THE 1981 SNOWPACK SURVEY IN THE AOSERP STUDY AREA

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for

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ABSTRACT

Snow samples were collected in the Athabasca Oil Sands region of northeastern Alberta in mid-January and late February 1981. The snow depth was measured and snow cores were taken at 60 sites around the oil sands plants. Snow sample collectors were set out at six of the sites in mid-January and removed in late February. Quantitative chemical analyses of the samples were carried out by a commercial laboratory. Duplicate samples from nine of the sites were analyzed as an independent cross-check. Concentrations of the major ions ($SO_4^=$, NO_3^-, Cl^-, NH_4^+, K^+, H^+, Na^+, Mg^{++}, Ca^{++}) as well as the insoluble (Al, Mn, Ti, V) and soluble (Al, Fe, Ni, V) constituents were determined. Snowpack loadings were computed from the measured concentrations, snowmelt volume, and the area sampled. The amounts of sulphate and nitrate deposited in the snow within 25 km of the oil sands plants have increased by 88 and 27% respectively, since the previous study in 1978. The amounts of insoluble particulates have decreased markedly.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The fate of pollutants emitted into the atmosphere is a complex problem which has been under intensive scrutiny over the past few years. This effort has been spurred by the possible implications for lake or soil acidification, and the possible effects on vegetation.

In order to determine the disposition of pollutant emissions, one must understand the mechanisms of transport and dispersion, the chemical transformations of the pollutants, and the processes that remove material from plumes. Snowpack sampling and analysis is a convenient method of investigating the removal processes of wet and dry deposition. In the absence of substantial thawing, the snow cover retains a good portion of the annual precipitation and its chemical constituents.

There have been two studies of the deposition of pollutants to the snowpack in the Alberta Oil Sands Environmental Research Program (AOSERP) study area. In 1976, a snow chemistry survey at 55 sites in the area elucidated the spatial deposition patterns of sulphur and hydrogen (Barrie and Whelpdale 1978). (See Figure 1 which shows the AOSERP study area in the northeast corner of Alberta.) A second survey which extended the chemical analysis to include major ions and trace metals, was carried out at 60 sites in January 1978 (Barrie and Kovalick 1980). Both studies consisted of extensive sampling of the accumulated snowpack, followed by a chemical analysis of the snowmelt to determine its ionic and particulate constituents. The results delineated the deposition patterns and spatial variability of the snowpack loading around the Suncor plant.

Industrial emissions of contaminants into the atmosphere increased by up to a factor of two within the region when the Syncrude plant began operation in late 1978. The main purpose of the current study was to discover whether wintertime pollutant deposition rates, and resultant snowpack loadings, had increased proportionately.

In the current study, snow samples were collected following the methodology used in the previous winter deposition studies in the AOSERP area. Two surveys were performed about 6 wk apart, so that accumulated deposition of emissions could be compared to model predictions.

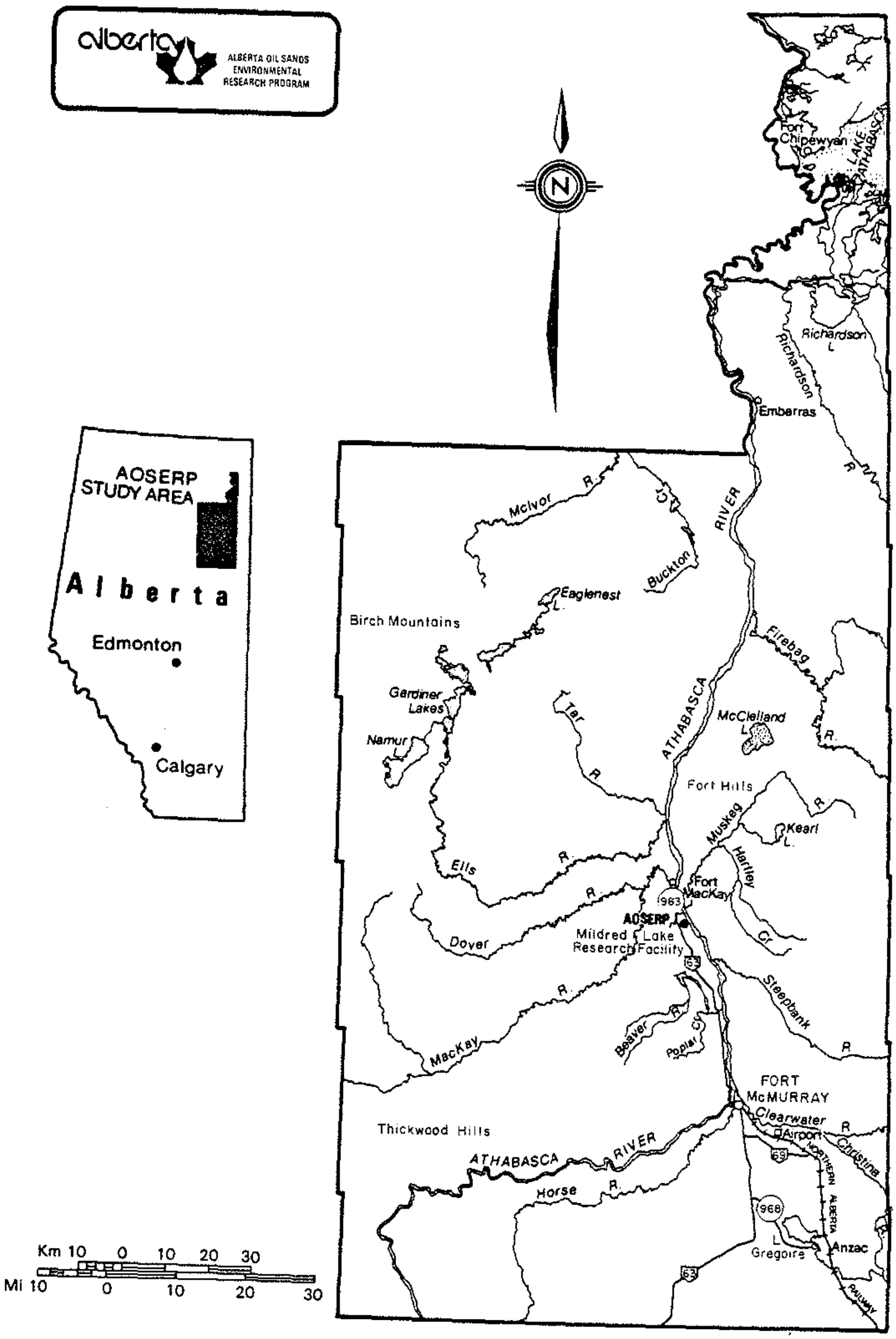


Figure 1. Map of the AOSERP study area.

2. METHODS

Two field studies were undertaken, spaced about 6 wk apart. The studies were carried out from 10 to 13 January, and from 20 to 23 February 1981.

2.1 SAMPLE COLLECTION AND HANDLING

Snow was collected at 60 sites, shown in Figures 2 and 3, within 100 km of the Syncrude and Suncor plants. All sites were serviced by helicopter, except for those along Highway 63.

At each site, two samples were collected in plastic bags: one for trace metal analysis and one for major ion analysis. Each sample consisted of three snow cores obtained with a device similar to that used in the previous studies (Barrie and Whelpdale 1978; Barrie and Kovalick 1980). The snow corer was a half-cylindrical, acrylic tube, 1 m long and 80 cm^2 in cross-section. The flat side of the device was removable to facilitate removal of the core.

The procedure for obtaining a snow core was as follows:

1. Measure the snow depth,
2. Clean the corer by shoving it in and out of the snowpack several times.
3. Insert corer vertically to the bottom of the snowpack.
4. Clear snow from the flat side of the sampler.
5. Insert an acrylic shovel, having the same cross-section as the corer, under the lower end of the sampler.
6. Tilt the sampler until horizontal.
7. Remove the flat side of the sampler.
8. Measure core length and crust positions.
9. Cut off and discard any snow containing grass or ground debris.
10. Measure the length of snow cut off, if any.
11. Slide the remaining core into a plastic bag.

At nine of the 60 sites, four samples of three cores were bagged. The first and second bags were sent to Chemex Laboratories (Alberta) Ltd. in Calgary; the third and fourth were sent to Barringer Magenta Ltd. in Toronto for chemical analysis. This procedure allowed an evaluation of the variability in results expected due to intra-site (within site) variability and analytical errors.

Snow collectors were deployed at six sites on 16 January. The collectors were 12 cm deep, 36 cm wide, and 49 cm long. They were light-coloured to avoid heat absorption. The snow in the collectors was bagged on 23 February and shipped in the frozen state to Chemex Laboratories for analysis.

The snow core samples were stored in freezers at the AOSERP Mildred Lake Research Facility until the end of each collection period, and then shipped in the frozen state to Chemex Laboratories. The 18 duplicate samples were melted, bottled in 1.5 L polyethylene bottles, and shipped to Barringer Magenta. Two blank samples of distilled water were also sent to Barringer.

2.2 CHEMICAL ANALYSIS

The analysis of the snow was undertaken through commercial laboratories. Snow samples from all 60 sites plus a blank sample were analyzed by Chemex, while duplicate samples from nine sites plus a blank were analyzed by Barringer. The six samples from the snow collectors were analyzed by Chemex. The following analyses were carried out:

1. Major ions: $SO_4^{=}$, Cl^-, NO_3^-, NH_4^+, K^+, Na^+, Mg^{++}, Ca^{++}, as well as pH and alkalinity
2. Particulates and heavy metals: Al, Fe, Ni, V, Mn, and Ti.

Blank samples were analyzed to determine detection limits and as a quality control measure.

The chemical techniques used by Chemex and Barringer for the quantitative analyses are shown in Tables 1 and 2, respectively. Chemex used the same analytical methods as Barrie and Kovalick (1980). Barringer used ion chromatography for the major ions, and an inductively coupled plasma technique for the metals.

Upon arrival in Calgary, the frozen samples were stored in freezers at a temperature of about -20°C. The samples were melted on 15-16 January and 26-27 February for the first and second surveys, respectively. Melted samples from nine sites plus two blanks were packed in an insulated container and shipped by unheated truck to Barringer. Chemex finished their analyses by 23 February and 27 March for the two groups of samples. Barringer completed their analyses by 31 January and 16 March.

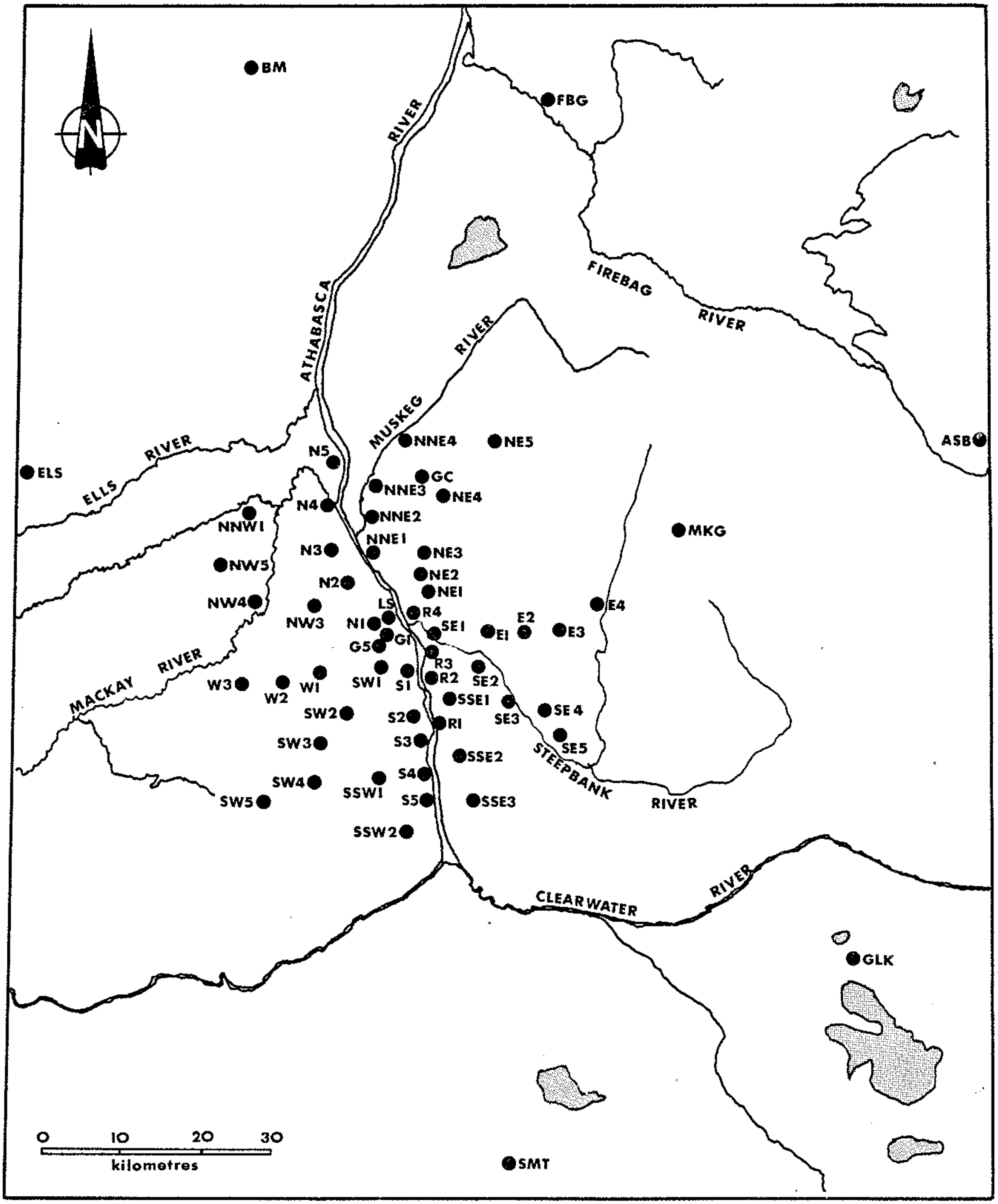


Figure 2. Map of the study area. Dots mark the locations at which snow was sampled.

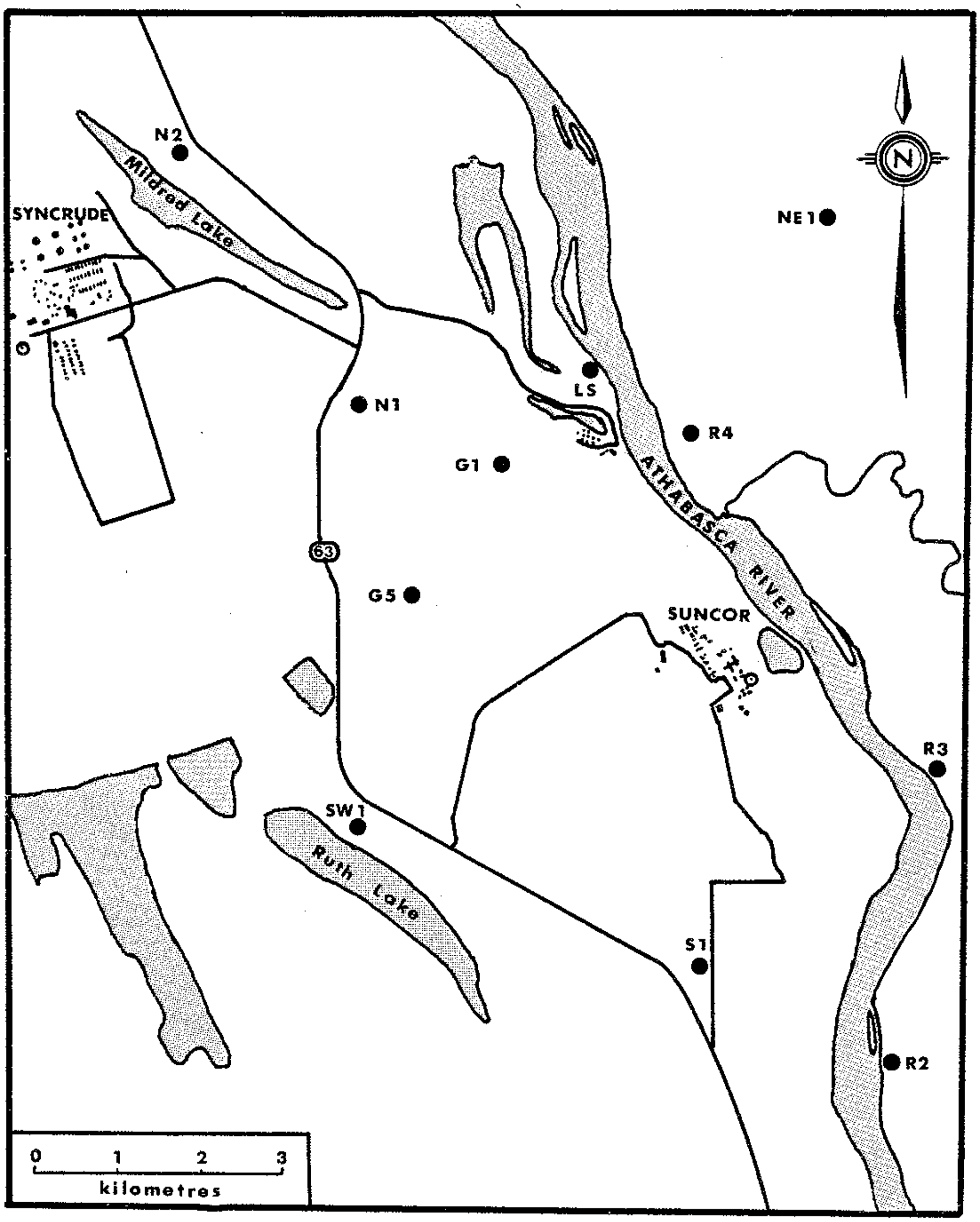


Figure 3. Map of the study area near the extraction plants. Solid circles indicate snow sampling locations which could not be clearly identified in Figure 2.

Table 1. Analytical techniques used in the quantitative determination of major ion and trace metal concentrations by Chemex Laboratories Ltd.

	Method	Detection Limit[a]
Sulphate	ion chromatography	0.01
Chloride	mercury thiocyanate (colorimetric)	0.06
Nitrate	cadmium reduction (colorimetric)	0.003
Ammonia	alk. Phenol (colorimetric)	0.001
Potassium	flame photometric	0.06
Sodium	flame photometric	0.02
Magnesium	atomic absorption	0.01
Calcium	atomic absorption	0.05
Aluminum (Soluble)	solvent extraction (atomic absorption)	0.001
Iron (Soluble)	solvent extraction (atomic absorption)	0.002
Nickel (Soluble)	solvent extraction (atomic absorption)	0.001
Vanadium (Soluble	solvent extraction (atomic absorption)	0.001
Aluminum (Insoluble)	neutron activation[b]	1.0 μg
Vanadium (Insoluble)	neutron activation[b]	0.1 μg
Manganese (Insoluble)	neutron activation[b]	0.1 μg
Titanium (Insoluble)	neutron activation[b]	50.0 μg
pH	electrode	
Alkalinity	titration to pH 4 then back to 5.6 under N_2	

[a] mg/L unless otherwise stated

[b] filtered samples of the insoluble metals were analyzed by Nuclear Activation Services Ltd., Hamilton, Ontario.

Table 2. Analytical techniques used in the quantitative determination of major ion concentrations and heavy metal amounts by Barringer Magenta Ltd.

	Method	Detection Limit (mg/L)
Sulphate	ion chromatography	0.01
Chloride	ion chromatography	0.01
Nitrate	ion chromatography	0.01
Potassium	ion chromatography	0.02
Sodium	ion chromatography	0.01
Ammonia	ion chromatography	0.01
Calcium	ion chromatography	0.01
Magnesium	ion chromatography	0.01
Aluminum (Soluble)	inductively coupled plasma	0.005
Iron (Soluble)	inductively coupled plasma	0.002
Nickel (Soluble)	inductively coupled plasma	0.005
Vanadium (Soluble)	inductively coupled plasma	0.001
Aluminum (Insoluble)	inductively coupled plasma[a]	0.005
Vanadium (Insoluble)	inductively coupled plasma[a]	0.001
Manganese (Insoluble)	inductively coupled plasma[a]	0.010
Titanium (Insoluble)	inductively coupled plasma[a]	0.005
pH	electrode	
Alkalinity	titration to pH 4 then back to 5.6 under N_2	

[a] samples from the second study period were analyzed for insoluble heavy metals using the neutron activation method.

3. RESULTS

The following sections present the data and results for the January and February 1981 snowpack surveys.

3.1 METEOROLOGICAL HISTORY OF THE SNOWPACK

A summary of the weather at Fort McMurray Airport prior to and during the snow surveys is presented in Table 3. The early winter was cold with a mean temperature of -22.9°C in December 1981, compared to the long-term normal (Environment Canada 1973) of -18.4°C. January and February 1981 were very mild with mean temperatures of -9.4 and -10.9°C, compared to the normals of -21.5 and -19.2°C, respectively. The trends of air temperature and snowpack depth over the winter of 1980-81 are illustrated in Figure 4.

Positive temperatures were observed on several days prior to the first sampling period. However, the snow depth measurements indicate that this did not result in significant melting. Between the two surveys, there were 11 d with positive temperatures. The snow depth data indicate that there was significant melting on 14 and 15 February when the maximum temperatures were 7.5 and 9.9°C, respectively. It was not possible to restrict the core samples to the layer above the crust formed on 15 February because there was very little snowfall from then until the beginning of the second sampling period on 20 February. The meltwater trickling through the snowpack would have tended to leach out the contaminants.

The frequency distributions of surface wind direction at Mildred Lake from 7 November 1980 to 13 January 1981 (prior to the first sampling period) and from 14 January to 23 February are shown in Figure 5. The prevalent directions during both periods were southeasterly and northerly. In contrast, during the winter of 1977-78, when the previous snowpack survey was conducted, there was a maximum of southerly rather than southeasterly winds.

Table 3. Daily weather summaries at Fort McMurray airport prior to and during the snow survey.

Date	Air Temperature		Precipitation				
	Maximum (°C)	Minimum (°C)	Snowfall Amount (cm)	Water Equivalent (mm)	Rainfall (mm)	Total Amount (mm)	Snow Depth (cm)
1980							
1 Dec.	-23.5	-29.0	tr	tr	0	tr	3
2	-23.0	-31.8	0	0	0	0	3
3	-21.7	-30.0	2.4	2.4	0	2.4	3
4	-24.8	-31.2	tr	tr	0	tr	5
5	-24.2	-27.6	4.2	5.0	0	5.0	7
6	-25.2	-33.1	tr	tr	0	tr	10
7	-20.9	-34.0	tr	tr	0	tr	10
8	-19.0	-32.2	0.4	0.4	0	0.4	10
9	-27.4	-34.2	0	0	0	0	10
10	-21.9	-36.6	3.2	0.6	0	0.6	8
11	-18.1	-23.8	9.2	8.0	0	8.0	12
12	-18.7	-26.8	0	0	0	0	18
13	-15.7	-24.9	1.0	1.0	0	1.0	17
14	-7.8	-17.5	0.8	0.8	1.1	1.9	16
15	-1.4	-9.6	0	0	0.3	0.3	17
16	5.4	-15.0	1.8	1.0	1.0	2.0	16
17	-15.0	-24.8	tr	tr	0	tr	15
18	-23.7	-30.5	tr	tr	0	tr	14
19	-28.5	-36.1	tr	tr	0	tr	14
20	-30.6	-39.7	tr	tr	0	tr	14
21	-30.0	-38.1	tr	tr	0	tr	14
22	-26.6	-32.2	tr	tr	0	tr	14
23	-24.2	-34.6	tr	tr	0	tr	13
24	-23.0	-34.3	tr	tr	0	tr	13

tr-trace

continued...

Table 3. Continued.

Date	Air Temperature Maximum (°C)	Air Temperature Minimum (°C)	Precipitation Snowfall Amount (cm)	Water Equivalent (mm)	Rainfall (mm)	Total Amount (mm)	Snow Depth (cm)
1980							
25 Dec.	-19.4	-30.0	1.8	0.4	0	0.4	13
26	-13.3	-19.6	3.8	2.4	0	2.4	15
27	-18.2	-24.4	9.1	8.0	0	8.0	22
28	-18.2	-28.2	3.6	2.8	0	2.8	24
29	-3.4	-19.4	1.0	1.0	tr	1.0	28
30	0.7	-9.4	tr	tr	0	tr	27
31	-1.4	-17.8	tr	tr	0	tr	26
1981							
1 Jan.	-17.5	-24.2	tr	tr	0	tr	26
2	-13.9	-19.9	tr	tr	0	tr	26
3	-12.0	-16.3	0	0	0	0	25
4	0.1	-13.0	0	0	0	0	25
5	-7.5	-17.2	0.9	0.7	1	0.7	24
6	-10.1	-23.2	2.7	2.7	0	2.7	25
7	-10.0	-14.3	3.7	3.4	0	3.4	30
8	-14.0	-24.4	2.2	0.7	0	0.7	32
9	-15.8	-25.8	tr	tr	0	tr	31
10	-8.0	-17.4	0.4	0.4	0	0.4	31
11	2.2	-15.4	0	0	0	0	30
12	3.6	-10.7	0	0	0	0	29
13	0.0	-6.1	0	0	0	0	29
14	-5.0	-10.5	tr	tr	0	tr	27
15	-5.4	-11.2	tr	tr	0	tr	26
16	-3.8	-15.3	0	0	0	0	26

continued...

Table 3. Continued.

Date	Air Temperature		Precipitation				
	Maximum (°C)	Minimum (°C)	Snowfall Amount (cm)	Water Equivalent (mm)	Rainfall (mm)	Total Amount (mm)	Snow Depth (cm)
1981							
17 Jan.	-0.8	-17.9	0	0	0	0	25
18	2.4	-15.5	0	0	0	0	25
19	-0.1	-14.8	0	0	0	0	25
20	8.5	-6.3	0	0	0	0	25
21	1.0	-7.2	0	0	0	0	24
22	-1.7	-10.3	0	0	0	0	23
23	5.2	-5.2	0	0	0	0	23
24	3.3	-5.2	tr	tr	0	tr	23
25	-1.8	-9.1	3.1	1.6	0	1.6	23
26	-8.5	-13.7	0.7	tr	0	tr	25
27	-8.4	-10.5	tr	tr	0	tr	26
28	-6.7	-13.1	tr	tr	0	tr	26
29	-10.2	-16.0	0.6	tr	0	tr	26
30	-7.8	-10.5	0.6	0.4	0	0.4	26
31	-8.5	-12.8	1.4	0.2	0	0.2	27
1 Feb.	-11.1	-19.8	tr	tr	0	tr	28
2	-6.2	-20.6	tr	tr	0	tr	27
3	-0.7	-16.0	0	0	0	0	27
4	0.5	-7.6	tr	tr	0	tr	26
5	-7.6	-12.7	tr	tr	0	tr	25
6	-8.2	-25.3	1.0	0.3	0	0.3	26
7	-19.5	-31.7	1.4	1.3	0	1.3	25
8	-18.8	-25.2	1.0	0.3	0	0.3	24
9	-23.7	-30.7	0.4	0.3	0	0.3	24

continued...

Table 3. Concluded.

Date	Air Temperature		Precipitation				
	Maximum (^oC)	Minimum (^oC)	Snowfall Amount (cm)	Water Equivalent (mm)	Rainfall (mm)	Total Amount (mm)	Snow Depth (cm)
1981							
10 Feb.	-20.7	-32.8	0	0	0	0	24
11	-21.1	-37.5	tr	tr	0	tr	24
12	-17.4	-37.3	0	0	0	0	24
13	-11.1	-26.0	0.8	0.8	0	0.8	24
14	7.5	-14.0	0	0	0	0	24
15	9.9	2.4	0	0	0	0	21
16	2.9	-13.3	0	0	0	0	16
17	-2.6	-14.0	0	0	0	0	16
18	7.6	-8.7	0	0	0	0	16
19	3.2	-12.3	1.6	1.3	0.3	1.6	16
20	-0.1	-9.6	0.7	0.2	0	0.2	18
21	3.7	-16.4	tr	tr	0	tr	18
22	5.2	-12.6	tr	tr	0.3	0.3	17
23	-0.3	-6.5	0	0	0	0	16

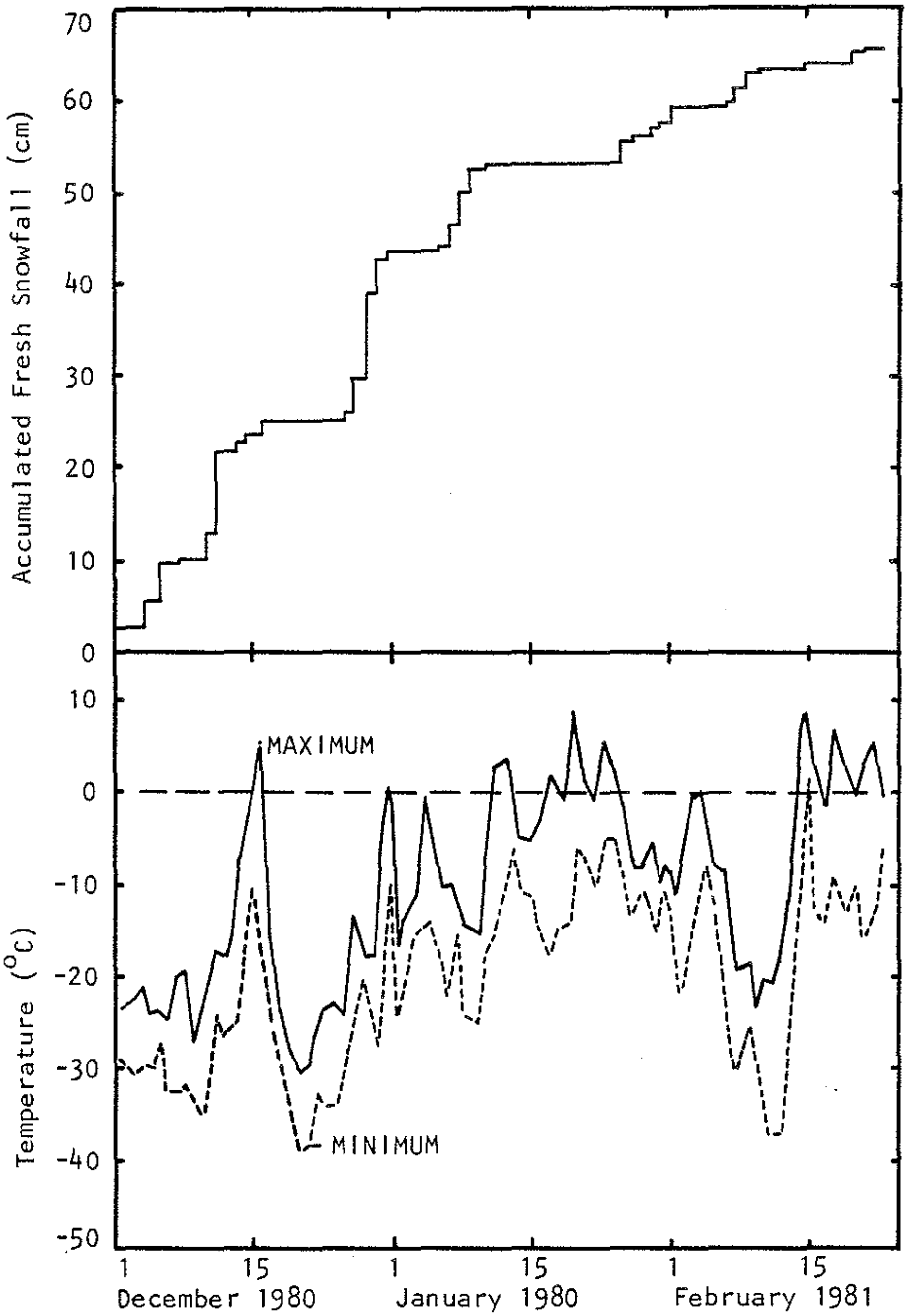
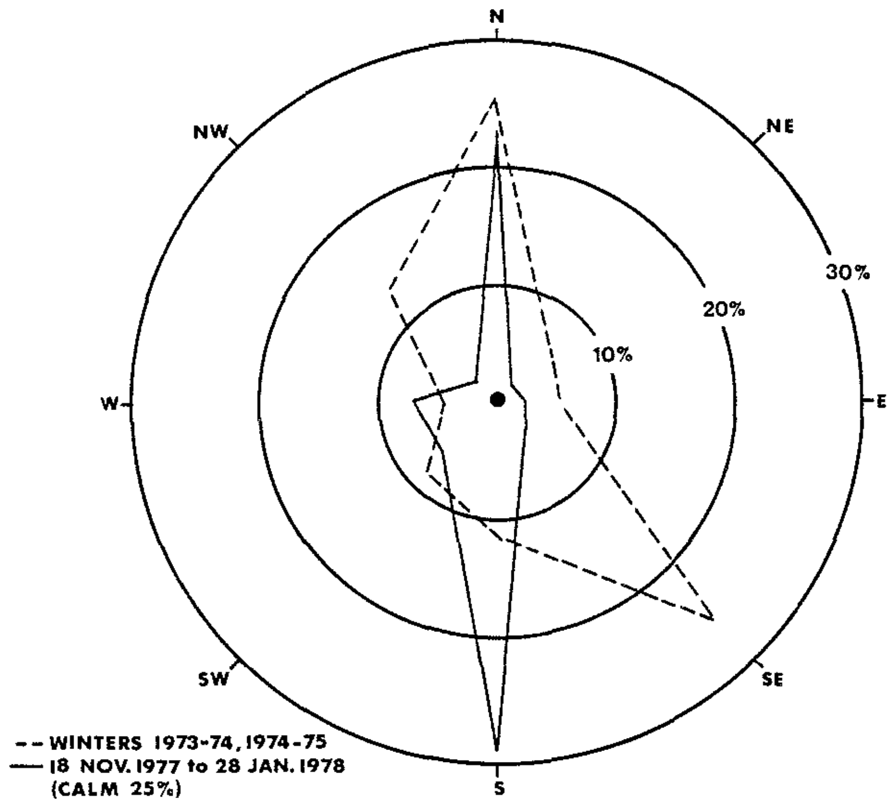


Figure 4. Accumulated fresh snowfall and air temperatures for the study area from 1 December 1980 to 23 February 1981.



