HYDROLOGY OF STOCKPILES OF SULFIDE BEARING GABBRO IN NORTHEASTERN MINNESOTA

Minnesota Department of Natural Resources
Division of Minerals
St. Paul, Minnesota
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by

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FOREWORD

This report is essentially in final form although certain typographical problems still exist. Rather than delay the release of this report any longer, it is being issued in its present form. The appendices are quite lengthy and are not included with this document. They are available for those who are interested.

TABLE OF CONTENTS

DATA

ANALYSIS

CONCLUSIONS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

INTRODUCTION

Purpose

Studies of leaching from sulfide bearing gabbro were initiated in response to proposals for copper-nickel mining in northern Minnesota. Studies of the hydrology of waste rock piles were undertaken along with the leaching studies to help estimate the impacts of the proposed mining.

The purposes of this case study were to develop a conceptual model of the inputs, outputs and flow paths of water within stockpiles, and to develop generalizations concerning the hydrologic behavior of stockpiles which would be useful in evaluating impacts. The study also provides a base from which to develop mitigation measures.

Description of the Study Sites [1]

1. Erie Mining Company's Dunka Pit

The Dunka Pit (Erie Mining Company Area 8) is located in the northwest quarter of the Babbitt NE 7.5' quadrangle, south of Birch Lake. The pit is approximately 2.5 miles long, 0.25 miles wide and 350 feet deep, and follows the strike of the Biwabik Iron Formation (N30E). The Biwabik Iron Formation dips southeast underneath the basal mineralized zone of the Duluth Gabbro Complex. Millions of tons of stripped overburden, including sulfide bearing gabbro, are stockpiled near the pit (Figure 1).

Variable thickness of glacial till, outwash and pit overlie massive, crystalline bedrock in the area. The bedrock is essentially impermeable, while the glacial material has low to moderate yields (Siegel and Ericson, 1979).

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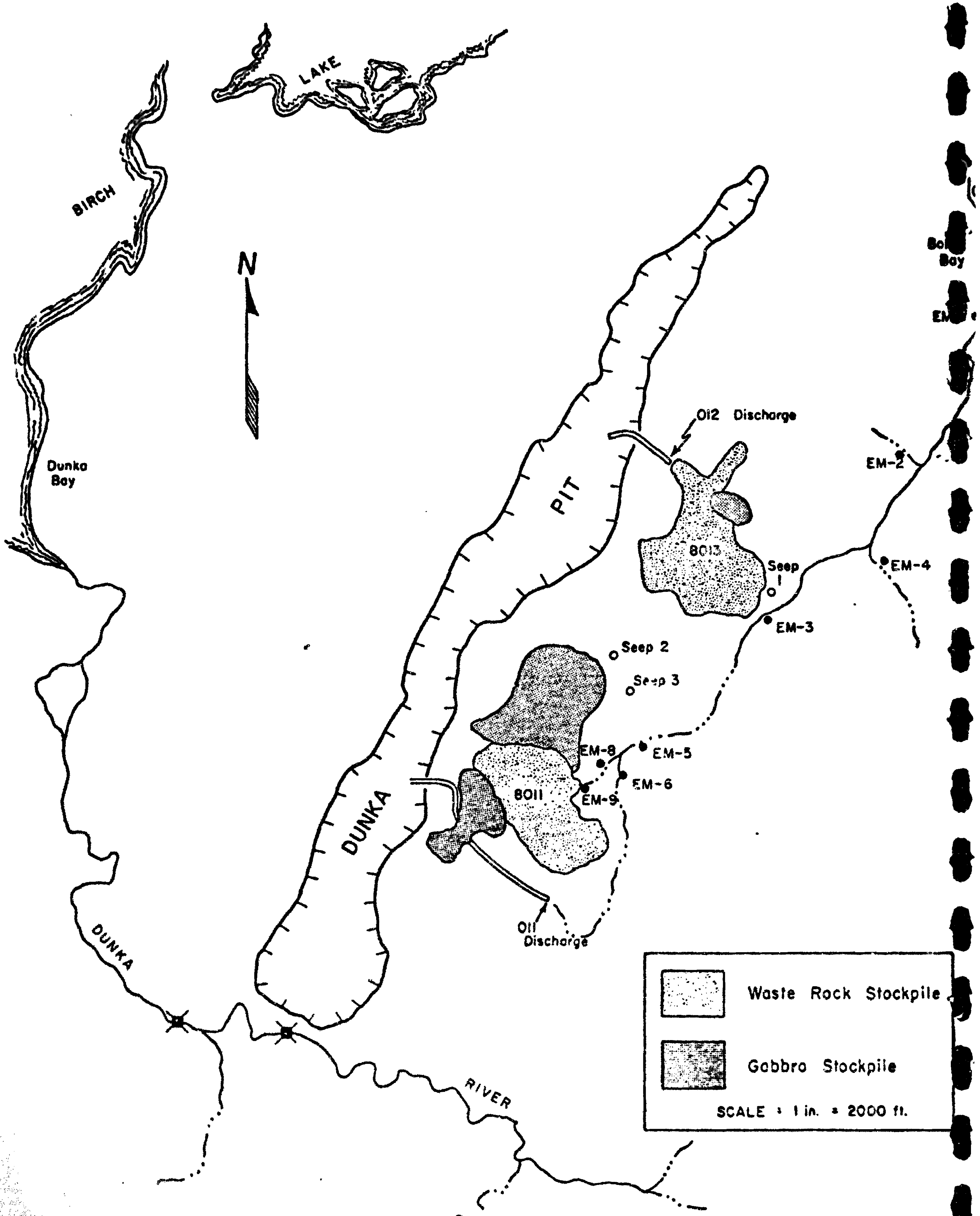
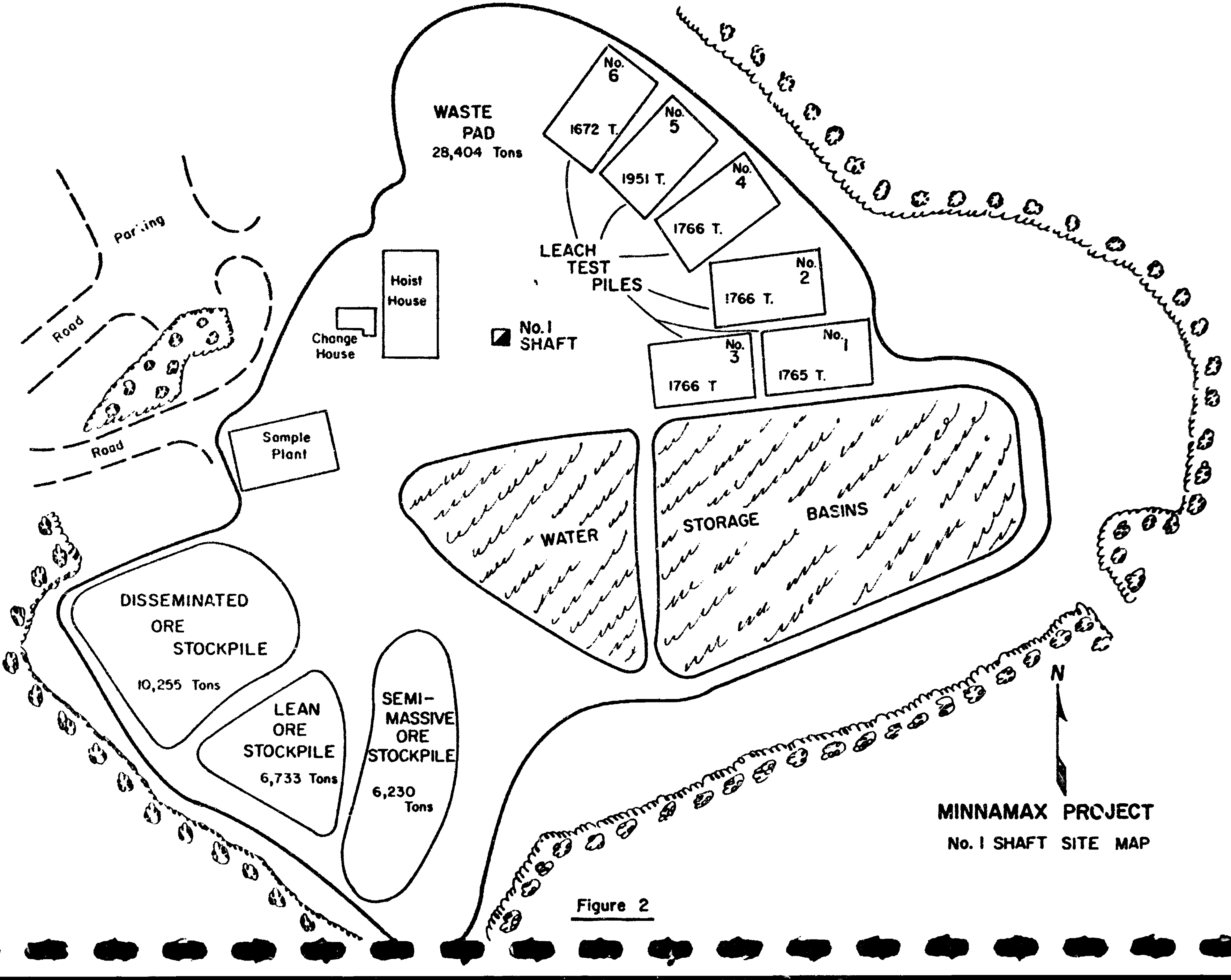
[1] Much of the description is from Eger, Johnson and Otterson, 1977, pp. 2-12, 97, 99.

Figure 1. Erie Mining Company's Dunka Pit, 1977



2. Minnamax

AMAX, Inc. has completed a copper-nickel exploration shaft at the Minnamax site, four miles southwest of the Dunka Pit. AMAX has constructed six leaching and reclamation test piles at the site (figure 2). Each pile is approximately 40 ft. x 80 ft. and contains 1700 to 2000 tons of lean ore. The piles are on impervious liners, and all runoff is measured and analyzed.



MINNAMAX PROJECT

No. I SHAFT SITE MAP

Figure 2

Regional Climate and Hydrology

The Copper-Nickel Study Region has a continental climate with cold winter and warm summers (Figure 3) (Watson, 1978, p. 1). Distinct wet and dry seasons correlate with the warm and cold seasons (Fig. 4 and table 1); roughly 70% of the annual precipitation falls in the six months between mid-April and mid-October (Watson, p. 26). The period from June to early September is characterized by convective storms, while frontal storms dominate the period from late October through May (Watson, p. 11-14). There is usually snow on the ground from mid October to mid May (Watson, 1978, Figs. 9.1 - 9.2). Precipitation data from Babbitt were taken to represent precipitation in the Study Area. Babbitt is near the middle of the copper-nickel resource zone, and has a 56 year record which correlates well with the longer record from Virginia and the record from Hoyt Lakes, where pan evaporation data are also collected (Hickok, 1977, p. 7). Average annaul precipitation at Babbitt is 28.57" (for 56 years of record adjusted by Watson on the basis of 83 years of record at Virginia). The driest year of record had 16.4" of precipitation, and the wettest year, 37.56" (Watson, 1978, p. 35). Frequency analysis of the 56 years of record predicts a 100 year low of 16" and a 100 year high of 39" (see appendix 1).

Annual pan evaporation at Hoyt Lakes is 725 mm (28.5"), roughly equal to precipitation. Monthly values are shown in table 1 and Figure 5.

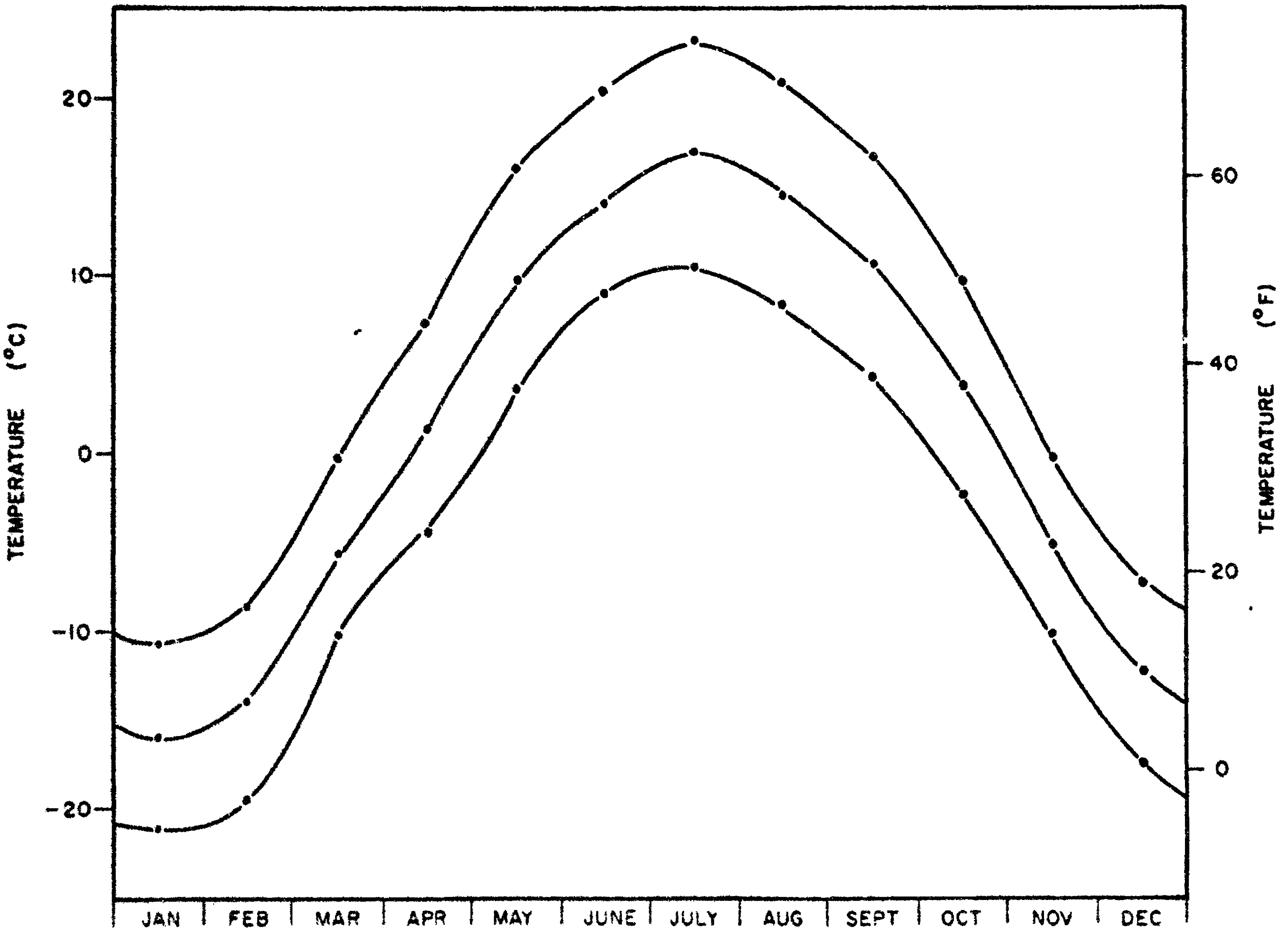
Seasonal variations in streamflow have been described by Garn (1975, p. 18):

> The pattern of runoff is typical of areas where snowmelt is the major source of runoff, which is augmented by spring and summer rainfall. From the spring peak flows, streamflow recedes steadily through the summer, reacting only temporarily to heavy rainfall. Streamflow stabilizes in late summer and fall, reaching a summer low in late August or September. Streams

Figure 3

MONTHLY MEAN, MEAN MINIMUMUM and MEAN MAXIMUM TEMPERATURES

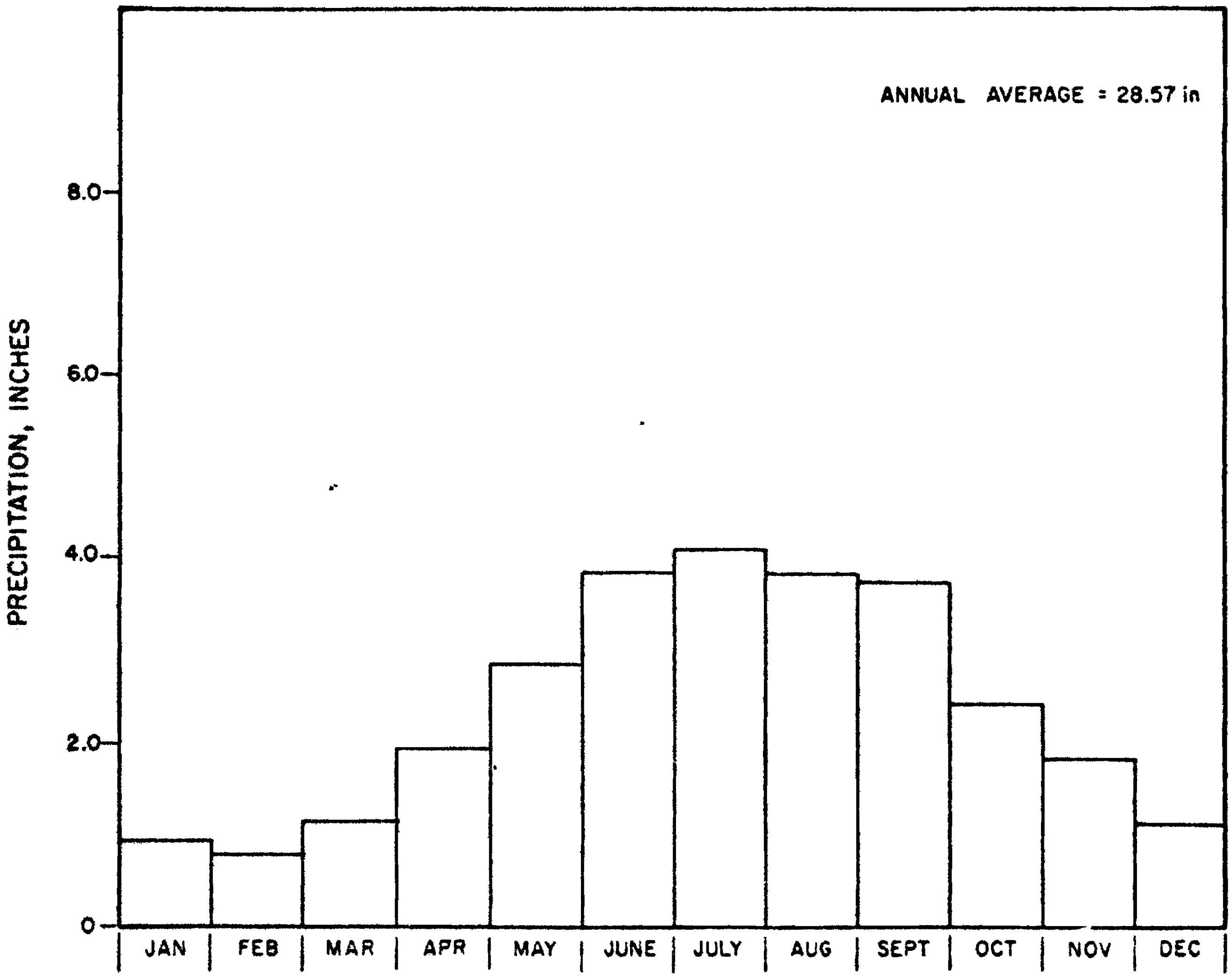
BABBITT



from WATSON, 1978; table 4.1

Figure 4

AVERAGE MONTHLY PRECIPITATION, BABBITT



from Watson, 1978, table 5.5

Table 1 : MONTHLY AND ANNUAL PRECIPITATION, RUNOFF AND PAN EVAPORATION IN THE STUDY AREA

	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	ANNUAL
PRECIPITATION [1]													
inches	0.92	0.79	1.15	1.92	2.87	3.86	4.09	3.85	3.74	2.43	1.84	1.11	28.57
% of annual	3.2	2.8	4.0	6.7	10.0	13.5	14.3	13.5	13.1	8.5	6.4	3.9	100
RUNOFF [2]													
inches	.26	.22	.29	1.86	2.60	1.65	.90	.54	.77	.62	.61	.39	10.72
% of annual	2.47	2.05	2.73	17.3	24.2	15.4	8.38	5.06	7.16	5.81	5.66	3.66	100
PAN EVAPORATION [3]													
inches	--	--	--	2.95	4.41	5.43	6.34	5.00	2.83	1.57	--	--	28.54
% of annual	0	0	0	10.3	15.5	19.0	22.2	17.5	9.9	5.5	0	0	100

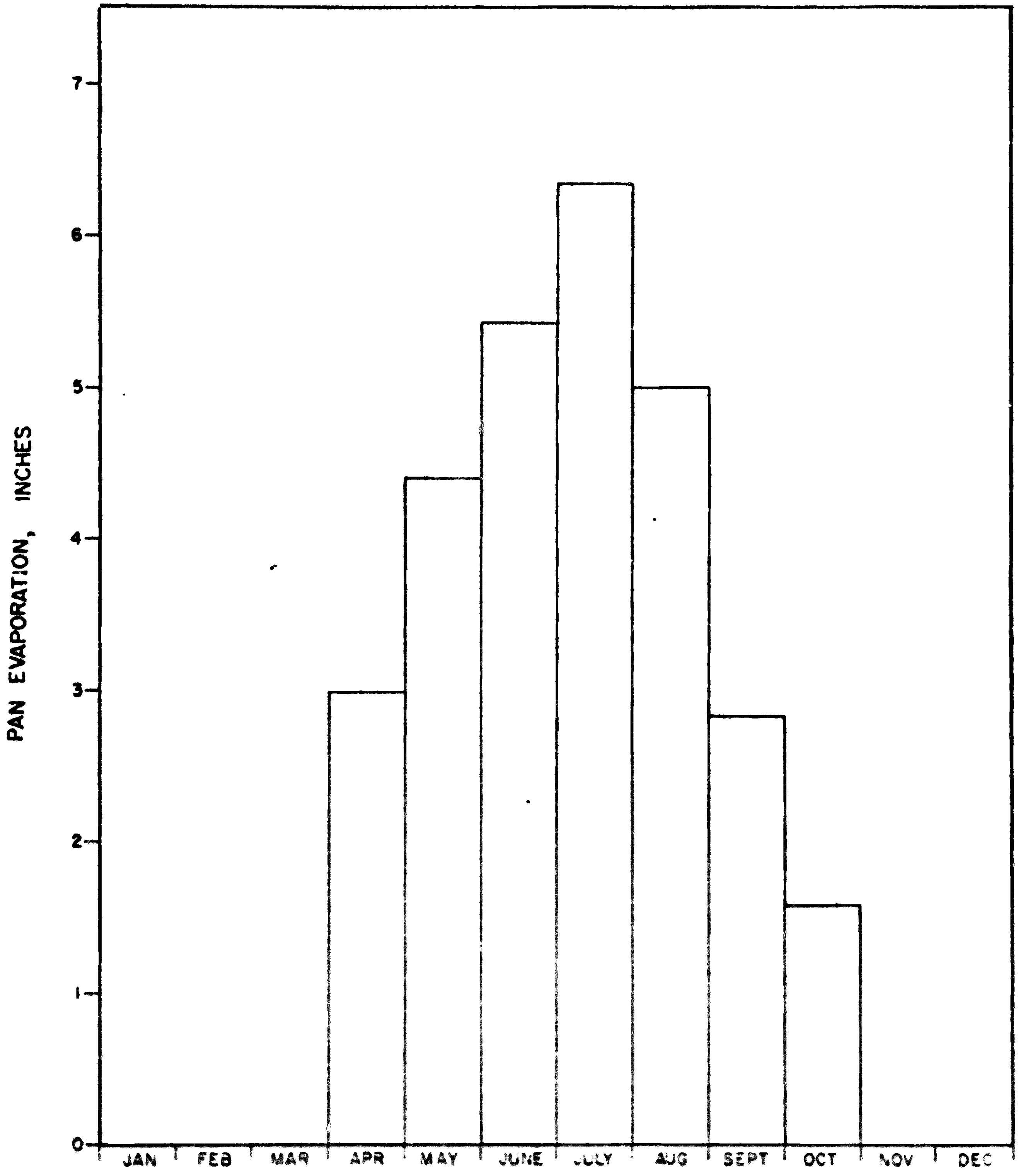
[1] from Watson, 1978, Table 6.5

[2] from Siegel and Ericson, 1979, from preliminary draft

[3] from Watson, 1978, Table 7.2

Figure 5

AVERAGE MONTHLY PAN EVAPORATION AT HOYT LAKES



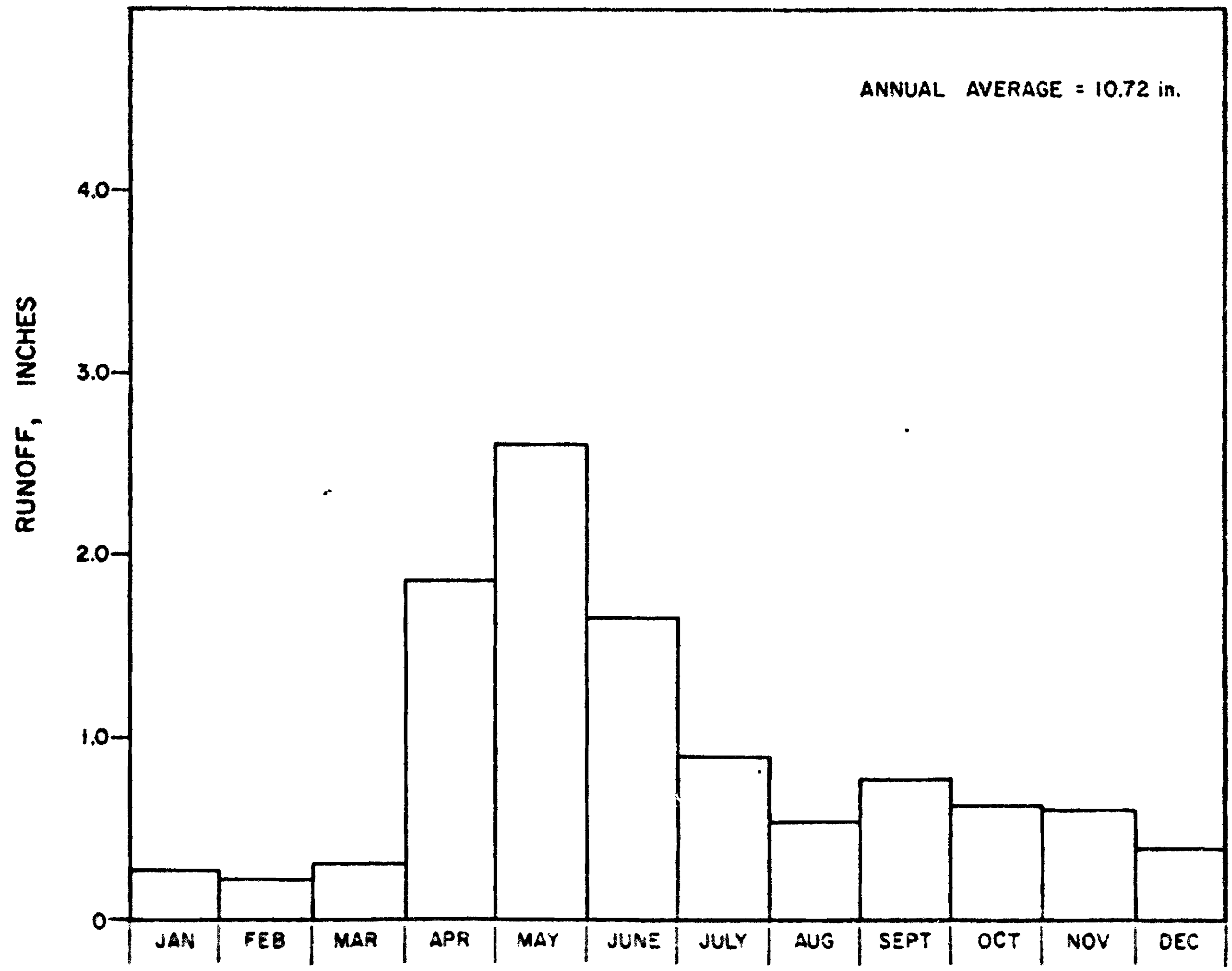
From Watson, 1978, Table 7.2

> occasionally exhibit an increase in flow during October and November as evapotranspiration decreases. Streamflow recedes slowly during the late fall and winter, reaching an annual minimum during Febraury and March. Occasionally some of the streams experience annual minimum flows during late summer or fall as a result of extended dry periods. Annual peak flows across the Superior National Forest most commonly occur in April or May as a result of rapid melting of the accumulated snowpack. However, annual peak flows may also occur during the summer and fall from excessive rain.

Siegel and Ericson (1979, from preliminary draft) estimated the average annual runoff for the study area to be 0.79 cfs/mi^2 (10.72" or 38% of precipitation). Runoff from individual streams ranged from 8.17" to 11.97". Garn (1975, p.10) estimated the average yeild of the Superior National Forest to be 12", with a range of 8 to 16" for individual watersheds. The average yield for the St. Louis and Kawishiwi River systems has been estimated at 0.72 cfs/mi^2 (Bowers, 1977, p.27). Table 1 and figure 6 show the average monthly distribution of streamflow in the study area. Snowmelt and spring rains in April, May and June account for 56.9% of annual runoff (Siegel and Ericson, 1979, from preliminary draft). Streamflow statistics are discussed in Siegel and Ericson (1979), Brooks and White (1978) and Bowers (1977).

Figure 6

AVERAGE MONTHLY RUNOFF IN STUDY AREA



from Siegel and Ericson, 1979, preliminary draft,
based on U. S. G. S. streamflow data

Previous Work

Although much attention has been given to the hydrology of coal mine spoils and refuse and of tailing basins, very little work has been done with coarse wastes from metallic sulfide ores. The work that is relevant comes from experience with dump leaching of low grade ores, and is confined primarily to rule-of-thumb observations based on engineering practice.

The physical characteristics of leach dumps are similar to those of the stockpiles under study. The run-of-mine material ranges up to several feet in diameter, but is mostly less than 2 feet, with many fine particles (Sheffer and Evans, 1968, p.9). Dumps are generally constructed in lifts 50 to 100 feet high (Sheffer and Evans, 1968, p.8). Dumping and bulldozing tend to create alternate layers of coarse and fine materials within the dumps (Sheffer and Evans, 1968, p.18; Howard, 1968, pp.72-73). Neutron logging by Howard (1968, pp.72-73) also detected stratification related to compaction by haul trucks, clayey zones, and iron precipitates deposited in leach ponds on lifts subsequently buried. Porosities within the dumps studied by Howard ranged from 5 to 65% (pp. 71 and 74).

Reported infiltration rates for leach dumps and waste rock piles are typically high. In a study by Armstrong et al. (1971, pp.7, 16), tritiated water was added to a leach pond at an effective rate of 6.3 inches/hour. Burton, Gifford and Hart (1978) ran rainfall simulation tests on mine spoils in Utah, using a maximum application rate of 3 inches per hour. They observed final infiltration rates for non-porous igneous and metamorphic waste rock of 3.3 to 6 cm/hr (1.3 to 2.4 in/hr) (p.274). Leach dumps are engineered to prevent surface runoff, so no observations of runoff rates or volumes are available.

The layering within dumps causes lateral flow of water at intermediate depths within the pile. This has long been suspected to prevent optimal contact of leach solutions and removal of metals (Sheffer and Evans, 1968, p. 18; Howard, 1968, p. 70). Neutron logging by Howard (p. 71) showed wet, porous zones 10 to 25 feet thick over compacted layers and clayey layers at the Chino dump. According to his data, the compacted and clayey layers were saturated, but the porous zones, while containing more water per unit volume, were not fully saturated. Perched water zones were later confirmed with piezometers which showed saturated thickness of at least 15 feet (Armstrong, 1971, p. 15). Armstrong (p. 21) followed the path of water over perching beds with a tritium tracer: "In the unsaturated zone above the water table, leach water percolates downward to a perching zone, flows laterally to the edge, and falls to the next zone."

The result of lateral flow over the impeding layers and slow transmission through them is that "in some areas a significant portion of the dump material is infrequently, or never, contacted by leach solutions" (Howard, 1968, p. 73). The pyrite content of the dry zones is roughly the same as that in the unleached material, indicating that little or no leaching has occurred (Howard, 1968, p. 73). Such dry zones would probably be minor or non-existent in wastes deposited by conveyor (cf. Burton et. al., 1978, p. 278).

Although some of the water above semipermeable layers may move as saturated flow, some apparently moves rapidly out of the pile as interflow. Armstrong (p. 23) observed that the tritiated tracer moved at least 1000 feet and probably through the entire dump (8000 feet) within 24 hours of introduction. Malouf and Prater (1962, p. 83) give times of travel for leach solutions of 2 to 12 days, depending on dump height.

Development of saturated zones at the base of stockpiles has been noted for many types of materials (Anderson and Youngstrom, 1973; Corbett, 1968; Good et al., 1970; Armstrong et al., 1971). Corbett (1968, p.164) found that aquifers formed in cast overburden from coal mining stored large volumes of precipitation, "materially reduc(ing) major flood flows...and increas(ing) flows during extended dry periods..." Drilled wells at the Chino mine showed saturated thicknesses of up to 120 feet in a leach dump sited on impermeable bedrock, with thicknesses of 20 to 50 feet more common (Armstrong, 1971, p.17). Groundwater flow followed the buried bedrock surface. Calculated flow velocities for the tracer front in the saturated zone ranged from 10 to 21.6 feet/hour (0.085 to 0.18 cm/sec) (pp.21 and 22). The tritium pulse spread through the entire dump in 15 days, but the tail of the pulse did not arrive until 41.3 days later (56.3 days total), indicating an average residence time on the order of 30 to 40 days (Armstrong, p.23). Residence time calculated as total volume of water in the dump divided by daily flow was 140 days (see appendix 2). This may relate to Armstrong's observation (p.25) that there appears to be a certain volume of fairly stagnant water within the dump, based on gradual dilution of the tritium over time. Permeabilities calculated from velocity and potential gradient data given by Armstrong ranged from 200 to 1000 ft/day (0.06 to 0.4 cm/sec) (see appendix 2).

Field Methods

Precipitation

Erie: A standard rain gauge with accuracy of ±0.01 inch was in operation at Erie from July 30, 1976 to October 24, 1977, and from May 1 to November 13, 1978, and was read approximately weekly. A Friez recording rain gauge operated from July 30 to December 7, 1976, March 9 to September 13, 1977 and May 1 to November 26, 1978. Daily rainfall read from the chart was adjusted by a multiplication factor so that the total rainfall for the week matched the total from the more accurate standard gauge.

When the gauges were not on site or did not function correctly, precipitation data were taken from Babbitt, six miles to the west. The preponderance of unevenly distributed convective storms in summer, coupled with variations due to rain gauge exposure, makes correlation of rainfall data even between closely spaced stations tenuous (Watson, 1978, p. 12-14, 29). Comparison of Babbitt data with data collected at Erie (table 2) indicates that Babbitt data provide a fairly good estimate of annual precipitation at Erie (8% error over 13 months), but are poor estimators for individual months. Comparison of daily data shows that storms of roughly similar magnitudes tend to occur on the same day or adjacent days at the two stations (appendix 3). When the recording gauge did not function properly in 1978, the total volume of rainfall was apportioned on the basis of AMAX data.

Table 2 Comparison of Babbitt and Dunka precipitation data

	Precipitation, Inches		
Period	Dunka	Babbitt	Error(%)*
Aug, 1976- Aug 1977	31.53	28.97	8
Aug, 1976	1.71	.59	65
Sep.	1.60	1.61	1
Oct.	.30	1.32	340
Nov.	.79	.24	70
Dec.	.90	.66	27
Jan. 1977	.40	.52	30
Feb.	.43	.24	44
Mar.	1.60	1.70	6
Apr.	1.20	1.20	0
May	4.50	4.58	2
June	5.44	6.15	13
July	3.82	3.49	9
Aug.	8.84	6.67	25

Average magnitude of monthly error, .51 inches.

$$\text{Error} = \left| 100 \times \left(\frac{P_{\text{Babbitt}} - P_{\text{Dunka}}}{P_{\text{Dunka}}} \right) \right|$$

AMAX: During 1977, precipitation at AMAX was measured with a standard rain gauge (Science Associates, Inc. NWS Spec. 450.230) read each weekday. In 1978, a recording gauge was added (Science Associates, Inc. NWS Spec. 450.220). The standard gauge is used to determine the amount of rainfall, while the recording gauge gives the time and duration of the event (Eger et al., 1979, pp.16-17).

Flow Data

Erie: A continuous flow record was collected at EM-8, (see Figure 1) downstream of the seep at EM-9, from July 1 to October 25, 1976, April 27 to September 27, 1977 and April 28 to October 30, 1978. Data consist of continuous stage measurements taken on a Stevens Type F recorder in a stilling well upstream of a 60^{o} V-notch sharp crested weir. Stage records were converted to flows by standard methods (Eger et al., 1979, pp.78-79). The rating curve was developed on the basis of periodic flow measurements taken with a Pygmy meter. The meters have an accuracy of ± 5 to 10% under optimal conditions, but may seriously underestimate low flows, especially in wide, shallow channels. The stilling well at EM-8 tended to remain frozen for some time after the seep began to flow in spring. Spring flows in 1977 were estimated using spot readings taken with the Pygmy meters. Since flows were low throughout the region in spring of 1977, the error in using this method was probably small.

Flow data at seep 1 and seep 3 consist of individual readings taken approximately every two weeks with a Pygmy meter. Because flows were generally low, they are not likely to be highly accurate.

AMAX: The runoff from all six field leaching piles at AMAX flows to a sump which is kept at a constant level by an automatically operating pump. The discharge of the pump is measured by a meter accurate to ± 5%. Individual flow meters (Badger Recordall Model 15) were installed on the pipes leading from each pile in 1978. The meters give cumulative volume readings. FL-1 was equipped with the meter in 1977. The meters have tended to cause backups during high flows and not operate during low flows.

Silt and sand washing out of the piles sometimes clogs the meters. Details of changes in the physical system and flow corrections which were made in 1978 may be found in Eger, Johnson and Hohenstein, 1979, pp.17, 73-75, 78-79.

Groundwater Data

Erie: Sixteen penetration test borings were performed at the Dunka site by Braun Engineering Testing, and 2 inch diameter 36 inch plastic well screens were installed in fourteen of the holes (Plate 1). The P series wells were backfilled with on-site soils. W series well points, finished in other than clean granular soils, were packed with Ottawa Sand above which a bentonite seal was provided. The W series wells were sampled periodically in 1976 and 1977 to monitor water quality and groundwater levels.

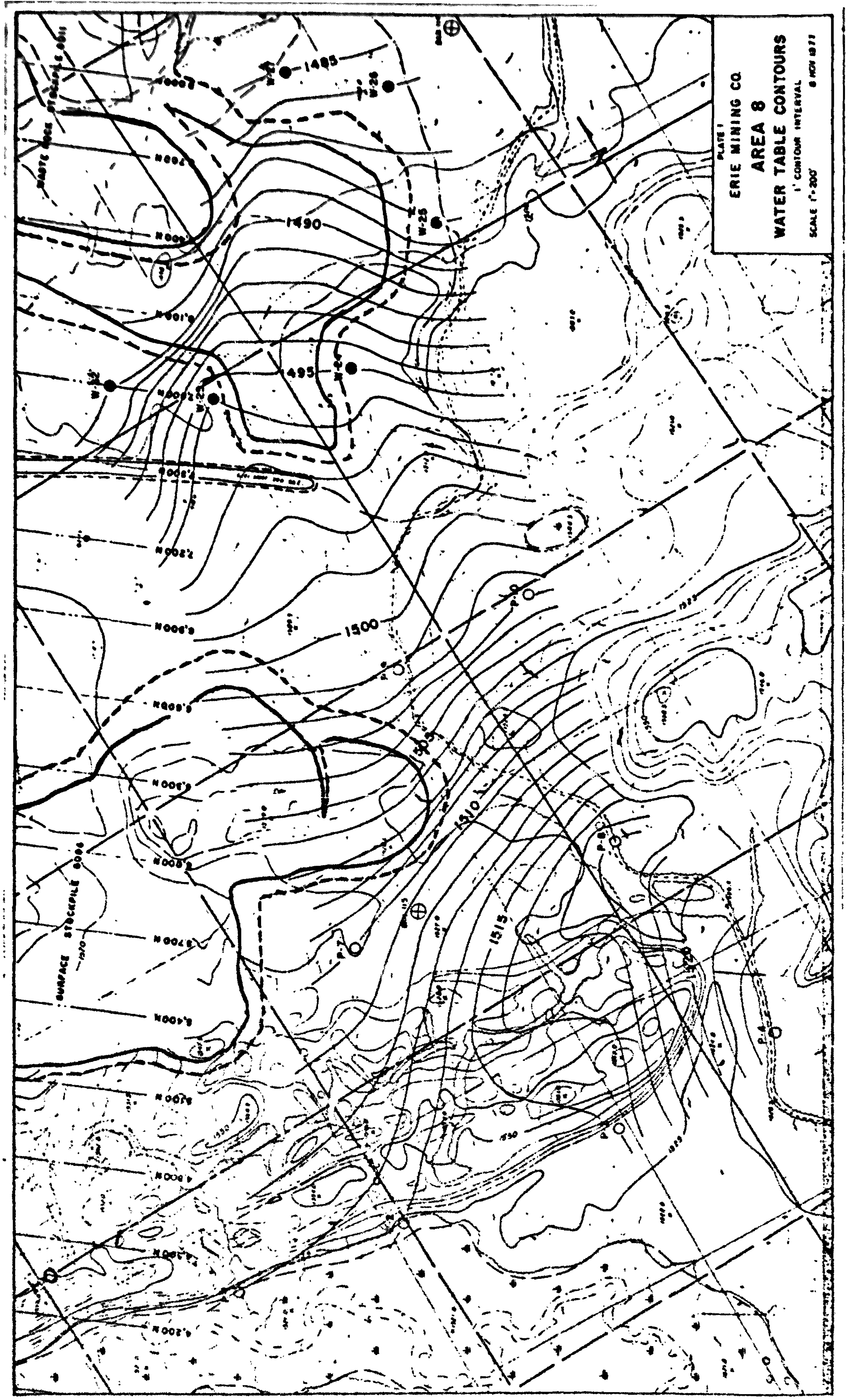


PLATE I
ERIE MINING CO.
AREA 8
WATER TABLE CONTOURS
1' CONTOUR INTERVAL
SCALE 1"=200'
8 NOV 1977
WASTE ROCK STOCKPILE 8011
SURFACE STOCKPILE 8004
1485
1490
1495
1500
1505
1510
1515
W-26
W-25
W-24
P-8
P-7
P-6
P-5
P-4

PLATE 1

Precipitation, Evaporation and Streamflow During the Study Period

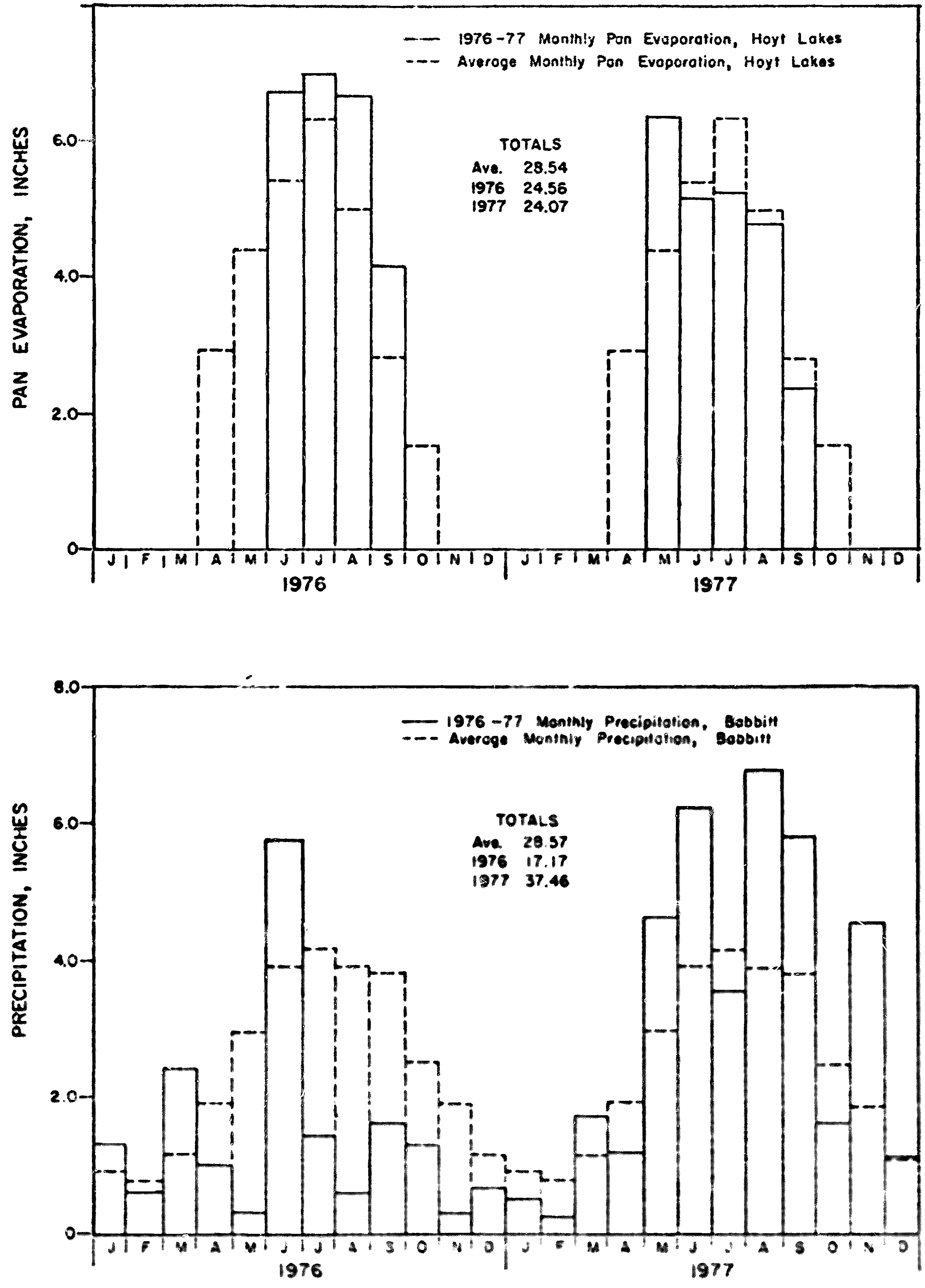
1976-1977 was a period of anomalous precipitation and streamflow. Precipitation at Babbitt in 1976 was 17.17", the second lowest of record and a scant inch above the 100 year drought. Precipitation was below normal for every month except January, March and June (fig. 7a). In 1977, 37.46" fell at Babbitt, making it the second wettest year of record. Most of the above-normal rainfall occurred during the period from May through September, with an additional contribution in November (fig. 7a).

In 1978, precipitation was 28.15" which is near normal. Precipitation was below normal for every month except May, July and August. In June, rainfall was 1.53" below normal (40% of the norm) while in May and July the average monthly rainfalls were exceeded by 1.25" and 2.67" (44% and 65% of the norms), respectively. Otherwise, monthly rainfalls were within 1.0" of the norms.

Although evaporation was minimized in spring of 1976 by freezing temperatures, evaporation from June through September exceeded the average by 5 inches (figure 7a). Total evaporation for the year was below normal. Evaporation for 1977 was below normal for every month except May, and for the year as a whole (fig. 7a). June through September evaporation fell 2 inches below normal. According to Bruce Watson (pers. comm., 1979) evaporation correlates inversely with precipitation in the study area.

Figure 7a

MONTHLY PRECIPITATION AND PAN EVAPORATION, 1976 - 77



Evaporation for 1978 was below normal in June and above normal during July through September. The total for the year was below normal because of the short period of record in 1978. Supplementing the data with the average monthly evaporation for April, May and October leads to estimates between 27.43" and 31.95" which lie about the norm.

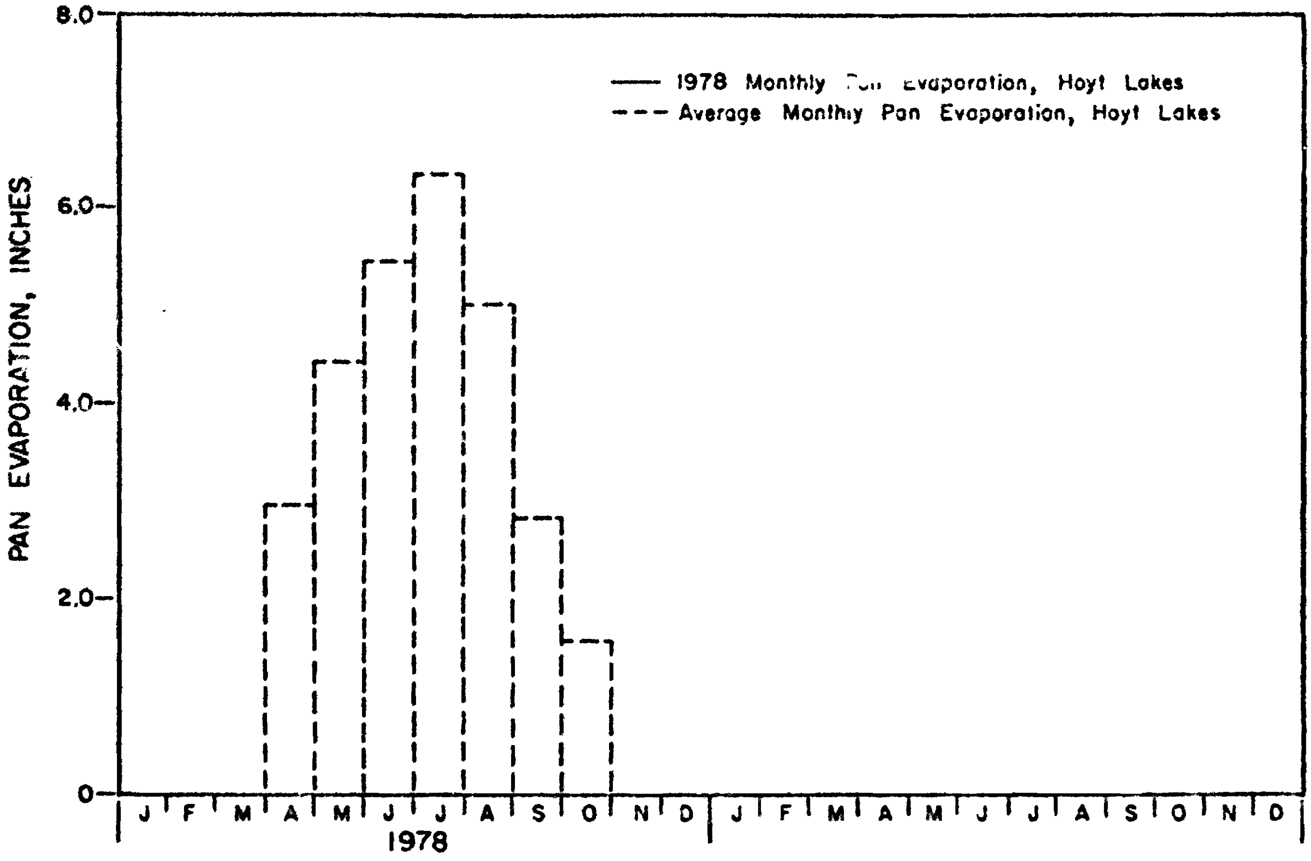
Figures 8 through 11 show the monthly discharge of four unregulated streams in the study area for 1976 and 1977. Streamflow was above normal for the first four months of 1976, but then fell well below normal from May of 1976 through May or June of 1977. Rainfall was above average in May and June of 1977, but minimal snowmelt combined with the extremely depleted soil moisture to keep runoff low. Runoff was much above average from September through December of 1977.

For the 1977 water year (Oct. '76-Sept. '77) precipitation was 117% of normal, but outflow from nine gaged stations averaged 58% of normal (table 3). For most of these watersheds, 1977WY flows fell at or below the 25th percentile level; again, minimal snowmelt and the need to replenish soil moisture depleted in 1976 are primarily responsible.

Figures 12 and 13 show the monthly discharge for two of the above four streams for 1978. During the first three months of 1978, streamflows gradually fell to near normal from the high levels in the last quarter of 1977. This was due to the below normal precipitation. During June and July, flows were above normal Though precipitation was below normal in June, moist soil conditions due to the high rainfall in May and low evaporative losses in June led to the high flows in June. During April through May and August through September there were no patterns in the flows of the two streams, though low precipitation and high evaporation would indicate below normal flows.

