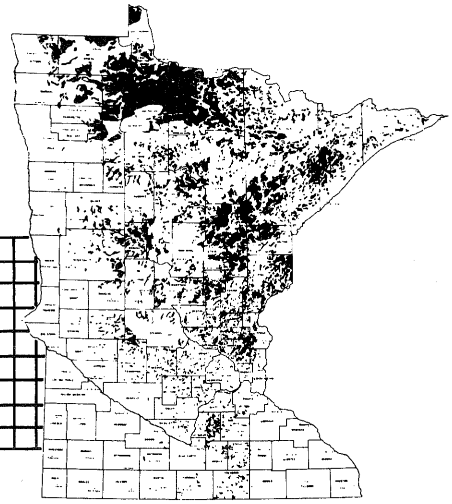
MINNESOTA PEAT PROGRAM

The Water Resources of Peatlands: Final Report

1982



esota Department
of Natural Resources

THE WATER RESOURCES OF PEATLANDS

FINAL REPORT

by

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Peatland Characteristics

- Runoff from fen peatlands was higher in temperature, pH, specific conductivity, alkalinity, calcium, magnesium, total phosphorus and nitrate-nitrogen but lower in acidity, color, aluminum, humic acid, fulvic acid and COD than runoff from bog peatlands.

- All water quality characteristics of peatland runoff, except acidity, varied considerably among sampling periods. Numerous samples and a careful sampling design are needed to characterize the water quality of peatlands.

- Water quality was linked to physical and biological characteristics of peatlands. Bog watersheds exhibited more fibric peat of a lower pH and ash content than fen watersheds. Vegetative characteristics were different between bogs and fens; fens contain more shrub species and a greater diversity of vegetation than bogs.

Mining Effects

- Runoff from a mined bog (milled peat method) was higher in temperature, specific conductivity, acidity, suspended sediment, arsenic, total Kjeldahl nitrogen, ammonia nitrogen and organic nitrogen than natural, undisturbed bogs. Drinking water standards were not violated, but additional nutrient loading to downstream lakes could influence the eutrophication process.

- Increased suspended sediment in runoff due to mining which results from wind-blown peat and runoff can influence light penetration and can carry additional nutrients to downstream receiving water.

- Intensive sampling is required to assess the impacts of peatland disturbance on most water quality constituents.

- The water quality characteristics of ponds, which were constructed to simulate a dredging operation, depended on whether they had been dredged to mineral soil. The pond with mineral soil contact exhibited higher pH, specific conductivity, alkalinity, Ca, Mg, and Na than the peat bottom pond. The peat pond had a higher color, acidity and K concentrations.

WATER QUANTITY RESULTS

Mining Effects

- For the same rainfall events, a mined bog exhibited a higher stormflow volume that occurred over a shorter period of time than the unmined bog. The magnitude of the peaks were similar for mined and unmined bogs. Greater volumes of runoff due to mining could affect downstream flooding depending on the size of the area affected.

- Monthly water budgets indicated that mined bogs showed a higher percentage of annual runoff during the snowmelt and early summer period than did the unmined bog. More detailed soil frost - snowmelt runoff experiments are continuing to better understand these processes.

- Adequate stormflow models, based on unit hydrographs could not be developed. A more process-oriented model is being developed to better address water yield and stormflow responses of peatlands.

Peatland Characteristics

- The snowmelt runoff and late spring rainfall largely determine the seasonal runoff from peatlands.

- Stormflow volumes are typically a low percentage of total rainfall for most peatlands. Ground water flow or baseflow dominates the hydrograph characteristics.

INTRODUCTION

Proposed utilization of portions of Minnesota's three million hectares of peatlands for horticultural and energy uses have prompted the Minnesota Department of Natural Resources to investigate the potential effects of peat development on water resources. The College of Forestry began a field study of the water resources of peatlands in 1977 because the potential water resources impacts were largely unknown. The study as originally designed had several water quality and water quantity objectives:

Water Quality Objectives:

1. To predict the impacts of large peatland developments on the quality of water resources.
2. To determine the important water quality parameters that may be affected by peatland development.
3. To evaluate the effects of alternative harvesting methods and alternative reclamation schemes.
4. To evaluate the process by which acid bog waters become buffered by receiving lakes and streams.

Water Quantity Objectives:

1. To develop a method of predicting the impacts of large peatland developments on water quantity.
2. To identify the critical elements and processes in peatlands that control water volume and rate of movement.

3. To evaluate the effects of alternative harvesting methods and alternative reclamation schemes.

To accomplish these objectives a literature review was performed and field investigations were conducted. Field studies of water budgets and water quality monitoring were conducted at several peatlands including an area presently being mined for horticultural peat, an agricultural area being used for reclamation, and two natural areas. This report summarizes the results obtained from these field studies. The literature review of the water resources of peatlands was previously submitted (Clausen and Brooks 1980), in addition to a summary of two-year results (Clausen et al. 1981). Some of the detailed information contained in the two-year report will not be repeated in this document.

STUDY AREAS

Four major study areas in northern Minnesota were investigated (Figure 1). Two of these peatlands are undisturbed natural areas; one is located in northwest Minnesota (Tamarac River) and one is in the northeast (Toivola). The other two peatlands have been drained; one area is presently being mined for horticultural peat moss (Corona), while the other area has been used for agriculture in the past and is currently the site of peatland reclamation studies (Fens). More detailed study area descriptions are given below and summarized in Table 1.

Toivola

The Toivola peatland is a 3758 ha transition area that is undrained (Figure 2). Most of the peat is moderately decomposed hemic, although about ten percent of the watershed is raised bog (Olson *et al.* 1979). Peat depths range from 1.2 to 4.9 m and average 3.7 m. About 90 percent of the watershed is forested in either black spruce (*Picea mariana* [Mill.] B.S.P.) or tamarack (*Larix laricina* [Du Roi] K. Koch). The two raised bogs in the northern part of the watershed are vegetated with black spruce up to 9 meters in height whereas the black spruce found elsewhere is stunted. A relatively pure stand of tamarack of 8 meter height is located in the west center of the watershed. Eight percent of the watershed is open being vegetated with sedge (*Carex spp.*). The major open area lies just south of the ovoid-shaped raised bog, possibly as a watertrack. The remaining three percent is in brush, primarily alder (*Alnus spp.*) and

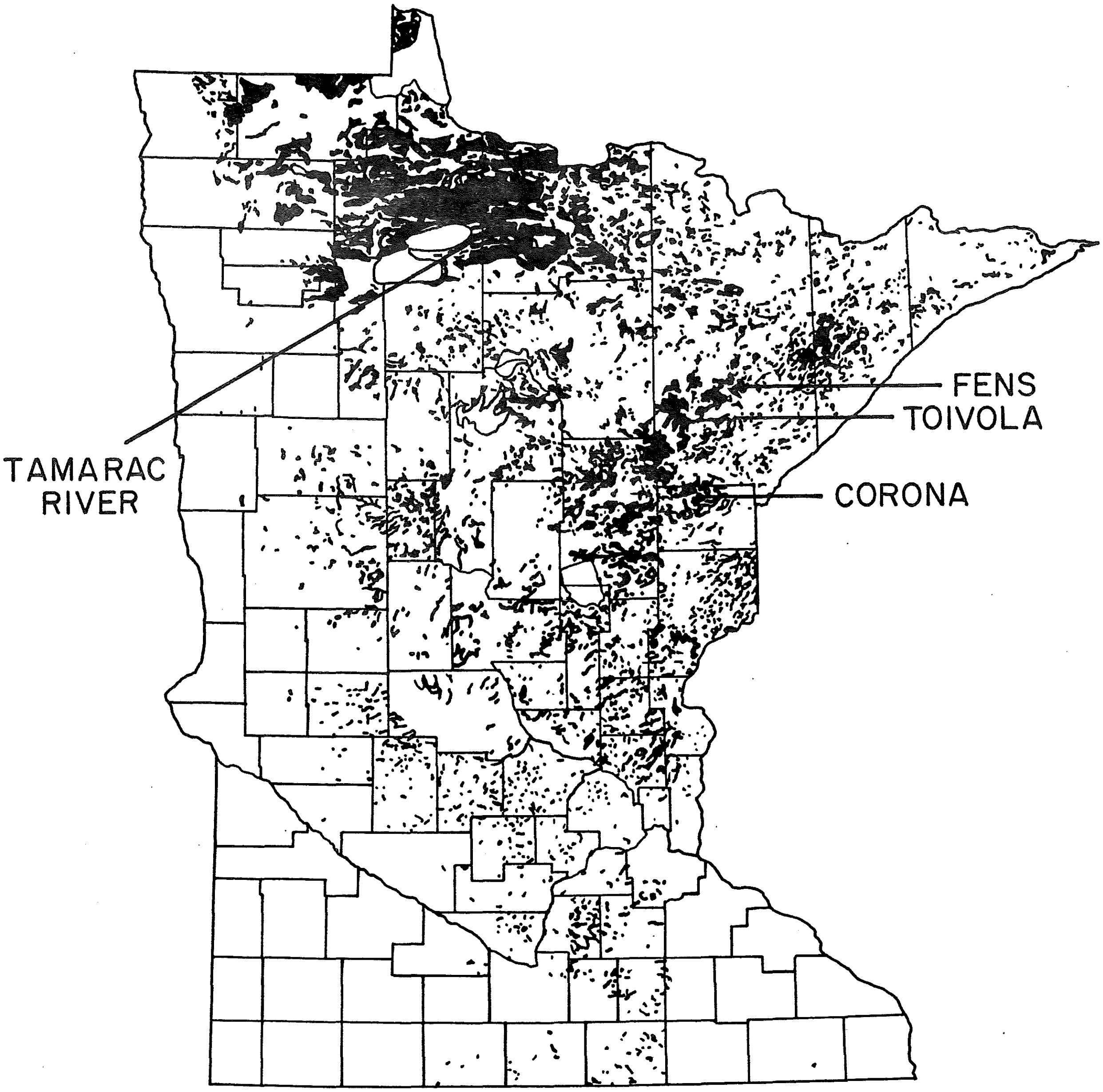

Figure 1. Map of Minnesota showing the location of the four intensively studied peatland watershed areas.

Table 1. Summary of study area characteristics.

		undisturbed		drained and	
				mined	cultivated
Characteristic		Toivola	Tamarac R.	Corona	Fens
Peatland type		Transition	Fen	Bog	Fen
Watershed area	ha	3758	14349	155(N)	93(N)
	ha	--	--	284(S)	36(S)
Average slope	m/km	1.3	0.6	1.0	0.9
Average peat depth	m	3.7	2	4.6	1.6
Range	m	1.2 - 4.9		1.5 - 10.7	0.6 - 3.4
Peat type fibric	%	11			15
hemic	%	84			66
sapric	%	5			19
Peat pH < 4.5	%	14			0
4.5 - 5.0	%	10			0
> 5.0	%	76			100
Vegetation open	%	8		100	100
spruce & tamarack	%	89		0	0
Brush	%	3		0	0

willow (*Salix spp.*), most of which is located near the mineral islands in the center and bottom of the watershed. *Sphagnum*, leatherleaf (*Ledum groenlandicum* [Oeder]) and Labrador tea (*Chamaedaphne calyculata* [L.] Moench) are found throughout the peatland. The Toivola peatland slopes toward the south at an average of 1.3 m/km and is underlain by sand and silt.

The Toivola peatland was instrumented for complete water budget and groundwater flow analysis (Figure 3). The weather station contained both a recording and nonrecording precipitation gauge, a recording air and peat thermograph, and a nonweighing bottomless lysimeter. In addition, 10 precipitation gauges were located at every other station along

Figure 2. Aerial photograph mozaic of the Toivola peatland.

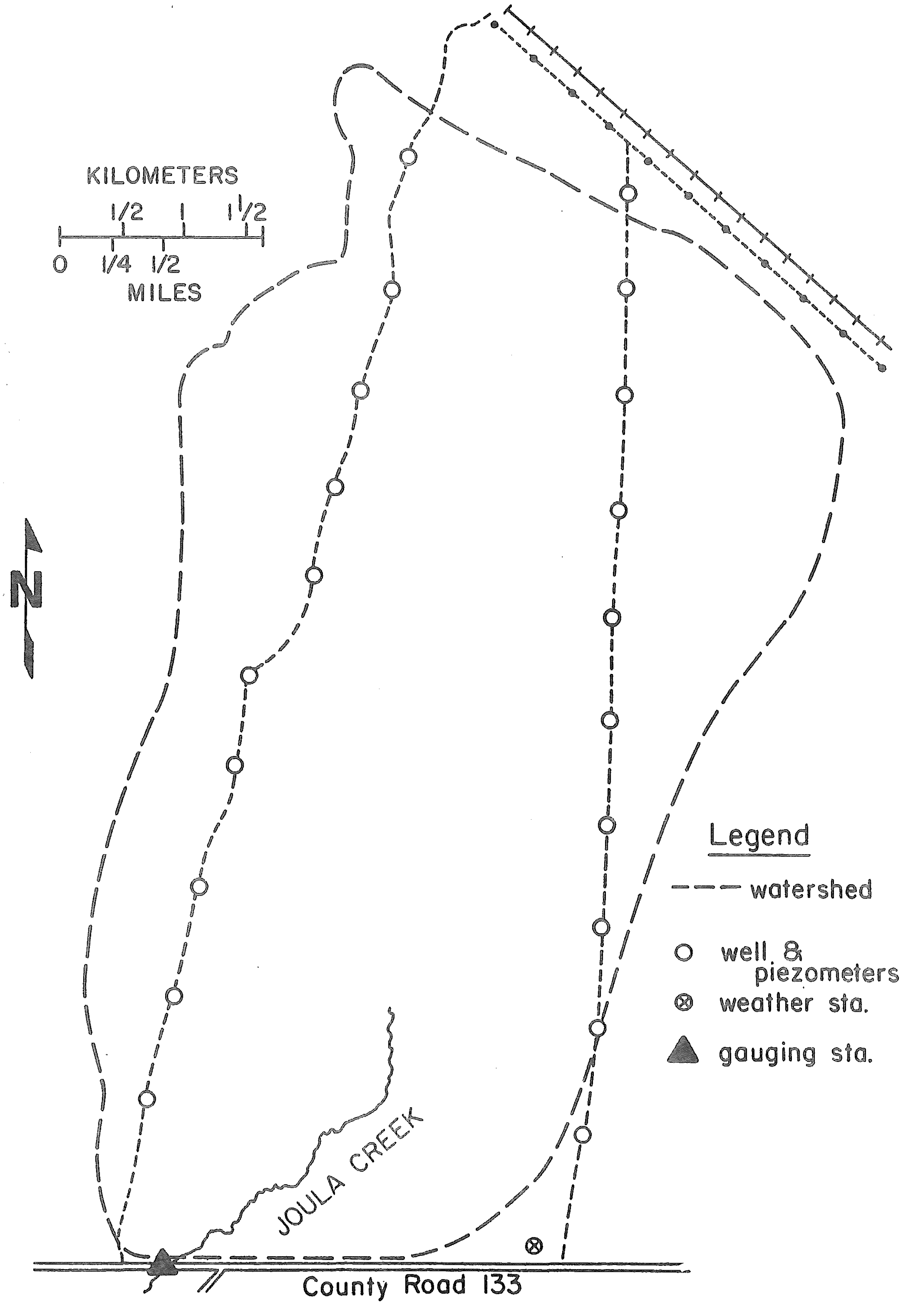

Figure 3. Map of the Toivola peatland.

the east and west transects. Runoff from the watershed was recorded at the intersection of Joula Creek and County Road 133 in a stilling well at a box culvert. Along the east and west transects were located 20 stations, each spaced at about 1.6 km and containing a water table well and three piezometers to determine the change in storage and the direction of groundwater flow. The groundwater level was continuously recorded at the third station from the south on the east transect.

Tamarac River

The Tamarac River drains a large (approximately 14,350 ha) fen into Upper Red Lake at Waskish (Figure 4). This peatland is composed mostly of hemic peat averaging 2 meters in thickness. There are several raised bogs and water tracks found within the peatland. Vegetation consists primarily of sedges with areas of alder brush and stunted black spruce and tamarack. The raised bogs contain larger black spruce with an understory of *Sphagnum*, Labrador tea, and leatherleaf. This peatland is relatively undisturbed although it contains 40 km of old ditches constructed in the early 1900's. The Tamarac River peatland is relatively flat with an average slope of 0.6 m/km.

This peatland was instrumented for water budget analysis with the weather station and runoff gauging station located at the intersection of the Tamarac River and an old ditch bank road (Figure 5). Two additional precipitation gauges were located out in the watershed. No groundwater information was collected.

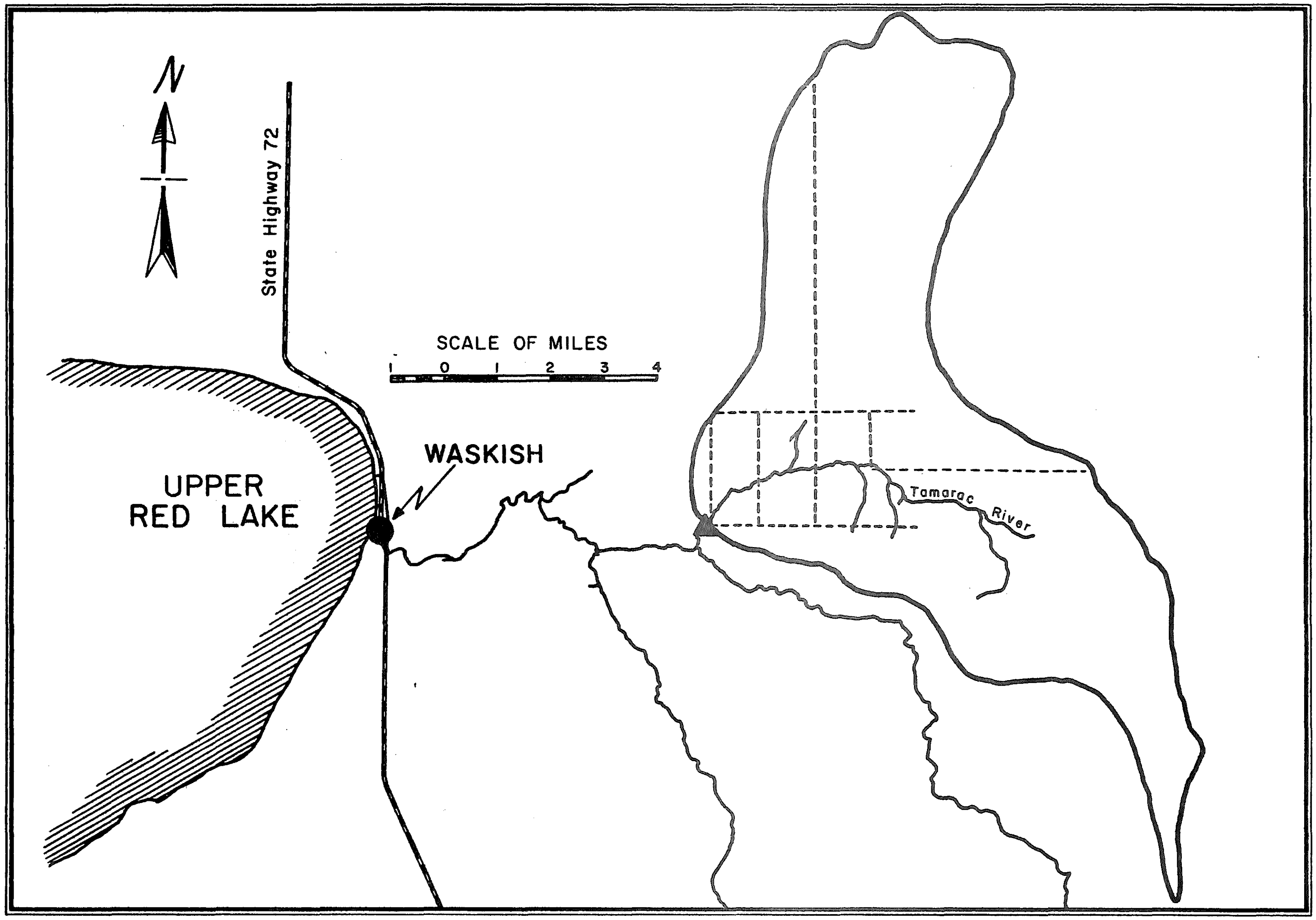

Figure 4. Map of the Tamarac River study area.

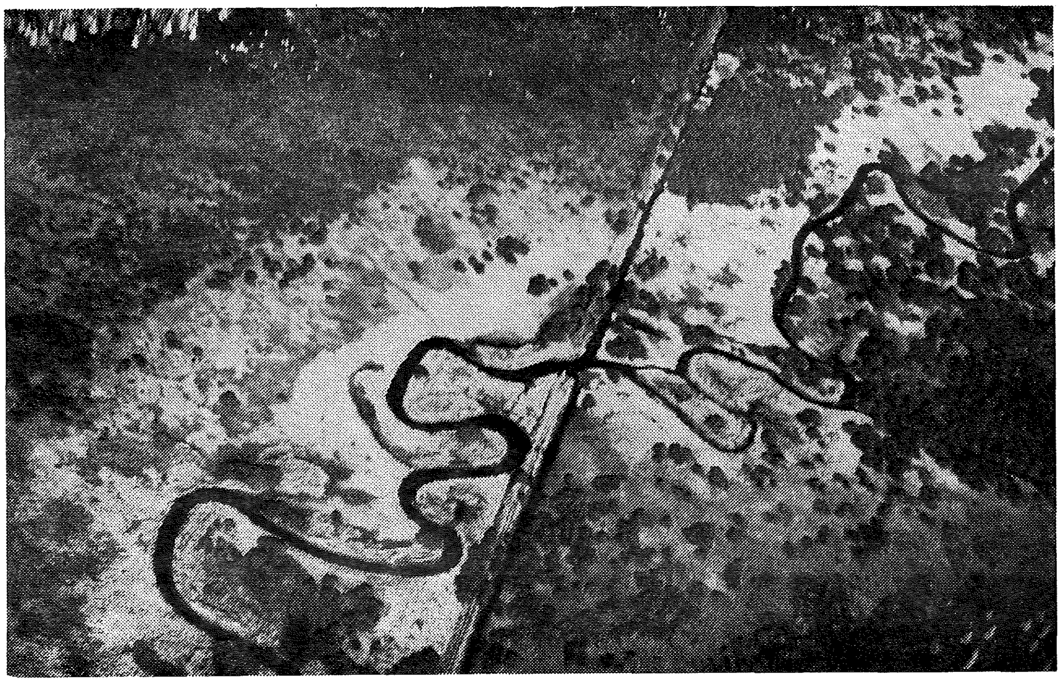

Figure 5. Aerial photograph of the Tamarac River gauging station.

Corona

The Corona area is a 290 ha *Sphagnum* bog that is currently being mined for horticultural peat moss using the milled-peat method (Figure 6). The area has been mined since 1958 by using pneumatic harvesters. The upper three meters of the bog is fibric *Sphagnum* moss, which is underlain by hemic reed-sedge peat with a substrate of sand and clay. The peat deposit ranges in thickness from 1.5 to 10.7 meters and averages 4.6 meters (Soper 1919). The watershed at present is almost entirely void of live vegetation, although prior to clearing there occurred spruce, tamarack, *Sphagnum*, leatherleaf, Labrador tea, sedge, and cotton grass (*Eriophorum spp.*) (Soper 1919). Ditches on the area are spaced at 60 to 100 meters and average 1.3 m deep. The surface slopes to the southwest at m/km.

The Corona area was instrumented for water budget analysis (Figure 7). The weather station included a recording air and peat thermograph and a recording and nonrecording precipitation gauge. Two other nonrecording precipitation gauges were located within the watershed. Three separate runoff gauging stations were used at the Corona bog. The Corona north gauging station drains 155 ha of mined area and Corona south drains 284 ha. The south station, located by the railroad tracks, drains the entire mined area but was abandoned because of water quality contamination from the old peat plant. The Corona control gauging station (not shown on map), draining a 58 ha bog, is located on the north side of state highway 210. A precipitation gauge was also located at the control. To determine the

Figure 6. Aerial photograph of the Corona milled peat mining operation.