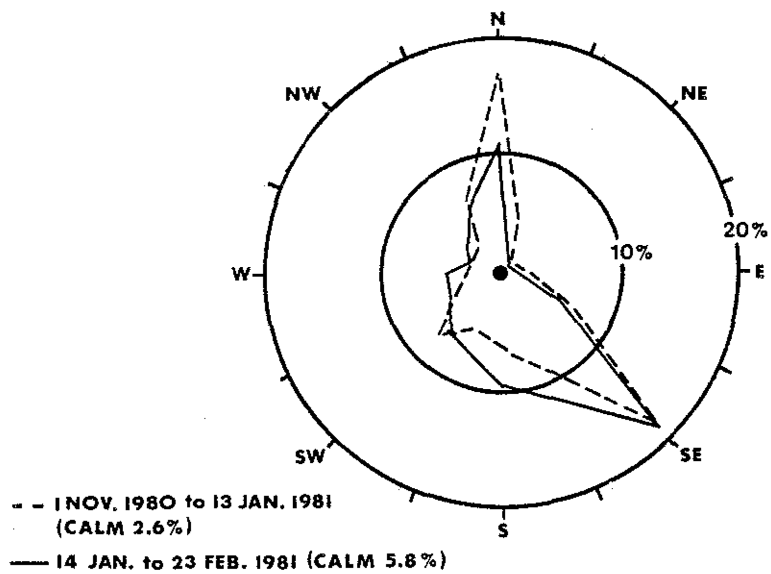


Figure 5. Wind roses showing the frequency distribution of wind direction at the Mildred Lake station during the lifetime of the snowpack. Wind roses, adapted from the original figures in Barrie and Kovalick (1980) for the winters of 1973-74, 1974-75, and 1977-78 are shown for comparison.

3.2 SNOW DEPTH STATISTICS

The means and standard deviations of snow depth at each of the sites are presented in Tables 4 and 5 for the first and second sampling periods, respectively. The average snow depth in the January survey was 32 cm. The standard deviation of 3 cm represents a variability of 10% about the mean for the network of sites. The intra-site variability of snow depth was typically about 2% of the mean, although, there were larger variations at some sites (e.g., 8% at R3).

The spatial variation of snow depth, illustrated in Figure 6, shows relatively low amounts at the northern sites, Birch Mountain and Firebag, and relatively high amounts at the extreme southern sites. This is related to the general north-south gradient of precipitation in the area from November through January, inclusive. There are relative maxima of snow depth to the north and south of the oil sands plants. These features may be related to 'snow out', the precipitation of ice particles from the smoke plumes from the plants.

In the second survey, the values were similar to those in the first, the average depth being 31 cm. There was more variability (8%) from site to site, however, with a standard deviation of 5 cm. The intra-site variability was again about 2% of the mean.

3.3 SNOW DENSITY

Snow densities are also reported in Tables 4 and 5. The values were estimated by dividing the meltwater volume by the volume of the snow cores. The average density over the network on 10 to 13 January was 0.17 g/cm^3. The values varied from 0.13 to 0.22 g/cm^3 with a standard deviation of 0.015 g/cm^3. The variability between samples at a given site was relatively low. Typically, the standard deviation about the mean at a site was 0.006 g/cm^3. Snow densities were higher in the second survey with an average value over the network of 0.23 g/cm^3. The values ranged from 0.19 to 0.30 g/cm^3 with a standard deviation of 0.025 g/cm^3.

Table 4. Snow depth and density statistics for 10 to 13 January 1981.

Site	Mean Depth (cm)	Standard Deviation (cm)	%	Number of Cores	Density (g/cm3)
NNE1	31.1	0.3	1.0	12	0.16
NNE2	32.2	0.3	0.8	6	0.16
NNE3	34.0	0.0	0.0	6	0.16
NNE4	31.2	0.4	1.3	6	0.16
NE1	31.0	0.0	0.0	12	0.17
NE2	32.0	0.0	0.0	6	0.17
NE3	32.0	0.0	0.0	6	0.18
NE4	38.7	2.0	5.1	6	0.17
NE5	32.2	0.3	1.0	12	0.17
E1	30.0	0.0	0.0	6	0.18
E2	32.0	0.0	0.0	6	0.19
E3	28.7	0.5	1.8	6	0.19
E4	30.0	0.0	0.0	6	0.18
MKG	29.7	0.5	1.7	6	0.20
SE1	32.2	1.9	6.0	6	0.15
SE2	28.7	0.8	2.8	6	0.16
SE3	30.8	0.4	1.3	6	0.19
SE4	34.3	0.8	2.4	6	0.16
SE5	29.2	1.1	3.8	12	0.19
SSE1	33.0	0.0	0.0	12	0.16
SSE2	29.5	0.6	2.0	6	0.17
SSE3	30.0	0.0	0.0	6	0.17
S1	39.0	2.3	6.0	6	0.16
S2	32.4	1.6	4.9	6	0.16
S3	36.9	1.7	4.6	6	0.13
S4	36.4	0.9	2.5	6	0.15
S5	34.8	0.4	1.2	6	0.14
SSW1	26.0	0.0	0.0	6	0.18
SSW2	29.5	0.5	1.9	6	0.17
SW1	38.0	0.0	0.0	6	0.19
SW2	31.0	0.0	0.0	6	0.17
SW3	29.0	0.0	0.0	12	0.17
SW4	29.0	0.0	0.0	6	0.18
SW5	26.0	0.0	0.0	6	0.19
W1	31.1	0.3	0.9	12	0.18
W2	30.0	0.0	0.0	6	0.16
W3	28.0	0.0	0.0	6	0.17
NW3	31.0	0.0	0.0	12	0.16
NW4	31.0	0.0	0.0	6	0.16
NW5	29.3	0.5	1.8	6	0.17

continued...

Table 4. Concluded.

Site	Mean Depth (cm)	Standard Deviation (cm)	%	Number of Cores	Density (g/cm^3)
NNW1	33.0	0.0	0.0	6	0.17
N1	29.0	0.6	2.2	6	0.19
N2	37.6	1.2	3.2	6	0.15
N3	37.7	0.5	1.4	6	0.17
N4	31.2	0.4	1.3	6	0.16
N5	35.0	0.0	0.0	6	0.16
G1	29.8	0.4	1.4	6	0.19
G5	28.0	0.0	0.0	6	0.17
R1	34.2	1.1	3.3	6	0.16
R2	29.7	0.5	1.7	6	0.18
R3	34.7	2.7	7.9	6	0.17
R4	28.0	0.0	0.0	12	0.18
LS	33.0	0.0	0.0	6	0.18
ELS	31.0	0.0	0.0	6	0.17
BM	26.0	0.0	0.0	6	0.22
FBG	28.0	0.0	0.0	6	0.16
ASB	30.7	0.8	2.7	6	0.16
GLK	35.0	1.1	3.1	6	0.16
SMT	33.0	0.0	0.0	6	0.19
GC	33.0	0.0	0.0	6	0.17

Table 5. Snow depth statistics for 20 to 23 February 1981.

Site	Mean Depth (cm)	Standard Deviation (cm)	%	Number of Cores	Density (g/cm^3)
NNE1	33.1	0.4	1.2	12	0.21
NNE2	32.5	0.4	1.2	6	0.25
NNE3	29.5	0.6	2.0	6	0.23
NNE4	33.3	1.2	3.6	6	0.20
NE1	26.1	0.2	0.8	12	0.26
NE2	32.1	0.6	1.9	6	0.24
NE3	33.2	0.3	0.9	6	0.23
NE4	28.3	0.4	1.4	6	0.22
NE5	18.1	0.2	1.1	12	0.22
E1	25.4	0.3	1.1	6	0.22
E2	31.8	0.9	2.8	6	0.22
E3	24.4	0.5	2.0	6	0.27
E4	33.8	0.6	1.8	6	0.24
MKG	34.2	0.3	0.8	6	0.20
SE1	26.3	0.4	1.6	6	0.23
SE2	30.7	0.4	1.3	6	0.21
SE3	27.6	0.4	1.4	6	0.21
SE4	23.3	0.3	1.2	6	0.24
SE5	29.2	2.0	6.9	12	0.24
SSE1	32.8	0.3	0.8	12	0.22
SSE2	29.0	0.4	1.2	5	0.22
SSE3	26.1	0.4	1.4	6	0.25
S1	36.8	1.0	2.8	6	0.21
S2	34.7	0.5	1.5	6	0.24
S3	29.7	0.4	1.4	6	0.22
S4	33.9	0.4	1.1	6	0.23
S5	34.9	1.1	3.1	6	0.23
SSW1	29.8	0.3	0.9	6	0.25
SSW2	27.5	0.3	1.1	6	0.25
SW1	28.1	0.9	3.3	6	0.28
SW2	36.8	2.2	6.1	6	0.24
SW3	27.1	0.5	1.8	12	0.24
SW4	27.9	0.2	0.7	6	0.27
SW5	23.5	0.0	--	6	0.29
W1	29.7	0.2	0.8	12	0.26
W2	27.3	0.3	1.0	6	0.25
W3	31.2	0.3	0.8	6	0.22
NW3	30.5	0.2	0.7	12	0.23
NW4	32.1	0.2	0.6	6	0.22
NW5	27.3	0.4	1.5	6	0.25

continued...

Table 5. Concluded.

Site	Mean Depth (cm)	Standard Deviation (cm)	%	Number of Cores	Density (g/cm^3)
NNW1	35.6	0.2	0.6	6	0.22
N1	33.1	1.2	3.5	6	0.20
N2	31.3	2.1	6.6	6	0.25
N3	37.1	0.4	1.1	6	0.19
N4	41.9	1.7	4.2	6	0.20
N5	37.7	0.3	0.7	6	0.21
G1	37.5	4.4	11.8	6	0.25
G5	30.3	0.6	2.0	6	0.24
R1	28.8	0.6	2.1	6	0.24
R2	28.8	0.3	0.9	6	0.23
R3	36.2	0.4	1.1	6	0.23
R4	28.0	0.4	1.4	12	0.28
LS	24.9	2.1	8.5	6	0.26
ELS	45.7	0.5	1.1	6	0.21
BCH	40.2	4.6	11.5	6	0.30
FBG	31.3	0.4	1.3	6	0.20
ASB	20.3	0.3	1.3	6	0.26
GLK	31.3	1.0	3.2	6	0.27
SMT	36.7	0.8	2.2	6	0.24
GC	35.3	0.4	1.1	6	0.24

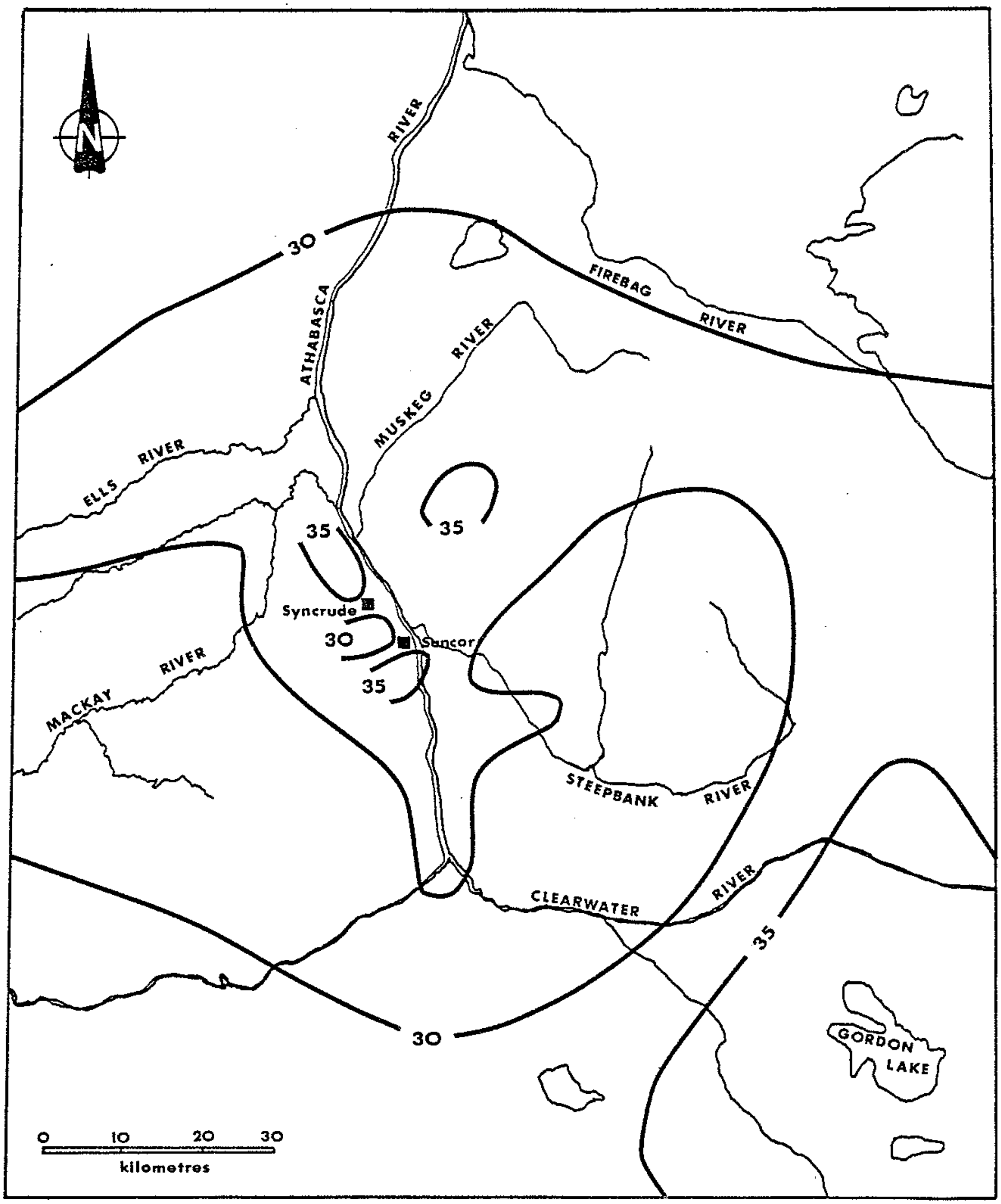


Figure 6. Snow depths (cm), 10 January 1981.

3.4 CONCENTRATIONS OF CONSTITUENTS OF THE SNOWMELT

The measured concentrations of major ions for the January and February 1981 collection periods are presented in Tables 6 and 7, respectively. Dissolved aluminum, iron, nickel, and vanadium concentrations are shown in Tables 8 and 9. Measured concentrations of the soluble constituents, and masses of insoluble trace metals found in the snowmelt from the snow collectors are shown in Tables 10 and 11, respectively.

3.5 SNOWPACK LOADING OF MAJOR IONS

Snowpack loading, the quantity of a substance in the snow per square metre of surface, was calculated for the major ions (see Tables 12 and 13) from the concentrations, snowmelt volume, and the area sampled. The hydrogen ion loadings were calculated from the pH measured in the laboratory. Major ion loadings for the six snow collectors are shown in Table 14. The variability of major ion loading at a given site due to sampling and analytical errors (Table 15) was less than 20% for $SO_4^=$, NO_3^-, and K^+ and less than 82% for the other ions. The change in pH with time (see discussion in Section 4.4) accounts for the large variability reported for the H^+ ion. (The two samples which are compared were analyzed by different laboratories at different times.) Mappings of the snowpack loading for each major ion are given in the Appendix.

3.6 SNOWPACK LOADING OF NON-ALKALINE METALS, INSOLUBLE AND SOLUBLE

The snowpack loadings of non-alkaline metals are presented in Tables 16 and 17 for the January and February 1981 collection periods, respectively. For the insoluble constituents, loadings were calculated from the weight of particulate matter filtered from the snowmelt and the area sampled. Loadings for the soluble metals were determined from the meltwater concentrations, snowmelt volume, and the area sampled. Metal loadings for the snow collectors are given in Table 18. The variability of trace metal loadings at a given site due to sampling and analytical errors (Table 19) was 29 to 73% for the insolubles, and 40 to 92% for the solubles. Maps showing the spatial distribution of metal loading in the study area are in Sections 7.1 and 7.2.

Table 6. Measured snowmelt major ion concentrations for each site on 10 to 13 January 1981 (see Figure 2 for site locations).

Site	Major Ion Concentrations (mg/L)										
	Major Ion Volume (mL)	pH	$SO_4^{=}$-S	Cl^-	NO_3^--N	NH_4^+-N	K^+	Na^+	Mg^{++}	Ca^{++}	Alkalinity (µeq/L)
NNE1C	1242	7.0	0.6	0.5	0.12	0.04	0.38	0.5	0.6	2.5	166
NNE1B	1245	7.2	0.8	0.1	0.13	0.05	0.42	0.3	0.4	1.7	240
NNE2	1230	5.2	0.3	0.1	0.10	0.02	0.12	0.1	D.L.	0.4	16
NNE3	1320	7.2	0.3	0.2	0.09	0.03	D.L.	0.4	0.7	1.8	156
NNE4	1216	6.8	0.3	0.1	0.10	0.02	D.L.	0.3	0.5	2.2	142
NE1C	1320	8.1	0.4	0.2	0.10	0.04	0.16	D.L.	1.0	2.3	192
NE1B	1245	6.5	0.5	0.1	0.12	0.11	0.07	0.8	0.5	1.2	88
NE2	1250	5.5	0.2	0.1	0.09	0.03	D.L.	0.3	0.2	0.2	22
NE3	1350	6.1	0.2	0.1	0.09	0.03	D.L.	0.3	0.4	0.5	58
NE4	1500	4.4	0.1	0.1	0.09	0.02	D.L.	D.L.	D.L.	0.1	0
NE5C	1320	6.9	1.0	0.1	0.10	0.02	0.22	2.5	1.9	0.8	178
NE5B	1290	6.0	0.7	D.L.	0.11	D.L.	D.L.	0.6	0.2	0.2	24
E1	1285	6.4	0.2	0.4	0.11	0.05	0.15	0.5	0.4	1.0	76
E2	1450	5.6	0.1	D.L.	0.09	0.02	D.L.	0.2	0.2	0.3	26
E3	1240	4.5	0.2	D.L.	0.09	0.02	D.L.	D.L.	0.1	0.2	0
E4	1300	6.2	0.2	0.9	0.08	0.03	D.L.	0.6	0.5	0.7	64
MKG	1180	4.6	0.2	0.2	0.08	0.03	D.L.	0.1	D.L.	0.2	4
SE1	1142	5.7	0.3	0.1	0.11	0.05	0.49	0.1	0.1	0.5	28
SE2	1100	4.8	0.2	0.1	0.10	0.01	D.L.	D.L.	D.L.	0.2	4
SE3	1380	5.1	0.1	0.1	0.10	0.03	D.L.	D.L.	0.1	0.2	12
SE4	1200	5.3	0.2	0.2	0.11	0.02	D.L.	0.1	0.1	0.3	18
SE5C	1300	4.6	0.1	D.L.	0.10	0.03	D.L.	0.1	0.1	0.2	6
SE5B	1290	5.3	0.2	D.L.	0.14	D.L.	0.16	0.1	0.1	0.3	0
SSE1C	1295	4.9	0.2	0.1	0.12	0.03	D.L.	0.1	0.1	0.3	8
SSE1B	1245	6.1	0.3	D.L.	0.13	D.L.	0.14	0.2	0.2	0.7	32
SSE2	1186	5.8	0.2	0.2	0.11	0.03	0.10	0.1	0.2	0.5	34
SSE3	1240	5.7	0.2	0.3	0.13	0.02	0.11	0.2	0.3	0.3	30
S1	1430	6.3	1.1	1.5	0.19	0.17	0.69	0.7	0.4	2.2	66
S2	1190	5.6	0.5	0.9	0.18	0.05	0.19	0.4	0.2	0.9	22
S3	1104	4.8	0.3	2.4	0.17	0.03	0.13	1.5	0.1	0.4	8
S4	1310	5.4	0.4	1.2	0.17	0.03	0.22	0.6	0.2	0.6	16
S5	1148	6.1	0.4	1.6	0.17	0.03	0.17	1.2	0.3	1.1	58
SSW1	1120	5.7	0.4	0.1	0.15	0.02	0.12	0.2	0.2	0.5	22
SSW2	1240	4.8	0.3	0.1	0.15	0.02	D.L.	0.1	0.1	0.3	10
SW1	1650	6.0	0.4	2.1	0.12	0.05	D.L.	1.4	0.5	1.3	74
SW2	1230	6.7	0.7	0.5	0.13	0.04	0.07	1.6	1.3	1.2	202
SW3C	1220	5.6	0.4	0.2	0.14	0.09	D.L.	0.2	0.1	0.6	22
SW3B	1185	6.1	1.0	D.L.	0.13	0.07	D.L.	0.9	0.2	1.0	36
SW4	1184	5.2	0.3	0.1	0.12	0.05	D.L.	0.3	0.2	0.2	18
SW5	1165	4.9	0.2	0.4	0.10	0.04	0.07	0.2	0.1	0.3	8
W1C	1320	6.5	1.0	0.1	0.12	0.15	0.14	1.1	0.5	1.2	84
W1B	1340	6.5	1.1	0.1	0.12	0.23	0.14	1.0	0.3	1.5	80
W2	1210	5.2	0.2	0.2	0.10	0.03	0.07	0.3	0.1	0.2	14
W3	1150	5.9	0.2	0.1	0.10	0.03	0.14	1.2	0.4	0.2	78
NW3C	1238	6.2	0.3	0.3	0.10	0.04	0.08	0.6	0.4	0.7	62
NW3B	1135	6.0	0.2	D.L.	0.11	0.17	D.L.	0.4	0.6	0.8	32
NW4	1234	8.9	2.7	0.6	0.11	0.02	0.32	3.8	3.6	2.0	360
NW5	1190	5.8	0.2	0.1	0.11	0.02	D.L.	0.2	0.2	0.4	26
NNW1	1340	5.8	0.3	0.3	0.11	0.03	D.L.	0.5	0.2	0.3	40
N1	1350	6.0	0.3	0.4	0.12	0.09	0.09	0.1	0.2	0.7	32
N2	1170	6.0	0.7	1.0	0.14	0.19	0.39	0.6	0.3	1.1	46
N3	1450	5.9	0.3	0.3	0.12	0.07	0.15	0.2	0.1	0.7	30
N4	1260	5.7	0.3	0.2	0.11	0.03	0.06	0.4	0.1	0.6	28
N5	1365	5.3	0.6	0.3	0.11	0.03	D.L.	0.4	0.2	0.4	12
G1	1280	6.5	1.1	1.2	0.20	0.18	0.31	0.5	0.5	2.6	86
G5	1122	7.2	0.5	0.2	0.13	0.09	0.09	0.3	1.0	3.5	226
R1	1182	5.5	0.4	0.6	0.13	0.04	0.10	0.4	0.1	0.8	24
R2	1218	4.7	0.4	0.3	0.13	0.05	0.09	0.3	0.1	0.4	6
R3	1250	5.3	0.4	0.1	0.12	0.06	0.25	0.1	0.1	0.4	12
R4C	1240	6.8	1.0	0.4	0.14	0.08	1.48	0.3	0.4	1.8	106
R4B	1255	6.7	1.5	0.2	0.20	0.22	1.62	0.3	0.4	2.3	112
LS	1380	6.3	1.4	0.3	0.20	0.13	2.47	0.3	0.2	1.5	60
ELS	1280	5.9	0.3	0.8	0.09	0.02	0.16	0.6	0.2	0.6	34
BM	1370	4.8	0.6	0.1	0.06	0.02	D.L.	0.3	0.2	0.3	6
FBG	1140	5.5	0.2	0.1	0.09	0.02	0.18	D.L.	0.2	0.2	16
ASB	1100	4.5	0.1	D.L.	0.07	0.03	D.L.	D.L.	D.L.	0.1	0
GLK	1560	4.5	0.2	0.5	0.10	0.03	0.10	0.2	D.L.	0.2	0
SMT	1450	4.4	0.2	0.2	0.10	0.02	D.L.	0.2	D.L.	0.1	0
GC	1320	6.1	0.2	0.3	0.09	0.02	0.15	0.3	0.3	0.7	58

D.L. - Detection Limit; C - Chemex; B - Barringer

Table 7. Measured snowmelt major ion concentrations for each site on 20 to 23 February 1981 (see Figure 2 for site locations).

Site	Major Ion Concentrations (mg/L)										
	Major Ion Volume (mL)	pH	$SO_4^{=}$-S	Cl^-	NO_3^--N	NH_4^+-N	K^+	Na^+	Mg^{++}	Ca^{++}	Alkalinity (μeq/L)
NNE1C	1675	6.4	0.6	0.1	0.12	0.08	0.43	0.1	0.4	1.8	100
NNE1B	1810	6.8	0.7	0.1	0.11	0.03	0.31	0.3	0.4	1.4	110
NNE2	1670	5.9	0.4	0.1	0.11	0.04	0.09	0.1	0.2	0.9	36
NNE3	1660	6.0	0.2	0.0	0.11	0.04	<0.06	0.1	0.2	1.5	92
NNE4	1510	4.4	0.3	0.1	0.12	0.04	<0.06	0.0	0.0	0.4	0
NE1C	1610	9.6	0.7	0.1	0.13	0.08	0.12	0.7	1.9	8.5	554
NE1B	1600	6.1	0.5	0.0	0.09	0.07	0.12	0.1	0.1	0.6	D.L.
NE2	1730	5.3	0.3	0.1	0.11	0.03	0.06	0.3	0.1	0.5	18
NE3	1880	5.2	0.2	0.1	0.09	0.03	<0.06	0.2	0.1	0.2	14
NE4	1650	5.4	0.3	0.1	0.09	0.03	<0.06	0.2	0.2	0.3	20
NE5C	1000	7.4	0.3	0.1	0.11	0.05	0.06	0.3	1.9	3.1	280
NE5B	980	6.9	0.3	0.0	0.09	0.05	0.12	0.4	2.7	3.2	180
E1	1410	8.5	0.3	0.2	0.09	0.10	0.07	2.6	1.5	1.7	284
E2	1720	8.5	0.2	0.1	0.08	0.04	0.08	1.1	0.8	2.1	200
E3	1620	5.9	0.2	0.1	0.09	0.04	<0.06	0.0	0.8	0.7	3
E4	2030	6.0	0.1	0.0	0.08	0.03	<0.06	0.1	0.2	0.4	32
MKG	1230	4.7	0.3	0.8	0.28	0.13	0.07	0.2	0.1	0.6	4
SE1	1530	7.0	0.5	0.1	0.11	0.09	0.66	0.1	0.7	2.0	135
SE2	1560	4.8	0.2	0.1	0.09	0.02	0.10	0.0	0.0	0.2	6
SE3	1400	5.8	0.2	0.1	0.09	0.07	<0.06	0.3	0.2	0.8	115
SE4	1340	5.9	0.2	0.1	0.09	0.11	0.21	0.2	1.1	0.9	130
SE5C	1540	7.4	0.2	0.1	0.09	0.03	<0.06	0.5	0.7	1.2	138
SE5B	1620	6.7	0.2	0.0	0.07	0.04	0.05	0.2	0.4	1.2	70
SSE1C	1770	4.9	0.3	0.1	0.12	0.05	0.07	0.1	0.1	0.4	10
SSE1B	1800	5.6	0.3	0.0	0.09	D.L.	0.12	D.L.	0.1	0.4	D.L.
SSE2	1560	4.9	0.2	0.1	0.11	0.03	0.03	0.0	0.1	0.3	11
SSE3	1535	5.5	0.2	0.6	0.15	0.05	0.09	0.3	0.2	0.4	20
S1	1910	5.6	1.1	1.9	0.17	0.14	0.64	1.2	0.3	2.0	54
S2	1970	5.0	0.5	0.3	0.16	0.07	0.11	0.2	0.1	0.8	12
S3	1650	5.6	0.3	0.2	0.14	0.05	0.06	0.2	0.1	1.0	44
S4	1910	5.1	0.4	1.4	0.15	0.04	0.06	0.8	0.1	0.8	22
S5	1895	6.6	0.4	2.3	0.16	0.03	0.16	1.5	0.3	1.8	89
SSW1	1800	6.5	0.5	0.1	0.14	0.05	0.12	0.5	0.3	0.7	59
SSW2	1670	5.5	0.3	0.1	0.14	0.04	0.07	0.2	0.2	0.7	36
SW1	1880	6.6	0.4	1.3	0.12	0.07	0.06	0.7	0.5	1.6	97
SW2	1820	5.2	0.3	0.3	0.12	0.07	0.17	0.2	0.1	0.6	18
SW3C	1560	4.7	0.3	0.1	0.11	0.11	<0.06	0.2	0.1	0.3	6
SW3B	1630	6.3	0.3	0.0	0.09	0.09	D.L.	0.8	0.1	0.3	30
SW4	1700	4.6	0.3	0.3	0.12	0.09	0.10	0.2	0.0	0.3	4
SW5	1560	4.3	0.2	0.1	0.10	0.05	<0.06	0.1	0.0	0.2	0
W1C	1860	4.7	0.4	0.1	0.11	0.16	0.08	0.1	0.1	0.4	4
W1B	1670	5.8	0.5	0.1	0.09	0.17	D.L.	0.1	0.1	0.5	D.L.
W2	1640	4.7	0.2	0.1	0.10	0.05	0.05	0.0	0.0	0.3	5
W3	1660	6.6	0.2	0.1	0.09	0.03	0.15	1.0	0.6	0.3	87
NW3C	1670	6.1	0.3	0.1	0.11	0.06	0.22	0.7	0.3	1.4	104
NW3B	1690	6.6	0.3	0.0	0.09	0.03	0.20	0.6	0.5	1.4	70
NW4	1650	6.3	0.6	0.1	0.10	0.02	0.07	0.9	1.6	2.1	230
NW5	1610	5.8	0.2	0.2	0.10	0.03	<0.06	0.4	0.5	0.7	74
NNW1	1850	5.4	0.2	0.1	0.10	0.04	<0.06	0.3	0.2	0.2	24
N1	1340	6.4	0.5	1.3	0.13	0.14	<0.06	0.8	0.4	1.3	50
N2	1570	6.5	1.0	0.2	0.15	0.27	0.17	0.3	0.4	1.5	63
N3	1375	5.7	0.4	0.1	0.13	0.10	0.12	0.1	0.2	1.1	50
N4	1980	4.6	0.4	0.2	0.14	0.07	<0.06	0.1	0.1	0.5	4
N5	1870	4.4	0.3	0.1	0.11	0.03	<0.06	0.1	0.1	0.2	0
G1	1810	6.4	16.3	0.5	0.63	0.49	17.5	0.7	2.0	13.8	220
G5	1700	6.9	1.2	0.2	0.14	0.12	0.08	0.2	1.0	2.8	140
R1	1675	4.9	0.3	0.1	0.15	0.05	0.26	0.1	0.1	0.4	13
R2	1575	5.0	0.5	0.1	0.14	0.08	0.27	0.1	0.0	0.6	14
R3	1890	4.9	0.6	0.1	0.13	0.09	0.62	0.1	0.1	0.6	12
R4C	1580	6.3	1.0	0.1	0.16	0.11	2.2	0.2	0.8	1.5	118
R4B	1640	6.8	1.0	0.1	0.14	0.07	2.62	0.2	0.9	1.8	130
LS	1630	6.7	1.4	0.1	0.20	0.14	3.5	0.1	0.2	1.5	82
ELS	2270	4.8	0.1	0.1	0.10	0.03	0.1	0.3	0.0	0.1	10
BM	3010	4.7	0.1	0.1	0.07	0.01	0.1	0.0	0.0	0.1	6
FBG	1550	4.7	0.2	0.1	0.10	0.02	<0.06	0.0	0.0	0.2	5
ASB	1290	6.4	0.1	0.1	0.07	0.07	<0.06	0.1	0.3	0.9	56
GLK	1725	5.1	0.2	0.1	0.11	0.25	0.10	0.1	0.0	0.1	20
SMT	1980	4.8	0.2	0.2	0.11	0.06	0.10	0.1	0.0	0.2	8
GC	1835	4.8	0.2	0.1	0.09	0.03	<0.06	0.0	0.0	0.3	6

D.L. - Detection Limit; C-Chemex; B-Barringer

Table 8. Measured soluble metal concentrations for each site on 10 to 13 January 1981 (see Figure 2 for site locations).