Figure 7b

MONTHLY PRECIPITATION and PAN EVAPORATION, 1978



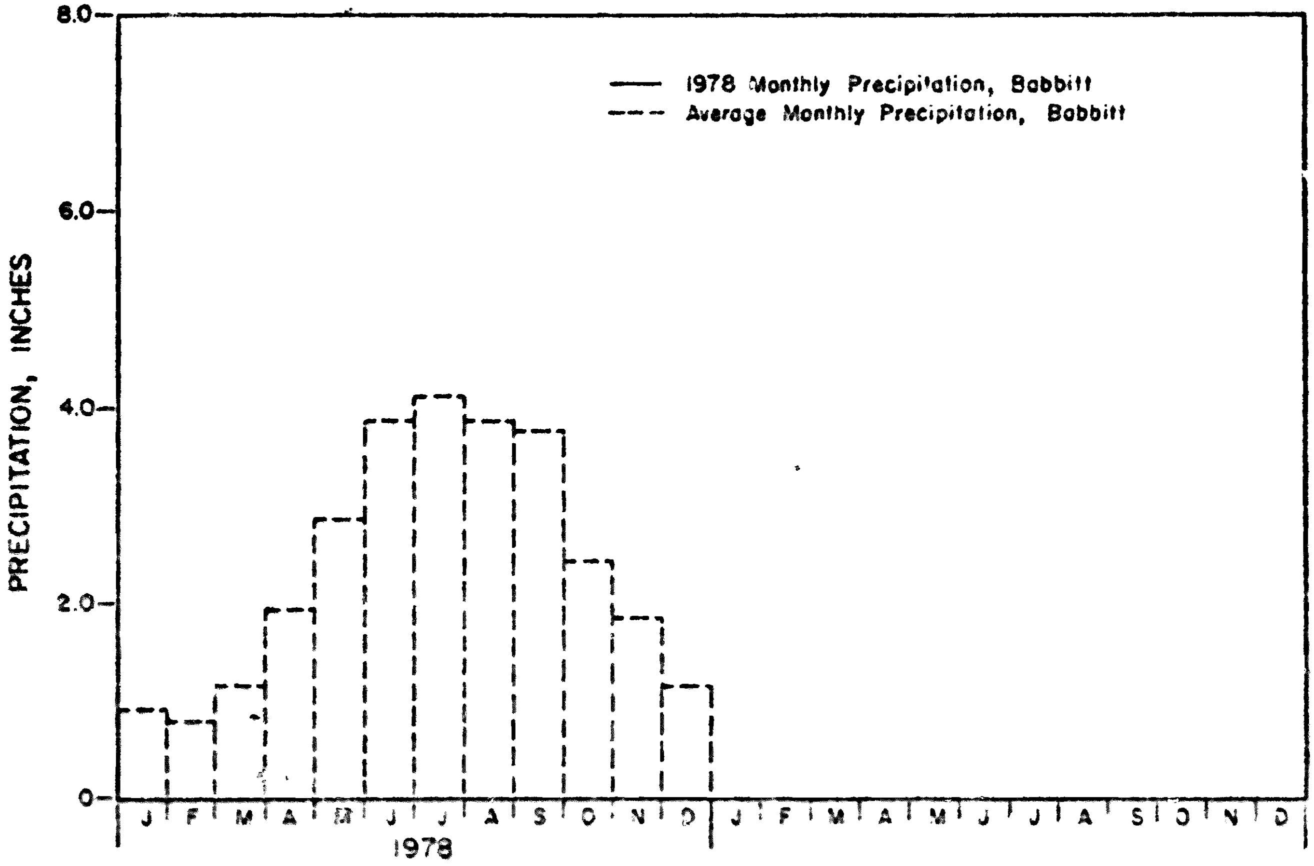


Figure 8

MONTHLY FLOW OF THE KAWISHIWI RIVER NEAR ELY

1976 and 1977

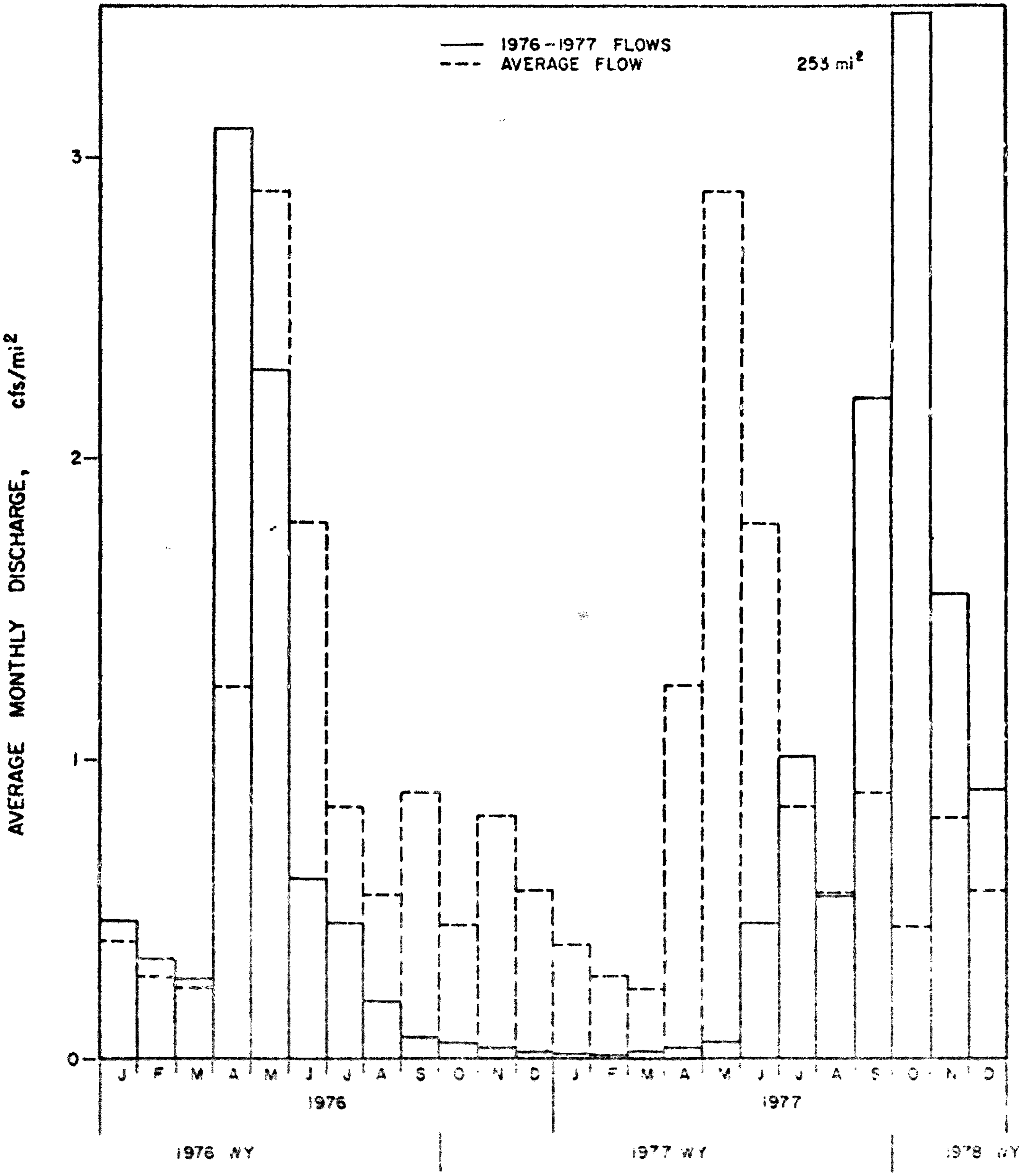


Figure 9

MONTHLY FLOW OF THE BEAR ISLAND RIVER NEAR ELY 1976 and 1977

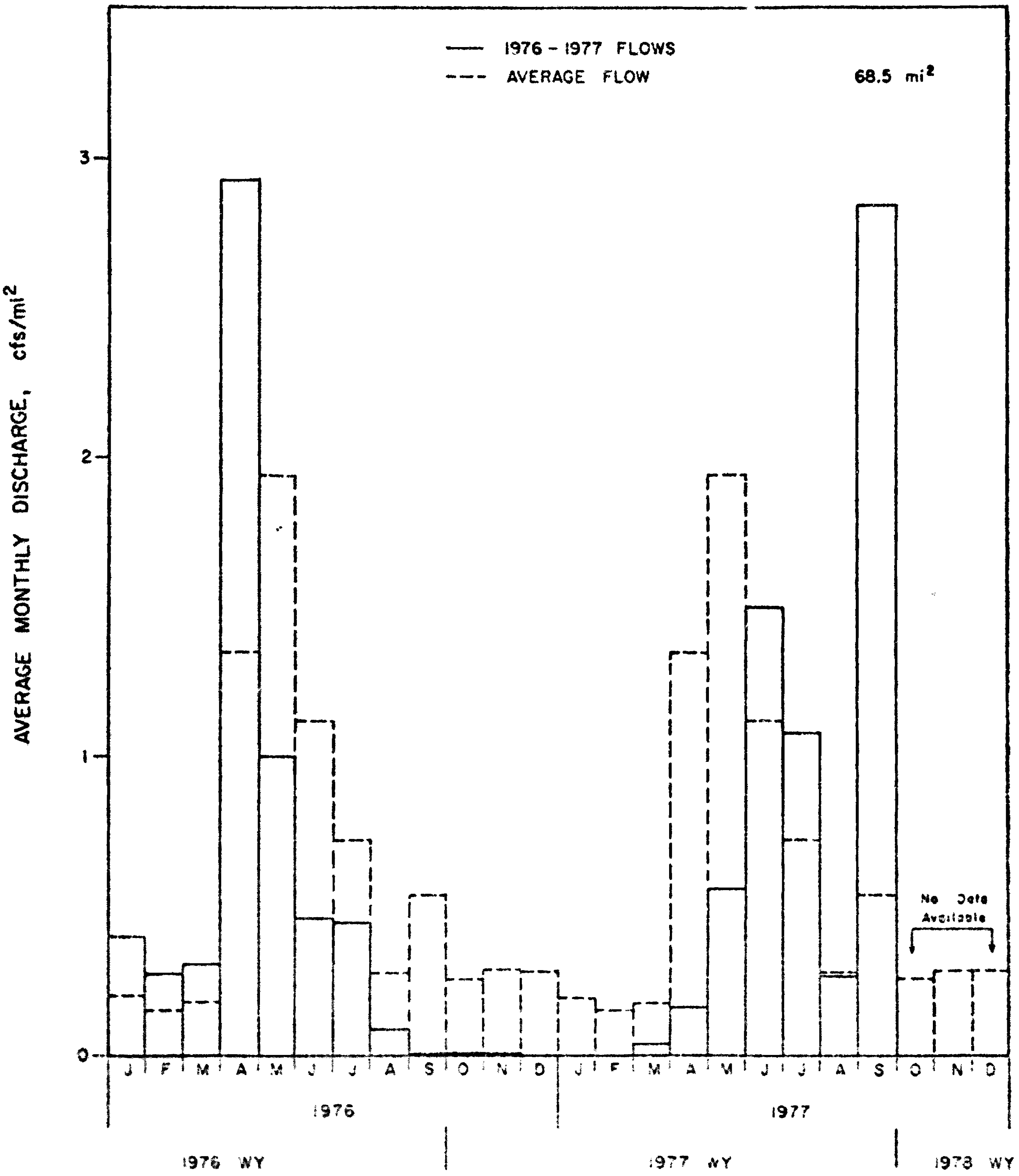


Figure 10

MONTHLY FLOW OF THE ISABELLA RIVER NEAR ISABELLA

1976 and 1977

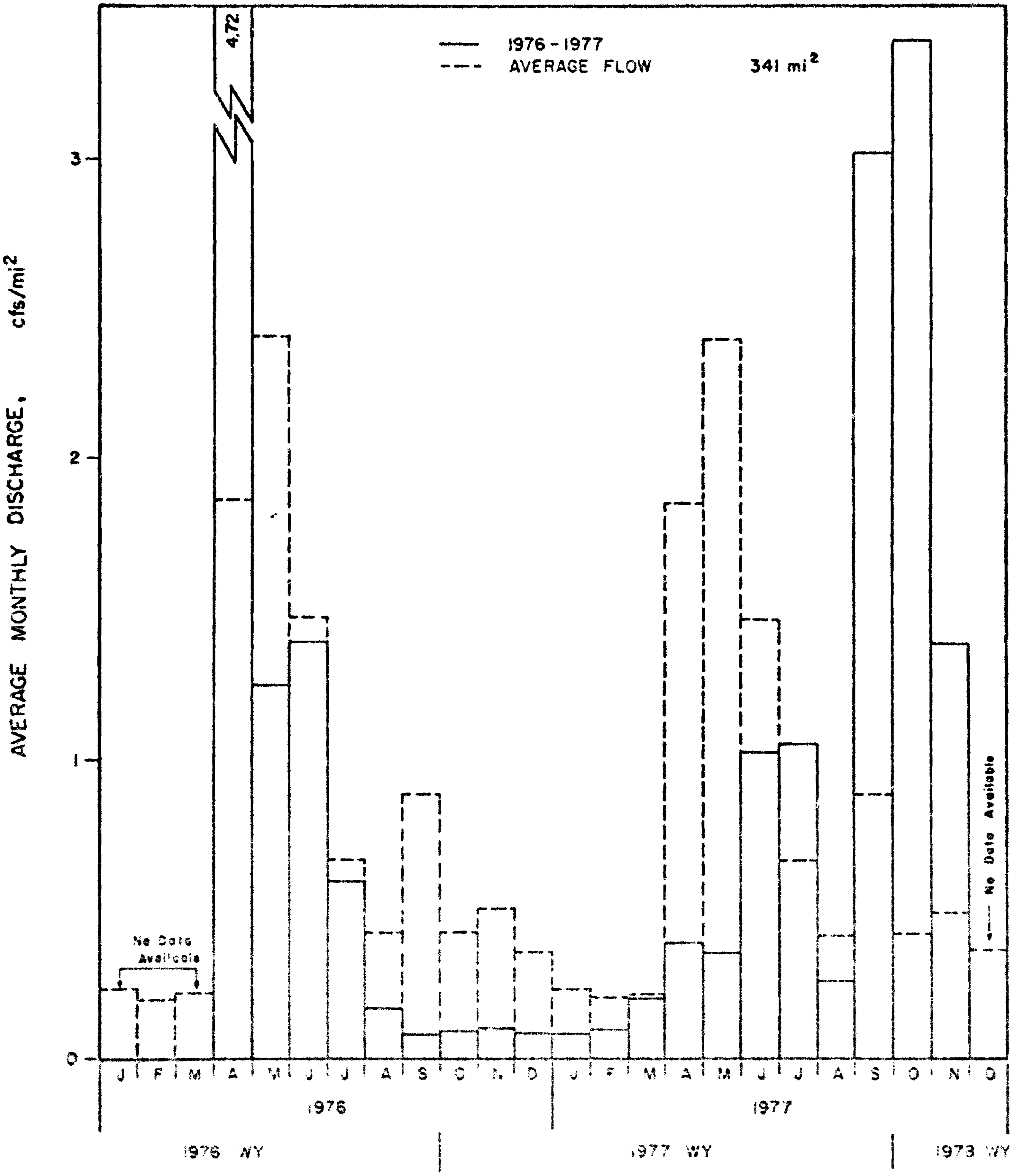
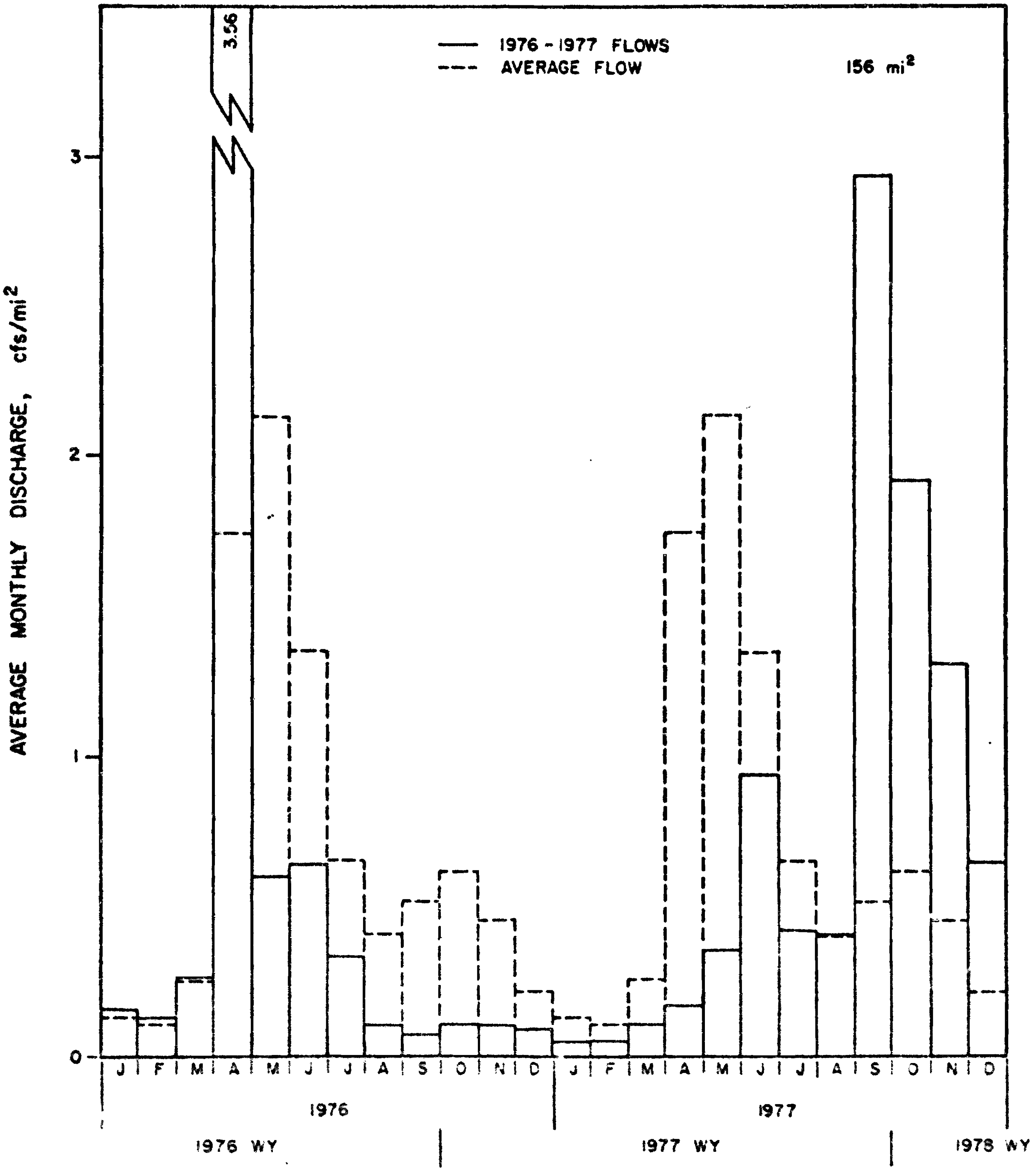


Figure 11

MONTHLY FLOW OF THE PARTRIDGE RIVER NEAR AURORA

1976* and 1977*



* Adjusted for storage & diversion by U S G. S.

Table 3. Comparison of 1977 Water Year with Annual Streamflow Statistics

Stream	Q_{ave} * average discharge	Q_{ave} * 50th percentile	Q_{ave} * 25th percentile	Q_{ave} * 75th percentile	Q_{1977} ** 1977 water year cfs	** 1977 water year cfs m
Second Ck nr Aurora	22.4	19.0	16.1	27.4	15.6	.54
Partridge R. nr Aurora	112	102	73.7	135	56.6	.35
St. Louis R. nr Aurora	230	218	168	270	111	.38
Kawishiwi R. nr Ely	223	216	167	259	94.5	.37
Isabella R. nr Isabella	272	246	187	331	193	.57
So. Kawishiwi R. nr Ely	419	362	236	596	236	--
Dunka R. nr Babbitt	36.6	33.5	26.8	40.0	24.9	.47
Bear Is. R. nr Ely	41.2	37.9	27.2	46.7	36.7	.54
Kawishiwi R. nr Winton	1019	883	599	1118	544	.46
Shagawa R. at Ely	86.6	83.4	45.5	107	41.0	.41
Average in cfsm	.77	.71	.52			.45

* All flows in cfs: Taken from Erickson, 1977,
Table: Statistic of monthly and annual discharges for gaging stations having 9 or more years of streamflow records available (obtained by written communication).

Copy very hard to read, so figures may not be correct.

** From unpublished prints of mean daily discharge provided by Erickson, 12 Oct. 1978

Figure 12

MONTHLY FLOW OF THE KAWISIWI RIVER NEAR ELY

1978

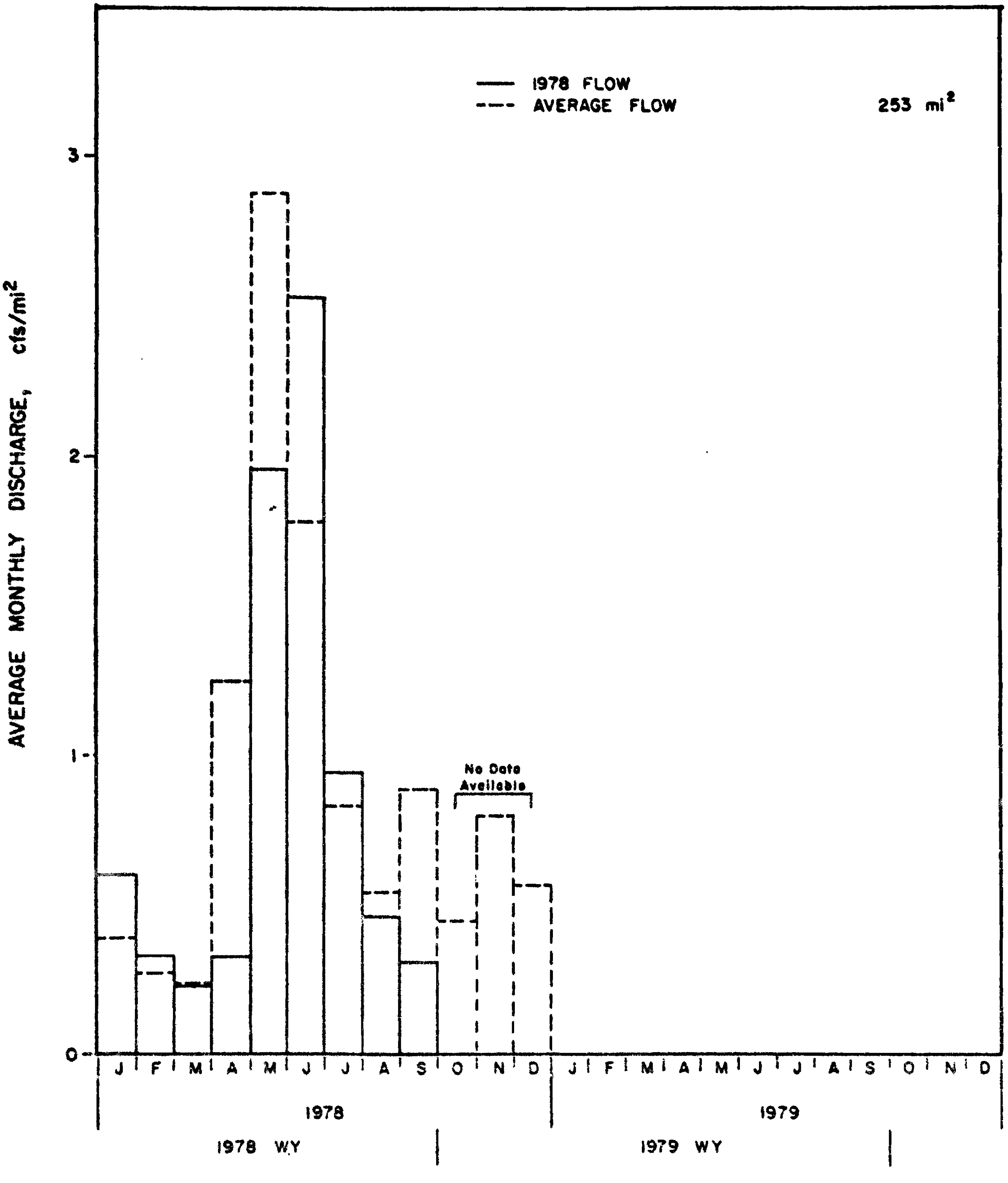
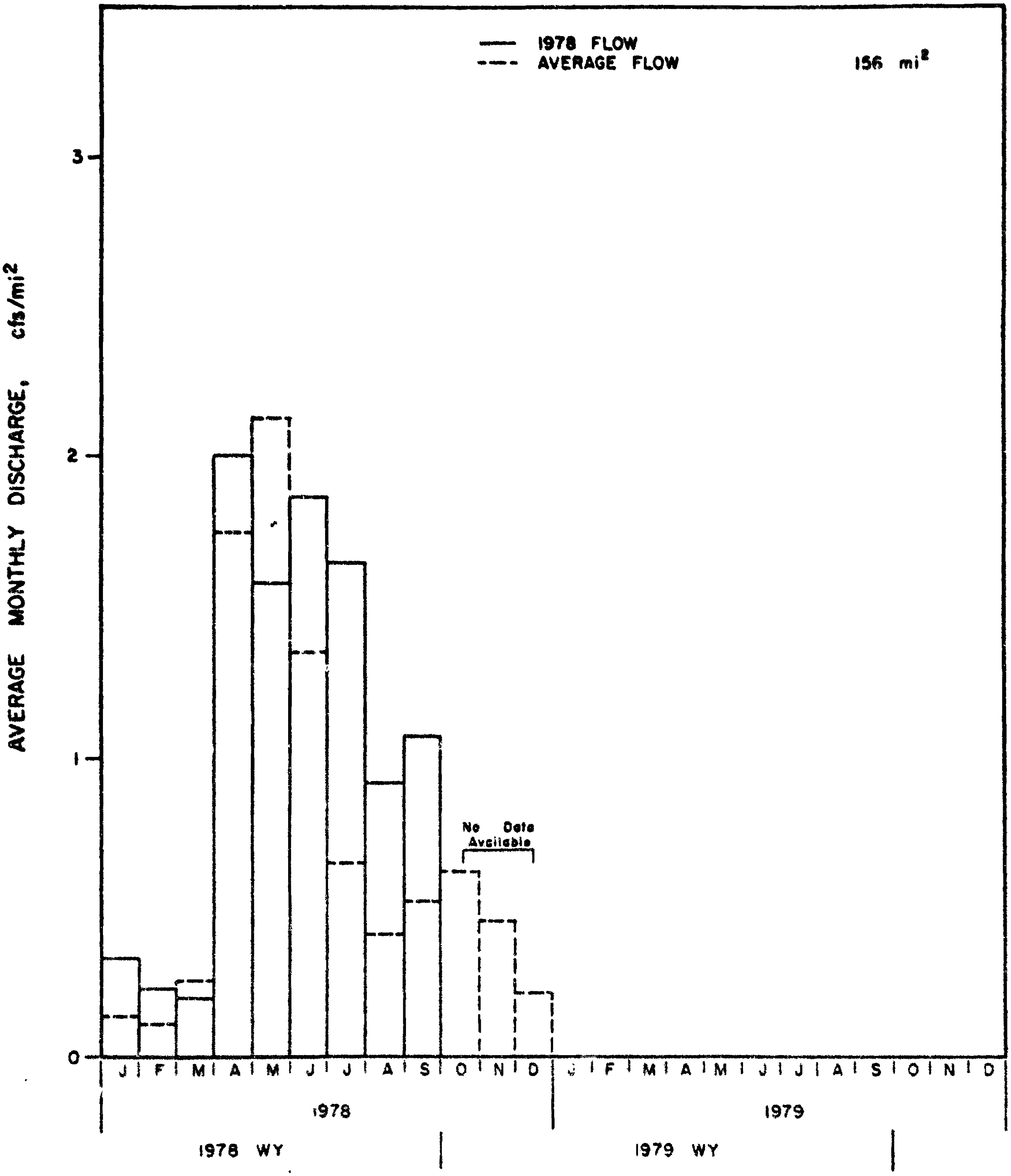


Figure 13

MONTHLY FLOW OF THE PARTRIDGE RIVER NEAR AURORA

1978*



* Adjusted for storage & diversion by U. S. G. S.

Precipitation at the Study Sites

Precipitation data collected at the Dunka mine and at Minnamax are summarized in table 4. Figures 14 and 15 compare the monthly data with average values for Babbitt. Precipitation at Erie in 1976 was 18.05", using Babbitt data for the first six months. Precipitation was 39.14" in 1977, exceeding that of the 100 year wet year at Babbitt.

Rainfall at AMAX in 1977 was 32.36".

For both stations the general patterns are similar to those at Babbitt, but the monthly values differ substantially (table 4).

Appendix 3 represents daily data for all three stations.

Table 4. Monthly and Annual Precipitation at Babbitt, Dunka and Amax

	1976		1977			1978		
	Babbitt	**Dunka**	**Babbitt**	**Dunka**	**Amax**	**Babbitt**	**Dunka**	**Amax**
J	1.34	(1.34)[1]	.52	.40	(.52)	.78	(.78)	(.78)
F	.60	(.60)	.24	.43	(.24)	.28	(.28)	(.38)
M	2.40	(2.40)	1.70	1.60	(1.70)	.71	(.71)	(.71)
A	.99	(.99)	1.20	1.20	1.23	1.06	(1.06)	1.28
M	.30	(.30)	4.58	4.50	4.84	4.52	4.37	3.37
J	5.70	(5.70)	6.15	5.44	4.59	2.33	2.43	2.21
J	1.42	(1.42)	3.49	3.82	2.46	6.76	5.44	6.38
A	.59	1.71	6.67	8.84	6.06	4.63	5.07	5.53
S	1.61	1.60	5.67	(5.57)	5.64	3.45	3.83	3.28
O	1.32	.30	1.60	(1.60)	1.59	1.40	1.08	1.05
N	.24	.79	4.52	(4.52)	2.80	1.25	(1.25)	(1.25)
D	.66	.90	1.12	(1.12)	1.19	0.98	(0.98)	(0.98)
TOTAL	17.17	18.05	37.46	39.14	32.86	28.15	27.28	27.10

[1] Dunka or AMAX data in parenthesis indicates Babbitt data.

Figure 14a

1976
PRECIPITATION AT ERIE'S DUNKA MINE
VS
AVERAGE PRECIPITATION AT BABBITT

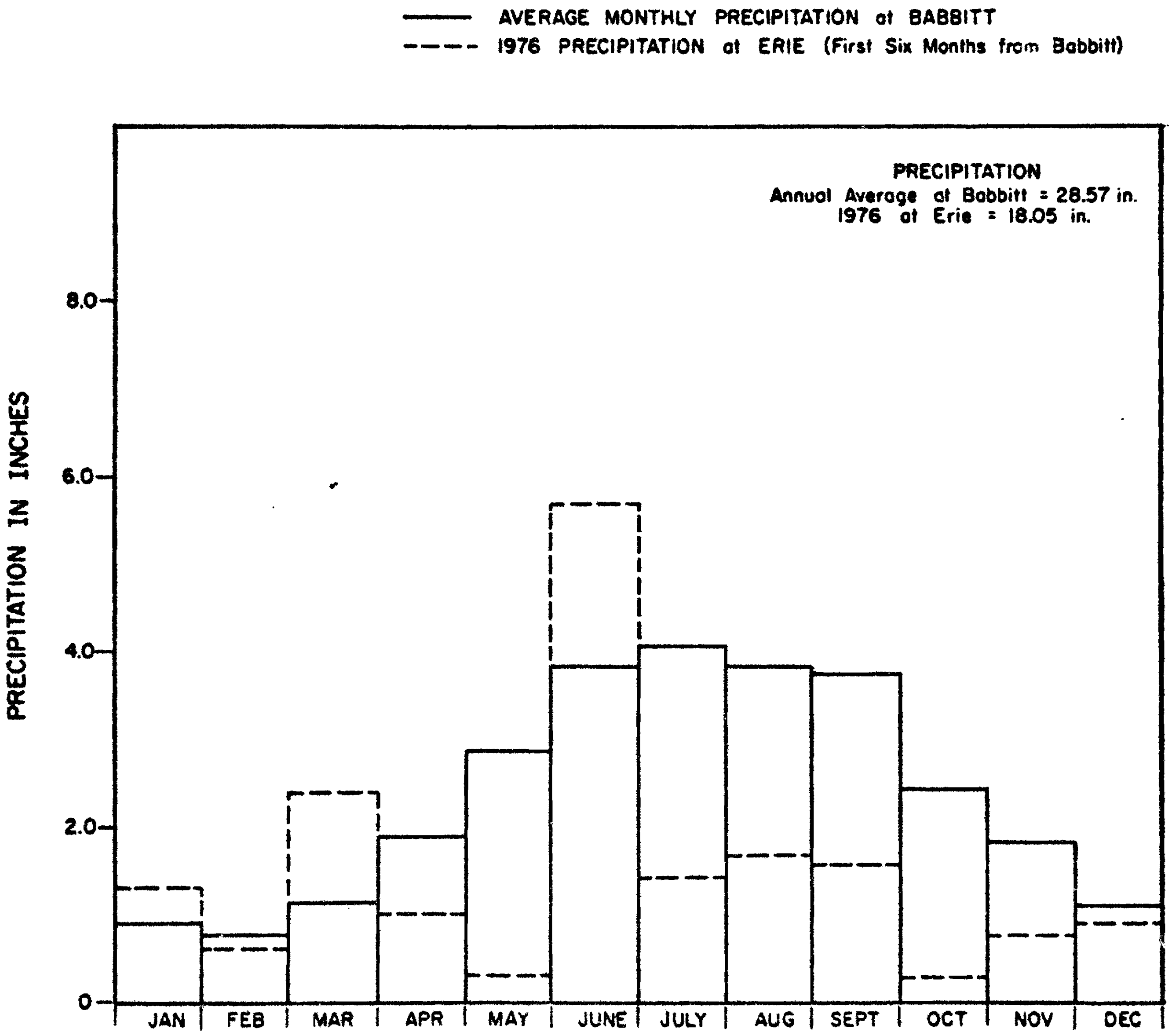


Figure 14b

1977
PRECIPITATION AT ERIE'S DUNKA MINE
VS
AVERAGE PRECIPITATION AT BABBITT

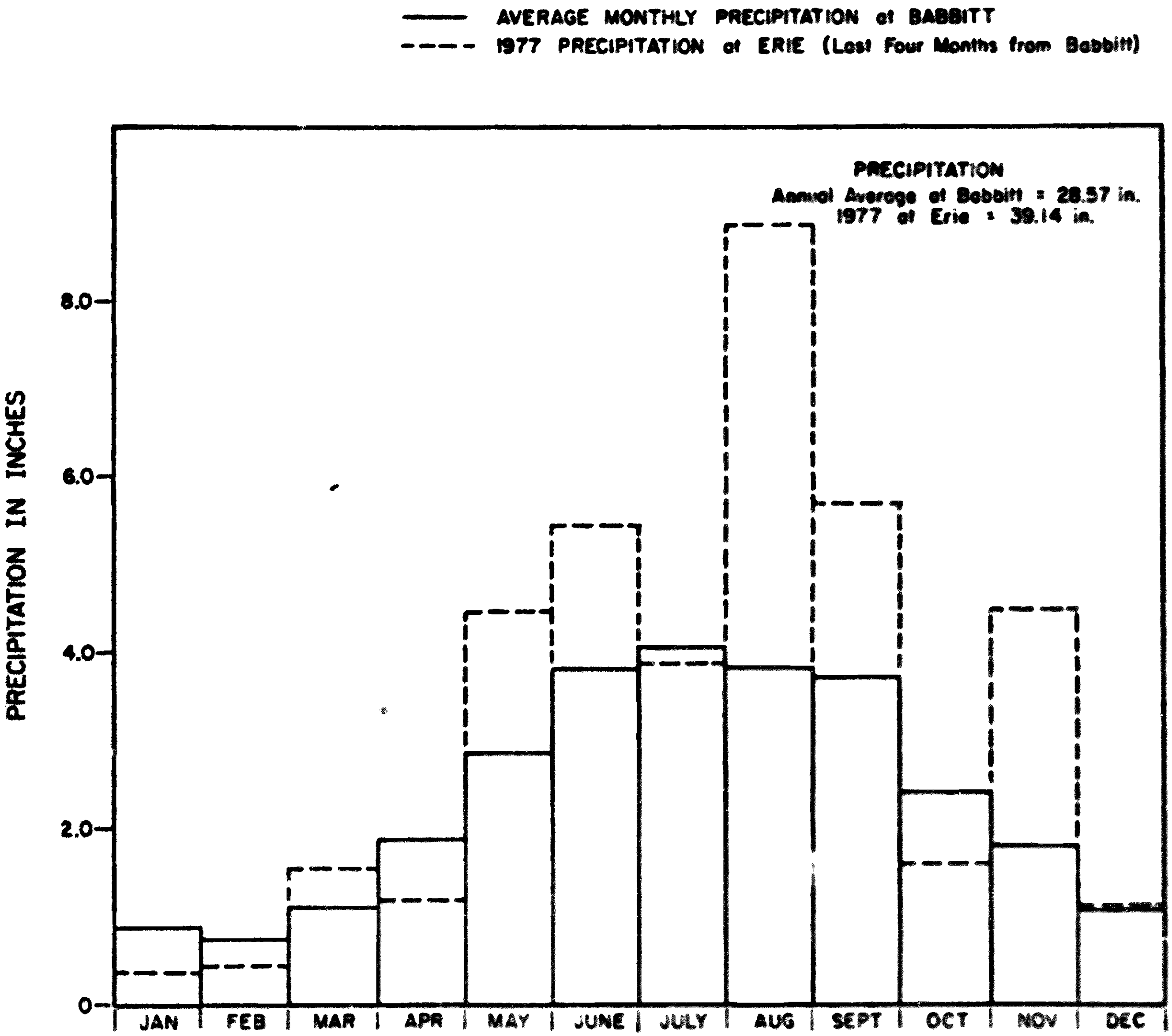


Figure 14c

1978
PRECIPITATION AT ERIE'S DUNKA MINE
VS
AVERAGE PRECIPITATION AT BABBITT

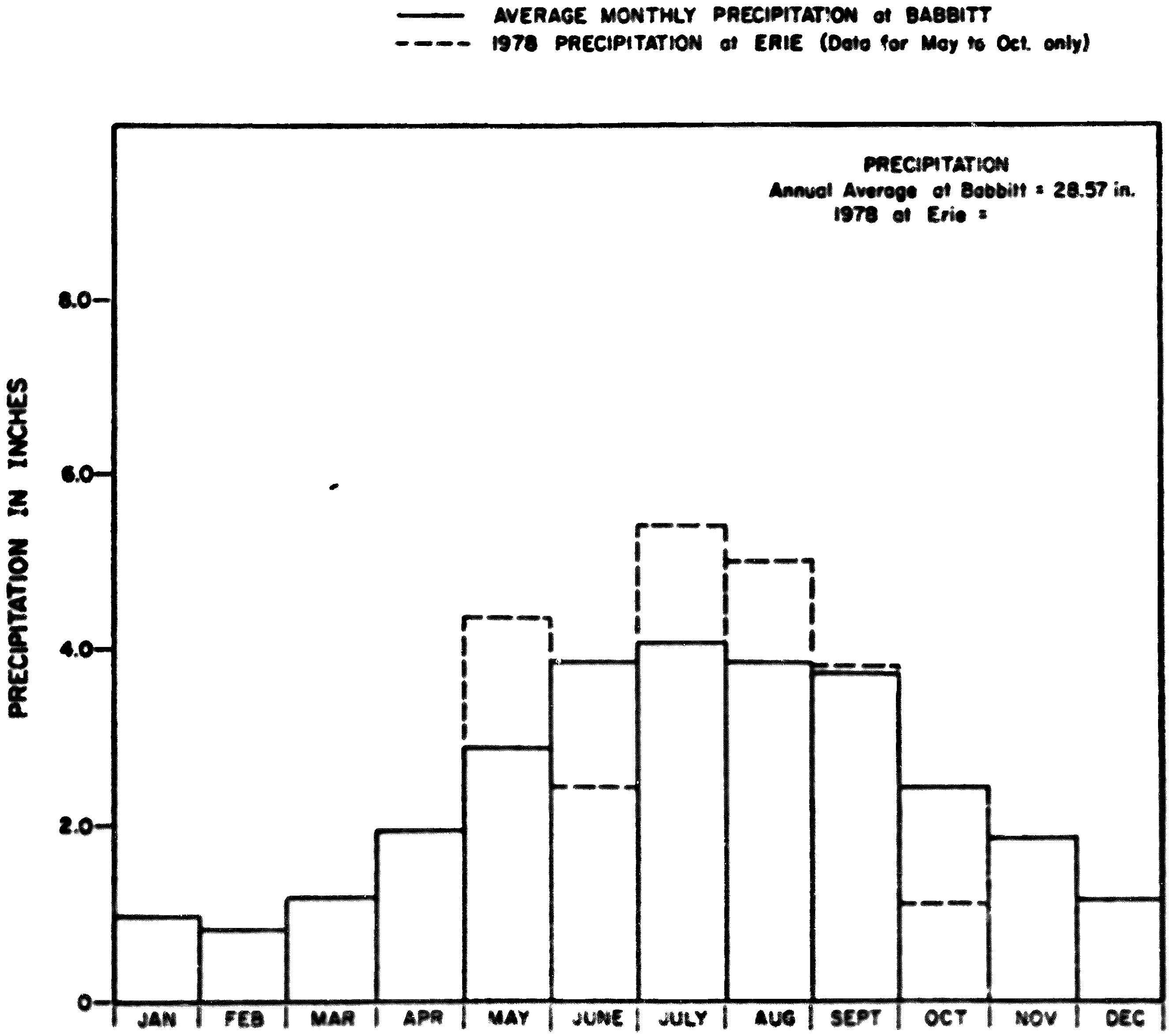


Figure 15a

1977
PRECIPITATION AT MINNAMAX
VS
AVERAGE PRECIPITATION AT BABBITT

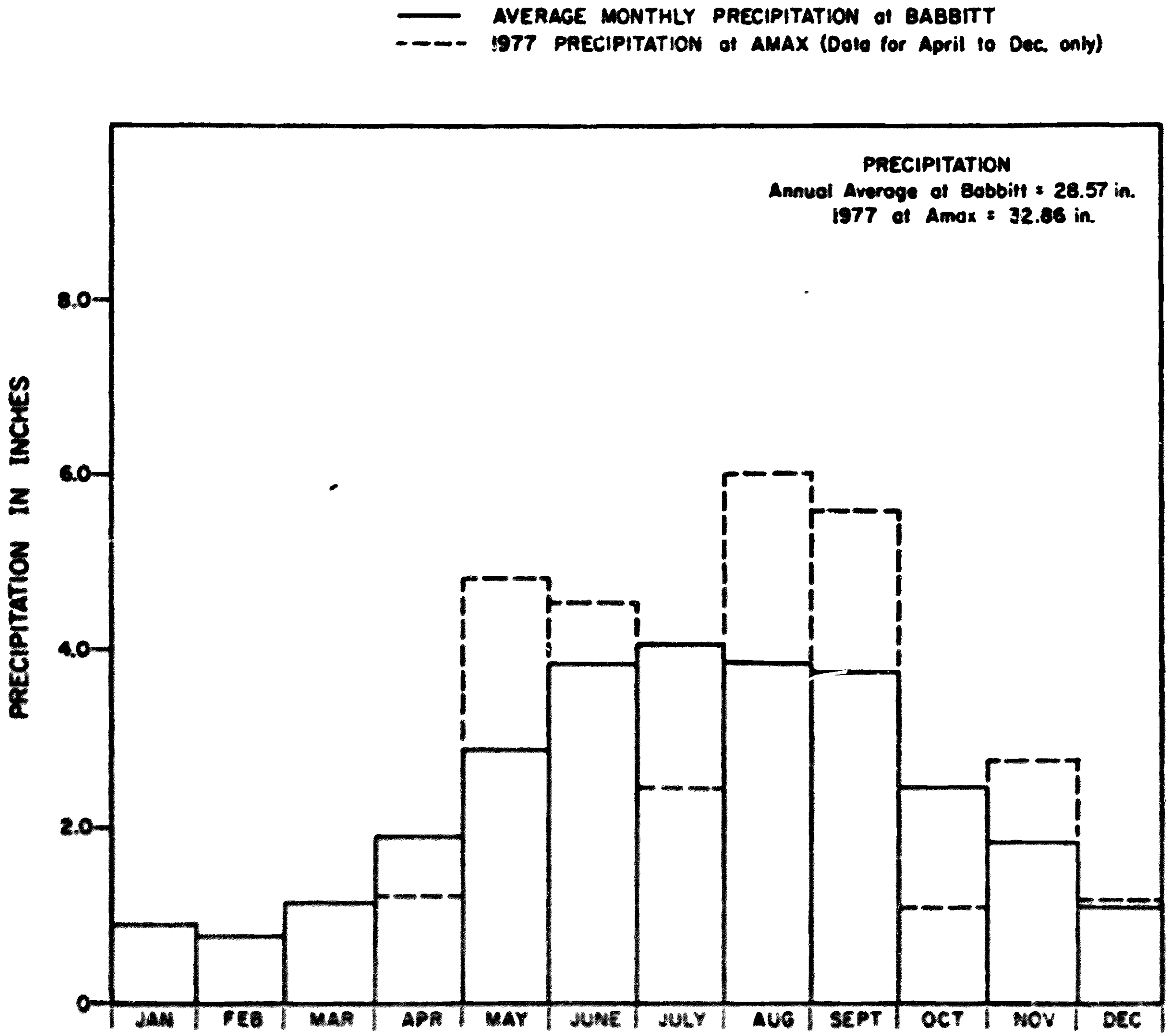
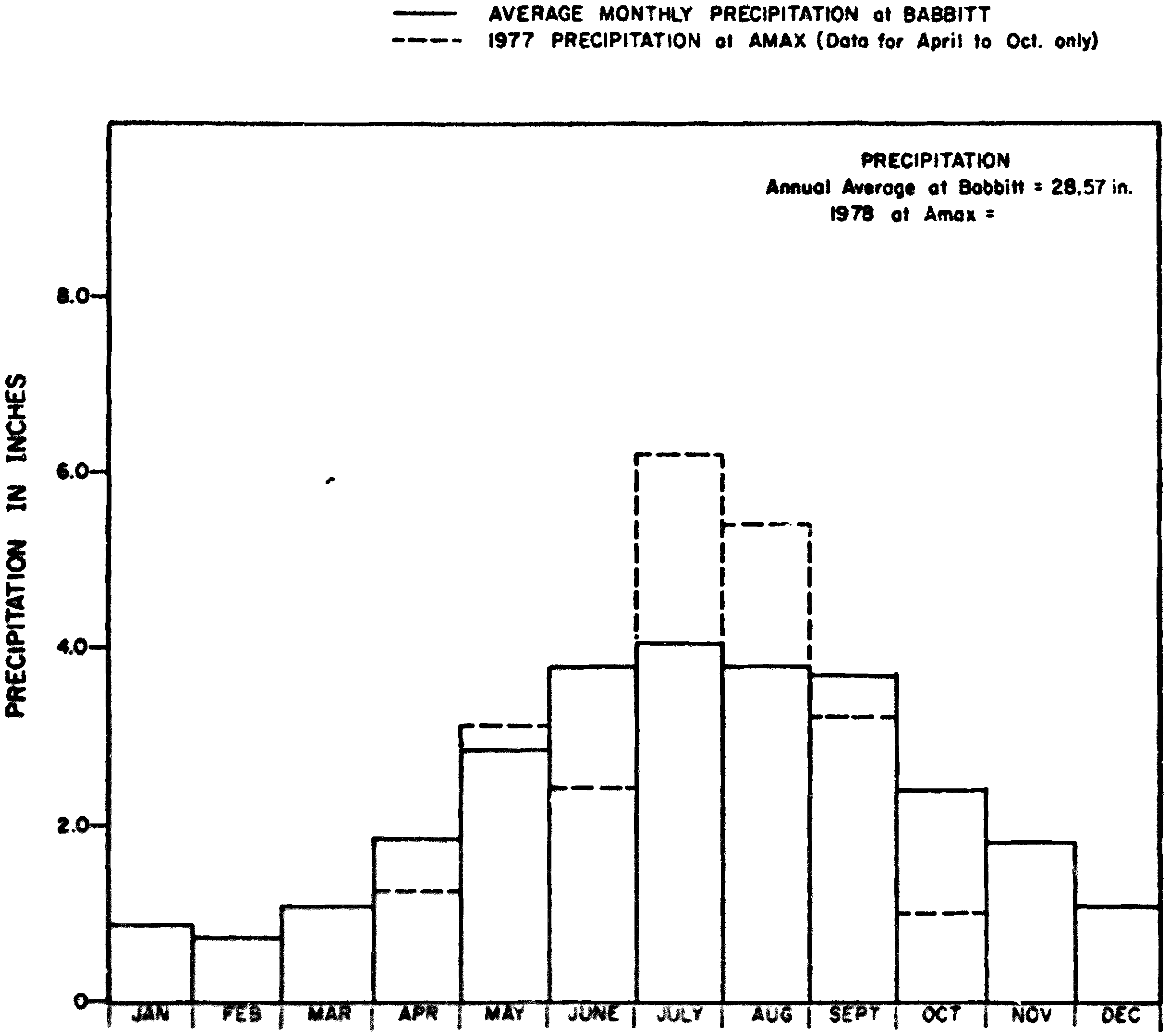


Figure 15 b

1978
PRECIPITATION AT MINNAMAX
VS
AVERAGE PRECIPITATION AT BABBITT



Physical Characteristics of the Stockpiles

1. Erie

Field Description: The stockpiled rock at Erie is a heterogeneous mixture of boulders, cobbles and smaller fragments produced by blasting and moved by truck to the margin of the pit. The piles range from 40 to 120 feet high and cover areas of 20,000 to 300,000 $ft.^2$. They are constructed in 40 foot lifts which are graded to a smooth surface having the appearance of a sandy gravel. Local borrow material, usually a gravelly sand till, is applied as a surfacing layer about 6 inches thick and compacted to a hard surface by the 80 ton haul trucks. On the side slopes of the piles, fragments 1 to 4 feet in diameter predominate. Table 5 summarizes the material, tonnage, area and height of the various stockpiles.

The nature of the materials underlying the piles will largely determine their interaction with the local groundwater system. Plate 1 shows the original topography of the site and the positions of the stockpiles. Plates 2 and 3 show Erie Mining Company's interpretation of the stratigraphy along two sections near the piles as determined by borings. The materials underlying the three large piles which generate seepage are of principal concern. Steep subsurface topography indicates that the northwestern part of the 8011 stockpile is on bedrock (figure 16). Six wells around the pile show that most of it rests on peat which overlies a variable thickness of till and outwash (figure 17).* The pile probably rests directly on till at the southernmost

---

*Divisions among peat, granular glacial deposits and bedrock were taken directly from the field logs by Braun Engineering Testing Company. Till was separated from outwash using several types of information. Where samples were taken, materials with an S-shaped, well-sorted particle size distribution were interpreted to be outwash, and those with a straight-line, poorly sorted distribution were interpreted to be till (cf. Olcott and Siegel, 1978, pp. 9,13,14). Where samples were not available, materials given in the field log as till were interpreted as such, and materials given as outwash or alluvium were interpreted as alluvium. Interpretations were checked by correlations among borings and by surface topography.

Table 5 : Stockpile Data, Erie's Dunka Mine

Stockpile #	Material [1]	Date Started [1]	Tons [2]	% Gabbro [1]	Area, ft^2 [3]	Area, m^2 [3]
8012	gabbro	Mar. 1967	1,162,341	100	538,452	50,024
8014	gabbro	Jun. 1967	4,190,806	100	1,880,464	174,701
8016	gabbro	Dec. 1968	629,577	100	266,338	24,744
unlabelled	waste rock				252,345	23,444
8017	waste rock				695,487	64,613
8011	waste rock	Dec. 1965	14,251,581	70	3,345,113	310,772
8013	waste rock	Apr. 1967	7,969,236	70	2,739,538	254,512
8022	lean taconite	Apr. 1968	211,315	0	204,638	19,012
8006	surface			0	2,158,705	200,551
8005	surface			0	228,292	21,209

[1] information supplied by Erie Mining Company

[2] tonnage based on Erie Mining Company yardage records. 1 yd^3 ~ 2.4545 ton

[3] areas planimetered by Liang on Erie Mining Company's "Map of Mining Area 8", 1" = 200'

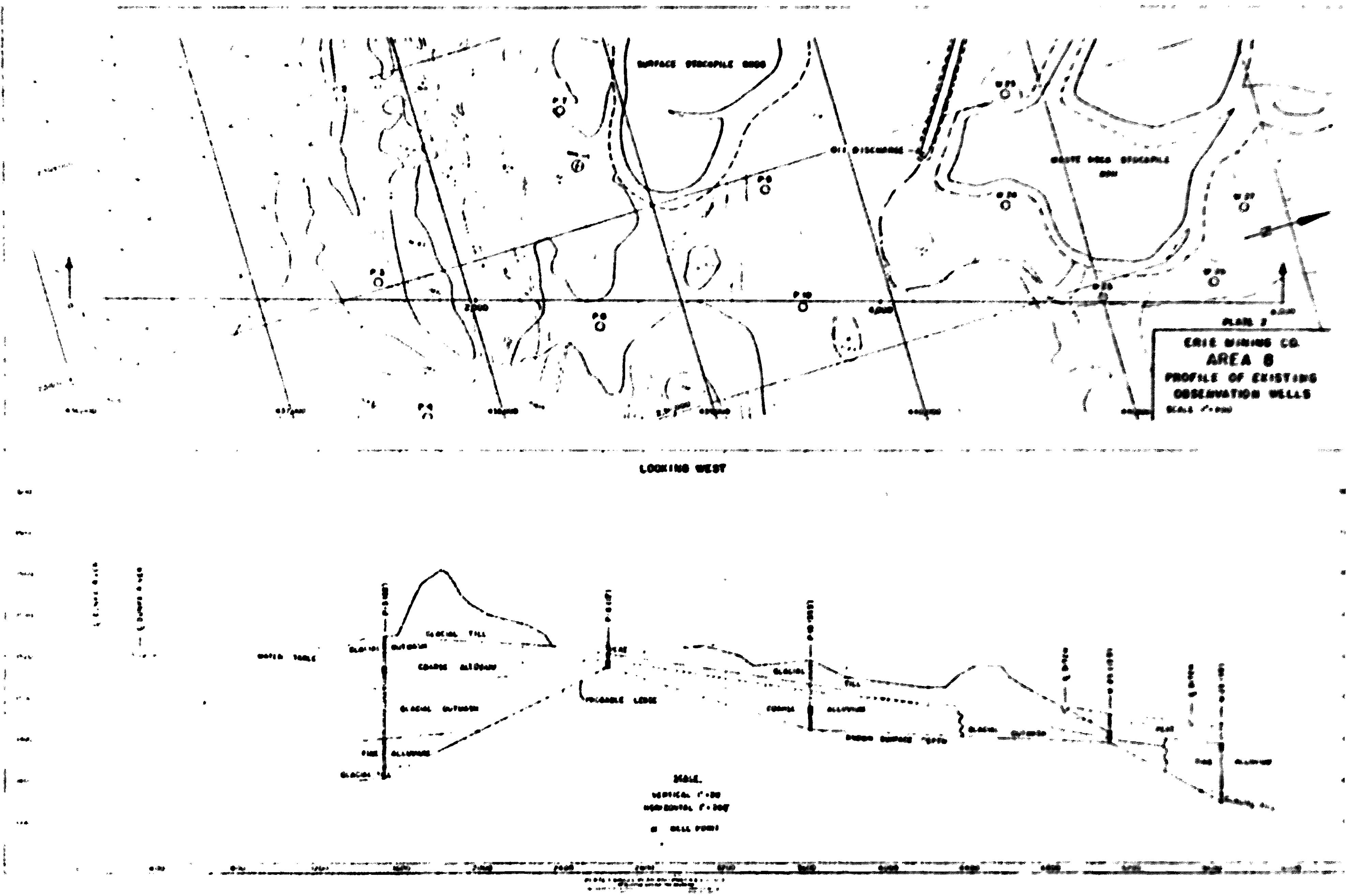

ERIE MINING CO.
AREA 8
PROFILE OF EXISTING
OBSERVATION WELLS
SURFACE STOCKPILE
WASTE ROCK STOCKPILE
OIL DISCHARGE
LOOKING WEST
WATER TABLE
GLACIAL TILL
GLACIAL OUTWASH
COARSE ALLUVIUM
FINE ALLUVIUM
PROBABLE LEDGE
PEAT
SCALE
VERTICAL 1"=30'
HORIZONTAL 1"=300'
WELL POINT

PLATE 3

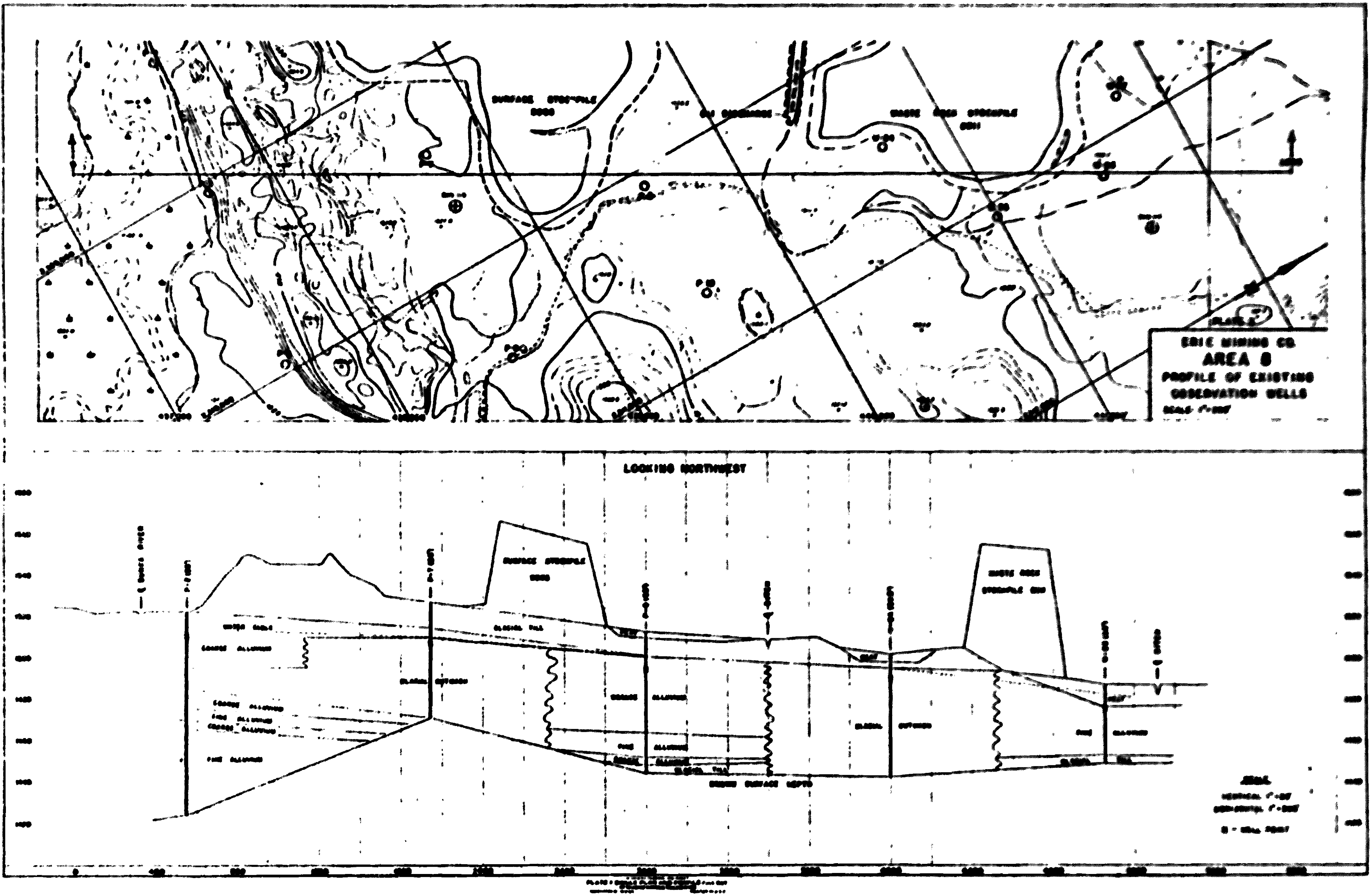

ERIE MINING CO.
AREA 8
PROFILE OF EXISTING
OBSERVATION WELLS
SURFACE STOCKPILE
WASTE ROCK STOCKPILE
LOOKING NORTHWEST
GLACIAL TILL
GLACIAL OUTWASH
COARSE ALLUVIUM
FINE ALLUVIUM
SCALE

