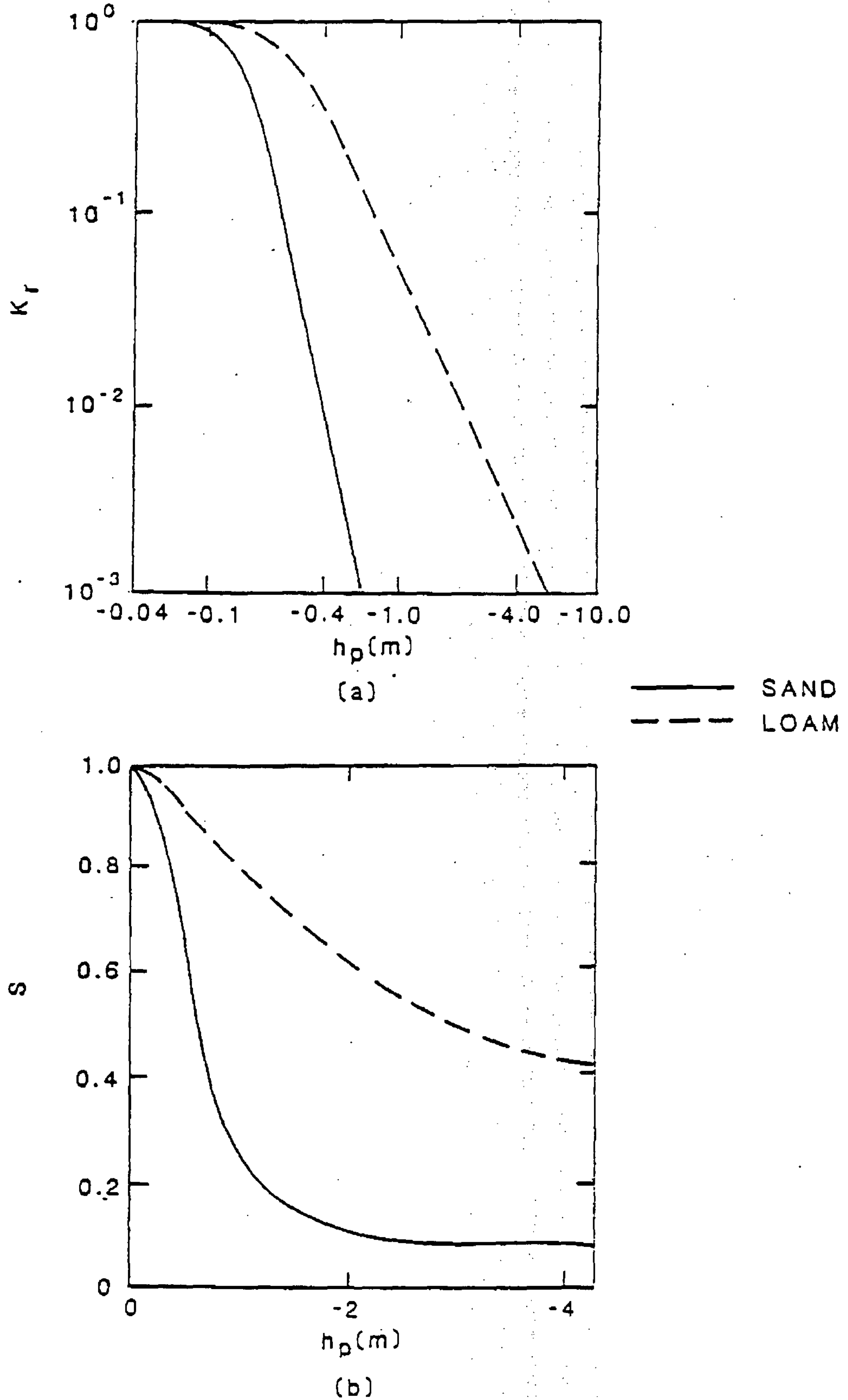


FIGURE 1. INFLUENCE OF SUCTION PRESSURE HEAD ON (a) HYDRAULIC CONDUCTIVITY AND (b) DEGREE OF SATURATION, (VAN GENUCHTEN et al., 1977)