Site	Snowmelt Metal Volume (mL)	Soluble Metal Concentrations (ug/L)			
		Aluminum (Al)	Vanadium (V)	Iron (Fe)	Nickel (Ni)
NNE1C	1570	25	9	17	3
NNE1B	1820	D.L.	25	D.L.	D.L.
NNE2	1650	11	5	11	4
NNE3	1590	2	6	7	3
NNE4	1495	12	6	11	4
NE1C	1580	14	15	11	6
NE1B	1650	D.L.	22	D.L.	D.L.
NE2	1625	14	12	12	2
NE3	1850	9	9	10	3
NE4	1650	7	6	13	3
NE5C	950	2	11	11	3
NE5B	980	D.L.	12	D.L.	D.L.
E1	1315	9	7	7	3
E2	1625	3	4	5	4
E3	1580	1	5	18	3
E4	1820	4	3	9	2
MKG	1670	<1	3	4	2
SE1	1430	9	28	15	3
SE2	1540	1	9	7	2
SE3	1370	<1	3	4	<1
SE4	1390	3	13	18	1
SE5C	1590	<1	5	12	2
SE5B	1820	D.L.	57	10	D.L.
SSE1C	1760	5	25	12	2
SSE1B	1780	D.L.	15	D.L.	D.L.
SSE2	1560	6	6	5	1
SSE3	1570	3	4	7	1
S1	1650	12	72	13	10
S2	1890	14	50	21	5
S3	1540	7	17	7	4
S4	1880	5	12	9	3
S5	1890	8	12	8	4
SSW1	1750	13	19	14	3
SSW2	1650	15	15	11	3
SW1	1740	8	13	16	2
SW2	2030	5	16	15	3
SW3C	1575	9	10	15	3
SW3B	1630	D.L.	12	D.L.	D.L.
SW4	885	3	8	12	4
SW5	1690	6	4	11	<1
W1C	850	8	8	11	4
W1B	1660	D.L.	7	D.L.	D.L.
W2	1640	8	3	9	1
W3	1680	7	1	9	<1
NW3C	1710	5	6	11	2
NW3B	1690	D.L.	6	D.L.	D.L.
NW4	1720	12	3	6	<1
NW5	1610	3	5	4	<1
NNW1	1850	7	6	13	<1
N1	1390	12	26	16	2
N2	1710	<1	28	21	2
N3	1820	4	17	7	2
N4	1870	1	21	16	2
N5	1890	1	14	6	<1
G1	2360	<1	16	24	4
G5	1730	12	14	19	2
R1	1590	6	27	15	3
R2	1565	12	43	18	5
R3	1940	10	61	18	7
R4C	2084	26	84	8	6
R4B	1670	D.L.	90	D.L.	D.L.
LS	1470	12	16	12	12
ELS	2200	2	1	3	<1
BM	2710	3	<1	3	<1
FBG	1500	5	<1	7	1
ASB	1280	2	<1	10	<1
GLK	2030	2	<1	2	<1
SMT	2130	<1	<1	4	<1
GC	1850	4	13	5	2

D.L.-Detection Limit; B-Barringer; C-Chemex

Table 9. Measured soluble metal concentrations for each site on 20 to 23 February 1981 (see Figure 2 for site locations.)

Site	Snowmelt Metal Volume (mL)	Soluble Metal Concentrations (ug/L)			
		Aluminum (Al)	Vanadium (V)	Iron (Fe)	Nickel (Ni)
NNE1C	1198	23	64	19	7
NNE1B	1245	20	42	30	D.L.
NNE2	1194	21	36	33	1
NNE3	1330	1	14	6	D.L.
NNE4	1170	10	12	9	D.L.
NE1C	1250	18	47	7	3
NE1B	1245	20	40	20	D.L.
NE2	1285	13	15	7	1
NE3	1340	4	13	7	D.L.
NE4	1400	10	5	6	D.L.
NE5C	1170	1	4	5	D.L.
NE5B	1290	20	10	1	D.L.
E1	1290	20	16	5	2
E2	1405	9	6	9	D.L.
E3	1360	15	6	16	D.L.
E4	1310	14	6	14	D.L.
MKG	1315	14	6	11	D.L.
SE1	1094	17	46	7	2
SE2	1110	6	15	9	D.L.
SE3	1360	4	14	11	1
SE4	1340	7	16	6	D.L.
SE5C	1246	17	7	7	D.L.
SE5B	1480	D.L.	6	30	D.L.
SSE1C	1188	3	37	7	4
SSE1B	1245	10	27	30	D.L.
SSE2	1250	D.L.	14	17	3
SSE3	1174	11	10	14	2
S1	1480	17	240	10	18
S2	1240	81	96	24	20
S3	965	26	34	13	D.L.
S4	1244	9	17	46	D.L.
S5	1180	6	14	5	D.L.
SSW1	1155	17	38	8	D.L.
SSW2	1220	8	20	27	D.L.
SW1	1725	14	12	5	D.L.
SW2	1295	D.L.	20	6	D.L.
SW3C	1214	12	15	14	D.L.
SW3B	1185	D.L.	7	30	D.L.
SW4	1250	D.L.	15	11	D.L.
SW5	1170	D.L.	7	16	2
W1C	1290	25	16	12	6
W1B	1340	30	17	30	20
W2	1150	6	3	10	4
W3	1170	4	3	18	D.L.
NW3C	1250	6	10	11	3
NW3B	1135	D.L.	1	30	10
NW4	1210	D.L.	4	8	D.L.
NNW1	1320	11	8	11	D.L.
N1	1290	60	44	61	6
N2	1325	20	44	150	6
N3	1340	9	18	10	1
N4	1180	11	25	19	3
N5	1380	18	20	D.L.	2
G1	1280	52	133	33	15
G5	1170	8	11	8	D.L.
R1	1300	D.L.	38	7	2
R2	1375	18	60	13	7
R3	1200	18	51	5	14
R4C	1208	18	82	5	16
R4B	1255	10	137	30	10
LS	1277	21	157	3	19
ELS	1300	D.L.	1	9	D.L.
BM	1350	6	D.L.	9	2
FBG	1050	9	1	4	2
ASB	1100	3	D.L.	6	2
GLK	1430	4	D.L.	4	D.L.
SMT	1440	2	1	3	D.L.
GC	1360	16	3	5	D.L.

D.L.-Detection Limit; B-Barringer; C-Chemex

Table 10. Measured concentrations[a] of major ions and soluble trace metals found in the snowmelt from the collector trays. Sample volume and pH are also listed.

	Site					
	N1	N2	N5	S2	S4	SW1
Sample volume (mL)	4380	2910	1820	3540	1960	2690
pH	6.70	6.05	4.91	4.90	6.66	7.52
Alkalinity (μeq/L)	102	128	16	10	73	383
$SO_4^{=}$-S	0.74	1.33	0.54	1.26	0.95	1.42
Cl^-	1.37	0.38	0.16	1.39	2.87	2.97
NO_3^--N	0.16	0.17	0.15	0.20	0.32	0.21
NH_4^+-N	0.13	0.32	0.08	0.14	0.07	0.18
K^+	0.21	0.50	0.13	0.84	0.32	0.64
Na^+	0.85	0.36	0.11	0.87	1.90	2.10
Mg^{++}	0.54	0.51	0.07	0.16	0.37	1.63
Ca^{++}	2.04	3.20	0.70	1.17	1.96	5.71
Aluminum	0.001	0.005	0.006	0.009	D.L.[b]	0.008
Iron	0.011	0.013	0.025	0.025	0.009	0.026
Nickel	D.L.[b]	0.003	0.001	0.006	0.002	D.L.[b]

[a]mg/L unless otherwise stated
[b]D.L. - Detection Limit

Table 11. Mass of trace metals in snowmelt from the collector trays (μg).

Site	Ti	Mn	V	Al
N1	300	23	53	2628
N2	300	74	168	5168
N5	<300	7	69	827
S2	300	14	264	1696
S4	<300	16	121	1223
SW1	900	116	169	8189

Table 12. Snowpack loadings of major ions for each site on 10 to 13 January 1981 calculated from measured concentrations, snowmelt volume, and area sampled (see Figure 2 for site locations.)

Site	Major Ion Loadings (mg/m^2)								
	H^+	$SO_4^=$-S	Cl^-	NO_3^--N	NH_4^+-N	K^+	Na^+	Mg^{++}	Ca^{++}
NNE1C	0.005	29	23	6.2	2.1	20	27	33	129
NNE1B	0.003	42	6	6.9	2.4	22	16	18	90
NNE2	0.323	13	5	5.0	1.0	6	5	2	23
NNE3	0.003	15	13	5.2	1.4	D.L.	21	41	96
NNE4	0.008	15	4	5.2	1.1	D.L.	13	29	111
NE1C	0.000	20	8	5.7	2.2	9	D.L.	54	126
NE1B	0.016	25	5	6.5	5.7	4	40	27	62
NE2	0.165	11	7	4.4	1.6	D.L.	16	10	12
NE3	0.045	13	8	5.0	1.7	D.L.	18	22	29
NE4	2.488	8	4	5.4	1.4	D.L.	D.L.	2	9
NE5C	0.007	56	8	5.7	1.1	12	135	102	43
NE5B	0.062	40	4	5.8	D.L.	D.L.	31	11	13
E1	0.021	10	22	5.7	2.5	8	25	21	51
E2	0.152	8	2	5.1	1.0	D.L.	10	10	17
E3	1.634	8	2	4.7	0.9	D.L.	D.L.	3	9
E4	0.034	11	49	4.2	1.4	D.L.	31	25	36
MKG	1.235	7	9	3.9	1.2	D.L.	6	2	9
SE1	0.095	15	4	5.2	2.2	23	4	4	25
SE2	0.726	7	5	4.5	0.6	D.L.	D.L.	2	8
SE3	0.457	8	7	5.9	1.6	D.L.	D.L.	8	13
SE4	0.251	8	11	5.3	1.2	D.L.	7	7	16
SE5C	1.361	8	2	5.6	1.4	D.L.	4	4	9
SE5B	0.295	10	4	8.3	D.L.	9	4	4	17
SSE1C	0.679	11	3	6.4	1.7	D.L.	4	3	14
SSE1B	0.046	16	D.L.	6.8	D.L.	7	11	10	34
SSE2	0.078	7	9	5.6	1.5	5	2	10	24
SSE3	0.103	8	18	6.5	1.1	6	10	15	13
S1	0.030	66	91	11.5	10.2	41	43	25	132
S2	0.125	27	47	8.7	2.5	9	20	9	46
S3	0.729	13	109	7.7	1.4	6	69	4	19
S4	0.217	19	63	9.1	1.4	12	31	8	34
S5	0.038	21	76	8.3	1.2	8	55	18	51
SSW1	0.093	18	4	7.0	1.0	6	10	8	25
SSW2	0.819	16	4	7.8	1.1	D.L.	5	7	15
SW1	0.069	25	146	8.5	3.4	D.L.	96	31	88
SW2	0.010	34	23	6.6	1.9	4	83	64	62
SW3C	0.128	19	11	7.3	4.4	D.L.	9	6	31
SW3B	0.044	49	1	6.6	3.5	D.L.	42	11	50
SW4	0.311	13	2	5.9	2.6	D.L.	13	8	11
SW5	0.611	11	17	4.8	2.0	3	12	4	16
W1C	0.017	52	7	6.6	8.1	8	60	28	64
W1B	0.018	62	7	6.9	12.6	8	56	16	83
W2	0.318	9	9	5.0	1.4	4	15	5	10
W3	0.060	12	7	5.1	1.3	7	59	22	11
NW3C	0.033	13	13	5.2	2.1	4	31	21	34
NW3B	0.045	10	D.L.	4.8	7.7	D.L.	17	26	39
NW4	0.000	139	28	5.5	1.2	17	194	183	103
NW5	0.079	8	5	5.5	1.0	D.L.	10	8	19
NNW1	0.088	14	14	5.9	1.7	D.L.	30	12	18
N1	0.056	19	22	6.8	5.2	5	7	12	41
N2	0.049	36	50	6.6	9.1	19	29	14	51
N3	0.076	21	17	7.3	4.1	9	13	7	41
N4	0.105	17	12	5.8	1.8	3	20	6	29
N5	0.285	33	19	6.0	1.7	D.L.	23	14	23
G1	0.017	60	66	10.4	9.5	17	27	28	138
G5	0.003	21	11	6.0	4.0	4	12	47	165
R1	0.156	18	29	6.6	1.9	5	20	5	39
R2	1.013	18	17	6.7	2.4	5	14	3	20
R3	0.261	19	6	6.1	3.2	13	4	4	23
R4C	0.008	50	20	7.4	4.0	76	14	20	94
R4B	0.012	80	9	10.4	11.4	85	17	21	119
LS	0.029	79	18	11.3	7.6	142	18	11	86
ELS	0.067	15	43	4.8	1.2	9	34	10	33
BM	0.905	32	6	3.6	0.9	D.L.	17	11	15
FBG	0.150	8	3	4.0	0.8	9	D.L.	10	9
ASB	1.449	5	2	3.3	1.5	D.L.	D.L.	2	5
GLK	2.055	8	24	4.5	1.5	5	11	1	8
SMT	2.405	11	11	6.2	1.0	D.L.	9	2	8
GC	0.044	12	15	5.1	1.3	8	17	18	39

D.L. - Detection Limit

Table 13. Snowpack loadings of major ions for each site on 20 to 23 February 1981 calculated from measured concentrations, snowmelt volume, and area sampled (see Figure 2 for site locations).

Site	Major Ion Loadings (mg/m2)								
	H^+	$SO_4^=$ -S	Cl^-	NO_3^- -N	NH_4^+-N	K^+	Na^+	Mg^{++}	Ca^{++}
NNE1C	0.028	41	7	8.6	4.3	30	9	31	125
NNE1B	0.013	50	4	8.5	4.1	23	21	33	99
NNE2	0.088	26	6	7.6	2.3	6	7	13	62
NNE3	0.065	11	2	7.6	2.0	D.L.	D.L.	15	102
NNE4	2.746	19	3	7.4	1.9	D.L.	D.L.	2	23
NE1C	0.00002	48	6	8.5	4.5	8	45	129	568
NE1B	0.053	33	1	6.0	5.2	8	7	6	36
NE2	0.353	21	7	7.8	6.1	4	9	6	37
NE3	0.494	19	5	6.9	1.8	D.L.	12	11	17
NE4	0.307	18	3	6.0	1.7	D.L.	13	13	23
NE5C	0.002	14	3	4.4	1.6	3	13	77	128
NE5B	0.005	13	2	3.7	2.2	5	17	110	128
E1	.0002	18	11	5.5	4.6	4	155	86	97
E2	.0002	15	7	5.5	2.4	6	82	59	149
E3	.085	16	3	6.2	2.3	D.L.	3	11	45
E4	.095	8	2	6.4	1.9	D.L.	8	16	36
MKG	1.046	15	40	14.4	5.2	4	11	3	32
SE1	.0072	31	4	6.9	4.3	42	7	43	130
SE2	1.079	12	7	5.8	6.5	7	2	3	16
SE3	.104	10	6	5.0	3.0	D.L.	18	13	45
SE4	.070	12	4	5.2	4.8	8	12	50	64
SE5C	0.0026	14	4	5.6	1.6	D.L.	31	46	78
SE5B	0.015	11	1	4.6	2.1	3	14	28	84
SSE1C	1.066	23	5	8.7	3.9	5	4	4	32
SSE1B	0.211	23	1	6.8	D.L.	9	2	4	23
SSE2	0.800	10	3	6.6	1.3	4	2	3	16
SSE3	0.184	12	41	9.4	2.6	8	12	12	27
S1	0.182	86	152	13.8	8.7	51	99	21	155
S2	0.921	43	21	12.9	4.4	9	12	8	65
S3	0.194	26	16	11.5	2.9	5	12	11	80
S4	0.604	33	111	11.6	2.3	5	65	10	62
S5	0.198	35	183	12.5	2.0	13	118	23	143
SSW1	0.024	36	9	10.1	3.0	9	38	25	55
SSW2	0.220	20	7	9.6	1.9	5	11	15	49
SW1	0.197	30	99	9.6	5.8	5	58	44	121
SW2	0.478	24	25	9.0	4.1	13	12	6	44
SW3C	1.297	20	7	7.0	5.6	D.L.	12	5	16
SW3B	0.034	20	1	6.1	5.3	D.L.	53	7	10
SW4	1.996	22	23	8.1	5.2	7	13	3	23
SW5	3.258	15	8	6.2	2.7	D.L.	5	3	14
W1C	1.735	32	9	8.1	9.6	6	6	5	30
W1B	0.124	32	3	6.3	13.5	D.L.	5	6	25
W2	1.272	15	6	6.8	2.9	3	3	1	19
W3	0.166	13	8	6.2	1.8	10	68	40	21
NW3C	0.055	23	7	7.5	3.5	15	49	22	97
NW3B	0.017	23	3	6.3	2.7	14	44	37	92
NW4	0.034	43	8	6.7	1.3	5	61	108	140
NW5	0.106	11	11	6.9	1.4	D.L.	27	38	48
NNW1	0.307	15	10	7.9	2.2	D.L.	20	13	19
N1	0.238	29	72	7.4	6.1	D.L.	44	21	70
N2	0.222	65	11	9.7	13.7	11	19	29	99
N3	0.128	24	7	7.6	4.4	7	6	11	64
N4	1.890	31	13	11.1	4.4	D.L.	7	6	41
N5	2.830	26	5	8.3	2.6	D.L.	5	8	16
G1	0.030	1232	40	47.5	28.7	1319	49	147	1039
G5	0.009	84	11	9.9	6.6	6	11	69	200
R1	0.986	23	8	10.2	2.5	18	4	4	31
R2	0.720	30	9	9.4	4.1	18	4	4	37
R3	1.014	46	7	9.8	5.5	49	4	8	44
R4C	0.037	65	9	10.3	5.6	144	14	51	95
R4B	0.011	74	10	9.2	4.8	179	15	61	116
LS	0.014	95	9	13.5	7.4	238	7	11	105
ELS	1.465	12	6	9.1	1.9	9	2	3	13
BM	2.682	14	10	8.5	1.5	14	5	3	6
FBG	1.231	10	5	6.6	1.2	D.L.	3	3	12
ASB	0.020	7	5	3.8	3.0	D.L.	6	15	47
GLK	0.545	14	10	7.9	14.0	6	5	2	7
SMT	1.249	18	14	8.9	3.9	8	7	2	18
GC	1.131	16	5	6.7	1.5	D.L.	3	2	24

D.L. - Detection Limit

Table 14. Loadings (mg/m^2) of major ions for the snow collector trays which were set out from 16 January to 23 February 1981. Loadings were calculated from measured concentrations, snowmelt volume, and tray area (see Figure 2 for site locations).

Site	H^+	$SO_4^{=}$-S	Cl^-	NO_3^--N	NH_4^+-N	K^+	Na^+	Mg^{++}	Ca^{++}
N1	0.036	18	34	4.0	3.2	5	21	13	51
N2	0.108	22	6	2.7	5.3	6	8	8	53
N5	0.933	6	2	1.6	0.9	1	1	1	7
S2	1.857	25	28	4.0	2.8	17	18	3	23
S4	0.018	11	32	3.6	0.7	4	21	4	22
SW1	0.003	22	45	3.2	2.7	10	32	25	87

Table 15. Variability of major ion loadings of the snowpack (determined from the average percent standard deviation about the mean of two samples taken in each of the 1981 surveys at the following sites: NNE1, NE1, NE5, SE5, SSE1, SW3, W1, NW3, and R4).

Constituent	Variability of Loading (%)
H^+	82
$SO_4^=$	17
Cl^-	61
NO_3^-	11
NH_4^+	32
Na^+	45
Mg^{++}	37
Ca^{++}	33
K^+	19

Table 16. Snowpack loadings (mg/m^2) of metals for each site on 10 to 13 January 1981 calculated from measured concentrations, snowmelt volume, and area sampled (see Figure 2 for site locations).

Site	Total	Insoluble				Soluble			
		Al	V	Mn	Ti	Al	V	Fe	Ni
NNE1C	710	24	3.0	0.2	2	1.15	3.19	0.95	0.35
NNE1B	M	3	2.9	D.L.	D.L.	1.04	2.18	1.56	0.00
NNE2	470	20	3.0	0.2	D.L.	1.04	1.79	1.64	0.05
NNE3	260	10	1.3	0.1	D.L.	0.06	0.76	0.33	D.L.
NNE4	180	8	1.0	0.1	D.L.	0.49	0.59	0.44	D.L.
NE1C	790	31	3.7	0.3	D.L.	0.94	2.45	0.36	0.16
NE1B	M	3	2.7	0	D.L.	1.04	2.08	1.04	0.00
NE2	360	13	1.5	0.1	D.L.	0.70	0.80	0.37	0.05
NE3	220	8	1.0	0.1	D.L.	0.22	0.73	0.39	D.L.
NE4	220	8	0.8	0.1	D.L.	0.58	0.29	0.35	D.L.
NE5C	160	6	0.7	0.1	D.L.	0.05	0.20	0.24	D.L.
NE5B	M	1	0.4		D.L.	1.08	0.05	1.61	0.00
E1	390	15	1.4	0.1	D.L.	1.08	0.86	0.27	0.11
E2	260	10	0.8	0.1	D.L.	0.53	0.25	0.53	D.L.
E3	140	7	0.6	0.1	D.L.	0.85	0.34	0.91	D.L.
E4	130	6	0.4	0.1	D.L.	0.76	0.33	0.76	D.L.
MKG	80	4	0.5	0.1	D.L.	0.77	0.33	0.60	D.L.
SE1	1590	62	3.7	0.4	4	0.93	2.52	0.38	0.11
SE2	170	6	0.7	0.1	D.L.	0.28	0.69	0.42	D.L.
SE3	160	8	0.9	0.1	D.L.	0.23	0.79	0.62	0.06
SE4	170	9	1.0	0.1	2	0.39	0.89	0.34	D.L.
SE5C	190	9	0.6	0.1	D.L.	0.88	0.36	0.36	D.L.
SE5B	M	2	0.7		D.L.	0.00	0.37	1.61	0.00
SSE1C	500	22	3.0	0.2	D.L.	0.15	1.83	0.35	0.20
SSE1B	M	3	2.1	D.L.	D.L.	0.52	1.40	1.56	0.00
SSE2	190	7	0.9	0.1	D.L.	D.L.	0.73	0.89	0.16
SSE3	200	6	0.6	0.1	2	0.54	0.49	0.68	0.68
S1	3350	190	21.3	1.2	17	1.05	14.80	0.62	1.11
S2	390	11	1.7	0.1	D.L.	4.19	4.96	1.24	1.03
S3	960	20	2.9	0.2	D.L.	1.05	1.37	0.52	D.L.
S4	520	19	1.4	0.2	D.L.	0.47	0.88	2.38	D.L.
S5	520	16	1.3	0.3	D.L.	0.30	0.69	0.25	D.L.
SSW1	500	23	2.5	0.2	D.L.	0.82	1.83	0.39	D.L.
SSW2	360	15	1.4	0.1	D.L.	0.41	1.02	1.37	D.L.
SW1	1620	81	1.5	0.6	13	1.01	0.86	0.36	D.L.
SW2	1025	49	2.0	0.4	17	D.L.	1.08	0.32	D.L.
SW3C	630	27	1.5	0.2	D.L.	0.61	0.76	0.71	D.L.
SW3B	M	4	1.5	D.L.	D.L.	D.L.	0.35	1.48	D.L.
SW4	400	17	1.0	0.1	D.L.	D.L.	0.78	0.57	D.L.
SW5	260	10	0.7	0.1	D.L.	D.L.	0.34	0.78	0.10
W1C	1250	38	1.6	0.4	2	1.34	0.86	0.65	0.32
W1B	M	9	1.6	0.4	1	0.56	0.34	1.68	0.56
W2	310	6	0.4	0.1	D.L.	0.29	0.14	0.48	0.19
W3	130	3	0.2	0.1	D.L.	0.20	0.15	0.88	D.L.
NW3C	270	8	0.4	0.1	2	0.31	0.52	0.57	0.16
NW3B	M	D.L.	0.4	D.L.	D.L.	D.L.	0.10	1.42	0.47
NW4	195	4	0.2	0.4	D.L.	1.64	0.40	0.55	D.L.
NW5	130	4	0.2	0.1	D.L.	D.L.	0.20	0.40	D.L.
NNW1	210	6	0.3	0.1	D.L.	0.61	0.44	0.61	D.L.
N1	580	24	1.1	0.2	2	3.23	2.37	3.28	0.33
N2	9580	298	6.8	2.0	13	1.10	2.43	8.28	0.33
N3	840	40	2.3	0.3	2	0.50	1.01	0.56	0.06
N4	450	18	1.8	0.2	2	0.54	1.23	0.93	0.15
N5	270	11	1.3	0.1	D.L.	1.04	1.15	D.L.	0.12
G1	4530	216	16.0	2.1	13	2.77	7.09	1.76	0.80
G5	3270	162	2.0	1.3	D.L.	0.39	0.54	0.39	D.L.
R1	790	35	2.8	0.3	D.L.	D.L.	2.06	0.38	0.11
R2	830	42	5.6	0.3	D.L.	1.03	3.44	0.74	0.40
R3	1840	85	6.7	0.5	D.L.	0.90	2.55	0.25	0.70
R4C	1208	56	6.8	0.4	D.L.	0.91	4.13	0.25	0.81
R4B	M	5	8.8	D.L.	1	0.52	7.16	1.56	0.52
LS	2100	101	11.9	0.8	13	1.12	8.35	0.16	1.01
ELS	100	3	0.1	0.1	D.L.	D.L.	0.05	0.49	D.L.
BM	110	2	0.1	0.1	D.L.	0.34	D.L.	0.51	0.11
FBG	100	2	0.1	0.1	D.L.	0.39	0.04	0.18	0.09
ASB	100	2	0.1	0.1	D.L.	0.14	D.L.	0.28	0.09
GLK	100	3	0.1	0.1	D.L.	0.24	D.L.	0.24	D.L.
SMT	260	2	0.1	0.1	D.L.	0.12	0.06	0.18	D.L.
GC	200	7	0.8	0.1	D.L.	0.91	0.17	0.28	D.L.

M - Missing

D.L. - Detection Limit

Table 17. Snowpack loadings (mg/m^2) of metals for each site on 20 to 23 February 1981 calculated from measured concentrations, snowmelt volume, and area sampled (see Figure 2 for site locations).

Site	Total	Insoluble				Soluble			
		Al	V	Mn	Tl	Al	V	Fe	Ni
NNE1C	817	34	4.1	0.3	D.L.	1.64	0.59	1.11	0.20
NNE1B	417	9.2	1.0	0.1	2	D.L.	1.90	D.L.	D.L.
NNE2	525	20	3.0	0.1	4	0.76	0.34	0.76	0.28
NNE3	383	16	215	0.1	4	0.13	0.40	0.46	0.20
NNE4	292	13	2.0	0.1	D.L.	0.75	0.37	0.69	0.25
NE1C	1013	32	5.0	0.3	4	0.92	0.99	0.72	0.40
NE1B	833	21	2.5	0.1	D.L.	D.L.	1.51	D.L.	D.L.
NE2	504	16	2.2	0.1	2	0.95	0.81	0.81	0.14
NE3	383	14	2.2	0.1	2	0.69	0.69	0.77	0.23
NE4	254	8	1.3	0.2	D.L.	0.48	0.41	0.89	0.21
NE5C	246	10	1.5	0.1	D.L.	0.08	0.44	0.44	0.12
NE5B	375	17	0.1	0.3	D.L.	D.L.	0.49	D.L.	D.L.
E1	296	9	1.0	0.3	D.L.	0.49	0.38	0.38	0.16
E2	233	7	0.9	0.1	2	0.20	0.27	0.34	0.27
E3	200	8	0.7	0.1	2	0.07	0.33	1.19	0.20
E4	179	7	0.7	0.1	D.L.	0.30	0.23	0.68	0.15
MKG	113	4	0.5	0.0	D.L.	D.L.	0.21	0.28	0.14
SE1	2017	94	5.3	0.7	12	0.54	1.67	0.89	0.18
SE2	325	11	1.3	0.8	2	0.06	0.58	0.45	0.13
SE3	246	6	0.6	0.1	2	D.L.	0.18	0.23	D.L.
SE4	288	10	1.1	2.4	D.L.	0.17	0.75	1.04	0.06
SE5C	163	6	0.7	0.1	2	D.L.	0.33	0.80	0.13
SE5B	83	2	0.1	0.5	D.L.	D.L.	4.32	0.76	D.L.
SSE1C	579	18	2.7	0.1	4	0.37	1.83	0.88	0.15
SSE1B	542	20	2.5	0.1	4	D.L.	1.11	D.L.	D.L.
SSE2	238	7	0.9	0.8	2	0.39	0.39	0.33	D.L.
SSE3	192	5	0.5	0.2	D.L.	0.20	0.26	0.46	0.07
S1	2392	101	15.5	0.7	12	0.83	4.95	0.89	0.69
S2	1192	45	5.7	0.4	D.L.	1.10	3.94	1.65	0.39
S3	579	19	2.6	0.2	D.L.	0.45	1.09	0.45	0.26
S4	608	19	1.7	0.2	4	0.39	0.94	0.71	0.24
S5	1779	28	2.1	0.6	4	0.63	0.95	0.63	0.32
SSW1	496	19	2.1	0.2	2	0.95	1.39	1.02	0.21
SSW2	458	18	2.1	0.1	2	1.03	1.03	0.76	0.21
SW1	2479	99	2.7	0.9	D.L.	0.58	0.94	1.16	0.15
SW2	1604	70	2.5	0.5	D.L.	0.42	1.35	1.27	0.25
SW3C	438	16	1.1	0.1	D.L.	0.59	0.660	0.98	0.20
SW3B	500	18	1.0	0.1	2	D.L.	0.82	D.L.	D.L.
SW4	688	22	1.7	0.2	4	0.11	0.30	0.44	0.15
SW5	229	8	0.6	0.1	D.L.	0.42	0.28	0.77	D.L.
W1C	1663	51	2.7	0.5	12	0.28	0.28	0.39	0.14
W1B	458	12	0.5	0.1	D.L.	D.L.	0.48	D.L.	D.L.
W2	296	46	0.3	0.1	D.L.	0.55	0.21	0.62	0.68
W3	138	3	0.2	0.0	D.L.	0.48	0.68	0.62	D.L.
NW3C	358	11	0.7	0.3	D.L.	0.36	0.43	0.78	0.14
NW3B	250	5	0.2	0.1	2	D.L.	0.42	D.L.	D.L.
NW4	188	4	0.2	0.1	D.L.	0.86	0.22	0.43	D.L.
NW5	163	4	0.2	0.4	D.L.	0.20	0.34	0.27	D.L.
NNW1	221	7	0.4	0.1	D.L.	0.54	0.46	1.00	D.L.
N1	1954	92	4.3	1.0	D.L.	0.70	1.51	0.93	0.12
N2	13870	397	9.2	5.2	50	D.L.	2.00	1.50	0.14
N3	1129	52	2.7	0.5	D.L.	0.30	1.29	0.53	0.15
N4	675	25	2.0	0.2	D.L.	0.78	1.64	1.25	0.16
N5	363	12	1.4	0.1	4	0.08	1.10	0.47	D.L.
G1	8983	399	19.6	5.2	50	D.L.	15.73	2.36	0.39
G5	4475	221	3.0	1.9	21	0.87	1.01	1.37	0.14
R1	467	17	2.6	0.1	2	0.40	1.79	0.99	0.20
R2	854	31	5.1	0.2	D.L.	0.78	2.81	1.17	0.33
R3	3883	114	8.7	0.7	12	0.80	4.93	1.46	0.57
R4C	1558	59	8.3	0.5	17	2.26	7.29	0.69	0.52
R4B	1458	43	5.1	0.4	6	D.L.	6.26	D.L.	D.L.
LS	2467	78	13.1	0.6	D.L.	0.74	0.98	0.74	0.74
ELS	179	3	0.1	0.0	D.L.	0.18	0.09	0.28	D.L.
BM	50	2	0.1	0.0	D.L.	0.34	D.L.	0.34	D.L.
FBG	83	2	0.2	0.0	D.L.	0.31	D.L.	0.43	0.06
ASB	75	2	0.1	0.0	D.L.	0.11	D.L.	0.05	D.L.
GLK	150	3	0.1	0.0	D.L.	0.17	D.L.	0.17	D.L.
SMT	267	4	0.2	0.0	D.L.	D.L.	D.L.	0.36	D.L.
GC	325	10	1.4	0.1	D.L.	0.31	1.00	0.39	0.15

D.L. - Detection Limit

Table 18. Loadings (mg/m^2) of metals for the snow collector trays which were set out from 16 January to 23 February 1981. Loadings were calculated from measured concentrations, snowmelt volumes, and tray area (see Figure 2 for site locations).

Site	Insoluble					Soluble			
	Total	Al	V	Mn	Ti	Al	V	Fe	Ni
N1	346	15	0.3	0.1	2	0.02	0.05	0.3	D.L.
N2	1073	29	1.0	0.4	2	0.08	0.13	0.2	0.05
N5	181	5	0.4	0.0	D.L.	0.06	0.22	0.3	0.01
S2	474	10	1.5	0.1	2	0.18	0.74	0.5	0.12
S4	259	7	0.7	0.1	D.L.	D.L.	0.18	0.1	0.02
SW1	1249	46	1.0	0.7	5	0.13	0.22	0.4	D.L.

D.L.-Detection Limit

Table 19. Variability of insoluble and soluble trace metal loadings (determined from the average percent standard deviation about the mean of two samples taken in each of the 1981 surveys at the following sites: NNE1, NE1, NE5, SE5, SSE1, SW3, W1, NW3, and R4).

Constituent	Variability of Loading (%)
Insoluble	
Total	29
Al	73
V	39
Mn	40
Ti	46
Soluble	
Al	66
V	40
Fe	64
Ni	92

4. DISCUSSION

4.1 DEPOSITION PATTERNS

The snowpack loadings (January 1981 data) of the major ions and metals which could originate at the oil sands plants are mapped in Figures 7 through 11, inclusive. Generally, the patterns reflect the wind roses shown in Figure 5. Maxima of loading occur to the northwest and south of each source. The spatial distributions of the metals show a much more rapid decrease with distance from the source than do the sulphate or nitrate ions.

The deposition patterns determined from the February 1981 data are shown in Figures 12 through 16. These patterns are similar to those observed in January with elongated lobes along the Athabasca River valley. For both nitrates and sulphates, the lobe to the northwest of Syncrude in January was absent in February. The insoluble aluminum and manganese patterns have a lobe to the southeast of the sources which was not present in January. Generally, the deposition values are higher than in January for the nitrates and insoluble metals. The calculated sulphate deposition values are lower over a large part of the study area.