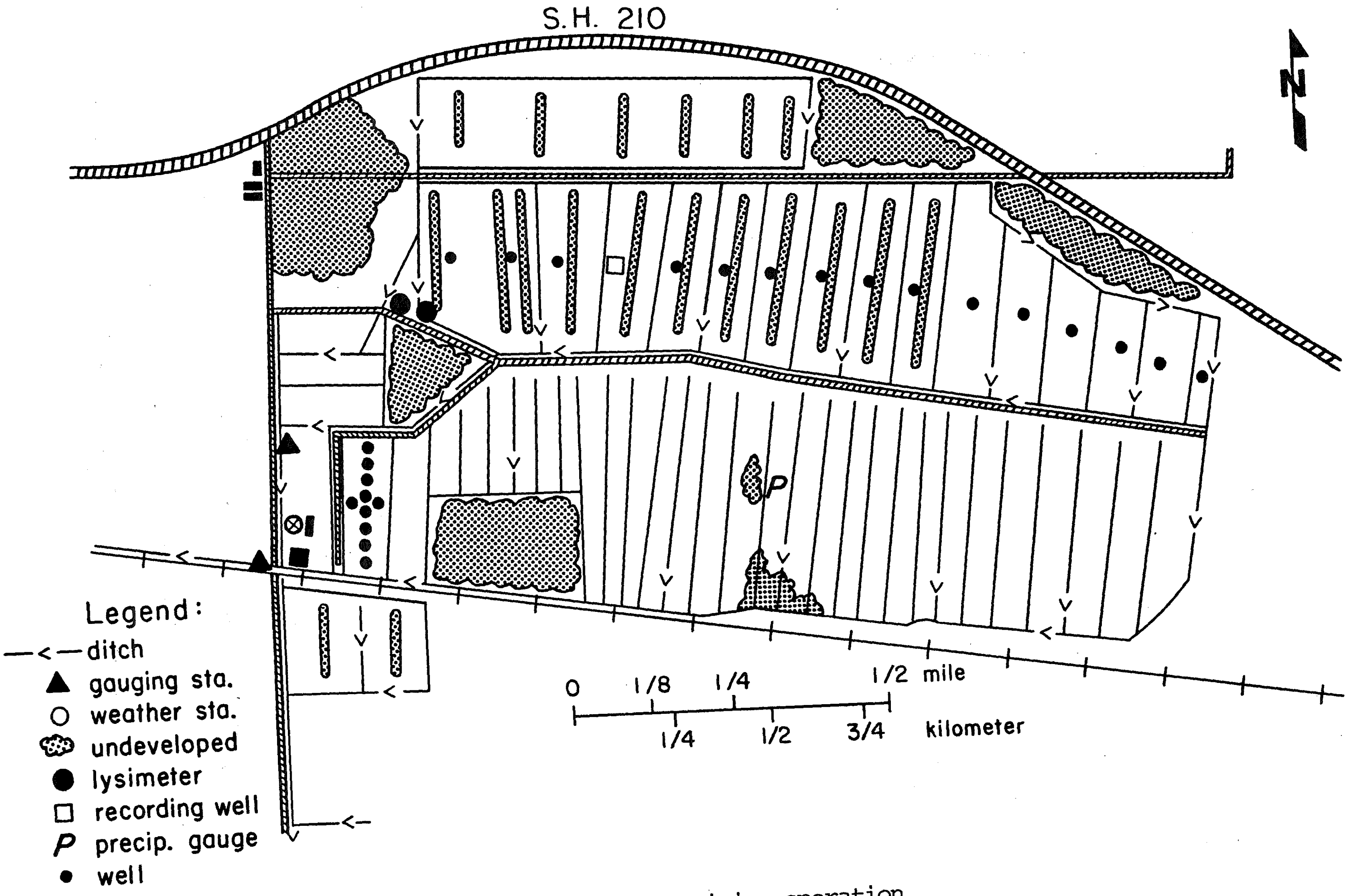

Figure 7. Map of the Corona bog milled-peat mining operation.

change in water storage within the peat, 35 nonrecording wells and one recording well were installed in the watershed. Two bottomless non-weighing lysimeters were located in the west central portion of the mined area, one on bare peat to measure evaporation from a mined surface and one in a vegetated unmined area to determine evapotranspiration. Two double-ring infiltrometers were installed near the lysimeters, one on bare peat, the other on vegetated peat. During 1980 an evaporation pan was added to the weather station at Corona. Additional infiltration data was gathered with several infiltrometers at Corona during 1980-81.

Fens

Although the Fens study area was originally ditched in 1915, there has been extensive drainage and cultivation for only the past 25 years (Clapp 1916) (Figure 8). Ditches are spaced at 50 and 100 meters and average 2 meters deep. This peatland is composed primarily of hemic reed-sedge peat varying in thickness from 0.6 to 3.4 meters and averaging 1.6 meters (Farnham and Grubich 1970). The area, called Wilderness Valley Farms, has been used for vegetable, small grain, and sod production in the past. The original vegetation consisted of alder and tamarack ranging from 9 to 15 meters tall with a diameter of 10 to 25 cm. The understory included grasses, ferns, heath plants, and *Sphagnum* (Clapp 1916).

Currently, Wilderness Valley Farms is the site of several peatland reclamation studies including agriculture, forestry, sewage treatment, and dredged ponds (Figure 9). Both agriculture and forestry reclamation

Figure 8. Aerial photograph of the Fens peatland area.

experiments are being conducted on mined and unmined peat. Forest reclamation includes both fertilized and unfertilized treatments of several forest species. The three sewage treatment methods are the Finnish system, the peat-over sand filter, and sludge disposal. Two one-acre dredged ponds were constructed, one with the bottom in peat, the other with the bottom in mineral soil. A control area was also monitored.

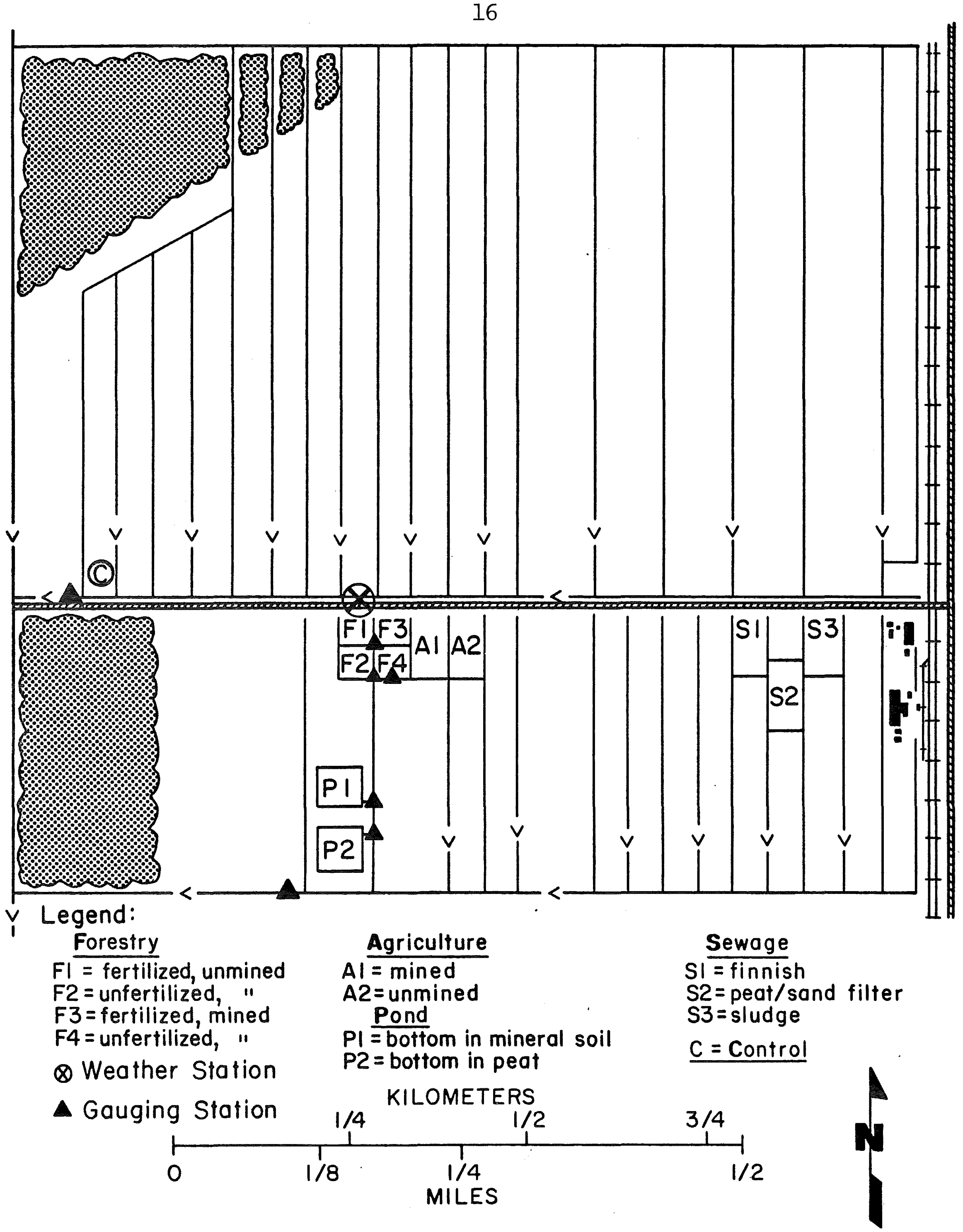

Figure 9. Map showing locations of reclamation studies at Wilderness Valley Farms.

Instrumentation at Wilderness Valley Farms was extensive. One weather station was located at the fertilized forestry field (F1) and included a recording and nonrecording precipitation gauge; a recording air and peat thermograph; evaporation pan; two bottomless lysimeters, one bare and the other vegetated; and two double ring infiltrometers, one bare and the other vegetated. Another recording precipitation gauge and a recording wind speed and direction meter were located at the Iron Range Resources and Rehabilitation Board offices. Before reclamation studies commenced, runoff was monitored at two locations, one draining the 93 ha north half, the other draining the 36 ha south half (Figure 9). After reclamation studies began, these stations were abandoned because water was coming from several different reclamation treatments. Runoff was recorded using V-notched wiers and stilling wells at five locations: the two forestry unmined plots, the mined area, and the two ponds. To complete the water budget analyses, two recording wells were installed, one in the unmined forestry fertilized plot, the other in the unmined agricultural field. In addition, 64 wells were located in the forestry mined and unmined fields and the unmined agricultural field. Soil suction lysimeters were also installed in the unmined forestry fields to monitor groundwater quality.

Multiple Watershed - Water Quality Study Sites

Forty-five natural peatland watersheds, located in northern Minnesota between latitudes 46°15' and 48°40' north, were selected for water quality investigations (Figure 10). Most of the watersheds are located in St.

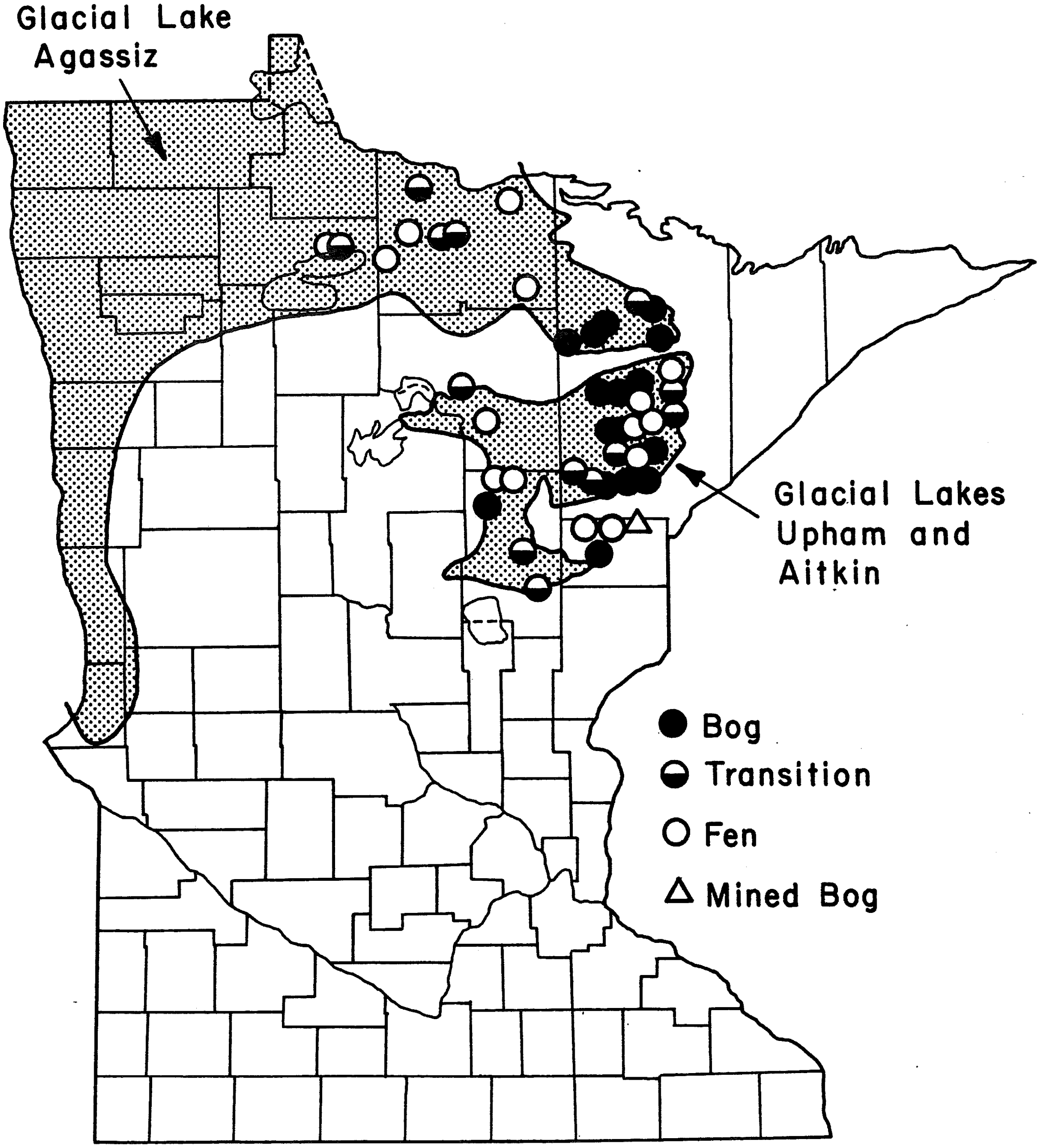

FIGURE MAP OF MINNESOTA SHOWING THE LOCATION AND PEATLAND TYPE OF WATERSHED STUDY AREAS.

Figure 10. Map of Minnesota showing the location and peatland type of watershed study areas.

Louis County whereas the remaining are located in Aitkin, Beltrami, Carlton, Itasca, and Koochiching counties.

Vegetation

The vegetation for the peatland study watersheds is described as the percent of the watershed that is forested, open, or shrub (Table 2). These simplifications were used because more detailed vegetative descriptions were lacking and because most bogs are forested and most fens are open and have shrubs. Watershed percents were used because several watersheds are large and contain many vegetative types. The mined bog watershed is almost entirely void of live vegetation except for scattered plants along some ditches.

Soils

There are three types of peat soil found in the study watersheds: fibric, hemic, and sapric. The percent of the watershed that is fibric, hemic, or sapric peat was summarized from peat inventory reports for both the surface peat and the total peat profile (Table 2). The percent mineral soil in the watershed was obtained from U.S.G.S. topographic maps.

Geology

Peatlands in Minnesota exist in part due to the surficial geology caused by glaciation. The last period of glaciation, called the Wisconsin Ice Stage, ended about 10,000 years ago and left several glacial lakes on the landscape as the glacier melted (Wright 1972a). All but three of the peatland study watersheds lie in former glacial lake beds (Figure 10).

Table 2. Watershed characteristics for 45 peatland study areas.

				Ditch	%	% Peat Type								
		Outlet	Watershed	Length	Mineral	Total Profile			Surface 30 cm			% Vegetation		
No.	Name	Type[a]	Area (ha)	(km)	Soil	Fibric	Hemic	Sapric	Fibric	Hemic	Sapric	Open	Forest	Shrub
1	MacGregor S.	D	2119	15.2	20.0	6	94	0	0	100	0	75	0	25
2	MacGregor	D	1099	16.4	13.5	17	66	17	38	62	0	100	0	0
3	Hill City SE.	D	359	1.6	18.4	42	58	0	59	41	0	44	56	0
4	Jacobson W. (A)	D	1364	6.0	10.9	47	38	15	42	58	0	66	17	17
5	Jacobson W. (B)	D	1572	5.8	28.6	35	47	18	0	100	0	0	25	75
6	N. Cromwell	S	2072	0	20.0	54	42	4	92	8	0	50	50	0
7	Cromwell NE	D	1878	11.8	41.4	53	29	18	81	12	7	0	100	0
8	S. Cromwell	D	233	1.6	15.0	62	19	19	100	0	0	50	50	0
9	Floodwood NW.	D	1678	13.2	10.1	26	72	2	60	40	0	13	84	13
10	Floodwood	S	1288	0	5.5	24	52	24	55	36	9	0	89	11
11	Floodwood E.	D	459	3.4	41.9	16	75	9	60	40	0	60	40	0
12	Arlberg (A)	S	982	8.4	22.2	83	16	1	89	8	3	29	71	0
13	Arlberg (B)	S	2034	12.9	35.2	86	13	1	86	14	0	47	53	0
14	Meadowlands E.	S	897	2.4	7.9	2	51	47	12	76	12	0	100	50
15	Canyon	S	1121	0	33.7	42	26	32	100	0	0	29	71	0
16	Toivola S.	S	638	2.3	26.6	79	17	4	100	0	0	7	93	0
17	Toivola E. (A)	D	673	14.2	6.0	50	23	27	82	18	0	36	64	0
18	Toivola E. (B)	D	84	0	69.0	-	-	-	-	-	-	-	-	-
19	Cotton	S	3409	10.5	47.5	9	9	82	33	33	33	0	100	17
20	Cotton E.	S	1210	0	18.0	6	67	27	25	67	8	0	50	50
21	Fens	S	1133	0	62.2	9	28	63	7	0	93	14	72	14
22	Riley	S	2581	0	34.3	-	-	-	-	-	-	-	-	-
23	Little Swan (A)	S	1730	0	42.7	-	-	-	-	-	-	-	-	-
24	Little Swan (B)	S	3325	4.8	0.1	-	-	-	-	-	-	-	-	-
25	Central Lakes	S	471	0	30.3	78	16	6	100	0	0	0	100	0
26	Ely Lake	S	714	0	40.0	0	50	50	0	100	0	0	100	100
27	Britt	D	791	3.7	47.3	-	-	-	-	-	-	-	-	-
28	Unnamed	S	618	0	38.2	-	-	-	-	-	-	-	-	-
29	Lost Lake	S	2784	0	51.2	37	30	33	81	14	5	10	90	0
30	Cook	S	1537	0	57.5	30	46	24	74	26	0	5	95	0
31	Sturgeon	D	229	0	16.3	47	40	13	100	0	0	23	77	0
32	Linden Grove	S	352	0	8.2	-	-	-	-	-	-	-	-	-
33	Sturgeon S.	S	1150	0	43.4	-	-	-	-	-	-	-	-	-
34	Cohasset	S	962	0	39.7	-	-	-	-	-	-	-	-	-
35	Deer River	D	5722	0	15.8	-	-	-	-	-	-	-	-	-
36	Nakoda	D	2622	0	44.9	37	49	14	80	20	0	0	100	20
37	Myrtle Lake	S	3960	0	3.0	30	70	0	-	-	-	16	84	68
38	Sturgeon River (A)	S	16722	47.3	10.8	12	77	11	60	30	10	5	95	25
39	Sturgeon River (B)	S	16059	12.6	7.7	24	70	6	56	44	0	0	100	19
40	N. Pine Island	D	1489	10.8	4.4	79	21	0	100	0	0	20	80	0
41	Pine Isl. Raised Bog	D	734	25.6	10.8	33	62	5	80	20	0	0	100	0
42	Red Lake (A)	D	1319	12.1	0	90	10	0	100	0	0	0	100	0
43	Red Lake (B)	D	1558	11.1	0	74	24	2	98	2	0	0	100	0
44	Tamarac River	S	14350	47.7	15.9	3	92	5	14	84	2	11	64	69
45	Joula Creek	S	3758	0	2.0	39	37	24	80	16	4	10	85	5

Table 2. Watershed characteristics for 45 peatland study areas (continued).

		% Peat pH								Mean surface pH	Mean Ash content %	Mean Peat Depth M
		Total Profile				Surface 30 cm						
No.	Name	<4.5	4.5-5	5-6	76	<4.5	4.5-5	5-6	76			
1	MacGregor S.	0	55	45	0	0	80	20	0	4.8	11.6	2.0
2	MacGregor	28	6	57	9	57	0	43	0	4.8	12.6	1.7
3	Hill City SE.	-	-	-	-	-	-	-	-	-	-	2.2
4	Jacobson W. (A)	7	15	61	17	8	42	50	0	5.0	9.7	1.5
5	Jacobson W. (B)	0	0	94	6	0	0	100	0	5.3	14.0	1.9
6	N. Cromwell	83	17	0	0	100	0	0	0	3.6	7.4	2.1
7	Cromwell NE.	77	17	6	0	100	0	0	0	3.5	7.5	3.3
8	S. Cromwell	81	12	7	0	100	0	0	0	3.4	5.6	2.3
9	Floodwood NW.	9	22	69	0	40	50	10	0	4.5	8.8	4.1
10	Floodwood	38	13	49	0	82	9	9	0	4.1	10.5	2.4
11	Floodwood E.	44	41	15	0	100	0	0	0	4.0	6.2	2.6
12	Arlberg (A)	72	21	7	0	92	8	0	0	3.8	8.3	4.3
13	Arlberg (B)	74	24	2	0	95	5	0	0	3.9	6.5	3.6
14	Meadowlands E.	0	0	89	11	0	0	100	0	5.3	12.0	1.9
15	Canyon	-	-	-	-	-	-	-	-	-	-	2.1
16	Toivola S.	75	18	7	0	100	0	0	0	3.8	6.2	2.9
17	Toivola E. (A)	51	20	29	0	91	9	0	0	3.9	5.0	2.5
18	Toivola E. (B)	-	-	-	-	-	-	-	-	-	-	-
19	Cotton	18	15	64	3	66	17	17	0	4.5	13.4	1.8
20	Cotton E.	-	-	-	-	-	-	-	-	-	-	1.4
21	Fens	0	0	87	13	0	0	100	0	5.2	19.2	1.5
22	Riley	-	-	-	-	-	-	-	-	-	-	1.8
23	Little Swan (A)	-	-	-	-	-	-	-	-	-	-	2.0
24	Little Swan (B)	-	-	-	-	-	-	-	-	-	-	-
25	Central Lakes	100	0	0	0	100	0	0	0	3.6	6.3	2.7
26	Ely Lake	0	0	100	0	0	0	100	0	5.7	14.4	2.7
27	Britt	-	-	-	-	-	-	-	-	-	-	3.2
28	Unnamed	-	-	-	-	-	-	-	-	-	-	-
29	Lost Lake	38	12	47	3	85	5	10	0	3.9	6.9	3.3
30	Cook	37	8	53	2	100	0	0	0	3.5	4.5	5.7
31	Sturgeon	28	17	48	7	100	0	0	0	4.1	7.4	2.6
32	Linden Grove	-	-	-	-	-	-	-	-	-	-	1.0
33	Sturgeon S.	-	-	-	-	-	-	-	-	-	-	1.4
34	Cohasset	-	-	-	-	-	-	-	-	-	-	2.1
35	Deer River	-	-	-	-	-	-	-	-	-	-	2.6
36	Nakoda	6	0	88	6	40	0	60	0	5.1	9.6	3.5
37	Myrtle Lake	-	-	-	-	-	-	-	-	-	-	3.0
38	Sturgeon River (A)	25	18	57	0	60	30	10	0	5.5	8.8	1.7
39	Sturgeon River (B)	24	10	66	0	58	18	24	0	3.6	7.6	2.6
40	N. Pine Island	63	14	20	3	100	0	0	0	3.5	5.3	4.2
41	Pine Isl. Raised Bog	82	2	16	0	100	0	0	0	3.7	7.8	3.7
42	Red Lake (A)	86	14	0	0	100	0	0	0	3.4	5.6	4.3
43	Red Lake (B)	74	5	17	4	92	3	5	0	3.7	6.6	4.1
44	Tamarac River	3	8	81	8	8	11	70	11	-	10.1	2.4
45	Joula Creek	14	16	51	67	62	29	9	0	-	8.2	3.1

[a] D = Ditch; S = Stream

[b] Sources: Olson et al. 1979; Malterer et al. 1979; Severson et al. 1979; Heinselman 1963, 1970; Iron Range Resources and Rehabilitation, Peat Inventory Reports 1-46.

Glacial Lake Upham was located in southwestern St. Louis county where study watersheds numbered 9 to 26 are found (Wright 1972b). The northern part of the former lake bed is mostly sand and the southern part is silt and clay. The glacial drift is about 30 meters thick (Lindholm *et al.* 1979). Study watersheds 1 to 5, 34, and 35 are located in the lake bed of Glacial Lake Aitkin which is composed of lake washed silt, sand, and clay (Oakes and Bidwell 1968).

Glacial Lake Agassiz covered much of northwestern Minnesota where peatland watersheds 29 through 33 and 36 through 44 are located (Figure 10) (Wright 1972b). Most of the lake bed deposits are clay and silt. The thickness of glacial material is about 30 meters at the east end and 15 meters at the west end (Helgesen *et al.* 1975, 1976; Bidwell *et al.* 1970; Lindholm *et al.* 1976).

Peatlands 6, 7, and 8 and the mined bog lie outside former glacial lake beds in sandy till about 30 meters thick (Helgesen *et al.* 1973; Lindholm *et al.* 1979). The watershed geology is more important when considering fens than bogs because fens are fed by groundwater.