Figure 16

SURFICIAL GEOLOGY NEAR WASTE ROCK STOCKPILE 8011

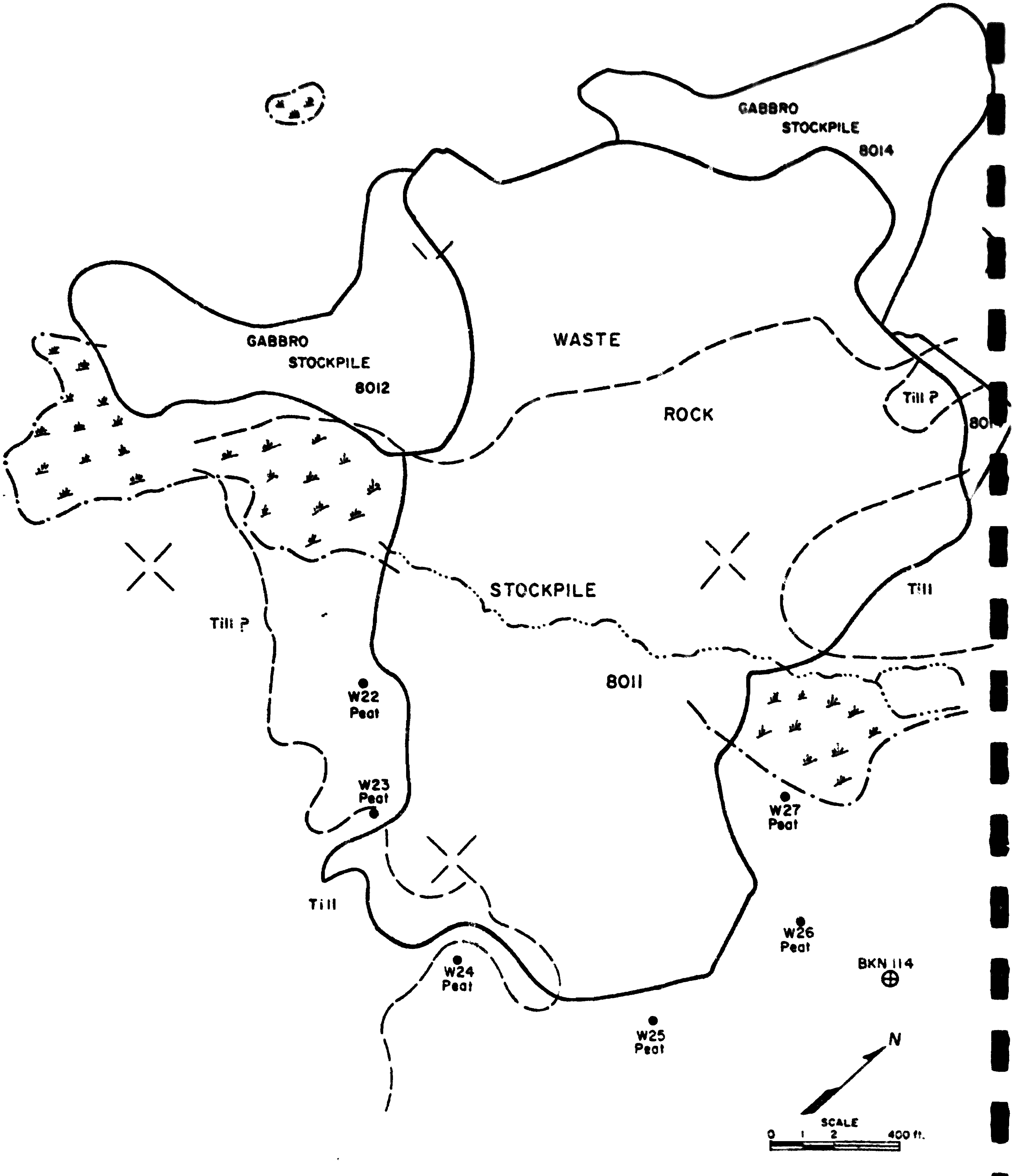
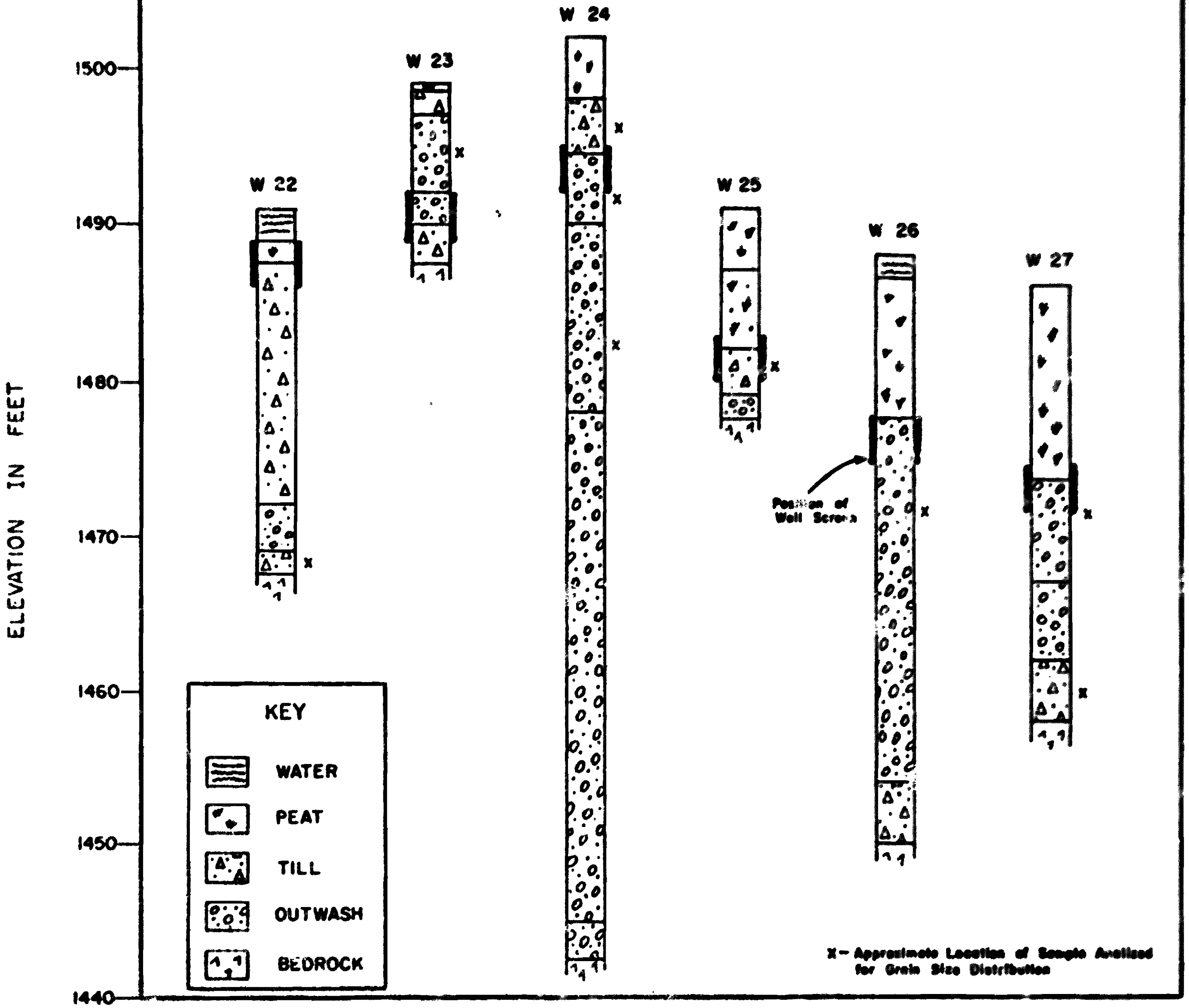


Figure 17

LOGS OF WELLS AROUND STOCKPILE 8011



end, between wells W23 and W24. Based on topography and field observation, the 8014 pile is probably underlain by bedrock at the northwest and peat in the central area.

Till and bedrock probably underlie the eastern portion. The mining company blasted through a bedrock ridge when installing the seep 3 pipe (Peterson, pers. comm., 1979). Northeast trending bedrock ridges underlie the eastern margin of the 8013 pile in the vicinity of seep 1. Most of the eastern part of the pile is probably on till or bedrock.

Porosity: The overall porosity of the stockpiles is estimated by Erie Mining Co. to be 33%. Since the waste rock and lean ore have densities of 3 g/cm^3, the weight per cubic meter of bulk stockpile is 2 x 10^6 g or 2 metric tons.

Grain Size: Little information is available concerning the grain size distribution of the stockpiles. The maximum diameter of the blasted rock is roughly four feet, and mining company personnel have estimated that less than 0.1% by weight of the material in the stockpiles is less than 2 mm in diameter (Stanhope, pers. comm., 1978).

Data on the grain size distribution of rock processed by cone crushers and jaw crushers (Iwasaki, 1978; from Lapakko, 1979, "Methods of Calculations" pp. 1-2) are give in figure 18. Although they pertain to crushed rock rather than blasted rock, they constitute the best information available. The data were fit by Lapakko (1979) to a curve of the form

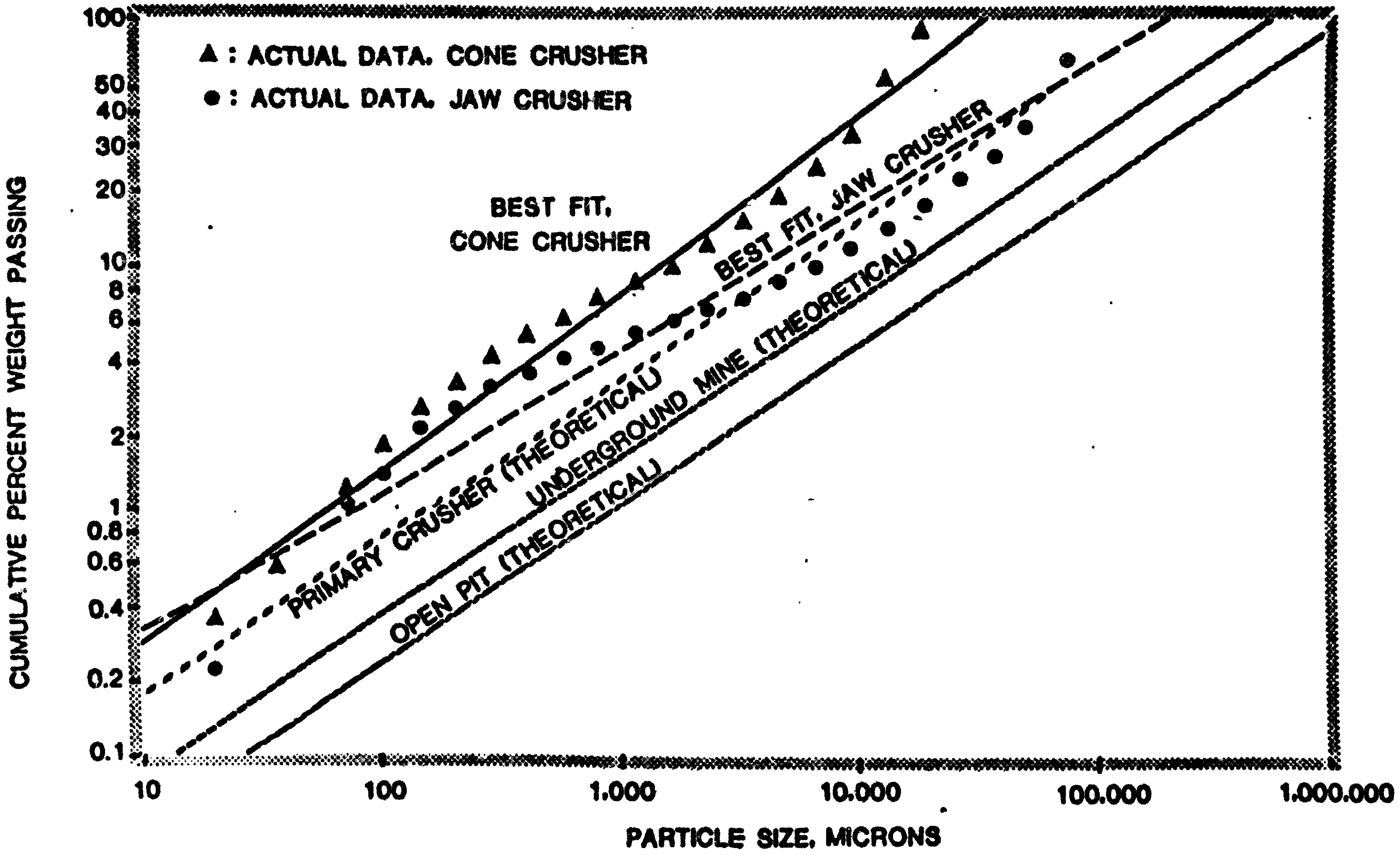
$$\log P = a \log d + b$$

$$P = b_1 * d^a, \qquad (b_1 = 10^b)$$

where d is the diameter in microns and P is the percent by weight of material of diameter d or smaller. Extrapolating this data to material with

FIGURE 18. GRAIN SIZE DISTRIBUTION OF CRUSHED GABBRO

PERCENT PASSING VS PARTICLE SIZE



SOURCE : LAPAKKO, 1978

a maximum diameter of four feet (= 1.22×10^6 microns), the size distribution equation is

$$P = 0.0127\, d^{0.64}$$

(Lapakko, 1979, "Methods of Calculations", p.4). This equation gives 1.65% by weight less than 2 mm, over 10 times as much as estimated by Erie Mining Company.

Specific Surface Area: Using the grain size distribution given above, and assuming spherical particles, Lapakko (1979, "Methods of Calculations", p.8) derived the following equations for particle surface area per unit mass of stockpile rock:

$$S = (6*10^4*a*b)\ \sigma^{-1} \int_{d_1}^{d_2} d^{a-2}\, d(d)$$
$$= (6*10^4*a*b)\ \sigma^{-1}(a-1)^{-1}\ (d_2^{\,a-1} - d_1^{\,a-1})$$

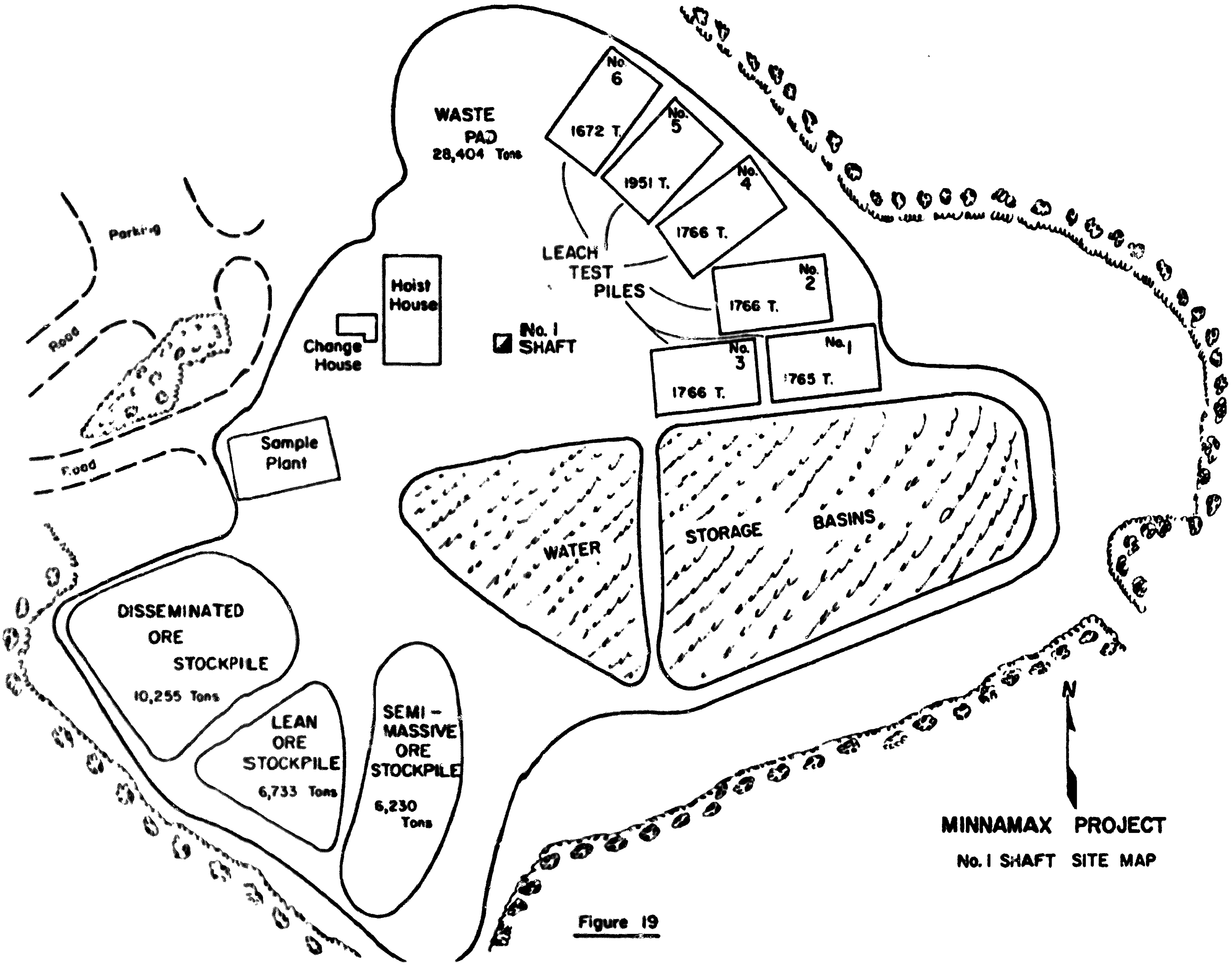
where S is the specific surface area in m^2/MT, σ is the density of gabbro in MT/m^3, d_2 and d_1 are the maximum and minimum grain diameters in microns (μm), and a and b_1 are as defined above.

For the Erie stockpiles, the upper limit is fixed at 4 ft. (1.22×10^6 microns), but the lower limit is unknown, and S does not converge for decreasing d_1. S for selected values of d_1 is given below:

d_1 (μm)	S(m^2/MT)
10	195
100	83.4
1000	34.7
20000	26.4

2. AMAX

Field Description: The leach test piles at the Minnamax site are laid out as shown in figure 19. Each pile is roughly 13 feet high and 3000 $ft.^2$ in area at the base (specifications in figure 20, field measurements in table 6). Piles 1 to



MINNAMAX PROJECT

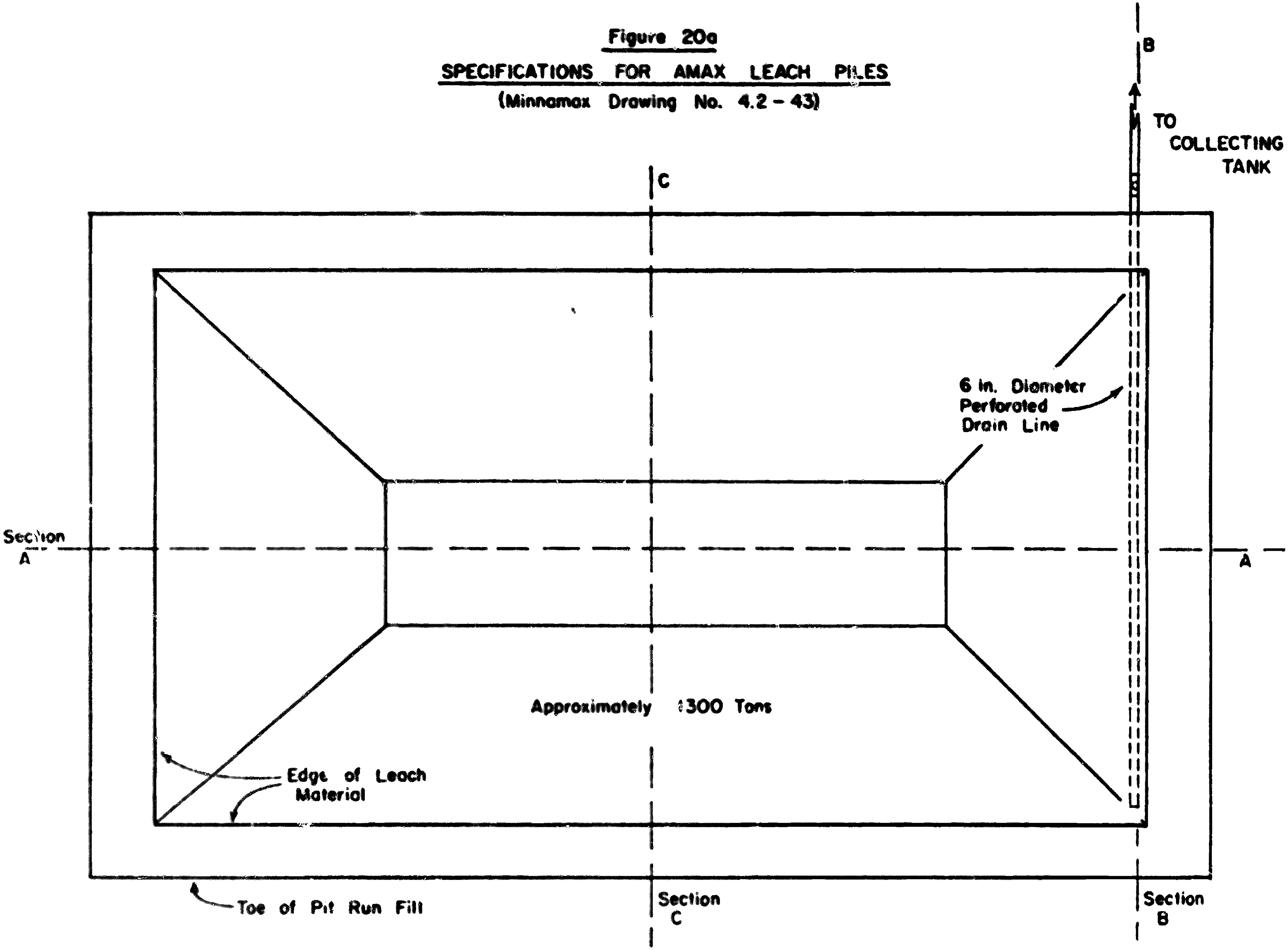
No. 1 SHAFT SITE MAP

Figure 19

Figure 20a

SPECIFICATIONS FOR AMAX LEACH PILES

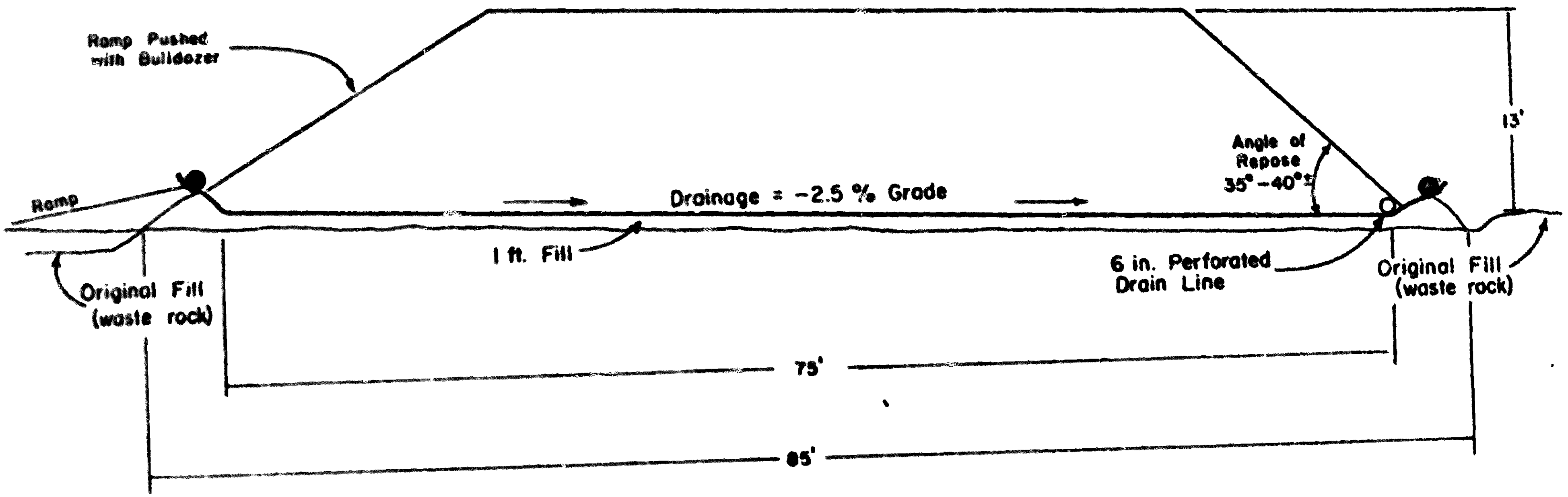
(Minnamax Drawing No. 4.2 - 43)



PLAN VIEW LEACH PILE

SCALE : 1" = 10'

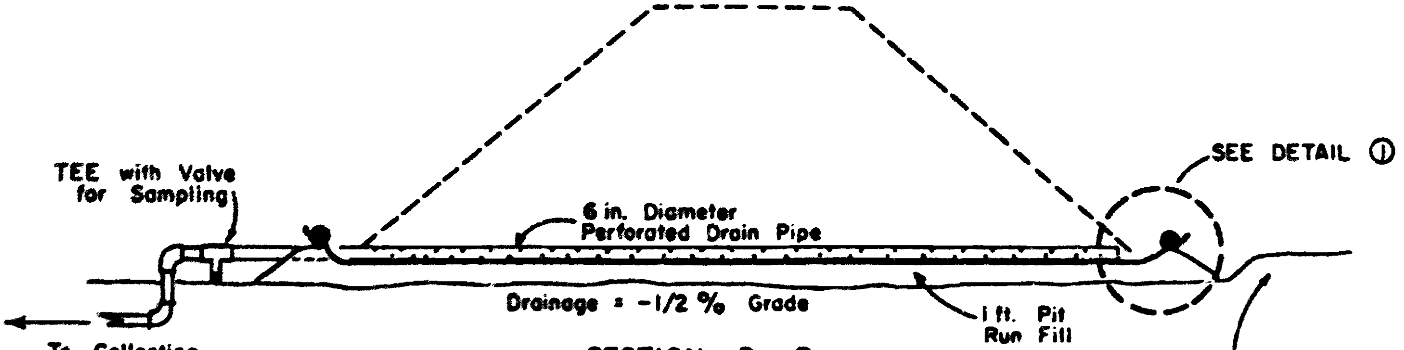
Figure 20b



SECTION A - A

SCALE : 1" = 10'

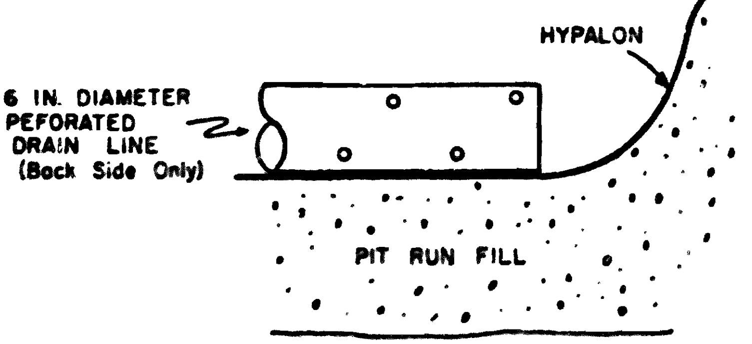
Figure 20c

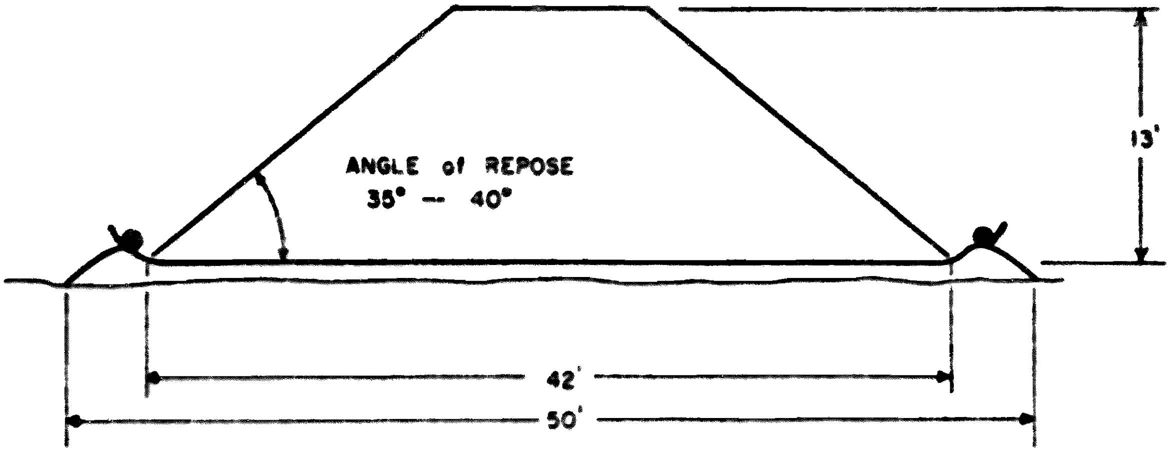


SECTION B – B

SCALE : 1" = 10'

DETAIL ①





SECTION C – C

SCALE : 1" = 10'

Table 6. Leach pile data, Minnamax

				Area (ft.^{2})			
	Source[1]	Tonnage[1]	Rock Volume[2] Ft.^{3}	Total	Rock	Hypalon	Treatment[4]
FL 1	Shaft	1760	28210	3195.5	3157	38.5	None, control
2	Shaft	1760	28210	3648	3493	155	top soil, reveg.
3	Shaft	1760	28210	3270	3240	30	Overburden, reveg.
4	Shaft	1760	28210	3531	2993	538	None, control
5	Drift	1951	31270	3669	3530	109	Overburden, reveg.
6	Drift	1672	26800	3515	3177	338	None, control
TOTAL				20830	19590	1240	

1) Letter, Thomas M. Hargy, AMAX, Feb. 22, 1978.

2) Based on 16.03 ft^3/ton.

3) Field measurements by Bruce Johnson. AMAX estimate was 4250 ft^2/pile.

Area calculations by Paul Eger as of 8-24-78. For revised estimates see Eger, Johnson and Hohenstein, 1979.

4) Eger, 1978.

4 contain material blasted from the exploration shaft. Piles 5 and 6 contain material from the horizontal drifts cut laterally off the shaft. The rock is considerably finer grained than that at Erie, and appears to have abundant sand sized grains.

Construction of the piles was as follows (field report by Eger, 1977): A sand layer was placed on the waste rock pad and then contoured and sloped. Hypalon was then laid on the sand, and a 5 to 6 inch perforated sewer pipe placed in the lower end of the sand pad. Test material was then loaded onto the hypalon and contoured with a small bulldozer. Examination of the hypalon after large rocks had been dumped on it did not show any rips, tears, or punctures. The sand is contoured to provide a lip around the pile and the hypalon extends over this lip and is weighted down. All of the piles drain to a central sump.

Piles 1 through 4 were constructed in April of 1977, piles 5 and 6 in September 77. In spring of 1978, selected piles were covered with various top dressings and revegetated to test possible reclamation measures (see Table 6).

Piles 1 and 3 have a southern exposure, which may affect their response to rain events.

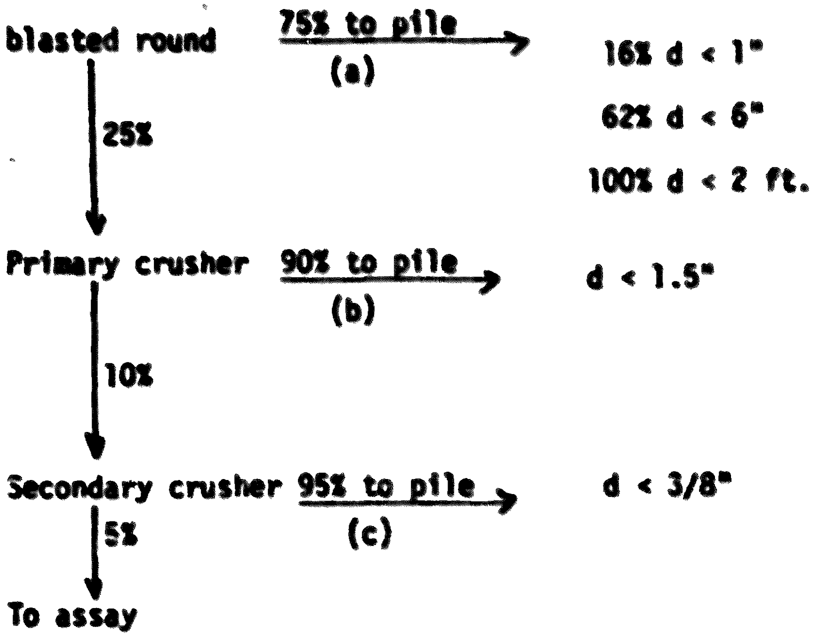
Porosity: The bulk porosity of in-place samples was estimated to be 1/3, based on estimates by the Technical Assessment Group of the Copper-Nickel Study.

Grain Size: A grain size analysis of material in the leach piles at Amax is given in Figure 21. Regression of log P on log d for the shaft round data (the size breakdown of component a) gives:

$$P = 0.0413\, d^{0.585}$$

Since only three data points are known, the grain size distribution based on crusher data is thought to be more reliable, and the three components of the test piles were fit with the following three equations:

Fig. 21 : Grain Size Distribution of Minnamax Leach Test Piles*



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* data from Sturgis, pers. comm., 1978

a) $P = 0.01984\ d^{0.64}$

b) $P = 0.117\ d^{0.64}$

c) $P = 0.2841\ d^{0.64}$

The surface area in M^2/MT for each component is:

a) $S_a = -7.0554 \times 10^2\ d^{-0.36} \Big|_{d}^{d_{max\ a}}$

b) $S_b = -4.160 \times 10^3\ d^{-0.36} \Big|_{d_1}^{d_{max\ b}}$

c) $S_c = -1.010 \times 10^4\ d^{-0.36} \Big|_{d_1}^{d_{max\ c}}$

And combined in the appropriate ratio of (.75): (.225): (.0238), they give a total surface area per metric ton of test pad of:

$S_t = -34.253 + 1705.6\ d_1^{-0.36}$

For $d_1 = 10$ microns, $S_t = 710.3 m^2/MT$. For $d_1 = 1000$ microns, $S_t = 107.6 m^2/MT$. Use of the grain size distribution based on the 3 shaft round data points gives

$S_t = 940\ m^2/MT$ for $d_1 = 10$ microns, and

$S_t = 115.9\ m^2/MT$ for $d_1 = 1000$ microns.

Stockpile Runoff

1. Erie. During the study no surface runoff from the stockpiles at Erie was observed. Seeps emerge at the base of the piles in three places: EM-9, seep 1 and seep 3 (Plate 1, figure 1). Each seep is located in a natural drainageway of the original subpile topography. There are other less pronounced lows in the original topography from which seepage was not observed (Plate 1). In 1975 Erie installed a non-perforated 14 inch diameter steel tailing pipe in an effort to reduce leaching (Stanhope, pers. comm, 1978). The pipe was then covered with a pad of blasted waste rock. The area from EM-9 to EM-8 was ditched for drainage in Summer, 1975.

The continuous flow data from EM-8 provide the best picture of stockpile seepage (figure 22). Flow declined steadily from July through November of 1976. Rainstorms were few and small, and provoked only minor increases in flow. Flow stopped completely in late November of 1976 and did not resume until late March of 1977. A sharp peak apparently related to snowmelt occurred in mid-April. Throughout 1977 the seep clearly responded to significant rain events, reaching peak flow about one day after the rain. Between storm events, flow was sustained at a lesser level. Figure 23 shows monthly discharges for EM-8. The large difference in rainfall between the two years is reflected in differences in flow. Figure 24 gives flow duration curves for July-September of 1976 and 1977, and again indicated the overall higher flows and marked peak flows for 1977.

The pattern of flow in 1978 was similar to that in 1977, with clear response to rain events. Summer flow was higher in 1978 than in 1977, though precipitation was lower (Figs. 23a and 23b). Depleted storage and a large soil moisture deficit at the start of the 1977 season

Figure 22 a

PRECIPITATION AND FLOW AT EM – 8

1976

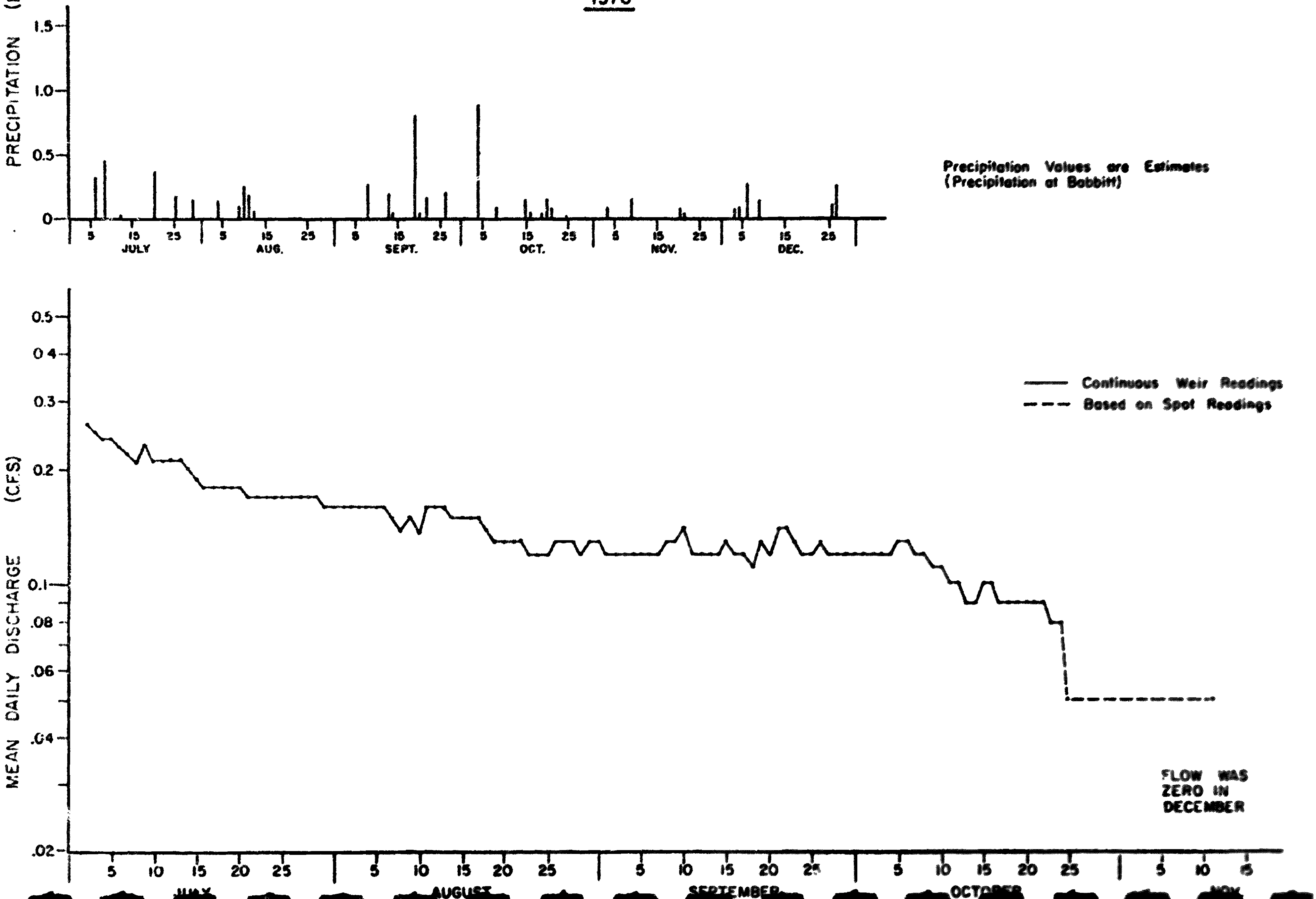


Figure 22b: PRECIPITATION AND FLOW AT EM-8, 1977

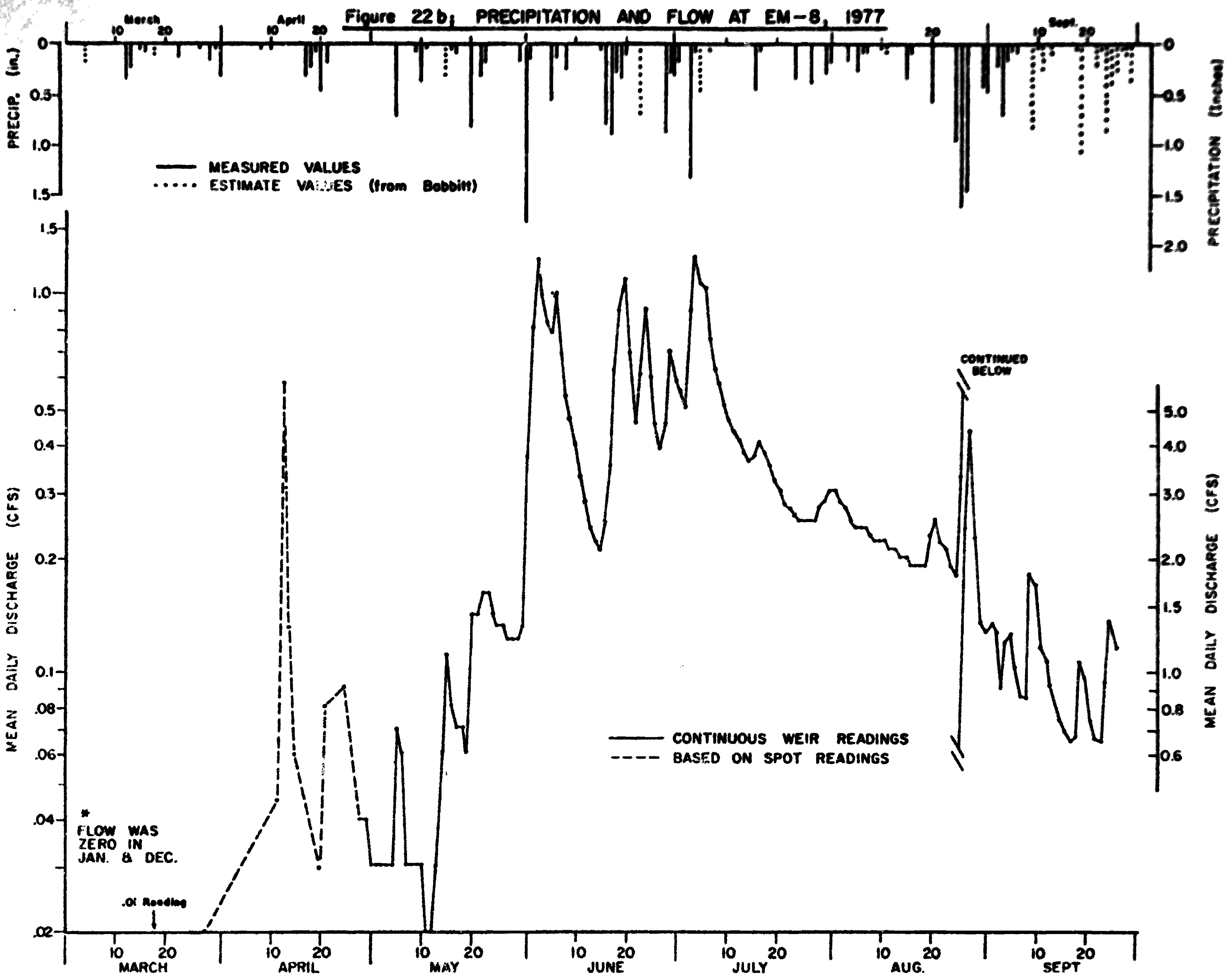
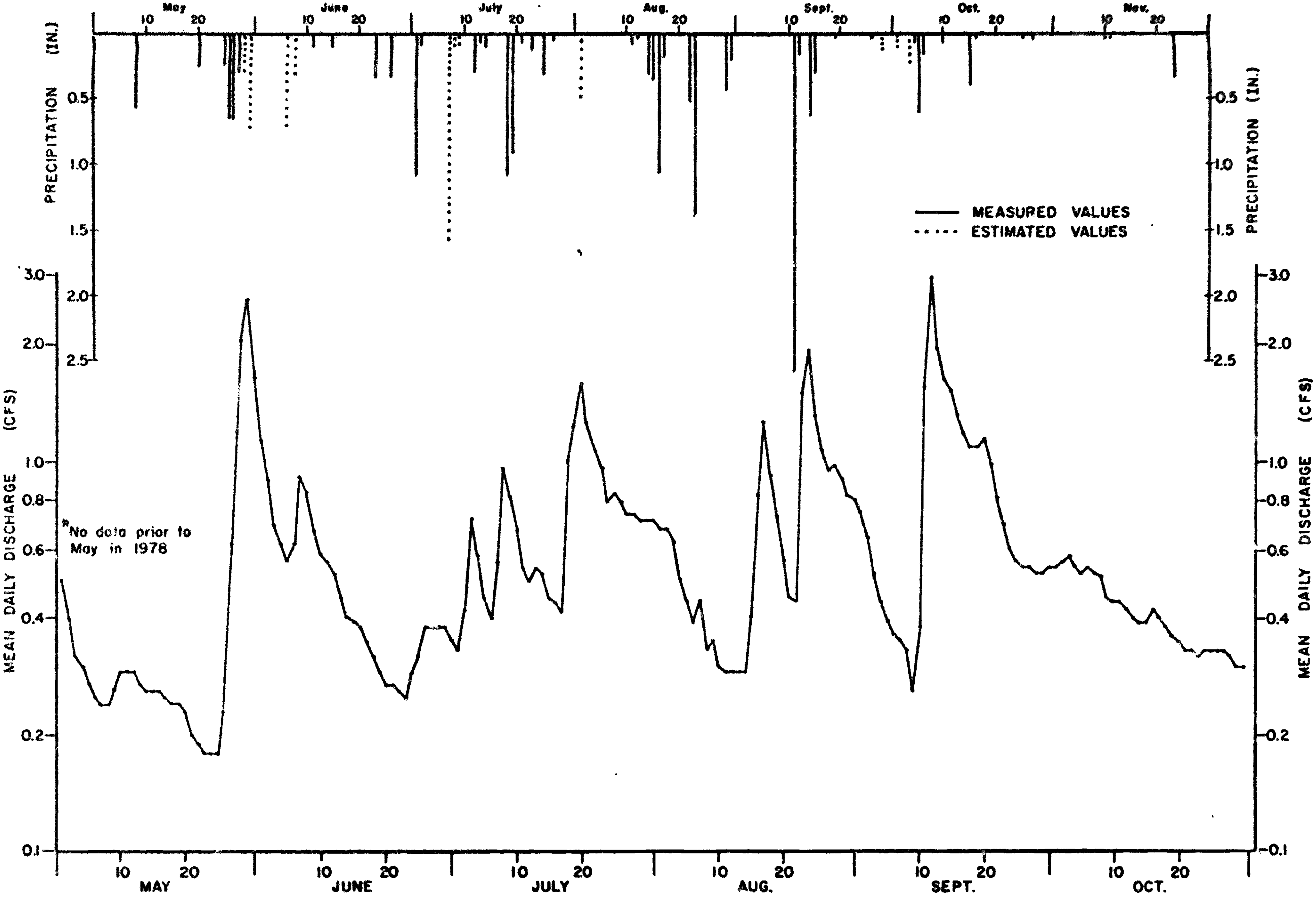


Figure 22c; PRECIPITATION AND FLOW AT EM-8, 1978



*No data prior to May in 1978

Figure 23a

MONTHLY PRECIPITATION AND MONTHLY FLOW AT EM-8

1976-1977

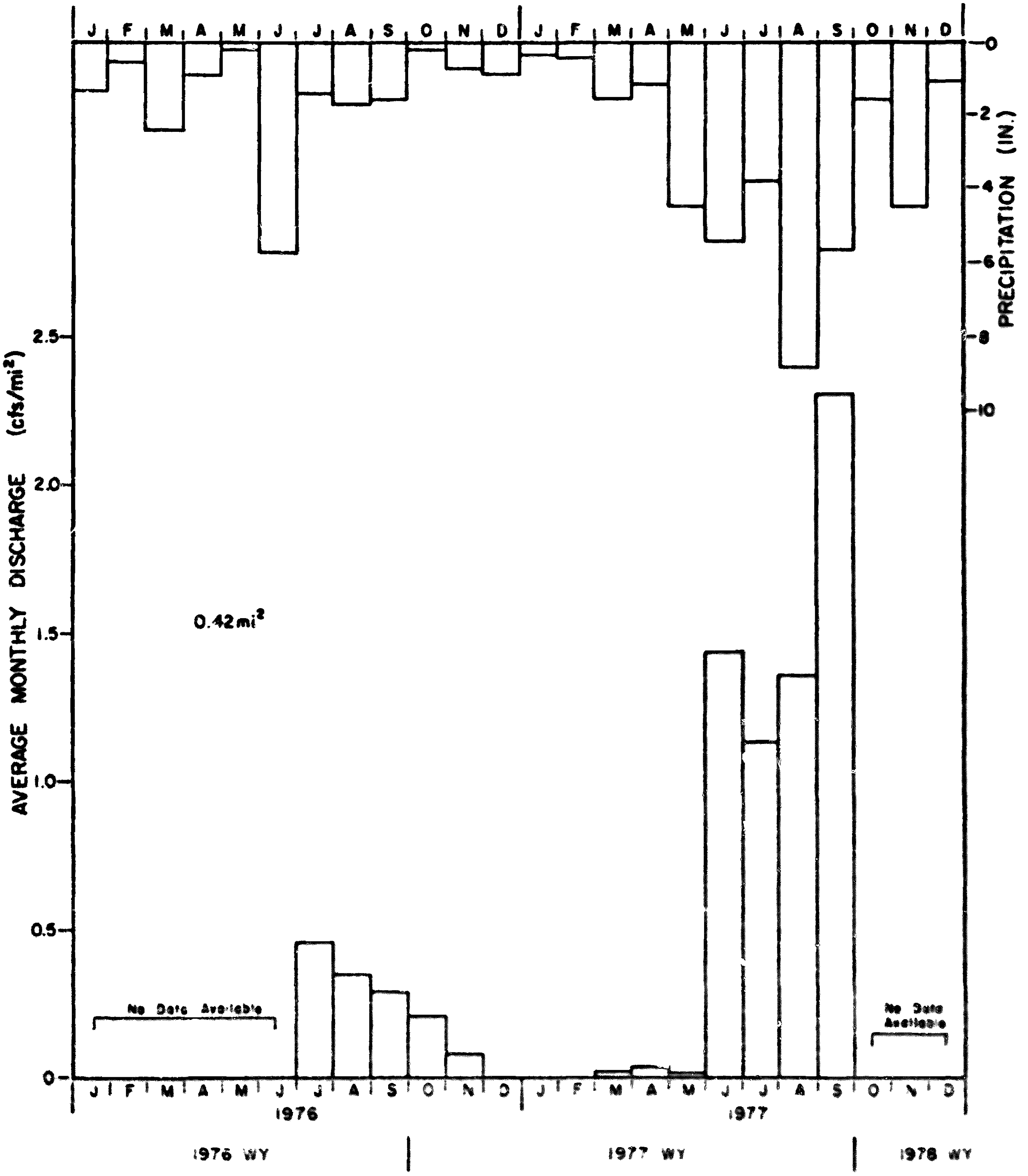


Figure 23b

MONTHLY PRECIPITATION AND MONTHLY FLOW AT EM-8

1978

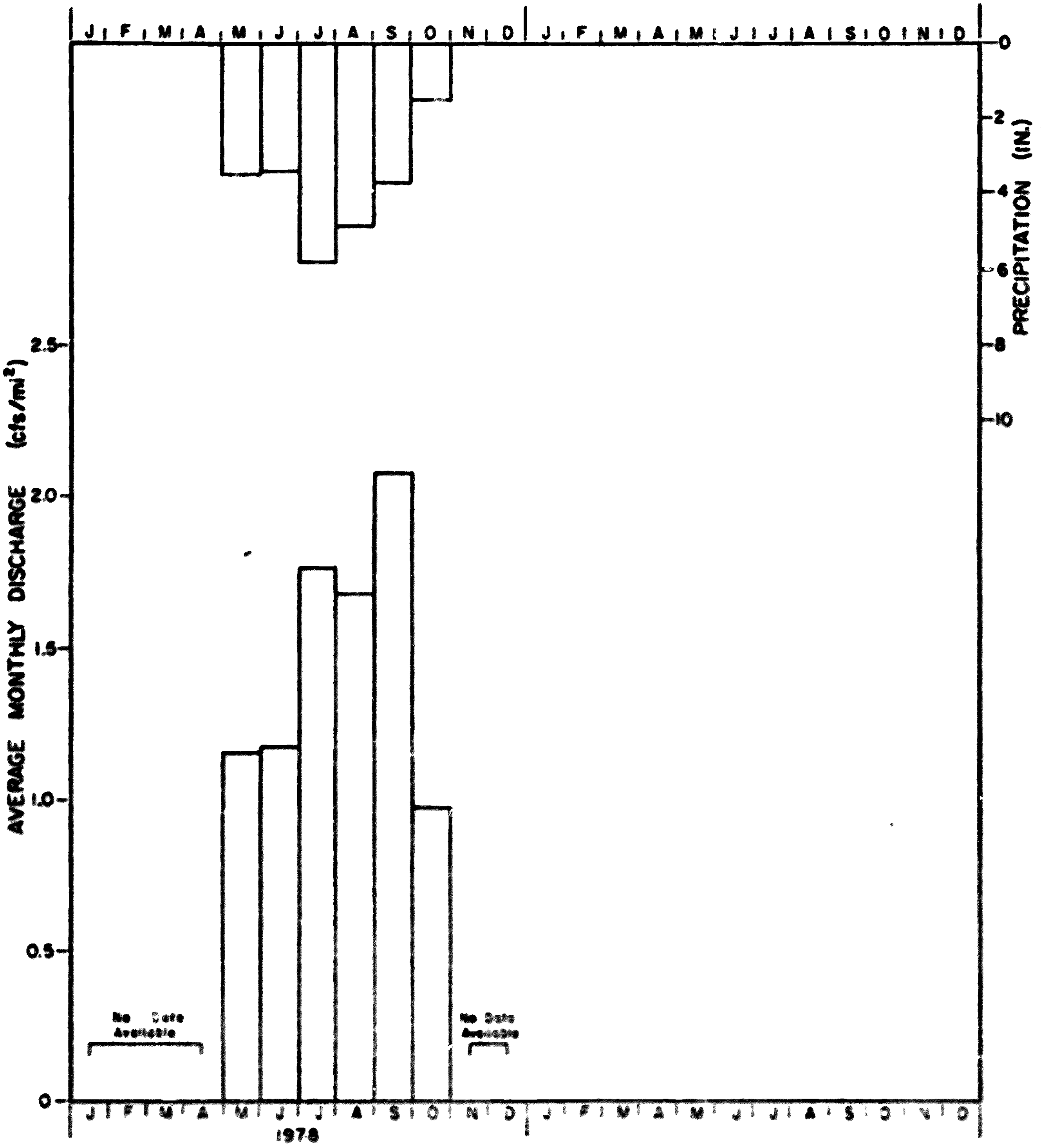
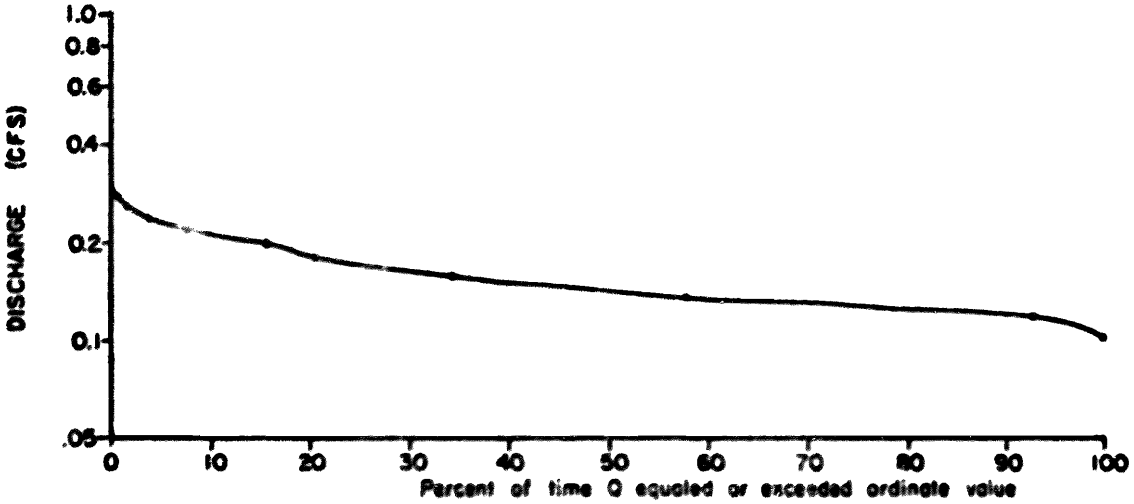


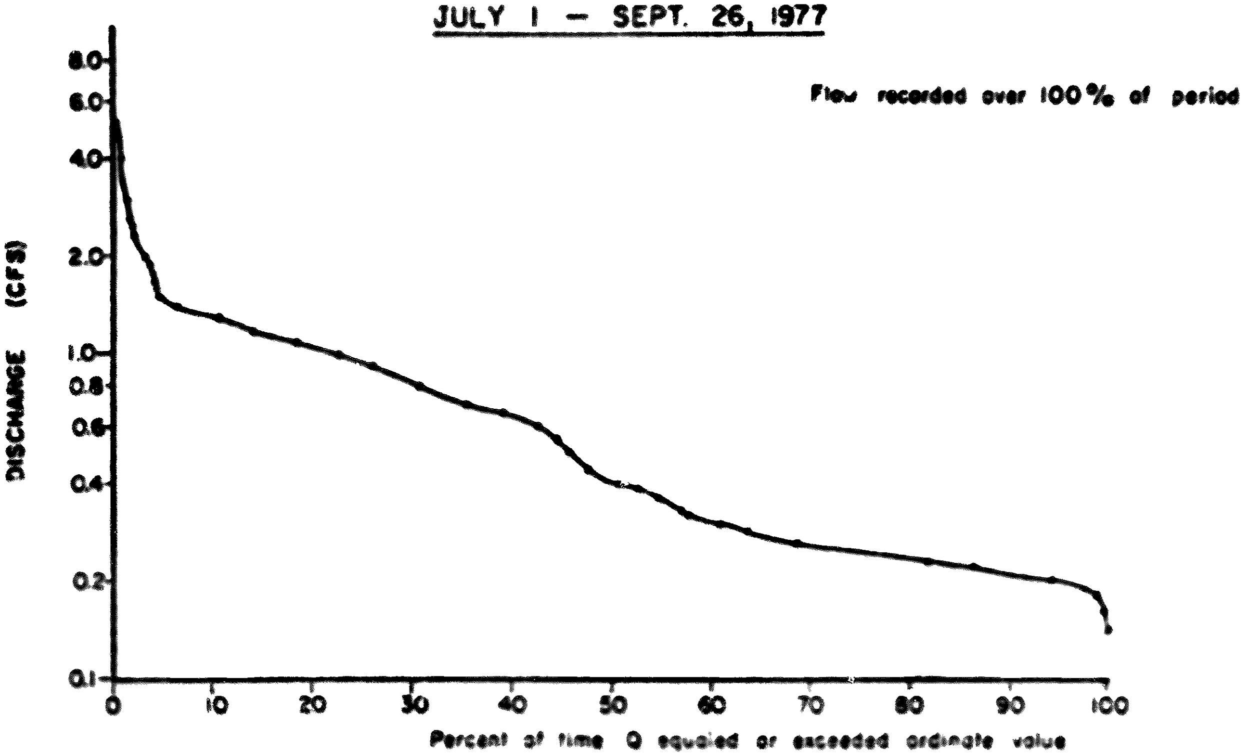
Figure 24

FLOW DURATION CURVE AT EM – 8

JULY 1 – SEPT. 26, 1976



JULY 1 – SEPT. 26, 1977



probably account for this.