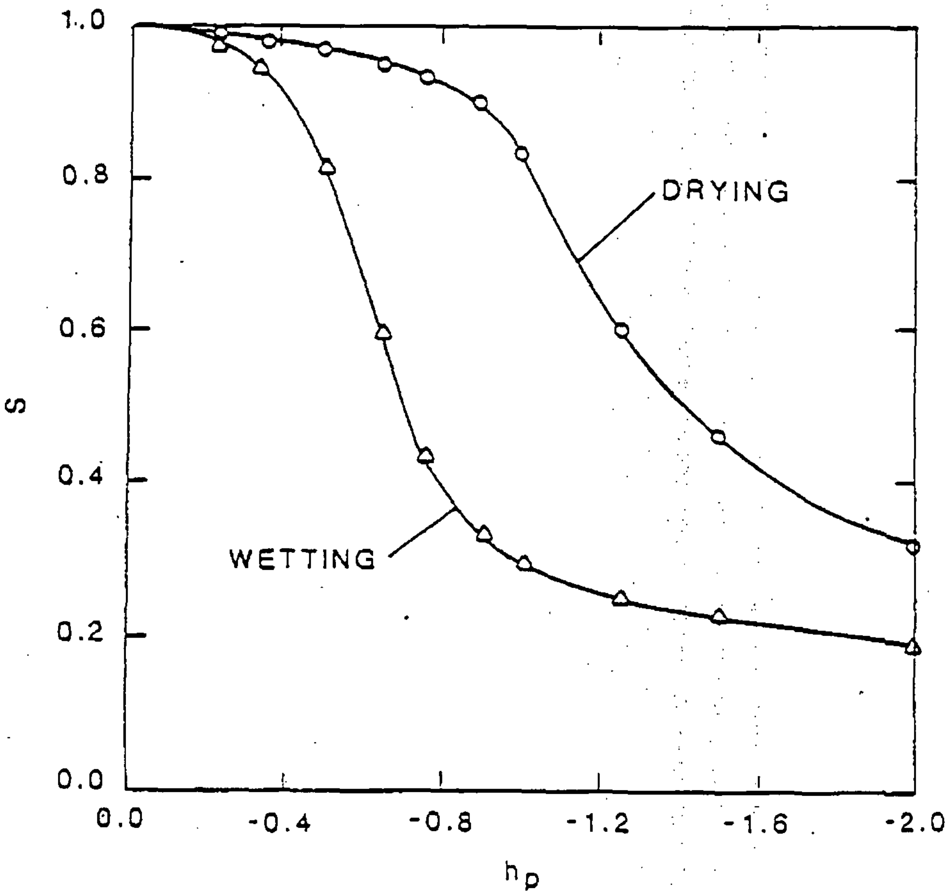


FIGURE 2. HYSTERESIS BETWEEN DEGREE OF SATURATION AND PRESSURE HEAD FOR SANDY SOILS, (LIAKOPOULOS, 1965)