Other Watershed Characteristics

The watershed area, extent of ditching, outlet type (ditch vs. stream), and the peat pH, ash content, and thickness are other watershed characteristics that describe the study areas (Table 2). The peat pH classes were selected based upon their relationship with peat types. Peat with a pH less than 4.5 is normally fibric, sapric peat usually has a pH greater than 6.0, and hemic peat is between 4.5 and 6.0 (Farnham and Finney 1965).

WATER QUALITY METHODS

Water quality samples were collected from both surface and ground water. Samples were collected weekly from study area outlets during 1978 and monthly in 1979-81. Samples were not taken during summer when flow ceased or during winter when the stream froze to the bottom. Water quality samples were also collected from the 45 peatland watersheds during 1979 and 1980.

Collection

Water quality samples were collected in various containers depending upon the characteristics to be analyzed (Table 3). Most samples were collected in polyethylene bottles that had been pre-washed with a no-phosphate detergent and rinsed in 1N hydrochloric acid and double distilled water. Samples intended for cation analysis were taken in 5 ml plastic tubes.

Table 3. Sample volume, container, and preservative for water quality characteristics measured in peatland runoff.

Sample Volume (ml)	Container[a]	Water Quality Characteristic	Preservative
500	P	acidity, alkalinity, color	4°C
500	P	organic acids, COD	4°C
500	G,P	suspended sediment	4°C
250	P	Hg, As, Se	HCL
50	P	nitrogen, phosphorus	$HgCl_2$
5	P	Ca, Mg, Al, Na, Fe, Mn	HCL

[a] P = polyethylene; G = glass

Suspended sediment samples were taken either in plastic containers or glass sediment bottles. Mercury, arsenic, and selenium samples were only collected from the 45 peatland watersheds during the first three sampling periods and from the four major study areas prior to June 1980. The organic acids and COD samples were collected from the peatland watersheds during the last three sampling periods and from the study areas in the winter 1980-81.

All samples were systematically taken just below the water surface without disturbing the stream bottom. Samples were unfiltered; therefore, total rather than dissolved values were obtained. Temperature, dissolved oxygen, and specific conductivity were measured in-situ. One of the 500 ml samples was used for an immediate pH determination. Discharge was determined as the product of the estimated cross-sectional area of the outlet and the velocity which was estimated by determining the time for a floating object to travel a known distance times 0.8.

Preservation and Storage

All samples collected were kept in cold storage at approximately 4°C (Table 3). Refrigeration inhibits bacterial action and retards chemical reaction rates (U.S. Environmental Protection Agency 1976). The 50-ml sample, intended for nitrogen and phosphorus analysis, was preserved at the sample site with $HgCl_2$, a bacterial inhibitor, to yield a concentration of 40 mg/l of $HgCl_2$. The 5-ml sample for cation analysis and the 250-ml sample for mercury, arsenic, and selenium analysis were preserved at the site with concentrated HCL, at a ratio of one part acid to five parts water, to yield a sample pH less than 2.0. Acidification prevents metal precipitation (U.S. Environmental Protection Agency 1976).

Analysis

Water quality samples were analyzed for 34 characteristics at four different locations: at the site, the Cloquet Forestry Center, the University of Minnesota Research Analytical Laboratory in St. Paul, and at the Enviornmental Research Group Laboratory in Roseville. In-situ measurements of temperature, specific conductivity, and dissolved oxygen were made by using the appropriate instruments (Table 4). Specific conductivity was adjusted to the conductivity at 25°C (American Public Health Association *et al.* 1971). The percent oxygen saturation was determined from the dissolved oxygen and temperature by using Rawson's nomogram (Welch 1948). The water pH was determined immediately after sample collection by using a portable pH meter (Table 4).

Color, acidity, alkalinity, and suspended sediment were analyzed at the Cloquet Forestry Center Laboratory. Analysis was conducted according to standard methods (American Public Health Association *et al.* 1975). The Hellige aqua tester and color discs were used to determine apparent color (unfiltered). One color unit is equivalent to the color of water containing 1 mg/l of platinum as expressed on the Hazen Platinum-Cobalt scale. Sample dilutions were used for colors greater than 70 units. Acidity was determined by titrating a 200-ml sample with 0.02N NaOH to an end point pH of 8.3. Alkalinity was measured by titrating a 200-ml sample with 0.02N HCl to the end point pH of 4.6. Both acidity and alkalinity titrations were made while the sample was constantly stirred with a magnetic stirring bar. Suspended sediment was analyzed by

Table 4. Methods of water quality analysis.

Characteristic	Method	Reference
Temperature	YSI Model 33 S-C-T meter	Yellow Springs Instrument Co.
Specific conductivity	YSI Model 33 S-C-T meter	Yellow Springs Instrument Co.
Dissolved oxygen	YSI Model 57 oxygen meter	Yellow Springs Instrument Co.
% Saturation	Rawson's nomogram	Welch 1948
pH	Radiometer PHM meter	Radiometer Co.
Color	Hellige Aqua tester	Helleige Inc.
Acidity	Titration to pH 8.3	Amer. Public Health Assoc. et al. 1975
Alkalinity	Titration to pH 4.6	Amer. Public Health Assoc. et al. 1975
Suspended sediment	Filtration (0.45µ)	Amer. Public Health Assoc. et al. 1975
K, Ca, Mg, Al, Fe, Na, Mn, Zn, Cu, B, Pb, Ni, Cr, Cd	Inductively coupled emission spectroscopy (Plasma)	Kornblum and de Galan 1977
Hg	AA cold water vapor	U.S. Environ. Protection Agency 1976
As, Se	AA gaseous hydride	Amer. Public Health Assoc. et al. 1975
Total phosphorus	Technicon Auto Analyzer II	Technicon Inc. 1971a
Total Kjeldahl nitrogen	Technicon Auto Analyzer II	Technicon Inc. 1974
$NO_3 + NO_2 - N$	Technicon Auto Analyzer II	Technicon Inc. 1971b
$NH_4 - N$	Technicon Auto Analyzer II	Technicon Inc. 1974
Organic - N	Total - Ammonia N	Amer. Public Health Assoc. et al. 1975
Humic, Fulvic acid	Absorbance	Environmental Research Group 1981
COD	Dichromate reflux, titration	Amer. Public Health Assoc. et al. 1975

filtration through a 0.45 micron glass, fiber filter. The net dry filter weight, before and after filtration, represents the suspended sediment. Six samples were run simultaneously with Millipore filter flasks and a vacuum pump.

Cations, nitrogen and phosphorus, and mercury, arsenic, and selenium were analyzed by the Research Analytical Laboratory, University of Minnesota, in St. Paul. Calcium, magnesium, aluminum, iron, sodium, manganese, zinc, copper, boron, lead, nickel, chromium, and cadmium were analyzed by using inductively coupled plasma-optical emission spectroscopy (Table 4). Total phosphorus and total Kjeldahl nitrogen were analyzed on a three-channel Technicon Autoanalyzer II after digesting with fuming sulfuric acid using mercuric oxide as a catalyst (Table 4). This method of total nitrogen analysis includes ammonia and most organic nitrogen compounds but does not include either nitrate or nitrite. Nitrate, nitrite, and ammonia nitrogen were also analyzed on the Technicon Autoanalyzer (Table 4). Nitrate was determined by copper-cadmium reduction to nitrite. Organic nitrogen was determined as the difference between total Kjeldahl nitrogen and ammonia nitrogen (American Public Health Association *et al.* 1975). Mercury was determined by the atomic-absorption (AA) cold vapor technique (Table 4). Arsenic and selenium were analyzed by using the AA gaseous hydride method.

The detection limits for the analysis performed at the Research Analytical Laboratory vary for the water quality characteristics (Table 5). Because lead, nickel, zinc, copper, boron, chromium, and cadmium concentrations in peatland runoff were near detection limits, values for these characteristics were not generally reported.

Table 5. Detection limits for water quality analysis performed at the Research Analytical Laboratory.

Characteristic	Detection limit (mg/l)	Characteristic	Detection limit (mg/l)
K	<.75	Total P	<.01
Pb	<.13	Total N	<.1
Na	<.12	NO_3-N	<.05,.005[a]
Ni	<.04	NO_2-N	<.01
Zn	<.03	NH_4-N	<.1
Ca, Mg, Al, Fe, Mn,	<.01	Hg, As, Se	<.001
Cu, B, Cr, Cd	<.01		

[a] <.05 mg/l for samples collected before 1980; <0.005 mg/l for samples collected thereafter.

Analysis of water quality samples for chemical oxygen demand (COD), humic acid, and fulvic acid were performed by the Environmental Research Group Inc. in Roseville, Minnesota. COD was determined by the dichromate method (American Public Health Association *et al.* 1975). Humic and fulvic acid were determined by absorbance after filtration, acidification, and alkalization (Environmental Research Group, Inc. 1981).

WATER QUANTITY METHODS

To evaluate the potential effects of peat development on water quantity, the following components of the water balance equation were monitored: precipitation, runoff, evapotranspiration, and change in storage. Infiltration and groundwater flow were also measured. To evaluate the effects of peat development on stormflow, peak discharge, response factors, and unit hydrograph analyses were performed. The methods used to measure each component of the water balance equation and each process are discussed in greater detail.

Precipitation

All four of the study areas were instrumented with weighing bucket Belfort universal recording rain gauges with battery clocks and Altar windshields.[1] Clocks were weekly except at the Tamarac River, where a monthly clock was used. To determine basin precipitation and adjust recording precipitation, standard 8-inch Belfort nonrecording rain gauges were used in the watersheds: Toivola (11), Tamarac R. (3), Corona (3), and Fens (2). Rain gauges were run year-round with an antifreeze mixture of ethylene glycol, methyl alcohol, and 10W motor oil. Basin precipitation was determined by averaging the gauge readings for the watershed. Winter snow water equivalent was determined from snow courses by using the Mt. Rose snow tube as described by Haertel (1978).

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[1] Names and products are given for the convenience of the reader and do not indicate endorsement by the College of Forestry. Similar types can be obtained from other suppliers.

Runoff

Runoff was monitored using stilling wells and various types of control sections: wiers (Fens ponds and forestry plots), a box culvert (Toivola), circular culverts (Corona south and control), and a natural channel (Tamarac R.). At Corona north, both the natural channel and a box flume have been used. Stage of the ditch or stream was recorded in stilling wells constructed of 12" diameter PVC by using Belfort FW-1 portable water level recorders with battery clocks. Recorder clocks were weekly except at the Tamarac River, where they were monthly. Discharge stations were shut down during the winter of 1977-78 but were kept running during the winter of 1979-80 by using propane pilot light heaters. Discharge was determined from stage data by using rating equations developed from numerous discharge measurements obtained with a Gurley pygmy current meter and revolution counter. Low flows at Corona on several occasions required using the salt-dilution technique for discharge:

$$Q = q\,\frac{C_1 - C_2}{C_2 - C_0}$$

where Q = discharge (cfs), q = constant rate of added salt concentration (cfs = gpm x 0.00223), C_0 = background specific conductivity (μmhos/cm), C_1 = specific conductivity of salt solution, and C_2 = specific conductivity of ditch after mixing (U.S. Bureau of Reclamation 1967).

Evapotranspiration

Monthly potential evapotranspiration (PET) was determined for all study areas by using the method of Thornthwaite and Mather (1957). This method uses mean monthly temperature and station latitude in the relationships:

$$PET = 1.6 \left(\frac{10T}{I}\right)^{A}$$

$$\text{and} \quad I = \Sigma i \text{ where } i = (T_M/5)^{1.514}$$

$$\text{and} \quad A = 6.75 \times 10^{-7} (I)^3 - 7.71 \times 10^{-5} (I)^2 + 1.792 \times 10^{-2} (I) + 0.49239$$

where PET = potential evapotranspitation (cm), T = mean monthly temperature (°C), T_M = normal mean monthly temperature (°C), and i = monthly heat index. Monthly values of PET are adjusted for day length using correction factors based on station latitude. Mean monthly temperature was obtained from a recording Belfort thermograph with battery clock in a standard instrument shelter. Initially, all charts except at the Tamarac River were weekly, but were later made monthly.

Vegetated bottomless lysimeters were used to estimate evapotranspiration at all areas except at the Tamarac River. Lysimeters at Fens were constructed of 10 ga. galvanized corregated culverts 1.2 m in diameter by 1.8 m deep and installed by gradual lowering and pressing as outside peat layers were removed by using a post hold digger. The remaining lysimeters were constructed of 16 ga. galvanized sheet metal 1.2 m deep by 0.9 m in diameter. These smooth wall lysimeters were much easier to press into the peat. All lysimeters were sunk to the mineral substrate underlying the peat. Aluminum water table wells were installed inside and outside the lysimeters to measure water levels. Evapotranspiration was determined from changes in lysimeter water levels by using water yield coefficients. Additional lysimeters without any surface vegetation were installed at Fens and Corona to determine evaporation from an exposed (mined) peat surface. Generally, weekly lysimeter readings were taken during the frost-free period.

Standard U.S. Weather Bureau evaporation pans were also used at Fens and Corona to estimate evapotranspiration between 1979-81 and 1980-81, respectively. The water balance method was also used to estimate ET on all areas by using the equation:

$$ET = P - RO \pm \Delta S$$

where ET = evapotranspiration, P = precipitation, RO = Runoff, and ΔS = change in storage. The ΔS term was not used for the Tamarac River watershed.

Change in Storage

The change in storage was determined from recording and nonrecording water table wells. Recording wells, located on all areas except the Tamarac River, were constructed of 15 cm diameter PVC pipe that was perforated and pressed into a hole made with a post hole digger. Water table levels were monitored by using a Belfort water level recorder. Recording wells were shut down during the winter of 1977-78, but the Corona well and the Fens forestry well were kept running during the winters of 1979-80 and 1980-81 by using propane pilot light heaters.

Nonrecording water table wells were constructed of 3.8 cm O.D. aluminum tubing that was perforated and pinched at one end and pounded into the peat. Levels were run each year on well top elevations. Biweekly readings were taken with a bubbler tube.

Water yield coefficients, used to convert the change in water level to the change in storage, was determined by correlating precipitation amount to the rise in water level over a short time span by using the methods described by Heikurainen (1963).

Infiltration

Several infiltration curves were run for bare and vegetated sites at Fens and Corona with double ring infiltrometers by using the methods described by Black *et al.* (1965) except that a shorter time period of 90 minutes and a constant head of 9 cm were used.

Groundwater Flow

Sixty piezometers in clusters of three at 1.6 km spacings were located throughout the Toivola peatland along two transects. Piezometers were constructed of 3.8 cm O.D. aluminum tubing that was pinched and perforated at one end. At each of 20 stations, a cluster of piezometers was installed at three depths: at the bottom of the peat or 3.66 m whichever was less, at 0.6 to 1.0 m below the surface, and at an intermediate depth between the former two. Piezometers were placed in a line about 3 m apart with the cluster being at least 15 m from the access trail. Piezometer runs were made monthly by using a Muskeg Carrier bombardier. Elevations of piezometers and the peat surface were determined from benchmarks made of galvanized pipe augered through the peat into the mineral substrate.

Response Factors

The hydrologic response factor is the ratio of stormflow to precipitation where stormflow equals total flow minus baseflow (Hewlett and Hibbert 1967; Hewlett and Moore 1976). Precipitation events greater than 3.8 mm were used for the analysis of response factors at Toivola and Corona. A variable baseflow separation line was determined for each hydrograph beginning at the hydrograph rise and ending at the inflection point of the recession.

Basin lag times were calculated as the time from the centroid of the total precipitation event to the peak discharge.

Unit Hydrograph Analysis

Unit hydrographs were determined from streamflow hydrographs as discussed by the Hydrologic Engineering Center (1973). Isolated flood hydrographs were selected from recorded streamflow records. Stormflow was separated from baseflow by constructing a straight line from the point on the recession limb of the hydrograph where streamflow "flattens out." Unit hydrograph characteristics were then compared among study watersheds.

WATER QUALITY RESULTS

Controlled "paired watershed" experiments were not possible in this study, largely because of time constraints. Also, at the beginning of the study it was uncertain what types of large-scale mining operations should be studied. Thus, it would have been necessary to perform several paired watershed experiments, examining different mining operations. In addition, several years of pre-treatment (mining) and post-treatment monitoring would have been necessary. Because we did not have such a controlled experiment, we characterized the quality of runoff from natural peatlands and then made comparisons with a milled peat operation.

Differences Among Peatland Types

Each water quality characteristic is discussed with respect to differences among peatland types, seasonal variability, and correlations with other water quality characteristics. The study peatlands were classified according to water quality indicators (Table 6). The mean water quality values for all five sampling periods are found in Table 7.

Table 6. Water quality indicators of streamflow from Minnesota bog, transition, and fen peatlands.

Characteristic		Peatland Type Bog	 Transition	 Fen
pH		<6.3	5.8 - 7.0	>6.4
Specific conductivity	μmhos/cm	< 55	30 - 80	> 70
Alkalinity as $CaCO_3$	mg/l	< 15	10 - 35	> 25
Calcium	mg/l	< 10	5 - 15	>7.5
Magnesium	mg/l	< 3	1 - 5	> 3

Table 7. Mean values of water quality characteristics in peatland runoff for five sampling periods in 1979 and 1980.

		Peatland Type		
Characteristic		Bogs	Transitions	Fens
No. of samples		66	55	54
Discharge	cfs	2.54	9.28	9.28
Temperature*	°C	11.1	13.4	12.8
Specific conductivity*	µmhos/cm	45	72	171
Dissolved oxygen	mg/l	6.4	5.4	5.6
O_2 saturation	%	56	50	53
pH*		5.6	6.5	7.0
Acidity as $CaCO_3$*	mg/l	21.3	17.1	17.7
Alkalinity as $CaCO_3$*	mg/l	10.1	28.8	74.5
Color*	mg/l	311	260	242
Suspended sediment	mg/l	5.1	5.3	5.4
Potassium	mg/l	1.24	0.99	1.15
Calcium*	mg/l	6.76	11.57	27.27
Magnesium*	mg/l	2.37	3.93	7.90
Aluminum*	mg/l	0.55	0.25	0.25
Iron	mg/l	2.64	2.07	2.37
Sodium*	mg/l	1.84	1.32	2.74
Manganese	mg/l	0.14	0.27	0.29
Mercury	µg/l	6	3	5
Arsenic*	µg/l	2	3	3
Selenium	µg/l	1	1	1
Total Phosphorus	mg/l	0.06	0.05	0.08
Total Kjeldahl Nitrogen	mg/l	1.5	1.6	1.8
Nitrate-N*	mg/l	0.06	0.05	0.08
Ammonia-N*	mg/l	0.1	0.2	0.2
Organic-N	mg/l	1.4	1.4	1.6
Humic Acid*	mg/l	11	9	8
Fulvic Acid*	mg/l	100	89	86
COD*	mg/l	118	104	97

* Significant difference among peatland types at α = 0.10.

1. Discharge

Peatland discharge, measured in cubic feet per second (cfs), was not different among peatland types or among the sampling periods. Discharge did not consistently correlate to any water quality characteristics which is contrary to the findings by Verry (1975). However, during three sampling periods, discharge was inversely correlated to color and during four periods discharge was directly correlated to location (Figure 11). It is reasonable to expect that lower discharges would be of a higher (darker) color because color forming materials would be more concentrated. Since the watershed area was found to correlate positively with location, i.e., increase from south to north, the discharge (cfs) would also increase with the watershed area from south to north (Table 24). The area discharge, expressed in cubic feet per second per square mile (CSM), also correlated poorly with water quality characteristics (Figure 11).

2. Temperature

The temperature of peatland runoff varied from 2 to 24°C during the sampling periods and was found to be normally distributed (Figure 12). The October 1980 sampling period was the coolest of the five periods and is responsible for the lower peak of the distribution in Figure 12. Peatland runoff temperature was different among peatland types during the September, 1979, and May and August, 1980, sampling periods, according to the analysis of variance. The two-way analysis of variance for all sampling periods revealed that runoff temperature varied among peatland types and for different seasons. In general, for each sampling period,

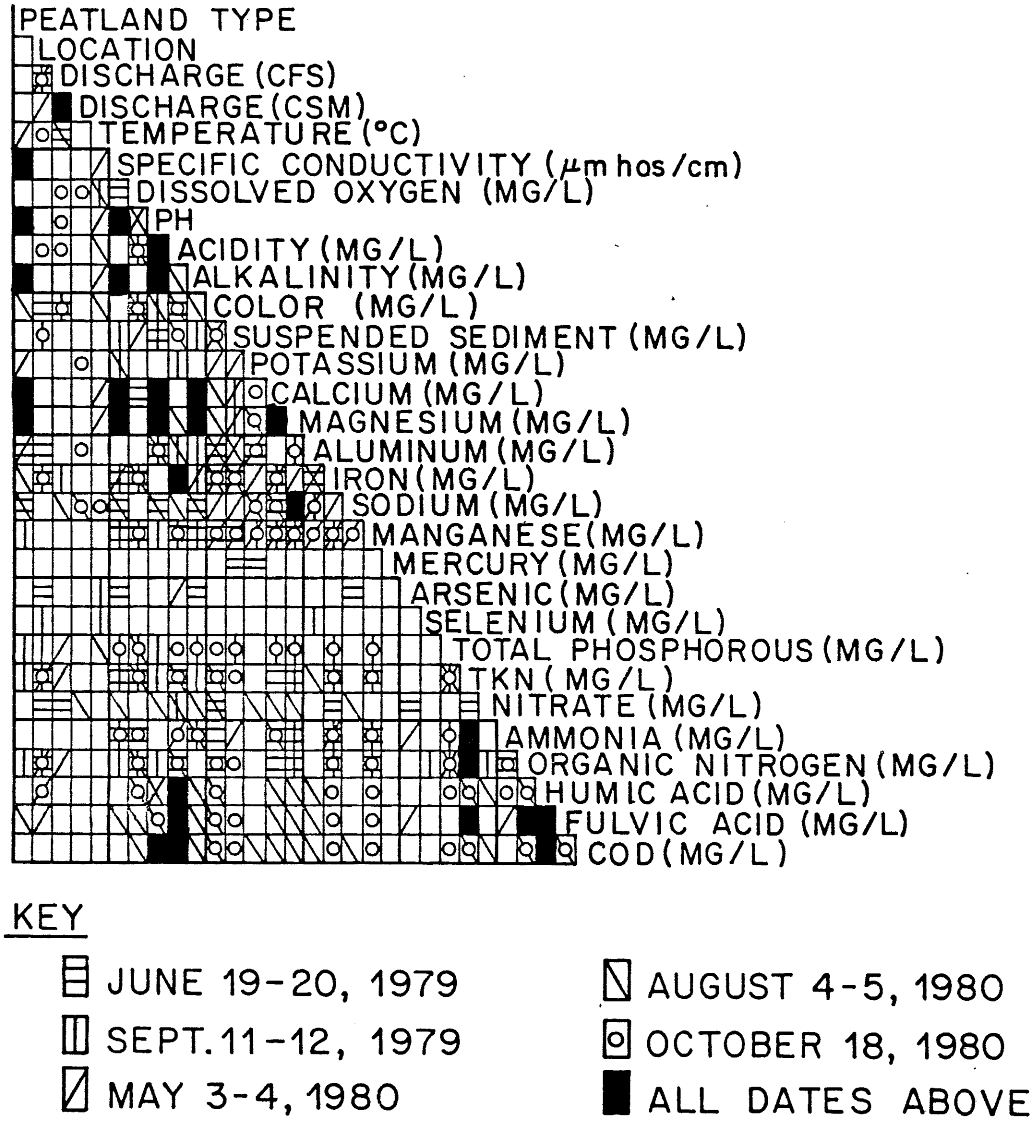

Figure 11. Matrix of water quality characteristics with significant ($\alpha = 0.05$) correlation coefficients for all peatland watersheds during each sampling period.

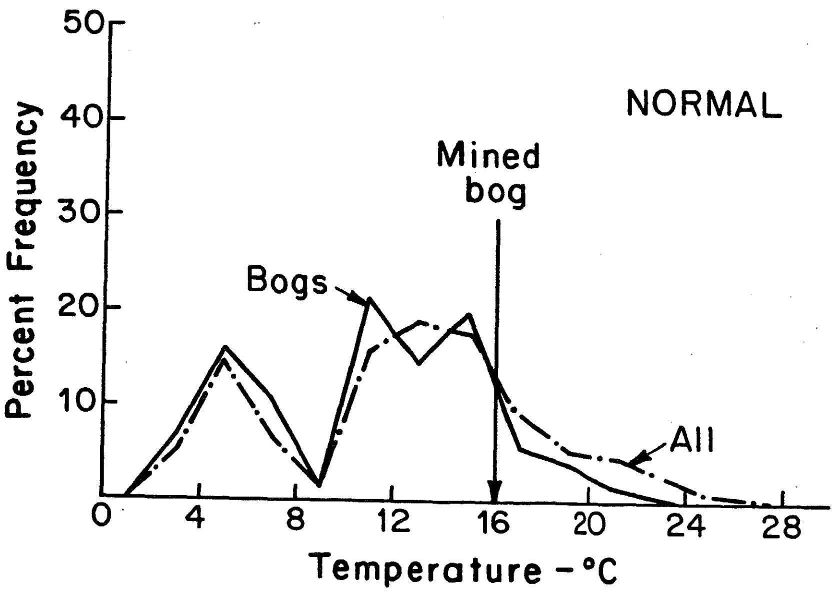

Figure 12. Frequency distributions of temperature in peatland runoff.

bog runoff was cooler than either transition or fen runoff. For the entire study period, bog runoff averaged about 2°C cooler than transition or fen runoff (Table 7). Temperature was positively correlated to the point discharge (cfs) but not the area discharge (CSM) and inversely related to dissolved oxygen during two sampling periods but not consistently during the study period (Figure 11). The temperature of runoff leaving peatland watersheds appears to be a function of watershed area.