The changes in the sulphate ion and insoluble aluminum loadings from January 1978 to January 1981 are mapped in Figures 17 and 18. The sulphate loadings show increases to the northwest and south of the Syncrude plant, the prevailing direction of emission transport. The metals tend to show a decrease in the same directions from the Suncor plant.

The amounts of major ions and trace metals which originate at the oil sands plants, and are deposited within 25 km of the sources, were calculated from the deposition patterns and compared to the 1978 results (Barrie and Kovalick 1978) in Table 20. With the additional Syncrude source, sulphates and nitrates were higher by 88 and 27%, respectively. The amounts of insoluble metals were much lower than in 1978.

A mapping of snowmelt pH for the study area in January 1981 is shown in Figure 19. Areas of relatively high pH occur to the west-northwest and north-northeast of the sources. The pH falls off rapidly with distance in other directions. The changes in pH of the snowmelt from the results of the January 1978 survey are shown in Figure 20. The increases of pH to the north-northeast and west-northwest are correlated with the increases of calcium ion loadings as shown in Figure 21. The linear correlation coefficient between the differences of pH and the differences of calcium ion loadings was 0.75.

4.2 MASS BUDGET

The measured deposition patterns and the estimated emission rates from the plants were used to calculate the total amounts that were deposited in the snowpack within 25 km, as shown in Table 21. Emission rates were based on the normal values given in their EIA (1978) for Syncrude, and on the values given by Barrie and Kovalick (1980) in their Table 12, for Suncor. However, the particulate emission rate was reduced to 16 t/d to account for the installation of electrostatic precipitators (60% efficiency) at the Suncor power plant.

Only 0.23% of the total sulphur was deposited to the snowpack within 25 km of the sources. This result is similar to the value of 0.30 reported by Barrie and Kovalick (1980) for material deposited to the snow in the winter of 1977-78. Most of the particulate matter is deposited near the sources. Of the estimated amount emitted by the Suncor and Syncrude stacks over the 67 d history of the snowpack, 96% settled to the snowpack within 25 km. It is possible that low level fugitive emissions of particulates contribute to the deposition within 25 km so that the figure of 96% may be too high.

4.3 SNOW COLLECTOR TRAYS

The contaminant loadings determined from the snow collector trays showed little agreement with the snow core results. With the exception of the ammonium ion, the variation between the loadings computed from the tray data, and those computed from the two sets of core data were larger than the expected variability, due to the sampling and analytical errors shown in Tables 15 and 19. The average variability of the ammonium loadings calculated by the two different methods was 17% compared to the estimated variability of 32% given in Table 19. The linear correlation coefficient was 0.86 for the two estimated of ammonium loadings. The correlation was poor for most of the other constituents of the snowmelt. In fact, the soluble metals and the ions $SO_4^{=}$, Na^+, K^+, Ca^{++}, and Mg^{++} showed apparent decreases in loadings at some sites according to the snow core results.

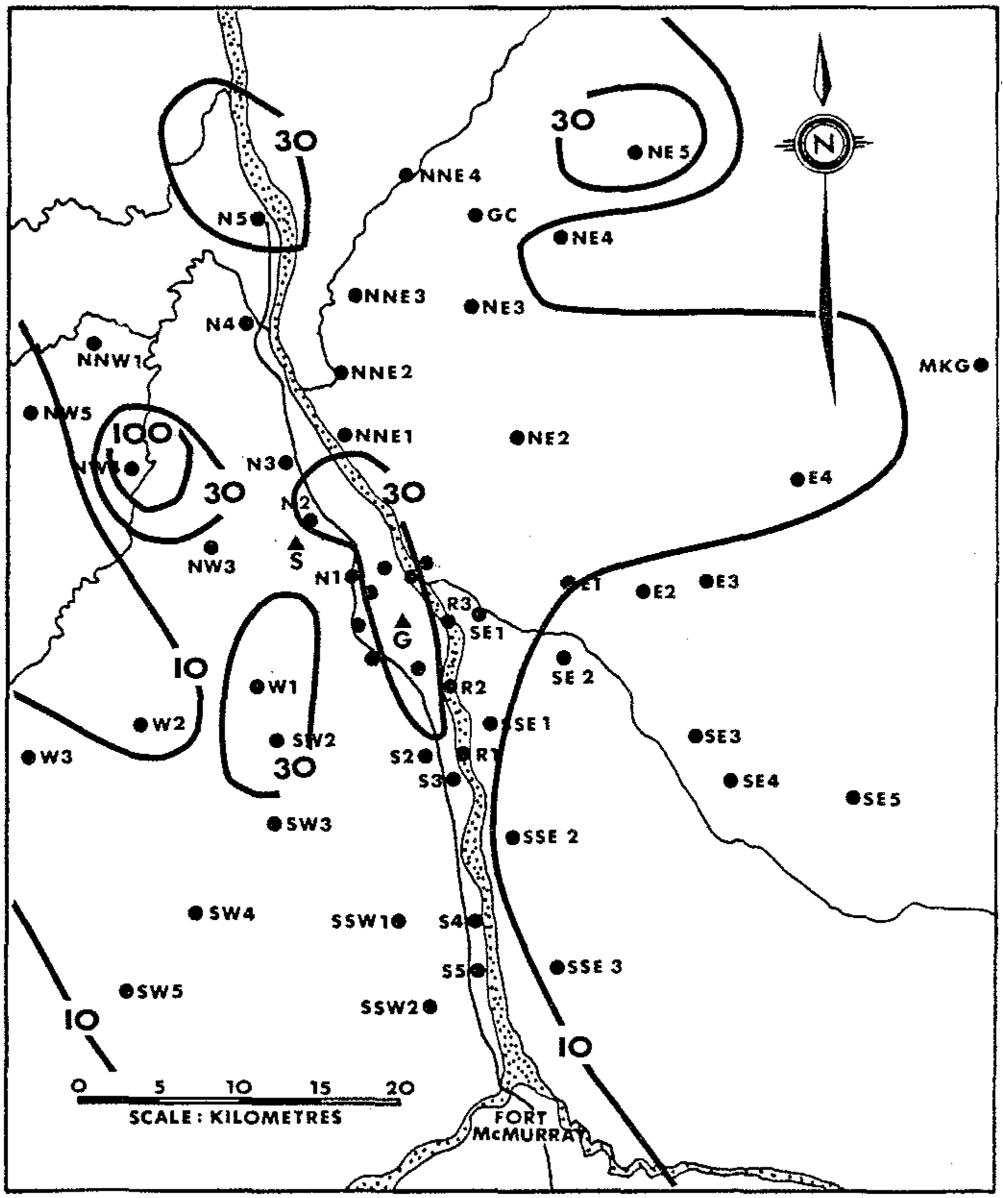


Figure 7. The spatial distribution of snowpack loading (mg/m^2) of the sulphate ion in the study area, 10 January 1981. Triangles indicate the locations of Syncrude (S) and Suncor (G) extraction plants.

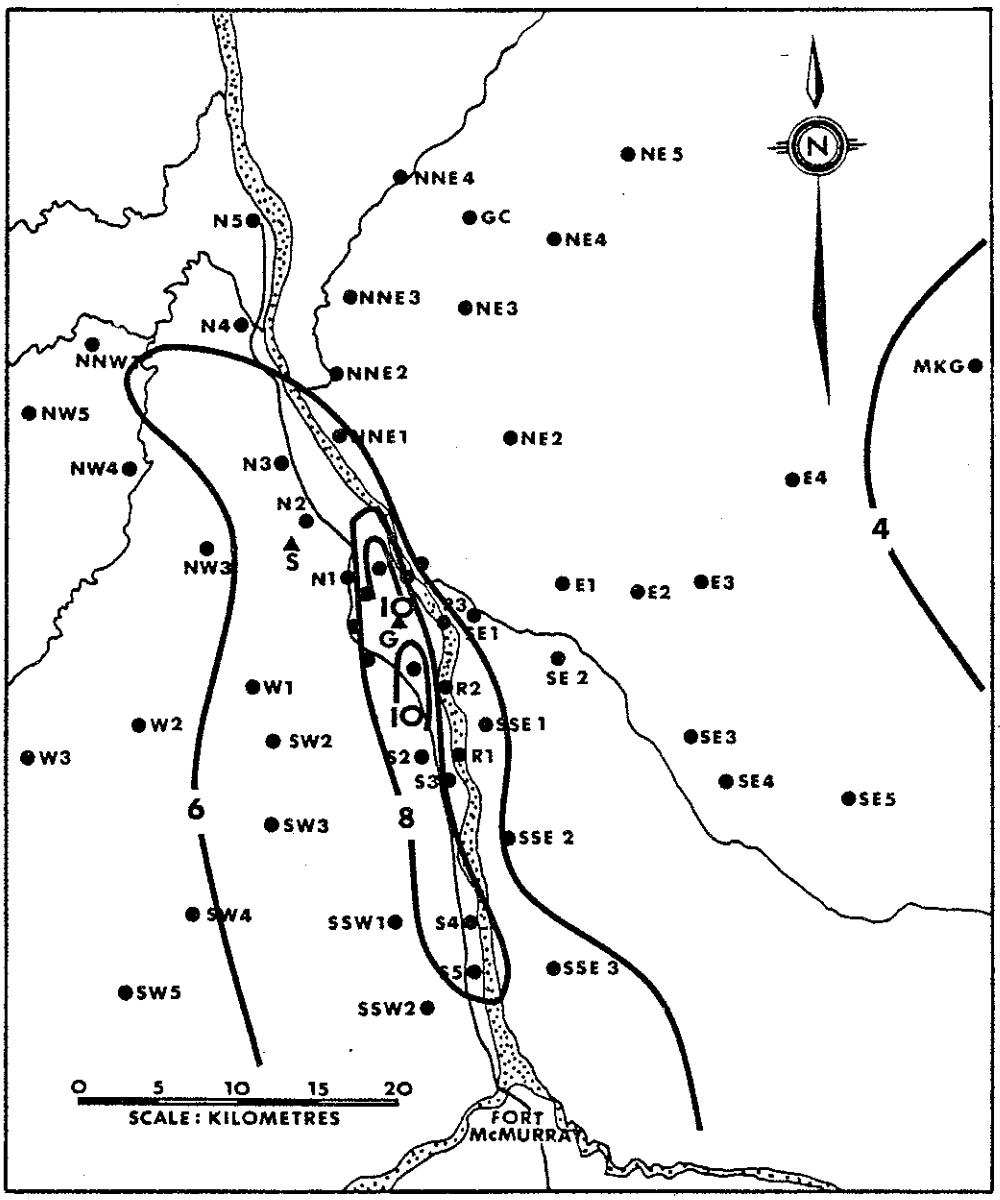


Figure 8. The spatial distribution of snowpack loading (mg/m^2) of the nitrate ion in the study area, 10 January 1981.

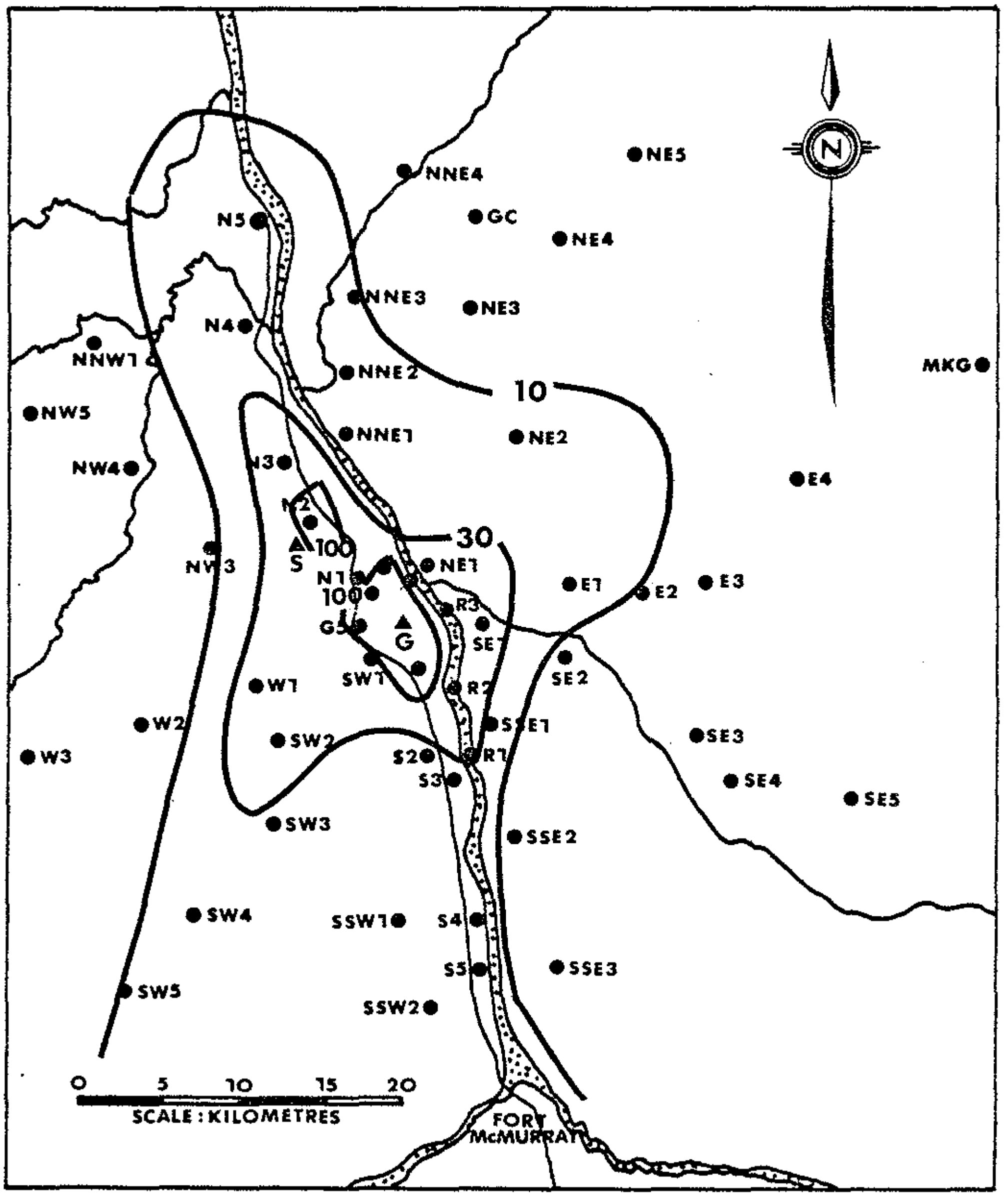


Figure 9. The spatial distribution of snowpack loading (mg/m^2) of insoluble aluminum in the study area, 10 January 1981.

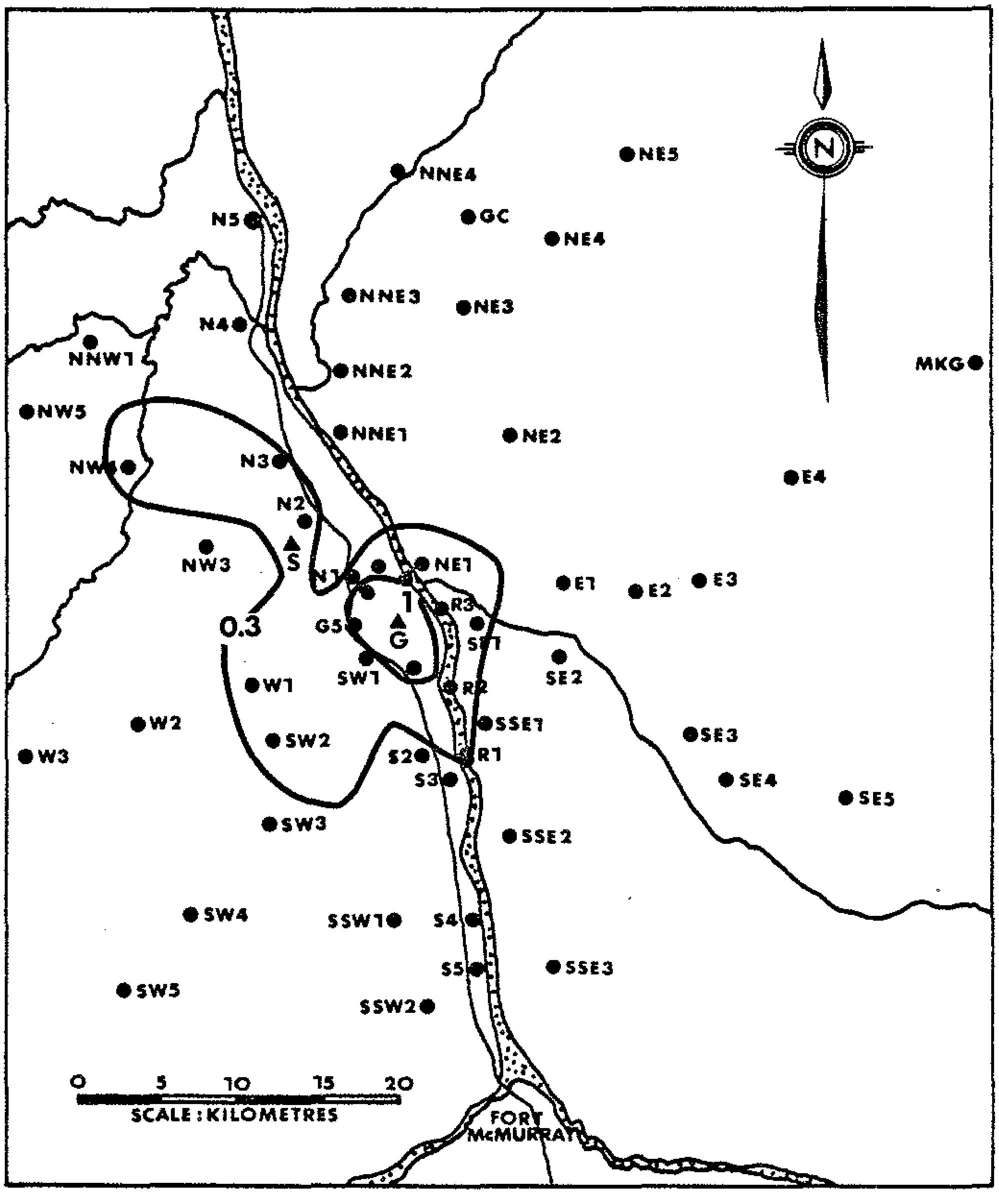


Figure 10. The spatial distribution of snowpack loading (mg/m²) of insoluble manganese in the study area, 10 January 1981.

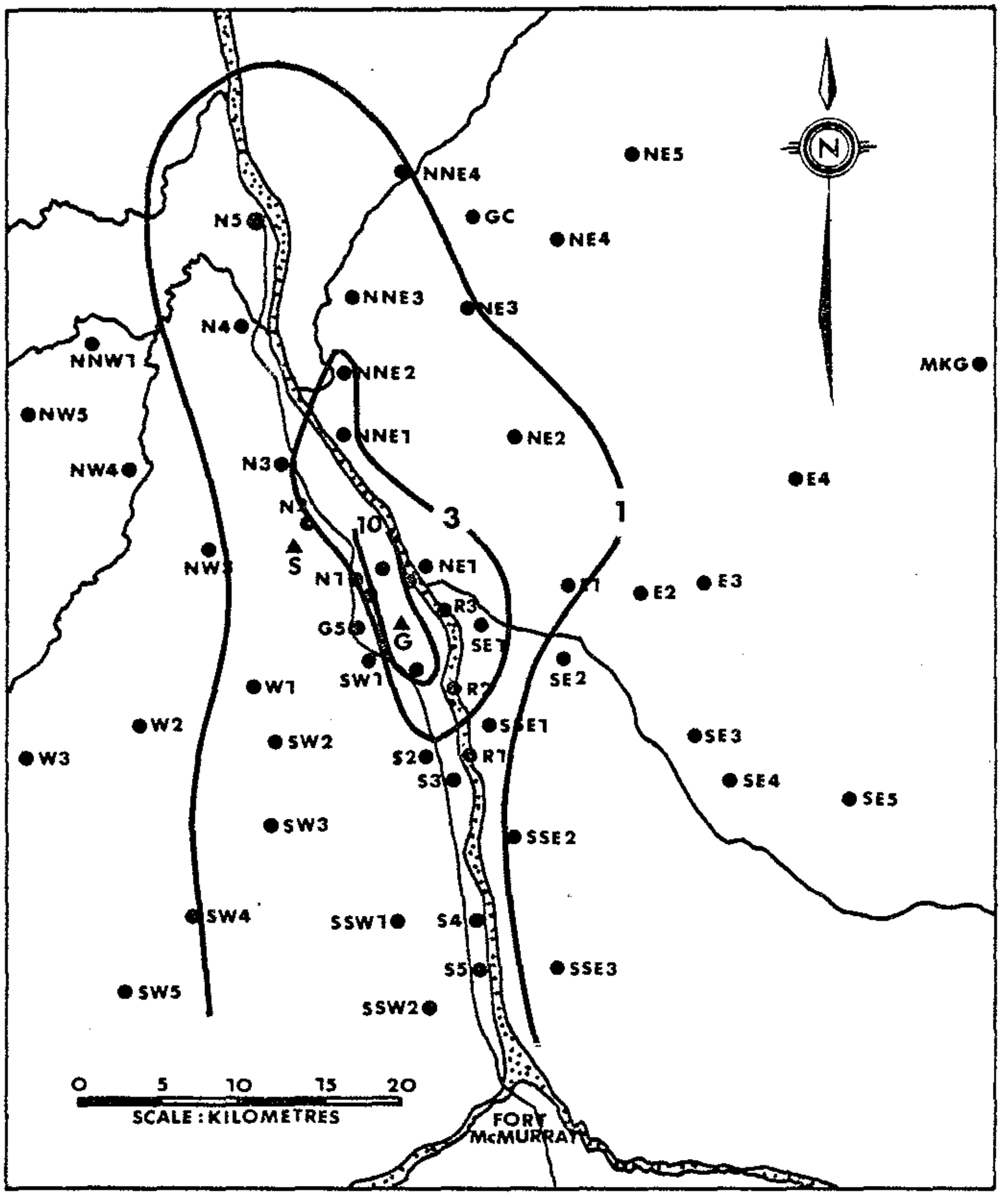


Figure 11. The spatial distribution of snowpack loading (mg/m^2) of insoluble vanadium in the study area, 10 January 1981.

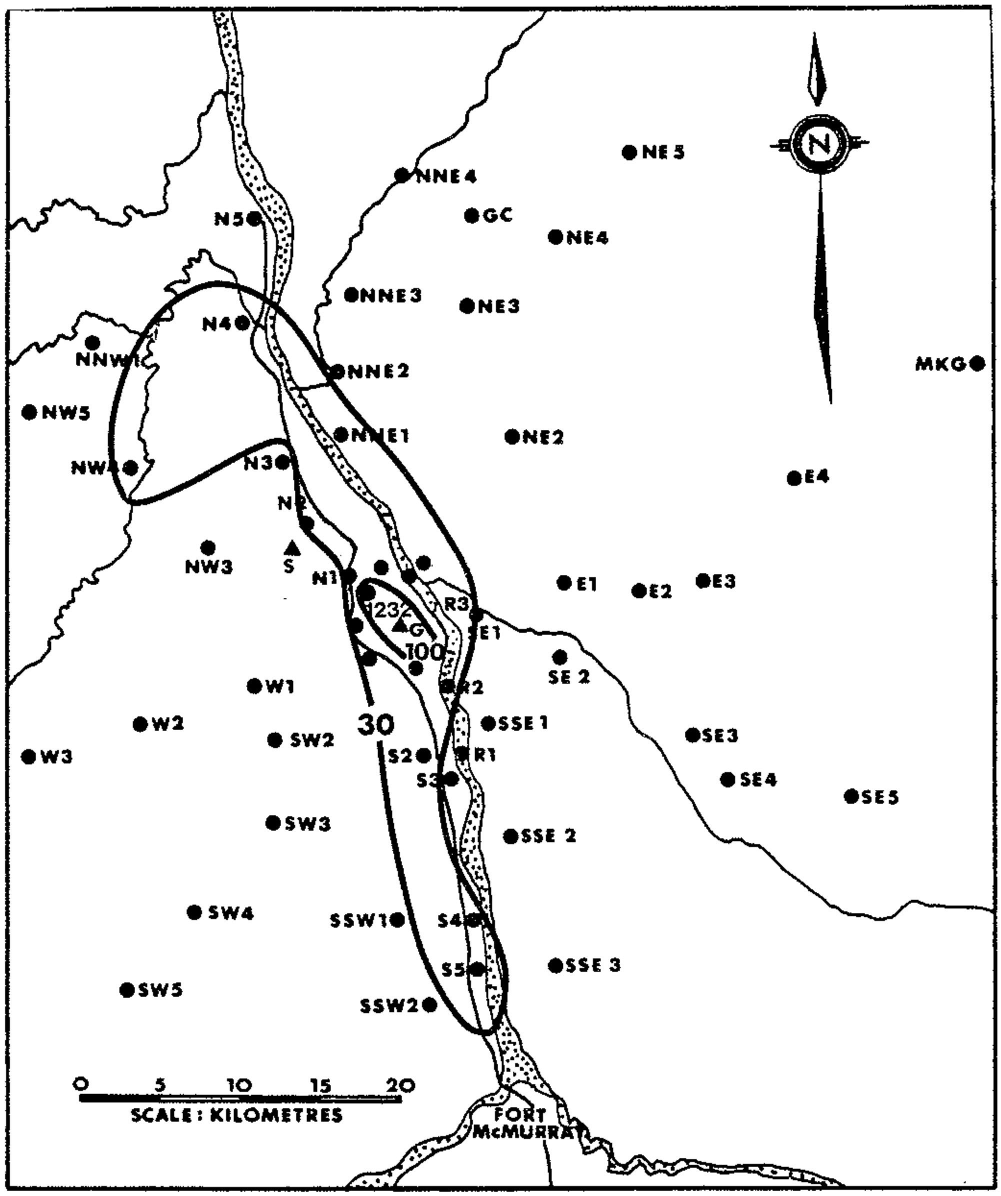


Figure 12. The spatial distribution of snowpack loading (mg/m^2) of sulphate ion in the study area on 20 February 1981.

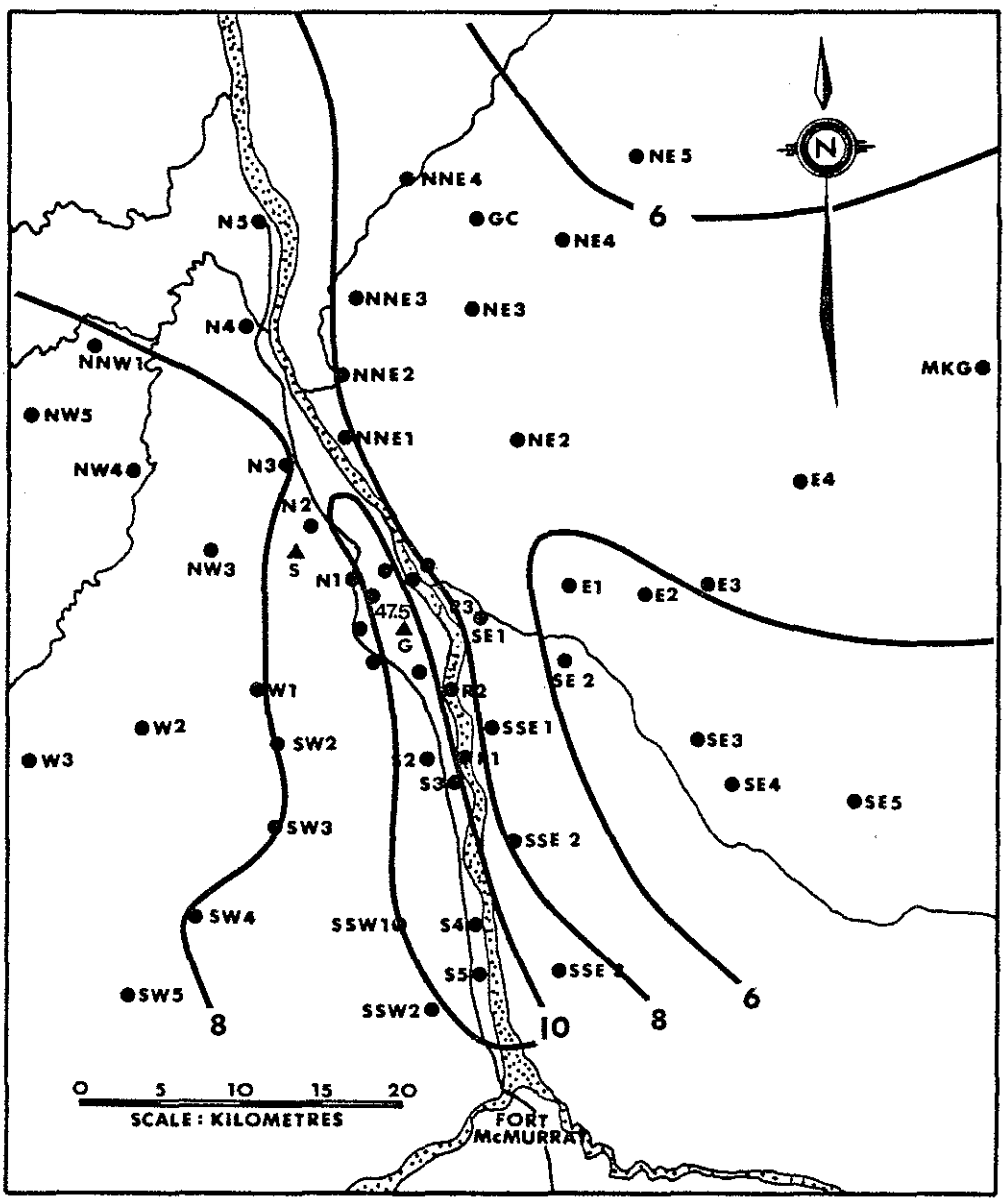


Figure 13. The spatial distribution of snowpack loading (mg/m^2) of nitrate ion in the study area on 20 February 1981.

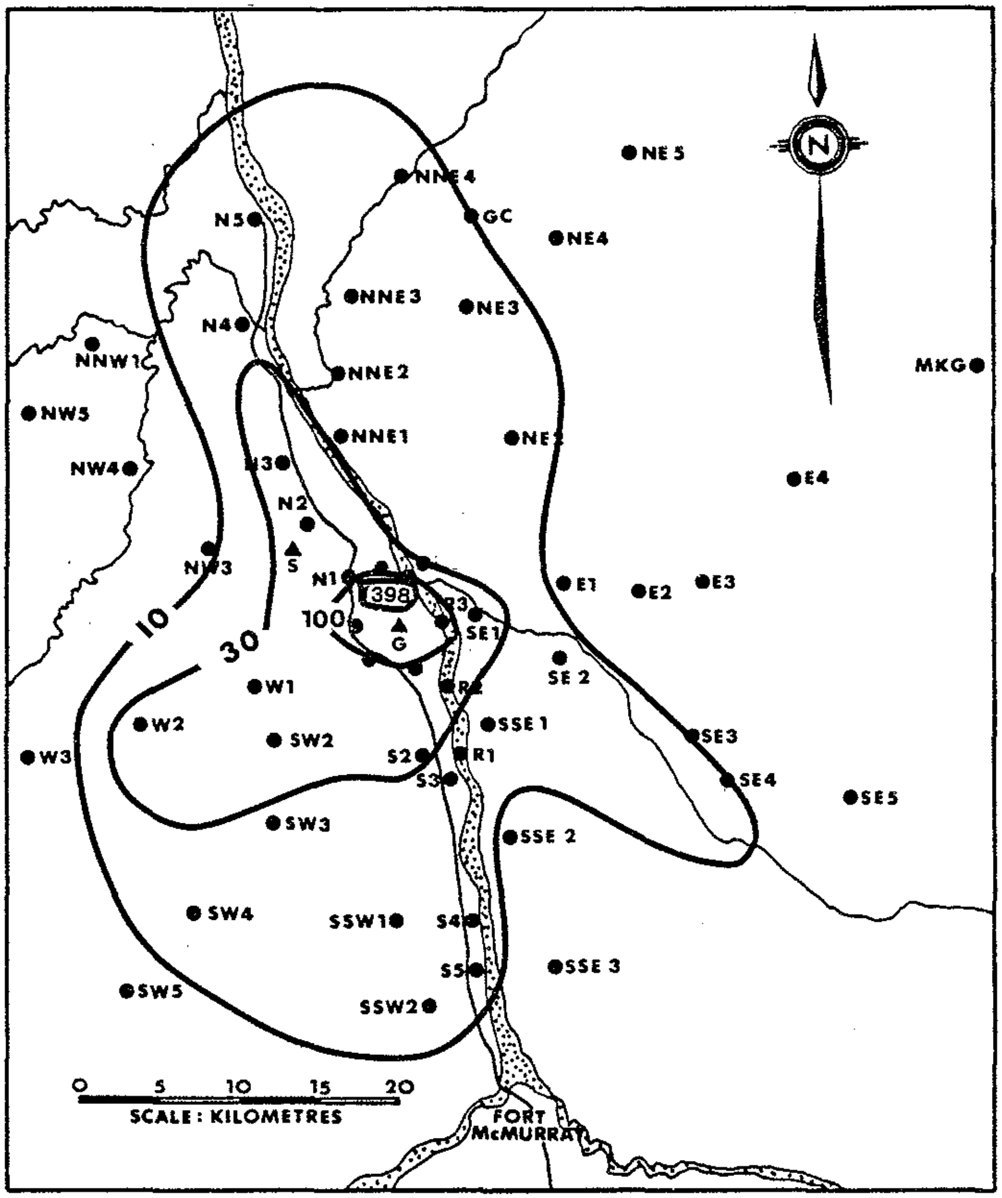


Figure 14. The spatial distribution of snowpack loading (mg/m^2) of insoluble aluminum in the study area on 20 February 1981. Triangles indicate the locations of Suncor and Syncrude plants.