Seeps 1 and 3 appeared to follow a pattern of flow similar to that at EM-8, based on spot readings of discharge (figs. 25 and 26). Flow declined from July through November of 1976. Flows at seep 1 appeared to decline less sharply than those at seep 3 or EM-8, but this may be due to limited precision with the flow meter for flows below 0.1 cfs. Flow stopped over the winter and resumed at a low rate in late March of 1977. In the summer of 1977 all three seeps responded to the increase in rainfall with higher flows.

The ratio of monthly flow at seep 1 or seep 3 to monthly flow at EM-8 varied considerably (table 7). The ratio of monthly flow at seep 3 to that at EM-8 varied from 0.05 to 0.68, with typical values near 0.5. The ratio of their watershed areas is 0.2. The ratio of monthly flow at seep 1 to that at EM-8 varied from 0.11 to 1.0. Typical values in 1976 were near 0.45, while typical values in 1977 were near 0.16. The ratio of the areas of the seep 1 watershed to the EM-8 watershed is in the range of 0.03 to 0.15. The water yielding characteristics of the three watersheds clearly differ. The EM-8 watershed may have higher evapotranspiration, since it has more vegetation and more wet, flat marshy areas. Water seeping into large till areas in the EM-8 watershed may flow out under the gage.

2. AMAX. No surface runoff has been observed from the field leaching piles at AMAX. Water drains from the bottoms of the piles via perforated sewer pipes.

Sump discharge records show a sharp response to storm events (figs. 28 and 29). Between storms, flow drops off more rapidly than at Erie and frequently declines to zero. Comparison of monthly flows for the

Figure 25

PRECIPITATION AND SEEP DISCHARGE AT ERIE'S DUKA MINE 1976

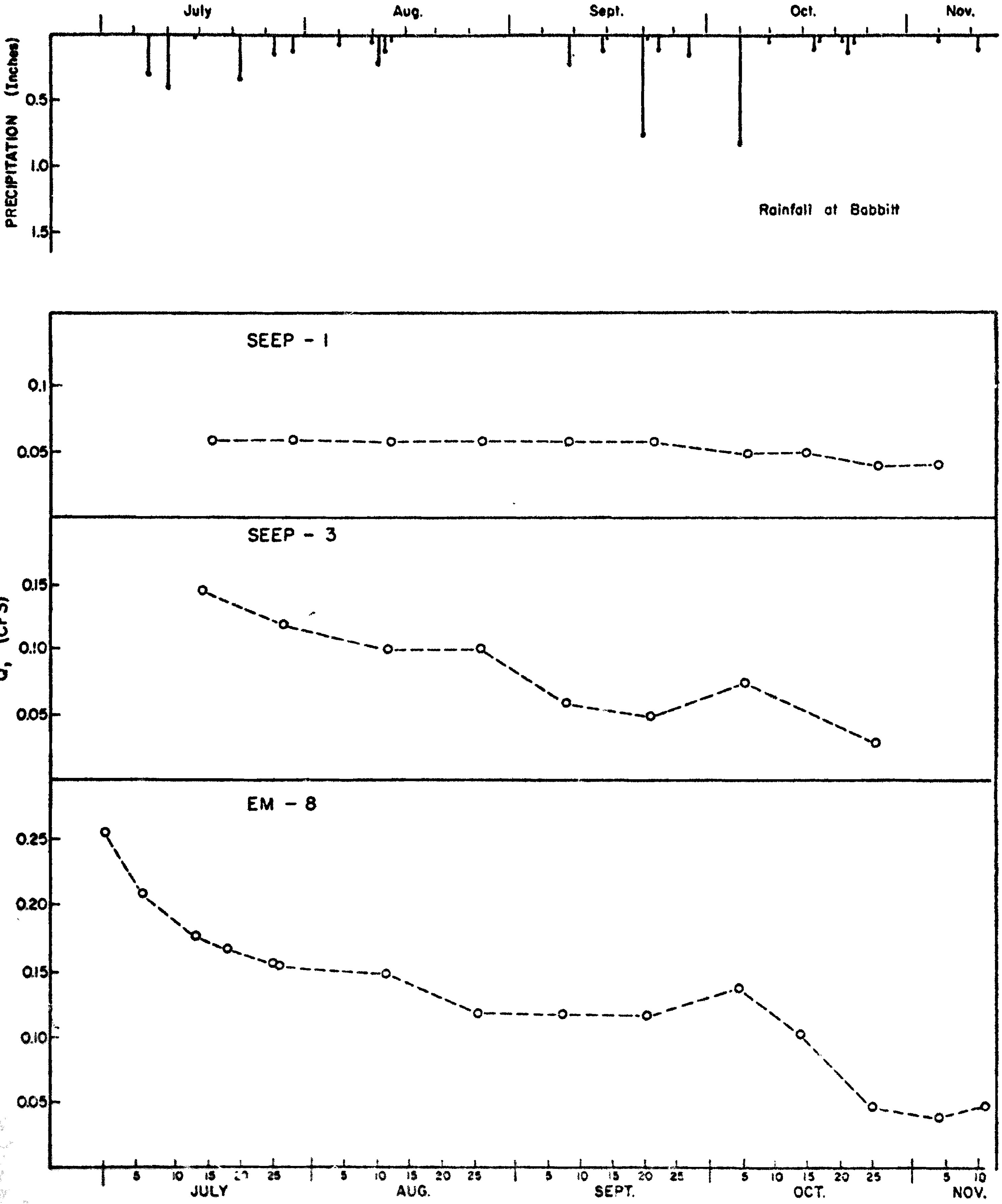


Figure 26

PRECIPITATION AND SEEP DISCHARGES AT ERIE'S DUNKA MINE 1977

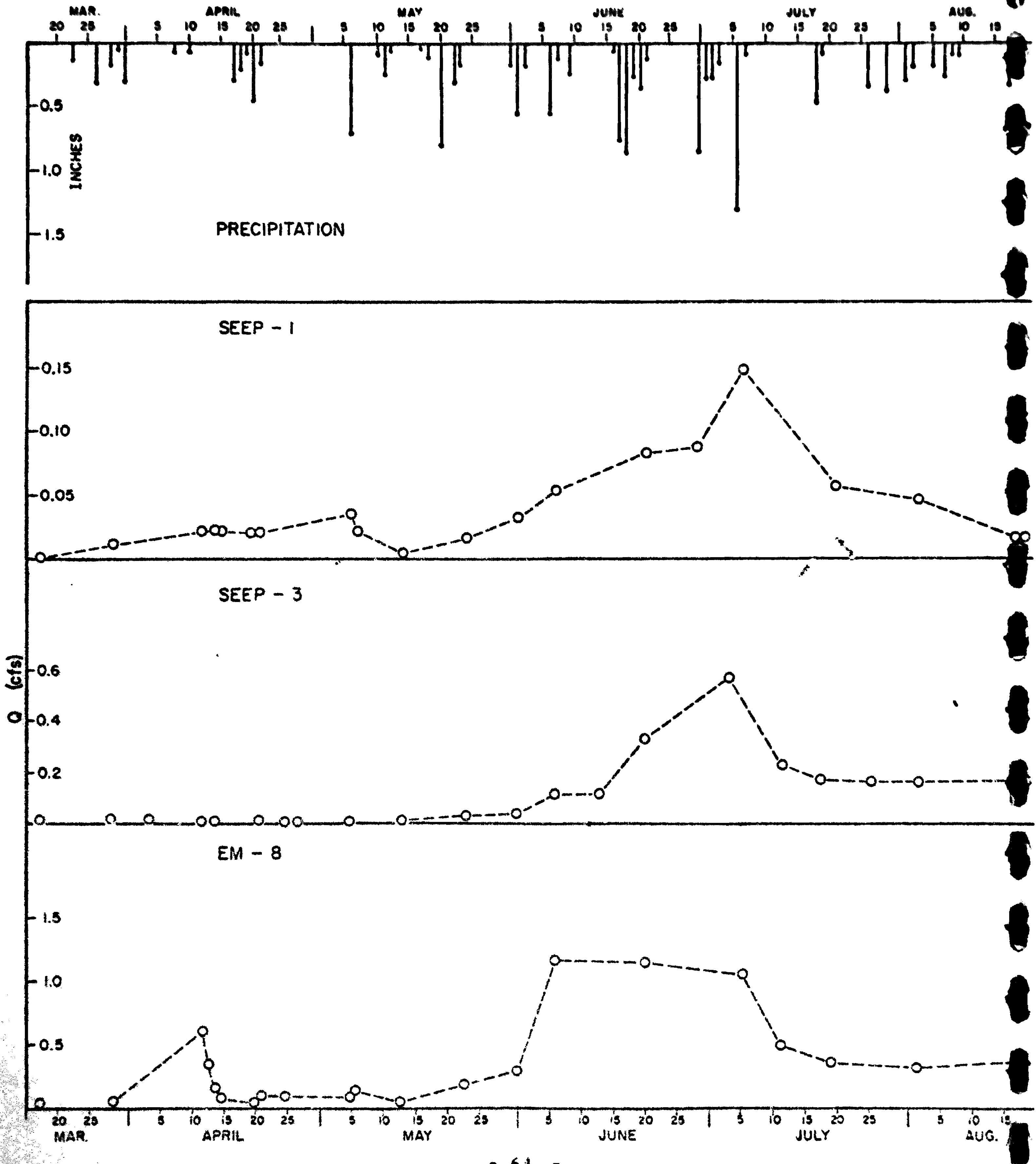


Table 7. Comparison of monthly flows of stockpile seepages at Erie.

Average flow, cfs

		EM-8	Seep 3	Seep 1	Seep 3/ EM-8	Seep 1/ EM-8	Seep 1/ Seep 3
1976	J	0.198	nd	nd	---	---	
	A	0.147	0.10	0.06	.68	.41	.6
	S	0.124	0.061	0.059	.49	.48	.97
	O	0.100	0.048	0.045	.48	.45	.94
	N	0.032	0.0017	0.032	.05	1.0	19.
	D	0	0	0.0045	---	----	-----
1977	J	0	0	0	---	----	-----
	F	0	0	0	---	----	-----
	M	0.0068	0.0035	0.0034	---	.50	-----
	A	0.13	0.0077	0.021	.059	.16	2.7
	M	0.088	0.020	0.016	.23	.18	0.8
	J	0.61	0.25	0.070	.41	.11	0.28
	J	0.47	0.29	0.084	.60	.18	0.3
	A	0.49	nd	nd	---	----	-----
	S	0.76	nd	nd	---	----	-----
	O	nd	nd	nd	---	----	-----
	N	nd	nd	nd	---	----	-----
	D	nd	nd	nd	---	----	-----

nd = not determined

Figure 27

MONTHLY FLOW AT SEEP 3

1976 and 1977

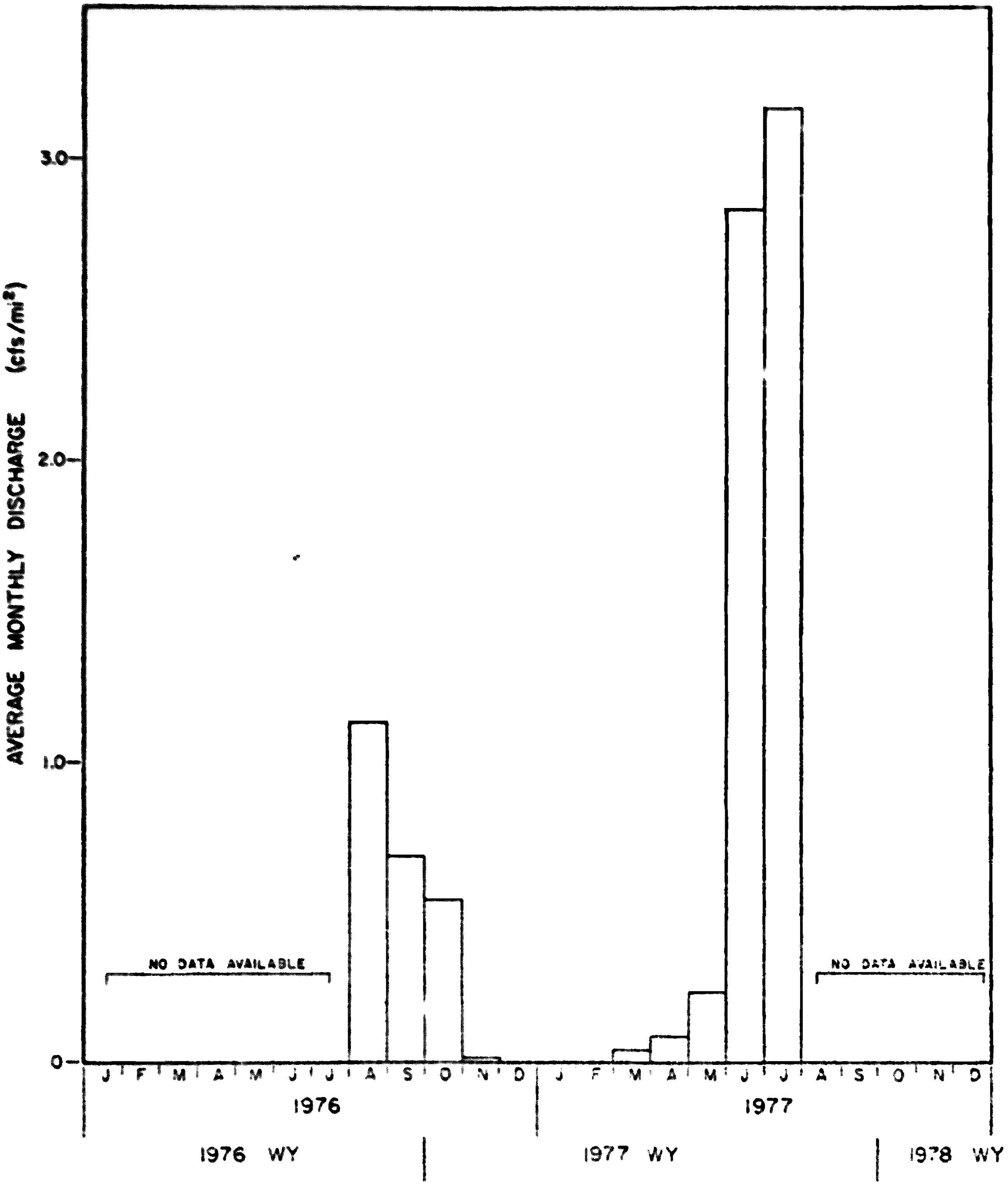


Figure 28

PRECIPITATION AND DISCHARGE AT FL - 1, 1977

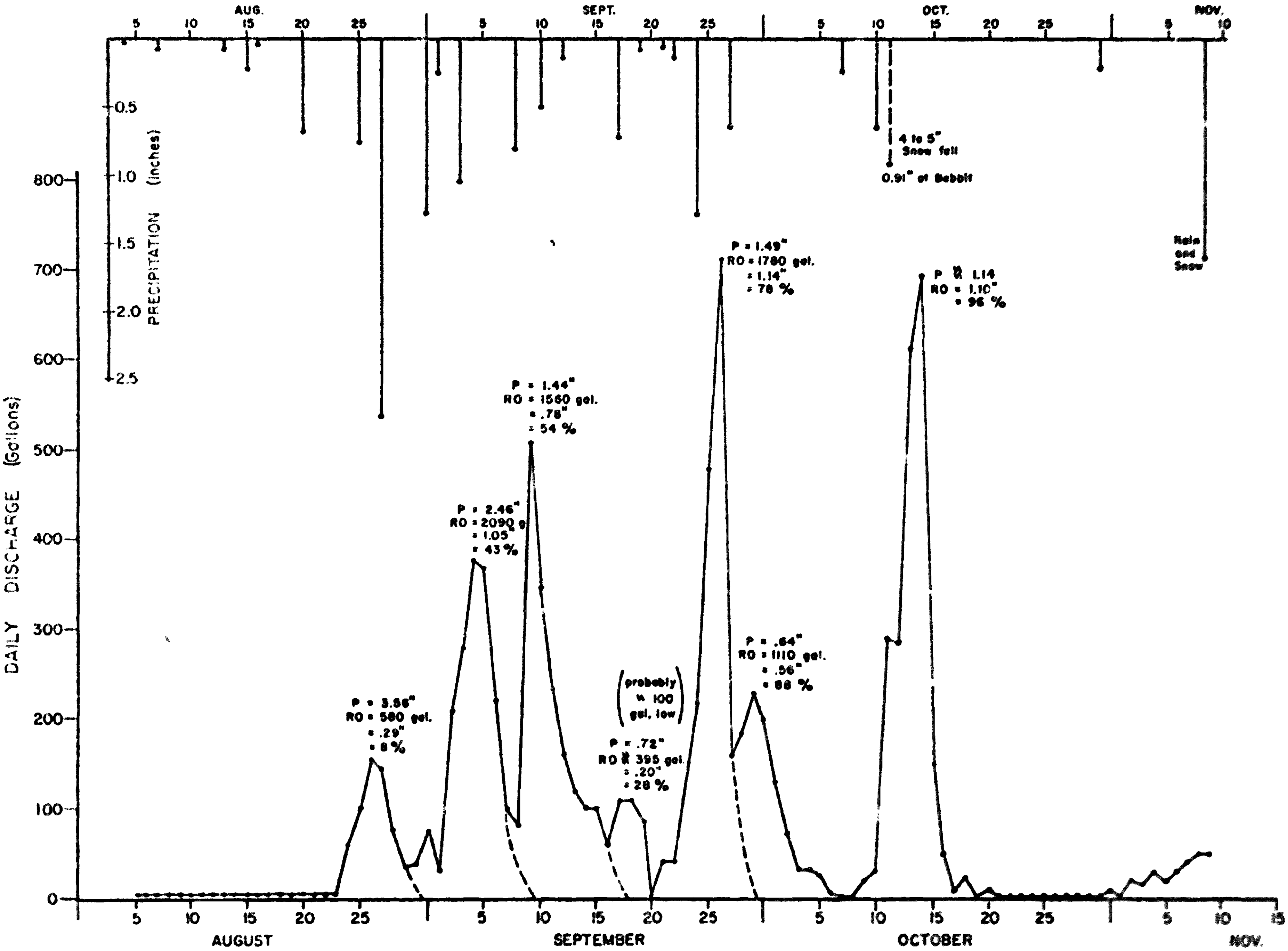
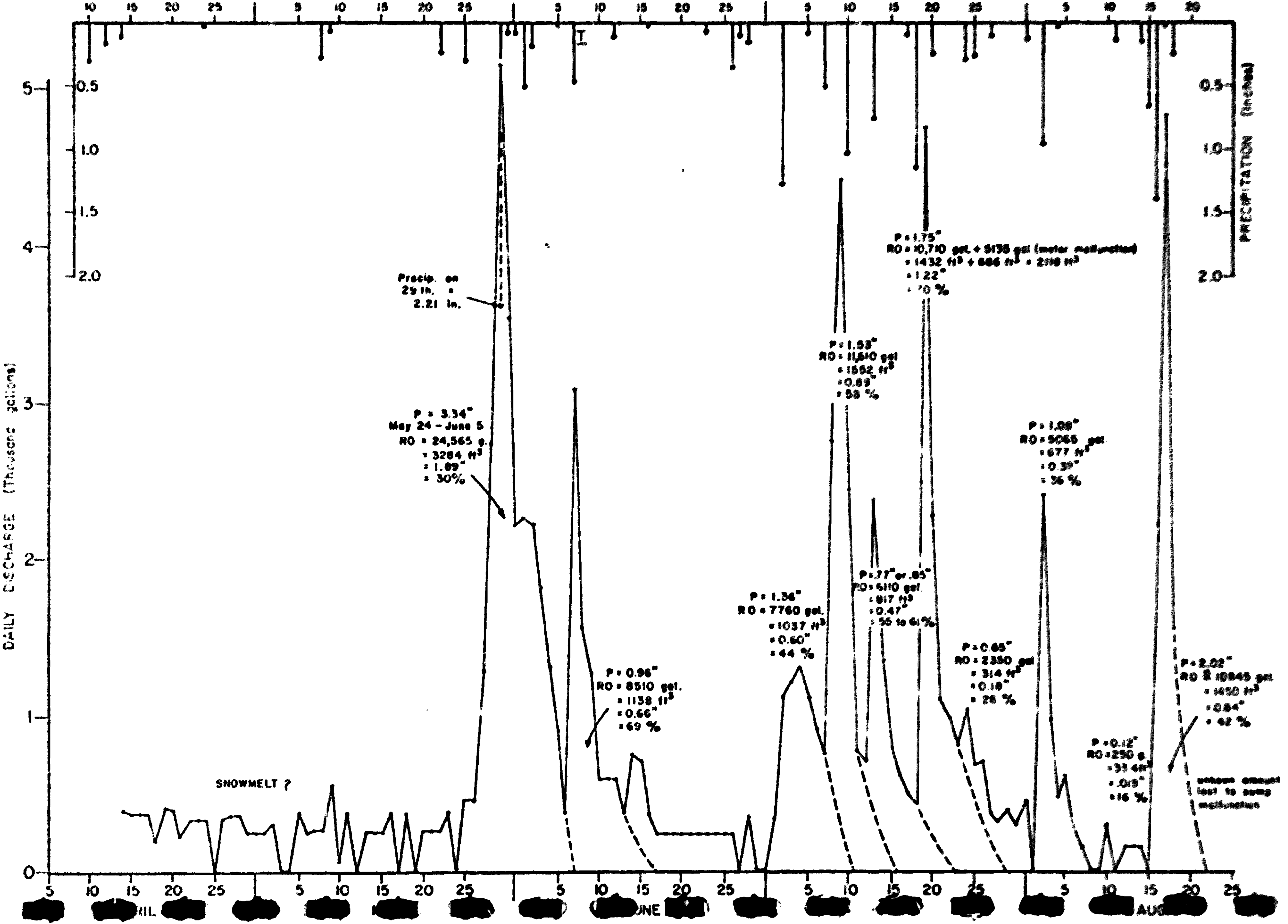


Figure 29

DAILY PRECIPITATION AND SUMP DISCHARGE AT AMAX, 1978

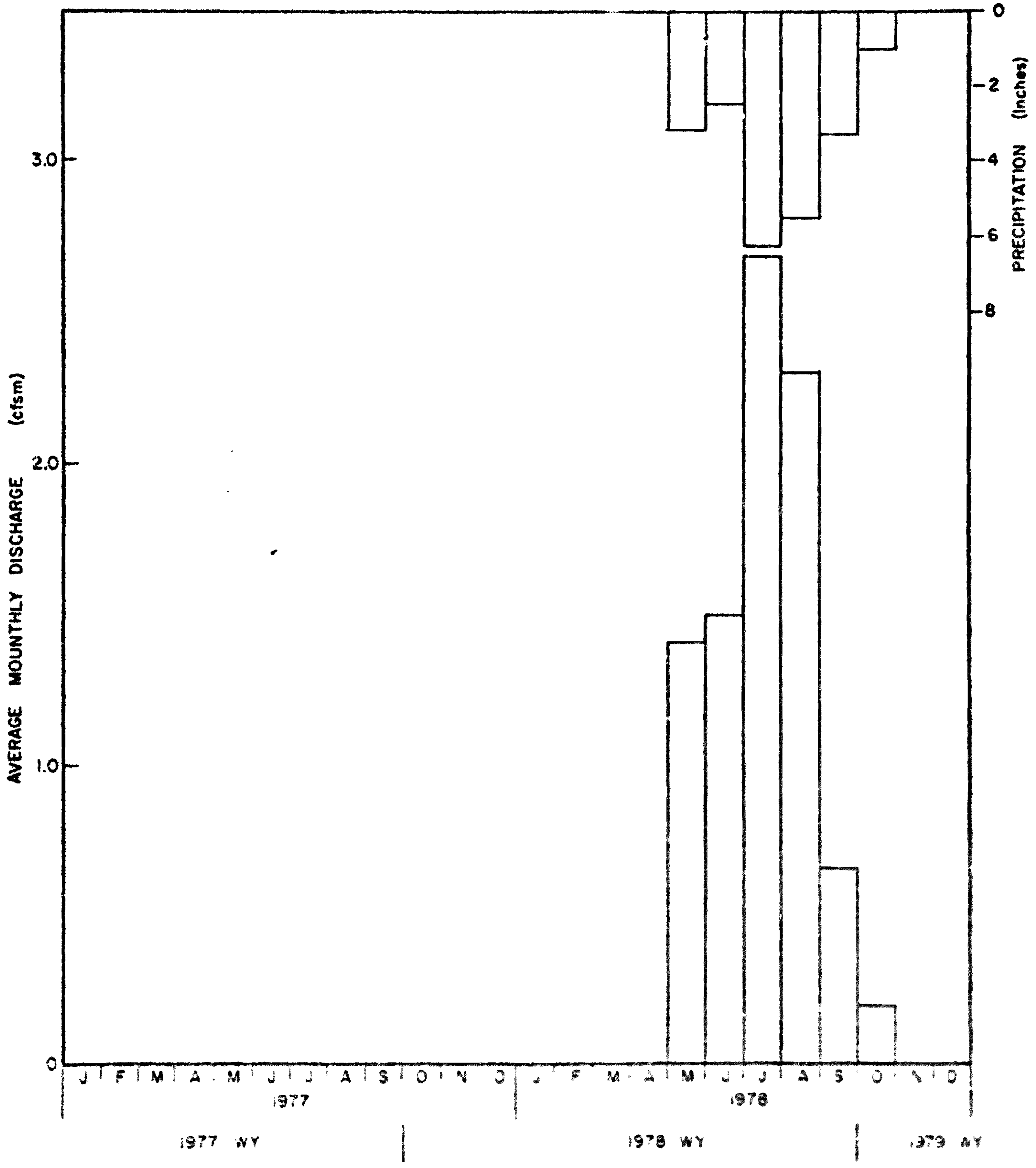


Amax sump (figure 30) and EM-8 in 1978 (fig. 23) shows that the Amax piles yielded more water per unit area from May through August, but less in September and October. This is indicative of the rapid response and lack of significant storage of the Amax piles.

Figure 30

PRECIPITATION AND SUMP DISCHARGE AT AMAX

1978



Seep Temperature

Temperatures at all three seeps stayed below 4°C in July through November of 1976, with temperatures generally between 0.5 and 2.5°C (fig. 31). Temperature data from the weir at EM-8 show that considerable warming occurred between the seep at EM-9 and the weir during July and August.

In 1977 temperatures covered a wider range (fig. 32). The temperature at seep 1 was below zero in late March and early April, but rose to 5°C by mid May and remained there through August, following a pattern roughly parallel to air temperatures. Seep 3 displayed the opposite pattern, with high temperatures in April and early May and lower temperatures from late May through August. Temperatures there appear to be lagging behind the seasonal surface temperature wave. This may indicate that the water in the 8014 stockpile has a residence time of several months. It could also indicate that seasonal variations in the temperature of the rock material at depth within the pile lag behind surface variations, and that the rocks then cool or heat the water flowing over them. That the stockpiles act as a thermal reservoir is supported by field observations. A cool breeze emanates from the base of the piles in summer (Eger, pers. comm, 1978). Snow cover does not develop on some areas of the stockpile surfaces in winter, and vapor rises out of the piles in these areas (Peterson, pers. comm, 1978). It is not clear why seep 3 shows a temperature lag while seep 1 does not.

No temperature data were taken at EM-9 in 1977. The data from EM-8 are dominated by the effects of heating and cooling in the pool and bog behind the weir.

Figure 31
SEEP DISCHARGE TEMPERATURES
1976

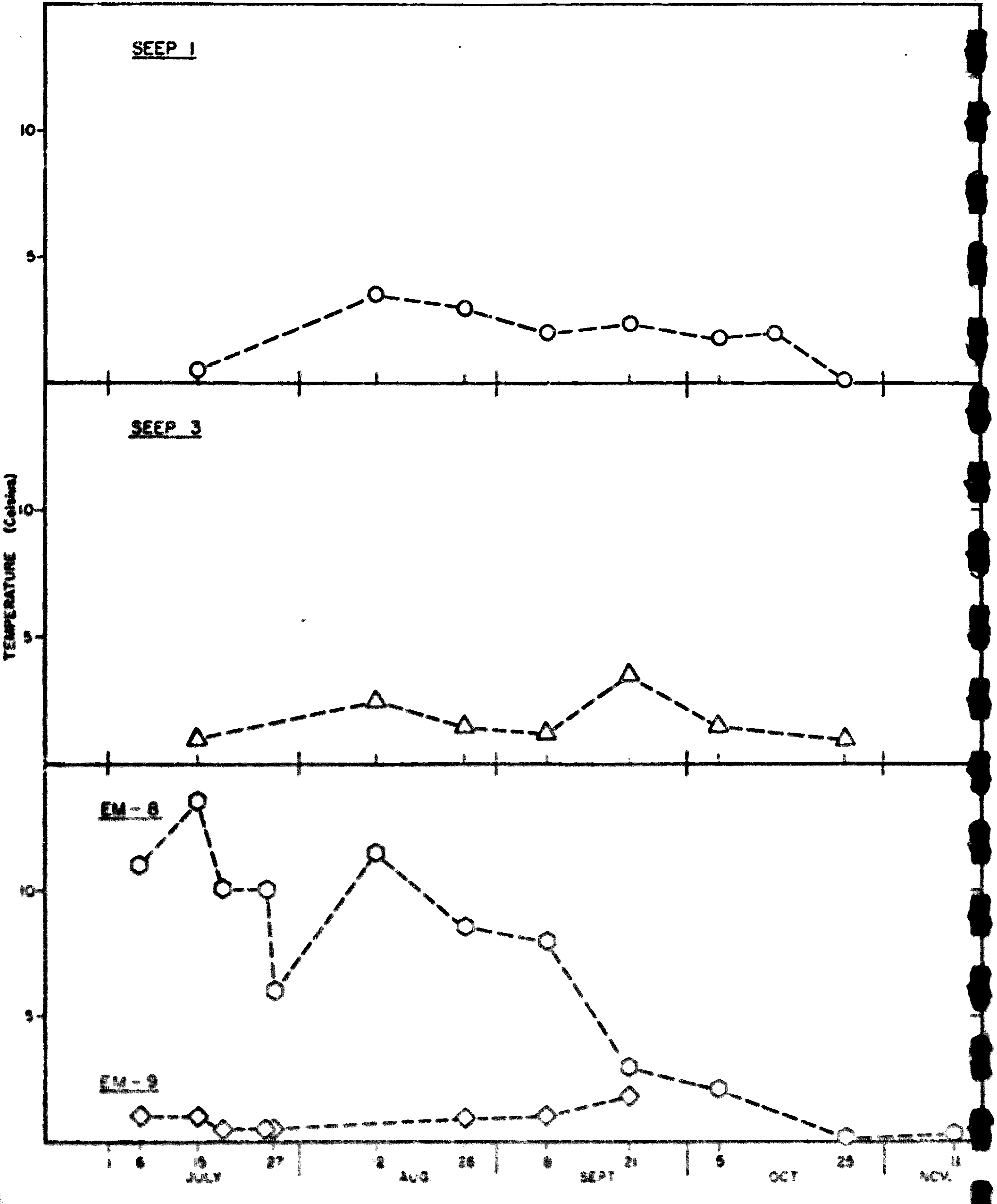
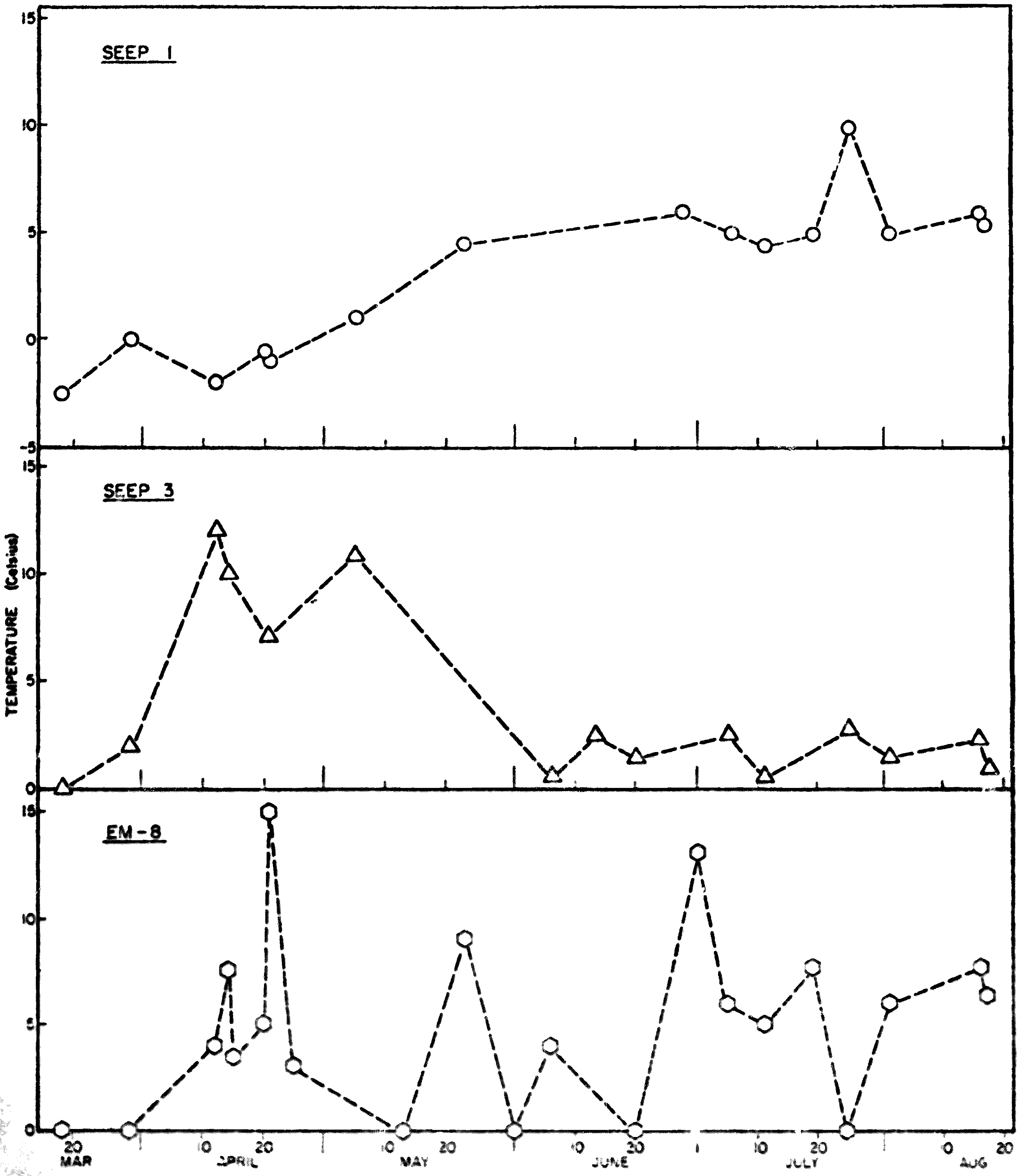


Figure 32

SEEP DISCHARGE TEMPERATURES

1977



Groundwater Levels and Groundwater Chemistry Around the 8011 Stockpile:

Figure 33 shows the water levels in the wells around the 8011 stockpile over the course of the study period. For three of the wells, water levels were considerably higher in the spring of 1976 than at any other time in the period. Water levels in all wells declined through spring and summer, then increased slightly through fall and winter and into spring of 1977. Levels dropped again in the summer of 1977 but recovered in the fall. The typical water levels for the period may have been somewhat lower than normal. Siegel and Ericson (1979, p. 23) found that "the water table (in surficial aquifers in the study area) fluctuated parallel with and as much as 1 to 1½ months behind major trends in the cumulative departure from mean monthly precipitation" from 1975 through spring of 1978. Most of the wells they studied recovered from the 1976 drought more rapidly than those at Erie, with water levels in the last half of 1977 and the spring of 1978 equal to or higher than those in the spring of 1976.

Water table contours and cross-sections constructed on the basis of the well data (figures 34-38) suggest that the groundwater in the surficial materials does not extend up into the stockpile. Water table elevations shown in the cross sections are from March 17, 1976, when water levels were generally at their highest. However, the cross sections show the original topography below the 8011 pile, while in fact the peat layer has probably been compressed by the weight of the overlying material. Loading at the base of the pile is calculated to be about 1 x 10^4 lb/ft^2, which could cause a 30 to 50 percent reduction in thickness of the peat, based on

Figure 33

WATER TABLE ELEVATIONS OF THE ERIE WELLS

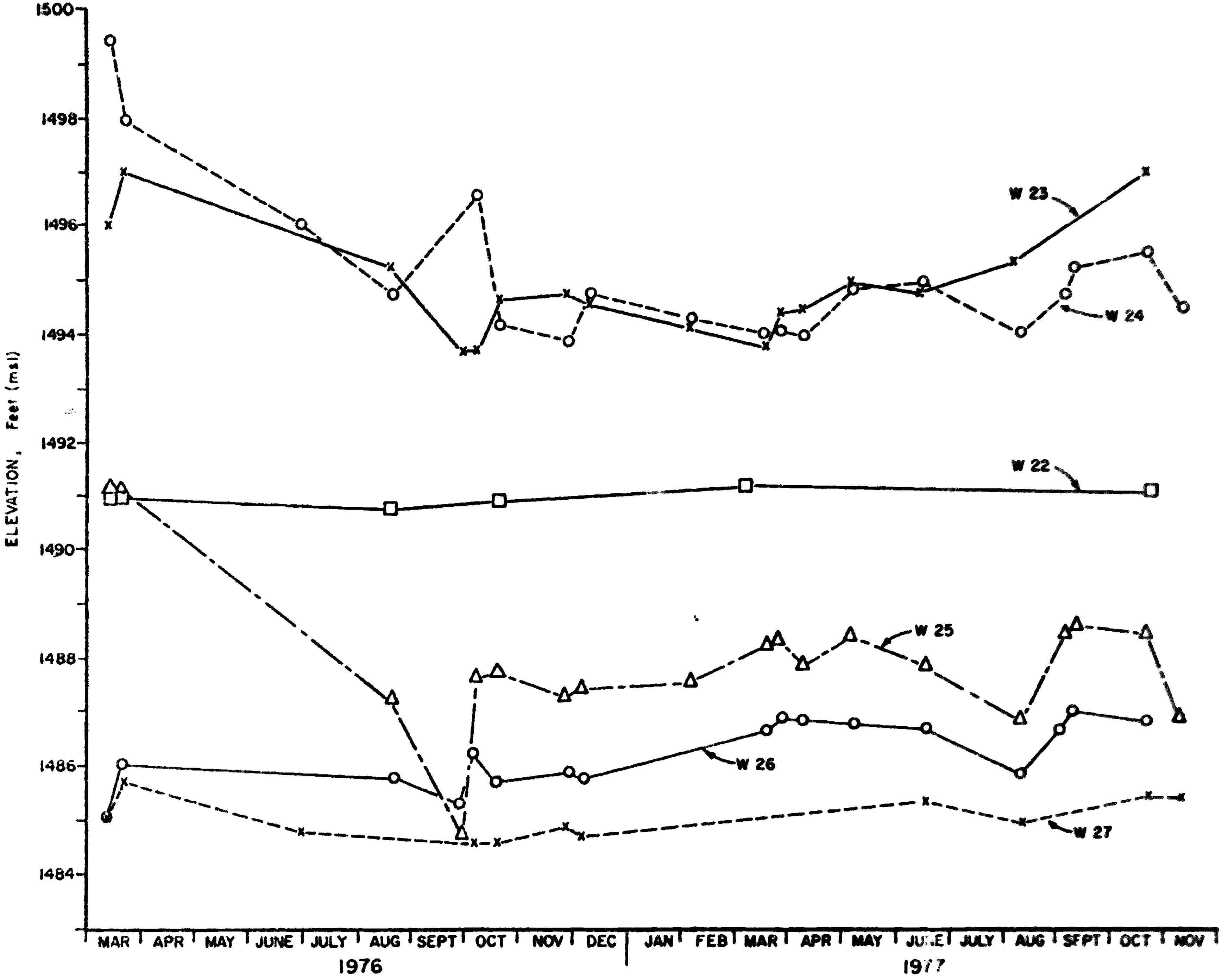


Figure 34

WATER TABLE COUNTOURS NEAR THE 8011 STOCKPILE
(feet, msl)
March 17, 1976

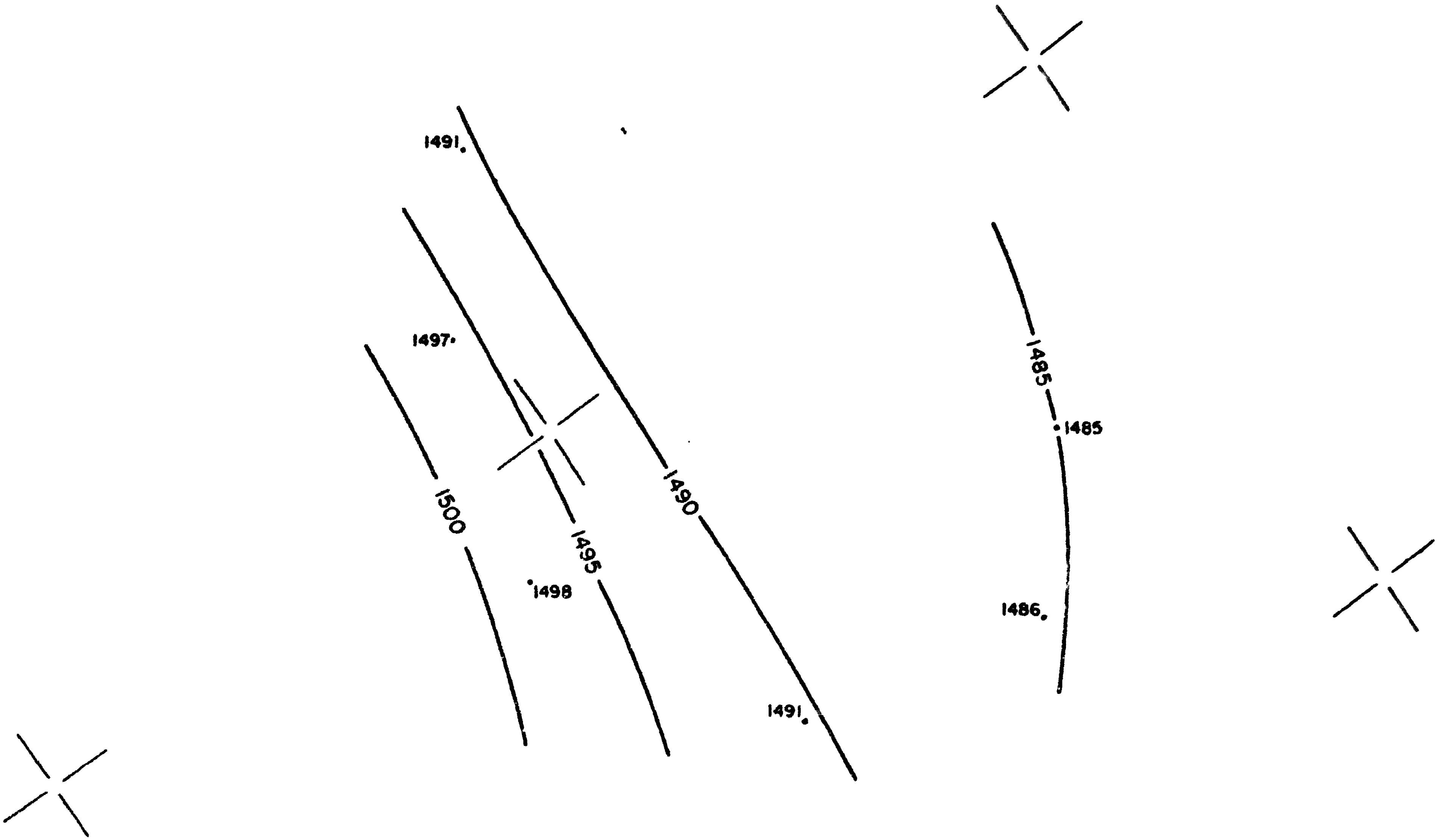
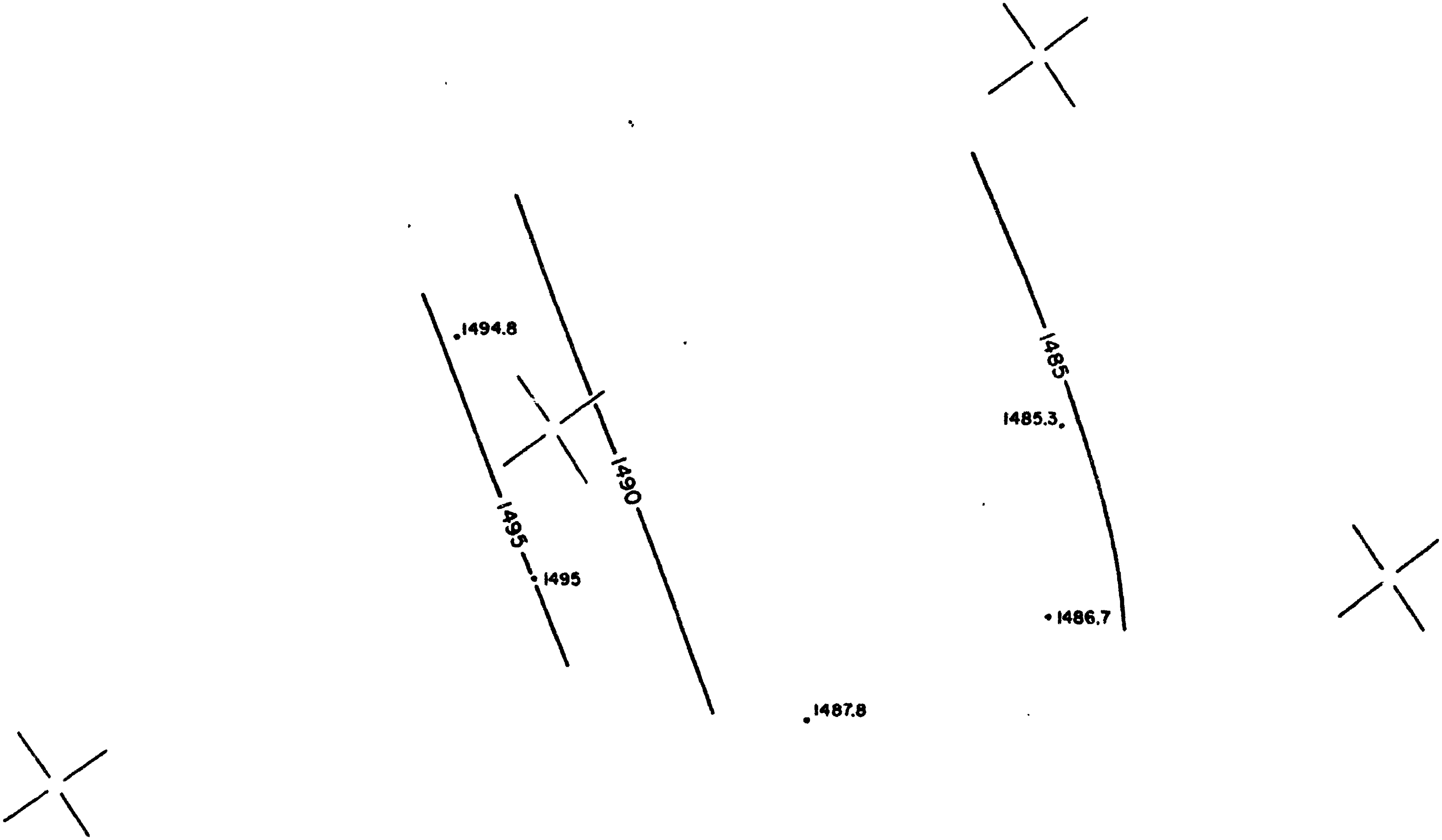


Figure 35

WATER TABLE COUNTOURS NEAR THE 8011 STOCKPILE
(feet, msl)
June 17, 1977



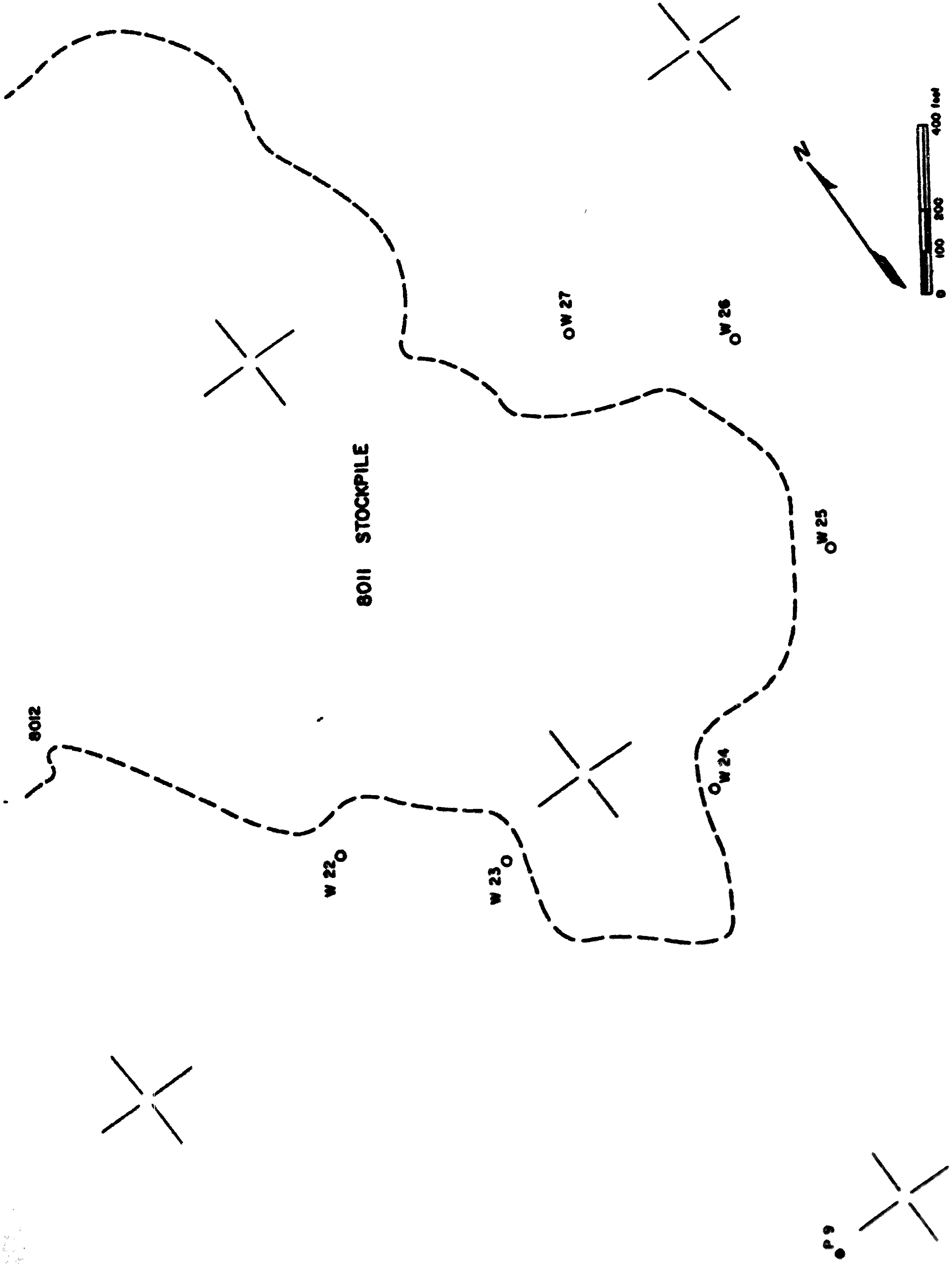

8011 STOCKPILE
8012
W 22
W 23
W 24
W 25
W 26
W 27
P 9
P 10
N
0
100
200
400 feet

Figure 36

SECTION A-A' THROUGH THE 8011 STOCKPILE

(Looking NW)