3. Specific conductivity

The specific conductivity of runoff from all peatland types combined followed a log-normal distribution, although the conductivity of runoff from bogs appears to be normally distributed (Figure 13). Distribution-free analysis of variance of specific conductivity indicated differences among peatland types for all sampling periods. Fen runoff had the highest conductivity with an overall mean of 171 μmhos/cm, followed by transition runoff with a mean of 72 μmhos/cm, and bog runoff with a mean of 45 μmhos/cm (Table 7). These differences are in general agreement with Verry's (1975) results and are not surprising because specific conductivity was used to differentiate among the peatland types. The specific conductivity of peatland runoff was also found to be lower in May, 1980.

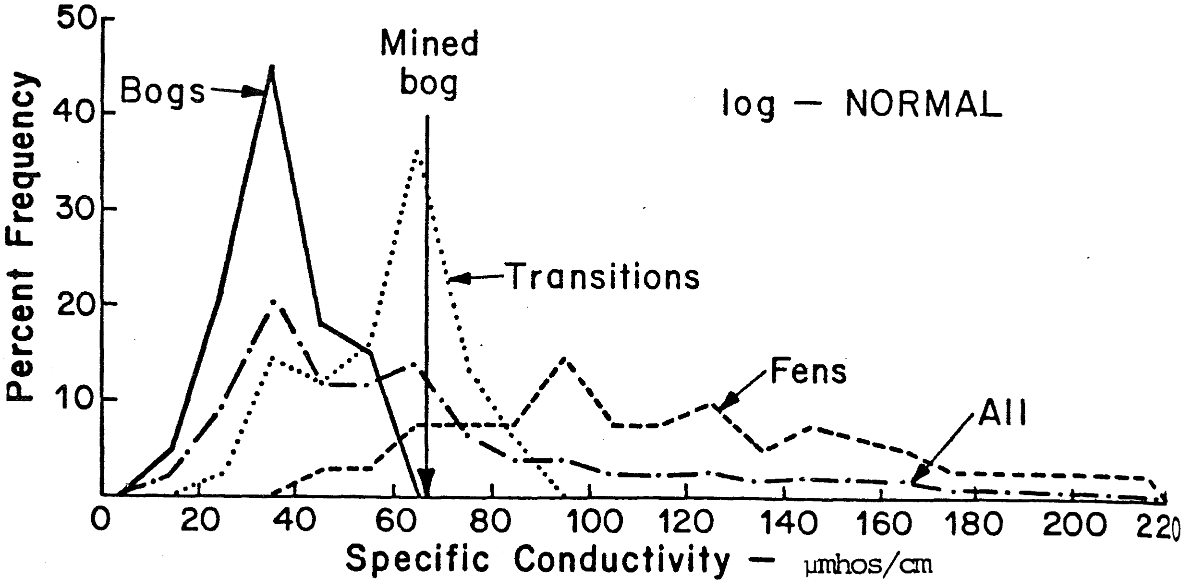

Figure 13. Frequency distribution of specific conductivity in peatland runoff.

Specific conductivity correlated positively with pH, alkalinity, calcium, and magnesium values during all five sampling periods (Figure 11). During three of the five periods, conductivity was also positively correlated with iron and ammonia concentrations. Such relationships are useful because the measurement of conductivity is easy and inexpensive and regressions may thus be used to predict the values of other characteristics.

4. Dissolved oxygen

The concentration of dissolved oxygen in peatland runoff follows a normal distribution (Figure 14). The two-way analysis of variance showed seasonal differences in dissolved oxygen and percent saturation, which were highest in May, 1980. The dissolved oxygen in bog runoff was greater than that of transition runoff for samples collected in June 1979. The percent saturation of bog runoff was greater than the percent in both transition and fen runoff during October 1980 sampling. However, there were no differences in the concentration of dissolved oxygen in bog, transition, or fen runoff for all samples combined.

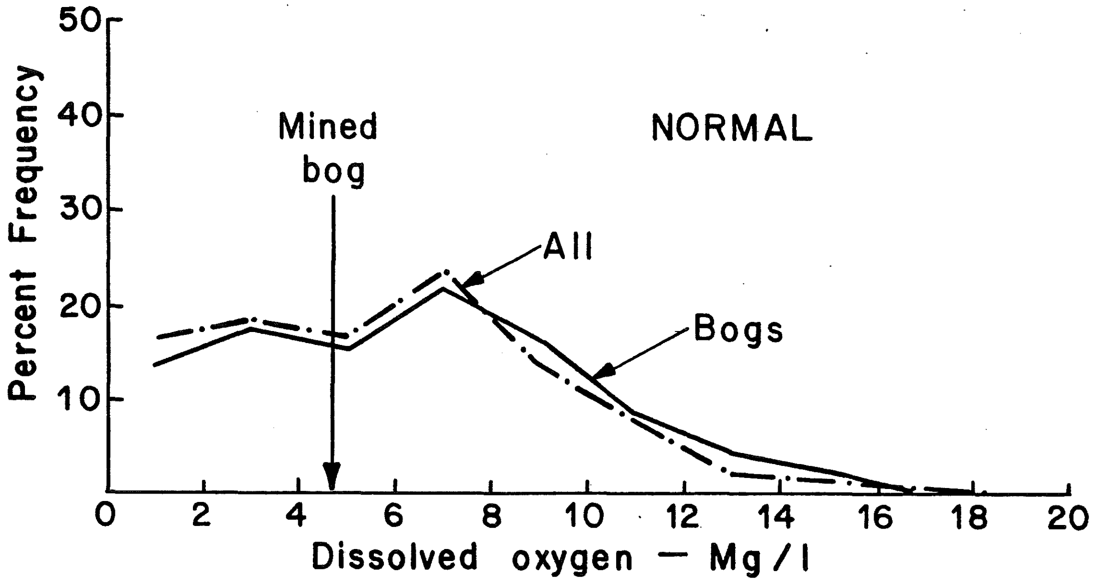

Figure 14. Frequency distribution of dissolved oxygen in peatland runoff.

Dissolved oxygen did not correlate with any other water quality characteristics during all five sampling periods. During four periods, dissolved oxygen correlated inversely with acidity, color, iron, and total and organic nitrogen; and during three periods with total phosphorus (Figure 11). Dissolved oxygen also related inversely to humic acid during two of the three periods humic acid was measured.

5. pH

The pH of peatland runoff, a characteristic used to distinguish among peatland types, was normally distributed (Figure 15). Bog runoff had the lowest mean pH of 5.6, transition runoff was intermediate at a pH of 6.5, and fen runoff had the highest mean pH of 7.0 (Table 32). These differences in pH occurred during all five sampling periods and for all samples combined. Verry (1975) also found bog runoff to be more acidic than fen runoff. Runoff pH also varied seasonally and was greatest for samples collected in August 1980.

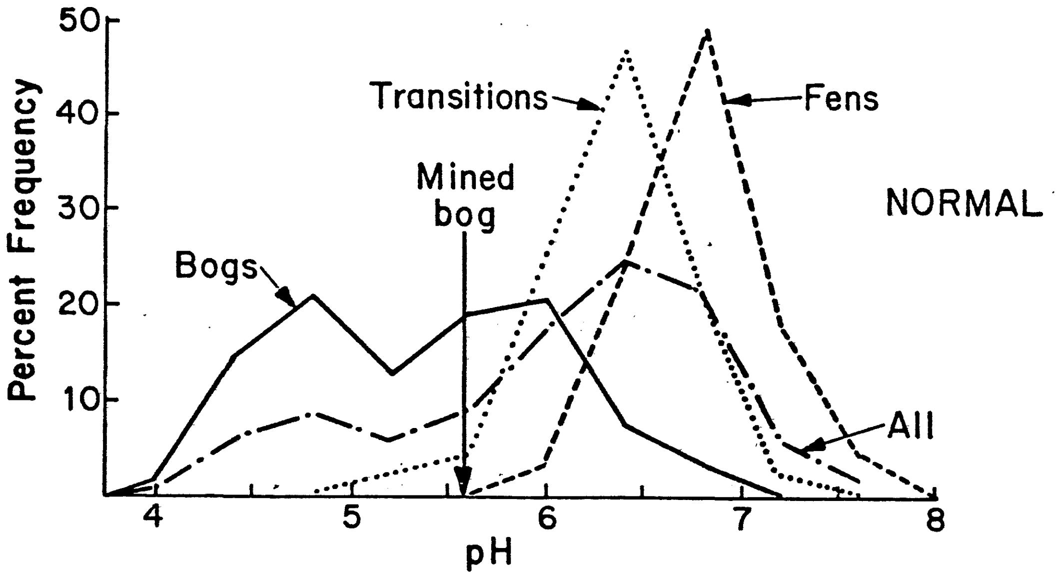

Figure 15. Frequency distribution of pH in peatland runoff.

The pH of peatland runoff correlated positively with specific conductivity, alkalinity, calcium, and magnesium and inversely with acidity and COD during all five sampling periods (Figure 11). Runoff pH also correlated inversely with aluminum during four sampling periods and with humic and fulvic acid during two of the three periods these characteristics were measured.

6. Acidity

The acidity concentration in peatland runoff follows a Pearson Type III distribution (Figure 16). Bog runoff averaged higher in acidity (21.3 mg/l) than either transition runoff (17.1 mg/l) or fen runoff (17.7 mg/l) for all samples combined (Table 7). A higher acidity concentration in bog runoff than in fen runoff has been reported by Verry (1975). The acidity concentrations in peatland runoff varied seasonally.

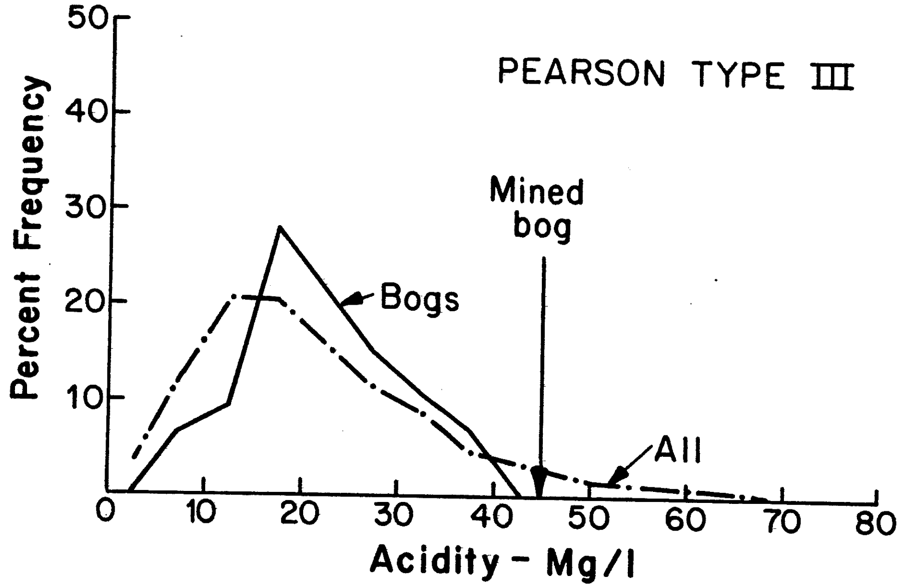

Figure 16. Frequency distribution of acidity in peatland runoff.

Acidity concentrations in peatland runoff correlated positively with humic acid, fulvic acid, and COD values during the three sample periods these characteristics were measured (Figure 11). Acidity also was positively correlated to iron during all five sampling periods.

7. Alkalinity

Alkalinity concentrations in peatland runoff were found to be log-normally distributed (Figure 17). Alkalinity was used to classify the peatlands and averaged lowest in bog runoff (10.1 mg/l), intermediate in transition runoff (28.8 mg/l), and was highest in fen runoff (74.5 mg/l) (Table 7). This trend among peatland types was consistent for all sampling periods. Alkalinity concentrations in peatland runoff varied among sampling periods and were lowest in May 1980. A significant date by type

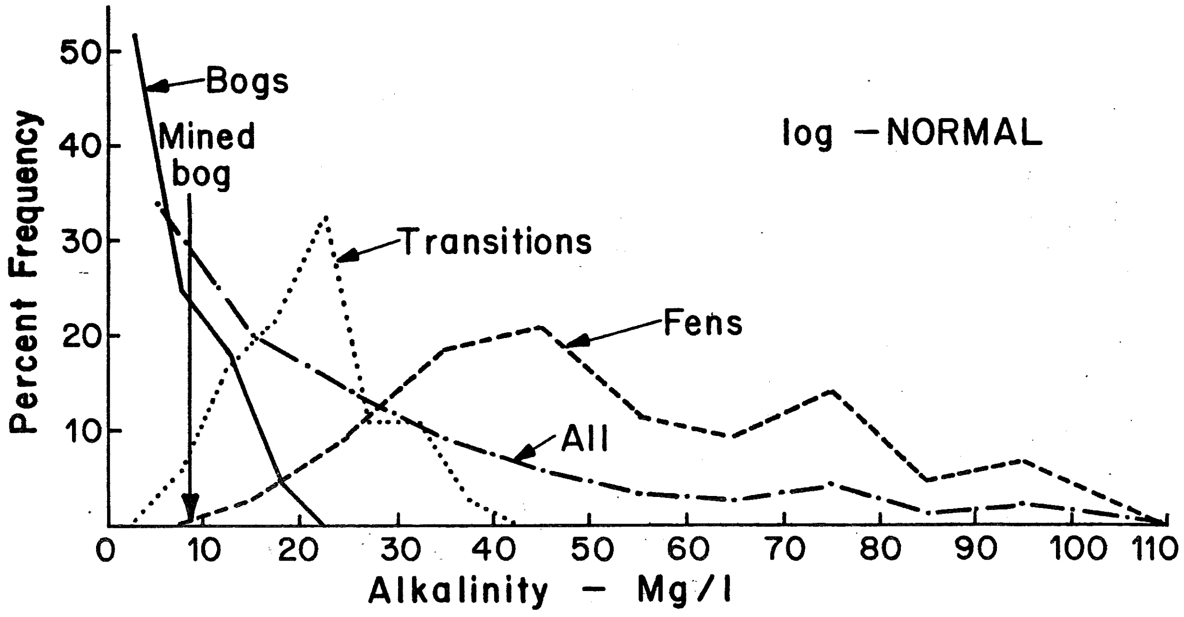

Figure 17. Frequency distribution of alkalinity in peatland runoff.

interaction occurred which may mean that certain peatland types may vary more than others. Boelter and Verry (1977) found bog runoff to be more variable in alkalinity than fen runoff.

Alkalinity concentrations correlated positively with values of specific conductivity, pH, calcium, and magnesium for all five sample periods (Figure 11). During four sampling periods alkalinity also correlated positively with ammonia nitrogen.

8. Color

The apparent color of peatland runoff follows a Pearson Type III distribution (Figure 18). Bog runoff averaged over 50 units (15 percent) higher in color than transition and fen runoff for all samples combined (Table 7). The color of peatland runoff varied among sampling periods.

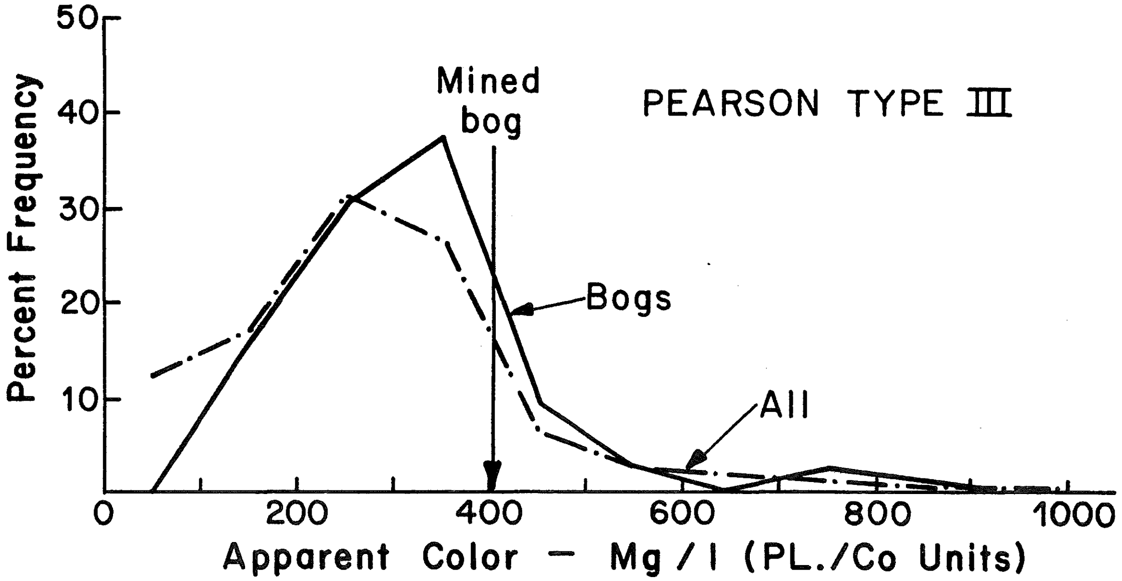

Figure 18. Frequency distribution of apparent color in peatland runoff.

These differences may be seasonal. Also, the date by type interaction was significant, indicating seasonal variation for certain peatland types.

Color did not correlate with any other water quality characteristic during all five sampling periods. However, during four periods color correlated positively with iron and inversely with dissolved oxygen (Figure 11). Color has been related to iron concentrations in lake waters (Lamar 1968). For two of the three periods that organic acids were measured, color correlated positively with humic acid, fulvic acid, and COD. Both humic and fulvic acids contribute to color (Shapiro 1964; Steelink 1977).

9. Suspended Sediment

The concentration of suspended sediment in peatland runoff follows a log-normal distribution (Figure 19). For the samples collected in June and September 1979, the runoff from bogs was lower in suspended sediment

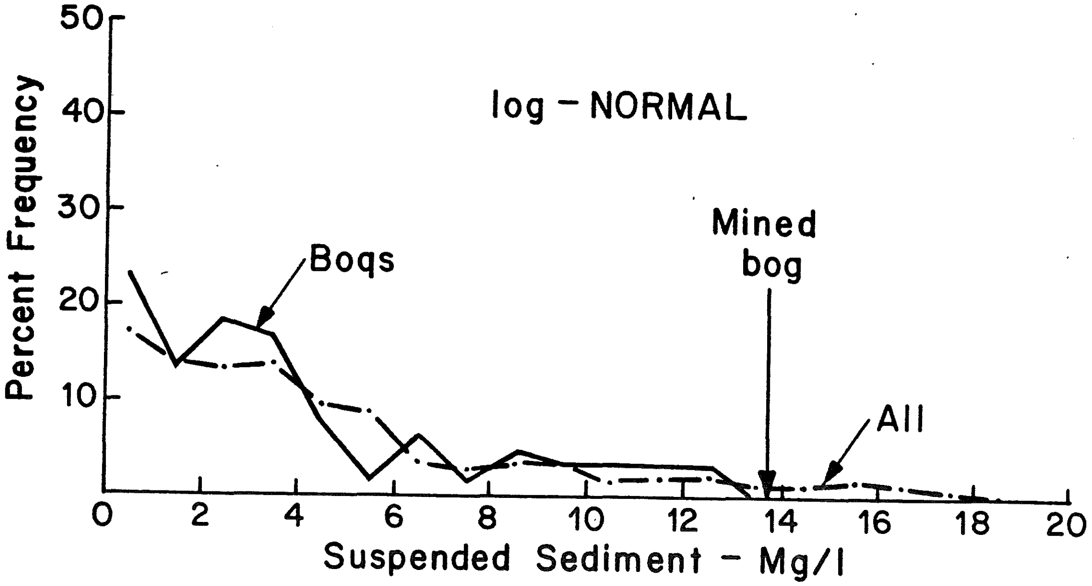

Figure 19. Frequency distribution of suspended sediment in peatland runoff.

than the fen runoff; however, no difference among peatland types occurred for all samples combined. Suspended sediment concentrations were lowest in May 1980.

Suspended sediment concentrations correlated positively with iron during four sampling periods and with color and manganese during three periods (Figure 11).

10. Potassium (K)

The concentration of potassium in peatland runoff follows a log-normal distribution. This distribution is expected for water quality characteristics at very low concentrations near detection limits (Moser and Huibregtse 1976). The overall mean concentration of potassium in peatland runoff was 1.13 mg/l which is near the detection limit of 0.72 mg/l (Tables 5, 7). Potassium concentrations were not different among peatland types but potassium values were higher in 1980 than in 1979. Potassium generally correlated poorly with other water quality characteristics. Potassium concentrations correlated positively with aluminum, sodium, and manganese concentrations during three of the five sampling periods (Figure 11).

11. Calcium (Ca)

The concentration of calcium in runoff for all peatland types combined follows a log-normal distribution (Figure 20). Average calcium concentrations were lowest in bog runoff (6.76 mg/l), intermediate in transition runoff (11.57 mg/l), and highest in fen runoff (27.27 mg/l) for all samples combined and during all five sampling periods. Since

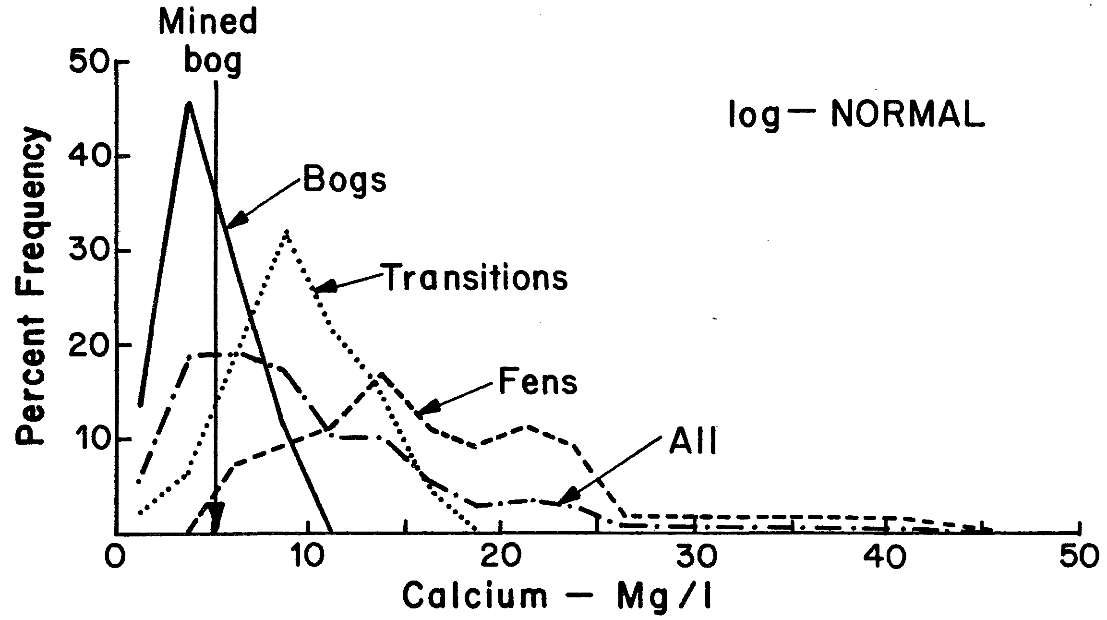

Figure 20. Frequency distribution of calcium in peatland runoff.

calcium concentrations were used to classify the watersheds into peatland types, it is not surprising that these differences occurred. Verry (1975) reported lower concentrations of calcium in bog runoff than in fen runoff. A significant date by type interaction was observed which indicates seasonal variability in some peatlands.

Calcium correlated positively with conductivity, pH, alkalinity, and magnesium during all five sampling periods (Figure 11). During four of these periods, calcium also correlated positively with iron and manganese.

12. Magnesium (Mg)

Similar to calcium, magnesium concentrations in runoff from all peatlands combined are log-normally distributed (Figure 21). During all five sampling periods, the concentration of magnesium in fen runoff was about

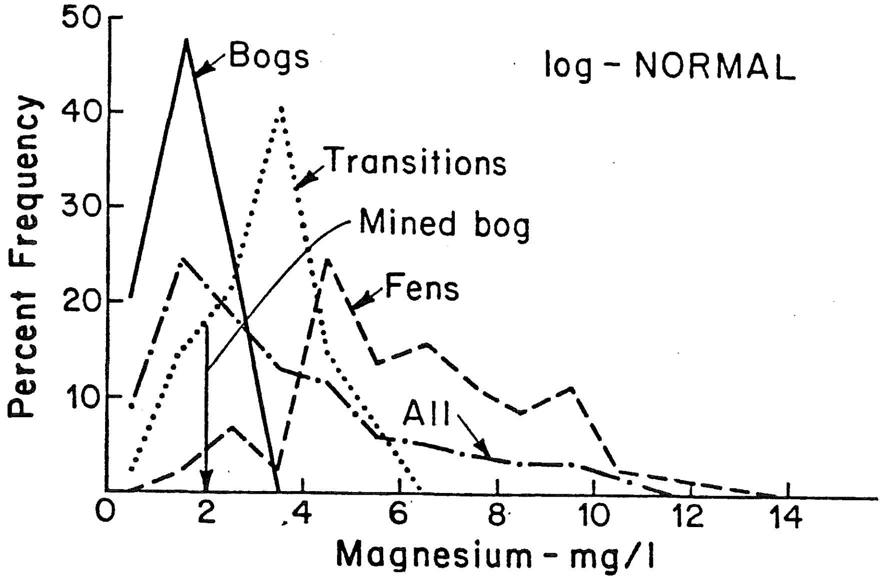

Figure 21. Frequency distribution of magnesium in peatland runoff.

twice as great as the concentration in either transition or bog runoff (Table 7). During the first three sampling periods, magnesium concentrations in transition runoff were also greater than in bog runoff. Like calcium, magnesium concentrations in peatland runoff were lowest in May of 1980. Also, a significant date by type interaction occurred for magnesium concentrations.