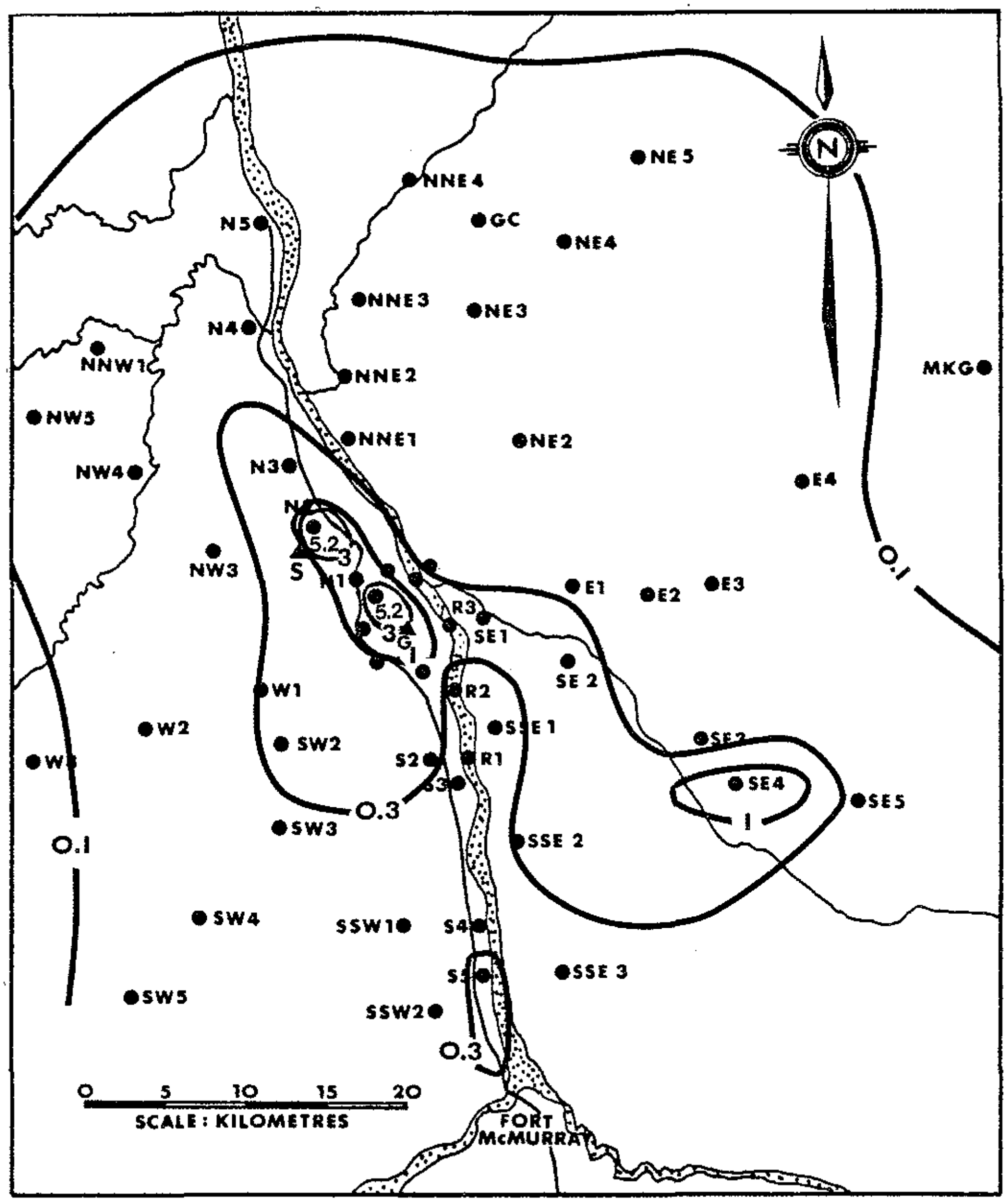


Figure 15. The spatial distribution of snowpack loading (mg/m^2) of insoluble manganese in the study area on 20 February 1981.

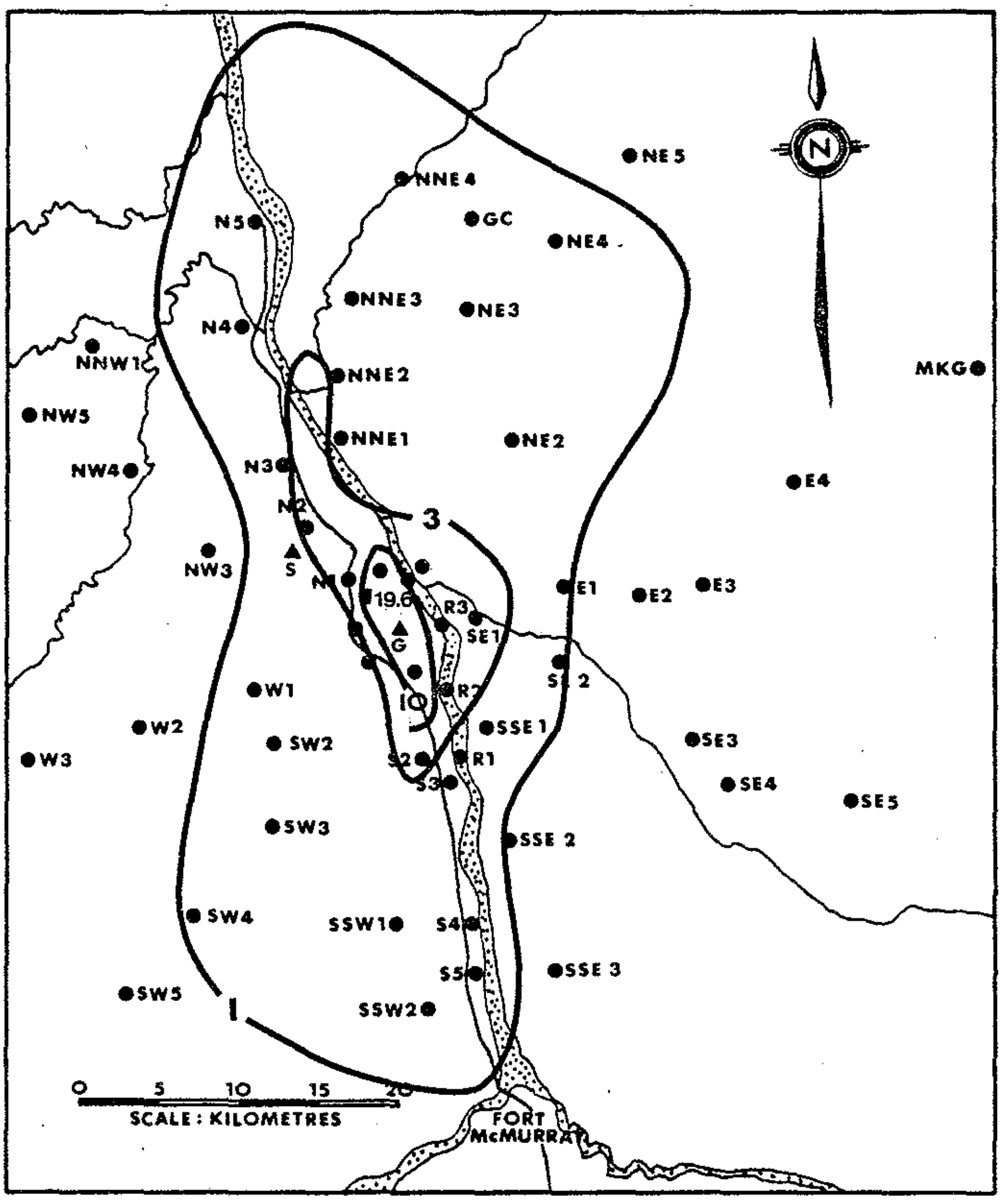


Figure 16. The spatial distribution of snowpack loading (mg/m^2) of insoluble vanadium in the study area on 20 February 1981.

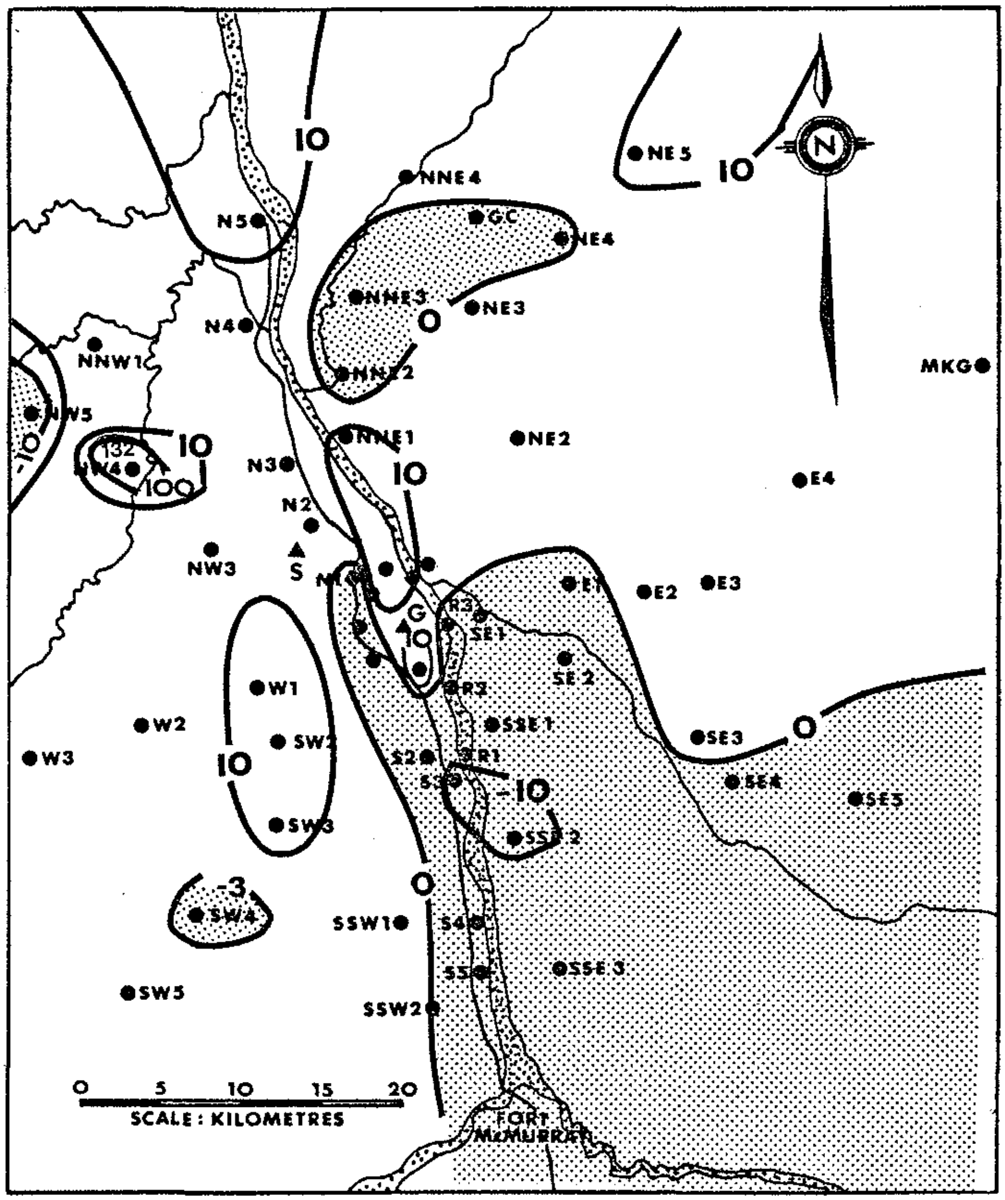


Figure 17. The spatial distribution of the difference in sulphate ion loadings (mg/m^2) in the AOSERP study area between January 1978 and January 1981. Shading indicates areas of decreased loading.

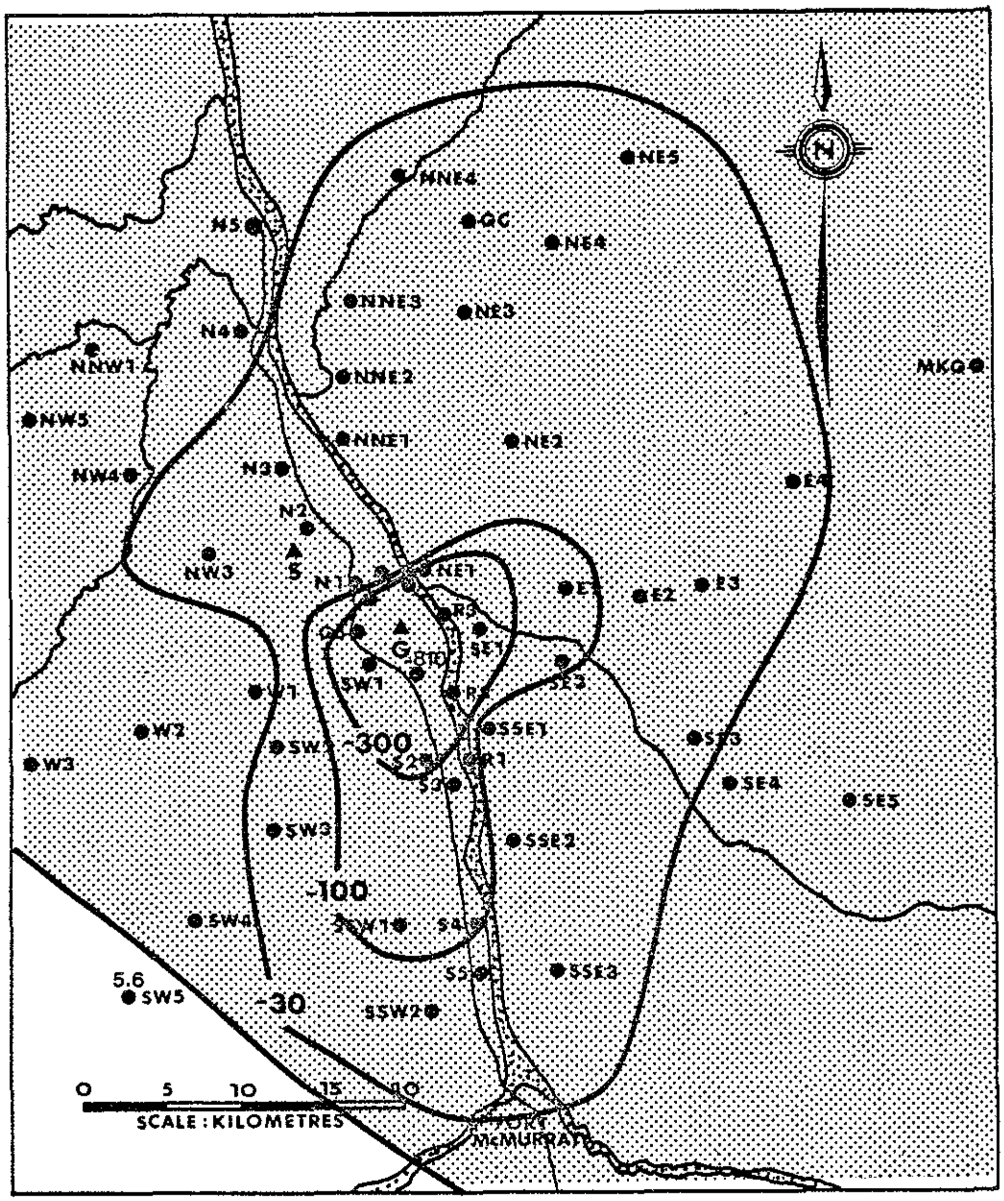


Figure 18. The spatial distribution of the difference in insoluble aluminum loadings (mg/m^2) in the AOSERP study area between January 1978 and January 1981. Shading indicates areas of decreased loadings.

Table 20. Average mass of substances deposited per day (t/d) within 25 km of site N1 (midway between Syncrude and Suncor) from 6 November 1980 to 10 January 1981.

	$SO_4^{=}$-S	NO_3^{-}-N	Al	Mn	V
1978[a]	0.33	0.15	2.97	0.024	0.41
1980	0.62	0.19	0.78	0.007	0.58

[a]Based on deposition amounts reported by Barrie and Kovalick (1980).

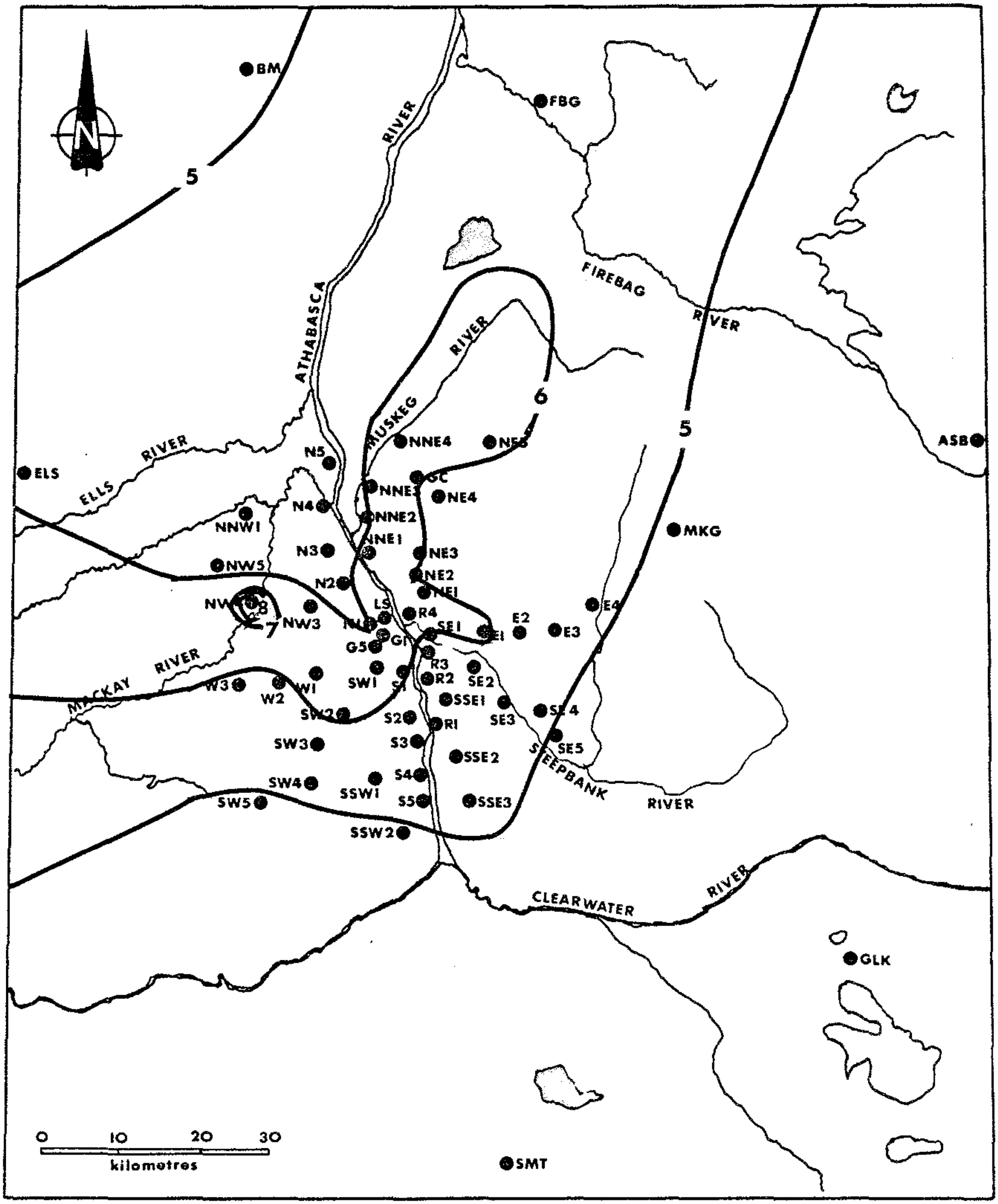


Figure 19. The spatial distribution of snowpack pH in the study area on 10 January 1981.

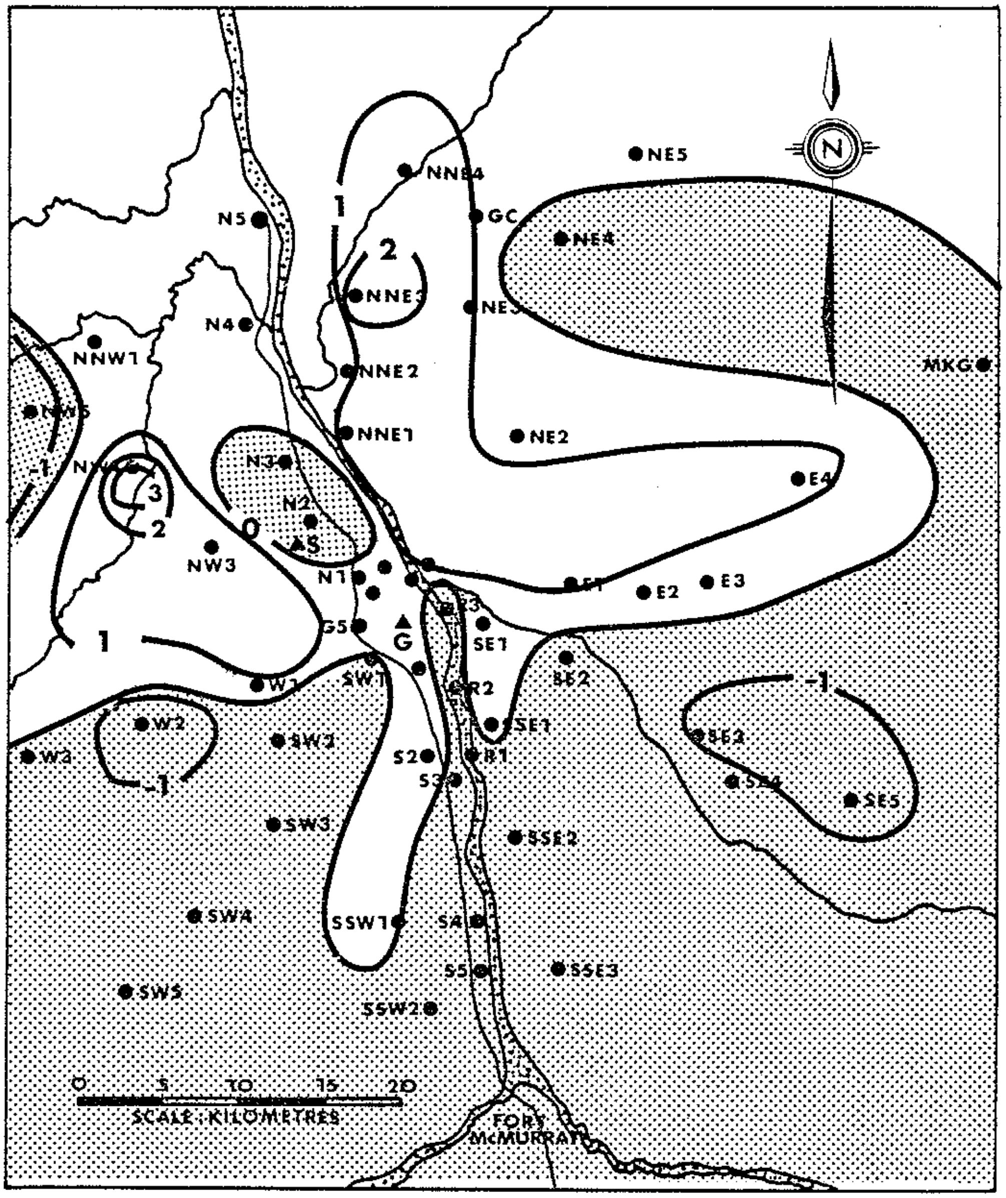


Figure 20. The spatial distribution of the difference in snowpack pH in the study area between January 1978 and January 1981. Shading indicates areas of decrease.

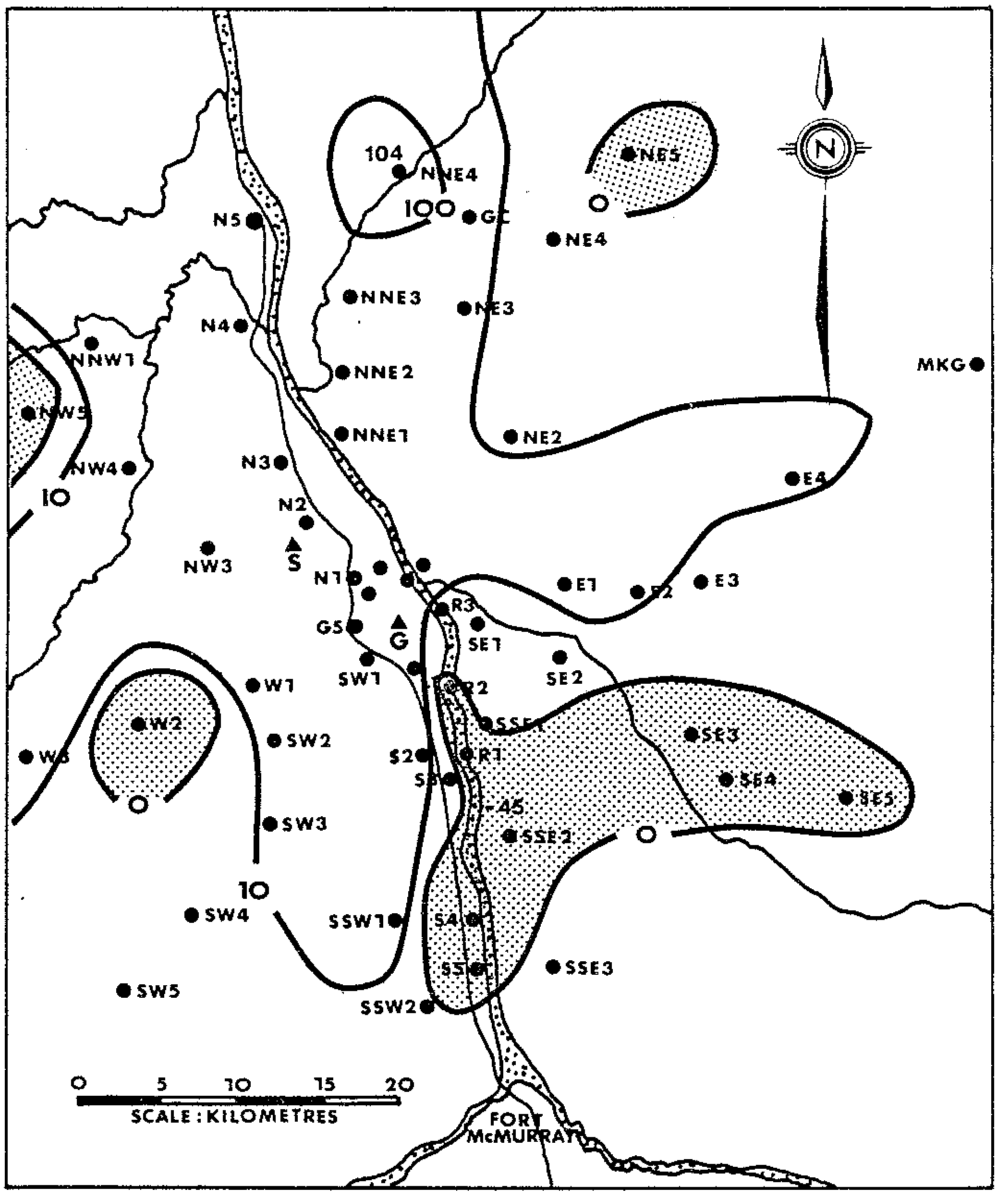


Figure 21. The spatial distribution of the difference in calcium ion loadings in the study area between January 1978 and January 1981. Shading indicates areas of decrease.

Table 21. The mass budget of various substances released to the atmosphere by the Suncor and Syncrude plants and deposited within 25 km from 6 November 1980 to 12 January 1981.

Pollutant	Amount Released (t)	Amount Deposited Within 25 km (t)	Fraction Deposited Within 25 km (t)
$SO_2/SO_4^{=}$-S	18,500	42	0.2%
NO_x/NO_3^--N	2,200	13	0.6%
Total Particulates	1,166	1,125	96.0%

4.4 ION BALANCE

An ion balance of major ions in snowmelt (Tables 22, 23, and 24) was performed to check the accuracy of the analysis and to identify the dominant ions at each site. Generally, the sums of the positive and negative ions differed by 10% or less. However, there were no larger discrepancies when the pH was less than 5. This may have resulted from the gradual dissolving of particulates in the snow: although the pH was measured immediately after melting, the chemical analyses took several weeks to complete. The release of acid-neutralizing hydroxyl ions when the particulate calcium oxides dissolved would have lowered the hydrogen ion concentration. Hence, the major ion imbalance at low pH arose from the measurements not being carried out simultaneously.

When the pH was below 4.8, hydrogen was the dominant positive ion (Figures 22 and 23). At higher values of pH, calcium, or in some cases, magnesium ions predominated. There are a few exceptions in that the sodium ion prevailed at sites NNW1, S3, W2, and W3 in the January study and the ammonium ion prevailed at site GLK in the February study.

The spatial distribution of the hydrogen ion's contribution to the total positive ion-equivalents in snowmelt are shown in Figures 24 and 25. Its contribution was small near the source in the areas where the Ca^{++} or Mg^{++} cations were dominant, but it was large in the outlying areas.

Near the oil sands plants, the alkalinity of the snow was high and the dominant cations were Ca^{++} or Mg^{++}. At the outlying sites, H^+, $SO_4^=$, and NO_3^- were the dominant ions. The area with alkaline snow was larger than in the 1978 study, and the deposition pattern was more complex with lobes to the northwest and east in addition to those along the valley.

Table 22. Results of an ion balance done with snowmelt major ion concentration for each site of the January 1981 snow survey.