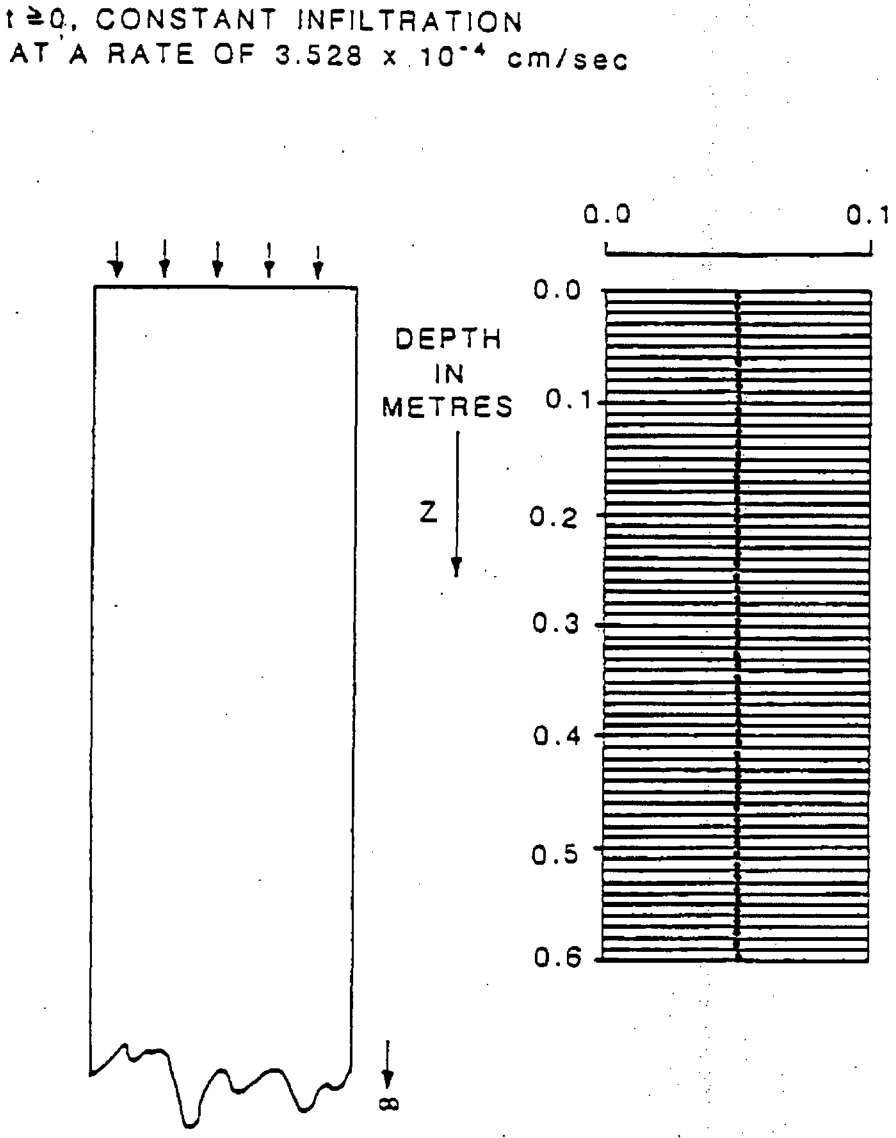


FIGURE 3. BOUNDARY CONDITIONS AND GRID FOR CONSTANT INFILTRATION TEST PROBLEM

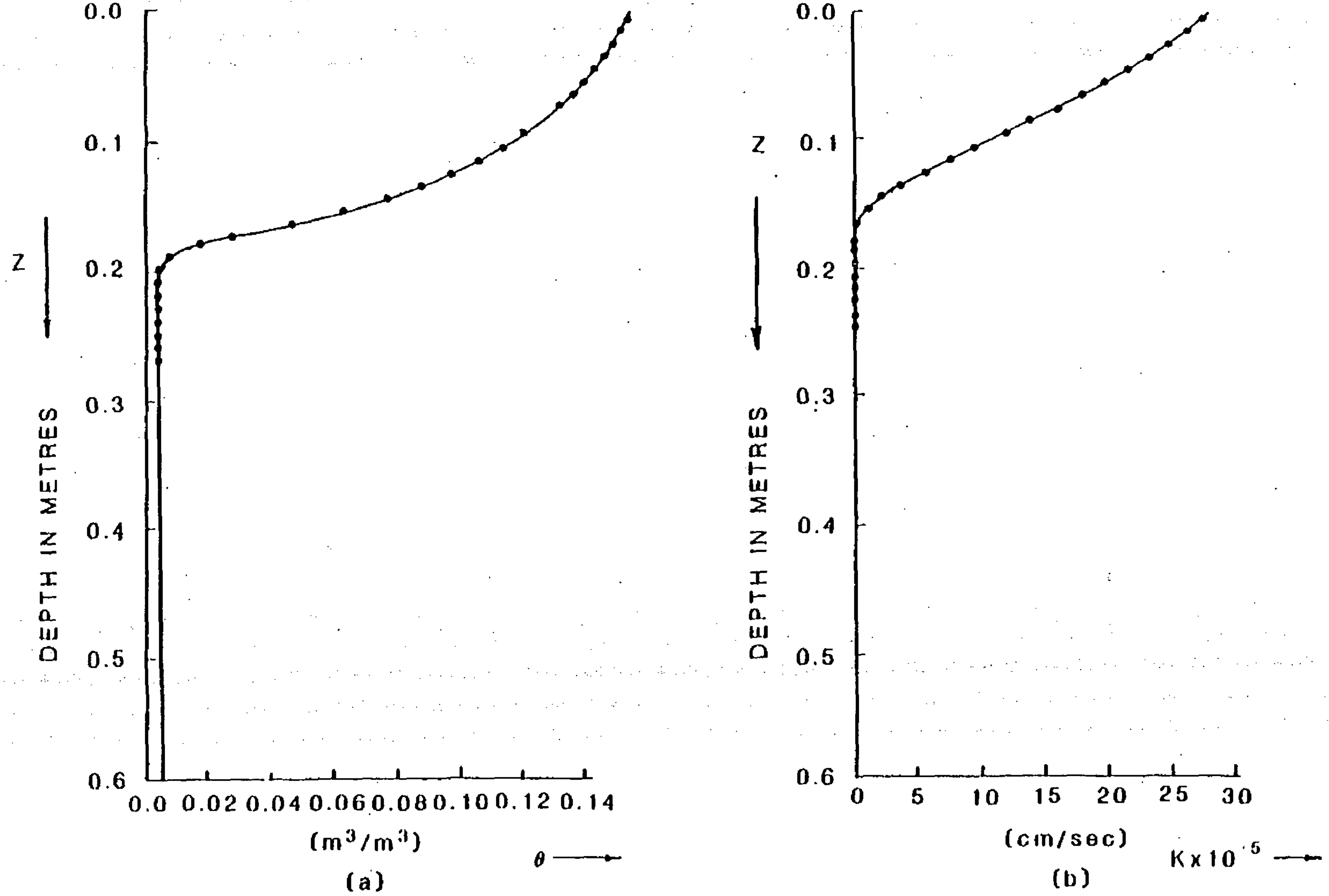