The concentration of magnesium in peatland runoff correlated positively with conductivity, pH, alkalinity, calcium, and sodium during all five sampling periods (Figure 11). Magnesium also correlated positively with manganese during four of these periods.

13. Aluminum (Al)

Like other cations in peatland runoff, aluminum concentrations are log-normally distributed. The mean aluminum concentration in bog runoff (0.55 mg/l) was about two times greater than in transition or fen runoff (0.25 mg/l) (Table 7). Aluminum is more soluble under the acidic conditions characteristic of bogs (Lucas and Davies 1961). The concentration of aluminum in peatland runoff varied among sampling periods.

Aluminum concentrations correlated inversely with pH during four sampling periods and positively with color, potassium, iron, and sodium during three of the five periods (Figure 11).

14. Iron (Fe)

Iron concentrations in peatland runoff follow a log-normal distribution (Figure 22). Generally, there was no difference in the concentration of iron in runoff from bogs, transitions, and fens (Table 7). Bog runoff

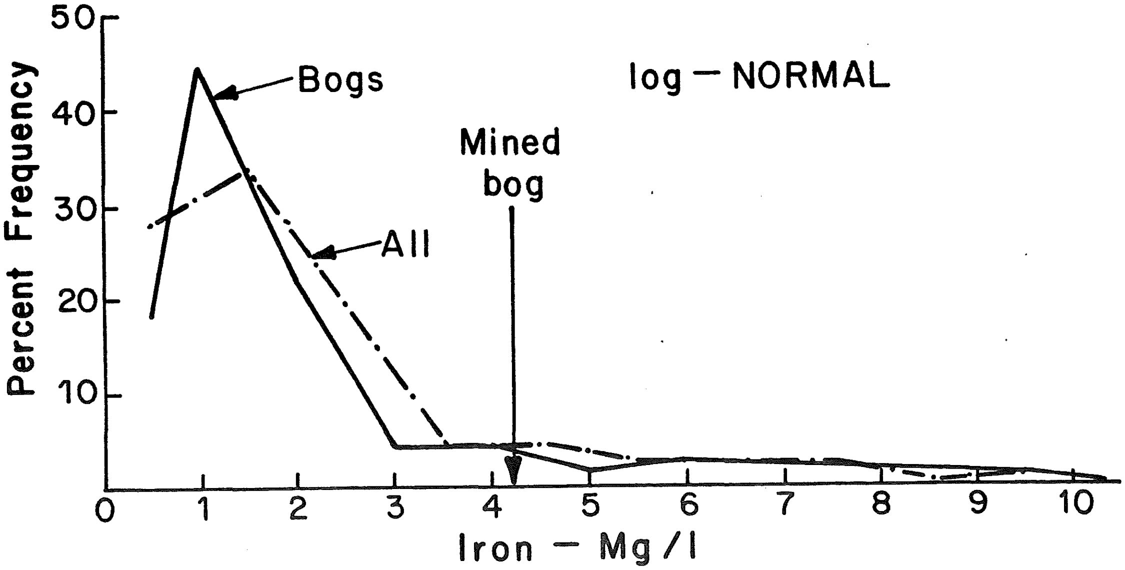

Figure 22. Frequency distribution of iron in peatland runoff.

contained about two times the iron concentrations of transition and fen runoff during the low-flow conditions in August, 1980. Iron concentrations were lowest in the spring of 1980.

Iron concentrations correlated positively with acidity during all five sampling periods (Figure 11). During four periods, iron correlated positively with color, suspended sediment, and aluminum values and correlated inversely with dissolved oxygen.

15. Sodium (Na)

The concentration of sodium in peatland runoff is log-normally distributed (Figure 23). Fen runoff contained about twice the concentration of sodium as transition and bog runoff during June, 1979, and August, 1980, but not during any other sampling periods. Verry (1975) in Minnesota and

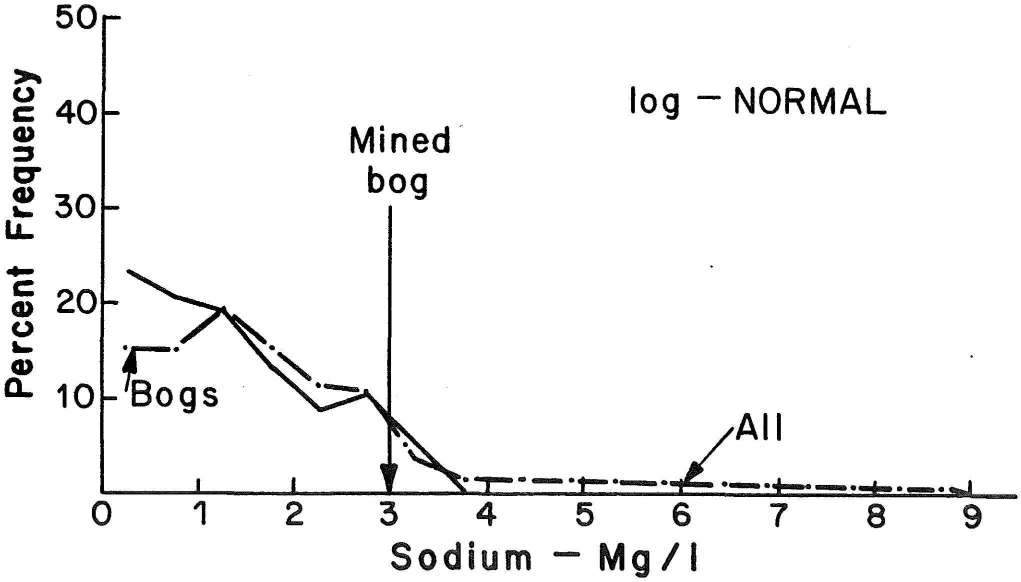

Figure 23. Frequency distribution of sodium in peatland runoff.

Tolonen and Seppanen (1976) in Finland also found greater concentrations of sodium in fen runoff than in bog runoff.

Sodium correlated positively with magnesium during all five sampling periods (Figure 11). During three periods, sodium correlated positively with potassium, calcium, and aluminum.

16. Manganese (Mn)

Like other cations found in low concentrations, manganese is distributed log-normally. The overall mean concentration of manganese in peatland runoff was 0.22 mg/l (Table 7). The concentration of manganese in fen runoff was greater than that in bog runoff for samples collected in September, 1979, and May, 1980. Both Verry (1975) and Tolonen and Seppanen (1976) found little difference in the manganese concentrations of bog and fen runoff. The concentration of manganese in runoff during the low-flow period in August, 1980, was much higher than during other sampling periods.

Manganese correlated positively with calcium, magnesium, and iron during four of the five sampling periods (Figure 11).

17. Mercury (Hg)

The concentration of mercury in peatland runoff is distributed log-normally. There was no difference in the concentration of mercury in runoff from bogs, transitions, and fens and concentrations were low, averaging 5 μg/l in peatland runoff (Table 7). Mercury concentrations correlated poorly with other water quality characteristics (Figure 11).

18. Arsenic (As)

The concentration of arsenic in peatland runoff is distributed log-normally (Figure 24). Arsenic concentrations in bog runoff were less than those in fen runoff during June, 1979, and were less than arsenic concentrations in transition runoff during September 1979. The concentration of arsenic in runoff samples collected in 1979 were higher than those collected in 1980. Arsenic concentrations correlated poorly with other water quality characteristics (Figure 11).

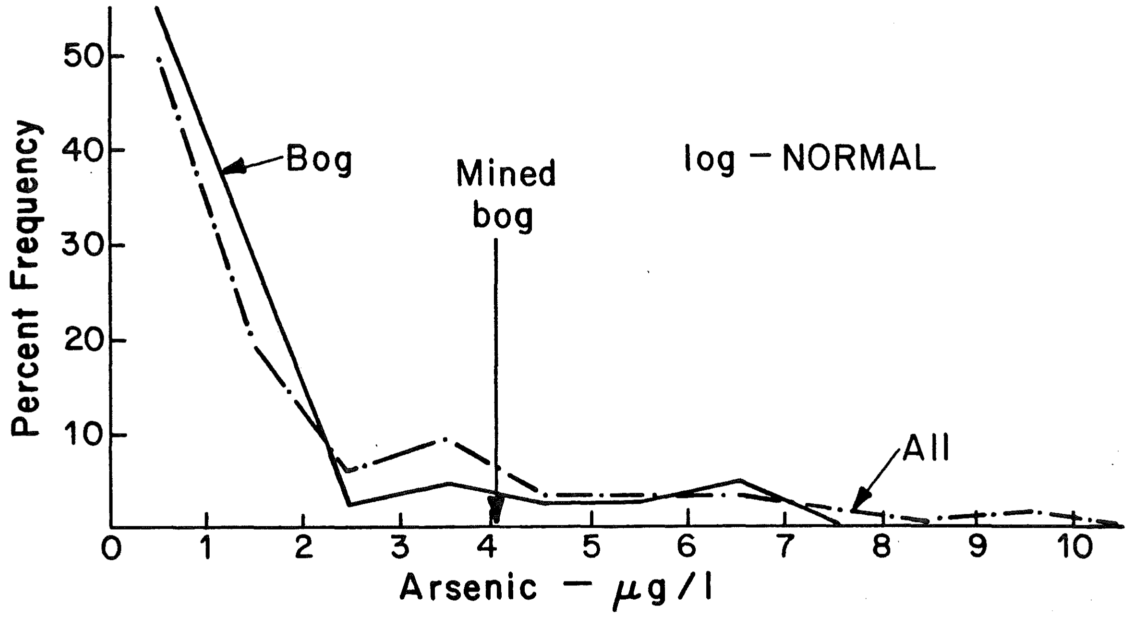

Figure 24. Frequency distribution of arsenic in peatland runoff.

19. Selenium (Se)

The overall mean concentration of selenium in peatland runoff was 1 μg/l which is also the detection limit (Table 5). Selenium concentrations follow a log-normal distribution and did not vary among peatland types (Table 7). However, higher selenium concentrations occurred in samples collected in June, 1979, than in September, 1979, or in May, 1980. There is no reasonable explanation for these differences. Selenium concentrations correlated poorly with other water quality characteristics (Figure 11).

20. Total phosphorus

The concentration of total phosphorus in peatland runoff is log-normally distributed (Figure 25). The concentration of total phosphorus ranged from 0.01 to 0.71 mg/l. The phosphorus concentrations in fen runoff

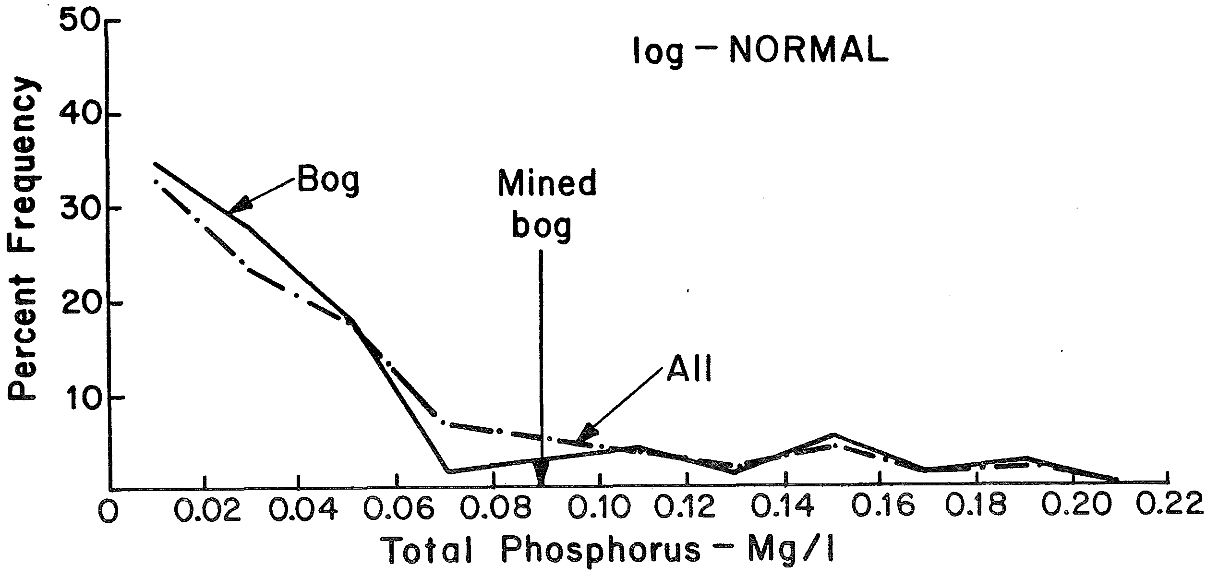

Figure 25. Frequency distribution of total phosphorus in peatland runoff.

were higher than in runoff from transitions and bogs during three of the five sampling periods but when all periods were analyzed together there was no difference (Table 7).

Verry (1975) found higher concentrations of total phosphorus in bog runoff than in fen runoff in Minnesota but Tolonen and Seppanen (1976) found no differences in phosphorus concentrations between bog and fen runoff in Finland. Total phosphorus correlated positively with total and organic nitrogen during all but the first sampling period in June, 1979 (Figure 11).

21. Total Kjeldahl Nitrogen (TKN)

The concentration of total Kjeldahl nitrogen in peatland runoff was found to fit a Pearson Type III distribution (Figure 26). Total Kjeldahl nitrogen in peatland runoff ranged from 0.3 to 4.4 mg/l. Generally, the concentration of TKN in runoff did not vary among peatland types (Table 7). However, samples collected during September, 1979 from fen runoff were higher in total nitrogen than those collected from transition or bog runoff. For the upland-peatland watersheds studied by Verry (1975), the bog runoff was higher in TKN than fen runoff. The concentration of TKN in peatland runoff sampled during the lowest flow observed (August 1980) was higher than the concentrations obtained during the four other periods.

Total Kjeldahl nitrogen concentrations correlated positively with ammonia and organic nitrogen and fulvic acid concentrations during all five sampling periods (Figure 11). The high correlation between TKN and organic nitrogen is expected because organic nitrogen is equal to the difference

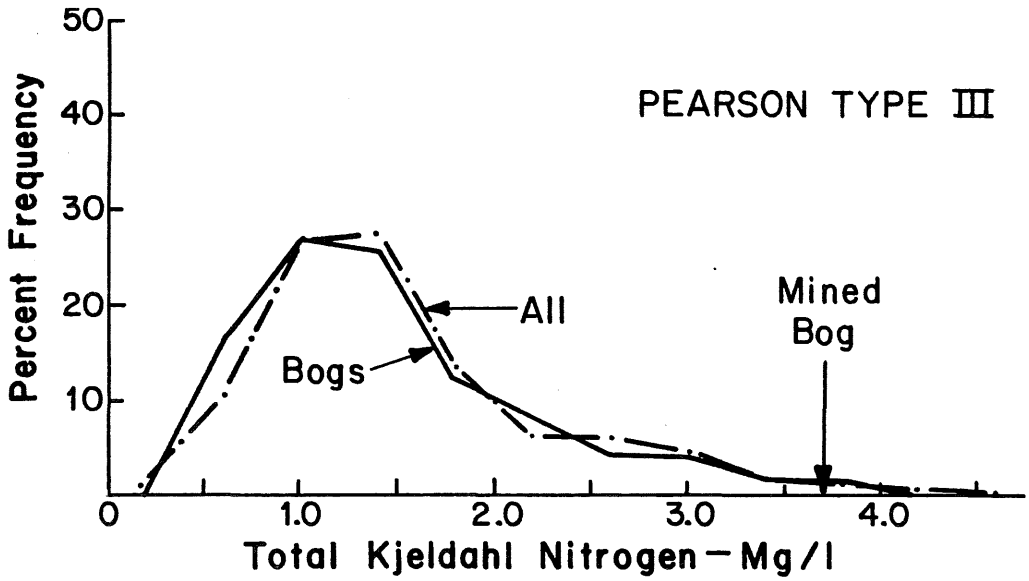

Figure 26. Frequency distribution of total Kjeldahl nitrogen in peatland runoff.

between total and ammonia nitrogen (American Public Health Association *et al.* 1975). During four sampling periods, TKN correlated positively with total phosphorus and inversely with dissolved oxygen. Total Kjeldahl nitrogen also correlated positively with humic acid and COD during two of the three sampling periods these characteristics were measured (Figure 11).

22. Nitrate nitrogen (NO_3-N)

The concentration of nitrate nitrogen in peatland runoff follows a log-normal distribution. The mean concentration of nitrate-N averaged 0.06 mg/l and ranged from 0.005 to 0.21 mg/l or about 25 percent of total nitrogen. Nitrate-N concentrations in fen runoff were higher than in either transition or bog runoff for all sampling periods combined (Table 7). Verry (1975) previously reported higher nitrate-N concentrations in bog runoff than in fen runoff. Nitrate-N varied with sampling date; higher concentrations were observed in the spring of 1980. Nitrate-N concentrations correlated poorly with other water quality characteristics (Figure 11).

23. Ammonia nitrogen (NH_4-N)

The concentration of ammonia nitrogen in peatland runoff averaged 0.17 mg/l and ranged from 0.10 to 2.0 mg/l (Table 7). The distribution of ammonia concentrations in peatland runoff is log-normal. The runoff from fens was higher in ammonia than the runoff from bogs during samples collected in 1979 but not during 1980, thus, little can be concluded about ammonia differences. Verry (1975) found higher concentrations of ammonia in bog runoff than in fen runoff in upland-peatland watersheds in Minnesota. However, Tolonen and Seppanen (1976) found no difference in the ammonia concentrations between bog and fen runoff in Finland.

Ammonia concentrations correlated positively to total nitrogen during all five sampling periods (Figure 11).

24. Organic nitrogen

The concentration of organic nitrogen in peatland runoff follows a Pearson Type III distribution as does total Kjeldahl nitrogen (Figure 27). Organic nitrogen concentrations ranged from 0.2 to 4.1 mg/l and constitute the major form of nitrogen in peatland runoff. The concentration of organic nitrogen was not consistently different among peatland types (Table 7). The organic nitrogen concentration during the low-flow period in August, 1980, was higher than other periods. The reducing conditions that typically prevail during low flow could cause the higher organic nitrogen.

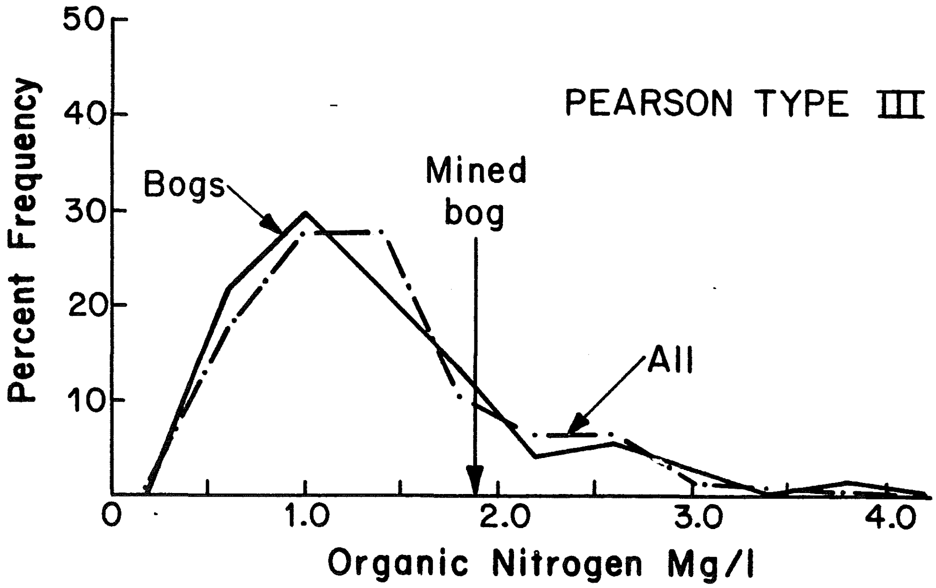

Figure 27. Frequency distribution of organic nitrogen in peatland runoff.

Organic nitrogen correlated positively with TKN during all five sampling periods (Figure 11). During four periods, organic nitrogen correlated positively with total phosphorus and inversely with dissolved oxygen.

25. Humic acid

The concentration of humic acid in peatland runoff follows a Pearson Type III distribution (Figure 28) with concentrations averaging from 5.0 to 12.0 mg/l. Greater humic acid concentrations occurred in bog runoff than in transition or fen runoff (Table 7). The concentration of humic acid in runoff was highest in all areas in the May 1980 period.

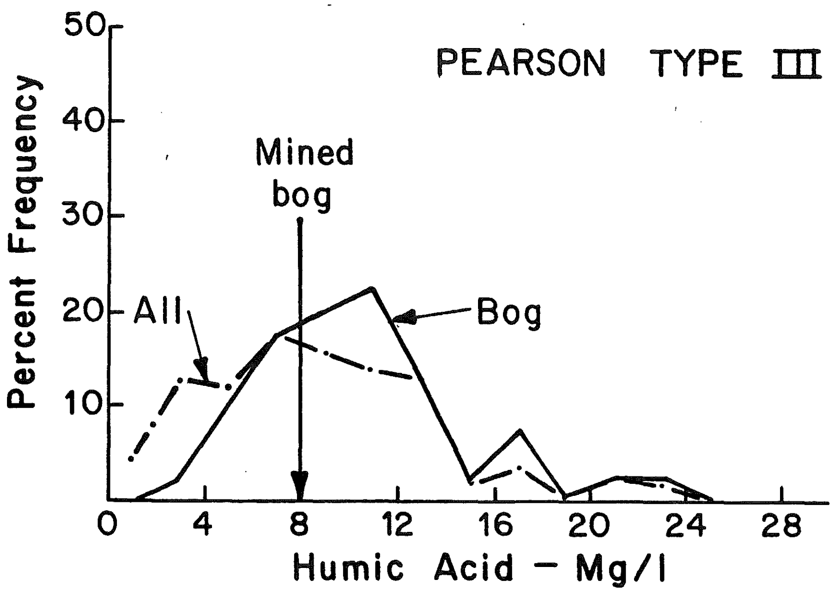

Figure 28. Frequency distribution of humic acid in peatland runoff.

Humic acid concentrations correlated positively with fulvic acid and COD during all three sampling periods humic acid was measured (Figure 11). During two of the three periods, humic acid correlated positively with color, total nitrogen and organic nitrogen and inversely with pH and dissolved oxygen. These correlations may be useful because the procedure for determining humic acid content is difficult.

26. Fulvic acid

The concentration of fulvic acid in peatland runoff was found to be normally distributed (Figure 29). Average fulvic acid concentrations were higher than humic acid values and ranged from 68 to 118 mg/l (Table 7). Largin (1976) also found more fulvic acid than humic acid in runoff from peatlands in the Soviet Union. Bog runoff was higher in fulvic acid

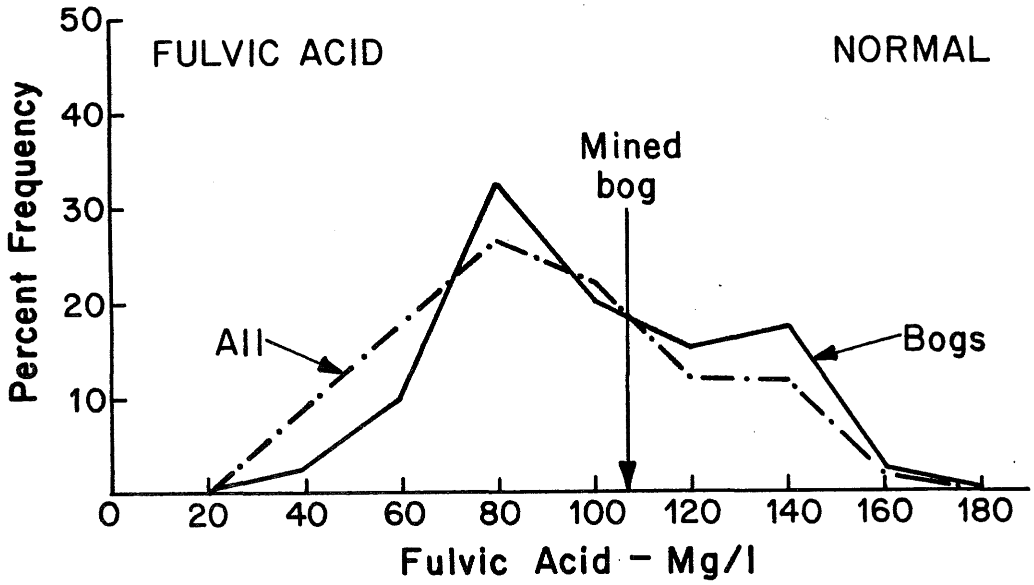

Figure 29. Frequency distribution of fulvic acid in peatland runoff.

concentrations than fen runoff for all sampling periods combined (Table 7). An increase in fulvic acid concentrations was observed from spring to fall in 1980.