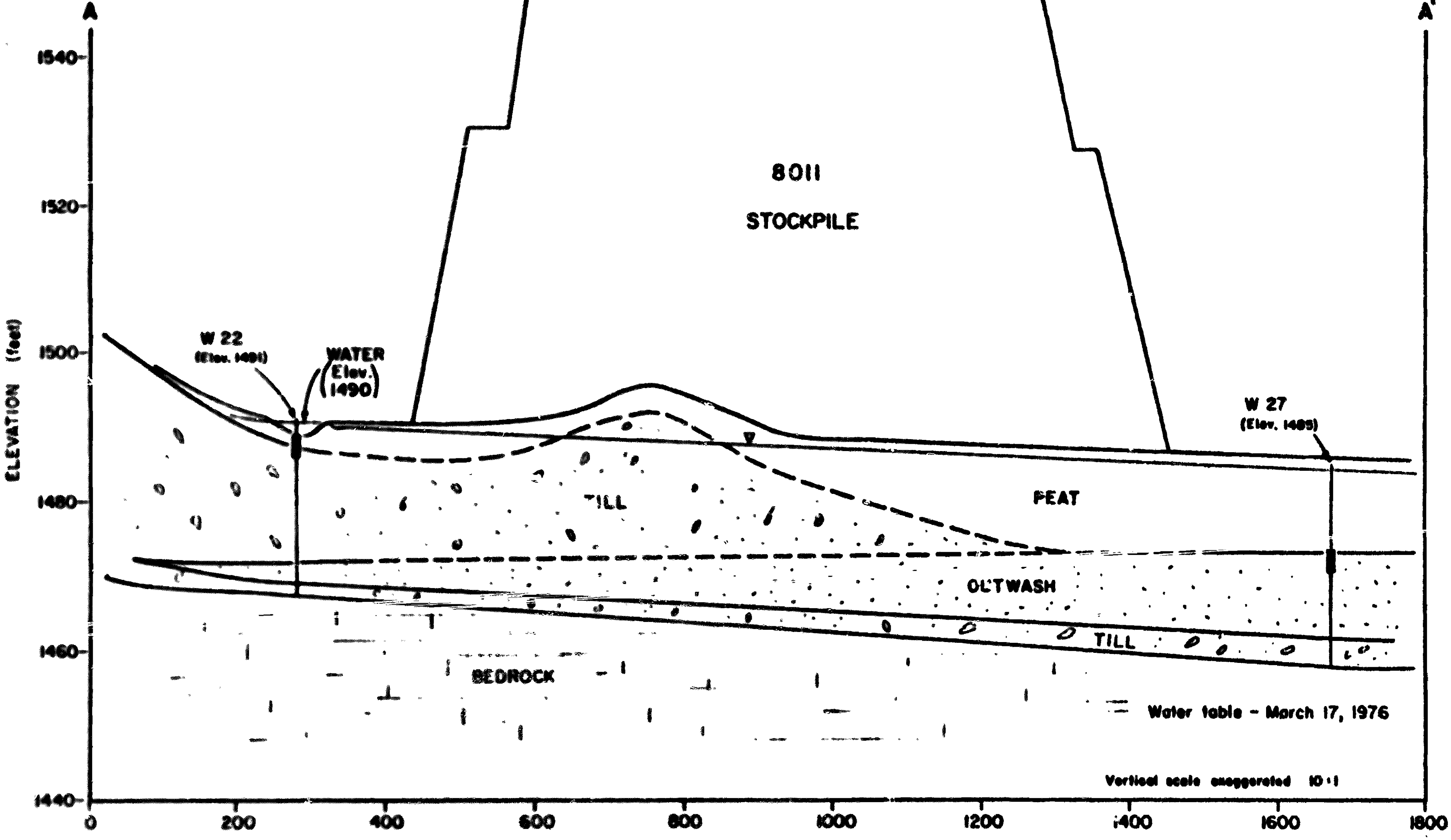


Figure 37

SECTION B - B' THROUGH THE 8011 STOCKPILE

(Looking NE)

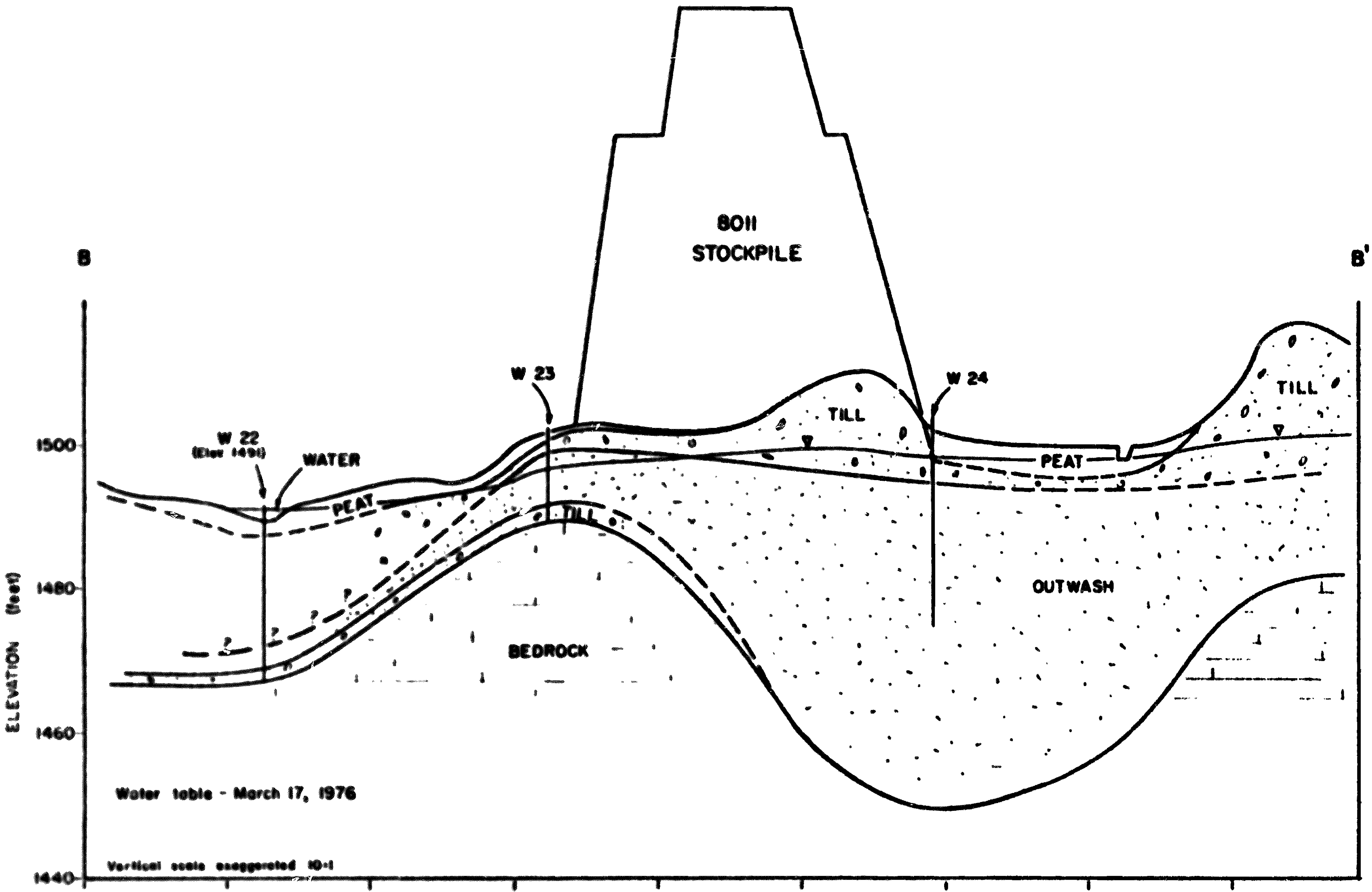
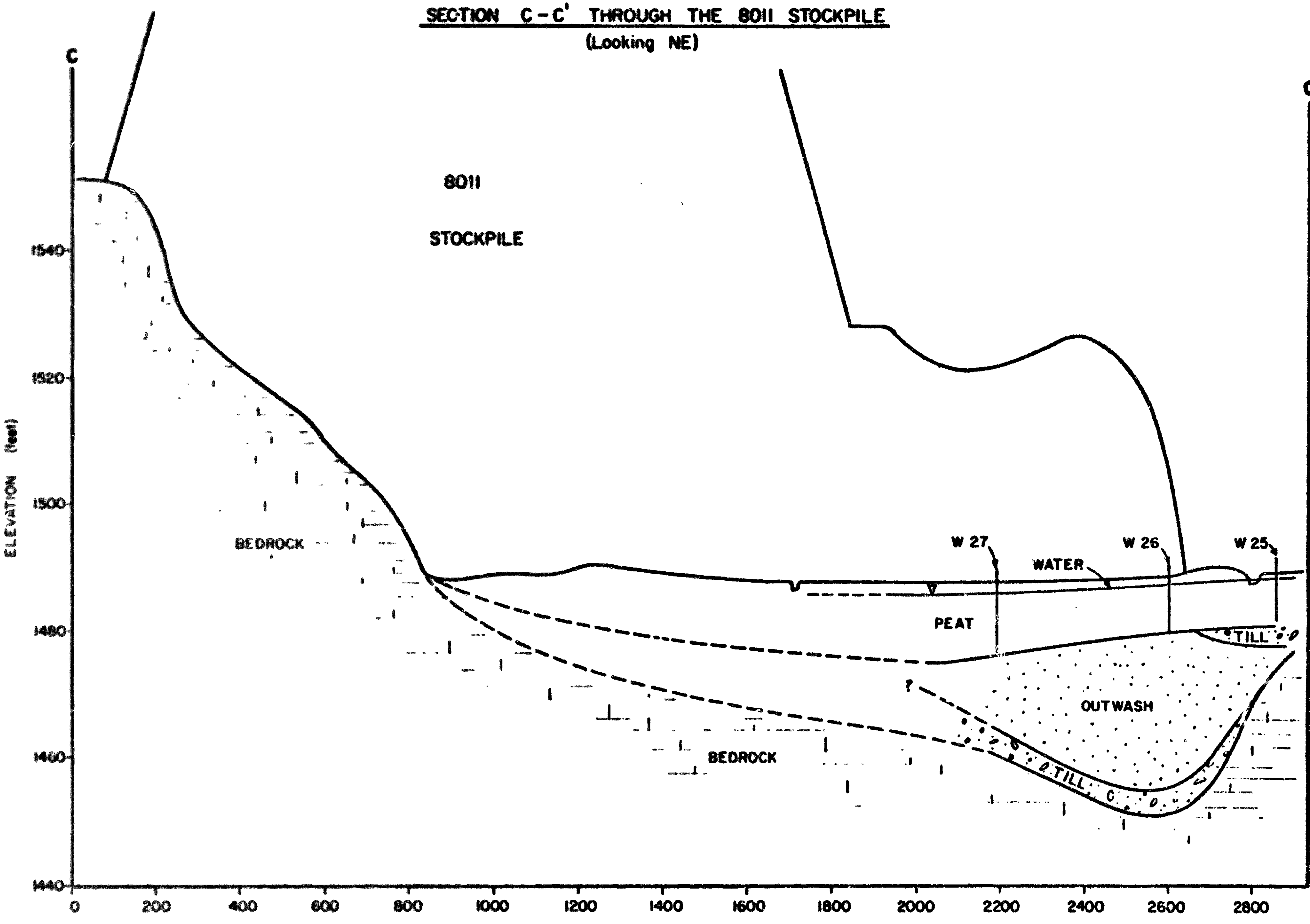


Figure 38

SECTION C-C' THROUGH THE 8011 STOCKPILE

(Looking NE)



examples of peat compressibility given by MacFarlane (1969, pp.108-114). Compression may have moved the pile down below the level of the local water table. On the other hand, even moderate loading can reduce the permeability of peat by several orders of magnitude (MacFarlane, p. 108), which may form an effective barrier to vertical water movement.

Piezometers were installed at wells 24 and 27 to determine the vertical component of groundwater flow near the stockpile. Flow is downward at W24, suggesting that the saturated peat may be perched over a deeper water table in the outwash (fig. 39). Data for W27 indicate that flow there is primarily horizontal (fig. 40).

Water samples from the wells around the 8011 stockpile were collected periodically during the last half of 1976 and the first half of 1977. Some of the wells were sampled eight times while others were sampled fewer times. Not all samples were analyzed for all parameters.

The summary statistics (table 8) show that water from all of the wells except W24 is a bicarbonate type, and is typical of groundwater in surficial aquifers in the region. Copper concentrations (figure 41) are generally above 3 micro-grams/liter, as is to be expected near the mineralized zone (Siegel and Ericson, 1979, p. 71), but nickel concentration in wells other than W24 are below the 5 micro-grams/liter expected near the mineralized zone (figure 42).

Well 24 shows anomalously high concentrations of sulfate, copper, nickel and calcium, and appears to be intercepting leachate from the 8011 stockpile (figures 41-44). None of the other wells shows any indication of interaction with stockpile seepage. A small area of the 8011 stockpile near W24 lies directly on till. This probably allows water to seep from the stockpile into the local groundwater system, and thence to W24. It is also possible

Figure 39

HEAD AS A FUNCTION OF DEPTH

WELL 24

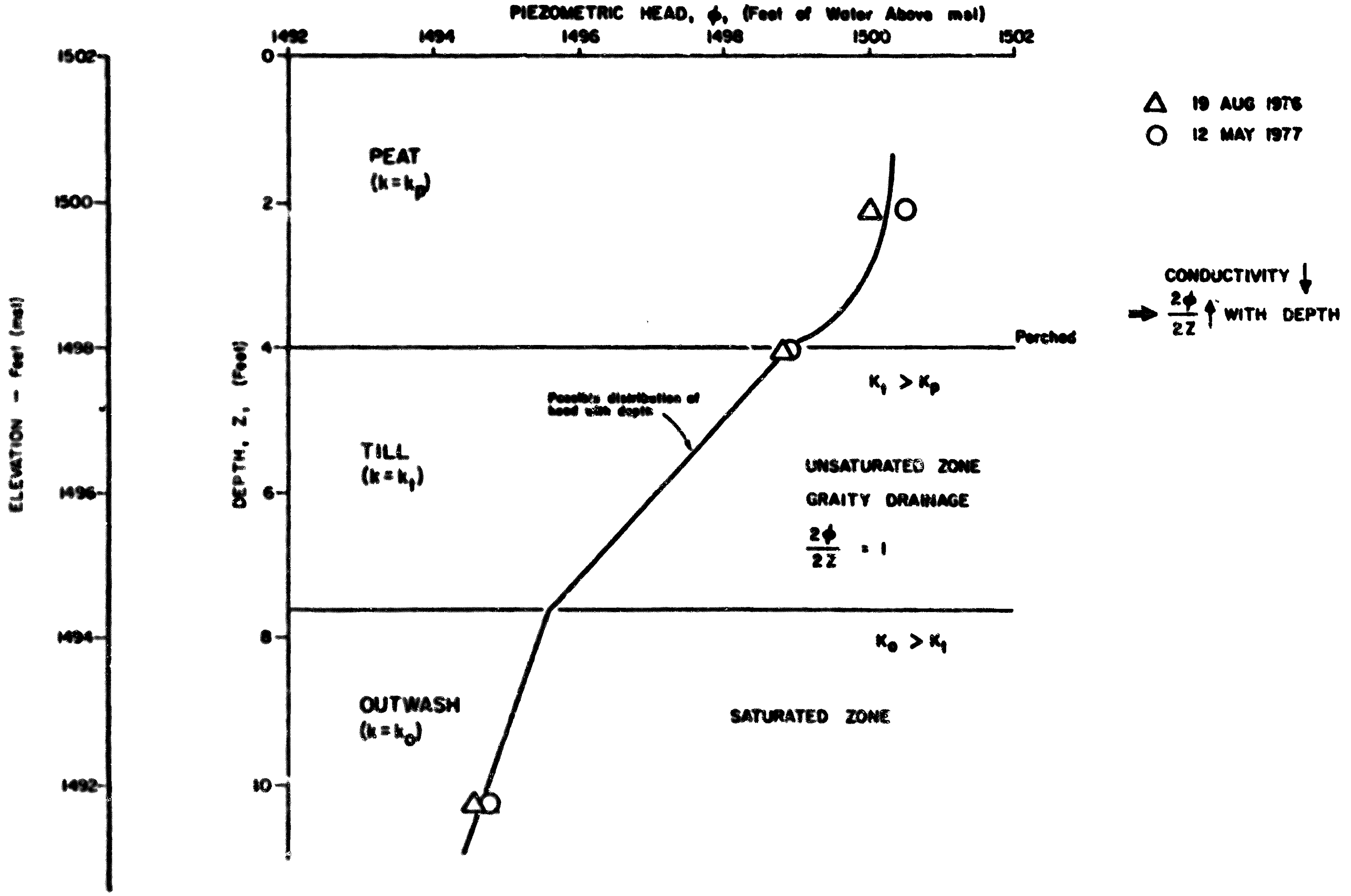


Figure 40

HEAD AS A FUNCTION OF DEPTH, WELL 27

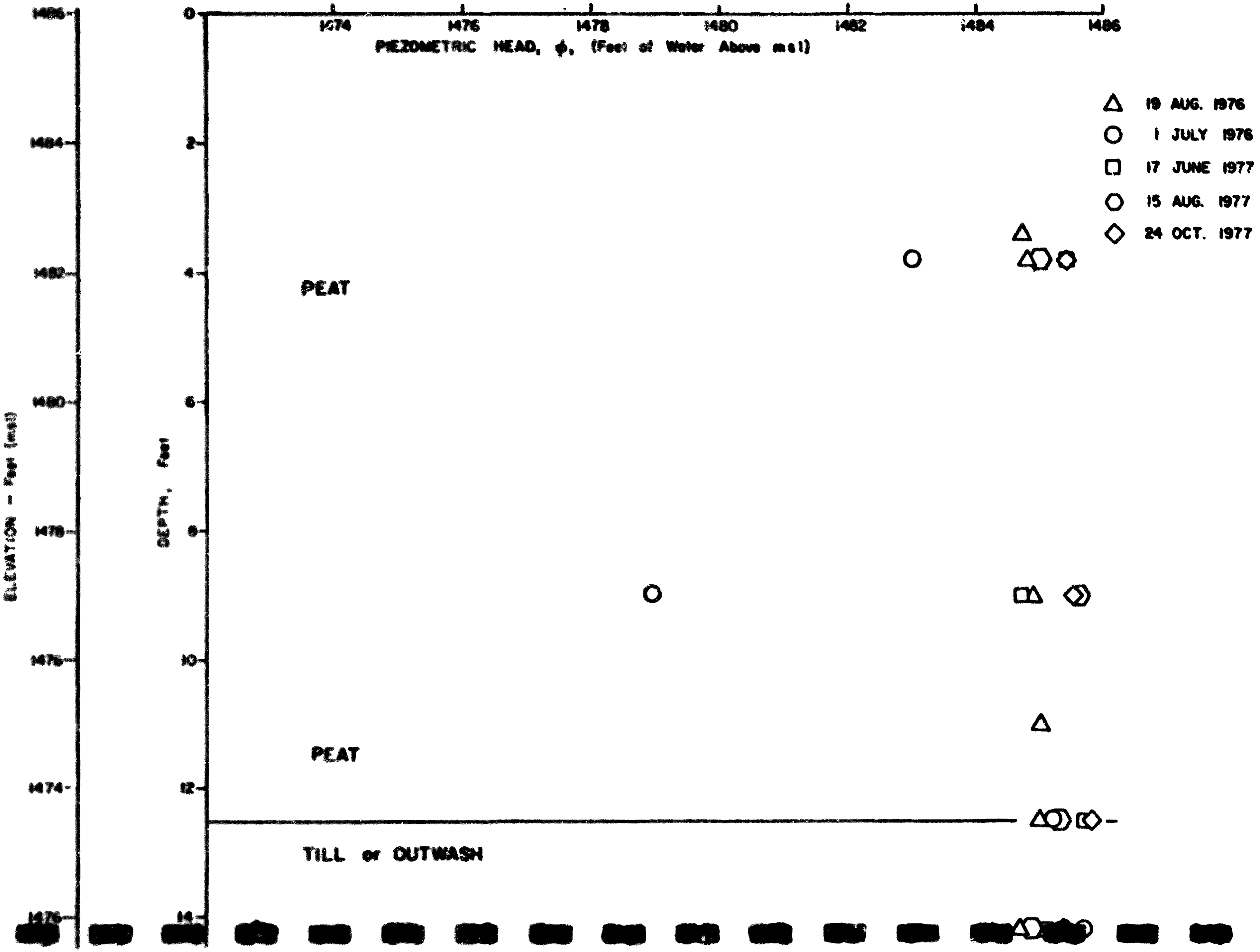


Table 8. Summary statistics for water quality in wells around the 8011 stockpile, and for stockpile seepage and surficial aquifers in the region.

	W22		W23			W24			W25			W26		W27		EM-8[1]			Till[2]			Sand + Gravel[2]		
	Range	N	Ave	Range	N	Ave	Range	N	Ave	Range	N	Range	N	Range	N	Ave	Range	N	Ave	Range	N	Ave	Range	N
pH	6.88	1	6.9	6.60-7.12	6	6.55	5.67-6.90	6	7.60	7.28-7.85	6	7.2-7.75	2	7.20-7.82	2	7.20	6.50-7.65		6.9	6.2-8.0	12	6.5	5.6-7.1	14
Alkalinity	84.0	1	43.0	38.5-54.2	6	84.0	5.7-98	6	128	104-140	6	142-156	2	109-110	2	137	103-178							
Spec. cond	130	1	112	95-165	8	600	254-1540	8	246	195-284	8	285-330	4	210-280	4	2020	186-2800		285	144-1255	13	172	55-200	15
DO	0	1			1			2			2	0-1.0	2	0-1.5	2				--	--	--	--	--	--
Temp	5.0	1	5.9	3.7-7.8	5	4.9	3.5-6.3	5	6.5	2.0-8.6	5	2.5-5.8	4	4.5-6.8	4	6.77	0.100-13.5		--	--	--	--	--	--
Cl	1.4	1	0.83	<0.5-0.83	6	2.3	0.91-9.03	6	3.3	1.1-4.1	6	1.4-1.7	2	2.9-3.3	2	41.3	29.2-56.5		1.5	0.6-35.0	13	2.3	?-18.0	15
Mg	11.8	1	7.68	6.71-9.60	5	38.4	15.1-84	6	18.5	15.8-25.2	6	17.0-17.8	2	11.0-12.0	2	123	82.0-178		15.0	7.3-64	13	7.6	1.9-31.0	16
Ca	16.4	1	7.20	6.00-10.0	6	52.0	21.6-192	6	18.0	14.8-29.2	6	25.2-25.6	2	18.8-19.6	2	200	64.9-301		26.0	4.6-150	13	15.1	6.1-58.0	16
SO_4	37	1	12.0	7.5-15	6	290	35-730	6	6.8	<1.0-8.6	6	<1.0	2	2-<5.0	2	1260	708-1680		11.0	3.3-450	13	8.2	3.0-35.0	15
Si	24	1	35.0	25-74	6	51	12-85	6	20	17-25	6	24-25	2	21-22	2				18.5	14.0-27.0	6	19.5	11.0-28.0	8
NO_2	0.04	1	<.01	<.01-.03	6	0.02	<0.01-0.22	6	0.02	0.01-0.12	6	<0.01	2	<.01	2				--	--	--	--	--	--
NO_2-NO_3	0.07	1	0.01	<0.01-0.20	5	>0.01	<0.01-12	5	0.02	<0.01-0.34	5	0.02-0.07	2	<.01	2				0.4	0.12	11	0.62	0.01-10	37
Cu	--		4.4	2.8-5.7	6	8.7	4.8-65	6	5.2	3.2-6.0	5	1.9-5.1	2	0.9-1.4	3	19	10-53		3.8	0.6-190.0	30	4.2	0.2-45.0	30
Ni	--		2.1	<1.0-3.0	6	18.0	5.4-82	6	2.2	<1.0-3.0	5	0.5-2	2	1.2-<3	3	1890	580-2420		9.0	1.0-120.0	27	5.0	0.7-40.0	29
Zn	--		9.3	2.5-13	5	7.6	1.9-63	5	8.9	1.9-22	4	.13	1	9.5-12	2	31	18-40		8.9	3.9-170.0	30	14.1	0.7-620.0	30
Fe	--		2200	1300-4100	5	14,000	1100-73000	6	1600	1200-3700	5	5800-11000	2	1500-5440	3	131	84-208		25.0	0.0-3100	30	45.0	0.0-67000	38
Co	--		1.3	0.8-2.5	5	4.5	1.2-27	5	0.8	<0.5-0.9	4	1.3	1	<0.5-1.0	2	21	16-29		1.4	0.3-28.0	30	0.7	0.1-46.0	30
Mn	--		400	240-570	6	630	350-3100	6	390	360-420	5	860-900	2	350-380	3	1300	680-2850		330.0	10.0-7190	31	45.0	0.0-26000	38
Doc	--		4.6	2.7-6.0	6	15	12-19	6	12	10-16	5	12-14	2	8.2-16	3	20.9	11.5-36.3		17.6	2.1-41.0	10	5.4	0.7-26.0	12

[1] seepage from 8011 stockpile, 1976

[2] till and sand and gravel in the region, Siegel & Ericson, 1979, p. 63

Units: pH - log (H^+); alk mg/l; spec cond μmho cm^{-1}; DO mg/ℓ; temp °C; Cl, Mg, Ca, SO_4, Cu, Ni, Zn, Fe, Co, Mn μg/ℓ

Figure 41

COPPER CONCENTRATION IN WELLS AROUND THE 8011 STOCKPILE, IN STOCKPILE SEEPAGE AND SURFICIAL AQUIFERS IN THE REGION

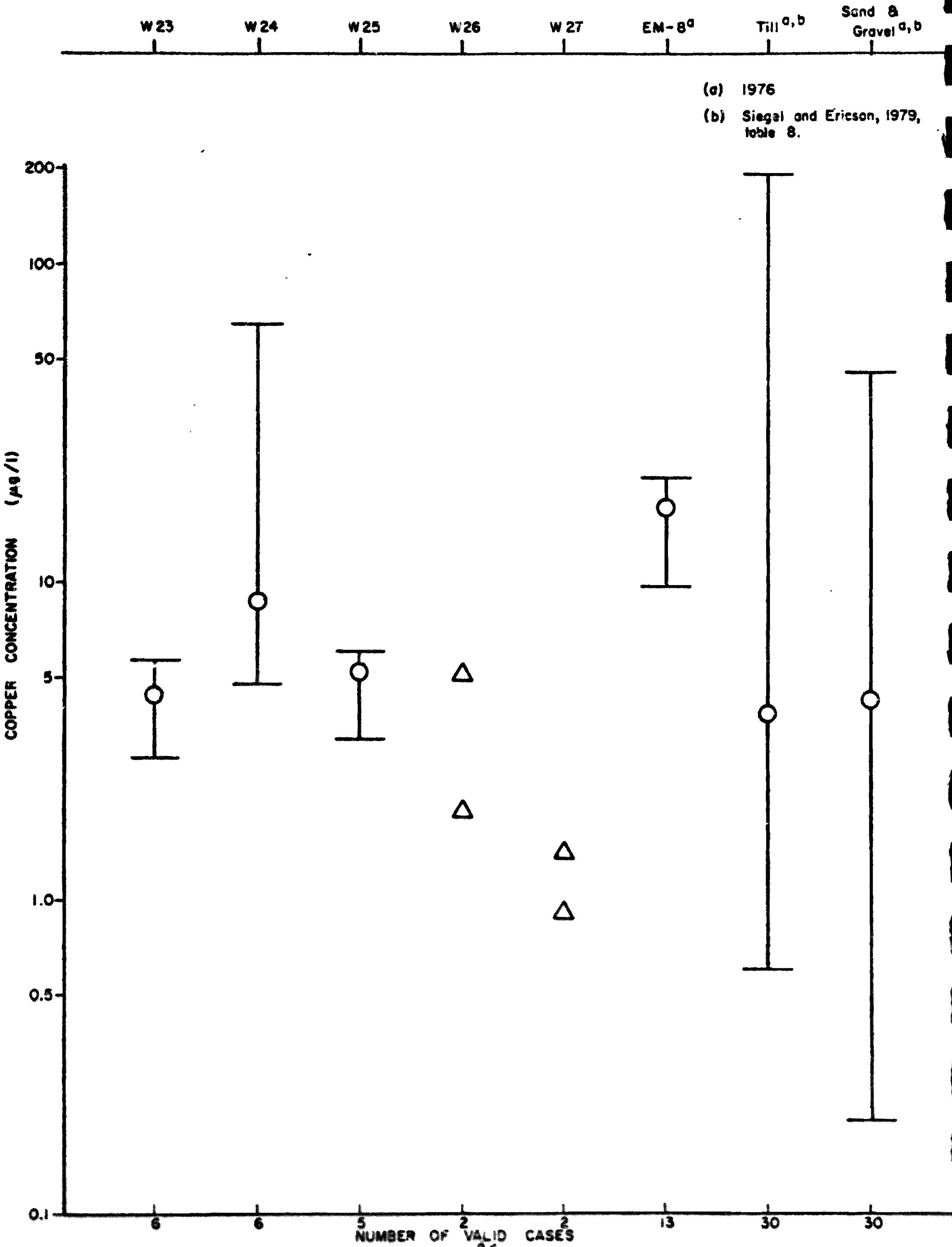


Figure 42

NICKEL CONCENTRATIONS IN WELLS AROUND THE 8011 STOCKPILE, IN STOCKPILE SEEPAGE AND SURFICIAL AQUIFERS IN THE REGION

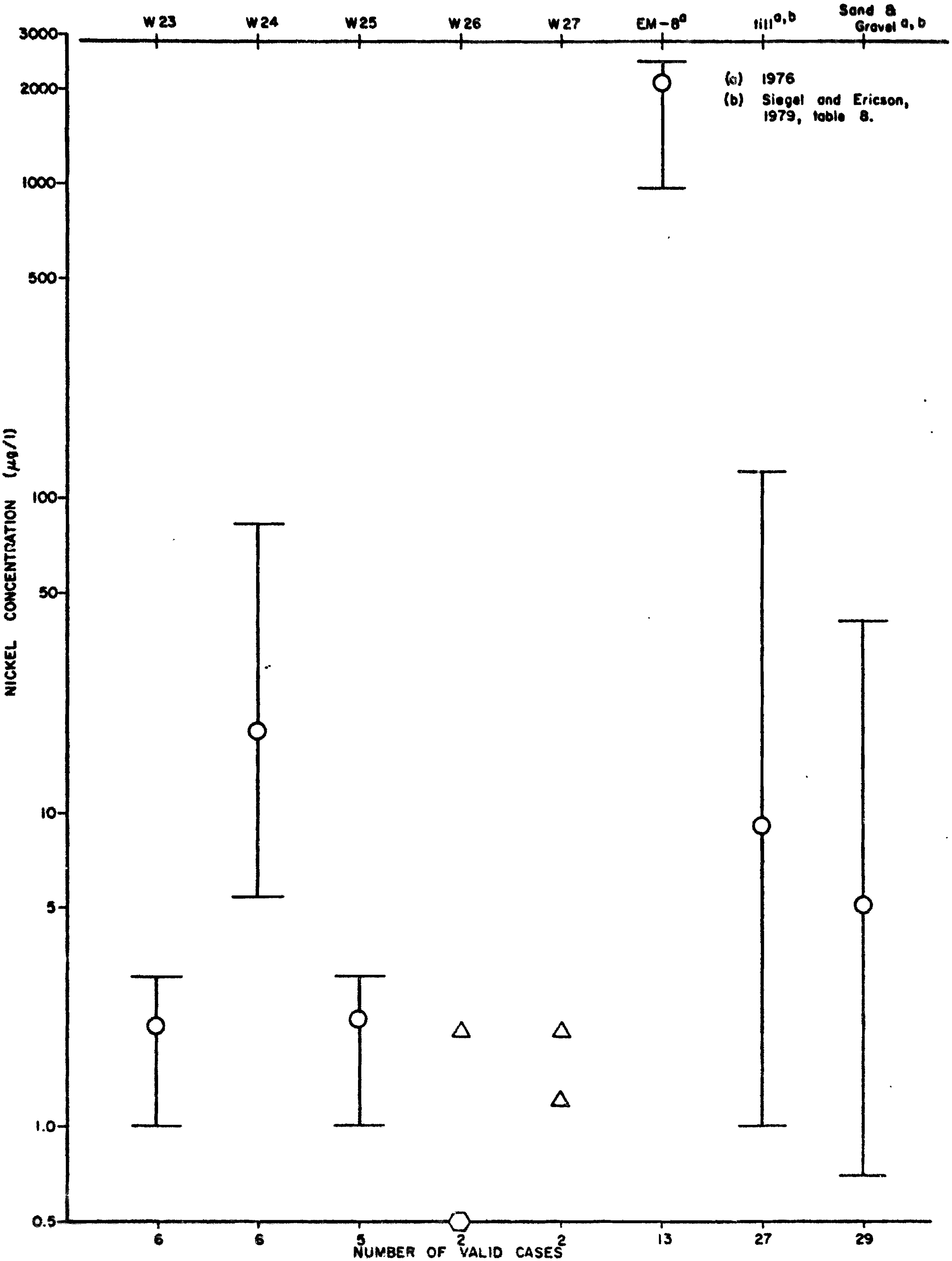


Figure 43

SULFATE CONCENTRATIONS IN WELLS AROUND THE 8011 STOCKPILE, IN STOCKPILE SEEPAGE AND SUFFICIAL AQUIFERS IN THE REGION

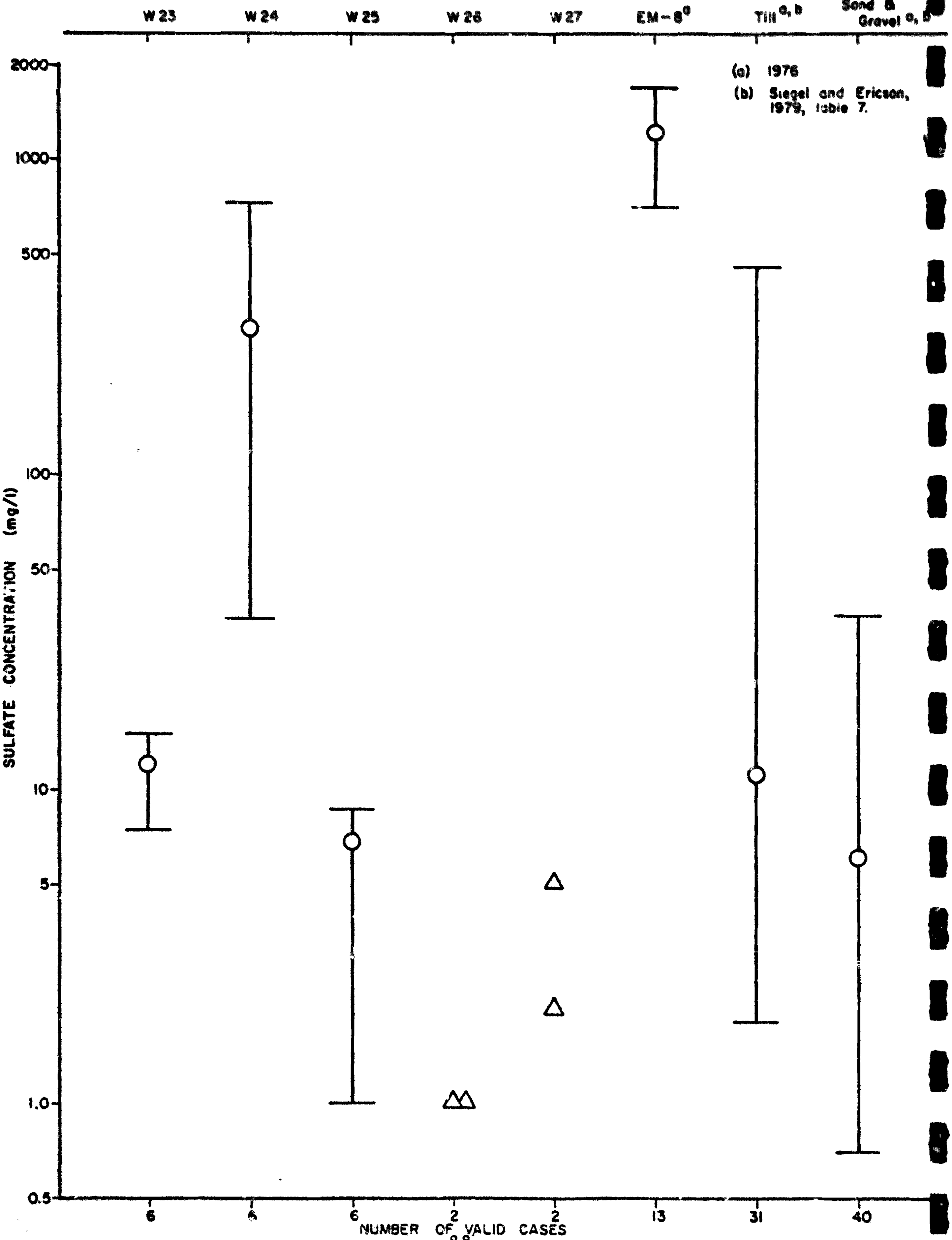
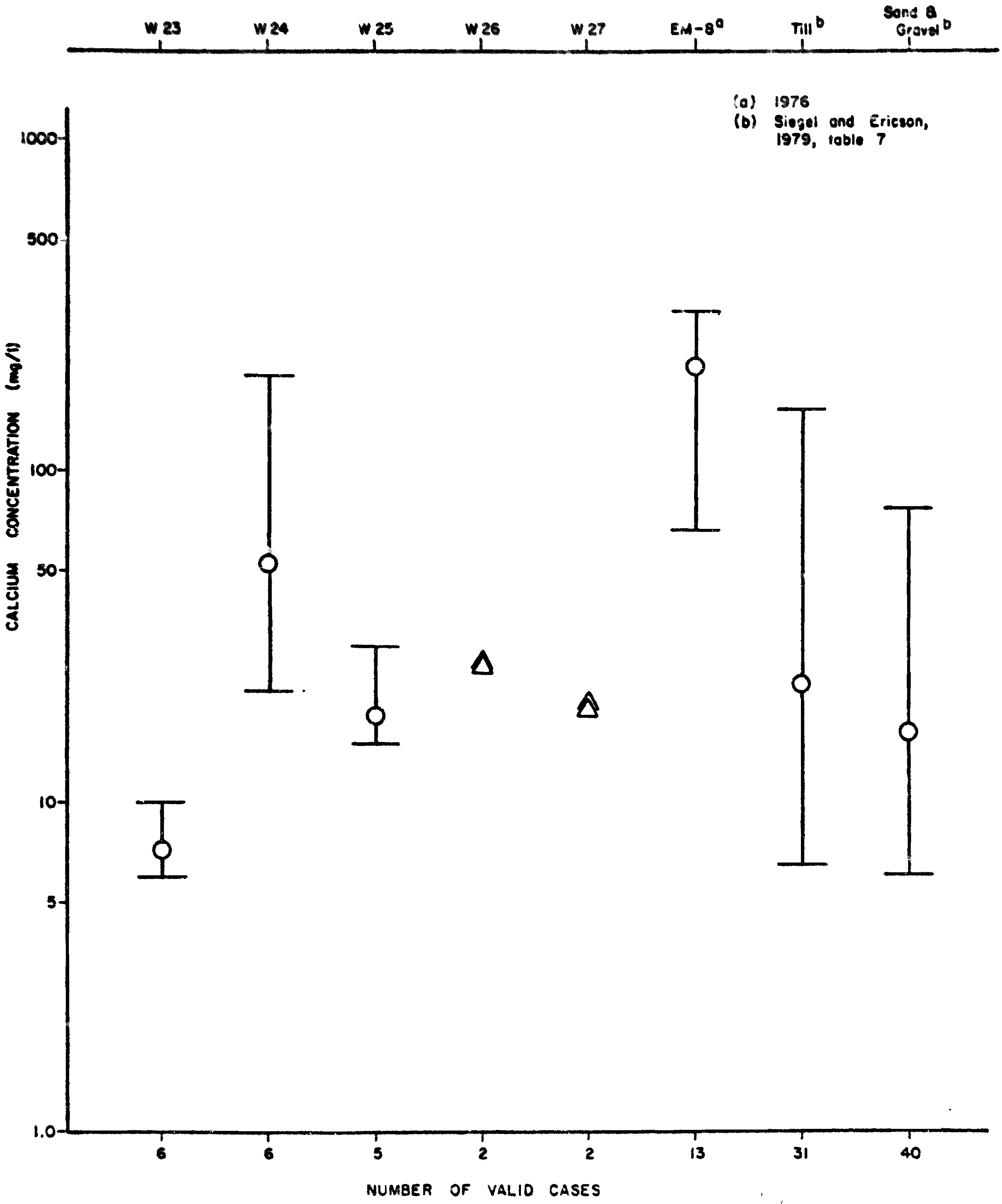


Figure 44

CALCIUM CONCENTRATIONS IN WELLS AROUND THE 8011 STOCKPILE, IN STOCKPILF SEEPAGE AND SURFICIAL AQUIFERS IN THE REGION



that water seeps out of the stockpile at the ground surface and then moves down through the peat to W24. Differences in water quality among the other wells are minor by comparison, and may be due to differences in the materials in which the wells are finished. Wells W25, W26, and W27 have higher values of pH, specific conductance, calcium and magnesium than W23, although sulfate, nickel and copper are the same or lower. Siegel and Ericson (1979, p. 62) found that concentrations of the major ions, specific conductance and hardness in water from till aquifers in the study area were about twice those in water in sand and gravel aquifers. The differences are attributed to the finer grain size and lower hydraulic conductivity in the till, which provide a larger specific surface area and longer residence time. (Siegel and Ericson, 1979, p. 65). Although W23, W26 and W27 are all finished in outwash, the outwash in W26 and W27 is considerably finer grained than that in W23 (appendix 4). Well 25 is finished in till which is actually coarser than the outwash in W23, but poor sorting may give it a lower hydraulic conductivity.

Concentrations of sulfate, calcium, nickel and copper in W24 followed a well defined seasonal variation (fig. 46). Sulfate and calcium levels fell through late autumn of 1976, were low through the winter, and rose rapidly in early April. Copper and nickel followed similar patterns, except for an increase from October through mid December of 1976.

These variations parallel changes in flow at EM-8: flow declined through fall of 1976, dropped to zero over the winter, and resumed sharply in early April.

Quality changes at W23 and W25 were smaller and the four parameters did not follow a consistent pattern (figs. 45 and 47).

Figure 45

WELL W 23

COPPER, NICKEL, CALCIUM & SULFATE

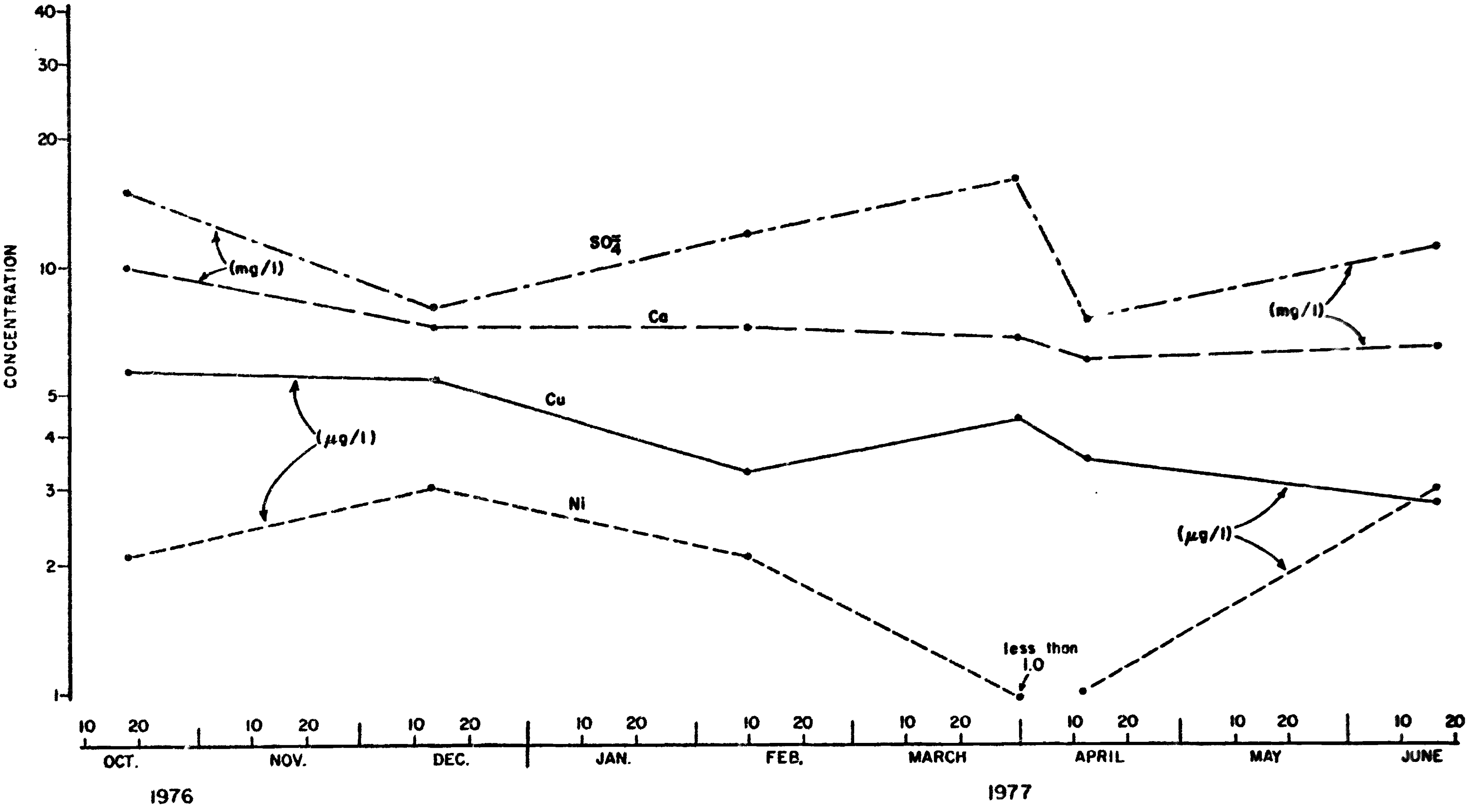


Figure 46

WELL W 24

COPPER, NICKEL, CALCIUM & SULFATE

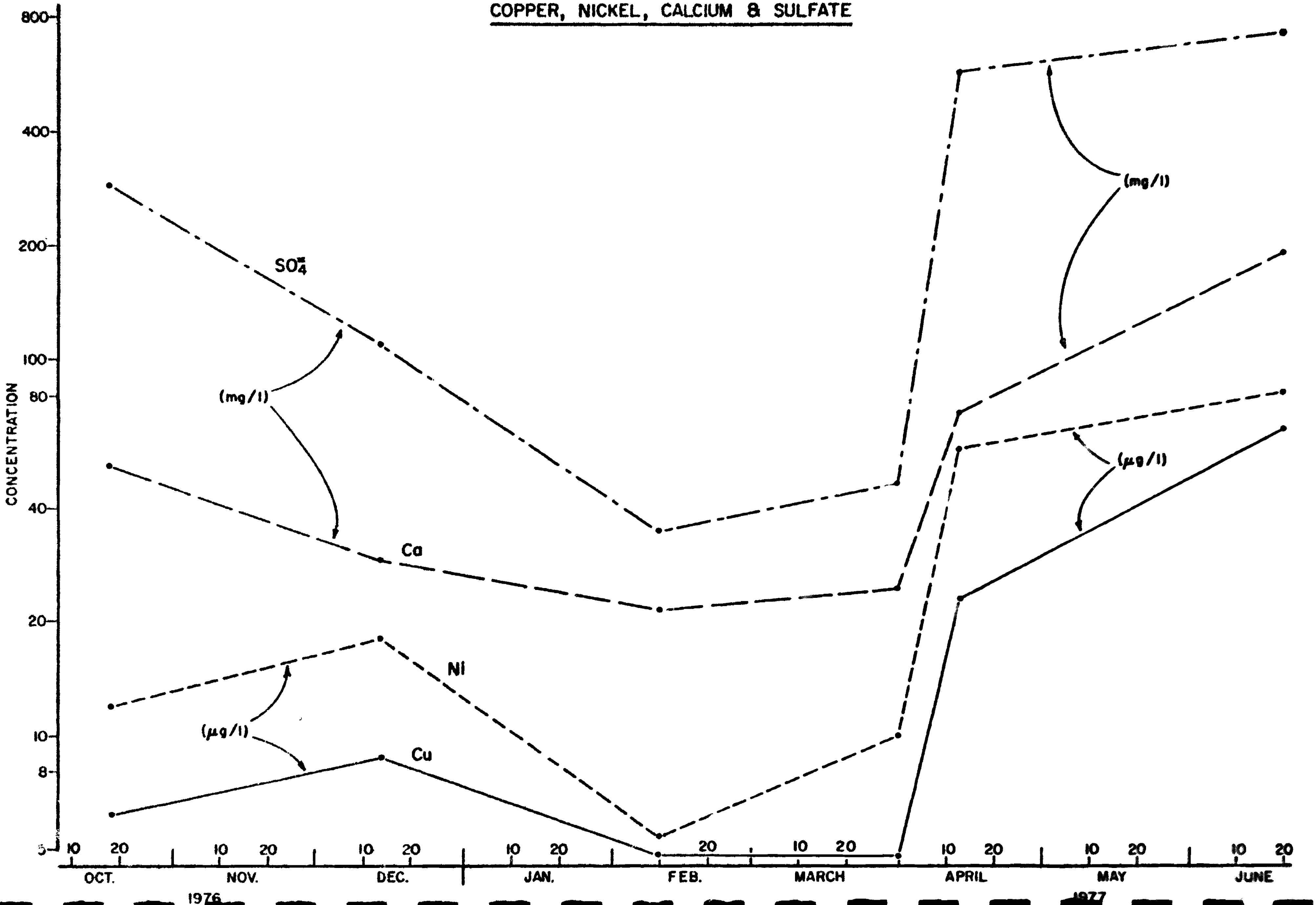
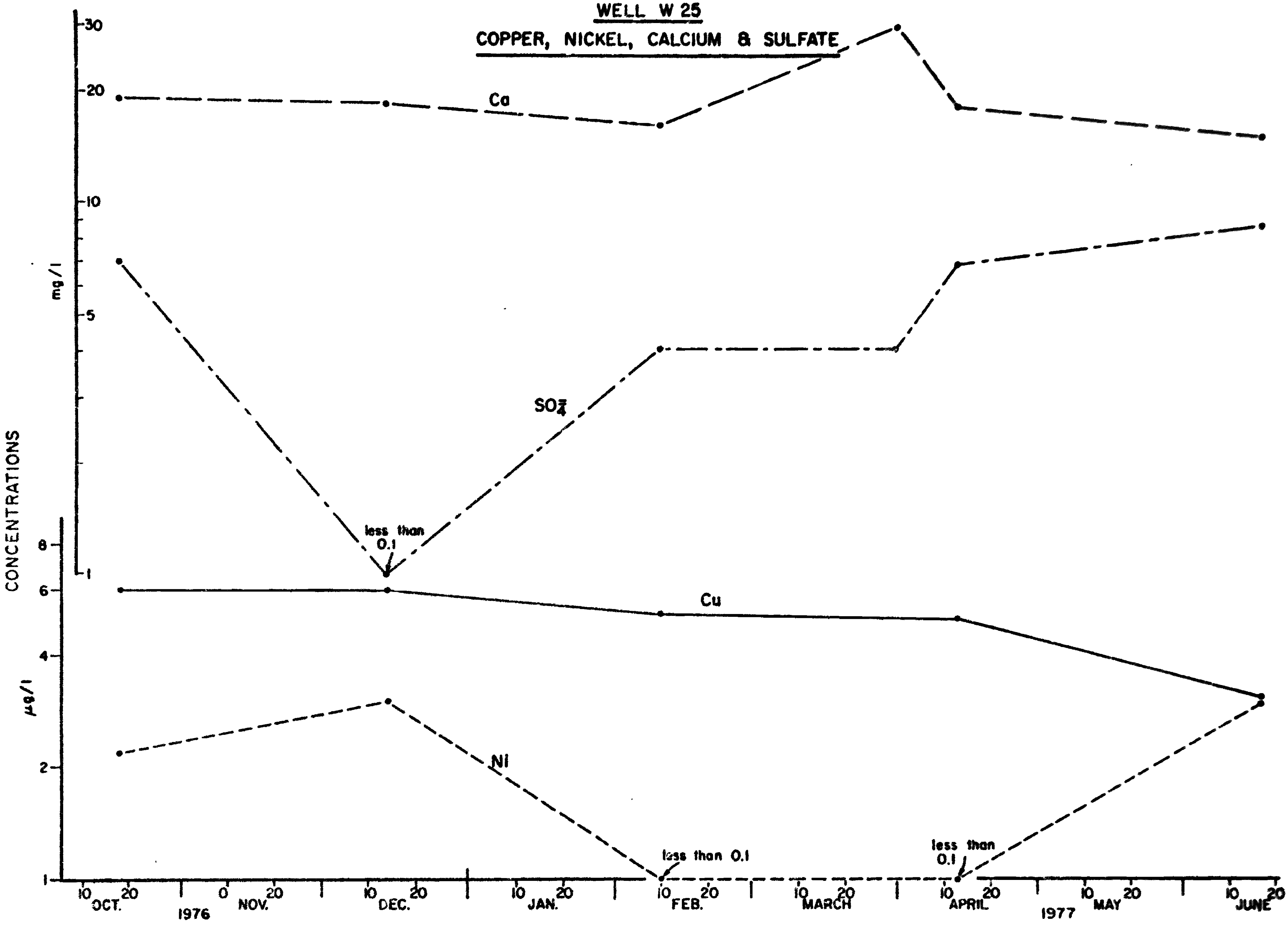


Figure 47

WELL W 25

COPPER, NICKEL, CALCIUM & SULFATE



ANALYSIS

Conceptual Model of Stockpile Hydrology

A conceptual model of stockpile hydrology has been developed on the basis of field observations, literature and basic hydrologic concepts. The model describes sources of water input, locations of output and flow paths within stockpiles. In the analyses which follow, this model is used as a framework for interpreting observations at Erie and AMAX. The interpretations are thought to be the best explanation of stockpile behavior based on present data, although some alternative interpretations are also discussed. Further data are needed to verify the model or evaluate alternatives.

Development of a conceptual model serves two purposes. First, if stockpile hydrology can be related to climate, stockpile characteristics and site characteristics, then stockpile behavior can be predicted and evaluated prior to construction. Second, since physical differences among the flow paths within stockpiles may influence the types and rates of chemical reactions which occur, understanding the flow paths can be one key to interpreting observed chemical release and predicting release from future piles.

Water can enter a stockpile by direct precipitation or by runoff from surface or groundwater catchments draining to the stockpile site. Precipitation falling on the pile can either run off over the surface or infiltrate into the pile. Much of the water which infiltrates is subsequently lost to evaporation. Water moving down through the pile may run laterally over impeding layers and emerge along the margin of the pile as interflow. Some water may be stored in a groundwater mound within the pile and sustain seepage from the margins of the pile during dry periods. If the pile is on permeable material, water will also move out of the pile vertically, eventually reaching the local groundwater system. Interflow, baseflow and vertical seepage derived from precipitation on the pile can be augmented by surface or subsurface flow into the pile from catchment areas. Flow paths are diagrammed in figure 48 and discussed in more detail below.