Site	Total +ve ions (µeq/L)	Total -ve ions (µeq/L)	Ratio of Total +ve:-ve	Snowmelt Ion Balance: Fraction of Total +ve Ion Equivalent Due To						Fraction of Total -ve Ion Equivalent Due To			
				H^+	NH_4^+	Ca^{++}	Mg^{++}	Na^+	K^+	$SO_4^=$	NO_3^-	Cl^-	HCO_3^-
NNE1C	211.9	221.1	0.96	0.00	0.01	0.59	0.24	0.11	0.05	0.15	0.04	0.06	0.75
NNE1B	140.6	311.2	0.45	0.00	0.02	0.60	0.20	0.10	0.08	0.16	0.03	0.01	0.80
NNE2	39.9	41.7	0.96	0.16	0.04	0.55	0.08	0.10	0.08	0.39	0.17	0.06	0.38
NNE3	167.9	186.6	0.90	0.00	0.01	0.52	0.36	0.10	<0.01	0.09	0.04	0.04	0.83
NNE4	161.7	170.2	0.95	0.00	0.01	0.67	0.24	0.07	<0.01	0.11	0.04	0.01	0.83
NE1C	202.3	226.3	0.89	0.00	0.02	0.56	0.40	0.00	0.02	0.10	0.03	0.02	0.85
NE1B	146.5	129.5	1.13	0.00	0.05	0.41	0.29	0.23	0.01	0.23	0.07	0.02	0.68
NE2	46.3	44.9	1.03	0.07	0.05	0.24	0.34	0.29	<0.03	0.29	0.14	0.08	0.49
NE3	75.4	82.6	0.91	0.01	0.03	0.34	0.43	0.18	<0.02	0.17	0.08	0.05	0.70
NE4	52.1	16.1	3.24	0.76	0.03	0.13	0.05	<0.02	<0.03	0.49	0.39	0.12	0.00
NE5C	305.6	315.0	0.97	0.00	0.00	0.13	0.50	0.35	0.02	0.20	0.02	0.01	0.75
NE5B	57.2	79.3	0.72	0.02	0.02	0.21	0.30	0.43	0.02	0.57	0.10	0.03	0.30
E1	108.3	106.8	1.01	0.00	0.03	0.44	0.30	0.19	0.04	0.11	0.07	0.11	0.71
E2	39.9	41.5	0.96	0.06	0.03	0.35	0.35	0.19	0.02	0.20	0.15	0.03	0.63
E3	45.7	17.3	2.64	0.69	0.03	0.16	0.09	<0.02	<0.03	0.57	0.37	0.06	0.00
E4	99.0	107.6	0.92	0.00	0.02	0.33	0.38	0.25	<0.02	0.12	0.05	0.24	0.59
MKG	46.4	24.2	1.92	0.57	0.04	0.19	0.07	0.11	<0.03	0.39	0.24	0.21	0.17
SE1	54.9	57.5	0.95	0.04	0.06	0.48	0.12	0.07	0.23	0.33	0.14	0.04	0.49
SE2	37.8	23.7	1.59	0.47	0.02	0.22	0.09	0.17	<0.04	0.41	0.30	0.13	0.17
SE3	34.5	30.9	1.13	0.26	0.06	0.32	0.33	<0.02	<0.04	0.26	0.24	0.11	0.39
SE4	40.6	41.6	0.97	0.12	0.04	0.38	0.28	0.15	<0.04	0.25	0.18	0.14	0.43
SE5C	44.5	23.0	1.93	0.56	0.04	0.18	0.13	0.07	<0.03	0.37	0.32	0.05	0.26
SE5B	30.4	23.9	1.27	0.16	<0.03	0.44	0.16	0.09	0.13	0.43	0.42	0.07	< 0.17
SSE1C	38.1	30.8	1.24	0.37	0.06	0.34	0.13	0.08	<0.04	0.42	0.28	0.05	0.26
SSE1B	63.2	61.2	1.03	0.01	0.02	0.52	0.25	0.14	0.06	0.32	0.15	0.00	0.50
SSE2	49.9	56.8	0.88	0.03	0.04	0.48	0.36	0.04	0.05	0.17	0.14	0.09	0.60
SSE3	51.5	58.3	0.88	0.04	0.03	0.24	0.46	0.17	0.05	0.17	0.15	0.16	0.51
S1	206.9	191.8	1.08	0.00	0.06	0.54	0.17	0.15	0.09	0.36	0.07	0.22	0.34
S2	89.9	94.5	0.95	0.03	0.04	0.52	0.17	0.19	0.05	0.35	0.13	0.28	0.23
S3	114.1	104.2	1.10	0.14	0.02	0.18	0.06	0.57	0.03	0.17	0.12	0.64	0.08
S4	79.4	82.2	0.97	0.05	0.02	0.40	0.15	0.31	0.07	0.27	0.14	0.39	0.19
S5	137.8	141.7	0.97	0.01	0.01	0.38	0.20	0.36	0.03	0.19	0.09	0.32	0.41
SSW1	57.0	59.5	0.96	0.04	0.03	0.46	0.25	0.17	0.05	0.41	0.18	0.04	0.37
SSW2	47.7	41.7	1.14	0.33	0.03	0.30	0.22	0.09	<0.03	0.45	0.26	0.05	0.24
SW1	166.2	165.4	1.00	0.00	0.02	0.38	0.22	0.36	<0.01	0.14	0.05	0.36	0.45
SW2	237.8	265.3	0.90	0.00	0.01	0.25	0.43	0.30	0.01	0.16	0.03	0.05	0.76
SW3C	55.8	61.5	0.91	0.04	0.11	0.54	0.16	0.13	<0.03	0.38	0.17	0.10	0.36
SW3B	113.3	108.1	1.05	0.01	0.04	0.44	0.16	0.33	0.01	0.57	0.09	0.01	0.33
SW4	47.6	45.1	1.05	0.13	0.08	0.24	0.29	0.24	<0.03	0.38	0.19	0.03	0.40
SW5	51.8	39.7	1.30	0.27	0.06	0.31	0.13	0.20	0.03	0.37	0.18	0.25	0.20
W1C	161.0	155.3	1.04	0.00	0.07	0.36	0.26	0.29	0.02	0.38	0.06	0.02	0.54
W1B	161.2	161.7	1.00	0.00	0.10	0.46	0.15	0.27	0.02	0.43	0.06	0.02	0.49
W2	40.4	37.0	1.09	0.16	0.05	0.24	0.20	0.31	0.04	0.29	0.19	0.14	0.38
W3	102.9	103.8	0.99	0.01	0.02	0.10	0.34	0.49	0.03	0.14	0.07	0.04	0.75
NW3C	96.9	92.3	1.05	0.01	0.03	0.33	0.34	0.27	0.02	0.17	0.08	0.08	0.67
NW3B	117.3	54.1	2.17	0.01	0.10	0.35	0.39	0.14	0.01	0.26	0.14	0.01	0.59
NW4	567.4	551.3	1.03	0.00	0.00	0.18	0.52	0.29	0.01	0.31	0.01	0.03	0.65
NW5	44.7	46.7	0.96	0.04	0.03	0.43	0.30	0.19	<0.03	0.21	0.17	0.07	0.56
NNW1	61.8	69.9	0.88	0.02	0.03	0.27	0.29	0.37	<0.02	0.22	0.11	0.10	0.57
N1	69.5	72.6	0.96	0.02	0.10	0.52	0.25	0.08	0.03	0.29	0.12	0.15	0.44
N2	125.5	130.1	0.96	0.01	0.11	0.42	0.18	0.20	0.08	0.35	0.07	0.22	0.35
N3	63.0	67.9	0.93	0.02	0.08	0.54	0.16	0.14	0.06	0.32	0.13	0.12	0.44
N4	60.2	62.2	0.97	0.03	0.04	0.46	0.16	0.27	0.02	0.32	0.13	0.10	0.45
N5	66.1	65.5	1.01	0.08	0.03	0.31	0.30	0.26	<0.02	0.56	0.11	0.15	0.18
G1	214.3	204.1	1.05	0.00	0.06	0.60	0.20	0.10	0.04	0.34	0.07	0.17	0.42
G5	278.3	269.7	1.03	0.00	0.02	0.63	0.30	0.04	0.01	0.10	0.03	0.03	0.84
R1	74.0	72.8	1.02	0.04	0.04	0.53	0.11	0.24	0.04	0.31	0.13	0.22	0.33
R2	63.4	46.9	1.35	0.35	0.05	0.31	0.06	0.18	0.04	0.47	0.20	0.20	0.13
R3	47.0	46.9	1.00	0.12	0.09	0.47	0.12	0.06	0.14	0.49	0.18	0.07	0.26
R4C	178.0	186.6	0.95	0.00	0.03	0.51	0.18	0.07	0.21	0.32	0.06	0.06	0.57
R4B	218.9	226.7	0.97	0.00	0.07	0.52	0.15	0.07	0.19	0.42	0.06	0.02	0.49
LS	176.9	168.0	1.05	0.00	0.05	0.42	0.09	0.08	0.36	0.51	0.08	0.05	0.35
ELS	80.9	81.5	0.99	0.02	0.02	0.38	0.19	0.34	0.05	0.22	0.08	0.28	0.42
BM	59.3	48.5	1.22	0.27	0.02	0.22	0.26	0.22	<0.03	0.73	0.09	0.06	0.12
FBG	35.0	34.9	1.00	0.09	0.03	0.26	0.47	<0.03	0.13	0.31	0.17	0.06	0.46
ASB	42.2	13.1	3.22	0.75	0.03	0.12	0.08	<0.02	<0.04	0.53	0.39	0.08	0.00
GLK	57.5	33.2	1.73	0.55	0.04	0.15	0.04	0.17	0.05	0.34	0.21	0.45	0.00
SMT	63.9	23.8	2.68	0.70	0.04	0.11	0.04	0.10	<0.02	0.46	0.31	0.23	0.00
GC	81.9	85.4	0.96	0.01	0.02	0.43	0.33	0.16	0.05	0.16	0.08	0.09	0.68

B-Barringer; C-Chemex

Table 23. Results of an ion balance done with snowmelt major ion concentration for each site of the February 1981 snow survey.

Site	Total +ve Ions (μeq/L)	Total -ve Ions (μeq/L)	Ratio of Total +ve:-ve	Snowmelt Ion Balance: Fraction of Total +ve Ion Equivalent Due to						Fraction of Total -ve Ion Equivalent Due to			
				H^+	NH_4^+	Ca^{++}	Mg^{++}	Na^+	K^+	$SO_4^=$	NO_3^-	Cl^-	HCO_3^-
NNE1C	148.4	148.7	1.00	0.00	0.04	0.60	0.24	0.04	0.07	0.25	0.06	0.02	0.67
NNE1B	130.3	195.2	0.67	0.00	0.03	0.54	0.27	0.10	0.06	0.21	0.26	0.01	0.74
NNE2	70.2	69.0	1.02	0.02	0.04	0.63	0.21	0.06	0.03	0.33	0.11	0.03	0.52
NNE3	102.2	110.3	0.93	0.01	0.03	0.72	0.18	0.06	<0.01	0.09	0.07	0.01	0.82
NNE4	68.2	29.0	2.35	0.63	0.04	0.26	0.04	<0.01	<0.02	0.66	0.29	0.05	0.00
NE1C	618.2	610.3	1.01	0.00	0.01	0.68	0.26	0.05	0.01	0.07	0.01	0.00	0.91
NE1B	52.6	70.4	0.75	0.02	0.10	0.60	0.13	0.10	0.06	0.44	0.09	0.01	0.45
NE2	47.7	46.8	1.02	0.10	0.05	0.55	0.16	0.12	0.03	0.39	0.16	0.06	0.38
NE3	38.2	36.8	1.04	0.16	0.05	0.28	0.30	0.17	<0.04	0.40	0.17	0.09	0.38
NE4	48.5	43.6	1.11	0.09	0.05	0.35	0.32	0.17	<0.03	0.37	0.14	0.03	0.46
NE5C	323.7	310.3	1.04	0.00	0.01	0.47	0.47	0.04	0.00	0.07	0.02	0.01	0.90
NE5B	409.0	240.4	1.70	0.00	0.01	0.39	0.54	0.05	0.01	0.09	0.03	0.00	0.88
E1	326.3	314.6	1.04	0.00	0.02	0.25	0.37	0.35	0.01	0.06	0.02	0.02	0.90
E2	227.1	221.4	1.03	0.00	0.01	0.46	0.30	0.22	0.01	0.06	0.02	0.01	0.90
E3	53.9	52.8	1.02	0.02	0.06	0.60	0.26	0.03	<0.03	0.28	0.13	0.03	0.57
E4	44.9	43.6	1.03	0.02	0.05	0.46	0.34	0.09	<0.03	0.13	0.12	0.01	0.73
MKG	76.2	63.4	1.20	0.27	0.12	0.41	0.05	0.13	0.02	0.28	0.32	0.34	0.06
SE1	185.0	174.6	1.06	0.00	0.03	0.55	0.30	0.03	0.09	0.17	0.04	0.01	0.77
SE2	37.4	26.9	1.39	0.44	0.04	0.32	0.04	0.03	0.07	0.43	0.24	0.10	0.22
SE3	76.2	75.6	1.01	0.02	0.06	0.50	0.22	0.17	<0.02	0.14	0.08	0.04	0.74
SE4	160.2	152.4	1.05	0.01	0.05	0.28	0.59	0.06	0.02	0.09	0.04	0.01	0.85
SE5C	143.3	159.5	0.90	0.00	0.02	0.42	0.40	0.15	<0.01	0.08	0.04	0.01	0.87
SE5B	104.5	103.8	1.01	0.00	0.02	0.58	0.29	0.10	0.01	0.10	0.05	0.01	0.85
SSE1C	49.1	40.2	1.22	0.30	0.08	0.44	0.10	0.05	0.04	0.49	0.21	0.05	0.25
SSE1B	34.1	29.5	1.16	0.08	<0.03	0.60	0.14	0.06	0.09	0.63	0.22	0.01	0.14
SSE2	33.5	29.0	1.16	0.37	0.05	0.37	0.12	0.04	0.04	0.32	0.25	0.05	0.38
SSE3	56.9	60.6	0.94	0.05	0.07	0.37	0.26	0.21	0.04	0.20	0.17	0.30	0.33
S1	201.5	188.5	1.07	0.01	0.05	0.48	0.11	0.27	0.09	0.36	0.07	0.29	0.29
S2	73.1	63.2	1.16	0.15	0.07	0.54	0.11	0.09	0.04	0.52	0.18	0.12	0.19
S3	73.2	79.4	0.92	0.04	0.04	0.66	0.15	0.09	0.02	0.25	0.13	0.07	0.55
S4	96.2	97.2	0.99	0.08	0.03	0.41	0.10	0.37	0.02	0.26	0.11	0.40	0.23
S5	184.5	193.2	0.95	0.00	0.01	0.48	0.13	0.35	0.02	0.14	0.06	0.34	0.46
SSW1	92.2	101.6	0.91	0.00	0.04	0.39	0.29	0.24	0.03	0.29	0.09	0.03	0.58
SSW2	66.9	66.6	1.00	0.05	0.04	0.51	0.27	0.10	0.03	0.27	0.15	0.04	0.54
SW1	161.4	164.8	0.98	0.00	0.03	0.47	0.29	0.20	0.01	0.14	0.05	0.22	0.59
SW2	59.1	55.6	1.06	0.11	0.08	0.48	0.14	0.12	0.07	0.36	0.15	0.17	0.32
SW3C	54.6	35.4	1.54	0.36	0.14	0.22	0.10	0.14	<0.03	0.54	0.21	0.08	0.17
SW3B	62.2	65.8	0.95	0.01	0.11	0.20	0.13	0.54	<0.02	0.28	0.10	0.01	0.61
SW4	64.8	40.6	1.60	0.44	0.10	0.24	0.05	0.13	0.04	0.48	0.20	0.22	0.10
SW5	70.6	24.6	2.87	0.70	0.05	0.15	0.02	0.05	<0.02	0.57	0.28	0.15	0.00
W1C	63.3	40.3	1.57	0.35	0.18	0.30	0.08	0.06	0.03	0.63	0.19	0.08	0.10
W1B	49.8	39.1	1.28	0.04	0.28	0.46	0.13	0.08	<0.03	0.71	0.16	0.03	<0.10
W2	40.8	27.9	1.46	0.46	0.10	0.34	0.04	0.04	0.03	0.48	0.25	0.09	0.18
W3	112.3	108.5	1.04	0.00	0.02	0.14	0.42	0.38	0.03	0.11	0.06	0.03	0.80
NW3C	138.1	135.5	1.01	0.01	0.03	0.50	0.19	0.23	0.04	0.15	0.06	0.02	0.77
NW3B	149.9	116.4	1.29	0.00	0.02	0.47	0.29	0.19	0.03	0.18	0.06	0.01	0.76
NW4	272.2	278.9	0.98	0.00	0.01	0.37	0.47	0.14	0.01	0.14	0.03	0.01	0.82
NW5	100.6	95.7	1.05	0.02	0.02	0.35	0.43	0.17	<0.01	0.10	0.08	0.05	0.77
NNW1	44.5	47.0	0.95	0.09	0.06	0.26	0.31	0.25	<0.03	0.25	0.16	0.08	0.51
N1	137.8	128.7	1.07	0.00	0.07	0.45	0.22	0.25	0.01	0.26	0.07	0.28	0.39
N2	146.7	140.3	1.05	0.00	0.13	0.50	0.25	0.09	0.03	0.44	0.08	0.03	0.45
N3	87.5	89.6	0.98	0.03	0.08	0.62	0.19	0.05	0.04	0.30	0.11	0.04	0.56
N4	62.8	41.9	1.50	0.36	0.08	0.39	0.09	0.06	<0.02	0.57	0.23	0.11	0.10
N5	60.6	30.1	2.01	0.59	0.04	0.17	0.13	0.04	<0.02	0.69	0.25	0.06	0.00
G1	1347.2	1300.7	1.04	0.00	0.03	0.50	0.12	0.02	0.33	0.78	0.03	0.01	0.17
G5	236.5	228.9	1.03	0.00	0.04	0.58	0.34	0.03	0.01	0.33	0.04	0.02	0.61
R1	52.4	48.3	1.08	0.27	0.06	0.41	0.08	0.05	0.13	0.45	0.22	0.07	0.27
R2	59.1	57.3	1.03	0.19	0.10	0.47	0.08	0.04	0.12	0.51	0.18	0.07	0.24
R3	73.5	59.9	1.23	0.18	0.09	0.38	0.11	0.03	0.22	0.61	0.15	0.04	0.20
R4C	209.6	194.5	1.07	0.00	0.04	0.34	0.30	0.04	0.27	0.32	0.06	0.02	0.61
R4B	242.8	237.3	1.02	0.00	0.02	0.36	0.30	0.04	0.28	0.29	0.04	0.02	0.66
LS	193.2	187.4	1.03	0.00	0.05	0.39	0.07	0.02	0.46	0.47	0.08	0.02	0.44
ELS	29.2	25.3	1.15	0.53	0.07	0.24	0.05	0.03	0.08	0.26	0.24	0.06	0.34
BCH	31.1	20.1	1.55	0.69	0.04	0.08	0.05	0.05	0.09	0.34	0.24	0.11	0.30
FBG	35.9	24.4	1.47	0.52	0.05	0.25	0.09	0.05	<0.04	0.41	0.30	0.08	0.20
ASB	76.4	71.5	1.07	0.01	0.07	0.56	0.29	0.06	<0.02	0.11	0.07	0.03	0.78
GLK	38.2	44.1	0.87	0.20	0.47	0.13	0.07	0.08	0.06	0.28	0.18	0.09	0.45
SMT	38.3	33.8	1.13	0.39	0.11	0.28	0.04	0.10	0.07	0.39	0.23	0.14	0.24
GC	36.0	27.1	1.33	0.40	0.05	0.41	0.04	0.05	<0.04	0.48	0.23	0.06	0.22

B-Barringer; C-Chemex

Table 24. Results of an ion balance done with major ion concentrations for each of the snow sampler sites. The collection period was 16 January to 23 February 1981.

Site	Total +ve Ions (μeq/l)	Total -ve Ions (μeq/l)	Ratio of Total +ve:-ve	Snowmelt Ion Balance Fraction of Total +ve Ion Equivalent Due to						Fraction of Total -ve Ion Equivalent Due to			
				H^+	NH_4^+	Ca^{++}	Mg^{++}	Na^+	K^+	$SO_4^=$	NO_3^-	Cl^-	HCO_3^-
N1	196.3	198.5	0.99	0.00	0.05	0.51	0.23	0.19	0.03	0.23	0.06	0.19	0.51
N2	251.1	233.8	1.07	0.00	0.09	0.62	0.17	0.06	0.05	0.36	0.05	0.05	0.55
N5	66.4	65.2	1.02	0.19	0.09	0.52	0.09	0.07	0.05	0.52	0.17	0.07	0.25
S2	147.5	141.9	1.04	0.09	0.07	0.39	0.09	0.22	0.15	0.55	0.10	0.28	0.07
S4	272.3	236.0	0.94	0.00	0.02	0.43	0.14	0.37	0.04	0.25	0.10	0.34	0.31
SW1	534.5	570.1	0.94	0.00	0.02	0.52	0.25	0.17	0.03	0.16	0.03	0.15	0.67

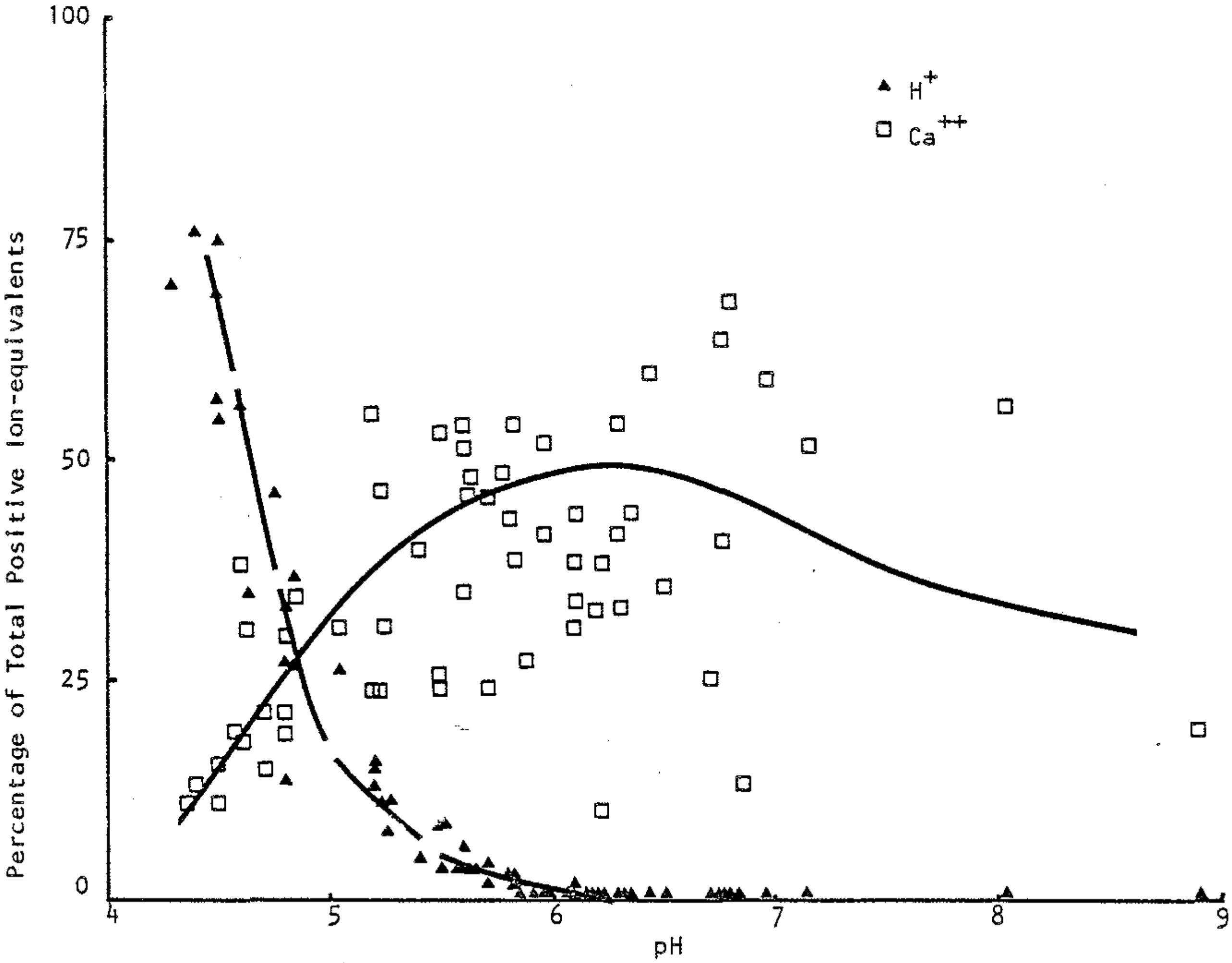


Figure 22. The contribution of hydrogen and calcium ions to the total positive ion-equivalents in snowmelt collected from the oil sands area on 10 January 1981 as a function of pH.

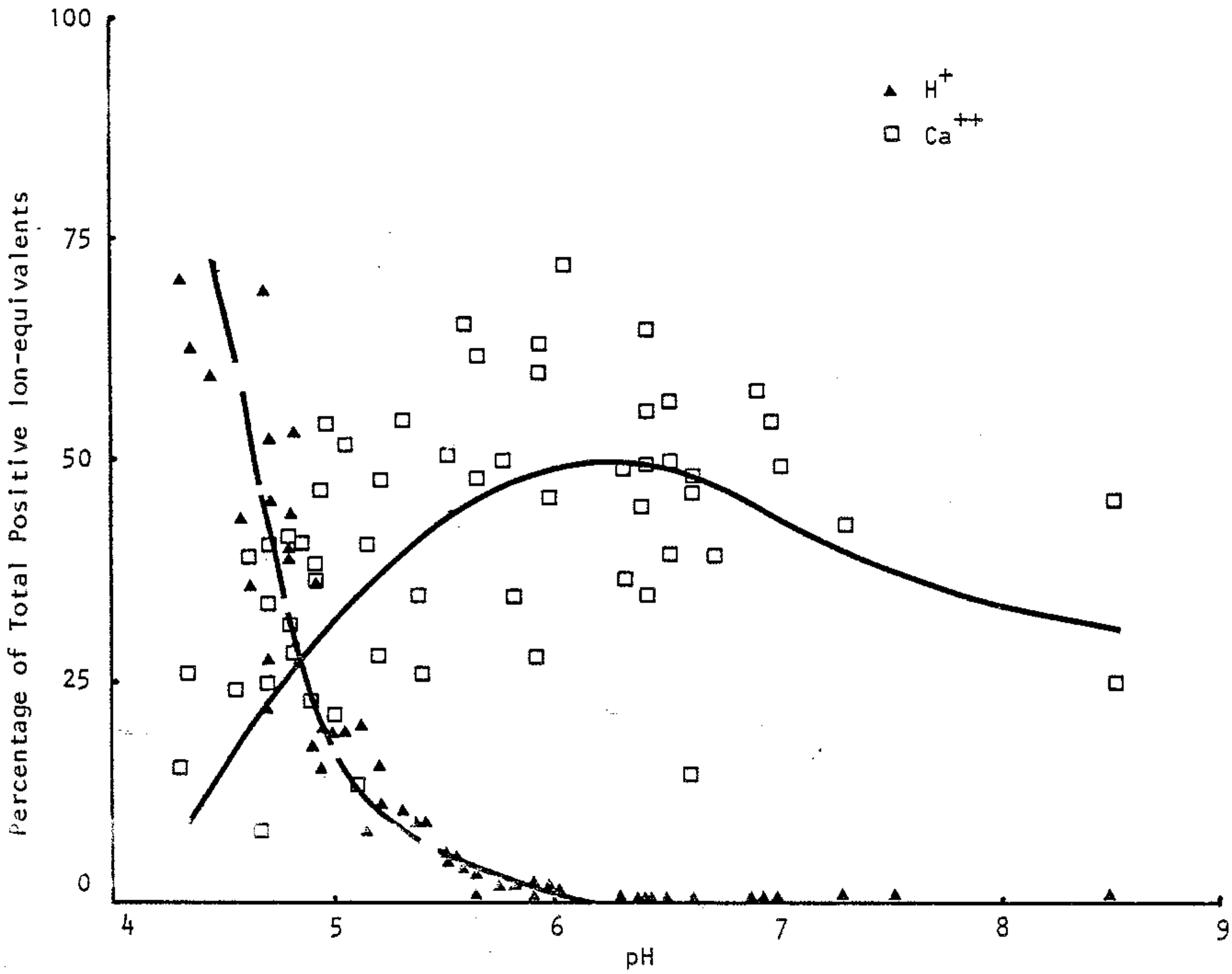


Figure 23. The contribution of hydrogen and calcium ions to the total positive ion-equivalents in snowmelt collected from the oil sands area on 23 February 1981 as a function of pH.

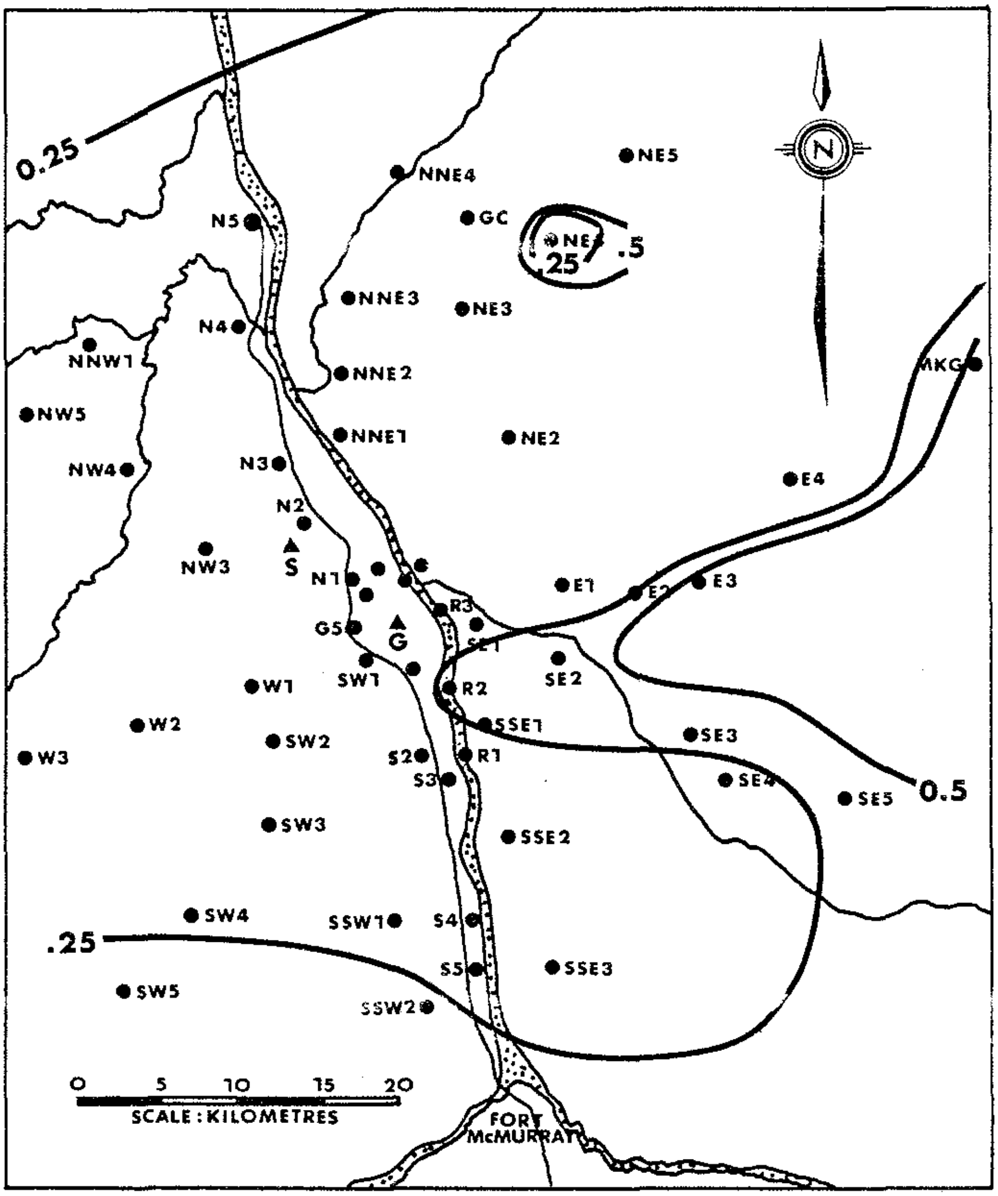


Figure 24. The spatial distribution of the contribution of hydrogen ions to the total positive ion-equivalents in snowmelt collected from the oil sands area on 10 January 1981.

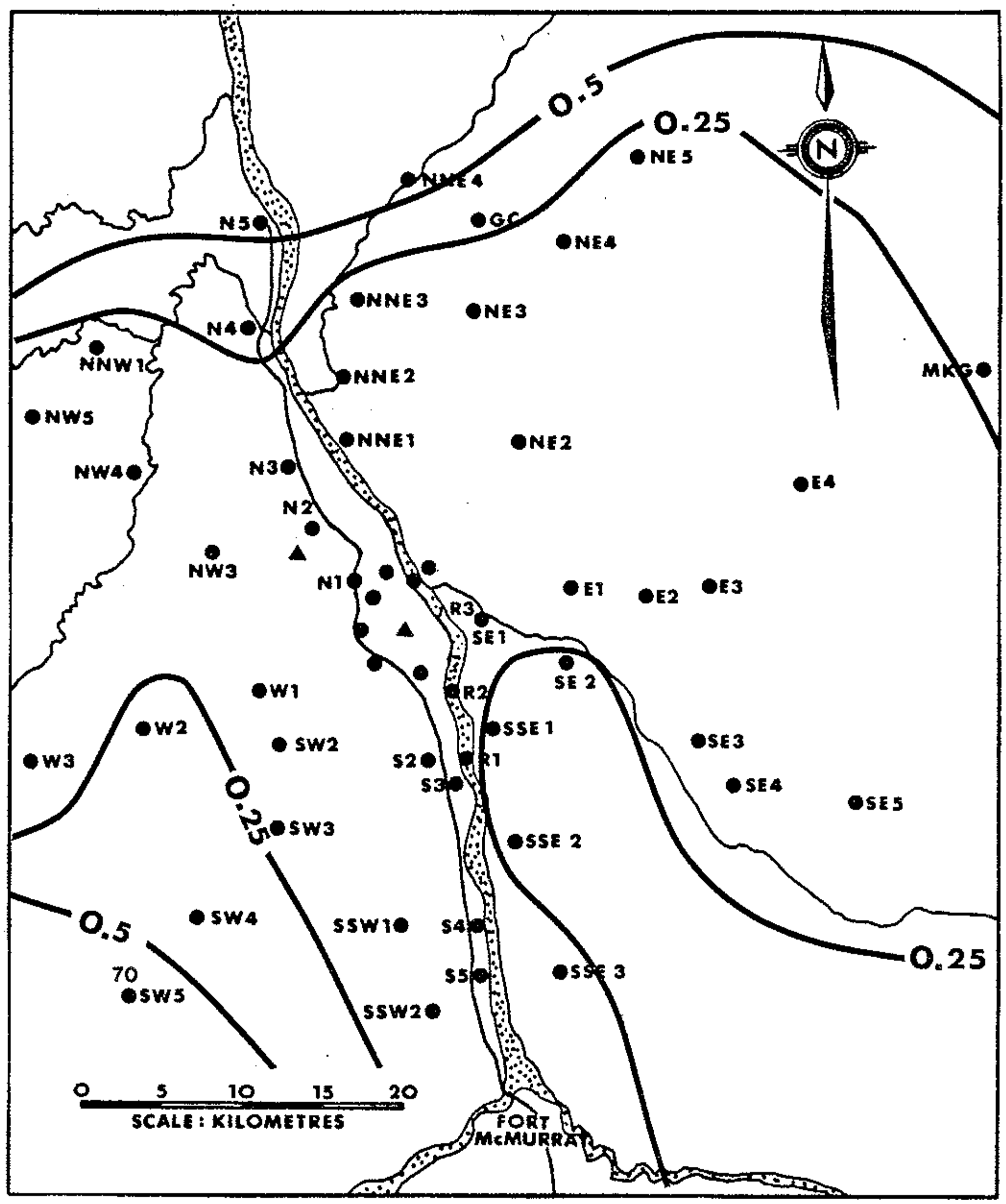


Figure 25. The spatial distribution of the contribution of hydrogen ions to the total positive ion-equivalents in snowmelt collected from the oil sands area on 23 February 1981.

4.5 PRINCIPAL COMPONENT AND CLUSTER ANALYSIS OF THE DATA

Two multivariate statistical methods, principal component analysis (PCA) and cluster analysis, were performed on the snowpack data. Snowpack loadings of H^+, NH_4^+, Na^+, Mg^{++}, Ca^{++}, $SO_4^=$, NO_3^-, insoluble Al, insoluble Mn, and insoluble V were used in the analyses. A PCA followed by an orthogonal (varimax) rotation was performed using the Factor routine in version 8.0 of the Statistical Package for the Social Sciences (Nie et al. 1975). A hierarchical algorithm using a single linkage algamation rule was used to cluster the data (Green 1978:429).

In a PCA, linear combinations (components) or the original variables which exhibit maximal variance are obtained subject to being uncorrelated with previously obtained components. The subsequent orthogonal rotation is performed to transform the initial principal components solution to one which is more easy to understand physically.