Fulvic acid concentrations were positively correlated to humic acid, total and organic nitrogen, and acidity during all three sampling periods (Figure 11). During two periods, fulvic acid correlated positively with color and COD and inversely with pH.

27. Chemical oxygen demand (COD)

Like humic acid, COD appears to follow a Pearson Type III distribution (Figure 39). The average COD in peatland runoff ranged from 47 to 176 mg/l with bog runoff having higher concentrations of COD than fen

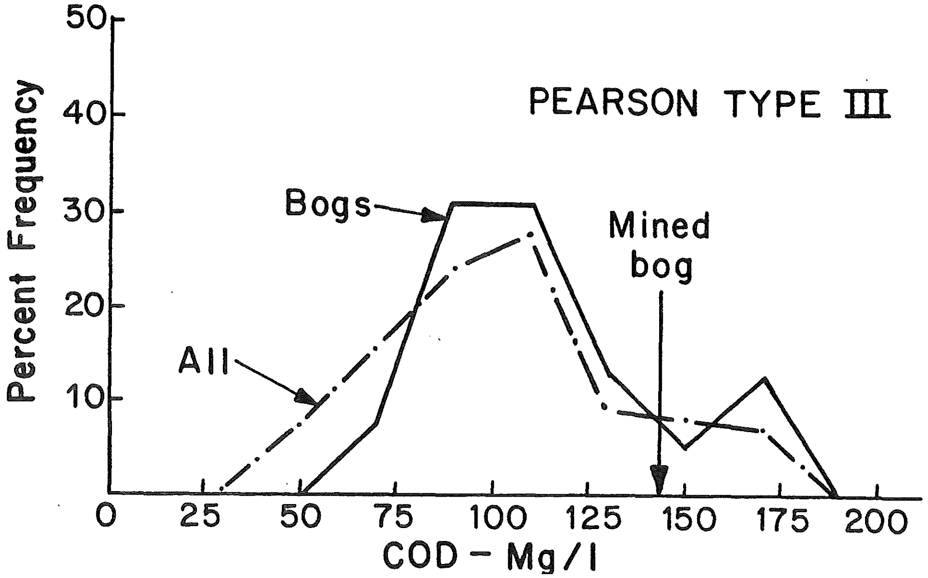

Figure 30. Frequency distribution of COD in peatland runoff.

runoff (Table 7). Concentrations of COD in peatland runoff followed a seasonal trend, increasing from spring to fall.

COD values were correlated positively to humic acid and acidity and inversely to pH during all three sampling periods. During two periods, COD was positively correlated to color, total nitrogen, and organic nitrogen (Figure 11).

Effects of Peat Mining

The effects of a single milled peat mining operation on runoff water quality, a major focus of this study, were estimated by using multiple watersheds. The multiple watershed approach, as developed during this study, entailed the following steps:

- Selecting several natural peatland watersheds (controls).

- Sampling the quality of runoff from these watersheds and from a mined bog (treatment) five times during different seasons and flow conditions.
- Classifying the watersheds, based on the quality of runoff, to determine which bog watersheds most resemble the mined bog watershed.
- Statistically comparing the quality of runoff from the mined bog watershed to the distribution of the quality of runoff from the natural bogs for each water quality characteristic.

Only the water quality characteristics which exhibited significant differences ($\alpha = 0.10$) between the mined bog and the natural bogs will be discussed below (Table 8).

1. Temperature

The temperature of runoff from the mined bog averaged 5°C higher than the temperature of runoff from the natural bogs (Table 8, Figure 12). The removal of both surface and riparian vegetation on the mined bog likely increased runoff temperature. Vegetation removal on peatlands has been reported to increase the surface peat temperature (Brown 1976). The increases in stream temperature following the removal of riparian vegetation are well documented in the western United States (Brown 1980).

2. Specific conductivity

The specific conductivity of runoff from the mined bog averaged 67 μmhos/cm which was 50 percent higher than the average conductivity of runoff from the natural bogs (45 μmhos/cm) (Table 8, Figure 13). The increased

Table 8. Mean values of water quality characteristics in runoff from the mined bog and the natural bogs for five sampling periods in 1979 and 1980.

Characteristic		Mined Bog	Natural Bogs
Number of samples		5	66
Discharge	cfs	1.02	1.70
Temperature*	°C	16.1	11.1
Specific Conductivity*	μmhos/cm	67	45
Dissolved Oxygen	mg/l	4.8	6.4
O_2 saturation	%	70	56
pH		5.6	5.6
Acidity as $CaCO_3$*	mg/l	45.0	21.3
Alkalinity as $CaCO_3$	mg/l	8.6	10.1
Color	mg/l	401	311
Suspended sediment*	mg/l	13.7	5.1
Potassium	mg/l	0.94	1.24
Calcium	mg/l	5.14	6.76
Magnesium	mg/l	2.03	2.37
Aluminum	mg/l	0.41	0.55
Iron	mg/l	4.26	2.64
Sodium	mg/l	3.00	1.84
Manganese	mg/l	0.16	0.14
Mercury	μg/l	4	6
Arsenic*	μg/l	4	2
Selenium	μg/l	1	1
Total Phosphorus	mg/l	0.09	0.06
Total Kjeldahl Nitrogen*	mg/l	3.7	1.5
Nitrate-N	mg/l	0.05	0.06
Ammonia-N*	mg/l	1.8	0.1
Organic-N*	mg/l	1.9	1.4
Humic Acid	mg/l	8[a]	11
Fulvic Acid	mg/l	136[a]	100
COD	mg/l	143[a]	118

[a] n = 1.

* significantly different at α = 0.10.

peat decomposition, caused by aeration after drainage, is suspected to cause a higher specific conductivity in mined bog runoff.

3. Dissolved oxygen

Althought no difference in the dissolved oxygen concentrations or the percent saturation between runoff from the mined bog and the natural bogs were observed for all periods (Table 8, Figure 14), some differences were observed during three periods. Natural bog runoff sampled in August and October of 1980 was higher in dissolved oxygen than mined bog runoff. During May, 1980, mined bog runoff was higher in dissolved oxygen. The percent saturation in runoff from the mined bog was higher in May and October, 1980, but lower in September, 1979, than that in runoff from the natural bogs. However, both dissolved oxygen and percent saturation values were lowest during the low-flow sampling period in August, 1980.

4. Acidity

The acidity of runoff from the mined bog was about twice that from natural bogs (Table 8, Figure 16). Runoff from the mined bog averaged 45.0 mg/l acidity compared to 21.3 mg/l acidity for natural bogs. Higher acidity in runoff from the mined bog could be caused by greater concentrations of hydrogen ions or humic acids (Hem 1970; McKee and Wolf 1963).

5. Suspended sediment

The suspended sediment concentration of runoff from the mined bog was greater (13.7 mg/l) than that from the natural bogs (5.1 mg/l) (Table 8, Figure 16). These values are small compared to other studies of land use effects on suspended sediment in runoff from mineral soils (Brown 1980).

Largin (1976) reported no difference in suspended sediment concentrations of runoff from mined and unmined bogs in the Soviet Union. Both water and wind erosion of the bare peat surfaces on the mined bog are probably responsible for the higher suspended sediment concentrations in mined bog runoff.

6. Arsenic

The concentration of arsenic in runoff from the mined bog averaged 4 μg/l which was about twice as great as the average arsenic concentration in runoff from the natural bogs (2 μg/l) (Table 8, Figure 24). These values are low in relation to the U.S. Public Health Service drinking water standard of 50 μg/l arsenic (U.S. Department of Health, Education, and Welfare 1969). It is not known why greater concentrations of arsenic, even at the low values observed, occurred in runoff from the mined bog.

7. Total Kjeldahl nitrogen

The concentration of total Kjeldahl nitrogen in runoff from the mined bog was slightly more than twice that from the natural bogs (Table 8, Figure 26). Increased peat decomposition, caused by drainage in the mined bog, is probably responsible for the greater concentration of total nitrogen in mined bog runoff (Avnimelech *et al.* 1978).

8. Ammonia nitrogen

The concentration of ammonia nitrogen averaged 1.8 mg/l in runoff from the mined bog and 0.1 mg/l in runoff from the natural bogs (Table 8). This difference is likely caused by increased peat decomposition in the mined bog. Ammonia accounted for 49 percent of total nitrogen in runoff from the mined bog but only seven percent of total nitrogen in natural bog runoff.

9. Organic nitrogen

The concentration of organic nitrogen in runoff from the mined bog was higher than in runoff from the natural bogs (Table 8, Figure 27). Runoff from the mined bog averaged 1.9 mg/l of organic nitrogen whereas runoff from the natural bogs averaged 1.4 mg/l organic nitrogen. Organic nitrogen accounted for 51 percent of total nitrogen in mined bog runoff compared to 93 percent of total nitrogen in natural bog runoff.

10. Other characteristics

There was no difference ($\alpha = 0.10$) in values for pH, alkalinity, K, Ca, Mg, Al, Na, Hg, Se, nitrate nitrogen, humic acid, fulvic acid, and COD in runoff from the mined bog as compared to the natural bogs (Table 8). Mined bog runoff was higher in color (darker) than natural bog runoff for samples collected in October, 1980. Iron and manganese concentrations were higher in mined bog runoff than in natural bog runoff for samples collected in May, 1980. Total phosphorus concentrations were higher in mined bog runoff than in natural bog runoff for samples collected in September, 1979. Largin (1976) reported greater values for pH, Ca, and Mg in runoff from mined bogs as compared to unmined bogs in the Soviet Union, however, such differences were not observed here. Largin *et al.* (1976) further noted that values for pH, Ca, Mg, and humic and fulvic acid in runoff increased with the age of drainage.

Corona Mined vs. Control

Runoff from the Corona mined area was also compared to the unmined "control" bog adjacent to the mined area. Runoff from the mined bog was higher in suspended sediment, color, acidity, Na, Al, total phosphorus, total Kjeldahl nitrogen, ammonia nitrogen, organic nitrogen, COD, humic acid, and fulvic acid but was lower in pH, specific conductivity, alkalinity, Ca, Mg and Fe than runoff from the control (Table 9). The differences related to dissolved cations, i.e., pH, conductivity, etc. were believed to be due to the influence of mineral soil at the control outlet. However, the differences in nutrients and suspended sediment are consistent with the multiple watershed results and are believed to result from peat mining.

Considerable water quality variation was evident in dissolved oxygen, sediment, nutrient and humic substance concentrations over the sampling period (Figures 31 to 33). Many metal cations (trace elements) were found to be below or at the detection limits for these constituents (Table 9).

Unlike the peatland study above, the comparison of samples from the mined and control area showed no significant difference in temperature or arsenic. Differences in color, total phosphorus, humic acid, fulvic acid and COD, not indicated by the peatland study, were apparent between mined and control areas (Table 9, Figures 31 to 33). However, these characteristics did differ at least once of the five sampling periods of the peatland study. Aside from these differences, this comparison of the mined to a nearby control area tends to substantiate the observations found from the larger peatland study.

Table 9. Corona water summary, 1978-1981.

		Means	
Parameter	Units	Mined	Control
Temperature	°C	11	9
pH*		5.2	6.1
Specific conductivity*	μmhos/cm	68	92
Dissolved oxygen	mg/l	4.8	4.3
% Saturation	%	44	40
Color*	Pl-Co units	379	321
Acidity*	mg/l $CaCO_3$	47.2	41.0
Alkalinity*	mg/l $CaCO_3$	10.1	37.7
Suspended sediment*	mg/l	17.5	7.6
K	mg/l	1.88	1.62
Ca*	mg/l	4.63	15.05
Mg*	mg/l	1.86	5.02
Na*	mg/l	3.24	2.22
Fe*	mg/l	4.16	5.86
Al*	mg/l	0.70	0.30
Mn	mg/l	0.16	0.15
Zn	mg/l	0.07	0.10
Cu	mg/l	<0.01	<0.01
B	mg/l	0.01	0.01
Pb	mg/l	<0.13	<0.13
Ni	mg/l	<0.04	<0.04
Cr	mg/l	0.02	0.02
Cd	mg/l	<0.01	0.02
Co	mg/l	0.24	0.92
Hg	μg/l	2	1
As	μg/l	2	2
Se	μg/l	1	<1
Total-P*	mg/l	0.12	0.08
Total Kjeldahl N*	mg/l	3.76	2.42
NO_3-N	mg/l	0.19	0.07
NO_2 - N	mg/l	0.01	0.02
NH_4 - N*	mg/l	1.98	1.30
Organic N*	mg/l	1.79	1.12
COD*	mg/l	143	71
Humic acid*	mg/l	8	3
Fulvic acid*	mg/l	132	68

* Significant difference between mined and control areas at $\alpha = .10$.

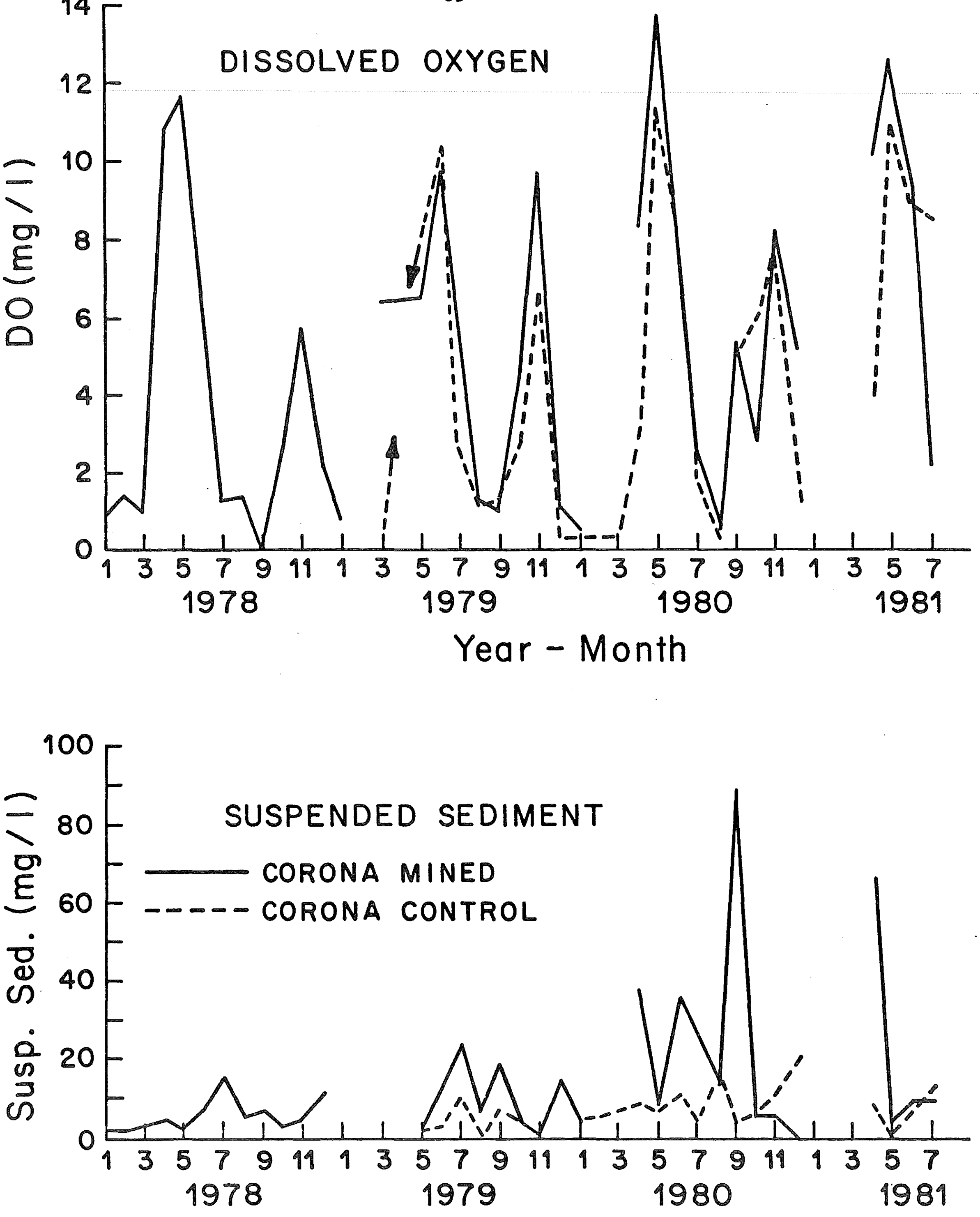

Figure 31. Dissolved oxygen and suspended sediment concentrations for Corona mined and Corona control.

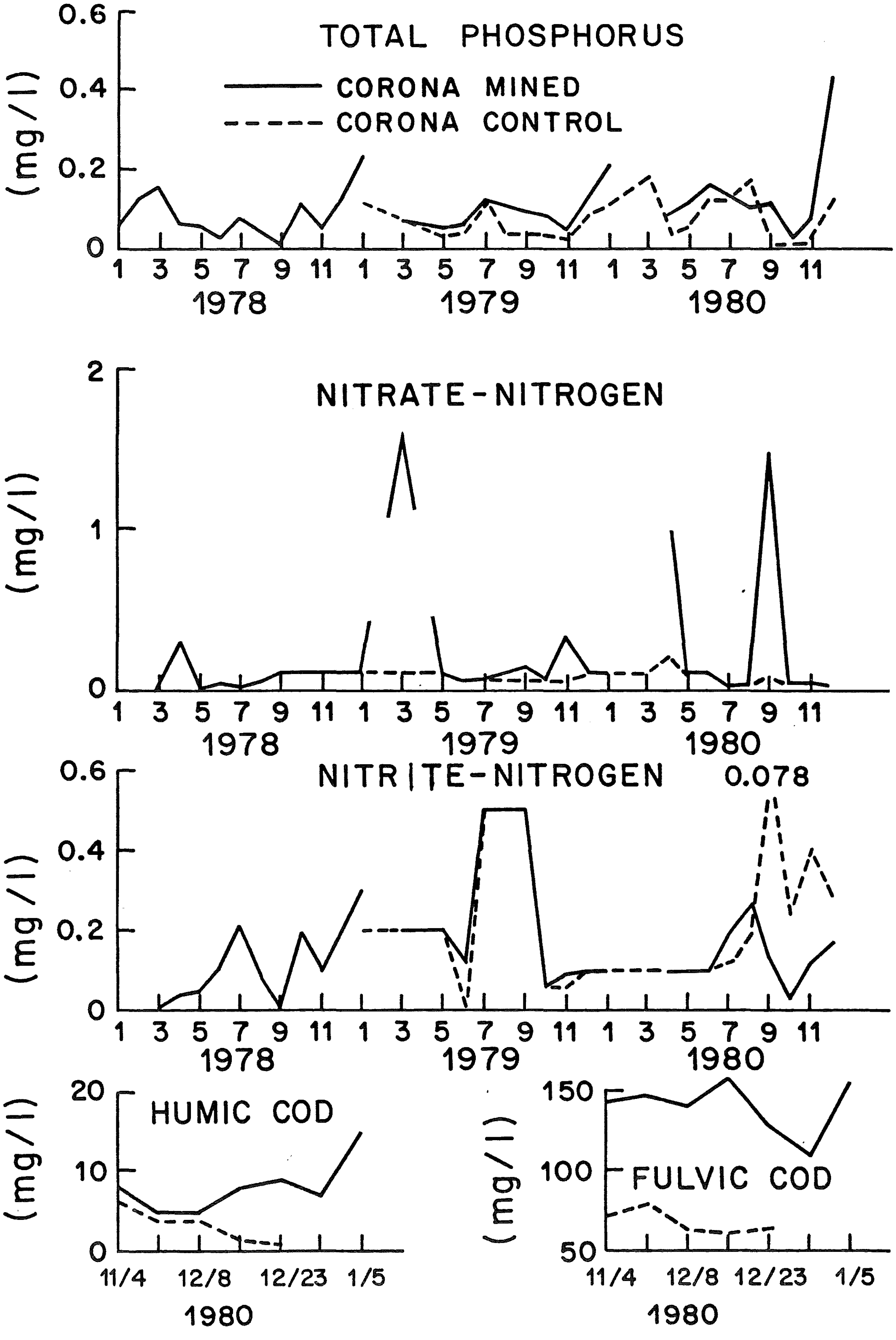

Figure 32. Total phosphorus, nitrate-nitrogen, nitrite-nitrogen, humic and fulvic acid concentrations for Corona mined and Corona control.

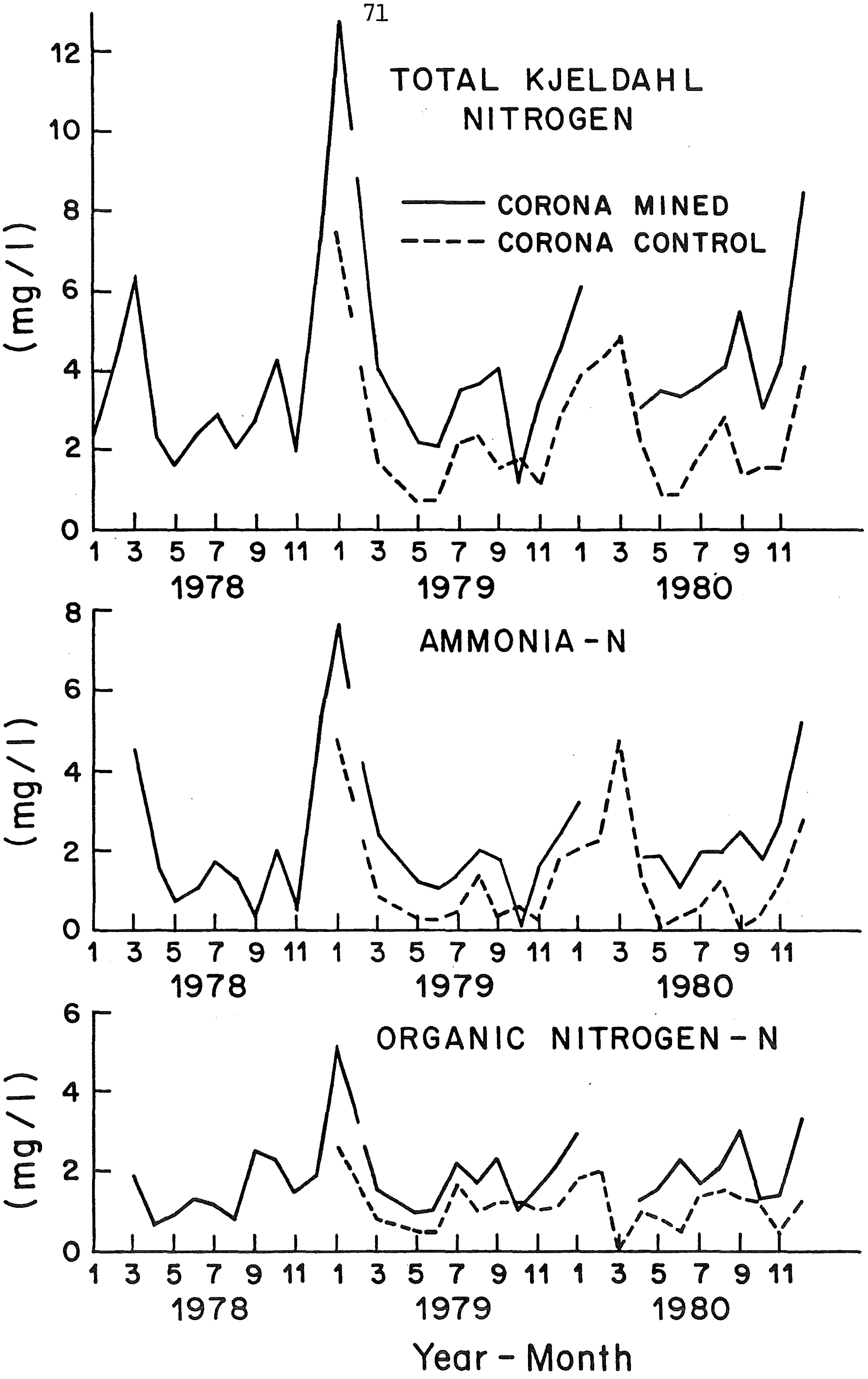

Figure 33. Total Kjeldahl-nitrogen, ammonia-N and organic-N for Corona mined and Corona control.