FIGURE 4. PREDICTED VARIATION OF (a) MOISTURE CONTENT, AND (b) HYDRAULIC CONDUCTIVITY WITH DEPTH AT t= 5625 SEC

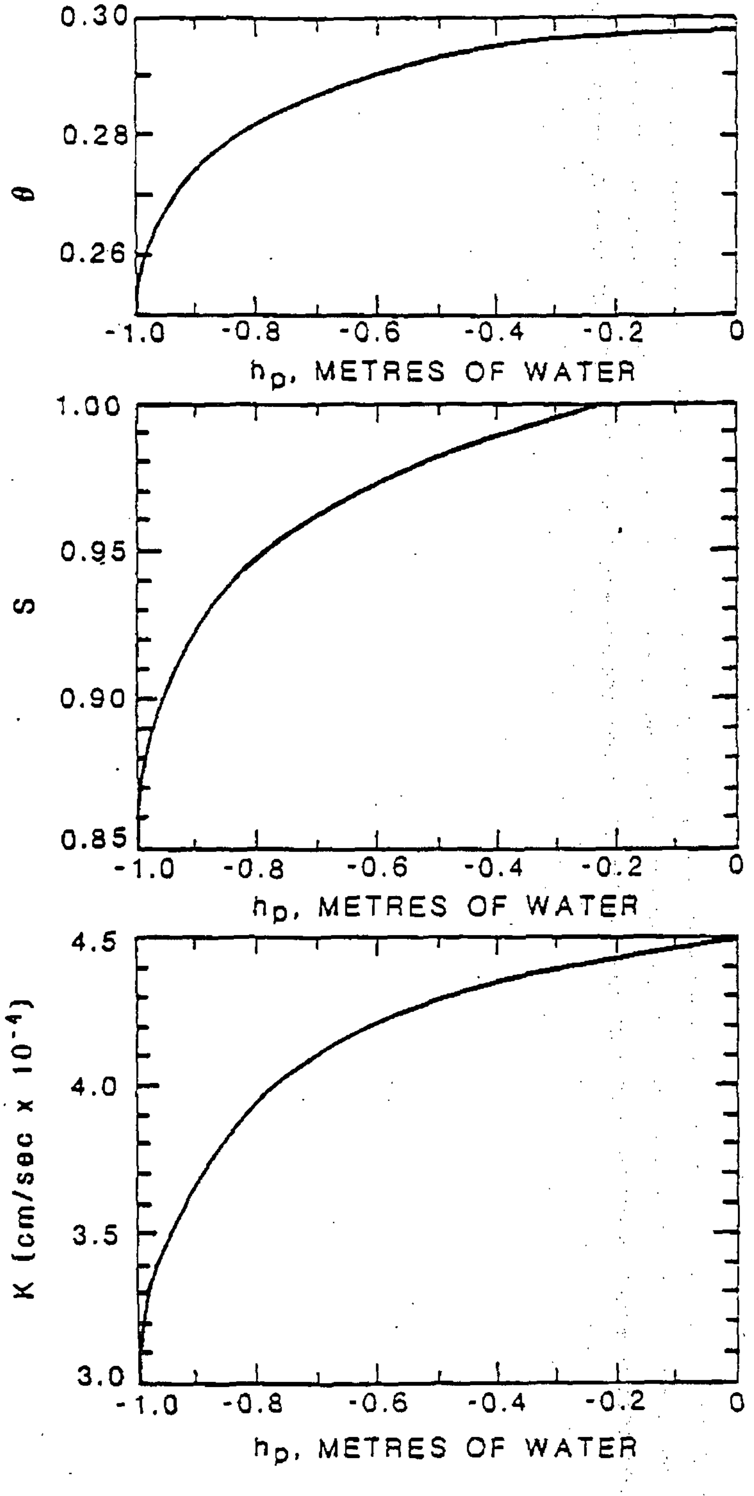


FIGURE 5. MATERIAL PROPERTIES OF SAND SUPPLIED