Of the total variance, 89% in the January study and 92% in the February study were explained by the first five principal components. In the first study of 1981, the chemical constituents associated with each component were as follows:

1. Insoluble Al, Mn, V
2. Na^+, Mg^{++}, $SO_4^=$
3. NH_4^+, NO_3^-, $SO_4^=$
4. Cl^-, Na^+
5. H^+

Somewhat different groupings were found for the second 1981 study, as follows:

1. $SO_4^=$, $NO_3^=$, Ca^{++}
2. Insoluble Mn, Al
3. Cl^-, Na^+
4. Mg^{++}, H^+
5. H^+, Ca^{++}

In both surveys, high values of Na^+ and Cl^- ion loadings occurred at sites S1, S2, S3, S4, SW1 which were along Highway 63 between Fort McMurray and Mildred Lake. This highway is sanded and salted regularly in winter. According to Ken Zelinski of Alberta Transportation at Fort McMurray a mixture of common salt and sand is used. North of Mildred Lake, where the road is cleared but not salted, the Na^+ and Cl^- loadings are lower.

At sites NE5 and NW4, both more than 10 km from the road, there were elevated values of Na^+ and Mg^{++}. These samples may have been contaminated by surface water from the ponds on which the snow was collected.

The principal components which correspond to chemical constituents originating from the oil sands plants (1, 3, 5 in January and 1, 2, 5 in February) were used as the axes of a three-dimensional diagram (Figures 26 and 27). The grouping of sites with similar chemistry is apparent. With a few exceptions, these groupings or clusters occupy contiguous geographical areas as shown in Figures 28 and 29.

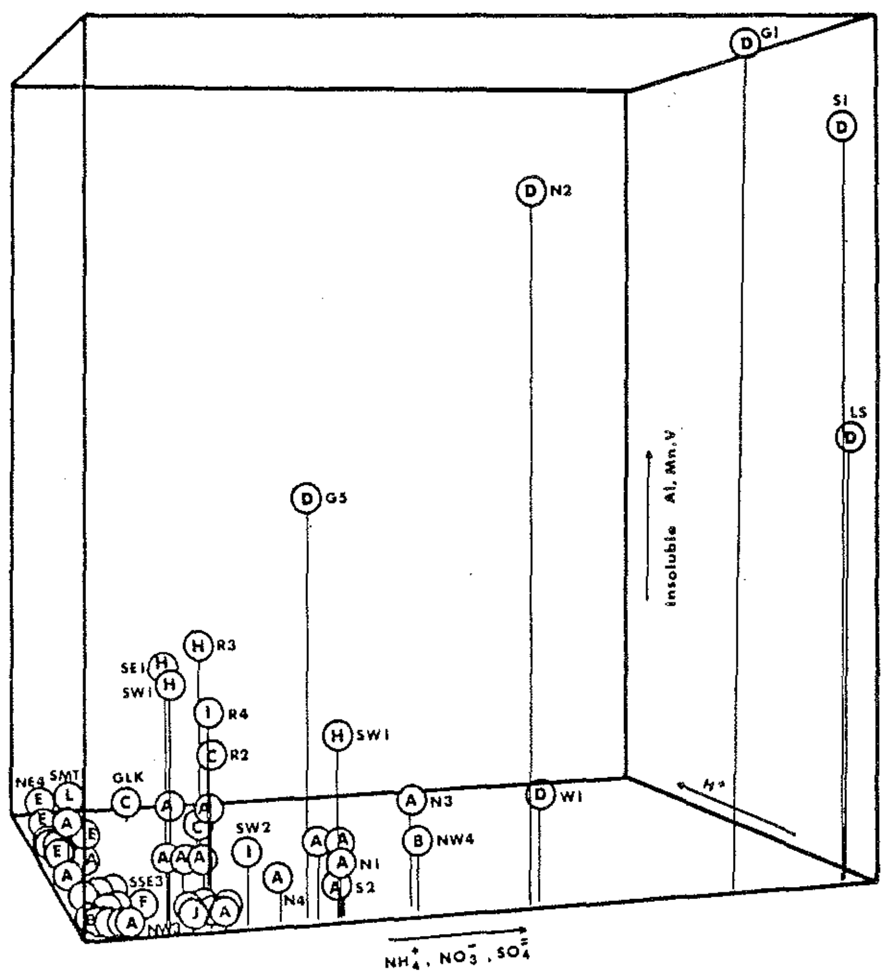


Figure 26. A three-dimensional representation of a principal component analysis of the January 1981 snowpack loading data.

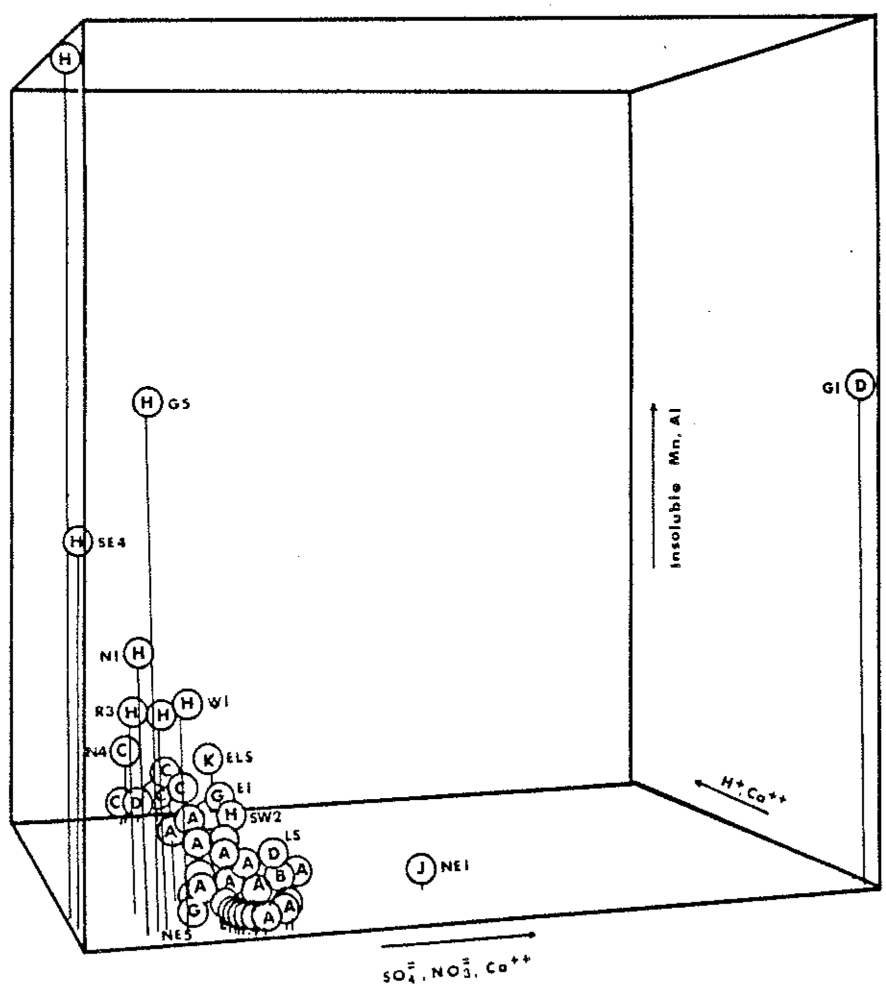


Figure 27. A three-dimensional representation of a principal component analysis of the February 1981 snowpack loading data.

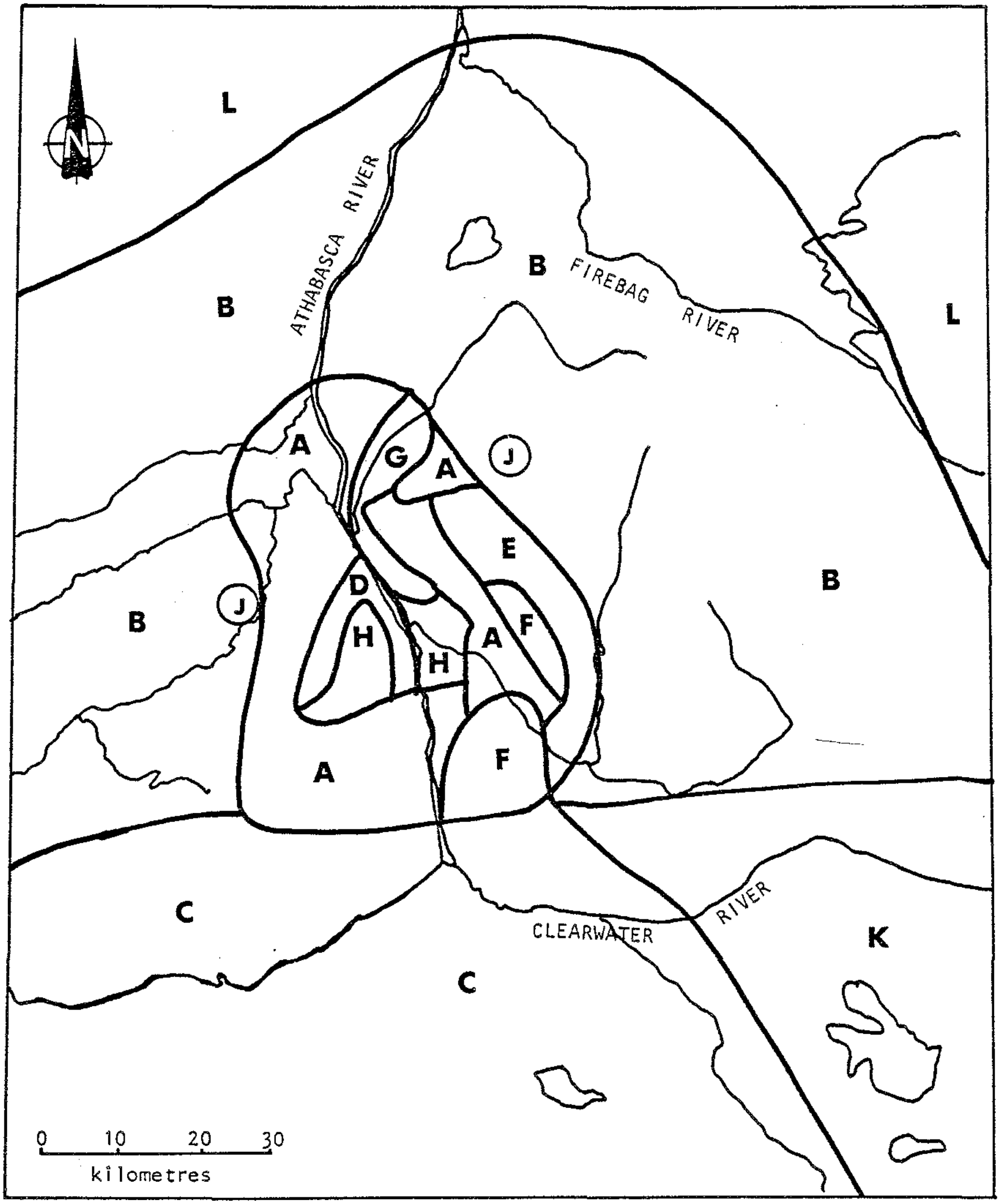


Figure 28. The geographical location of groups of sites identified by cluster analysis as having similar snow chemistry on 10 January 1981.

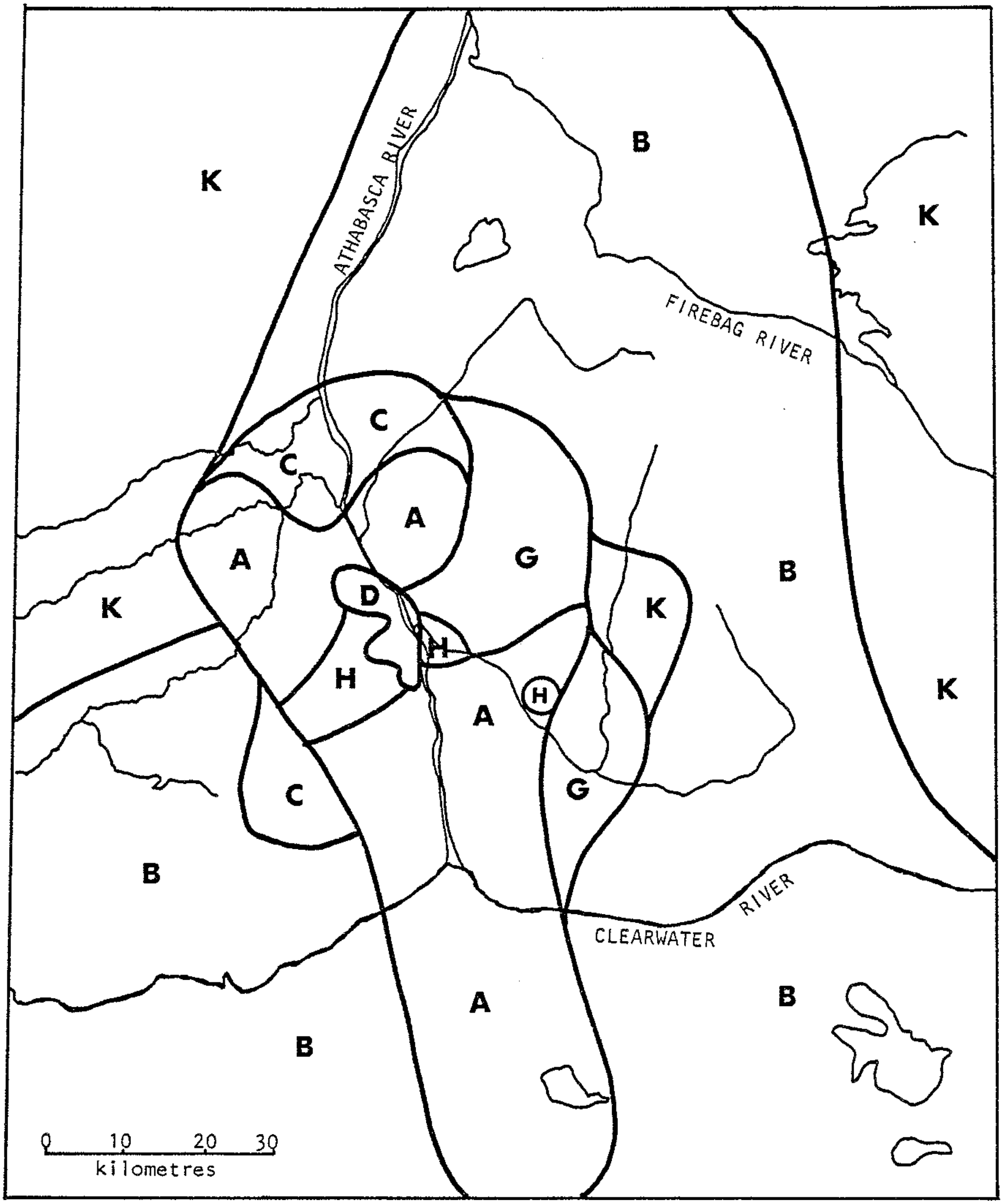


Figure 29. The geographical location of groups of sites identified by cluster analysis as having similar snow chemistry on 23 February 1981.

4.6 COMPARISON OF BARRINGER AND CHEMEX ANALYSIS

In each survey, samples from 9 sites plus a blank were analyzed by both Chemex and Barringer to permit an interlaboratory comparison of the results. Each laboratory analyzed similar but not identical samples from separate snowcores, so that sampling errors are present in addition to analytical and handling errors.

A comparison of the results for the blank samples is shown in Table 25. Barringer reports a pH which is 0.6 units higher than the Chemex result. The increase of pH does not appear to have resulted from the dissolution of calcium oxides because there was little difference in the calcium ion concentrations. The ratio of positive to negative ion-equivalents for the Barringer analysis is 1.2 which is within the expected error. For Chemex, the ratio is 5.2 indicating a surplus of positive ions.

A comparison of pH values obtained by the two labs is given in Figure 30. For pH values below about 6.5, there was an apparent increase of pH due to shipping of the melted snow from Chemex to Barringer.

There was good agreement between the analyses of the two laboratories for the sulphate, nitrates, ammonium, and potassium ions as shown in Table 26 and 27. The hydrogen, chloride, sodium, magnesium and calcium ions showed good agreement at a number of sites but large differences at others. This probably reflects the fact that different cores were analyzed by the two labs. Intrasite variability could lead to a difference in composition of the cores.

The correlation between the soluble vanadium concentrations was good, although different techniques were used. The agreement was not as good for the other soluble metals because the concentrations were near the detection limit for the plasma method.

There was good agreement for the mass of insoluble aluminum and vanadium. Insoluble titanium and manganese did not show good agreement. The amounts of these elements in the samples were relatively low.

Table 25. Comparison of analyses by Chemex and Barringer of blank samples. Units are: mg/L for major ions, μeq/L for alkalinity, μg/L for soluble metals, and μg for insoluble metals.

	Barringer	Chemex
pH	5.50	4.90
$SO_4^{=}$-S	<0.02	<0.003
Cl^-	0.02	<0.06
NO_3^--N	<0.01	0.005
NH_4^+-N	0.04	<0.004
K^+	0.06	<0.06
Na^+	<0.02	<0.01
Mg^{++}	<0.01	0.015
Ca^{++}	0.05	0.04
Alkalinity	8	2
Soluble Al	20	<1
Soluble Fe	<10	<2
Soluble Ni	10	<1
Soluble V	11	<1
Insoluble Al	<10	6
Insoluble Mn	<10	0.5
Insoluble Ti	<6	<50
Insoluble V	<6	0.2

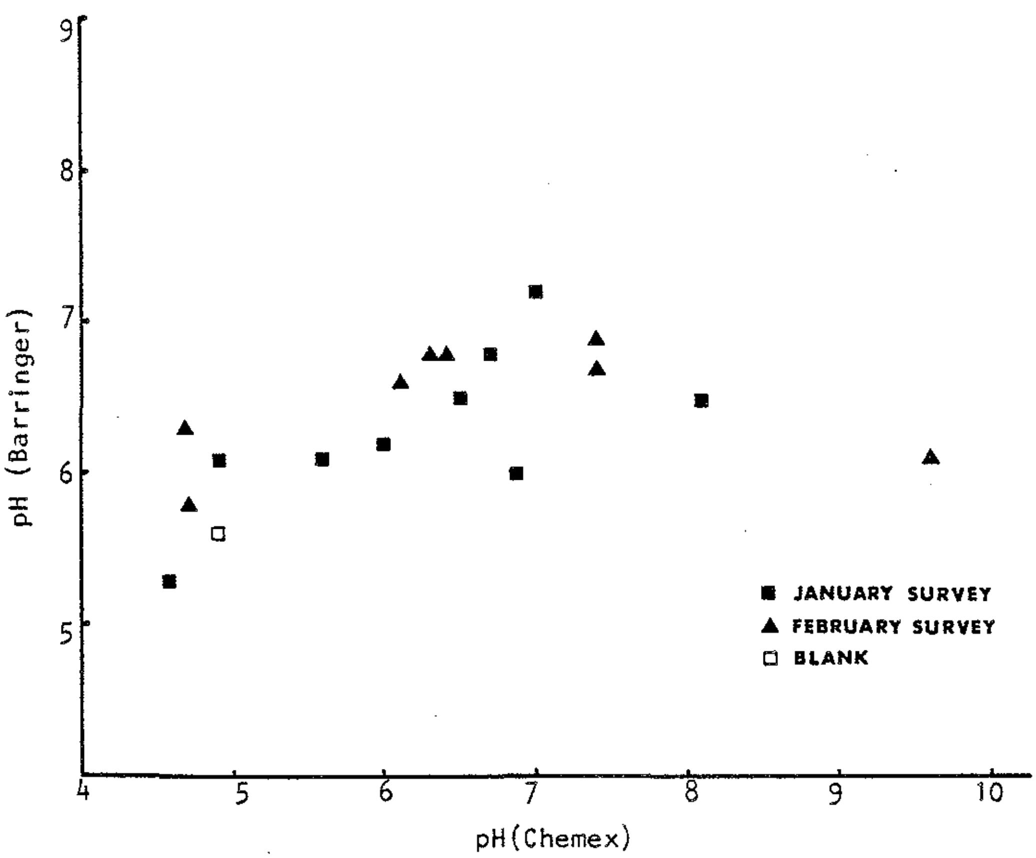


Figure 30. A comparison of pH measured by Chemex immediately after melting the snow with that measured by Barringer one to two weeks after melting.

Table 26. Comparison of Barringer and Chemex snow sample analyses for the 10 to 13 January 1981 survey. Units of the standard error of estimate[a] are: µg/L for major ions, µeq/L for alkalinity, µg/L for soluble metals and µg for insoluble metals.

Constituent	Linear Correlation Coefficient	Standard Error of Estimate
H^+	0.90	1
$SO_4^=$-S	0.83	300
Cl^-	0.57	50
NO_3^--N	0.91	20
NH_4^+-N	0.73	60
K^+	0.97	120
Na^+	0.34	350
Mg^{++}	0.25	190
Ca^{++}	0.77	490
Alkalinity	0.60	61
Soluble Al	0.61	7
Soluble Fe	0.38	14
Soluble Ni	0.61	4
Soluble V	0.90	20
Insoluble Al	0.73	49
Insoluble Mn	0.64	3
Insoluble Ti	0.48	5
Insoluble V	0.75	8

[a]Standard error of estimate, S_e is defined by:

$S_e^2 = \frac{1}{n-2} \sum_{i=1}^{n} \left(y_i - (a+bx_i)\right)^2$ where a and b are the intercept and slope, respectively, of the least-squares line between y_i, the Barringer measurement and x_i the Chemex observation.

Table 27. Comparison of Barringer and Chemex snow sample analyses for the 20 to 23 February 1981 survey. Units of the standard error of estimate are: µg/L for major ions, µeq/L for alkalinity, µg/L for soluble metals and µg for insoluble metals.

Constituent	Linear Correlation Coefficient	Standard Error of Estimate
H^+	0.61	1
$SO_4^=$-S	0.96	100
Cl^-	0.67	50
NO_3^--N	0.96	10
NH_4^+-N	0.88	30
K^+	0.99	80
Na^+	0.27	300
Mg^{++}	0.61	700
Ca^{++}	0.11	980
Alkalinity	0.25	76
Soluble Al	D.L.	
Soluble Fe	D.L.	
Soluble Ni	D.L.	
Soluble V	0.78	19
Insolubel Al	0.62	243
Insoluble Mn	0.19	3
Insoluble Ti	0.49	46
Insoluble V	0.90	19

D.L.-Detection Limit

5. CONCLUSIONS

An extensive sampling of the snow cover, and a subsequent measurement of the concentrations of major ions and trace metals in the snowmelt, was carried out within the AOSERP study area during the winter of 1980-81. Methods similar to those used in two previous studies (Barrie and Whelpdale 1978; Barrie and Kovalick 1980) were followed.

The observed deposition patterns of the particulate and gaseous matter emitted from the oil sands plants showed a strong lobe to the south and a weaker one to the northwest of the plants. These patterns would be expected due to the wind directions that occurred over the winter.

The January 1981 results showed that there has been an apparent increase in sulphate and nitrate loadings in the AOSERP study area since the Syncrude plant became operational in 1978. Sulphate deposition within 25 km of the plants doubled between 1978 and 1981. Nitrate deposition within the same area increased marginally.

The loadings of insoluble particulates have decreased substantially from January 1978. Electrostatic precipitators were installed at the Suncor power plant in November 1979 to reduce the emissions of particulate matter.

The differences between the results in 1978 and 1981 may arise from differences in the meteorological regimes. The early winter of 1980-81 had a similar temperature history to 1977-78, but there was no pronounced southeasterly maximum.

As in the previous studies, the percentage of sulphur emissions that were deposited within 25 km of the oil sands plants was very low-i.e., only 0.23%. In contrast, most of the particulates settled near the sources. Of the estimated amount emitted over the 67 d lifetime of the snow cover prior to the January sampling period, 96% was deposited within 25 km of the sources.

The discrepancies between loadings calculated from the snow tray data and the differences between loadings calculated from the January and February 1981 snow core data probably arose from leaching of the contaminants from the snow cover during the interval between the two surveys. One of the aims of this project was to provide the deposition increment for a 1-m sampling period in mid-winter, to be compared with the results of dispersion model calculations. In view of the problems with leaching, the February 1981 data should not be used for this purpose.

Continued monitoring of the snow cover is desirable in future winters, both to chart the changing impact of emissions as the oil sands deposits are exploited, and to provide a data base for modelling studies. The snowpack sampling method has the advantage of being relatively inexpensive; it does, however, bear the risk of failure if the winter is considerably milder than normal.

If snow sampling is continued, it would be desirable to redesign the network of sites. The emission configuration has changed significantly in the past few years resulting in a considerable expansion of the area with alkaline snow. Some of the sites within 25 km of the sources should be eliminated and relocated further away to depict better the spatial distribution of contaminant loadings. The sites along Highway 63, in particular, do not give representative results because of the contamination from road salt. It is important, however, that a core of the original sites are retained so that trends can be determined.

6. REFERENCES CITED

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7. APPENDIX

7.1 THE SPATIAL DISTRIBUTION OF THE MEASURED SNOWPACK LOADINGS ON 10 JANUARY 1981

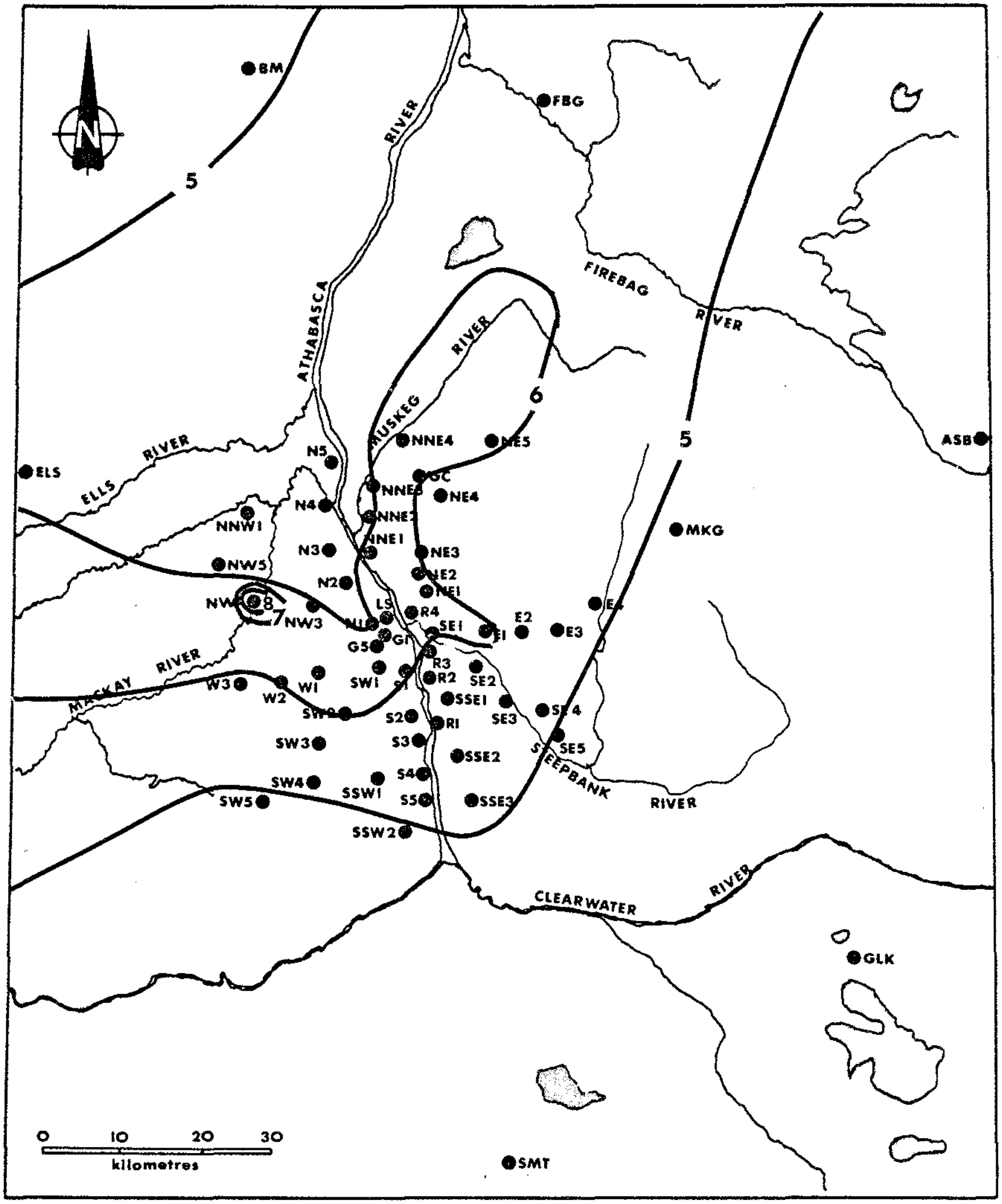

Figure 31. The spatial distribution of snowpack pH in the study area on 10 January 1981.

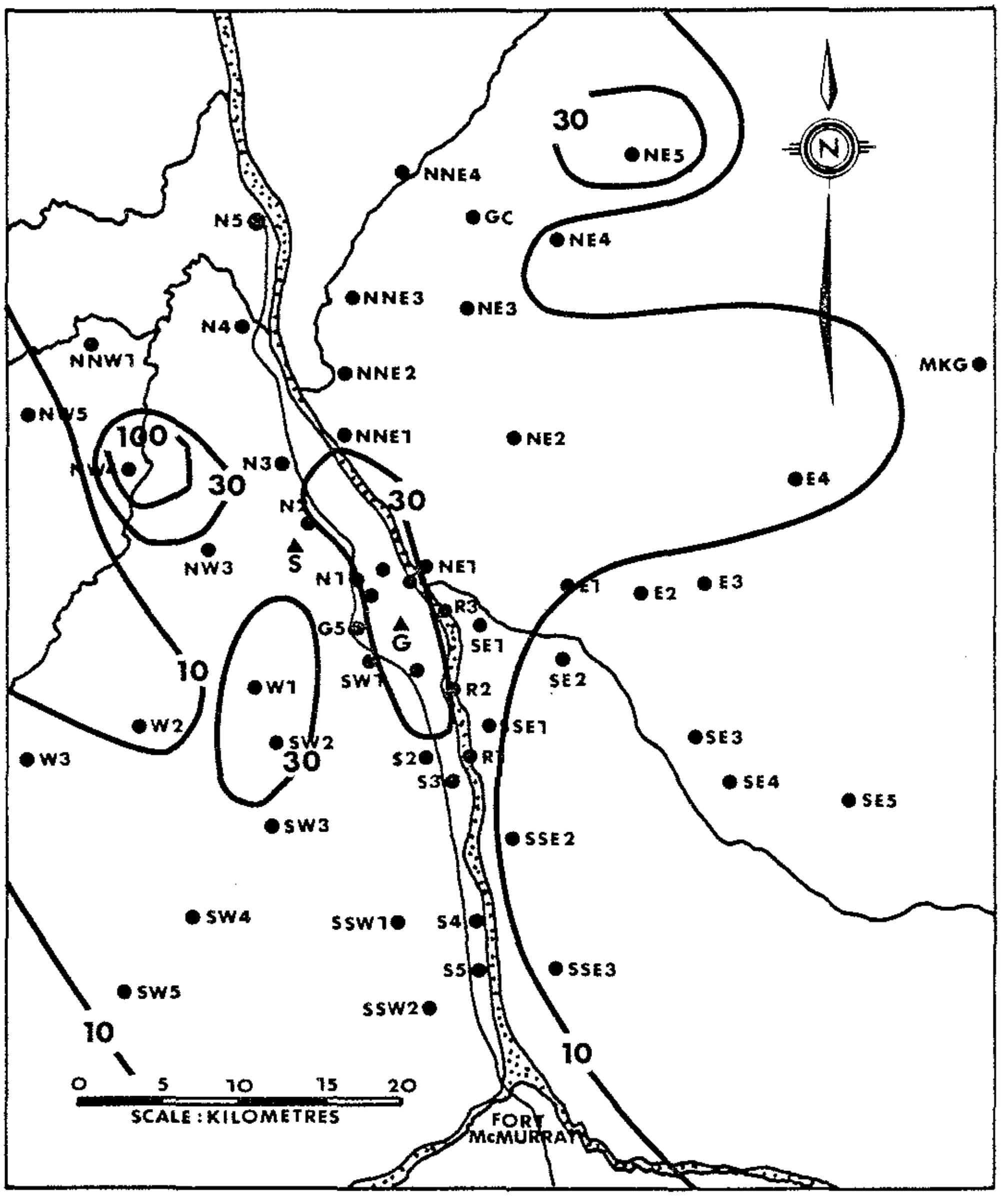

Figure 32. The spatial distribution of snowpack loading (mg/m^2) of sulphate ion in the study area on 10 January 1981.