Implications of Water Quality Changes

The changes in runoff water quality resulting from peat mining could have several implications. The 5°C average rise in runoff temperature could reduce the suitability of the runoff for downstream cold water fish, such as trout. The increases in specific conductivity and acidity are not expected to affect downstream aquatic life or the suitability of the water for other uses. Greater suspended sediment in runoff from the mined bog could reduce light penetration and thus inhibit plant growth and oxygen production but is not expected to directly affect fish life at the levels measured. However, suspended sediment fibers may carry nutrients to downstream waters. Arsenic concentrations in runoff from both the mined bog and the natural bogs are well below drinking water standards. The greater nitrogen concentrations in runoff from the mined bog as compared to the natural bogs may be of some significance. The total nitrogen concentration of mined bog runoff is similar to that of agricultural runoff in the eastern United States (Omernik 1976). The mean concentration of total nitrogen in mined bog runoff (3.7 mg/l) far exceeds the 0.6 mg/l concentration at which excessive algal growths may occur (MacKenthun 1969). Although little nitrate nitrogen is found in runoff from the mined bog and the natural bogs, the ammonia nitrogen in the mined bog runoff could be nitrified to nitrate in downstream aerobic water bodies. Nitrate nitrogen is readily available to plants for growth (MacKenthun 1969).

Any changes in water quality as a result of peat mining are influenced by changes in discharge timing and volume. The water yield effects of peat mining are discussed in the water quantity section of this study.

Dredged Ponds

Two ponds at the Fens study site were excavated and their water quality monitored. The north pond was dredged to mineral soil while the south pond was dredged so that a layer of peat remained on the pond bottom. Analysis of variance revealed that pH, conductivity, alkalinity, Ca, Mg, Na, COD, humic acid and fulvic acid were greater in the mineral pond than in the peat pond (Table 10). Values of color, acidity and K in the peat pond were greater than those of the mineral pond. Concentrations of the minor metal cations were low, most did not exceed detection limits. No differences in nutrient concentrations were found between the two ponds. Those constituents which were found to be significantly (α = .10) different for the two ponds can be explained by the bottom substrate present in each pond. The exposed mineral soil bottom of the north pond results in increased major ion concentrations due to interaction of water with the mineral substrate. These major ion (Ca, Mg, Na) concentrations also result in the higher specific conductivity of the north pond. The mineral sediment consists of a greyish clay, probably containing carbonate minerals. The presence of these carbonates in the mineral pond water may be seen in the concentrations of Ca and Mg ions and the alkalinity value which is predominantly influenced by bicarbonate ions at pH 7.6 (Hem 1970). The values of these constituents in the mineral pond are double those in the

Table 10. Fens ponds water quality summary.

Parameter	Units	North Pond Mean	South Pond Mean
Temperature	°C	9	9
pH*	units	7.6	7.2
Specific conductivity*	µmhos/cm	133	73
D.O.	mg/l	9.4	8.9
% saturation	%	82	77
Color*	Pl-Co units	62	82
Acidity*	mg/l $CaCO_3$	5.9	7.2
Alkalinity*	mg/l $CaCO_3$	58.2	25.0
K*	mg/l	2.58	3.52
Ca*	mg/l	20.97	10.25
Mg*	mg/l	7.65	4.01
Na	mg/l	4.82	3.80*
Al	mg/l	1.35	2.20
Fe	mg/l	.12	.34
Mn	mg/l	.03	.06
Zn	mg/l	.07	.12
Cu	mg/l	<.01	<.01
B	mg/l	<.01	<.01
Pb	mg/l	<.13	<.13
Ni	mg/l	≤.04	≤.04
Cr	mg/l	<.01	<.01
Cd	mg/l	<.01	<.01
Hg	µg/l	2	1
As	µg/l	1	1
Se	µg/l	<1	<1
TP	mg/l	.04	.04
NO_3	mg/l	.24	.13
NO_2	mg/l	<.01	<.01
NH_4	mg/l	<.1	<.1
TKN	mg/l	1.7	1.8
ON	mg/l	1.6	1.7
COD*	mg/l	95	67
Humic acid*	mg/l	9	3
Fulvic acid*	mg/l	80	62

* Significant difference between ponds at $\alpha = .10$.

peat pond (Table 10). Alkalinity buffers the mineral pond pH, retarding the influence of low pH inputs. However, the small difference in pH between the two ponds indicates this buffering capacity may be slight and may simply indicate that the major source of water to these ponds is the surrounding groundwater. The differences in COD, humic and fulvic acid is based on three pairs of samples, thus the significance of these differences may be suspect.

Seasonal differences were apparent for temperature, DO, percent saturation, conductivity, acidity, K, Ca, total phosphorus, total Kjeldahl nitrogen, ammonia-N, and organic nitrogen. Dissolved oxygen was lowest in the winter periods when ice isolated the liquid water in peat ponds from the atmosphere and when photosynthetic activity was minimal. The ponds entered the ice periods each year with DO in excess of 10 mg/l. DO measured 2.5 to 5.0 mg/l immediately before the ice (often 2 feet thick) began to break up. Such low values would be of importance for fish because the minimum limit for water containing fish is considered to be 5 mg/l DO (McKee and Wolf 1963). DO levels rose to 10 mg/l during the spring season then dropped to 7 to 8 mg/l in July and August. This drop can be associated with warm temperatures lowering the solubility of oxygen. Acidity, K, Ca, TP, TKN, and organic-N appeared to be higher in the winter than summer. Accumulations of carbon dioxide under the ice can account for the rise in acidity. The pH also dropped but was not considered significant. Nutrient concentrations may rise in winter due to plant release upon senescence, and a reduction of the volume of water containing these constituents. Since ice cover often reached 2 to 2½ feet in thickness and the depth of water averaged 4 to 5 feet, this decrease in volume could in itself cause concentrations to rise.

The nitrogen and phosphorus nutrient levels appear low (Table 10). However, both nutrients stimulate algal growth even at "low" levels. Phosphorus levels of 0.05 mg/l and total nitrogen concentrations of 0.3 to 0.6 mg/l may be sufficient to promote excessive algal growth (McKee and Wolf 1963). No algal blooms were observed at the ponds. The concentrations of phosphorus and nitrogen are not as critical as the form in which these nutrients are present. It is possible that nitrogen is predominantly in organic form, locked up in suspended ditritus. Nitrate-N often fell below detection limits. The major source of nitrogen in these ponds is apparently an organic form and must be altered for use by aquatic plants. Likewise, total phosphorus may be absorbed to humic substances or iron oxides at pH 7-8 (Clausen and Brooks 1980). This binding effect reduces availability of the phosphorus to algae.

Other Study Areas

Streamflow water quality samples were also taken at the Toivola, Tamarac River and Fens study areas. Mean values of constituents in these areas are presented in Tables 11 and 12. Although no statistical analysis was performed on these data, some general observations are made. The undisturbed natural peatlands, Toivola and Tamarac River, are transition and fen areas, respectively, according to the water quality criteria previously discussed (Table 6). Metals are at levels near or below detection limits (Table 11). Total phosphorus and iron concentrations are quite high on

Table 11. Toivola and Tamarac water quality summary, 1978-1980.

		Mean	
Parameter	Units	Toivola	Tamarac
Temperature	°C	9	13
pH	units	6.2	7.1
Specific conductivity	μmhos/cm	55	121
DO	mg/l	5.7	7.2
% saturation	%	50	71
Color	Pl-Co units	255	119
Acidity	mg/l $CaCO_3$	20.8	50.4
Alkalinity	mg/l $CaCO_3$	29.6	69.9
Suspended sediment	mg/l	5.6	6.6
K	mg/l	1.75	1.161
Ca	mg/l	11.1	21.52
Mg	mg/l	3.18	7.49
Na	mg/l	1.95	2.00
Fe	mg/l	3.13	.58
Al	mg/l	1.48	.50
Mn	mg/l	1.00	.23
Zn	mg/l	.24	.04
Cu	mg/l	.02	<.01
B	mg/l	<.01	<.01
Pb	mg/l	<.13	<.13
Ni	mg/l	<.04	<.04
Cr	mg/l	<.01	<.01
Cd	mg/l	<.01	<.01
Co	mg/l	.22	.15
Hg	μg/l	1	2
As	μg/l	<1	<1
Se	μg/l	<1	<1
TP	mg/l	.36	.06
NO_3-N	mg/l	.06	.06
NO_2-N	mg/l	<.01	<.01
NH_4-N	mg/l	.28	.19
TKN	mg/l	1.45	1.30
Organic-N	mg/l	1.18	1.16
COD	mg/l	120	--
Humic acid	mg/l	9	--
Fulvic acid	mg/l	110	--

the Toivola watershed. Organic nitrogen is the predominant form of nitrogen in both areas followed by ammonia nitrogen.

At Fens, data are available for four sites: a fertilized unmined area (north), unfertilized unmined area that was planted with five tree species (south), mined, and a control (Table 12).

These areas are classed as fen areas. Major cations were at relatively large values. Metal concentrations remained low except at the north area which had large Hg and As values and the control area which had large Zn, Ni, and As concentrations. Relatively high concentrations of phosphorus and total Kjeldahl nitrogen were also observed. Nitrate-N was quite apparent although often lower than organic-N and NH_4-N. Fertilization may be influencing these data, including those for the control because of the close proximity of the plots. No explanation can be made for the metal values of the control area.

Table 12. Fens water quality, 1978-1980.

Parameter	Units	Fertilized Unmined (North)	Mined	Planted Unfertilized (South)	Control
Temperature	°C	10	11	10	11
pH	units	6.7	6.6	6.6	6.5
Specific conductivity	µmhos/cm	249	202	240	168
DO	mg/l	8.0	9.8	7.3	7.2
% saturation	%	81	90	65	67
Color	Pl-Co	208	183	136	337
Acidity	mg/l $CaCO_3$	25.9	44.6	42.4	39.2
Alkalinity	mg/l $CaCO_3$	62.1	86.5	73.3	60.6
Suspended sediment	mg/l	9.1	16.6	6.2	24.1
K	mg/l	12.03	3.01	1.79	4.02
Ca	mg/l	23.63	27.79	33.23	33.12
Mg	mg/l	8.73	13.13	11.40	9.55
Na	mg/l	6.99	7.57	.32	2.53
Fe	mg/l	1.01	10.61	4.38	4.14
Al	mg/l	.26	.70	7.60	.29
Mn	mg/l	.10	.54	.37	.84
Zn	mg/l	.03	.05	.04	.18
Cu	mg/l	.02	<.01	.02	.03
B	mg/l	.02	.02	.03	.03
Pb	mg/l	<.13	<.13	<.13	<.13
Ni	mg/l	<.04	<.04	<.04	.42
Cr	mg/l	<.01	<.01	<.01	<.01
Cd	mg/l	<.01	<.01	<.01	<.01
Hg	µg/l	4	<1	1	2
As	µg/l	4	1	3	4
Se	µg/l	<1	<1	<1	<1
TP	mg/l	.24	.28	.13	.42
NO_3-N	mg/l	.45	.24	.38	.58
NO_2-N	mg/l	.02	.02	.02	.01
NH_4-N	mg/l	.229	1.0	.8	1.3
TKN	mg/l	3.5	7.3	3.3	5.1
Organic-N	mg/l	3.27	6.3	2.5	3.7
COD	mg/l	99	117	110	--
Humic acid	mg/l	3	2	8	--
Fulvic acid	mg/l	88	102	99	--

WATER QUALITY SUMMARY AND CONCLUSIONS

Peatland Types

Once peatlands were classified, a multiple watershed approach was used to evaluate differences in the quality of runoff from three peatland types and to evaluate the effects of peat mining on one watershed. This multiple watershed approach consisted of four steps:

1. Watershed selection
2. Water quality sampling
3. Classification
4. Statistically testing differences

The runoff from bogs had lower temperature, pH, specific conductivity, alkalinity, calcium, magnesium, total phosphorus, and nitrate nitrogen than fen runoff but higher acidity, color, aluminum, humic and fulvic acid, and COD than runoff from fens. All the water quality characteristics of peatland runoff, except acidity, varied among sampling periods. The bog watersheds had more fibric peat of a lower pH and ash content and less shrub species than the fen watersheds.

Most water quality characteristics of peatland runoff followed log-normal probability distributions. Exceptions were runoff temperature, pH, dissolved oxygen, and fulvic acid values which were normally distributed and color, acidity, total Kjeldahl and organic nitrogen, humic acid, and COD which followed Pearson Type III distributions.

Several water quality characteristics of peatland runoff were related to watershed characteristics. The relative amount of sapric peat in the watershed was positively related to sodium concentrations in runoff. The percent shrub in watersheds correlated positively with pH and inversely with acidity and COD. Peat pH correlated with pH, conductivity, calcium, and magnesium values in peatland runoff.

Effects of Peat Mining

The quality of runoff from the mined bog was compared to that from the 15 natural bogs previously classified and from an adjacent control area. Runoff from the mined bog was higher in temperature, specific conductivity, acidity, suspended sediment, arsenic, and TKN, ammonia-N, and organic-N than runoff from the natural bogs. These differences are believed to represent the effects of peat mining on the quality of runoff. There are several implications of these changes. A temperature rise could reduce the suitability of downstream waters for cold water fish. Greater suspended sediment could reduce light penetration and carry additional nutrients and greater concentrations of nitrogen could increase the likelihood of algal blooms. However, none of these changes exceed drinking water standards.

Ponds

A pond with mineral bottom was compared to one with a peat bottom in an attempt to simulate a dredge mining operation. As expected, the mineral pond had larger values of pH, specific conductivity, alkalinity, Ca, Mg, and Na. The peat pond exceeded the mineral pond in color, acidity, and K.

Although nutrient levels were sufficient to produce algal growth, no blooms were observed because phosphorus and nitrogen were apparently in forms not readily available for uptake by algae. Dissolved oxygen in both ponds fell below 5 mg/l after sustained ice cover. Alkalinity and pH of ponds supporting aquatic vegetation considered desirable for waterfowl should fall between 30 to 150 mg/l and 7 to 9.2 respectively (NAS-EPA, 1972). The lack of such vegetation in these ponds is probably due to the steep shoreline created by the dredging operation. Only after bank sloughing occurred, did vegetation begin to occupy the banks of the ponds. Thus, if a reclamation goal is to develop such ponds into waterfowl habitat after mining operations cease, the littoral area should be sloped to facilitate vegetation growth.

WATER QUANTITY RESULTS

Water Budgets

Monthly water budgets were determined for the mined bog (Corona North), the unmined bog (Corona Control), Toivola and the Tamarac River as follows:

$$R = P - PET - RO$$

where: R = residual in mm or inches
P = precipitation in mm or inches
PET = Thonthwaites potential evapotranspiration in mm or inches
RO = streamflow runoff in mm or inches

The residual term represents change in storage and (or) groundwater leakage into or out of the watershed.

Annual precipitation for the study sites are compared to annual average precipitation at respective nearby long record stations in Table 13. Although the study period was relatively short, considerable variability in annual precipitation was observed at all locations.

Runoff Characteristics

Water budgets of the mined and unmined bogs exhibited some characteristics worth noting (Tables 14 and 15). When summed over the total period, values of RO/P averaged .25 and .17 for the mined and unmined bogs, respectively. However, if we look more closely at the timing of runoff, the mined bog exhibited a greater percentage of streamflow earlier than the unmined bog (Figures 34 and 35). For the January through June periods, runoff averaged 32 percent of precipitation for the mined bog compared to ten percent for the unmined bog. Runoff for January-May averaged three

Table 13. Annual and normal precipitation for peatland study sites.

Study Site	Precipitation 1978	1979	1980	National Weather Service Station	Normal Precipitation at Station
	----	mm	----		(mm)
Corona	689	740	627	Cloquet	769
Toivola	760	809	579	Meadowlands	712
Tamarac R.	381*	509*	433*	Big Falls	670

* Incomplete record.

Table 14. Monthly water budgets for the mined bog (Corona North), January 1979 - June 1981.

Date		Precipitation	Evapotranspiration	Runoff	Residual
		- - - - - - - - - - -	millimeters	- - - - -	- - - - - - - -
1979	January	13	0	-	13
	February	79	0	-	79
	March	81	0	-	81
	April	24	0	157	-133
	May	123	19	45	59
	June	91	72	21	-2
	July	74	89	21	-36
	August	62	79	31	-48
	September	94	66	13	15
	October	88	27	7	54
	November	7	0	8	-1
	December	4	0	2	2
1980	January	39	0	-	39
	February	21	0	-	21
	March	17	0	18	-1
	April	4	36	31	-63
	May	30	68	3	-41
	June	60	92	4	-36
	July	120	118	9	-7
	August	112	106	13	-7
	September	170	61	21	88
	October	26	17	5	4
	November	17	0	1	16
	December	10	0	-	10
1981	January	7	0	-	7
	February	43	0	-	43
	March	37	0	-	37
	April	95	23	13	59
	May	34	68	3	-37
	June	152	92	5	55

Table 15. Monthly water budgets for Corona Control, January 1979 - June 1981.

Date		Precipitation	Evapotranspiration	Runoff	Residual
		- - - - - - - - - - - -	millimeters	- - - - - - - - - - - -	
1979	January	13	0	-	13
	February	79	0	-	79
	March	81	0	-	81
	April	24	0	-	24
	May	123	19	8	96
	June	91	72	26	-7
	July	74	89	27	-42
	August	62	79	24	-41
	September	94	66	11	17
	October	88	27	11	50
	November	7	0	6	1
	December	4	0	-	4
1980	January	39	0	0	39
	February	21	0	0	21
	March	17	0	0	17
	April	4	35	25	-56
	May	30	68	4	-42
	June	60	92	5	-37
	July	120	118	10	-8
	August	112	106	24	-18
	September	170	61	23	86
	October	26	17	23	14
	November	17	0	21	-4
	December	10	0	6	4
1981	January	7	0	-	7
	February	43	0	-	43
	March	37	0	-	37
	April	95	23	-	72
	May	34	68	13*	-47
	June	152	92	20	40

* Incomplete record.

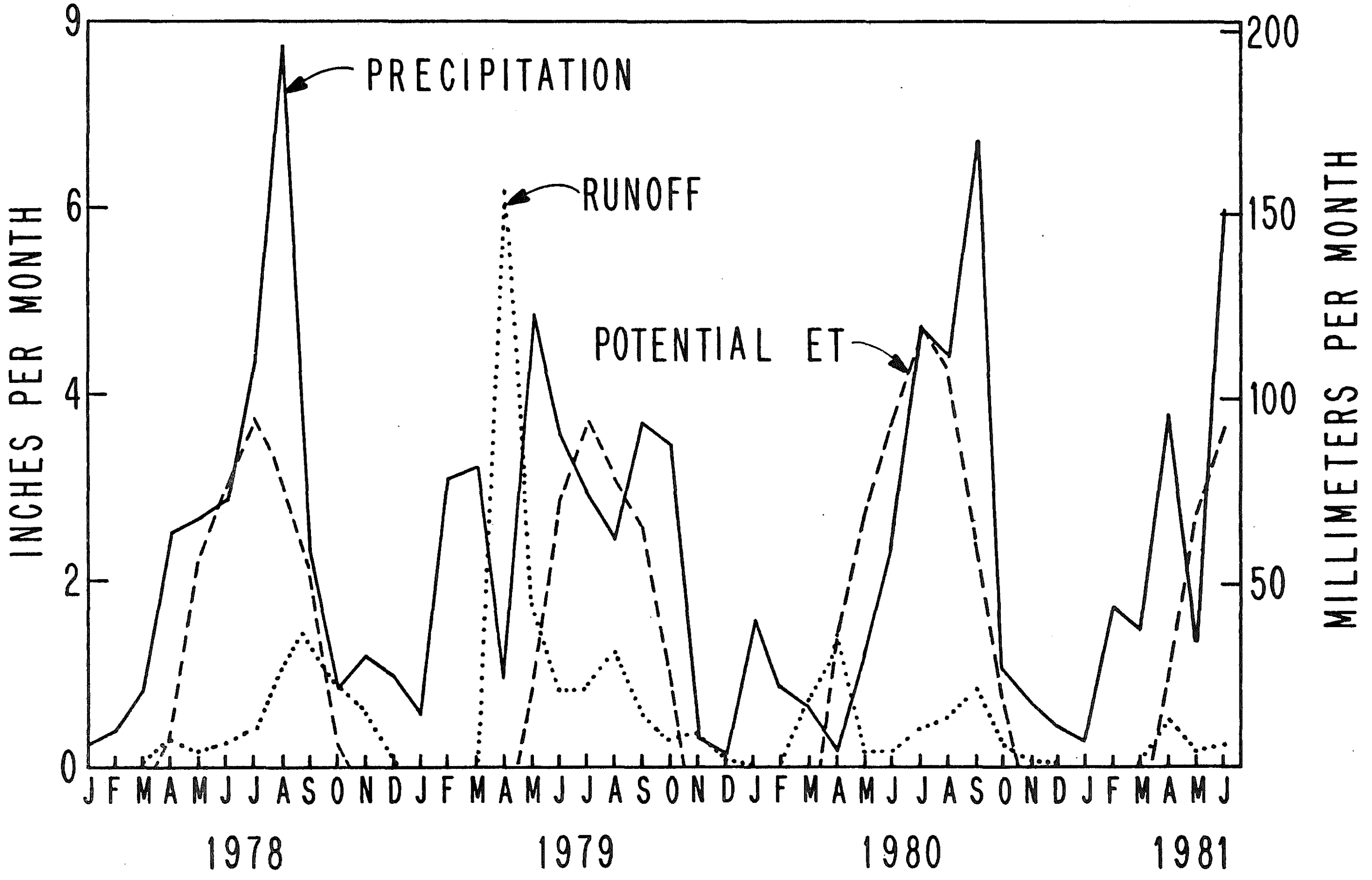

Figure 34. Monthly water budgets for the mined bog (Corona North), 1978-1981.

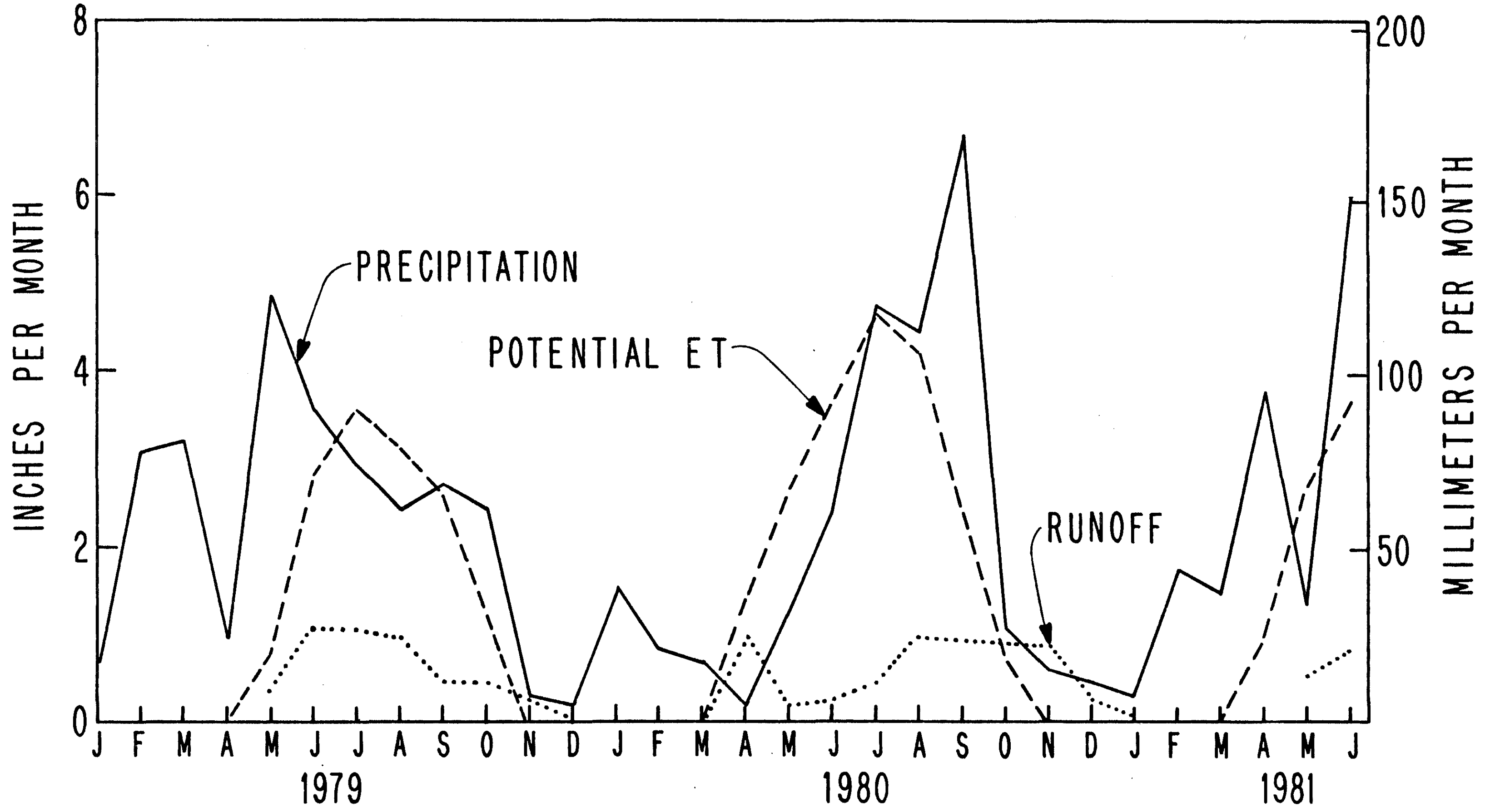

Figure 35. Monthly water budgets for the Corona Control watershed, 1979-1981.

percent of annual precipitation for the unmined bog compared to 17 percent for the mined bog. Pre-June runoff for the mined bog averaged 66 and 50 percent of annual runoff for 1979 and 1980, respectively. In comparison, pre-June runoff for the control bog was 7 and 25 percent of annual runoff for the same two years. Thus, the mined bog yielded more runoff which occurred earlier in the runoff season than the unmined bog.