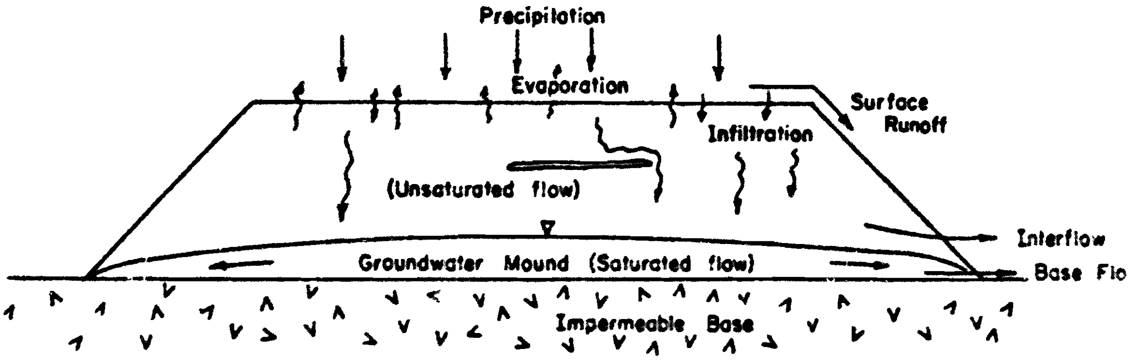
Surface Runoff Surface runoff can occur only when rain intensity exceeds the infiltration rate for the material at the top of the pile. Soil infiltrability depends on the texture, structure and uniformity of the soil profile, as well as on the time since onset of rain and the initial wetness of the soil (Hillel, 1971, pp. 132, 152-153). For an unsurfaced stockpile, the major factors affecting infiltrability are the grain size distribution of the waste and the extent to which dumping, grading and driving cause layering and compaction. For a surfaced pile, the texture and compaction of the surfacing material, and the discontinuity in conductivity at the boundary between the surfacing material and the waste, will control infiltrability. Coarse stockpile material below fine surfacing material can impede water movement and reduce the infiltration rate (Hillel, 1971, pp. 143, 153).

Evaporation Three conditions must be met in order for evaporation from a body to occur: 1) Heat must be supplied to vaporize the water, 2) There must be a vapor pressure gradient between the body and the atmosphere, maintained by transporting the vapor away by diffusion or convection, and 3) There must be "a continual supply of water from or through the interior of the body to the site of evaporation". Only the third condition is dependent on properties of the body itself. These include the content and potential of water in the body, and its conductive properties (Hillel, 1971, p. 184). According to Brady, "Soil physicists are agreed that the depth to which soils may be depleted by capillarity and evaporation is far short of the four, five or even more feet sometimes postulated" (1974, p. 207). Stockpile materials will generally be considerably coarser than most soils, so that capillary pores are few and discontinuous. Hence, it is hypothesized that evaporative losses occur only from the outer portions of the pile. In situ evaporation at depth followed by movement of water out of the soil

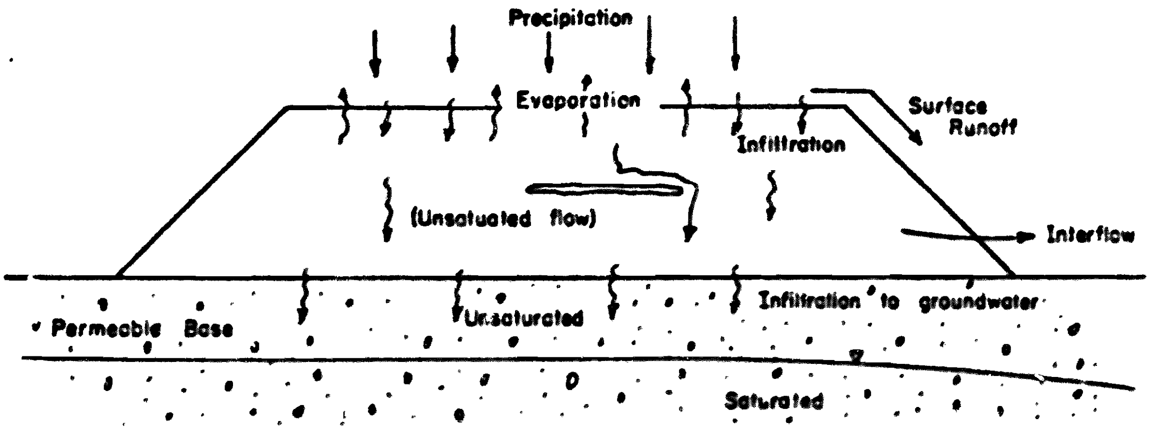
Figure 48

FLOW PATH WITHIN STOCKPILES

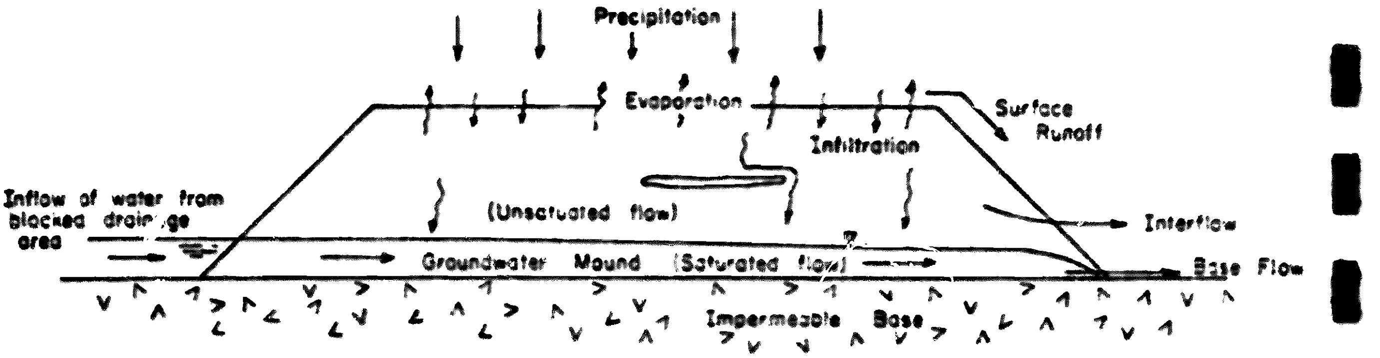
a. STOCKPILE ON IMPERMEABLE BASE



b. STOCKPILE ON HIGHLY PERMEABLE BASE



c. STOCKPILE ON IMPERMEABLE BASE, BLOCKING SURFACE DRAINAGEWAY



in the vapor state is possible (Hillel, 1971, p. 193), but the cold summer temperatures in the interior of the piles would inhibit <u>in situ</u> evaporation. In addition, vapor pressure gradients slope from warm areas to cold (Hillel, 1971, p. 197), so that diffusion would tend to move water vapor into, rather than out of, the piles. Convection of moist air out of the pile may remove some water vapor.

If evaporation occurs primarily in the outer portions of the stockpile, evaporative losses are limited by the ability of the near surface material to hold water long enough for it to evaporate. The amount of water held in the soil against the force of gravity, variously termed field capacity, pellicular water or specific retention (Todd, 1959, p. 23) depends on soil texture, clay mineralogy, percent organic matter and the presence of impeding layers (Hillel, 1971, pp. 164-165). Coarse textured natural soils have field capacities of 3 to 8% by volume (Todd, 1959, p. 24; Hillel, 1971, p. 164); stockpile material may have a lower retention capacity. Since impeding layers increase field capacity, layering created by placing cover material or by grading may increase the field capacity of stockpiles. Retention within the soil profile can be augmented by retention on vegetation (interception) and retention in surface depressions (depression storage).

Assuming evaporation occurs primarily from the outer portions of stockpiles, the controlling characteristics will include the texture, thickness and layering of cover material, texture of the near surface stockpile material, and nature of the hydraulic discontinuity between the two. The internal characteristics of the pile and its height will not be important. Vegetation could significantly increase evaporative losses by effectively increasing the depth from which water can be drawn, increasing the total conductive ability of the material, and exposing more surfaces to radiation and wind.

Interflow "Water infiltrating the soil surface and moving laterally through the upper horizons of the soil until it returns to the surface at some point downslope .... is known as interflow...Geologic conditions which favor interflow are those where the porous surface layers are underlain by relatively impervious strata" (Gray, 1970, p. 4.4). Interflow occurs when the rate of supply of water to some layer in the subsurface exceeds the infiltration rate for that layer. Layers of low infiltrability within stockpiles could include:

---- surfacing material spread on intermediate lifts and then compacted by haul trucks,

---- relatively fine grained, compacted layers of rock created by grading the tops of lifts,

---- stratification created as the rock is dumped,

---- layers created by fine grained material which works its way to the base of the pile and fills voids between larger fragments, and

---- the native materials on which the pile is sited.

Water may move some distance over a layer, and then encounter a break in the layer and resume downward movement. The increased rate of supply of water at that location enhances the likelihood of interflow over lower layers.

Base flow and seepage to groundwater Water can be supplied to the lower parts of a stockpile by infiltration, by flow of surface water or groundwater from catchment areas, or by a combination of these sources. Water arriving at the bottom of the pile can run off laterally as interflow, seep directly into the materials below the pile and eventually enter the groundwater system, or create a saturated zone within the pile which either discharges as base flow at the margin of the pile, seeps into the groundwater below the pile, or both. Factors governing production of interflow have already been discussed. Unless the material below the pile is impermeable, some of the water reaching the base of the pile will seep into the groundwater system. The amount may be controlled by the available supply of water or by permeability and pre-existing groundwater levels within the material below the pile. Development of a saturated zone within the pile, however, will only occur in some circumstances.

a) If the pile is sited so that catchment contributions are zero, the conditions required for development of a saturated zone at the bottom of the pile are:

-- that the rate of infiltration to the bottom of the pile be greater than the rate at which the material below the pile can transport water away, and

-- that the stockpile be capable of sustaining saturated conditions.

Infiltrated water available for base flow or seepage to groundwater (Ns) is equal to precipitation minus evaporation, surface runoff and interflow. The ability of the material below the pile to carry away water depends on its permeability (K_2). If the permeability is greater than the rate of supply of water to the base of the pile (Ns), water which infiltrates to the base of the pile will seep directly into the material below the pile. Stockpiles on highly permeable materials will not have a permanent saturated zone nor sustained baseflow at their margins (figure 49a).

If $K_2 <$ Ns, the subpile material will not be able to carry away all of the water, and a groundwater mound will develop within the pile. Whether the saturated zone within the pile will be continuous with that in the subpile material or will be perched depends on the distribution of permeabilities with depth (fig. 49b, c and d).

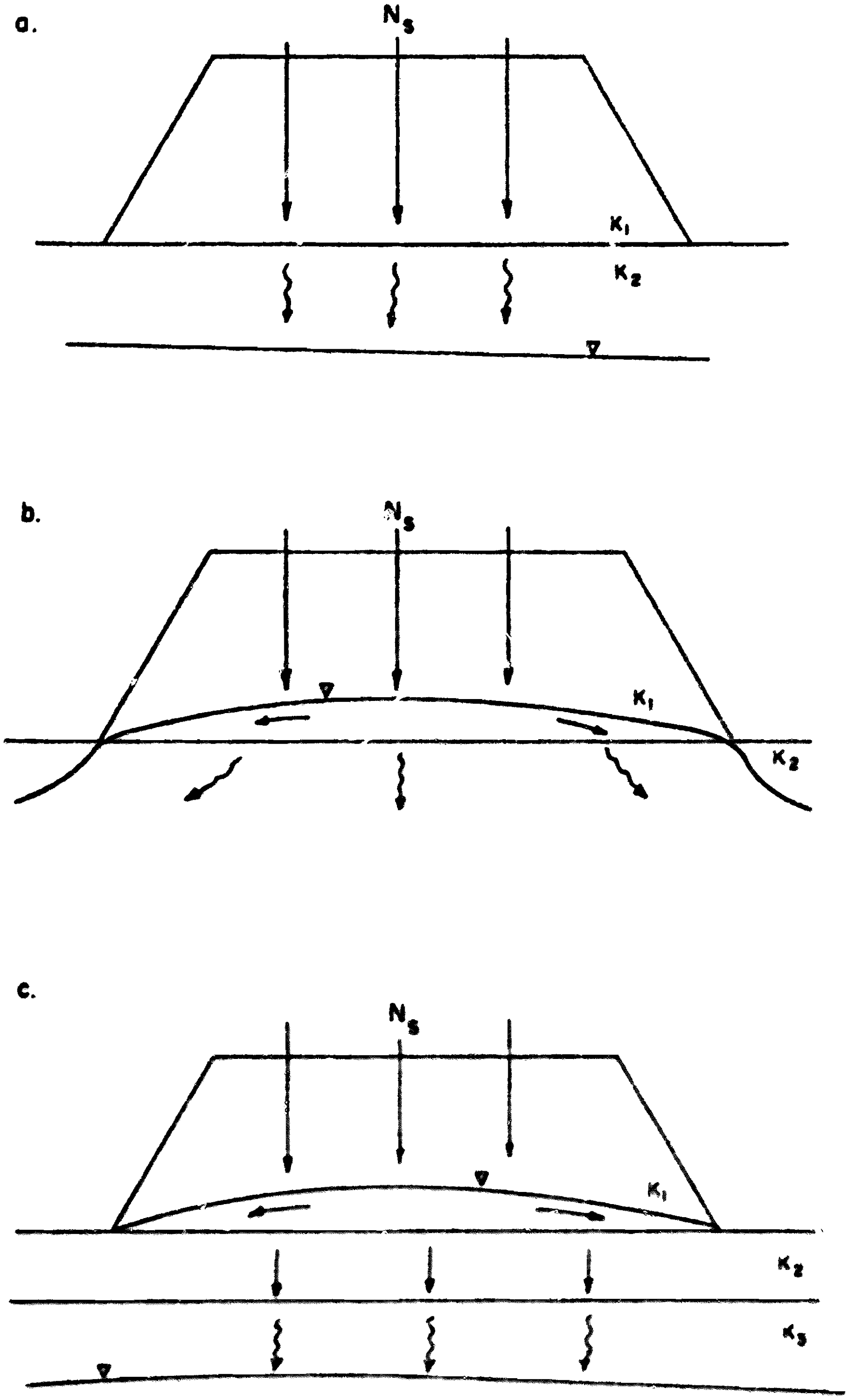
Lateral flow over impeding layers at intermediate heights within the stockpile may cause a non-uniform distribution of infiltration to the base of the pile. This could allow saturated areas to exist locally at the base of the pile, even though the average rate of supply of water were less than the permeability of the material below the pile.

Given an adequate supply of water, saturated conditions can be maintained within a stockpile in two ways.

1) The pile may have a permeability low enough to sustain saturated potential flow. If the pile is extremely coarse, water at the base of the pile will tend to flow toward the discharge point in discrete channels, and no saturated zone will

Figure 49

DEVELOPMENT OF SATURATED ZONES WITHIN STOCKPILES DUE TO INFILTRATION



a.

$K_2 > N_s$

$K_1 > N_s$

No mound within pile.
Seepage into local groundwater.

b.

$N_s > K_2$

$K_1 > N_s$

Mound in underlying material extends upward into pile.
Seepage from margin of pile and to local groundwater.

c.

$N_s > K_2$

$K_3 > K_2$

$K_1 > N_s$

Perched mound.
Seepage from margin of pile and to local groundwater.

form.

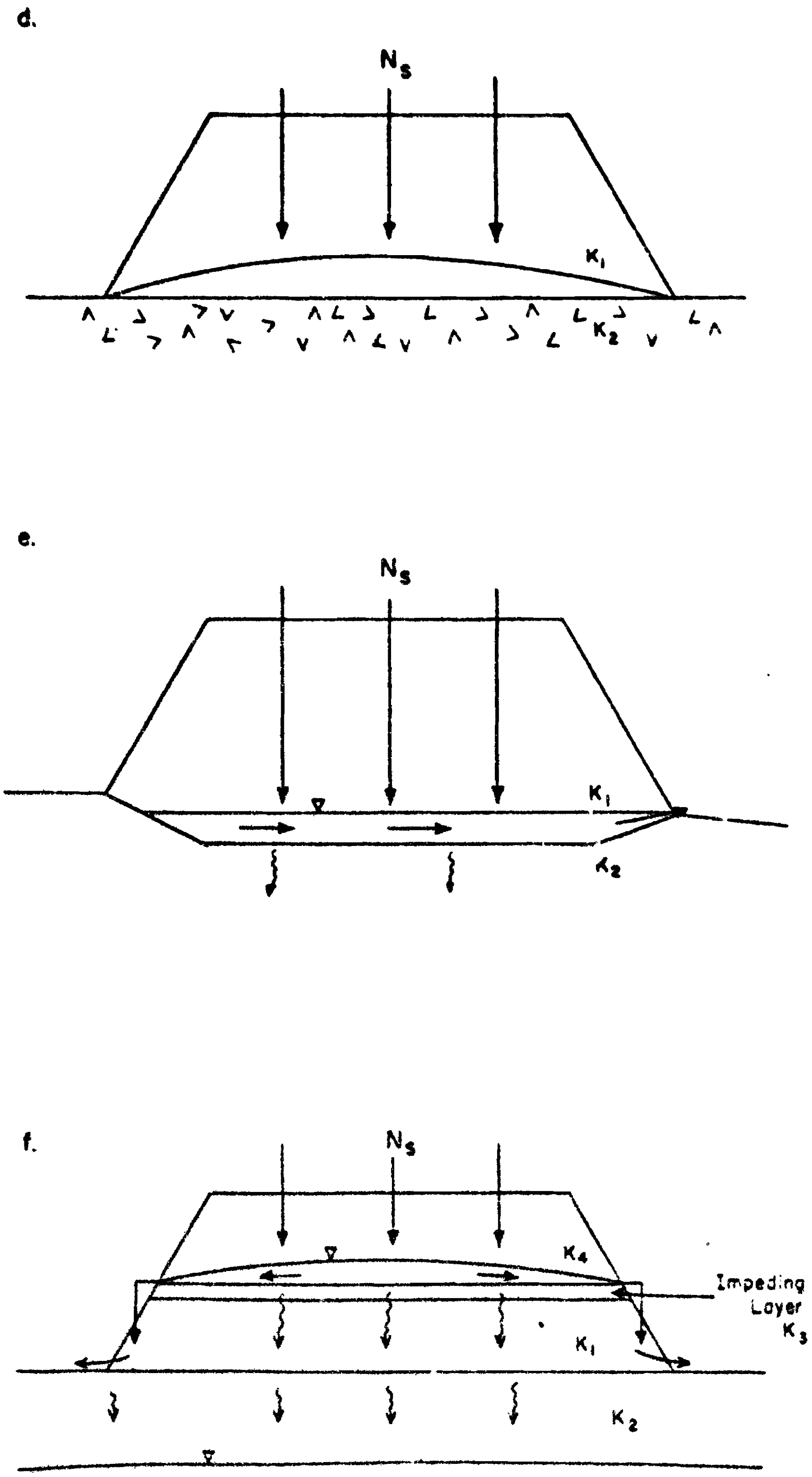
2) Even if the pile is coarse, materials of low permeability surrounding it may dam flow from the pile, causing pooling of water (fig. 49e).

Perched groundwater mounds could develop on top of impeding layers at intermediate heights within the pile if the rate of supply of water to the layer exceeded the permeability of the layer, and the material above the layer were of low enough permeability to sustain saturated flow (fig. 49f).

b) Groundwater could flow into the stockpile from catchment areas under several different conditions. If the pile is sited in a groundwater discharge area, the saturated zone will rise into the pile until the cross-sectional area of flow within the pile is large enough to carry away the discharge (fig. 50). Direct infiltration may further add to the mound. The cross-sectional area of the flow needed decreases as the permeability of the stockpile material or the slope of the base of the pile increases. Again saturated flow will occur only if the stockpile has low enough permeability to sustain it or if damming of stockpile outlets causes pooling. In areas with a shallow water table, a pile constructed on compressible materials may settle below the level of intersection with the water table (fig. 51), allowing groundwater to move into it. Some of the groundwater moving through the pile could be discharged from the margin of the pile as base flow, while some remains within the groundwater flow system.

c) If a stockpile blocks a surface drainageway, some of the runoff from the upstream watershed will move into the pile, while some may infiltrate into the surficial material upstream of the pile (figure 52). Once in the pile, water may either move through to the downstream side or seep out the base of the pile. The distribution of catchment runoff among these paths depends on the permeability of the stockpile and of the material below it, the volume of runoff, and whether or not the material below the pile is already saturated. Some examples are given in figure 52. Again, formation of a

Figure 49 (cont.)



$K_2 = 0$

$K_1 > N_s$

Perched mound.

Seepage from margin of pile only.

Saturated zone formed by ponding.

Seepage to groudwater will vary, depending on K_2.

Seepage from margin of pile controlled by permeability and topography of material around pile.

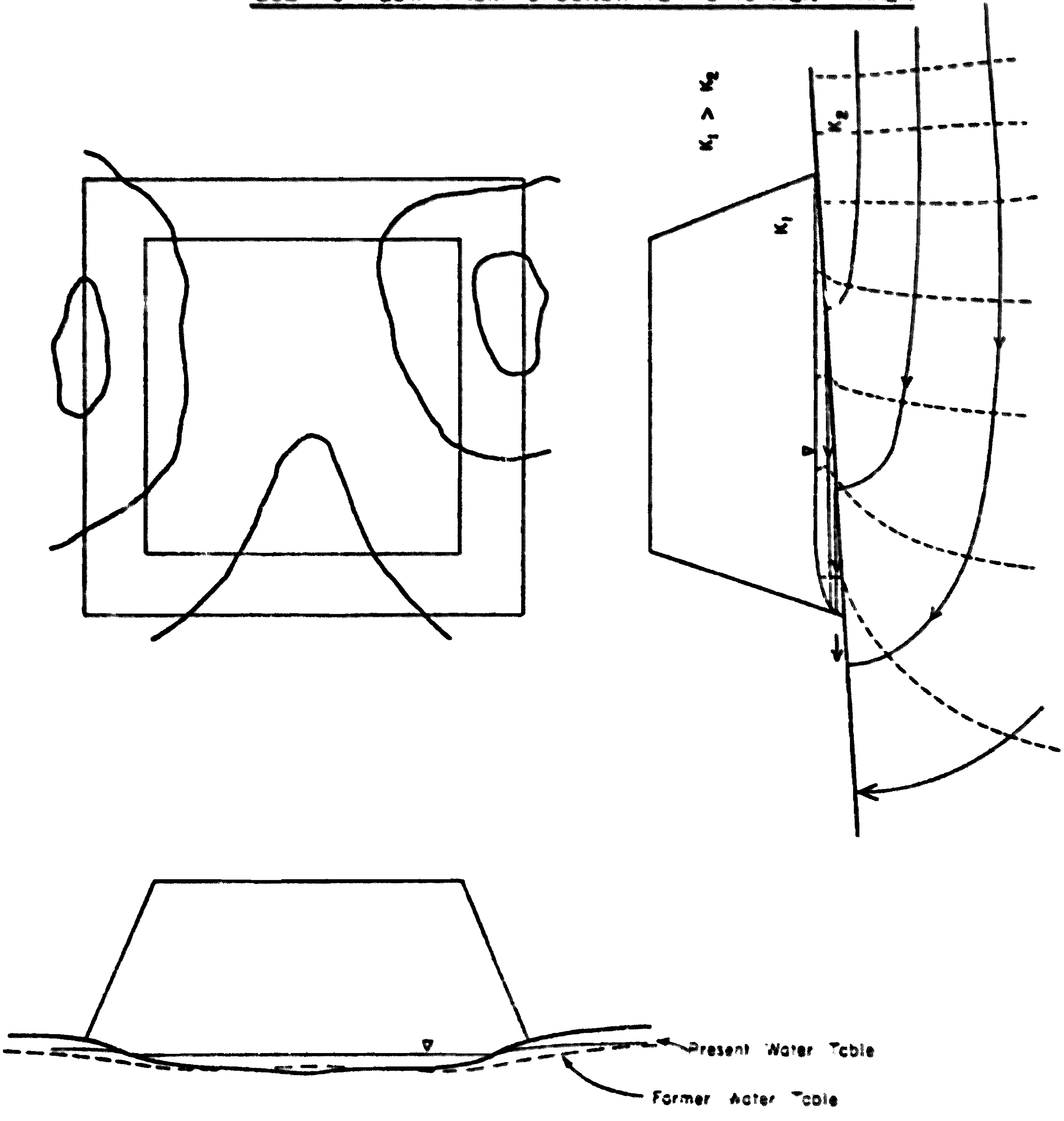
Perched mound at intermediate position within pile.

$N_s > K_3$

$K_4 > N_s$

Figure 50

DEVELOPMENT OF SATURATED ZONE WITHIN STOCKPILE DUE TO FLOW FROM GROUNDWATER CATCHMENT AREA



Pile located in groundwater discharge area

Figure 51

SATURATED ZONE WITHIN STOCKPILE PILED ON COMPRESSIBLE MATERIAL IN AN AREA WITH A HIGH WATER TABLE

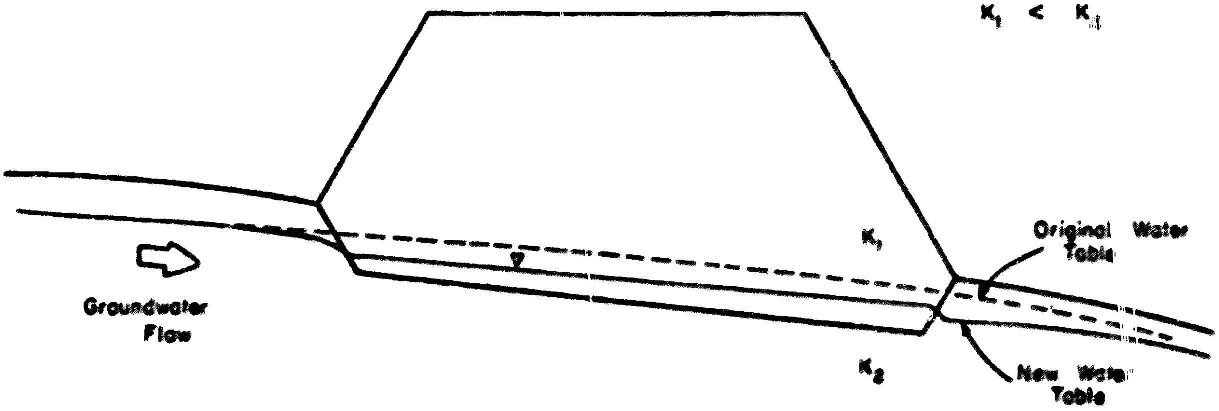
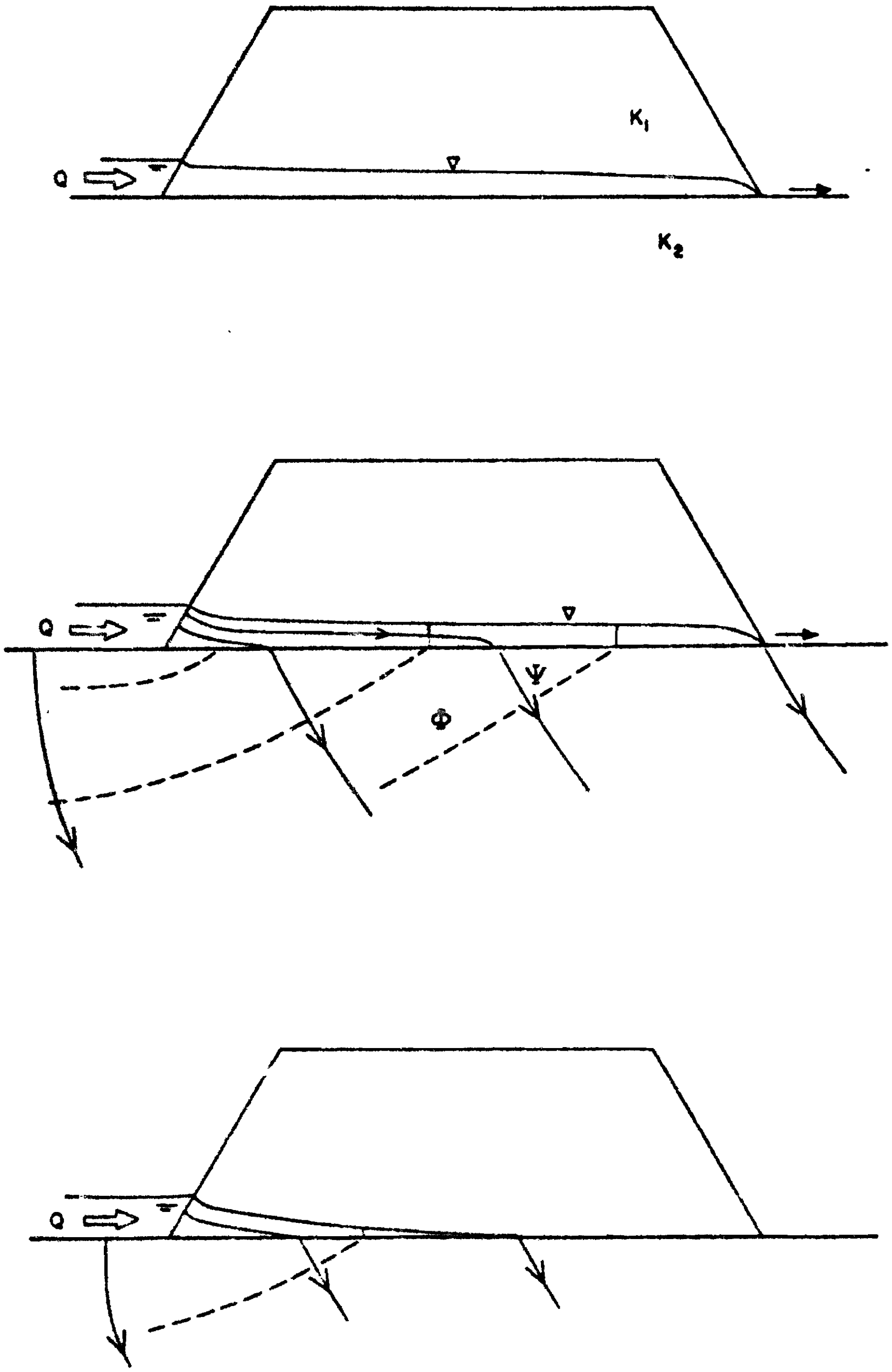


Figure 52

DEVELOPMENT OF SATURATED ZONE DUE TO SURFACE RUNOFF FROM CATCHMENT AREAS



$K_2 = 0$

Seepage from margin of pile only.

$K_1 > K_2$

Q Large

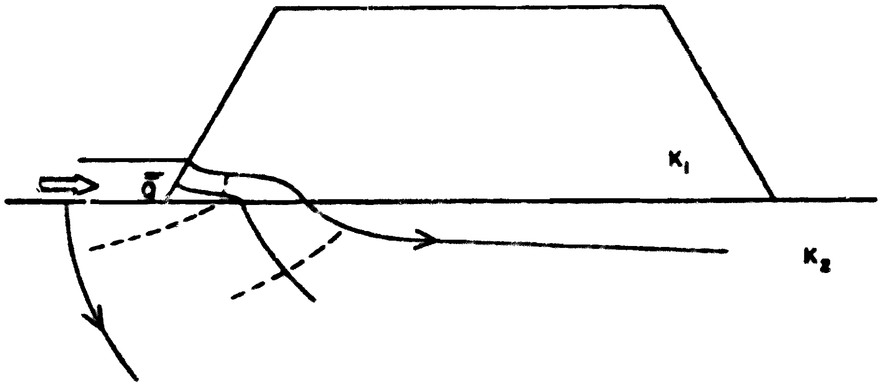
Seepage from margin of pile and to local groundwater.

$K_1 > K_2$

Q Small

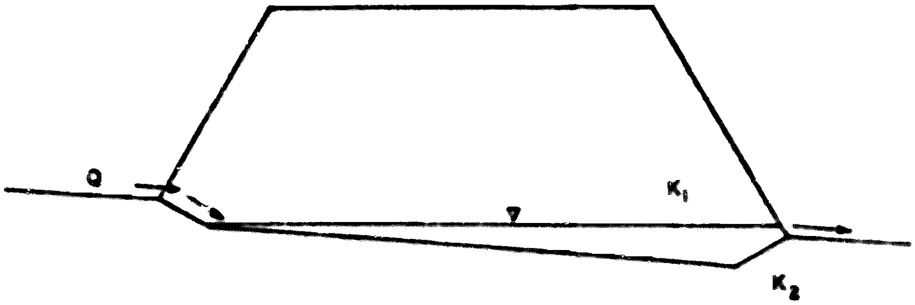
Saturated zone in pile discharges to local groundwater only.

Figure 52 (cont.)



$K_2 > K_1$

Saturated zone in pile discharges to groundwater only.



K_1 Large

K_2 Small

Saturated zone formed by pooling.

Seepage to groundwater will vary, depending on K_2.

Seepage from the margin of the pile is controlled by the conditions at the outlet.

saturated zone within the stockpile due to surface runoff from catchment areas requires either that the pile material be fine enough to sustain groundwater flow, or that less permeable materials around the pile dam the flow, creating pooling within the pile. The major factors affecting baseflow and seepage to groundwater from stockpiles are:

1) the grain size, layering and covering of stockpiles, which control the amount of infiltration reaching the base of the pile to sustain saturated flow;
2) site topography, which determines the surface catchment of the pile and affects the possibilities for pooling of water within the pile; and
3) the permeability of site materials and original water table elevation, which control groundwater flow into and out of the pile and affect possibilities for pooling.

Environmental significance of flow paths Differences among flow paths within stockpiles may affect the release of metals from stockpiles or impact of a given release. Release of metals from the pile may be limited by the availability of water for transport, so that the total water balance of the pile is important. Physical differences among flow paths which may affect the types and rates of chemical reactions occurring include gabbro surface area contacted, contact time, oxygen availability, temperature and wet/dry cycling (Lapakko, 1979). Leachate discharged to surface water has an immediate opportunity to affect aquatic organisms. These organisms may be affected in a different way by the short, sharp pulses of toxicants associated with interflow peaks than by the more uniform concentrations associated with base flow. Leachate released into the local groundwater system may move a considerable distance (time) before discharge to surface water or to a water well. Toxicants released to groundwater are more difficult to follow and collect, but the large absorbing surface area and anaerobic conditions in the saturated zone may limit transport. The significance of these releases also depends on the relative amounts of use of surface and groundwater resources.

The environmentally significant properties of flow paths within stockpiles are summarized in table 9.

Table 9 Environmentally significant properties of flow paths in stockpiles

flow path	gabbro surface area contacted	time in contact with gabbro	oxygen availability	temperature	wet/dry cyling	location of output	time distribution of output
surface runoff	small	very short	high	variable	yes	surface water	short,sharp peaks
interflow	large	short	high	variable	yes	surface water	short, sharp peaks
base flow	large to very large	long	restricted, depends on wet/ dry cyling	low	limited. depends on fluctuations of water table	surface water	steady flow over long periods
seepage into material below pile	large	1	1	1	1	groundwater	1

[1] If the lower part of the pile is unsaturated, water seeping out of the pile will have undergone conditions in the pile similar to those for interflow, while if the lower part is saturated, seepage into the material below the pile will have undergone conditions like those for base flow.

Stockpile Water Balance

Water transports the products of sulfide oxidation out of stockpiles, and hence the volume of water passing through a pile may be a limiting factor in the mass release. The cost and effectiveness of treatment, whether it involves diluting the discharge in natural streamflows, decreasing stockpile runoff by cover and revegetation, passing the water through filter beds, or processing it, depends in part on the volume of water discharged by the untreated piles. For these reasons the water balance of stockpiles is important.

A general water balance equation is:

$$P = E + RO + GW + \quad s$$

(input = output + change in storage)

P = precipitation
E = evaporation
RO = runoff
GW = ground water
S = storage

The gaged runoff at the outlet of the watershed is given by RO. The term GW can be either positive or negative. If positive, it denotes water percolating into the groundwater system and emerging downstream of the gaging point (underflow). If negative, it represents groundwater which flows into the watershed across surface drainage divide. Changes in storage (s) can occur in lakes, reservoirs, or groundwater, but for the stockpile watersheds only groundwater storage need be considered.

Any of these quantities can also be expressed as water depth times area, e.g., $P = p \times A$, $E = e \times A$. If the data permit, it is desireable to separate evaporative and runoff losses from stockpiles and those from non-stockpile areas, e.g.,

$$E = E_s + E_u = e_s \times A_s + e_n \times A_n,$$

since evaporation and runoff coefficients for the two areas are likely to differ.

1. Water balances for Erie stockpiles

EM-8: Precipitation input (p) to the EM-8 watershed was calculated using rainfall data from the Erie site when available, and data from Babbitt for other times (see appendix 3). The watershed area was determined as described in appendix 5, and is $1.17 \ast 10^7$ ft.^{2} (0.42 mi.^{2}) of which 52% is stockpile. Runoff (RO) was measured directly at the EM-8 weir (see appendix 6).

Losses to groundwater (underflow) were assumed to be zero. Most of the material underlying the 8011 stockpile is impermeable, and chemical data from wells around the pile indicate that leachate is moving into the groundwater only in the small area where till directly underlies the pile (see p. 81). Much of the EM-8 watershed upstream of the 8011 stockpile is on till or uncompressed peat, and underflow losses from this area could be significant.

Since two of the periods analyzed were shorter than a year, and all periods analyzed had markedly atypical precipitation, changes in storage could not be assumed to be zero. Changes in storage were estimated using the recession curve for the watershed. "The recession limb... represents the withdrawal of water from storage after excess rainfall has ceased. Consequently it may be considered as the natural decrease in the rate of discharge resulting from the draining-off process. The shape of the curve is independent of time variations in rainfall or infiltration and is essentially dependent on the physical features of the channel alone."(Gray, 1970, p. 7.7). "For most watersheds, groundwater-depletion characteristics are approximately stable, since they closely fit watershed geology. Nevertheless...recession...varies with seasonal effects such as evaporation and freezing cycles..."(Viessman et al., 1972, p. 69).

Analysis of the EM-8 hydrograph for periods between storm events indicates that the shape of the recession curve was reasonably constant throughout the study period. The composite curve constructed from rainless periods is shown in appendix 7.

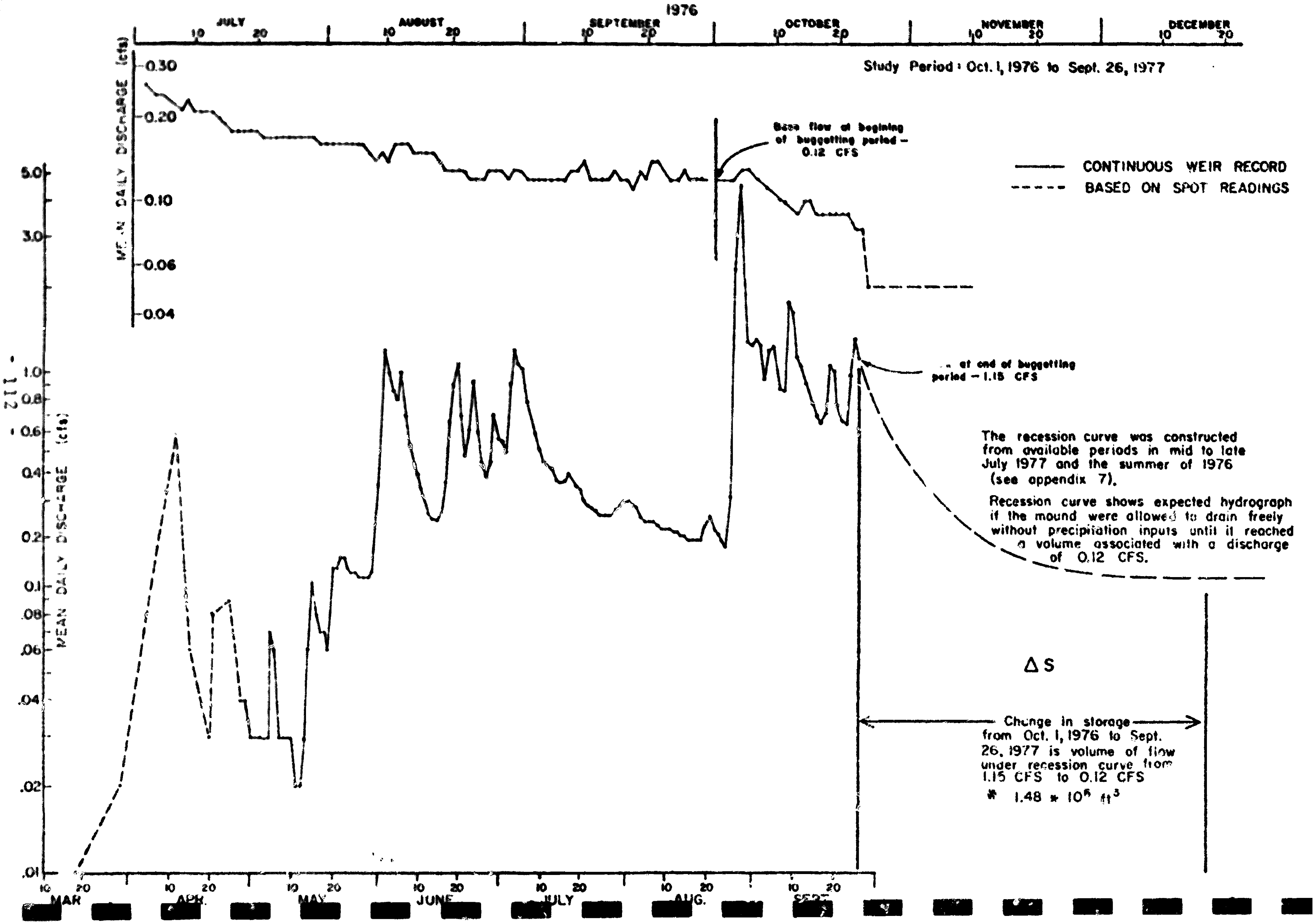
Each point on the curve corresponds to a given volume of water in storage (Viessman, 1972, p. 70). If the budgeting period begins and ends at different points on this curve, the volume of water in storage has changed. The magnitude of the change is the volume of water under the recession curve between the points corresponding to the flow rates at the end and beginning of the budgeting period (Viessman et al., 1972, pp. 69-70). Figure 53 illustrates this method of calculating changes in storage for the 1977 water year.

Water balances for the 1977 water year and for the common period from 1976 and 1977 data (July through September) are shown in table 10. For the 1977 water year, the total yield from the watershed (RO+ΔS) was 28% of input (precipitation). During the summer drought of 1976, virtually all of the rain that fell evaporated, and flow was sustained by discharge of stored water. During the wet summer of 1977, output was 31% of precipitation.

Seep 3 and Seep 1. Fewer data are available for the seep 3 and seep 1 watersheds, so the water balance calculations are less detailed. Precipitation input was calculated using rainfall data from the Erie site when available, and data from Babbitt at other times (see appendix 3). Watershed areas were determined as described in appendix 5 and summarized in table 11. Runoff was calculated by straight line interpolation between periodic measurements of

Figure 53

CALCULATION OF CHANGE IN STORAGE OVER 1977 WATER YEAR AT EM-8



Study Period : Oct. 1, 1976 to Sept. 26, 1977

Base flow at begining of buggetting period – 0.12 CFS

.. at end of buggetting period – 1.15 CFS

The recession curve was constructed from available periods in mid to late July 1977 and the summer of 1976 (see appendix 7).

Recession curve shows expected hydrograph if the mound were allowed to drain freely without precipitation inputs until it reached a volume associated with a discharge of 0.12 CFS.

Change in storage from Oct. 1, 1976 to Sept. 26, 1977 is volume of flow under recession curve from 1.15 CFS to 0.12 CFS

$\approx 1.48 \times 10^5 \ ft^3$

Table 10. **Water Balances For The EM-8 Watershed**

Period	P(in)	RO(ft^3)	RO(in)	ΔS(ft^3)	ΔS(in)	GW(in)	E(in)	$\frac{RO}{P}$(%)	$\frac{RO+\Delta S}{P}$ (%)
10/1/76 - 9/26/77	33.38	7.57×10^6	7.76	1.48×10^6(1)	1.52	0	24.1	23	28
6/27 - 9/25/76	4.76	1.27×10^6	1.30	-1.27×10^6(2)	-1.30	0	4.76	27	~ 0
6/27 - 9/25/77	18.93	5.26×10^6	5.39	0.44×10^6(3)	0.45	0	13.09	28	31

Table 11. Watershed areas of Erie seeps, millions of ft^2

Description		Watershed	Contained Stockpiles
EM-8			
total watershed		12.3	
included stockpile area			6.71
8006/8017	2.17		
8011	3.51		
8012	0.53		
8014	0.50		
Total	6.71		
area above sump	6.71		
included stockpiles	2.22		
area below sump	4.99		
included stockpiles	3.91		
Seep 3			
total watershed		2.46	
included stockpile area 8014/8011			1.16
Seep 1			
watershed			
alternative 1		1.83	
2		0.611	
3		0.424	
included stockpile area			
alternative 1			1.14
2			0.552
3			0.378

discharge (see Appendix F). When this procedure was applied to the periodic measurements at EM-8, the resulting volume exceeded that determined by continuous weir records by 13%. It is likely that the runoff estimates for Seep 1 and Seep 3 are somewhat high.

Since large parts of both watersheds are thought to be on bedrock or compressed peat, losses to groundwater probably are small and were assumed to be zero. By analogy with EM-8, storage probably increased over the budgeting period (August 1, 1976-July 31, 1977), but no data are available to make a quantitative estimate, so zero change in storage was assumed.

For the period from August 1, 1976 through July 31, 1977, the seep 3 watershed yielded runoff equal to 45 to 50% of input precipitation (table 12). Estimates of percent runoff from seep 1 vary considerably depending on watershed area estimates (table 11). The data suggest that the two smaller watershed areas are underestimates, since they result in 90 and 131% runoff. The largest watershed area estimate gives runoff of 30%.

Table 12

Water Balances For the Seep 3 and Seep 1 Watersheds

	Period	Estimated Watershed Area(ft^2)	Stockpile Area(%)	P(in)	RO(ft^3)	RO(in)	ΔS	GW	E(in)	RO/P(%)
Seep 3	8/1/76 - 7/31/77	2.46x10^6	47	22.69	2.03x10^6	9.9	0	0	12.8	44
		2.21x10^6	52			11.0			11.7	49
Seep 1	8/1/76 - 7/31/77	1.83x10^6	62	22.69	1.05x10^6	6.9	0	0	15.8	30
		0.611x10^6	90			20.6			2.1	91
		0.424x10^6	89			29.7			<0	131

2. Water balances for Minnamax field leaching piles.

Precipitation data used in the water balance for the Minnamax piles are from the standard gauge at the site (appendix 3). Watershed areas were measured in the field and are summarized in table 6. Initial calculations group the rock area with the exposed hypalon area in computing runoff coefficients. Because the exposed hypalon probably provides little opportunity for retention and evaporation, further calculations were made assuming a runoff coefficient for the hypalon of 70%. This figure was chosen arbitrarily to determine the extent to which this factor could change estimates of runoff from the rock material.

Runoff data for 1977 are from the current meter installed on FL-1, and may not be highly accurate (see p.18). Data for 1978 are from the recording flow meter on the sump that collects runoff from all six piles (see appendix 9).

The hypalon liners prevent interaction with groundwater. Storage is assumed to be zero, since flow falls to zero during dry periods between storm events. Budgeting periods begin and end during such zero flow periods.

For August through October of 1977, runoff from FL-1 was 38% of precipitation (table 13). For the eleventh month period from December 1977, through October of 1978 all of the piles together yielded 10.5 inches of runoff, or 40% of precipitation. The assumption of a higher percent runoff from the hypalon had a negligible effect on runoff coefficients for the rock material.

Table 13. Water Balances For the Minnamax Field Leaching Piles

Period	Watershed Area (ft^2)			P(in)	RO(ft^3)	RO(in)			RO/P (%)		
	Total	Rock	Hypalon			Total	Hypalon	Rock	Total	Hypalon	Rock
8/4 - 10/31/77	3196	3157	39	13.06(1)	1324(3)	4.97	9.14	4.83	38	70	37
5/6 - 8/11/78	20830	19590	1240	12.83(2)	12018	6.93	8.98	6.55	54	70	51
12/1/77 - 10/31/78	20830	19590	1240	25.85	18080	10.5			40		

(1) Precip. Aug. 4 - Oct. 29. Precip on Oct 30 and 31 ran off after budgetting period.

(2) Precip. May 6 - Aug. 10. Precip on Aug 11 ran off after budgetting period.

(3) RO = difference in flow meter readings on the two end dates, plus 110 gallon added as estimate of unrecorded flow on two separate days.

3. Discussion

Because the period of record for stockpile flows is short and had anomalous precipitation patterns, it is difficult to draw conclusions about the typical behavior of stockpile watersheds. A framework for analyzing the available data can be made by comparing the behavior of natural watersheds from 1976 to 1978 with their long term average behavior.

During the study period, the yield of stockpile watersheds at Erie exceeded that of natural watersheds in the region (table 14). From October, 1976 through September, 1977, runoff from the EM-8 watershed amounted to 7.76 inches, while runoff from nine gaged watersheds in the region averaged 6.00 inches. From August, 1976 through July, 1977, the seep 3 watershed yielded 9.9 inches, while natural watersheds averaged 3.39 inches. Comparison of monthly flows from EM-8(figure 23) and seep 3 (figure 27) with those from the Kawishiwi River near Ely (figure 8) and the Partridge River near Aurora (figure 11) indicates that two factors were responsible for the higher yields from stockpile watersheds. First, the higher yields of stockpile watersheds during the summer of 1977 compared with those of natural watersheds indicate less susceptibility of stockpiles to evaporative losses. The stockpiles are not vegetated, so transpiration losses are zero. In addition, only a limited amount of water can be retained in the active evaporation zone by the coarse material and only a limited soil moisture deficit can develop under prolonged evaporation. Secondly, higher flows in the fall of 1976 suggest that the stockpile watersheds have a better ability to sustain flow from storage during dry periods.

Table 14 Comparison of stockpile behavior with behavior of natural watersheds in the area.

	Stockpile Behavior						Natural Watershed Behavior				
Period	Watershed	P(in)[1]	RO(in)[2]	ΔS(in)[3]	$\frac{RO}{P}$ (%)[4]	$\frac{RO+\Delta S}{P}$ (%)[5]	RO(in)[6]	$\frac{RO}{P}$ (%)[7]	$\frac{RO\ ave}{P\ ave}$ (%)[8]	$\frac{P\ obs}{P\ ave}$ (%)[9]	$\frac{RO\ obs}{RO\ ave}$ (%)[10]
10/1/76-8/26/77	Erie IM-8	33.38	7.76	1.52	23	28	6.00	18	37	117	58
6/27-9/25/76	Erie IM 8	4.76	1.30	-1.30	27	0	.79	16	20	41	32
6/27-9/25/77	Erie IM-8	18.93	5.39	0.45	28	31	5.27	27	20	162	217
8/1/76-7/31/77	Erie Seep 3	22.69	9.9	0	44	44	3.39	15	37	79	32
8/4-10/31/77	Amax PL-1	13.06	4.97	0	38	38	nd	nd	19	130	nd
5/6-8/11/78	Amax Seep	12.83	6.92	0	54	54	nd	nd	41	110	nd
12/1/77-10/31/78	Amax Seep	25.85	10.5	0	40	40	nd	nd	38	nd	nd

nd = incomplete data
1 = Observed precip at Erie or Amax
2 = Observed runoff from stockpile areas
3 = Change in storage within stockpile areas estimated on the basis of base flow recession curves
4 = Runoff during the period as a percent of precip. during the period
5 = Estimate of the net yield from precip. during the period
6 = Average runoff from 9 gaged streams during the period (Siegel and Ericson, 1979)
7 = Runoff from 9 gaged streams as a percent of precip at Erie or Amax
8 = Average runoff from 9 gaged stream as a percent of precip at Babbitt
9 = Precip observed at Erie or AMAX over the period as a percent of the average precip at Babbitt
10 = Runoff observed at 9 gaged streams as a percent of average runoff from those streams (Siegel and Ericson, 1979)

Runoff from the Erie watersheds during an average year can be expected to exceed that of natural watersheds in the region, and will probably be 40 to 50% or more of precipitation. During the 1977 water year, runoff from the EM-8 watershed was 23% of precipitation, and runoff plus changes in storage totalled 28% of precipitation. Although rainfall over the period was 117% of normal, runoff from natural watersheds in the region averaged 58% of normal (table 15), and was only about 18% of precipitation. Runoff from the EM-8 watershed was probably below normal, also. Runoff from natural watersheds in an average year is 37% of precipitation, and it is likely that the runoff from the EM-8 watershed would exceed this amount. From August 1976 through July 1977 the runoff from seep 3 was 44% of precipitation. Precipitation was 79% of normal, but runoff from natural watersheds was 32% of normal (table 15) or 15% of precipitation. By analogy, the runoff from seep 3 is likely to be considerably greater than 44% of precipitation in an average year.

The annual yield of the seep 3 watershed is apparently much greater than that of the EM-8 watershed. Ambiguities in determining watershed areas and calculating seep 3 runoff from periodic measurements may account for part of the difference. Large marshy areas in the EM-8 watershed probably lead to greater evaporative losses. Underflow losses due to seepage into the till in upstream portions of the watershed may also reduce the flow of the EM-8 watershed.

For purposes of predicting impacts of runoff from stockpiles built during future copper-nickel mining in northern Minnesota, projections of stockpile behavior based on observations at Erie were developed. The average annual runoff of the Erie watersheds, which are only 32% covered by stockpiles, is estimated to be 40 to 50% or more of average annual precipitation. The stockpiles are thought to yield more runoff than the undisturbed area, so stockpile runoff is apparently upwards of 50%.

Table 15. Streamflows during budgetting periods and streamflow statistics

Stream	Watershed Area, mi^2	Annual Streamflow Statistics A ave	Q25	Q50	Q75	Q 10/1/76-9/30/77	Q 8/1/76-7/31/77
Second Ck nr Aurora	29.0	22.4	16.1	19.0	27.4	15.6	12.0
Partridge R. nr Aurora	156	112	73.7	102	135	56.6	34.5
St. Louis R. nr Aurora	291	230	168	218	270	111	56.8
Kawishiwi R. nr Ely	253	223	167	216	259	94.5	42.6
Isabella R. nr Isabella	341	272	187	246	331	193	106
Dunka R. nr Babbitt	53.4	36.6	26.8	33.5	40.1	24.9	12.3
Bear Isl. R nr Ely	68.5	41.2	27.2	37.9	46.7	36.7	19.8
Kawishiwi R nr Winton	1200	1019	599	883	1118	544	307
Shagawa R at Ely	99.0	86.6	45.5	83.4	107	41.0	18.8
average in cfsm		.77	.52	.71	.91	.45	.25
average in inches		10.5	7.06	9.64	12.4	6.11	3.39

All streamflows are in ft^3/sec unless otherwise noted.

Rough approximations of the variations in stockpile runoff in wet and dry years were made by assuming that the same amount of water is lost to evaporation in a wet or dry year as in an average year. This amount was subtracted from the wet or dry year precipitation to estimate runoff (figure 54). For the watersheds at Erie, this method predicts essentially zero runoff in a dry year, and 19 to 25 inches in a wet year. Although the method gives an indication of the range in a runoff which might occur, the actual runoff in a wet or dry year depends on many factors. Precipitation is not necessarily a good predictor of runoff. Precipitation and evaporation during the preceeding years have an effect, as the 1977 water year demonstrates. The storage characteristics of the watershed also have an effect. For instance, essentially all of the precipitation which fell from July through August of 1976 evaporated, as would be expected, but stockpile seepage was sustained by withdrawal from storage within the piles, and the ratio of stockpile flow to natural watershed flow was high.