TO MODEL (LIAKOPOULOS, 1965)

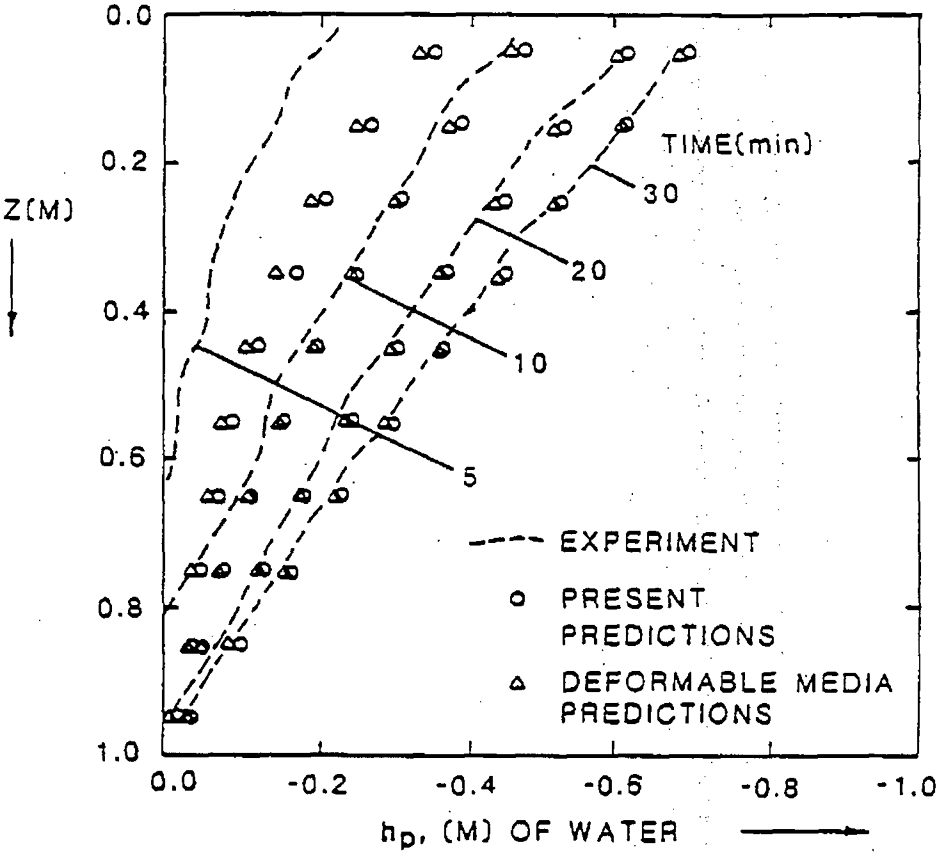


FIGURE 6. COMPARISON OF PREDICTED PORE PRESSURES IN A ONE-DIMENSIONAL DRAINING SAND COLUMN WITH EXPERIMENTAL DATA