Monthly water budgets for Toivola are presented in Table 16. Over the 1979 to 1980 period, runoff averaged 30 percent of precipitation at Toivola. The January through June runoff averaged 38 percent of precipitation for 1979 to 1980. However, 1979 was a high runoff year in which 63 percent of the annual runoff occurred in the January-June period (Figure 36). Much of the annual water yield resulted from snowmelt runoff. The March-May periods exhibited 56 to 58 percent of annual yield for 1979 and 1980, respectively.

Records for the Tamarack River were not as complete as the other areas (Figure 37) although a complete set of data were collected during 1980 (Table 17). Although only 12 percent of the annual precipitation resulted in runoff, 59 percent of the runoff measured occurred during April and May, primarily from snowmelt.

For all peatlands the streamflow response was dominated by snowmelt runoff.

Table 16 . Monthly water budget for Toivola, January 1979 - December 1980.

Date	Precipitation	Evapotranspiration	Runoff	Residual
	- - - - - - - - - - -	millimeters	- - - - - - - - - - -	
1979 January	25	0	0	25
February	38	0	0	38
March	102	0	12	90
April	49	3	89	-43
March	79	45	88	-54
June	94	92	22	-20
July	184	121	42	21
August	56	97	8	-49
September	94	68	26	0
October	71	0	15	56
November	13	0	30	-17
December	5	0	4	1
1980 January	32	0	1	31
February	20	0	0	20
March	41	0	1	40
April	40	26	32	-18
May	35	80	13	-58
June	93	95	7	-9
July	67	135	0	-68
August	102	107	1	-6
September	85	58	9	18
October	32	14	9	9
November	17	0	7	10
December	15	0	0	15

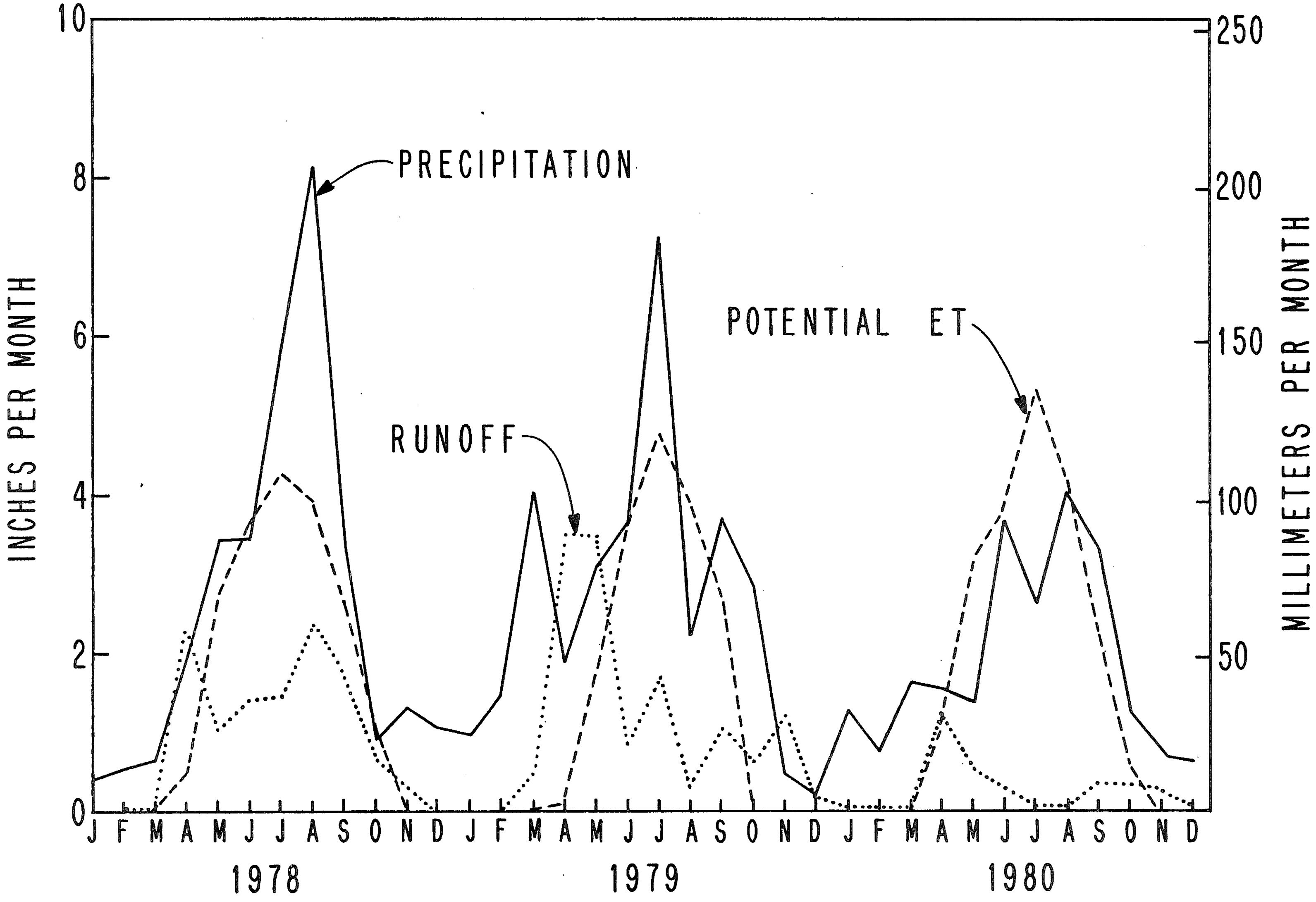

Figure 36. Monthly water budgets for the Toivola watershed, 1978-1980.

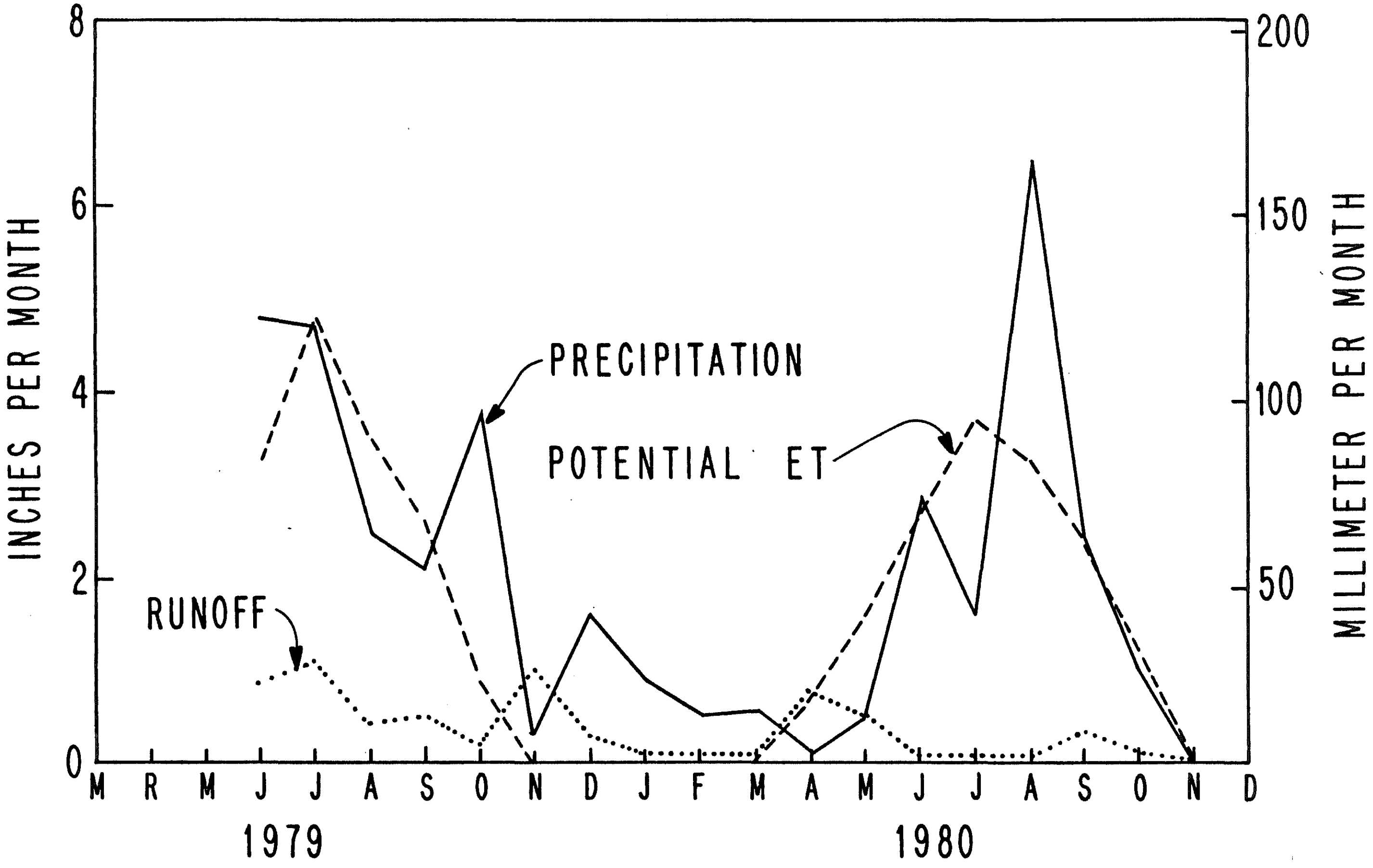

Figure 37. Monthly water budgets for the Tamarac River watershed, 1979-1980.

Table 17. Monthly water budget for Tamarack River, 1980.

Date	Precipitation	Evapotranspiration	Runoff	Residual[a]
	millimeters			
January	23	0	3	20
February	13	0	2	12
March	15	0	2	13
April	3	16	19	-32
May	13	39	12	-38
June	73	67	2	3
July	41	94	1	-54
August	164	83	2	79
September	62	60	8	-5
October	26*	31	2*	-7
November	-	-	-	-
December	-	-	-	-
Total	433	390	53	-9

* Incomplete record.

[a] R = P - PET - RO

Evapotranspiration

Some errors were present in the water budget estimates. Runoff could not be accurately measured during winter and early spring months. Likewise, as with most natural watersheds, some leakage may occur into and out of the watersheds via groundwater flow. In order to evaluate the validity of using Thornthwaite's PET as estimates of actual ET and as a check on the magnitude of leakage, change in storage was measured at the mined bog and at the Toivola watershed. Actual ET values were estimated from:

$$ET = P - RO - \Delta S$$

where

P = precipitation (mm)
RO = runoff (mm)
ΔS = change in storage ($S_2 - S_1$) where S_2 and S_1 are storage at the end and beginning of the month, respectively.

Evapotranspiration estimates are compared for the mined bog in Table 18. In most months the actual ET, calculated as a water budget residual, was greater than Thornthwaite's PET. These months were mostly in the spring and fall and could represent the magnitude of leakage out of the mined area. On the other hand, Thornthwaite's PET may simply underestimate the actual PET during colder periods (since it is solely a function of air temperature). During the months of greatest evaporative demand (June-August) actual ET averaged less than PET. For the entire period, actual ET was 111 percent of PET. However, considering the absence of live plants and the presence of ditches and lowered water tables in the mined area, we would expect actual ET to be less than PET.

Table 18. Comparisons of Thornthwaite's potential evapotranspiration (PET) with ET calculated as a residual of the monthly water budgets for the mined bog (Corona north).

Date		ET from Water Budget[a]	Thornthwaite's PET	(PET-ET)
		- - - - - millimeters	- - - -	
1979	May	69	19	-50
	June	58	72	14
	July	55	89	34
	August	33	79	46
	September	82	66	-16
	October	40	27	-13
	November	2	0	-2
	December	3	0	-3
1980	January	--	0	--
	February	--	0	--
	March	0	0	0
	April	0	36	36
	May	27	68	41
	June	57	92	35
	July	112	118	6
	August	104	106	2
	September	147	61	-86
	October	22	17	-5
	November	16	0	-16
	December	--	0	--
1981	January	13	0	-13
	February	50	0	-50
	March	38	0	-38
	April	32	23	-9
	May	77	68	-9
	June	114	92	-22

[a] $ET = P - RO - (S_2 - S_1)$

We suspect leakage to be the main source of error in the water budget estimates for the mined bog.

Comparisons between estimated actual ET and PET for Toivola showed a more consistent relationship than the mined bog (Table 19). In all but two months potential ET exceeded actual ET. For the entire period, estimated ET values were 82 percent of PET. Again, the results of these comparisons do not coincide with our expectations. As pointed out by Nichols and Brown (1980), a sphagnum moss surface can exhibit higher evaporative losses than a water surface and may use more energy in the evaporative process than is available from net radiation. The two summer periods (1979-1980) did not indicate excessive ET losses based on water budget estimates.

Stormflow

Before widespread peat mining or peatland development is undertaken, the consequences of such actions on stormflow should be understood. Any time the magnitude of peak flow or stormflow volume are measured or the timing of peak flow is reduced, localized and regional flooding may result. Concerns about flooding already exist in northern Minnesota, particularly those areas within the drainages to the Red River of the north and the upper Mississippi River. In this final report, we will characterize and compare stormflow from a mined and unmined bog and the Toivola watershed. In order to better understand the consequences of peatland mining on snowmelt flooding, our soil frost-runoff study will continue for one more year. The following stormflow analyses are strictly based upon rainfall-runoff events.

Table 19. Comparisons of Thornthwaite's potential evapotranspiration (PET) with ET calculated as a residual of the monthly water budgets for Toivola.

Date	ET from Water Budget[a]	Thornthwaite's PET	(PET-ET)
	- - - - millimeters	- - - -	
1979 May	0	45	45
June	74	92	18
July	141	121	-20
August	50	97	47
September	65	68	3
October	--[b]	--	--
November	--		--
:			
1980 June	89	95	6
July	71	135	64
August	103	107	4
September	58	58	0
October	23	14	-9
November	11	0	0

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[a] $ET = P - RO - (S_2 - S_1)$.

[b] $(S_2 - S_1)$ data not collected.

Several methods of examining and characterizing the stormflow response of peatlands were investigated. The intimate linkage between surface and groundwater flows in peatlands presented considerable difficulties in performing unit hydrograph analyses. Separation of stormflow from baseflow was arbitrary. The antecedent groundwater flow and soil moisture status strongly influenced stormflow response; storms with similar rainfall excess values exhibited variable peak and recession limb characteristics.

Seven rainfall storms were selected as a basis of comparing the stormflow response of the mined bog with that of the control (Table 20). The mined bog exhibited a higher percentage of stormflow for the same rainfall events. The magnitudes of peak flow on a per area basis were similar for both watersheds but the lag time was shorter for the mined bog. Thus, the mined bog with its system of ditches apparently conveyed a greater volume of stormflow over a shorter period of time than the control.

Unit hydrographs were developed from selected storms for the mined and unmined bogs, but timing and peak flow characteristics varied considerably even though rainfall events with similar durations and magnitudes were used. Thus, the unit hydrographs do not provide adequate models for determining stormflow response. Comparisons between the mined and unmined bog would, therefore, be meaningless. A more detailed process model is being developed to predict such stormflow responses.

Table 20. Stormflow characteristics of the mined (Corona north) and control bog watersheds for seven storms during 1979-1980.

Characteristic	Control Bog $\overline{X}$	Control Bog s	Mined Bog $\overline{X}$	Mined Bog s
Response factor[a]	.009	.004	.015	.009
Peak flows ($m^3s^{-1}km^{-2}$)	.0149	.0006	.0151	.0047
Lag time (hrs)[b]	6.9	3.1	5.7	4.0
Direct runoff (mm)	0.12	0.07	0.19	0.12

[a] Response factor = (mm stormflow ÷ mm precipitation).

[b] Lag time = time from centroid of precipitation to peak discharge.

Stormflow characteristics of the Toivola watershed are compared to those of the mined bog for the period of record in Table 21. The mined bog exhibited a slightly higher response factor, and greater direct runoff with the six additional storms as compared to Table 20. The mined bog exhibited a lower response factor and lower peak flows ($m^3s^{-1}km^{-2}$) than the transitional Toivola watershed (Table 21).

Studies are continuing to address some of the questions that remain unanswered. A soil frost-snowmelt runoff study of the mined and unmined bog is continuing with support from the Agricultural Experiment Station, University of Minnesota. In addition, a detailed computer simulation model is being developed to investigate the effects of various peatland management and mining activities on water yield and stormflow response.

Table 21. Stormflow characteristics of the Toivola watershed (n = 14 storms) and the mined bog at Corona (n = 13 storms).

Characteristics	Toivola Watershed $\overline{X}$	Toivola Watershed s	Mined Bog $\overline{X}$	Mined Bog s
Response factor[a]	.029	.026	.018	.013
Peak flows ($m^3 s^{-1} km^{-2}$)	.0145	.0096	.0129	.0071
Lag time (hrs)[b]	12.3	5.2	6.9	3.8
Direct runoff (mm)	0.50	0.72	0.28	0.37

[a] Response factor = (mm stormflow ÷ mm precipitation).

[b] Lag time = time from centroid of precipitation to peak discharge.

WATER QUANTITY SUMMARY AND CONCLUSIONS

Water Yield

Conclusive statements about the effects of peat mining on annual water yield cannot be made on the basis of three complete years of data. A long period (at least 7 to 10 years) paired watershed study would have been needed to determine such effects. However, monthly water budgets indicated that the mined bog yields a higher percentage of precipitation as runoff and a higher percentage of runoff occurs earlier than from the unmined bog. Snowmelt runoff and early summer rainfall dominate the annual runoff from all the peatlands studied. Evapotranspiration from all sites appeared to be near potential ET as estimated by Thornthwaite's method.

An increase in runoff and an earlier timing of runoff as a result of peat mining has implications with respect to snowmelt-runoff in the region. If mined areas represented a small percentage of a total watershed, less than 40 to 50 percent, a desynchronization of runoff may occur with a resulting attenuation of regional snowmelt flood hydrographs. If large percentages (greater than 50 percent) of watersheds are mined, the result may be an increased magnitude of snowmelt floods. These conclusions are based on our water budget studies and on previous studies on the effects of clearcutting forests on snowmelt runoff.

Stormflow

An adequate unit hydrograph model of rainfall-runoff was not developed. The characteristics of stormflow from peatland watersheds do not lend themselves to the unit hydrograph approach. Comparisons of stormflow between the mined and unmined bog at Corona, however, indicated that a higher percentage of rainfall resulted in stormflow for the mined than the unmined bog. Although the magnitudes of peak discharge were not different, a greater volume of stormflow and a quicker response was observed in the mined area. As with the monthly water yield analyses, the implications of such responses depend largely on the percentage of a watershed affected by mining activities.

In all peatland watersheds studied, the percentage of rainfall that resulted in stormflow runoff was quite low. In none of the storms analyzed did this percentage exceed 10 percent.

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Appendix A: Description of Peatland Watershed Sampling Sites.

PEATLAND Number	Name	Sample Site Location	Site Description
1*	McGregor S.	STH 65, 4 mi N Pliny T45N R 23W Sec. 8 Blacktop	"T" in Ditches E. Side Hwy. 65, Upstream of 5'x5' Cement Box Culvert
2*	McGregor	CSAH 8, 1/2 mi S. McGregor T47N R 23W Sec. 6 Blacktop	East Flowing Ditch Open Upland Area
3*	Hill City SE	Co. Rd. 18, gravel T50N R25W Sec. 7	South Flowing Old County Ditch
4*	Jacobson W	Site A, Blacktop STH 200 1 mi W. Rabey T52N R24W Sec. 8	South Flowing Ditch Open Swamp, Brush Area 5' Steel Culvert
5		Site B, Blacktop STH 200 2 mi E. Rabey T52N R24W Sec. 11	South Flowing Ditch with "T" EW Ditch Mostly Upland Area
6*	North Cromwell	Co. Hwy. 23 4 mi N. Wright T49N Rd. 21W, Sec. 15 Blacktop	L Tamarac R.X Co. Hwy 23 4 mi N. Wright
7	Cromwell NE	Site A SFR T49N R 19W Sec. 14 Gravel	Ditch X SFR N. Flowing
8	S. Cromwell	T48N R20W Sec. 25 Co. Rd. 21, Gravel	Ditch SW Flowing Culvert
9	Floodwood NW	T52N R21W Sec. 3 Dirt Road, CR. 148	East Flowing Old Co. Ditch
10	Floodwood	T52N R20W Sec. 5 Gravel Co. Rd. 191	W. Flowing Small Stream ag. area, 4' culvert
11	Floodwood E	T52N R19W Sec. 33 Gravel, CR 166	Old Ditch W Edge Gravel Pit Mineral

Appendix A: Description of Peatland Watershed Sampling Sites. (Cont'd).

PEATLAND Number	Name	Sample Site Location	Site Description
12	Arlberg	Site A (West) T52N R19W Sec. 35, CR.166 Gravel	Natural - Stream Deep Mineral
13		Site B (East) T52N R19W Sec. 25 CR.166, Gravel	Deep ravine, Natural Stream
14	Meadowlands E	T53N R18W Sec. 17 Gravel, CR211	6' Culvert, Uplands
15*	Canyon	CR 133, Blacktop T53N R17W Sec. 18	2-12' Box Culverts Bridge
16*	Toivola S	T54N R20W Sec. 13 Gravel, CR 159	At Wooden Bridge next to Road
17	Toivola E	Site A (North) T54N R19W Sec. 16, Gravel CR 230	Ditch Culvert
18		Site B (South) Gravel CR 230, T54N R19W Sec. 21	Stream Culvert
19	Cotton	CR 980, Gravel, T54N R18W Sec. 25	Bridge, Jenkins Creek
20	Cotton E	CR 979, Gravel, T54N R17W, Sec. 12	Stream
21	Fens	CR 207, Gravel, T55N, R18W, Sec. 28	Stream
22	Riley	CR 442, Gravel, T56N R20W, Sec. 32	Stream, 2-5' Culverts
23*	Little Swan	CR 534, Gravel, T56N R19W, Sec. 24	Stream
24			
25	Central Lakes	CR 572, Gravel, T55N R17W, Sec. 11	Stream, Culvert, Brushy lowland hardwoods

Appendix A: Description of Peatland Watershed Sampling Sites. (Cont'd).

PEATLAND			
Number	Name	Sample Site Location	Site Description
26	Ely Lake	T57N, R16W, Sec. 5 Bad Road	Stream, 5' Culvert
27*	Britt	CR68, Blacktop, T60N R17W, Sec. 26	Stream-Ditch, 6' Culvert, Bog
28	Unk #2	CR313, Gravel, T56N R18W, Sec. 6	Stream, 3' Culvert
29	Lost Lake S	CR948, Gravel, T62N R17W, Sec. 28	Stream, 6' Culvert
30	Cook	T62N, R18W, Sec. 3, CR421, Gravel	Stream, Bridge
31	Sturgeon	CR491, Gravel, T61N R20W, Sec. 3	Ditch, Culvert edge of bog
32	Linden Grove	CSAH 107, Gravel, T62N R21W, Sec. 36	Stream, Culvert, Ag-pasture, 1/4 mi from bog
33	Sturgeon S	CR356, Unimproved, T61N, R20W, Sec. 19	Stream, 3' Culvert, Swampy brush
34*	Cohasset	US#2, Blacktop, T55N R26W, Sec. 4	Stream, 8' Culvert, Concrete bog 300 ft. upstream
35*	Deer River	CSAH 6, Blacktop T146N, R25W, Sec. 3	Ditch - Stream 2-10' box culverts
36*	Nakoda	US71, Blacktop T69N, R25W, Sec. 5	Ditch, 2-4' Culverts Ag. Area
37	Myrtle Lake	Deer River Line T64N, R25W, Sec. 6	Reilly Creek 2-Concrete Culverts
38	Sturgeon River	Site A (North), Pine Island For. Rd. T115N, R27W, Sec. 27	River, No. Fork 2-Concrete Culverts
39		Site B (South) Pine Island For. Rd. T155N, R27W, Sec. 27	River, So. Fork 2-Concrete Culverts

Appendix A: Description of Peatland Watershed Sampling Sites. (Cont'd).

PEATLAND			
Number	Name	Sample Site Location	Site Description
40	N. Pine Island	CR86, Gravel, T158N, R27W, Sec. 22	Ditch
41	Pine Island Raised Bog	Pine I, For. Rd. T156N, R28W, Sec. 23	Ditch, 4' Culvert
42	Red Lake	Site A (East) Red Lake No. Shore Dr. T155N, R31W, Sec. 21	Ditch, 4' Culvert
43		Site B (West) Red Lake No. Shore Dr. T114N, R31W, Sec. 19	Ditch, Wooden Bridge
44	Tamarac River	Balsiger Rd. T154N, R29W, Sec. 16	Stream, end of ditch bank road
45	Joula Creek	CR 133 T53N, R20W, Sec. 17	Stream, box culvert

* Indicates access on all-weather road.