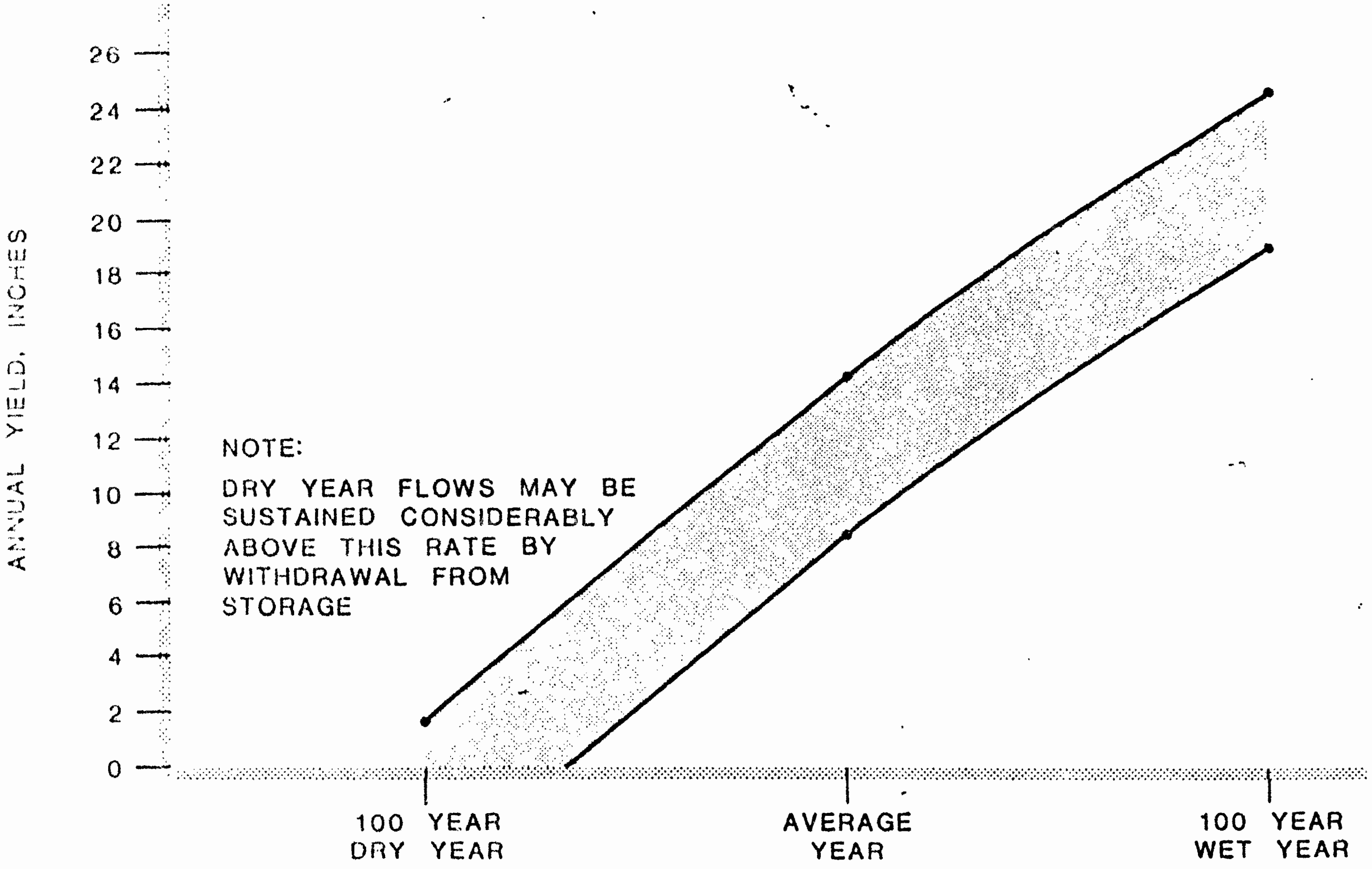
Physical properties of stockpiles which may affect the annual water balance are discussed in the "evaporation" section of the conceptual model. Assuming evaporation occurs primarily in the near surface portions of the pile, the controlling characteristics are the texture, thickness and layering of the cover material, the texture of the near surface stockpile material and the nature of the hydraulic discontinuity between the two. Vegetation may significantly increase evaporation. The internal characteristics of the pile and its height are not thought to be important. The nature of the surficial material below the pile may appear to have an effect, if seepage to groundwaters is not measured.

* In reality, there is a negative correlation between precipitation and pan evaporation (Bruce Watson, pers. comm., 1979), which would result in a somewhat more extreme range in runoff.

FIGURE 54

ESTIMATED ANNUAL STOCKPILE RUNOFF

BASED ON 80FT HIGH OPEN PIT MINED PILES



NOTE:

DRY YEAR FLOWS MAY BE SUSTAINED CONSIDERABLY ABOVE THIS RATE BY WITHDRAWAL FROM STORAGE

Seasonal Runoff Patterns

Runoff data from EM-8 provide the most complete and accurate information for describing seasonal runoff patterns. Flow was zero during the winter months, probably due to formation of ice dams within and near the margin of the 8011 stockpile. At other times, the flow never dropped to zero, but was sustained between storm events by discharge of stored water. Spring flow (March to May) was small in the one year of record (1977), reflecting the low snowfall and depleted soil moisture conditions. Summer and fall discharge varied with the number and size of rainstorms. Flows were substantial in 1977 and 1978, but in 1976, when rainfall was negligible, flows receded steadily from July through the fall and winter.

Because the period of observation was short and rainfall patterns during the period were unusual, the seasonal flow patterns observed may not be typical. As a further source of information, observed patterns at EM-8 are compared with patterns for natural watersheds during the same period. The long term average behavior of these watersheds is known, and provides a perspective for observations made in the period from 1976 through 1978. Three of the stream stations used were chosen because they are unregulated: the Kawishiwi River near Ely, the Isabella River at Isabella, and the Bear Island River near Ely. No data were collected for the latter two in 1978, so the Partridge River was substituted. Flows of the Partridge River were corrected for diversion and changes in reservoir storage by the USGS. All of these watersheds are much larger than the EM-8 watershed, and can only provide an integrated summary of typical runoff behavior in the study area. Natural watersheds the same size as EM-8 could have an infinite variety of seasonal runoff patterns.

The following discussion is based on figures 8 through 13 and 23. To facilitate comparison, all flows are plotted in cfs per square mile (cfsm).

The overall patterns of runoff from the EM-8 watershed during the study period were similar to those of natural watersheds, which suggests that runoff patterns during more typical periods may also be similar. Flows are very low during the winter of 1976-77. Spring flows from natural watersheds were very much below normal in 1977, which suggests that spring runoff from stockpiles may be a major fraction of annual flow in normal years. Summer and fall flows of natural watersheds, like flows at EM-8, were strongly dependent on rainfall. Flows were small and receded through summer and fall of 1976. Flows were moderate in June through August of 1977, but shot up in September and were high through December. Nineteen seventy eight summer flows were at or above normal.

In some significant respects the behavior of the EM-8 watershed differed from that of natural watersheds. Flows were better sustained during the dry period from July through November of 1976, suggesting that the EM-8 watershed has better storage. This is true of the seep 3 watershed as well. Flows did not increase as soon or as much in spring (March-May, 77, May-June, 78) as they did in natural watersheds. Persistence of cold temperatures in the pile probably causes a later and slower thaw. This appears to allow more of the spring melt to go into groundwater storage, helping to maintain base flows later. Summer flows (July-August, 77, July-September, 78) were higher than for natural watersheds, indicating less susceptibility to evaporative losses. Transpiration losses are small, since the piles which cover 52% of the watershed are unvegetated. Furthermore, only a limited amount of water can be retained in the active evaporation zone by the coarse stockpile material, and hence only a limited soil moisture deficit can develop under prolonged evaporation.

Surface Runoff

No water leaves the stockpiles at Erie as surface runoff, even though rainfall intensity sometimes exceeds the infiltrability of the stockpile surfaces. The infiltrability of the compacted gravelly sand till surfacing material is probably adequate to allow complete infiltration of many storms. Large (50 x 100 ft) uncovered patches of waste rocks on the stockpile surface probably allow complete infiltration of most storms locally.

The surfaces of the stockpiles have a poorly to moderatley well developed drainage network. Wide, shallow channels (1 or 2" or less deep and 6 to 12" wide) eroded into the till demonstrate that its infiltrability is exceeded at times. Some channels lead into scattered ponding areas, where claying silts cover areas 10 feet or more in diameter. Several inches of standing water has been found in these pools two days after a substantial rain. Other channels lead to exposed patches of waste rock. Sands and silts carried by runoff have been washed in between the cobbly rock fragments. This system of channels and minor depressions appears to keep most of the rainfall on the stockpile surface long enough to infiltrate or evaporate.

Water reaching the side slopes of the piles will infiltrate into the coarse rubble immediately. Most of the perimeter of the pile slopes back toward the center for personnel safety reasons, precluding water from running off the sides. In a few places channels lead to the edge, but disappear upon reaching the coarse side slopes.

The infiltrability of the stockpile surfaces has not been measured, but based on observation rainfall intensities at Erie (table 16) and the presence of channels on the pile, it is probably less than one inch per hour. This is lower than infiltrabilities found by Burton, Gifford and Hart (1978) for uncovered waste rock piles, but is of the same order as typical values for coarse soils (see table 16).

Neither the bare piles nor the soil-dressed piles at Minnamax yield surface runoff. The compacted rock and soil apparently have high infiltrabilities. The piles are too small in areal extent to develop significant channels, so that any surface runoff would be in the form of overland flow in rills and sheets.

Table 16. Summary data on rainfall intensities and soil infiltrability.

Rainfall intensity

Some observed intensities at Erie in 1977

date	Precip(in)	duration(hr)	intensity (in/hr)
5/31	1.24	6	0.38
6/5	.27	0.6	0.45
6/16	.42	0.75	0.56
6/17	.3	0.55	0.55
6/28	.72	0.74	0.97
7/3	.78	0.83	0.94
7/16	.34	1.85	0.18
9/19	.54	5.2	0.10

Rainfall intensities for selected return periods and durations (Watson, 1978, table 6.2)

	return period, years		
duration, min.	2	10	25
30	1.6-1.8	2.4-2.8	2.6-3.2
60	0.9-1.2	1.5-1.8	1.7-2.0
360	0.27-0.3	0.4-0.45	0.45-0.52

Infiltrability

Literature values for rock dumps inches/hour

6.3	- leach dump under ponded conditions (Armstrong et al., 1971, p 7)
1.3 to 2.4	- waste rock piles of non-porous igneous and metamorphic material under simulated rainfall (Burton, Gifford and Hart, 1978, p. 274).

Literature values for bare soils, inches/hour

0.3	- coarse and medium textured soils over outwash, coarse open till, or coarse alluvium (Gray, 1970, p. 5.5)
0.1	- medium textured soils over medium textured till (Gray, 1970, p. 5.5)
0.05	- medium and fine textured soils over fine textured clay till (Gray, 1970, p. 5.5)
1.0	- loose sandy soil (Linsley and Franzini, 1979, p. 47)
0.01	- heavy clay soils (Linsley and Franzini, 1979, p. 47)

Stockpile Water Retention Capacity

The water retention capacity of the stockpiles was estimated and compared with observed losses from storm rainfall to get a sense for the following:

-- Are evaporative losses from the EM-8 watershed dominated by losses from the vegetated/water covered undisturbed area?

-- Is the assumption that evaporated water is lost primarily from the near surface part of the piles reasonable?

-- Does the comparison suggest other losses, such as seepage, are necessary to account for the observations?

Evaporative losses are limited by the ability of vegetation, surface depressions and the soil to hold water long enough for it to evaporate. The processes involved are discussed in the "Conceptual Model".

The maximum retention associated with a single runoff event at Erie through 1977 was 2.3 inches, and the maximum observed at AMAX through 1978 was 3.0 inches (table 17). Retention was calculated to be that fraction of rainfall which does not run off and which is not evaporated during the storm period, and ignores soil moisture present when the storm began. Table 19 shows the evaporative losses for numerous other storms at Erie. Daily pan evaporation is given in appendix 10.

Retention capacities of the soil cover (if present) and the stockpile rock were estimated separately and are summarized in Table 18. The till covering the Erie piles is approximately 10 to 20% gravel, 30 to 45% sand, 20 to 40% silt and 10 to 20% clay (Olcott and Siegel, 1978, pp. 10-11), and may have a field capacity of 6 to 25% by volume, based on published data (appendix 11a). The retention capacity of the topsoil is estimated to be near the upper end of this range.

Table 17. Maximum retention associated with a single runoff event from Erie (1) and AMAX (2) stockpiles (inches)

Erie EM-8

Date	Precip (Erie)	Pan Evap (Hoyt Lakes)
8/25/77	.93	.08
26	1.6	.03
27	1.45	.10

total precipitation-total runoff (3) = total evaporation

3.98 - 1.46 = 2.52

total evaporation-evaporation during storm period = retention

2.52 - .21 = 2.31

AMAX FL-1

Date	Precip (AMAX)	Pan evap (Hoyt Lakes)
8/25/77	.77	.08
26	2.79	.03
27		.10
28		.11

total precipitation- total runoff= total evaporation

3.56 - .29 = 3.27

total evaporation - evaporation during storm period=retention

3.27 - .32 = 2.95

---

(1) observations through 1977

(2) observations through 1978

(3) total runoff= interflow plus baseflow

Table 18. Estimated retention capacities of stockpiles at Erie and AMAX

Erie

material	thickness (1)	retention	
	(ft)	volume%	inches of water
till cover	0.5	6 to 25(2)	0.36 to 1.5
stockpile rock	3	0.11 to 0.89(3)	0.04 to 0.32
"	5	0.11 to 0.89(3)	0.066 to 0.53
"	80	0.11 to 0.89(3)	1.1 to 8.5
"	3	3.5(4)	1.3
"	5	3.5(4)	2.1
"	80	3.5(4)	34

AMAX

material	thickness (1)	retention	
	(ft)	volume%	inches of water
till cover	0.60(5)	6 to 25(2)	0.43 to 1.8
"	0.92(5)	6 to 25(2)	0.66 to 2.8
topsoil	0.91(5)	20 to 25(2)	2.2 to 2.7
stockpile rock	3	0.40 to 3.1(3)	0.14 to 1.1
"	5	0.40 to 3.1(3)	0.24 to 1.9
"	13	0.40 to 3.1(3)	0.62 to 4.8
"	3	3.5(4)	1.3
"	5	3.5(4)	2.1
"	13	3.5(4)	5.5

(1) for stockpile rock, thickness indicates various estimates of the active retention/evaporation zone.
(2) based on published data for soils (appendix 11)
(3) based on model that considers water retained in pores in the fine fraction and in thin films on the course fraction (appendix 11)
(4) based on limiting value found by Eckis in studies of valley fill (appendix 11)
(5) from Eger, Johnson and Hohenstein, 1979, p. 22.

Table 19

Analysis of Total Storm Yield From The EM-8 Waterhsed Based on Daily Discharge Data.

Year	Date	Precip. (in)		Runoff (in)	(%)	Evap. (in)
1976	7/5	.31	B*	.0027	0.9	.31
	7/9	.42	B	.0013	0.3	.42
	7/20	.35	B	.0011	0.3	.35
	8/4	.10	B	.0003	0.3	.10
	8/9	.08	B	.0006	.08	.08
	8/10	.22				
	11	.16	.41B	.00126		.409
	12	.03				
	9/7	.25	B	.0028	1.1	.25
	9/13	.18	B	0	0	.18
	9/18	.80	B			
	9/26	.20	B	.0007	0.35	.20
	10/4	.87	B	.0017	0.2	.87
	10/15	.12	B	.00126	1	.12
1977	5/30	.18				
	31	1.79	2.13	.71	33	.142
	6/1	.16				
	6/5	.54				
	6	.11	.87	.16	18	.71
	8	.22				
	6/15	.03				
	16	.75				
	17	.85	2.29	.51	22	1.78
	18	.25				
	19	.31				
	20	.10				
	6/23	.72	B	.164	23	.556
	6/28	.85				
	29	.26	1.50	.367	24	1.133
	30	.26				
	7/1	.13				
	7/3	1.30				
	4	.06	1.82	.533	29	1.29
	5	.44				
	7	.02				
	7/16	.45				
	17	.05		.058	12	.442
	7/26	.31				
	27	.35				
	30	.29				
	31	.17				
	8/3	.15				
	5	.23				
	6	.08				
	7	.08	2.12	.16	7.3	1.96
	10	.01	B			
	11	.03	B			
	14	.05	B			
	15	.31				
	16	.06				
	8/19	.56		.049	8.8	.511
	8/25	.93				
	26	1.60	3.98	1.46	37	2.52
	27	1.45				
	8/30	.40				
	31	.45	1.05	.36	30	.69
	9/2	.20				
	9/4	.75				
	5	.05	.95	.336	35	.614
	6	.15				
	9/9	.83	B			
	10	.028	1.17	.77	66	.40
	11	.27	B			
	13	.05	B			
	9/18	.02	B			
	19	1.058	1.08	.272	25	.808
	20	.01	B			
	9/22	.21	B			
	23	.05	B			
	24	.858	1.73	.50	29	1.23
	25	.36	B			
	26	.26	B			

Year	Date	Precip. (in)		Runoff (in)	(%)	Evap. (in)
1978	5/26					
	6/2	2.47	4.26	1.20	28.1	3.06
	6/1-2	1.79				
	6/7-9	1.00		0.23	23	0.77
	7/2-6	1.18		0.11	9.3	1.07
	7/7-11	1.77		0.22	12	1.55
	7/12-15	0.46		0.03	6.5	0.43
	7/18-22	1.01	1.87	0.58	31	1.29
	7/19-22	0.86				
	7/23-26	0.33		0.03	9.1	0.30
	8/14-20	1.74	1.89	0.33	17	1.56
	8/18-20	0.15				
	8/23-28	1.89		0.61	32	1.28
	8/27-29	0.59		0.04	6.8	0.55
	9/10-16	2.73		0.86	32	1.87
	9/14-17	0.83		0.46	52	0.43

*B indicates rainfall data from Babbitt were used

The stockpile material is very coarse, and probably has a retention capacity much lower than that of the cover material. Laboratory data collected by AMAX showed that a composite sample of crushed gabbro ranging in size from 0.149 to 2.38 mm retained 4.44% water by weight (∿9% by volume) after 48 hours. Since only 1 or 2% of the stockpile material falls in the size range, this must be an upper limit on water retention. Work reported by Eckis (in Todd, 1959, p. 24) showed that the specific retention of valley fill tended to approach a limiting value of 3.5% by volume as grain size increased (see appendix 11a). A model of retention capacity that considered water retained in pores in the fine fraction and in thin films on the coarse fraction predicted a retention capacity of 0.11 to 0.89% by volume for the Erie piles and 0.40 to 3.1% by volume for the AMAX piles (appendix 11b).

The amount of water that can be retained for evaporation by stockpile material depends on both its retention capacity (volume percent) and the thickness of material accessible to evaporative processes. Following Brady's argument (1974, p. 207) that only the upper parts of the soil can be depleted by evaporation, an active thickness of 5 feet at most seems reasonable. On this basis the stockpile material at Erie is estimated to be able to retain 0.066 to 2.1 inches, and that at AMAX 0.24 to 2.1 inches. For the storm event of August 25-28, 1977, at AMAX, this retention capacity is not sufficient to account for the observed losses from the bare FL-1 pile. Measurements of runoff may have been low, or the volume percent retention or active thickness may be underestimated.

Cover material contributes to retention capacity more significantly than its thickness would suggest. The till on the Erie piles is estimated to be able to retain 0.36 to 1.5 inches of water, nearly as much as the stockpile material. The two together can retain up to 3.6 inches, which is sufficient to account for observed losses at Erie. The hydraulic discontinuity between cover material and stockpile material will tend to increase the retention capacity of the cover material (see p.96).

In addition, evaporation from the Erie stockpiles is facilitated by water held in surface depressions lined with silt that dot the tops of the piles. Evaporation from vegetated areas and low-lying wet areas of the watershed is probably greater than the average for the watershed, with evaporation from the stockpiles generally less than average. Nevertheless, the calculations suggest that evaporation from the stockpiles is not negligible.

Storm Yields

In this section, estimates are made of the total yield (interflow plus baseflow) and evaporation from rain events. Observed evaporative losses establish a lower limit for retention capacity of the watersheds, as discussed above. Total yield is subdivided into interflow and baseflow in subsequent sections. The two flow paths have different physical conditions which probably affect release and transport of trace metals.

The total yield from a storm is affected primarily by the volume and intensity of rainfall and the infiltrability and moisture deficit of the soil. The larger the volume of rainfall relative to the soil moisture deficit, the greater the yield will be. If storm intensity exceeds soil infiltrability, water may run off before it has a chance to replenish soil moisture, increasing yields.

The method employed was as follows:

1. An individual runoff event (hydrograph peak) was isolated. Recession curves spliced to the hydrograph prior to and following the peak enclosed a volume of outflow.
2. For the EM-8 watershed, the volume of flow enclosed was calculated from tabulated discharge data (appendix 6) and tabulated recession curves (appendix 7). For the AMAX piles, the volume was calculated from tabulated discharge data (appendix 9) and recession values read from the curves sketched on the hydrograph (fig. 28 and 29).
3. Each rainfall event was assigned to a runoff event, so that percent runoff could be calculated.

Ideally, the runoff from each rainfall event would be calculated separately, but frequently several rainfall events contribute to a single peak which cannot be subdivided to resolve the runoff associated with each event. The method used results in a narrower range of percent yield values. For example, runoff from the storm on May 30 and 31 and June 1 1977 (table 19) was estimated as 33% of precipitation, but it may be that the storm of May 31 yielded 40% and the storms of May 30 and June 1 yielded nothing. Computer modelling of daily rainfall, flow, evaporation and soil moisture could provide a better picture of the storm response of stockpiles.

EM-8: Data used are those described in the "Water Balance" section. As in that section, it is assumed that no water is lost by seepage to underflow.

The recession curve became less steep for flows over 0.3 cfs from June through September of 1977. That high base flows were sustained longer indicates that short term storage within the system increased.

Figure 55 shows the daily discharge hydrograph for EM-8, with recession curves separating it into different runoff events. Table 19 shows precipitation, runoff and evaporation for each event. Yield has ranged from 0 to 66% of precipitation, the latter figure based on precipitation recorded at Babbitt. Using only rainfall recorded at Dunka, the maximum observed yield for the two year study period is 37%. The yield of three natural watersheds in the study area ranges from 5 to 90%, based on a longer period of record (fig. 56). Considering the depleted state of soil moisture during much of the study period, it is reasonable to expect higher yields from stockpile watersheds in the future.

Due to the effects of soil moisutre, rain intensity, and other factors, the correlation between runoff and precipitation is only fair (fig. 57).

Figure 55 a

STORM RUNOFF AT EM - 8, 1977

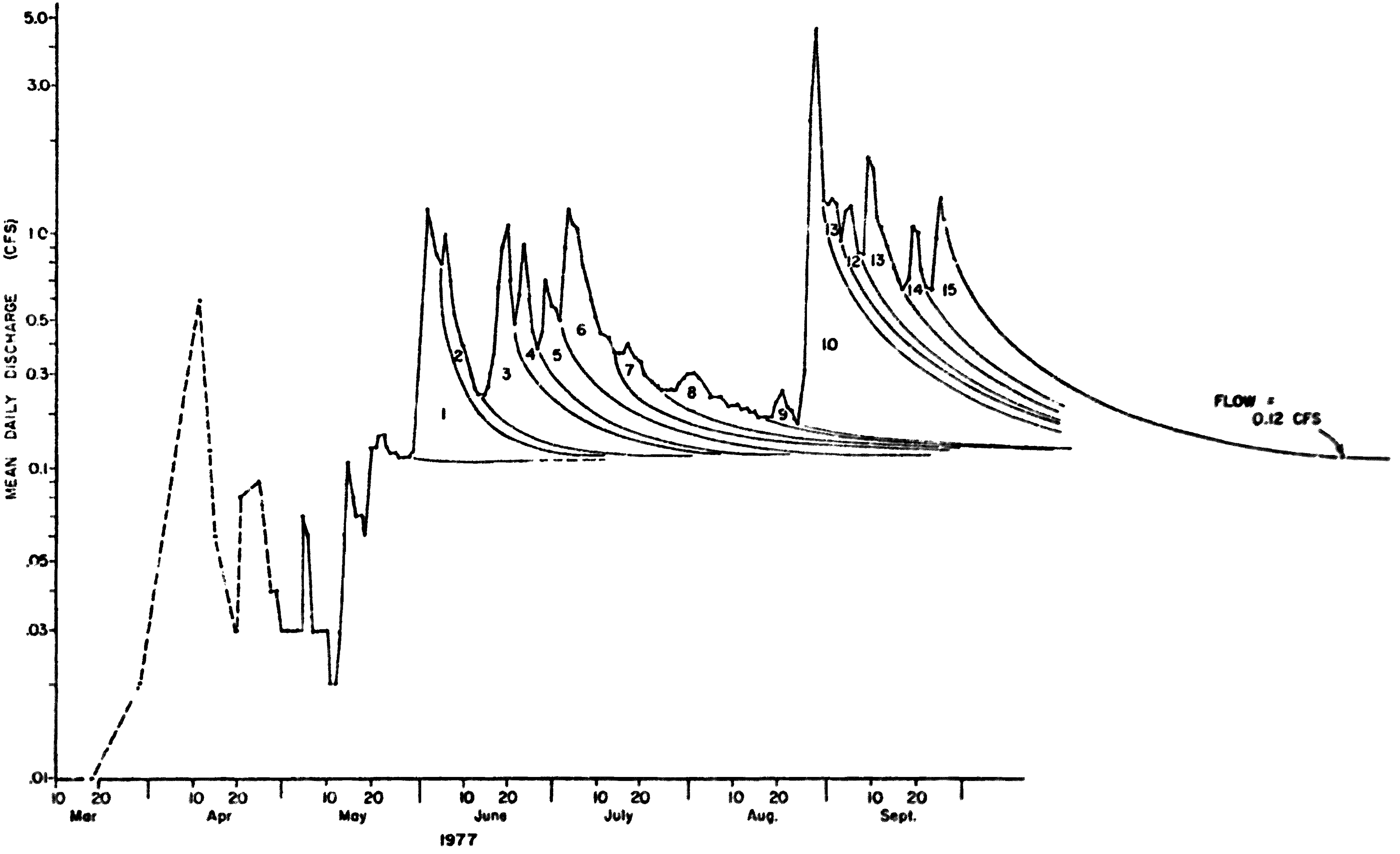
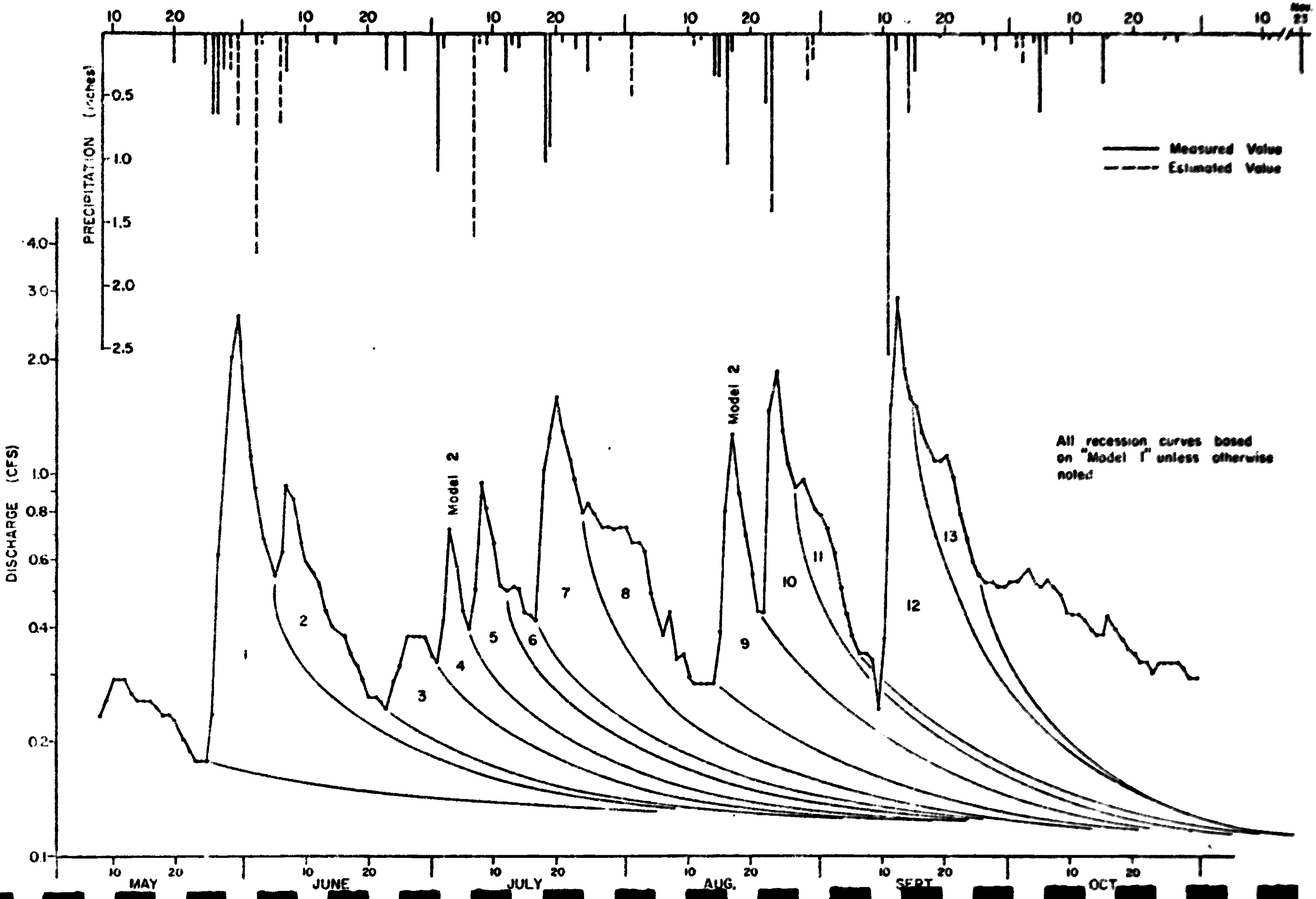


Figure 55b
STORM RUNOFF AT EM-8, 1978



All recession curves based on "Model 1" unless otherwise noted

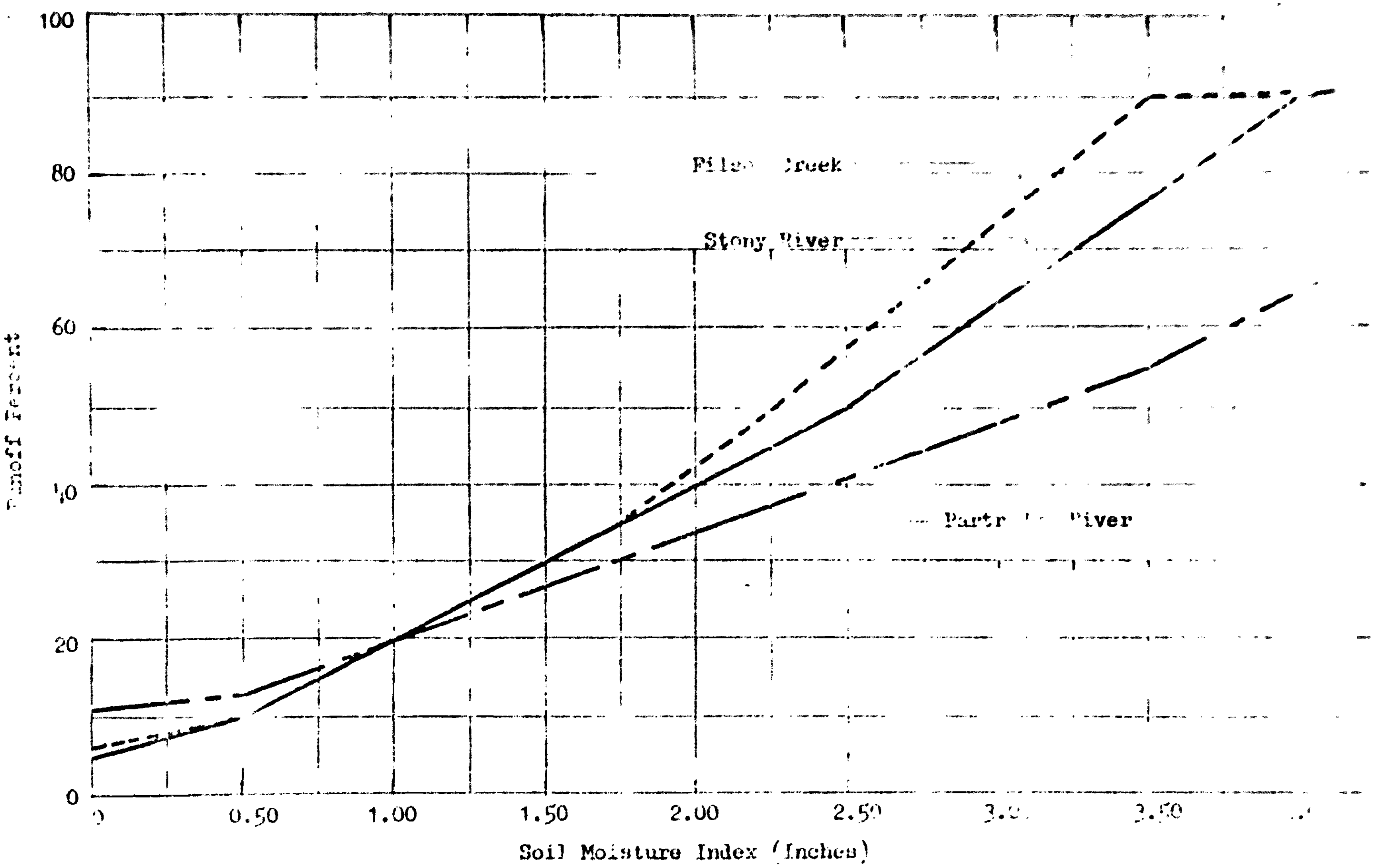


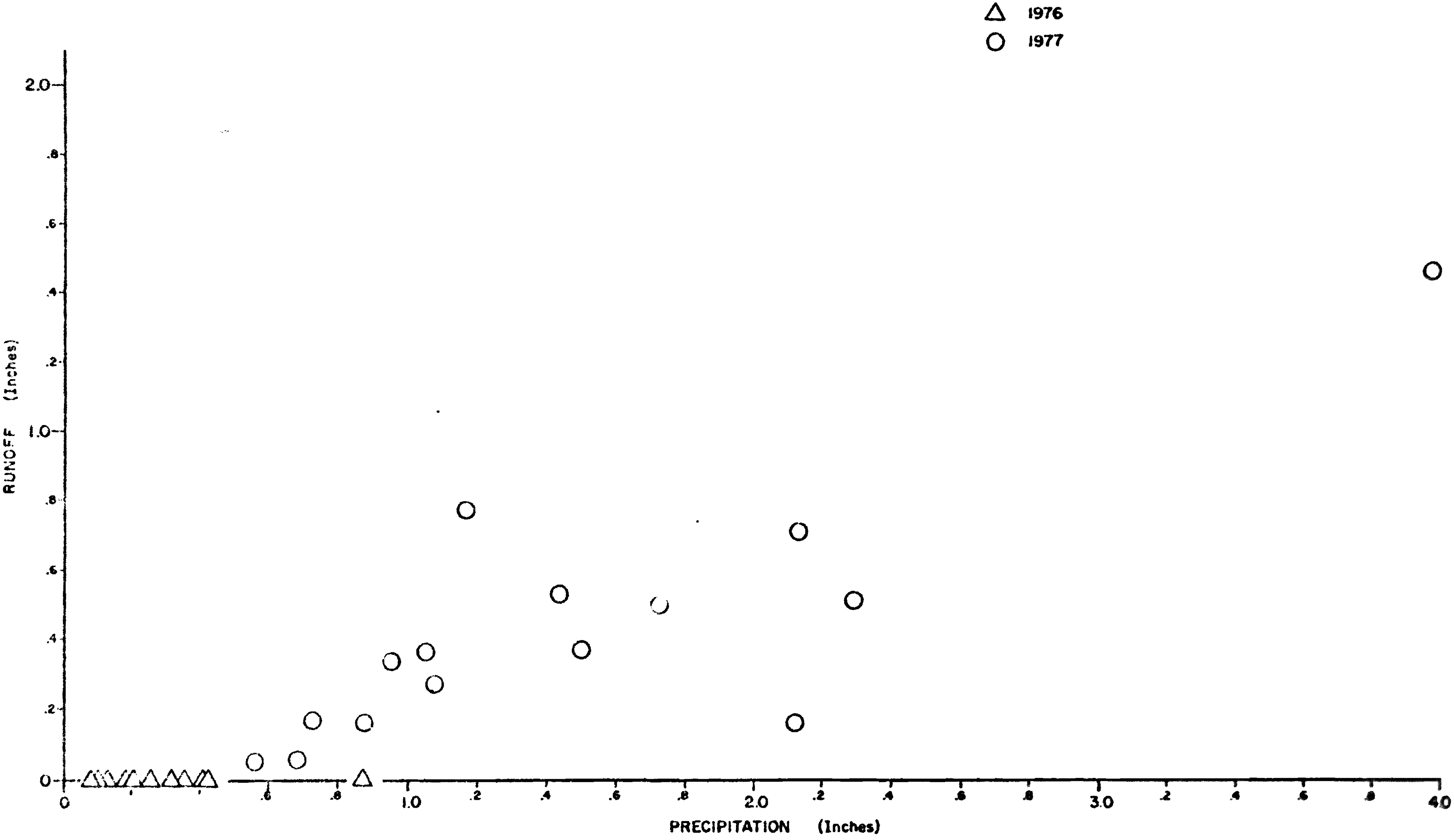
Fig. 56 – Rain Basin Soil Moisture Index-Runoff Relationships.

from Sevard, Nelson and Bowers, 1978, p. 18.

Figure 57

STORM RUNOFF AS A FUNCTION OF PRECIPITATION AT EM-8

1976 AND 1977



During 1976 the small, infrequent storms gave rise to few runoff peaks. Those which did occur were small, and accounted for a negligible fraction of input precipitation. All of the runoff generated in the summer of 1976 may have come from the small ($2.64 \times 10^5 ft^2$) bog between EM-9 and the weir, with the stockpiles and the undisturbed areas upstream of 8011 contributing no runoff. Storm yields in 1976 accounted for a maximum of 48% of the precipitation on the bog. The bulk of the flow for the period was base flow from storage.

Many of the 1977 storm hydrographs exhibited a double peak on the two-hour flow curves (see appendix 12). On the basis of timing and size, the first peak is thought to be the bog response and the second the stockpile response. Chemical data taken at close intervals across the peaks may verify this.

Percent runoff was high in the early summer of 1977, when storms were large and temperatures and evaporation potential were low. Storms in July and the first part of August were small, which combined with high evaporation potential to give low runoff.

<u>AMAX</u>: The data used are those described in the "Water Balance" section. Flow data for 1977 are from the flow meter installed on leach pile FL-1, and are not highly accurate. Flow data for 1978 are from the metered sump which drains all six piles. No consistent recession curve was observed, so recession curves were sketched individually for each storm. Flow from the piles drops off rapidly and base flow is small, so the volumetric error from estimating recession curves is small.

For the storms analyzed, yield has ranged from 8 to 96% of precipitation (fig. 58). Based on the more reliable 1978 data only, the range is 16 to 70%. Some smaller storms not analyzed yielded zero runoff. Percent runoff generally exceeded that from the EM-8 watershed for the overlapping time periods (fig. 47 and 58), probably due to higher losses from vegetation and standing water at EM-8, combined with less complete control of watershed outflow.

Table 20 summarizes observations of yield at Erie and AMAX, and compares them with the model results for three natural streams in the study area. The AMAX data cover a range comparable to that of the natural watersheds. EM-8 data, which are more representative of real stockpiles, cover a lower range. Comparison of summer flow patterns for the EM-8 watershed and natural watersheds during 1976 and 1977 indicated that stockpiles are less susceptible to evaporative losses than natural watersheds (see "Seasonal Runoff Patterns"). The low range of yields here is probably due to dry conditions during the short period of observation.

Figure 58

STORM RUNOFF AS A FUNCTION OF PRECIPITATION AT AMAX 1977 AND 1978

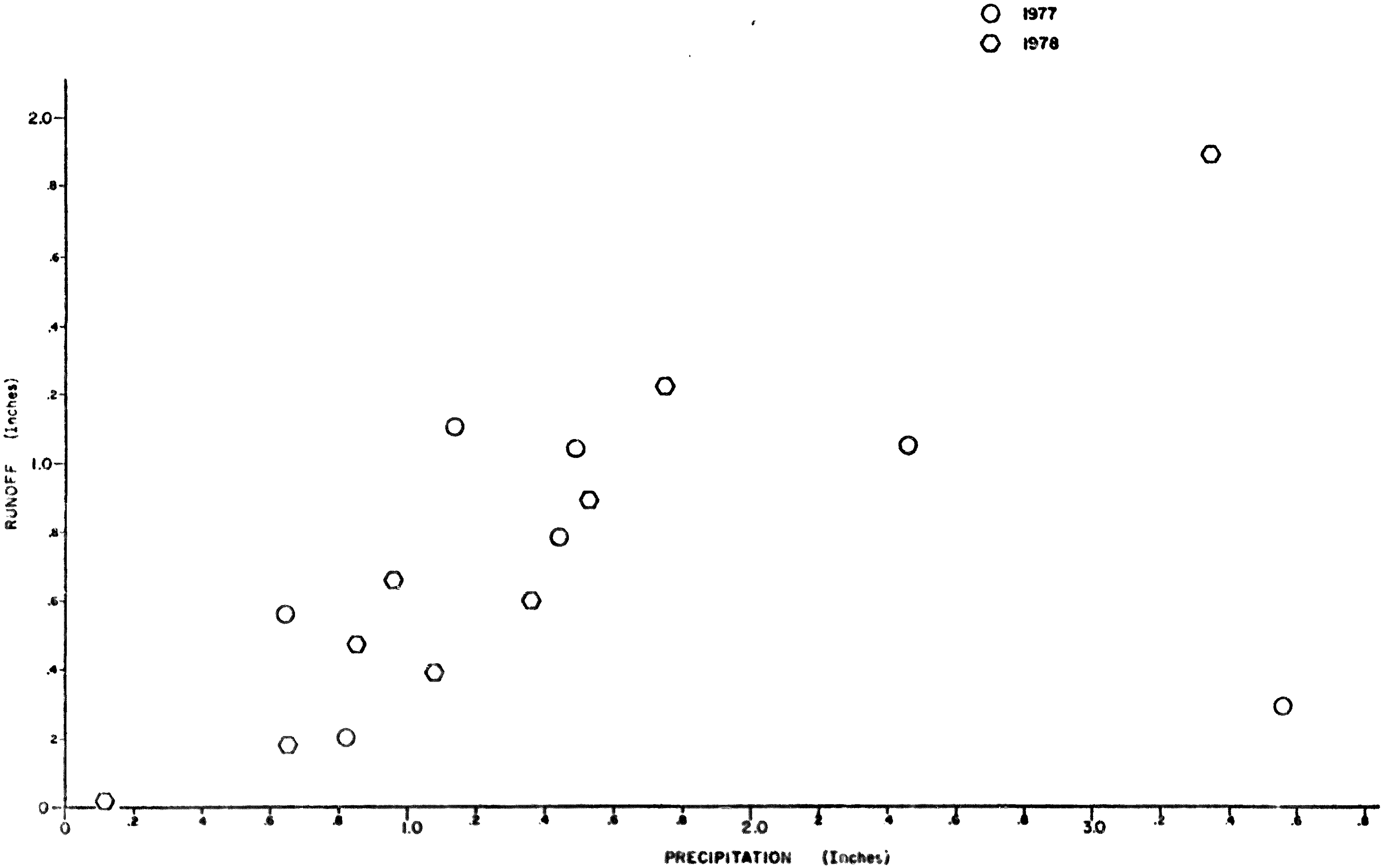


Table 20. Storm Yield as a Percent of Precipitation

	storm yield, %	
watershed	all data	best data
EM-8	0 to 66	0 to 37
AMAX	0 to 96	0 to 70
streams*	5 to 90	-----

*Sevard , Nelson and Bowers, 1979, p. 18.

Interflow from the EM-8 Watershed

Storm response of the EM-8 watershed is entirely interflow generated by lateral flow over impeding layers in the subsurface. All of the types of impeding layers discussed in the conceptual model could be present in the stockpiles in the EM-8 watershed, and may contribute to interflow. Direct surface runoff from the stockpiles is zero. Any direct surface runoff generated over the undisturbed portions of the watershed is prevented from flowing immediately to the weir because the 8011 stockpile blocks the drainageway.

Timing and shape of stockpile storm peaks: Interflow peaks from the EM-8 watershed are broad and low (fig. 22, and appendix 12). The maximum rate of flow observed from 1976 through 1978 was 5.3 cfs, in August of 1977. Most other peak flows for 1977 were between 1 and 1.5 cfs. Interflow from a single rain event generally persisted for 2½ to 4 days (table 22, and appendix 12). The gentle recession curve (appendix 7) is indicative of the high storage capacity of the watershed.

Flow at the weir began to rise almost immediately following the onset of rainfall (appendix 12). Many hydrographs from 1977 show a small peak 1 to 6 hours after the centroid of the rain event (table 21). This peak may contain runoff from the beaver pond immediately upstream of the weir, or from particularly rapid flow paths through the 8011 stockpile. The principal peak, thought to represent stockpile interflow, occurred 20 to 32 hours after the centroid of the rain event (table 21). This interval is referred to as the lag time of the basin (Gray, 1970, p. 8.6).

Table 21. Timing of rain events and flow peaks at EM-8, 1977

date	time	duration (hrs)	amount (in)	time to (hrs): 1st rise	1st peak	2nd peak	remarks
May 20	0400-0430	0.5	0.45	0	3	N	
	1130-1240	1.2	0.35	0	2	N	
May 22	0100-0340	2.7	0.30	2	5	N	
May 30	1540-1640	1.0	0.18	0	5	M	
May 31	0245-1030	7.8	0.55	0	4	M	0245-0545 0.49"
May 31-Jun 1	1450-0150	11	1.40	0	3	29	
June 5	1450-1640	1.8	0.32	0	4	20	
	1940-2130	1.9	0.16	M	M	M	
June 6	1250-2020	7.5	0.11	M	M	M	
June 8	0340-1640	13	0.22	0	3	N	0340-0500 0.16"
June 16	0115-1445	13.5	0.73	0	5	M	0115-0300 0.42"
June 17	1830-2230	4.0	0.78	0	6	M	
June 18	1720-1740	0.33	0.13	M	M	M	
June 19	1510-2210	7	0.34	0	M	M	→ 1510-1620 0.22"
June 28	0450-0530	0.67	0.72	0	2	31	daily data show 0.31" total for June 19: ambiguity in dates on cha
June 29	2240-2340	1.0	0.23	0	M	M	
July 3	0120-1110	9.8	1.24	0	3	25 →	0120-0345 1.11" 0120-0530 1.20"
July 16	0845-1020	1.6	0.33	0	3	32	
	1745-1830	0.75	0.12	M	M	M	
July 24	1730-1740	0.15	0.15	0	6	N	
Aug 20	0530-1010	4.7	0.43	0	5	17	
Aug 25	1450-1730	2.7	0.8	2	6	M	
Aug 26	1300-1310	0.15	0.13	M	M	M	
Aug 26-27	1930-2020	0.85	9.87	M	M	28	
	2020-0720	11	0.51	M	M		
Aug 27	1710-1800	0.85	1.27	M	M	M	
Aug 30	1450-2020	5.5	0.36	0	1	M	1545-1640 0.26"
Aug 31	1020-1350	3.5	0.44	0	M	N	
Sept 2	0210-0340	2.5	0.20	0	4	N	
Sept 3	1900-2400	5	0.70	2	4	24	

All of the precipitation on a given day may not be accounted for. Only described events are listed

N=no peak
M=masked by flows related to other events

Table 22. Total storm yields, interflow volumes, and peak flows at LM-8, 1977

				interflow 2								
	precip.	total yield		calc. over entire watershed			calc area area below sump			peak flow	peak flow - base flow,	time base
date of precip.	in	in	% of p	in	% of P	% of Y	in	% of P	% of Y	cfs	cfs	days
May 30-June 1	2.13	0.71	33	0.14-0.23	7-11	20-32	0.33-0.51	15-24	46-72	1.4	1.29	2.9-4.7
June 5-8	0.87	0.16	18							1.13		
June 15-20	2.29	0.51	22	0.22-0.28	10-12	43-54	0.52-0.65	23-28	102-127	1.25	1.08	
June 23	0.72(1)	0.16	23	0.084-0.10	12-14	51-61	0.20-0.24	28-33	122-146	1.15	0.85	2.9-3.9
June 28-29	1.11			0.056			0.13			0.75	0.44	2.8
July 3-7	1.82	0.51	29	0.12-0.16	7-9	24-31	0.29-0.37	16-20	57-73	1.5	1.1	2.4-3.7
July 16-17	0.50	0.058	12	0.012	2	21	0.028	6	48	0.41	0.08	2.5
August 19	0.56	0.049	8.8	0.012	2	24	0.028	5	57	0.27	0.095	3.3
August 25-27	3.98	1.46	37	0.68-0.86	17-22	47-59	1.60-2.0	40-50	110-137	5.30	5.15	3.9-5.9
August 30-Sept. 2	1.05	0.36	34	0.18	17	50	0.34	32	94	1.44	0.83	
September 4-6	0.95	0.34	35	0.086-0.12	8-11	24-33	0.2-0.29	19-28	56-81	1.35	0.70	2.2-3.2
September 9-10	0.85(1)	0.47	55	0.16-0.19	19-22	34-40	0.39-0.46	46-54	83-98	2.11	1.4	2.6-3.4
September 18-20	1.08(1)	0.27	25	0.71-0.083	7-8	26-31	0.17-0.20	15-18	61-72	1.2	0.71	2.6-3.3
September 22-26	1.73(1)	0.50	29	0.11-0.13	6-8	22-26	0.26-0.31	15-18	52-62	1.44	0.83	2.9-3.6
May 26-June 2	2.47	1.20	28.1	0.45-0.54	18-21	42-50	1.1-1.3	45-53	103-122	2.41	2.23	4.7-7.2
June 1-2	1.79			0.057-0.064	3.2-3.6		0.14-0.16	7.8-8.8		1.16	.48 4	2.2-2.9
June 7-9	1.00	0.23	23	0.053	5.3	23	0.13	13	57	.97	.39	2.5
July 2-6	1.18	0.11	9.3	0.044-0.055	3.7-4.7	40-50	0.11-0.14	9.1-12	100-127	.77	.44	3.0-4.0
July 7-11	1.77	0.22	12	0.097-0.14	5.5-7.7	44-64	0.24-0.34	14-19	109-155	.98	.59	2.7-4.6
July 12-15	0.46	0.03	6.5	0.0088	1.9	29	0.022	4.7	73	.51	0.082	2.4
July 18-22	1.01	0.58	31	0.087-0.13	10-15	34-47	0.21-0.32	21-32	83-116	1.25	.83	2.5-4.3
July 19-22	0.86			0.11-0.14	13-17		0.27-0.35	31-41		1.71	.91	2.4-3.4
July 25-26	0.33	0.03	9.1	0.012	3.6	40	0.029	8.9	97	.84	.14	1.8
August 14-20	1.74	0.33	17	0.068-0.12	3.9-7.0	28-44	0.17-0.30	9.6-17	69-109	1.31	1.02	3.6-5.9
August 18-20	0.15			0.024	16		[illegible]	39		1.11	.28	2.7
August 23-28	1.89	0.61	32	0.18-0.31	9.2-16	30-51	0.43-0.75	23-40	70-123	2.46	2.04	2.7-6.1
August 27-29	0.59	0.04	6.8	0.030	5.2	75	0.073	13	183	.99	.26	2.8
September 10-16	2.73	0.86	32	0.31-0.65	11-24	36-76	0.76-1.6	28-59	88-186	4.08	3.78	2.9-5.9
September 14-17	0.89	0.46	52	0.067-0.073	7.6-8.3	15-16	0.17-0.18	19-20	37-39	1.63	.60	2.7-3.4

(1) Precipitation based on Babbitt data
(2) Low estimate assumes interflow ends 1.5 days after peak flow. High estimate extends interflow as far as seems reasonable.
(3) Length of time from when interflow begins until interflow ends.
(4) Peak flow and peak flow minus base flow occurred at different time. The peak flow minus base flow given is the maximum difference between total flow and base flow.

Comparison of the behavior of the EM-8 watershed with that of undisturbed watersheds of similar size may illuminate the effect of stockpiles on streamflow patterns. Data from two small watersheds on the North Shore of Lake Superior were supplied by Kenneth Brooks, Dale Higgins and Ross Wolford of the Forest Resources Department, University of Minnesota. The watersheds, designated "Control" and "Old", cover 0.44 and 0.51 mi^2 respectively (Wolford, 1978, p. 1). Both are forested watersheds with moderate slopes (average of non-bog area = 7%), and each has a central bog covering 5 to 10% of the watershed (Wolford, 1978, p. 2). Soils generally consist of an organic layer 10 to 15 cm deep over massive clay, so that runoff is in the form of interflow over the clay layer (Brooks, pers. comm. 1979). Runoff peaks from these watersheds have been much higher than those from EM-8.. During 1977 the Control watershed had flows as high as 23, 26 and 110 cfs, and the Old watershed flows as high as 14, 20 and 67 cfs (Wolford, 1978, following pp. 25, B10-B13). Lag times for various storm events were approximately 2 to 7 hours (Wolford, 1978, following pp. 25, B10-B13, and data supplied by Higgins, 1979).

Comparison of these data with those from EM-8 emphasizes the slow response and low, broad peaks of the EM-8 watershed. Much of this behavior may be intrinsic to stockpiles like those at Erie. Percolation through the thick stockpile material could be expected to lead to a slow response. Numerous flow paths through the heterogeneous piles and over impeding layers probably tend to smear out the runoff peak. Another factor contributing to low peaks is that a large proportion of the runoff goes into storage. It is unknown how much of the storage in the EM-8 watershed is in the stockpiles themselves, but evidence from the seep 3 watershed and from the literature (Armstrong et al., 1971, p. 24) indicates that stockpiles can

Figure 59

MEAN DAILY FLOW AT EM - 8

1978

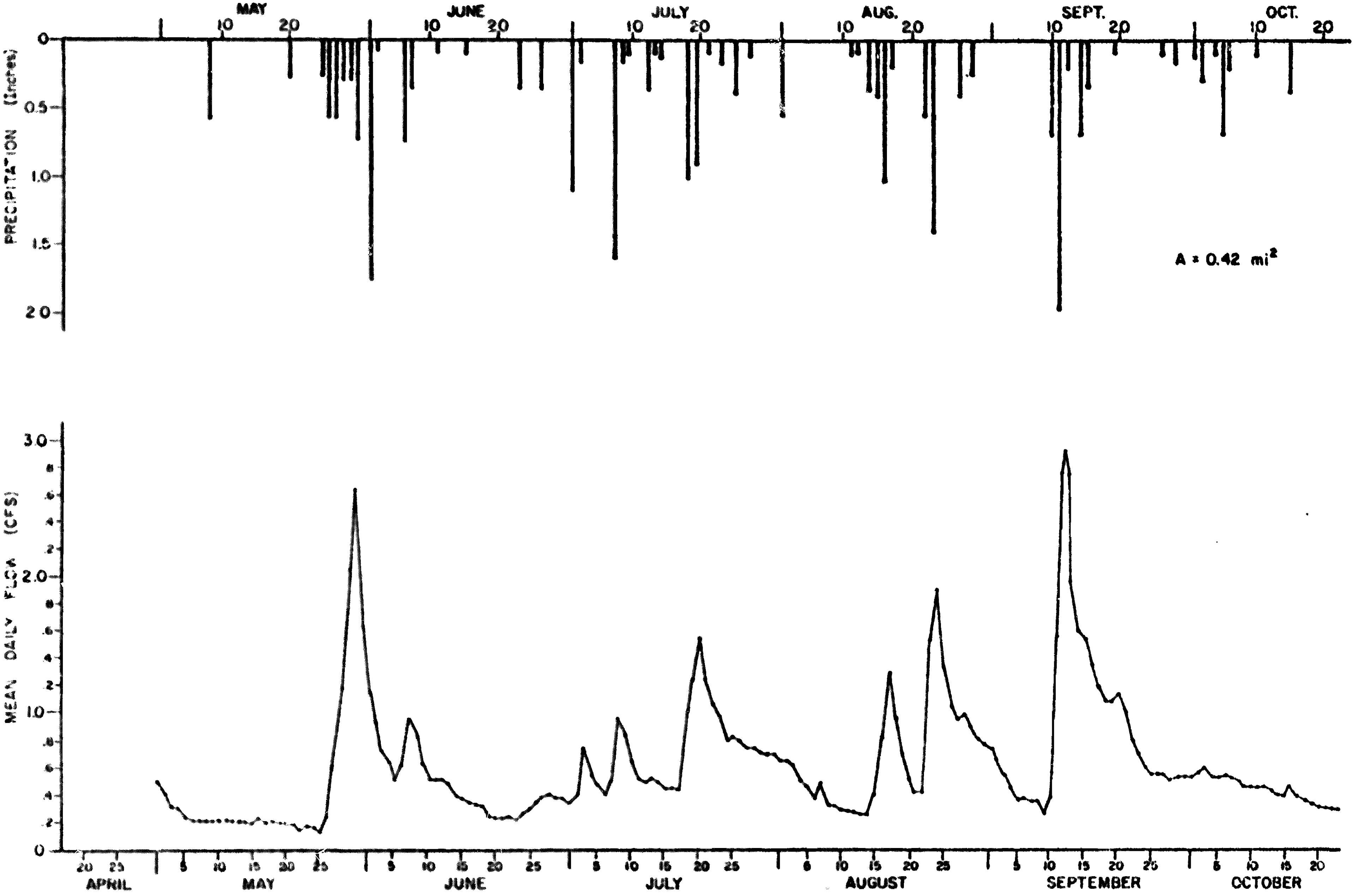
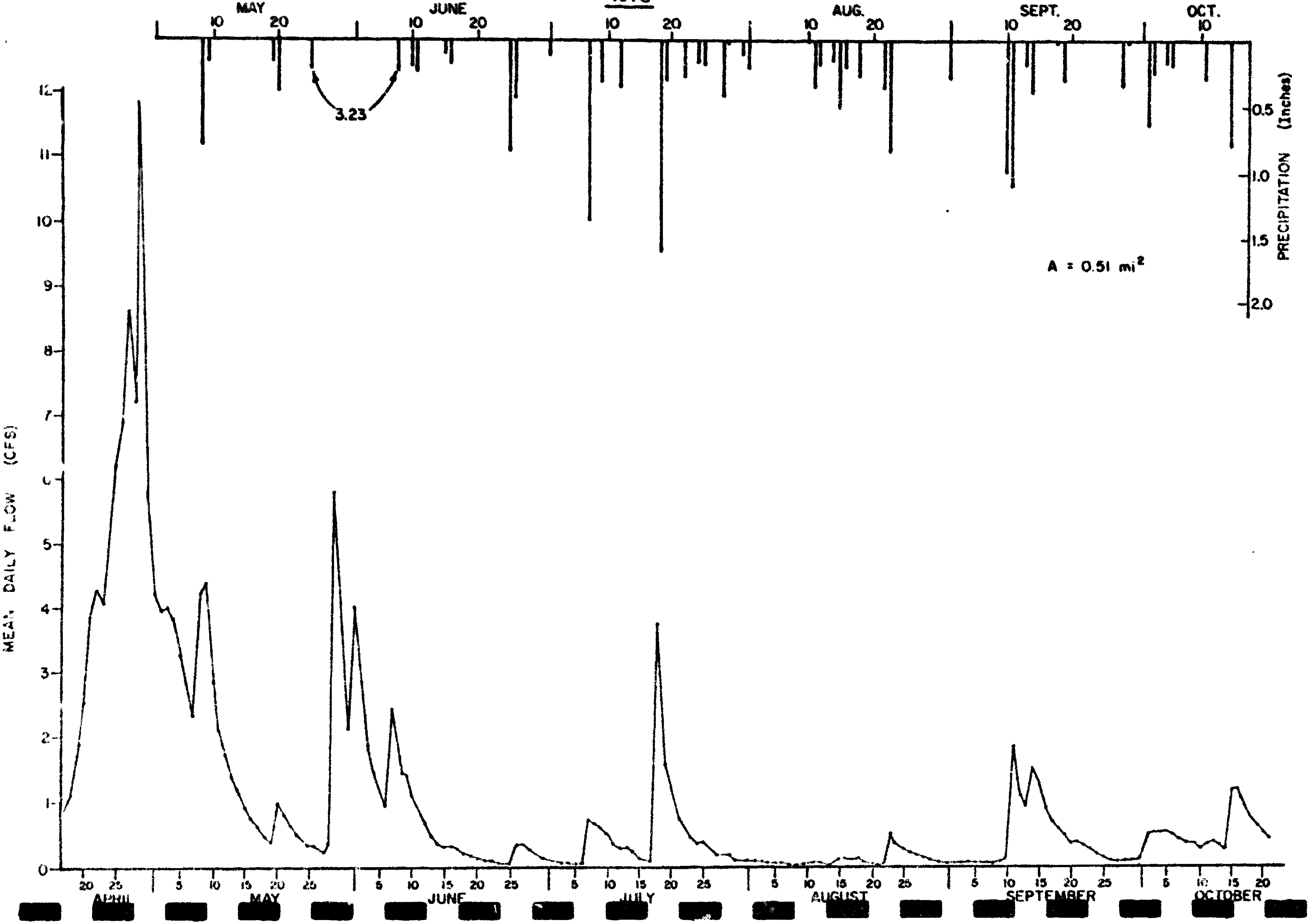


Figure 60

MEAN DAILY FLOW AT OLD LOWER WATERSHED

1978



store significant volumes of groundwater.

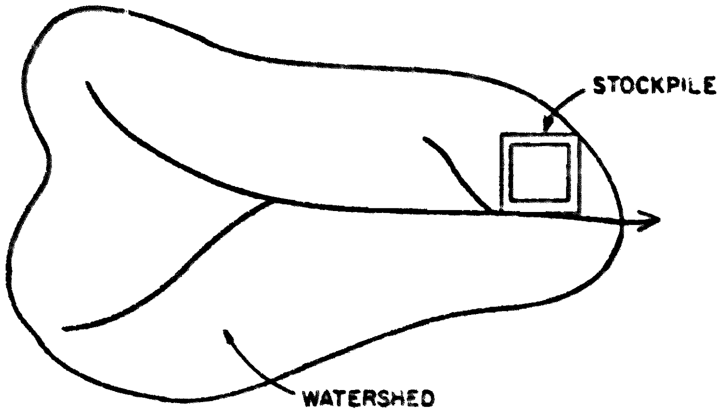
The EM-8 watershed is not entirely stockpile, and some of its peculiarities affect its storm response behavior. Storm runoff from the upper half of the watershed must seep through the 8011 pile before reaching the weir. The delay contributes to the slow response and low, broad peaks. It is unknown whether any of the runoff arriving at the sump contributes to the interflow peak at the weir, or whether all of it moves through the 8011 stockpile as baseflow. Storage in surficial materials in the undisturbed part of the watershed, combined with the damming effect of the 8011 stockpile, augments the baseflow from the stockpile itself to an unknown degree.

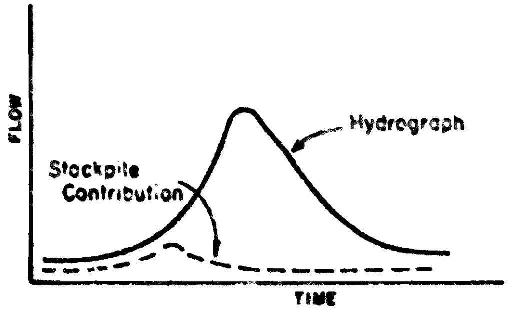
If runoff from a stockpile is allowed to flow unregulated into a receiving stream, the timing and shape of storm peaks from the stockpile relative to those from the receiving stream will have a strong effect on dilution as a function of time. The time of arrival of the stockpile peak at a given point on a stream is strongly dependent on the location of the pile within the watershed (figure 61), and in general will not coincide with the watershed peak. Even if the stockpile peak arrives at one point on the stream system at the same time as the watershed peak, for points upstream and downstream this will not be the case (figure 62). Dilution of stockpile peak flows varies as a function of the location of the stockpile relative to the point of observation. If the stockpile is immediately adjacent to the observer (figure 63, point A) or at the most distant point in the watershed (point C) dilution is minimized and impact is maximized. If the stockpile is located such that its peak passes at the same time as the watershed peak (point B) dilution is maximized and impact is minimized. Because stockpiles respond slowly compared with natural watersheds, dilutional watersheds below a certain size will always peak before the stock-

Figure 61

DILUTION OF STOCKPILE RUNOFF AT A GIVEN POINT AS A FUNCTION OF LOCATION OF STOCKPILE WITHIN THE WATERSHED

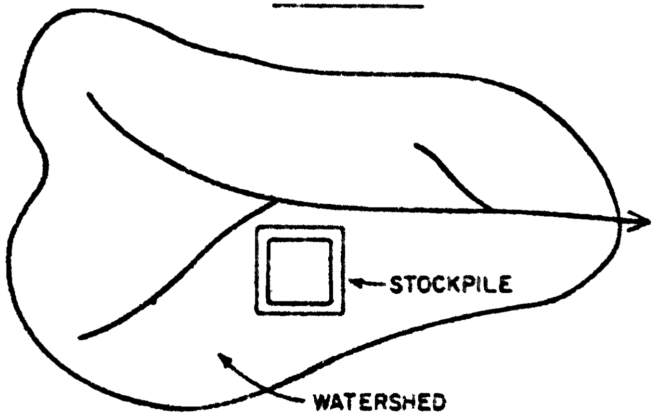
LOCATION 1

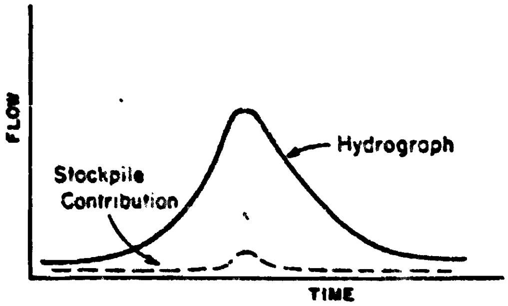




Stockpile peak occurs before main peak.

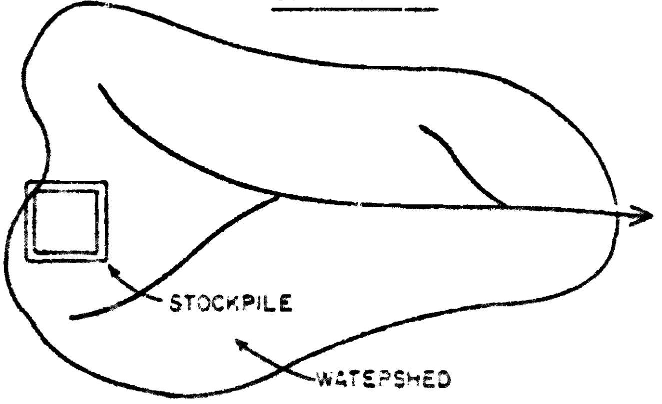
LOCATION 2

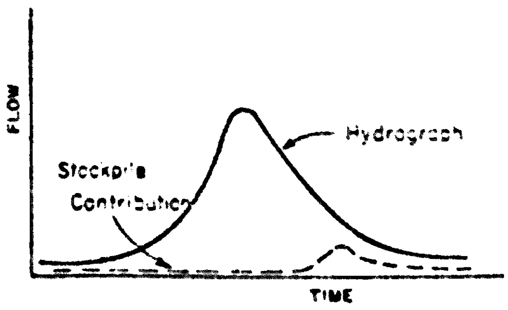




Stockpile peak occurs simultaneously with main peak.

LOCATION 3

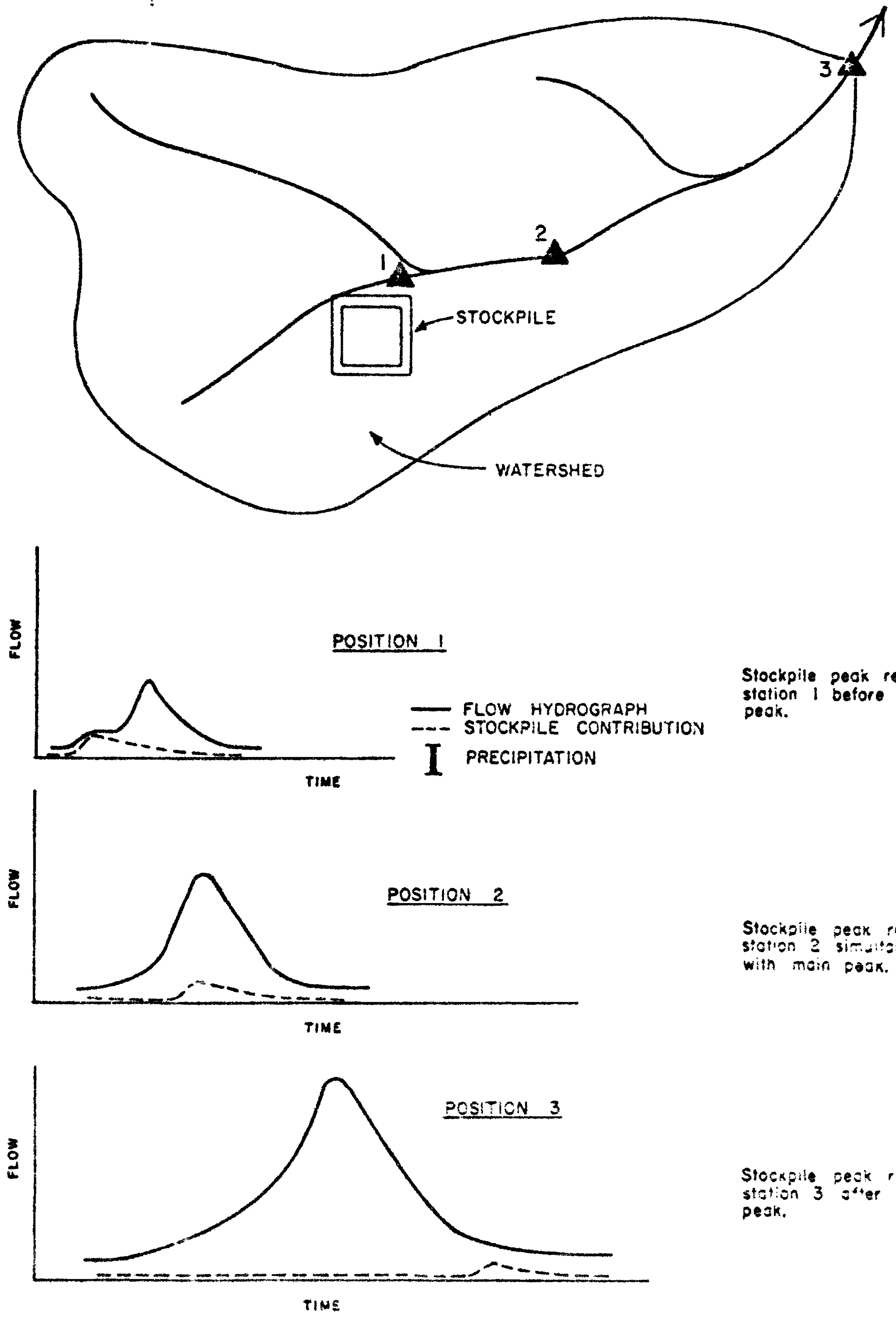




Stockpile peak occurs after main peak.

Figure 62

DILUTION OF STOCKPILE RUNOFF AS A FUNCTION OF POSITION OF OBSERVER ON THE STREAM



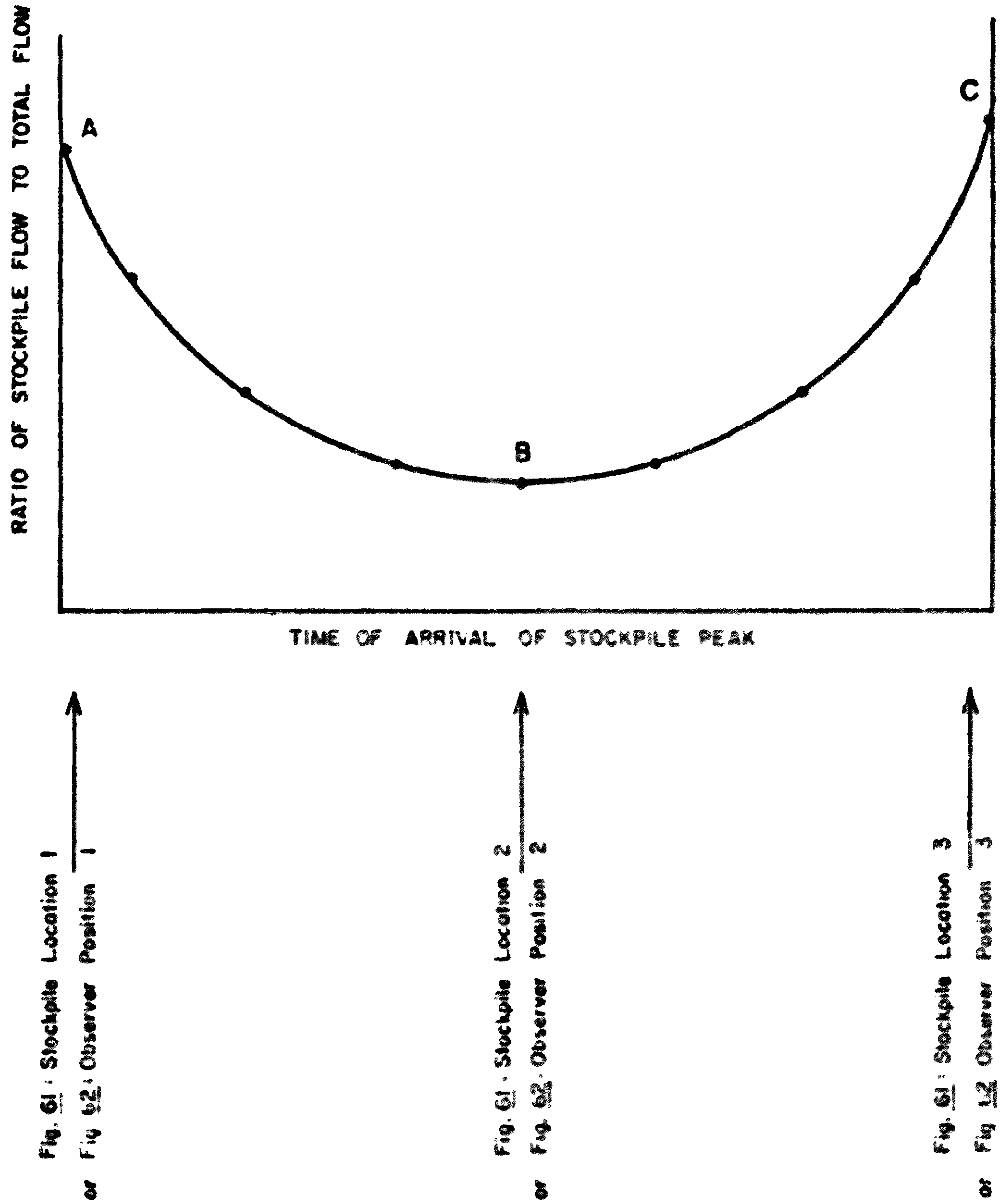
Stockpile peak reaches station 1 before main peak.

Stockpile peak reaches station 2 simultaneously with main peak.

Stockpile peak reaches station 3 after main peak.

Figure 63

DILUTION OF STOCKPILE PEAK FLOWS AS A FUNCTION OF RELATIVE TIMING OF STOCKPILE PEAK AND WATERSHED PEAK



pile, regardless of stockpile location (figure 64).

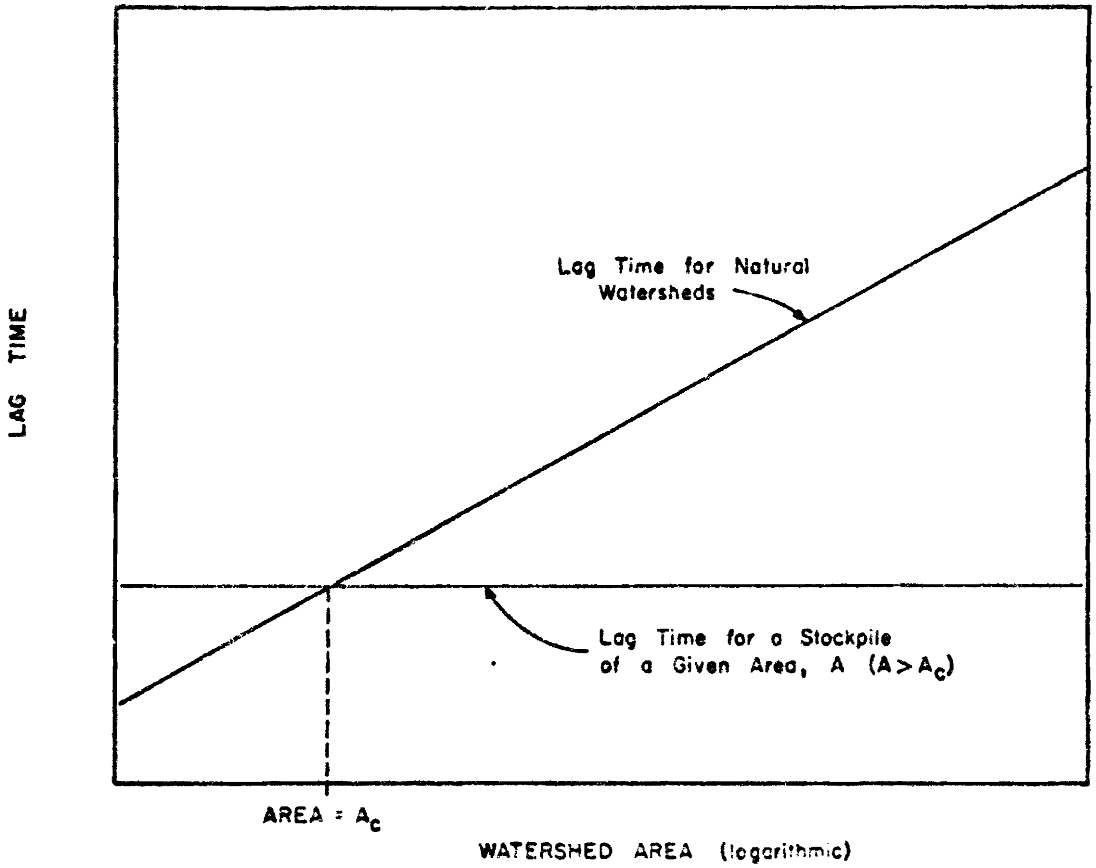
Volume of interflow: Because the different paths water may follow through a stockpile affect the quality, location, and timing of outflow, the apportionment of outflow among these paths is of interest. Interflow was separated from baseflow by a standard method normally used to separate surface runoff interflow, and channel precipitation as a group from baseflow (Viessman et al, 1972, pp. 67, 71-72). The pre-storm recession curve (A in figure 65) which represents base flow, was extended to a point directly below the hydrograph peak (B). Base flow was then assumed to increase exponentially ($Q = a * 10^{bt}$) until it comprised all of the flow (C). The time at which interflow declines to zero (C) could not be chosen unambigiously, because the hydrograph peaks tend to be broad and decline gradually. For many peaks, two estimates were made. The first chose point C to be 1½ days after the peak flow, since a number of the hydrographs had an inflection point there. The second, larger estimate was made by extending interflow as far as seemed reasonable in each case.

Interflow has comprised up to 22% of the precipitation falling on the EM-8 watershed during a given storm. For the storms analyzed, interflow has ranged from 20 to 61% of the total yield for the entire watershed.

Since water flowing to the sump from the upstream half of the EM-8 watershed is ponded against the 8011 stockpile and must seep through it, it may not contribute to interflow. Calculated on the basis of the area below the sump only, interflow has amounted to as much as 54% of precipitation. The interflow volume frequently exceeded the calculated total yield from the area below the sump, which could indicate that the area upstream of the sump contributes to interflow. It could also indicate that the area below the sump, which is almost entirely stockpile, contributes

Figure 64

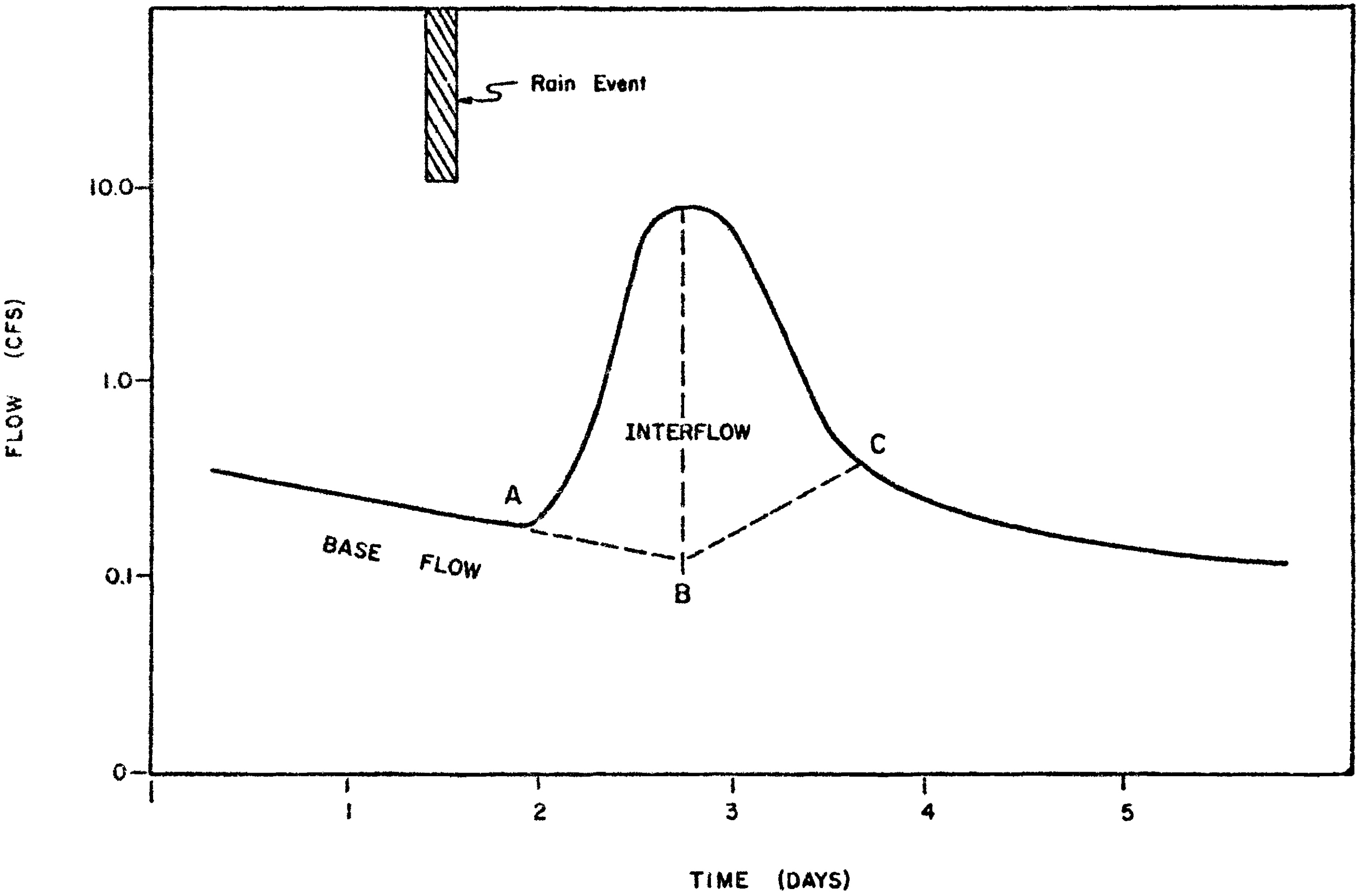
LAG TIME OF STOCKPILES COMPARED WITH LAG TIME OF NATURAL WATERSHEDS



STOCKPILE PEAK WILL ALWAYS OCCUR AFTER WATERSHED PEAK FOR WATERSHEDS OF AREA LESS THAN A_c.

Figure 65

EXAMPLE OF A HYDROGRAPH SHOWING INTERFLOW AND BASE FLOW



a higher percent yield than the upstream area. Observations made when the sump area is pumped in 1979 may resolve this question.

Base Flow of the Erie Watersheds

During the dry summer of 1976 storm runoff was negligible, and the watersheds at Erie yielded almost entirely base flow from storage. Flow at EM-8 receded gradually from 0.26 cfs in early July to 0.12 cfs in September, then declined to as low as 0.05 in late October and early November. Flow at seep 3 receded from 0.15 to 0.03 cfs over the summer, while seep 1 flows went from 0.06 to 0.04 cfs. Frequent storms kept flows high during much of the summer of 1977. Flow at EM-8 receded to 0.18 cfs during a relatively dry period in August. Flows at seep 3 and seep 1 at that time were 0.16 and 0.016 cfs respectively. During 1978 base flows of the EM-8 watershed between storms were typically around 0.3 cfs. Flow is zero at all three seeps during the winter. This is thought to be due not to lack of supply, but to freezing conditions along the margins of the stockpiles. The effect is to conserve water which later helps sustain summer base flows.

When interflow volumes were subtracted from total storm yields of the EM-8 watershed for 1977, base flow was found to range from 39 to 80 percent of storm yield. Most or all of the precipitation falling on the watershed upstream of the 8011 stockpile may be forced to seep through the 8011 pile as base flow, accounting in part for the fact that such a high proportion of storm yield goes into base flow. However, base flow in cfs/mi^2 from seep 3 has been as high as or higher than that from EM-8, demonstrating that the stockpiles themselves have significant storage.

An attempt was made to separate base flow derived from direct infiltration of rainfall into the 8011 pile from that flowing through the 8011 pile from upstream areas. The following method was used:

1. The total yield from a given storm was calculated and expressed as inches of rainfall over the entire EM-8 watershed (Y).
2. The volume of interflow was calculated and expressed as inches of rainfall over the area downstream of the sump (I).
3. The volume of water which infiltrated into the 8011 pile and emerged as base flow was calculated, in inches, as Y-I.

Step 1 assumes that yield is uniform over the entire watershed, whereas in reality stockpiles probably yield more than the undisturbed area. Step 2 assumes that all runoff from areas upstream of the sump seeps through the 8011 stockpile as base flow. These assumptions proved to be seriously limiting: the difference, Y-I, was frequently negative and the non-negative results are thought not to be valid estimates of the volume of direct infiltration.

Comparison of the base flow behavior of the EM-8 and seep 3 watersheds with that of undisturbed watersheds of similar size demonstrates the relatively high storage capacity of the stockpiles. The recession curve of the EM-8 watershed (appendix 7) is much more gradual than those of two small watersheds studied by Wolford (1978) and Higgins (written comm., 1979) (appendix 8), indicating a greater storage capacity. Base flows of these two watersheds were between 0.1 and 0.01 cfs in early summer of 1978 and fall of 1978, and were between 0.01 and 0.001 cfs in mid summer (Higgins, pers. comm., 1979). These flows are at least an order of magnitude lower than those at EM-8 for comparable periods. Normalized on the basis of watershed area, they are also more than an order of magnitude lower than seep 3 base flows.

Base flows (cfs/mi^2) at EM-8 and seep 3 during the dry period from July through November of 1976 were much better sustained than flows of three large natural watersheds in the region (figs. 8, 9, 10, 23 and 27) showing that the stockpile watersheds have unusually high storage capacities.

Groundwater storage within the stockpiles has been assumed to occur primarily in a saturated zone at the base of the piles. Some storage may occur in perched saturated zones at intermediate heights, but it seems likely that the bulk of the water is at the base of the pile. The EM-8 watershed also stores water in the sump and surficial material upstream of the 8011 stockpile. Probably due to throughflow from this area and perching within the pile, the transition between interflow and base flow is gradational, leading to a uniform recession curve with no obvious inflection point when interflow ends.

Simplified models of groundwater flow within the 8011 stockpile were developed to allow such parameters as permeability, saturated volume, flow velocity and residence time to be calculated. Two one dimensional steady state analytical models were used to model the flow. Both assume the stockpile is underlain by an impermeable base ("see Conceptual Model of Stockpile Hydrology"). It is further assumed that all flow is parallel to a line joining the center of the sump with EM-9.

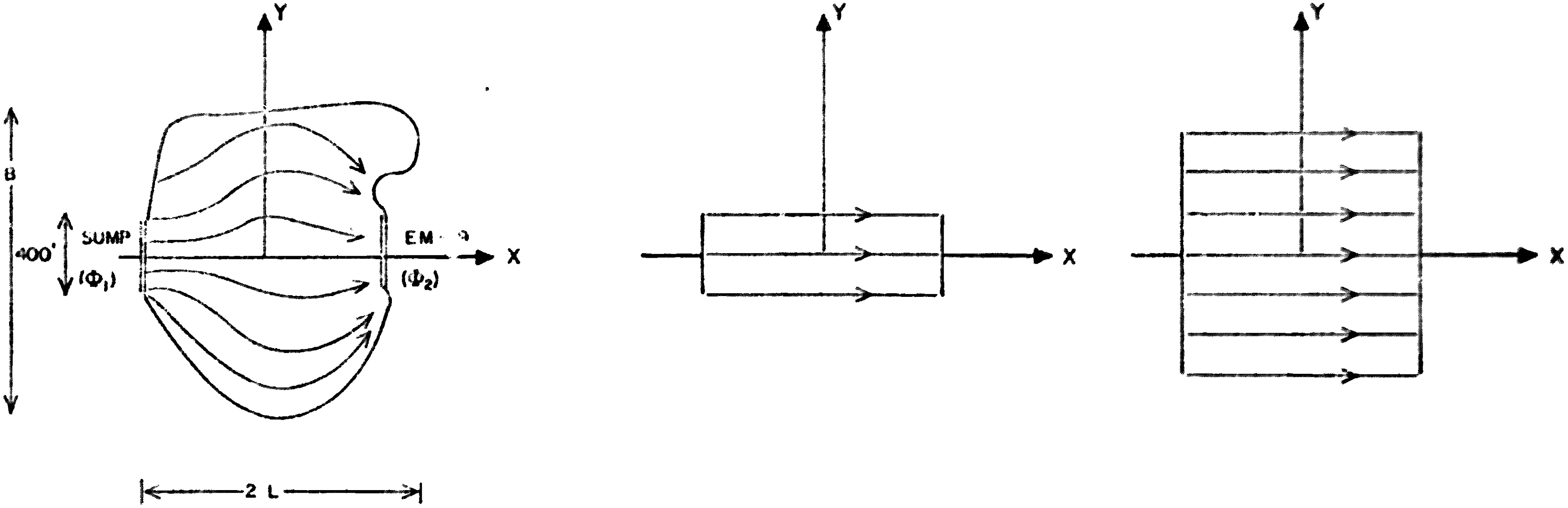
In reality the sump area and the bog near EM-9 are about 400 feet wide, whereas the broad, flat area under the stockpile is about 1200 feet wide. The model approximates the situation shown in figure 66 a by that in b or c. Model 1 (figure 67) assumes one-dimensional flow over a horizontal base. Plate 1 shows that the slope of the base of the stockpile is very gentle (less than 1%), so this assumption is justified. Model 2 assumes plug flow of constant depth over a sloping base (figure 68). Details of the models are given in appendix 13. Table 23 summarizes the input information used in the model.

The two models produced similar results (table 24). Permeability is in the range of 0.1 to 1.0 cm/sec. Such values are toward the upper end of those generally observed for clean sands and mixtures of clean sands and gravels (Todd, 1959, p. 53). Estimates of velocity and travel time vary considerably because the width and depth of flow and the porosity are not known very precisely. It is likely that the width of flow is closer to 1200 than to 400 feet. Eliminating extreme values on this basis, average velocity estimates range from 7 to 70 feet per day, giving travel times of 170 to 17 days. These figures are for travel time from the sump to the seep. Direct infiltration of rainfall on the stockpile into the saturated zone will have two effects on residence time. First, it increases the water table slope slightly so that the velocity of flow is faster. For the 8011 stockpile, calculations indicate this effect will be minor. Second, direct infiltration is distributed over the entire saturated zone, some near the outlet and some near the inlet.

Figure 66

SCHEMATICS OF ACTUAL GROUNDWATER FLOW AT EM-9

AND MODEL FLOW PATTERNS

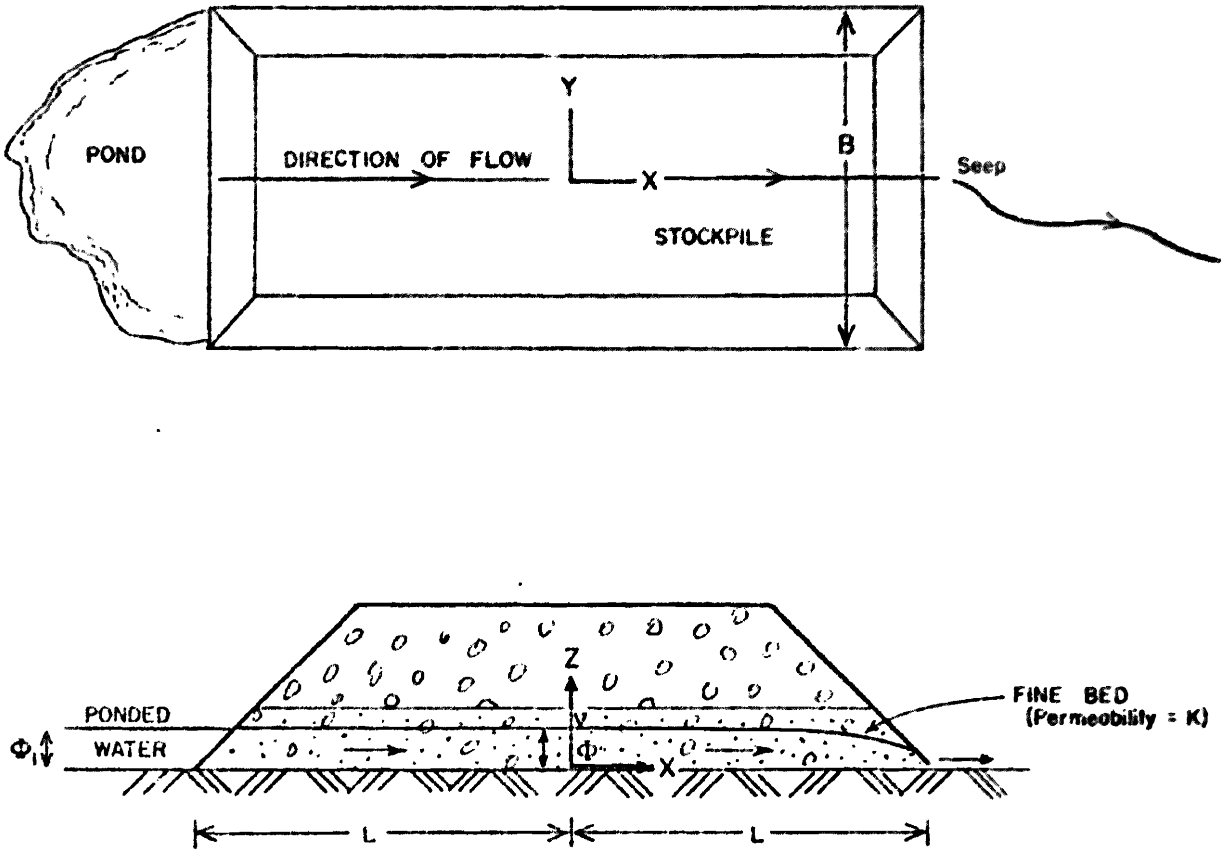


(a) ACTUAL FLOW PATTERN

(b) (c) MODEL FLOW PATTERNS

Figure 67

PLAN AND CROSS-SECTIONAL VIEWS OF MODEL I STOCKPILE



(Vertically exaggerated & distorted)

Figure 68

PLAN AND CROSS-SECTIONAL THROUGHFLOW VIEWS OF MODEL 2 STOCKPILE

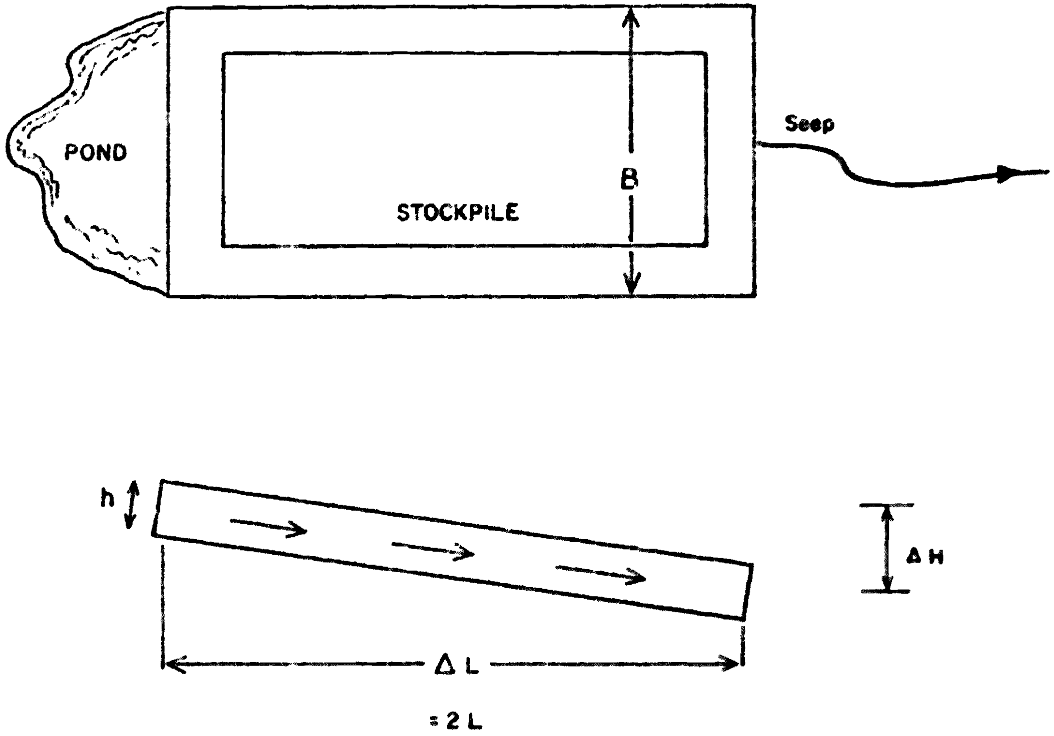


Table 25. Input values of variables for models of groundwater flow through the 8011 stockpile

$2L (= \Delta L)$:	The distance from the sump to the seep as measured on Erie Mining Co's "Map of Mining Area 8" is 1200 feet.
B:	The effective width of flow, as measured on the same map, is between 400 and 1200 feet.
Q_{vol}:	Steady state discharge was approximated as 0.12 cfs, based on flow readings in late summer of 1976.
H:	The elevation at the sump is 1493 feet, and that at the seep is between 1488 and 1485 feet. The difference in elevation, H, is 5 to 8 feet.
ϕ_2:	ϕ_2, the thickness of the saturated zone at EM-9, was assumed to be zero.
ϕ_1:	ϕ_1 is the thickness of the saturated zone at the sump side of the stockpile. It is roughly equal to the depth of ponded water in the sump plus the depth of compression of the peat below the stockpile. A range of values from 4 to 12 feet was used.
h:	h is the average depth of flow, and was taken to be between 2 and 8 feet.
n:	Porosity, n was assigned a value of 0.1 or 0.3.

Table 24 Results of Groundwater Models of the 8011 Stockpile

EM-9 Model 1: Horizontal Flow: Permeability, Velocity, Travel Time

B feet	Ø feet	k cm/sec	k ft/day	n = 0.3		n = 0.1	
				V_{ave} ft/day	t days	V_{ave} ft/day	t days
1100	4	.5	1420	23.5	51	70.5	17
1200	4	.46	1300	21.8	55	65.4	18
1200	5	.29	820	17.1	70	51.3	23
1200	8	.11	310	10.4	115	31.2	38
1200	12	.05	140	7.23	166	21.7	55
400	5	.88	2490	52.2	23	157	8

EM-9 Model 2: Plug Flow: Permeability, Velocity, Travel Time

B feet	h feet	ΔH/ΔL	k cm/sec	k ft/day	n = 0.3		n = 0.1	
					V_{ave} ft/day	t days	V_{ave} ft/day	t days
1200	4	5/1200	.18	520	7.2	167	21.6	56
1200	4	8/1200	.11	320	7.2	167	21.6	56
400	4	5/1200	.55	1560	21.6	56	64.8	19
400	4	8/1200	.34	970	21.6	56	64.8	19
1200	2	5/1200	.37	1040	14.4	83	43.2	28
1200	2	8/1200	.23	650	14.4	83	43.2	28
400	2	5/1200	1.1	3110	43.2	28	130	9
400	2	8/1200	.69	1940	43.2	28	130	9
1200	8	8/1200	.06	160	3.6	333	10.8	111

The average residence time for this water is thus about half that of the water coming from the sump. The corrected residence time is thus approximated by

$$t_{corr} \sim V_1 + \tfrac{1}{2} t_r V_2$$

where V_1 is the volume of water from the sump and V_2 the volume from direct infiltration. The relative amounts of these are unknown, but in late 1976 the latter contribution is assumed to have been zero.

Saturated volume is given by

$$V = \frac{2}{3} B\phi_1 (2L)$$

Since $4 \leq \phi_1 \leq 12$, $400 \leq B \leq 1200$ and $2L = 1200$,

$$1.23 \times 10^6 \leq V \leq 1.5 \times 10^7 \text{ ft}^3$$

A reasonable single estimate, assuming $\phi = 5$ and $B = 1200$, is 4.8×10^6 ft^3.

A steady state model of throughflow at seep 1 was developed, but recent field work has shown that throughflow from the marsh southwest of the pile cannot occur. The model is presented in appendix 14 because it was used as input in leaching computations. A steady state model of groundwater mounding in the absence of throughflow was also developed (appendix 15).

Permeabilities calculated from the models of groundwater flow through the 8011 pile are lower than would be expected for the coarse stockpile material, and so it is hypothesized that a layer of the fine grained material has developed at the base of the pile, serving to sustain saturated flow conditions. Few data are available on the movement of fine particles through a coarse matrix. Sheffer and Evans (1968, p. 12) observed that solutions percolating through leach dumps tend to transport the finer particles to the voids between larger particles contributing to settlement of the dumps. The verticle distance such particles move is unknown. At Erie, silt, sand and fine gravel sized gabbro has been found on the snow between large boulders at the base of the pile, demonstrating that some fine material does work its way to the bottom. Silt and sand sized material moving out of the piles at Minnamax has clogged the flow meters on the discharge lines. Layers within the stockpiles, such as the tops of intermediate lifts at Erie, may arrest the downward movement of the fine fraction, limiting the total amount that can reach the bottom.

Properties of the fine grained layer were estimated for use in analyzing the leaching behavior of the saturated zone. The estimates presented in table 25 are developed in appendix 16.

The occurrence of a saturated zone at the base of a stockpile is dependent on the permeability of the material below the pile, as discussed in the conceputal model. For a mound to form in the absence of throughflow, the rate of infiltration of water to the base of the pile must exceed the rate at which the material below the pile can carry it away. Assuming vertical seepage under a hydraulic gradient of unity, the latter rate is given by the hydraulic conductivity. The assumption that half of the rainfall in an average year is lost to evaporation, and that, as an upper limit, the remaining rainfall infiltrates to the base of the pile (interflow = 0) gives an average annual rate of supply of 14.3 inches/year, or 3.3×10^{-3} feet/day.

Table 25. Estimated properties of hypothesized fine grained layer at the base of the Erie stockpiles.

Thickness (meters)	0.3 to 5
porosity (%)	6 to 12
internal surface area (m^2rock/MT)	530 to 12,000
surface area loading (m^2rock/m^3 water)	4400 to 200,000

Comparison of this value with hydraulic conductivities of surficial materials in the Copper-Nickel Study Area (table 26) shows that groundwater mounds are only expected to form in stockpiles sited on bedrock, peat, or some Des Moines lobe till. These materials cover about 30% of the study area (Siegel and Ericson, 1979). Groundwater mounds are not expected to form in stockpiles on outwash, Rainy Lobe till, or alluvium, which cover the other 70% of the area. In these areas, water reaching the base of a stockpile will seep into the material below the pile, eventually reaching the local groundwater system.

Table 26. Estimated hydrualic conductivities of surficial materials in the Copper-Nickel Study Area.

MATERIAL	HYDRAULIC CONDUCTIVITY* (ft/day)	EXPECTED TO SUPPORT GROUNDWATER MOUND IN STOCKPILE**
Peat	10^{-3} to 10^{-1}	Y***
Alluvium	10^{1} to $10^{3.5}$	N
Des Moines lobe till	10^{-2} to 10^{-5}	N,Y
Glaciofluvial deposits	10^{1} to $10^{3.5}$	N
Rainy lobe till	10^{-2} to $10^{1.5}$	N
Bedrock	not estimated	Y

* from Siegel and Ericson, 1979, p. 37.

** Y = yes, N = no.

*** Assumes that peat compacted by the weight of a stockpile will be essentially impermeable.

CONCLUSIONS

Summary

The hydrology of waste piles of sulfide bearing gabbro was studied over three field seasons in connection with studies of leachate chemistry. The full scale stockpiles at Erie Mining Company's Dunka Mine are 40 to 120 feet high, and cover areas of ½ to 7 acres. Individual rock fragments range in diameter from a few microns to four feet, with an average diameter of one to two feet. The leaching test piles at the Minnamax site are 13 feet high and cover 3,000 feet^2 (0.07 ac) each. The piles are finer grained than those at Erie, the maximum diameter being two feet. The grain size of the Erie piles is typical of open pit mined material, while the Minnamax piles are more representative of underground mined material.

The study area has a continental climate with cold, dry winters and warm, wet summers. Average annual precipitation is 28.57" (at Babbitt), and annual pan evaporation is 28.5" (Hoyt Lakes) (Watson, 1978). "Snowmelt is the major source of runoff... From the spring peak flows, streamflow recedes steadily through the summer, reacting only temporarily to heavy rainfall" (Garn, 1975, p. 18). Flow sometimes increases in October and November due to decreased evapotranspiration. The annual minimum is usually in February or March (Garn, 1975, p. 18). Average annual runoff is estimated to be 10.72" (~ 38% of precipitation)(Siegel and Ericson, 1979).

A conceptual model of stockpile hydrology was developed on the basis of field observations, literature and basic hydrologic concepts. The model describes sources of water input, flow paths within the stockpile and locations of output. Sources of water input are precipitation on the pile and runoff from the surface of groundwater catchments draining to the stockpile site. Much of the precipitation falling on the pile is retained in surface depressions or the near-surface portion of the pile and eventually evaporates. Some precipitation may run off over the stockpile surface, although the back-sloped edges, high infiltrability, and depression storage of the full scale stockpiles studied combined to prevent this. Water infiltrating into a stockpile will move through it along complex pathways since dumping, bulldozing and compaction create discontinuous layers of coarse and fine or loose and dense material (Sheffer and Evans, 1968, p. 9; Howard, 1968, pp. 72-73). Water will percolate down to an impeding layer, flow laterally to the edge, then resume vertical percolation to the next impeding layer (Armstrong, 1971, p. 21). Interflow reaches the margin of the pile at its base within a few days or less, and is discharged as a storm peak. Some water may be stored in saturated zones within the pile, helping to sustain seepage from the margins of the pile during dry periods. If the pile is sited on permeable material, some water will also move out of the pile vertically, eventually reaching the local groundwater system.

During the study period, the yield of stockpile watersheds at Erie exceeded that of natural watersheds in the region. Runoff of the EM-8 watershed during the 1977 water year was 7.8 inches, or 23% of precipitation, while runoff from nine gaged streams averaged 6.0 inches, or about 18% of precipitation. The seep 3 watershed yielded 9.9 inches, or 44% of precipitation, for the period from August 1, 1976 to July 31, 1977, compared with 3.4 inches, or 15%, for natural watersheds. The difference in yield between the EM-8 and seep 3 watersheds is thought to be due to higher evaporative losses from marshes and a pond in the EM-8 watershed, and possibly some ungaged underflow.

Two factors appear to be responsible for the fact that stockpile watersheds yielded more runoff than natural watersheds. First, the stockpile watersheds yielded more runoff per unit area than the natural watersheds during the summer, indicating less susceptibility to evaporative losses. The stockpiles are unvegetated, which eliminates transpiration losses, and due to their coarse texture they have a limited capacity to retain water in the near surface active evaporation zone. Second, the stockpiles had higher flows per unit area than natural watersheds during the fall of 1976, suggesting that they are better able to sustain flow from storage during dry periods. Runoff from the Erie watersheds during an average year is expected to exceed that of natural watersheds in the region, and will probably be 40 to 50% or more of precipitation. The Erie watersheds are only 52% covered by stockpiles, and runoff from watersheds entirely covered by stockpiles may be even higher.

Data from EM-8 provide the most complete information on the seasonal runoff patterns of stockpiles. Flow was zero during the winter months, probably due to formation of ice dams along the margin of the 8011 stockpile. At all other times, flow was sustained continuously by storm events or discharge from storage. Spring runoff was small in the one year of record (1977), reflecting the low snowfall and depleted soil moisture. Summer and fall discharge varied with the number and size of rainstorms: storm peaks were numerous and overall flow high in the rainy summers of 1977 and 1978, but in 1976, when rainfall was negligible, flows receeded steadily from July through the winter. Rainfall patterns during the study period were unusual, so the observed seasonal flow patterns may not be typical.

Patterns of runoff from the EM-8 watershed were similar to those of natural watersheds in the study area, which suggests that runoff patterns during more typical periods may also be similar. Flows of natural watersheds were unusually low during the winter of 1976-1977. Spring flows were very much below normal in 1977. Analogy suggests that spring flows from stockpiles may be substantial in normal years. Summer and fall flows of the natural watersheds, like those at EM-8, were strongly dependent on rainfall.

In some significant respects the seasonal behavior of the EM-8 watershed differed from that of the natural watersheds. Flows were better sustained from July through November 1976 at both EM-8 and Seep 3, which suggests that stockpiles are better able to sustain flow from storage during dry periods. Flows did not increase as soon or as much in spring, probably due to persistence of cold temperatures in the pile. This appears to allow more of the spring melt to go into groundwater storage, helping to maintain base flows later. Summer runoff was higher than for natural watersheds, indicating less susceptibility to evaporative losses.

Neither the Erie piles nor the AMAX piles yielded any surface runoff. The tops of the Erie piles, which are surfaced with sandy till, have a moderately well developed system of shallow channels (6 to 12" wide and 1 or 2" deep) which lead surface flow to scattered depressions on the top of the pile. This system of channels and depressions keep most of the rainfall on the stockpile surface long enough to infiltrate or evaporate. Most of the perimeter of the pile slopes back toward the center, keeping water from running off the sides. Where water does reach the edge, it infiltrates immediately into the coarse rubble on the side slopes.

The storm response of all the stockpiles studied is entirely interflow. Continuous flow records for the EM-8 watershed show broad, low hydrograph peaks. The maximum flow observed from 1976 through 1978 was 5.3 cfs, and typical peak flows were in the range of 1 to 1.5 cfs. By comparison, two undisturbed watersheds of similar size on the North Shore of Lake Superior had flows of 23, 26, 110, 14, 20 and 67 cfs during 1977 (Wolford, 1978). The main peak of EM-8 hydrographs occurred 20 to 32 hours after the centroid of the rain event, compared with 2 to 7 hours for the undisturbed watersheds. Such broad, low responses may be intrinsic to stockpiles. Percolation through the stockpiles material helps delay the arrival of runoff, and the numerous flow paths through the heterogeneous mass probably tends to smear out the runoff peak. Interflow has accounted for only 20 to 61% of the total yield from individual storms. The rest of the runoff goes into storage, reducing peak flows and helping sustain high base flows between storms.

The stockpiles at Erie have a higher storage capacity than natural watersheds in and near the study area. The recession curve for the EM-8 watershed is much more gradual than those of Wolford's (1978) watersheds on the North Shore. Base flows at EM-8 and Seep 3 were at least an order of magnitude higher than those of the North Shore watersheds during comparable periods. Base flows of the EM-8 and Seep 3 watersheds during the extremely dry period from July through November of 1976 were better sustained than flows of three larger natural watersheds in the study area.

Storage in the stockpiles is thought to occur primarily within a saturated zone at the base of the piles. The EM-8 watershed also stores water in the sump and surficial material upstream of the 8011 stockpile. Simplified models of groundwater flow through the 8011 stockpile yielded an estimated permeability of 0.1 to 1.0 cm./sec. Flow velocity was calculated to be 7 to 70 ft/day, giving a travel time of 170 to 17 days. Formation of groundwater mounds within stockpiles depends on the presence of low permeability material underlying the piles.

Recommendations for Further Study

The following are thought to be useful areas for further study:

1. Check for seepage from other stockpiles on the Iron Range. For those with no surface seepage, a few could be checked for evidence of seepage to groundwater.
2. Pump the sump upstream of the 8011 stockpile to isolate the effects of the stockpile from those of the upstream watershed.
3. Establish continuous flow records at seep 3 to provide a second, well defined stockpile watershed.
4. Drill holes into one of the Erie stockpiles to check for internal layering, perched water table conditions, lateral flow over impeding beds, dry zones and the thickness of the saturated zone at the base of the pile.
5. Perform travel time studies from the sump upstream of the 8011 pile to the seep at EM-9.
6. Establish vegetation on a hydrologically well characterized stockpile and determine the effects on runoff behavior.
7. Collect better temperature data from EM-9 and seep 3.
8. Make further comparisons of the EM-8 and seep 3 watersheds with small natural watersheds in the study area.

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