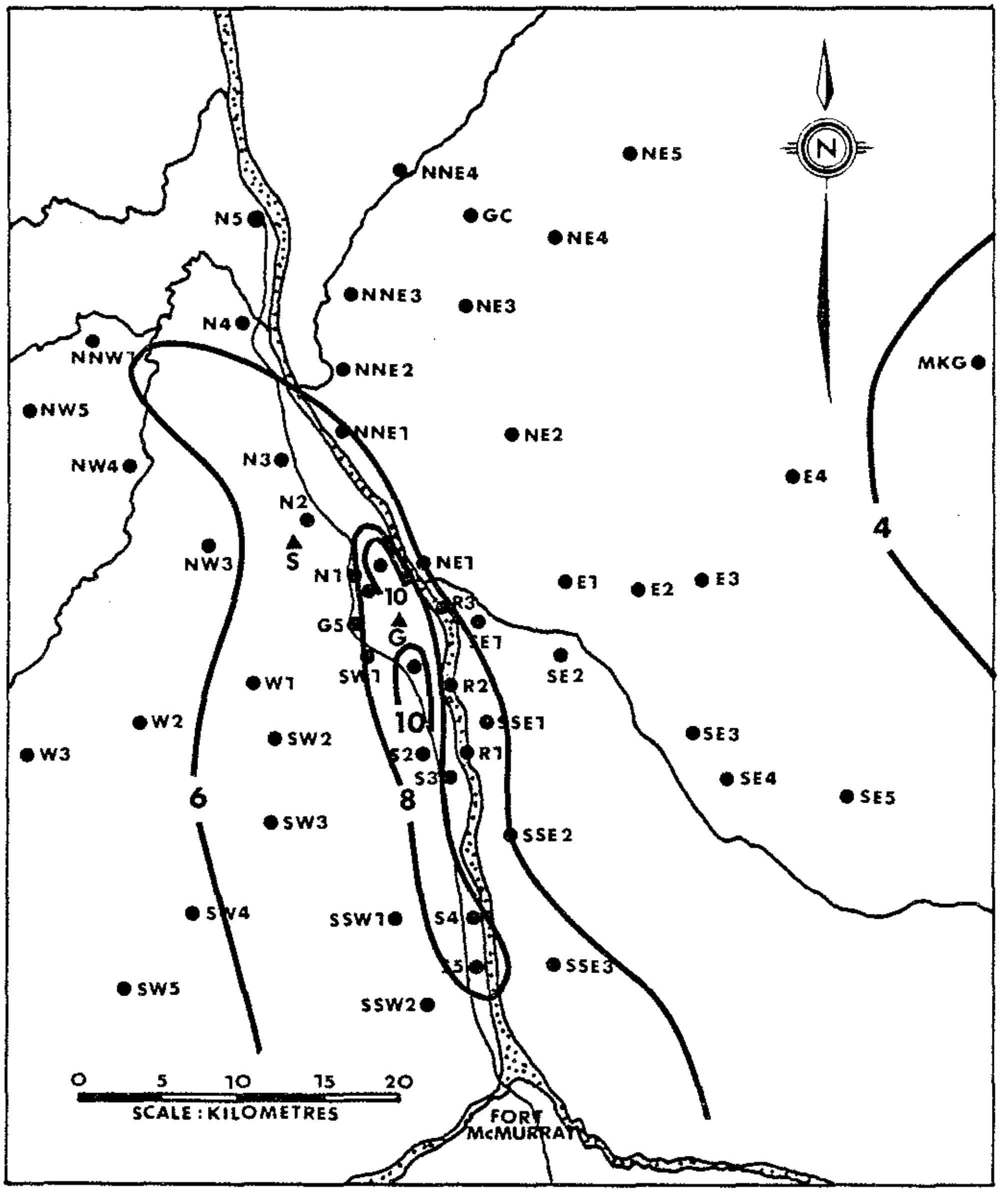

Figure 33. The spatial distribution of snowpack loading (mg/m^2) of nitrate ion in the study area on 10 January 1981.

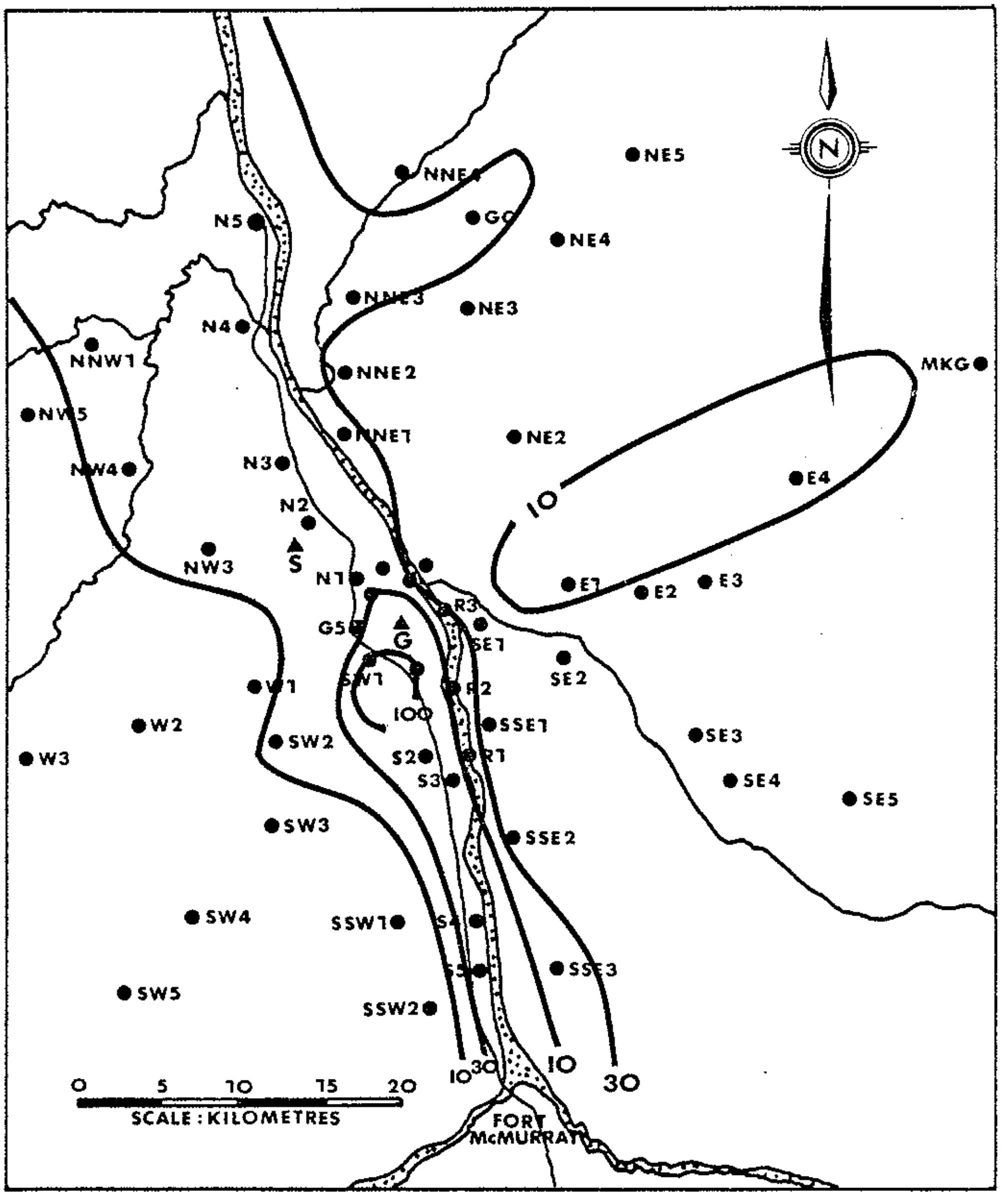

Figure 34. The spatial distribution of Cl^- snowpack loading (mg/m^2) on 10 January 1981.

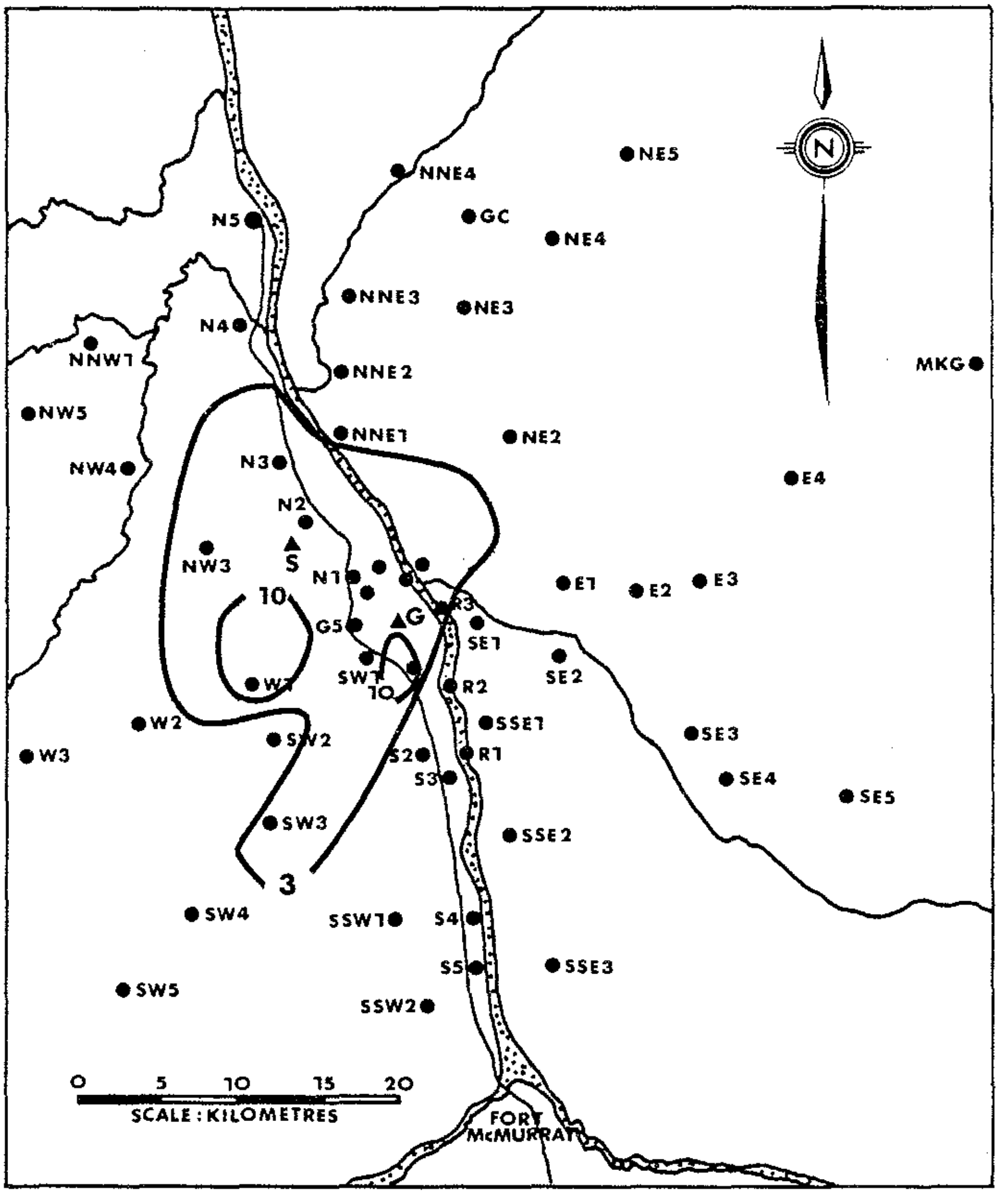

Figure 35. The spatial distribution of NH_4^+-N snowpack loading (mg/m^2) on 10 January 1981.

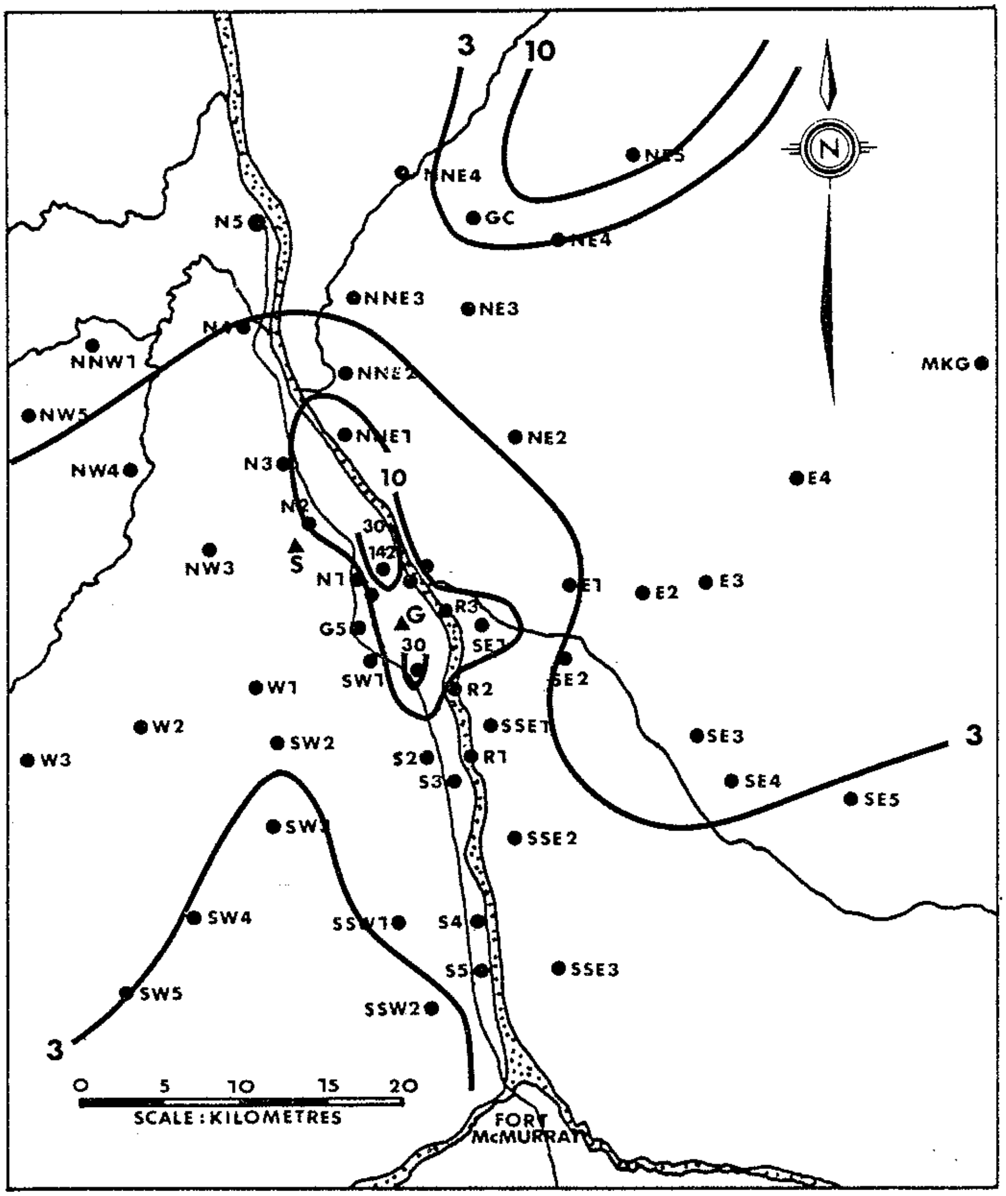

Figure 36. The spatial distribution of K^+ snowpack loading (mg/m2) on 10 January 1981.

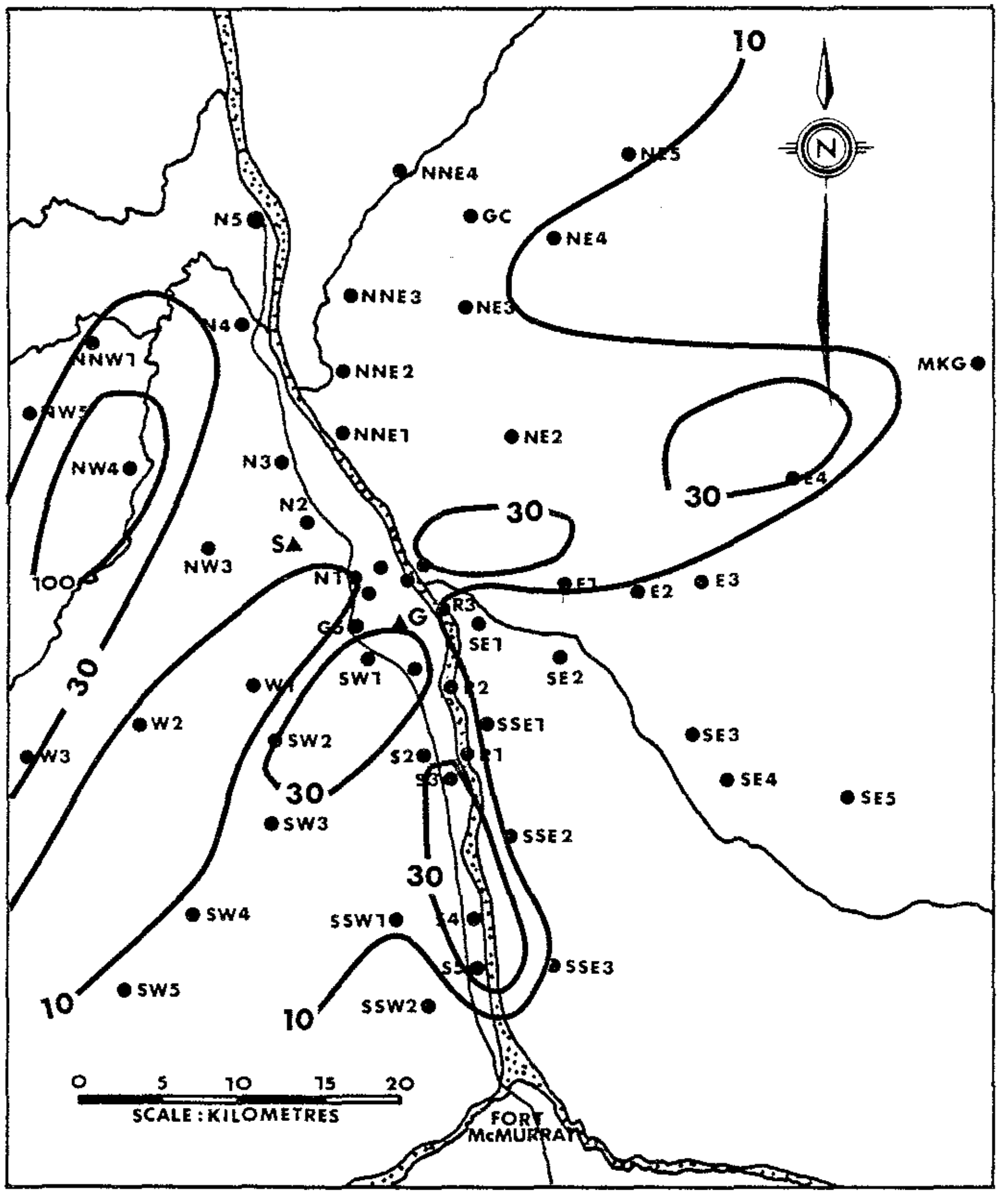

Figure 37. The spatial distribution of Na^{+} snowpack loading (mg/m^2) on 10 January 1981.

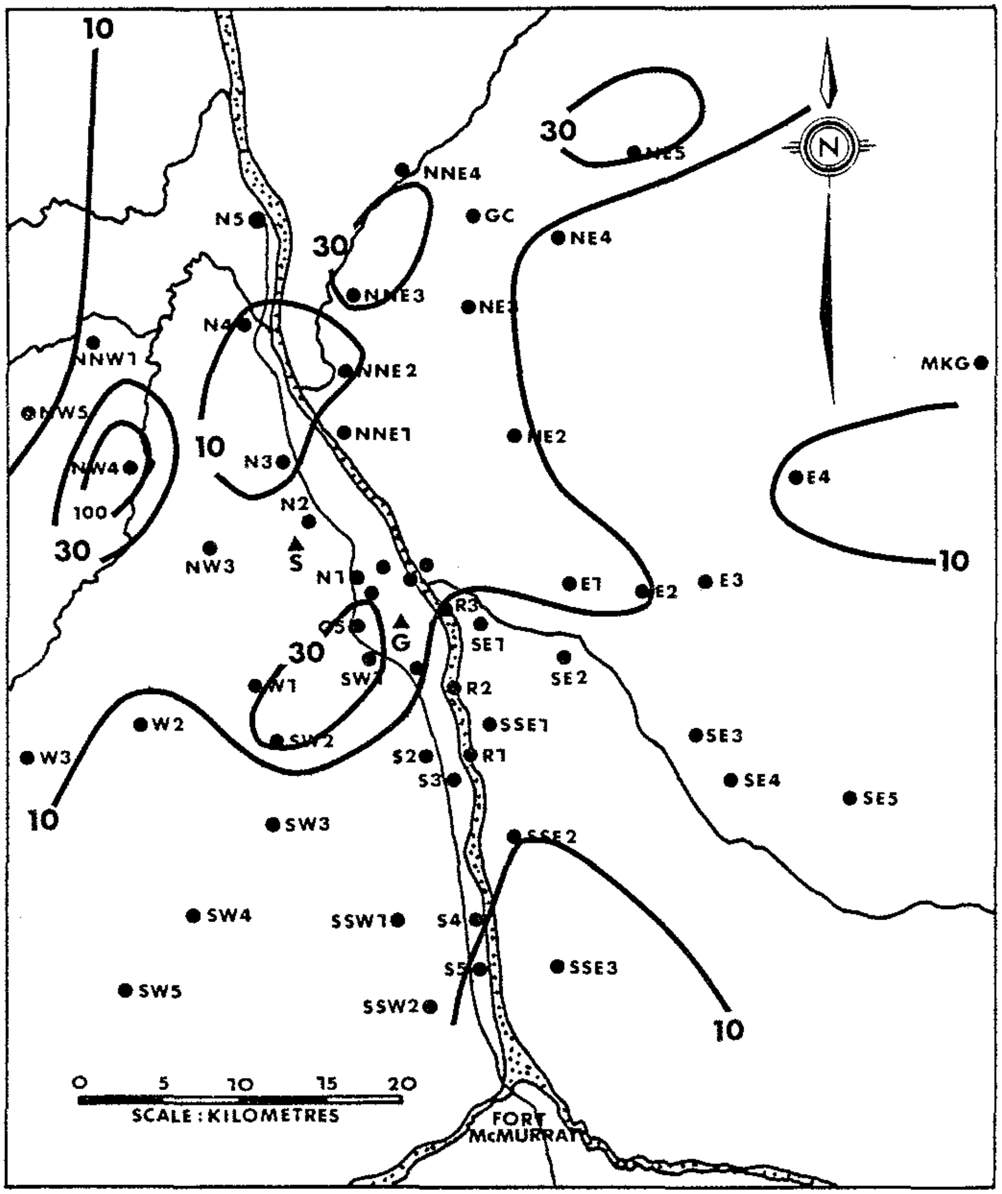

Figure 38. The spatial distribution of Mg^{++} snowpack loading (mg/m^2) on 10 January 1981.

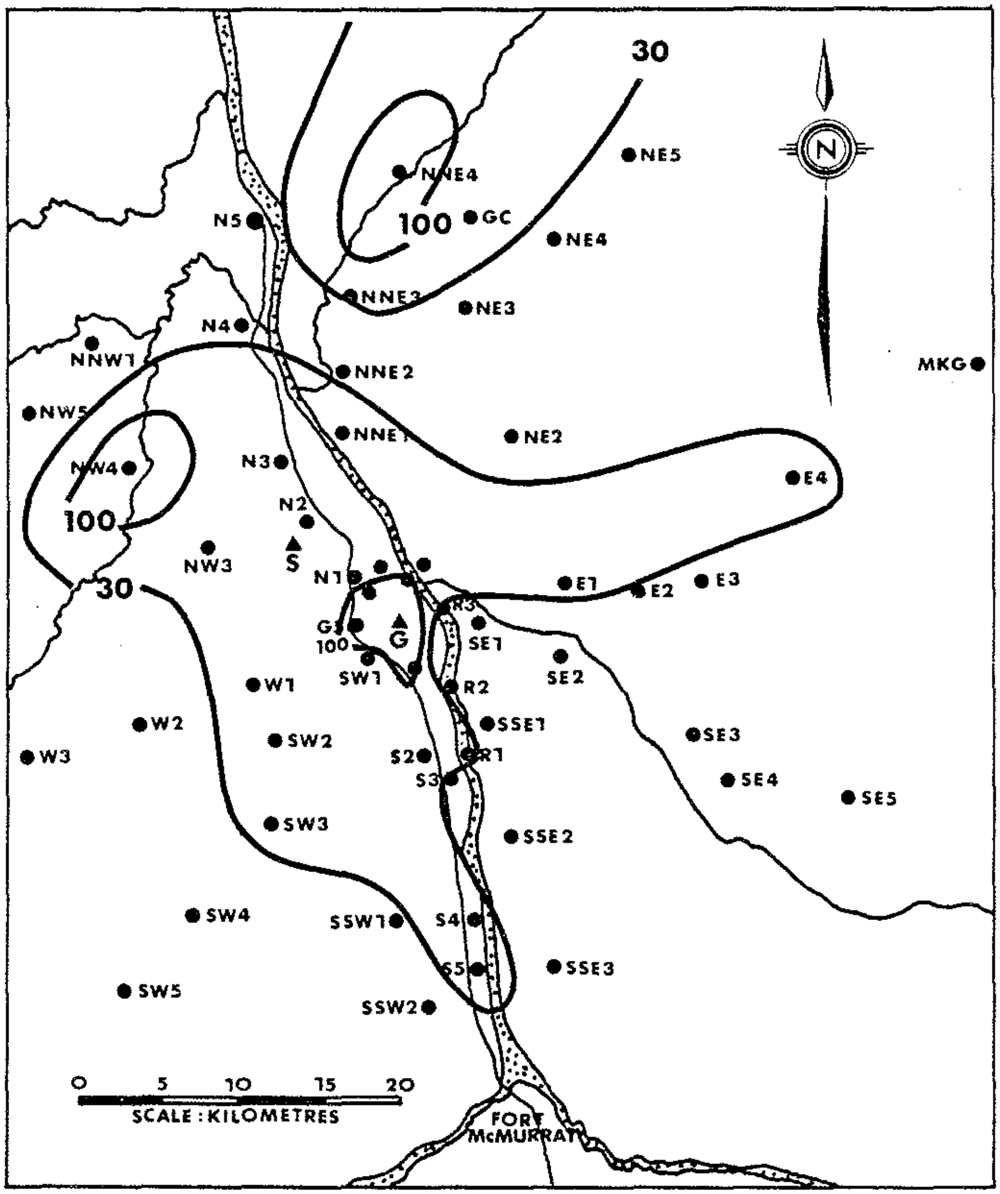

Figure 39. The spatial distribution of Ca^{++} snowpack loading (mg/m^2) on 10 January 1981.

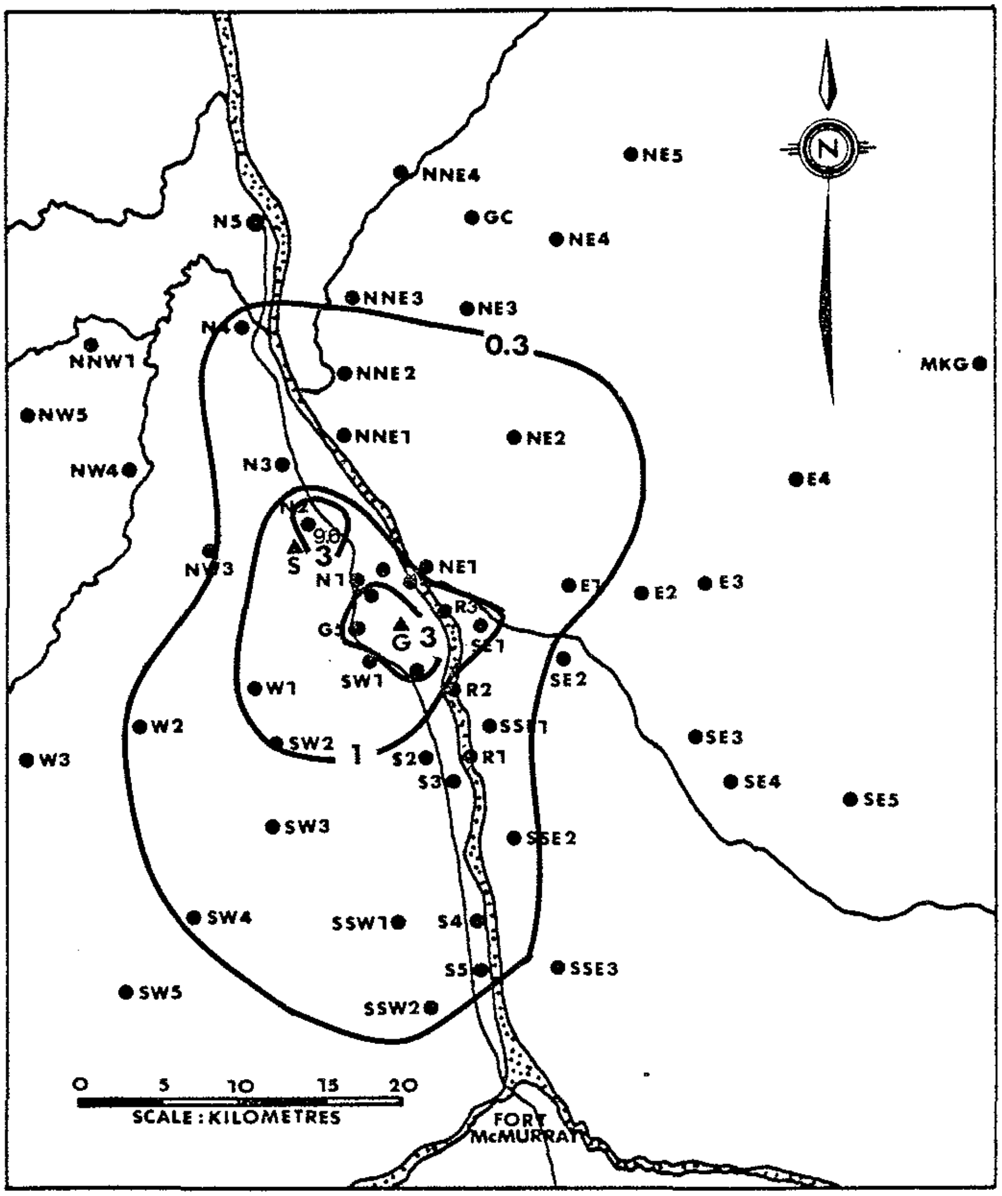

Figure 40. The spatial distribution of total insoluble metal loading (g/m^2) on 10 January 1981.

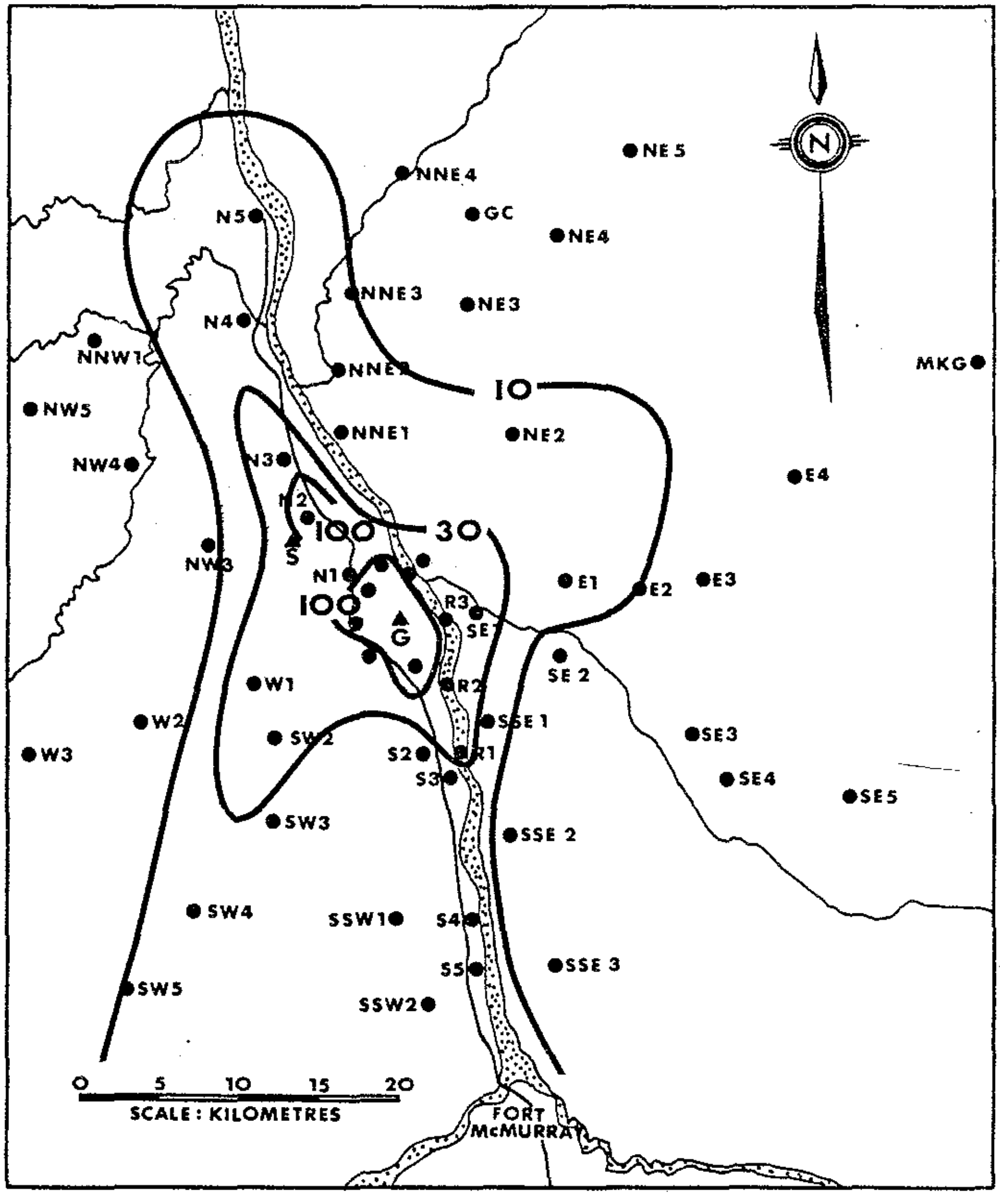

Figure 41. The spatial distribution of snowpack loading (mg/m^2) of insoluble aluminum in the study area on 10 January 1981.

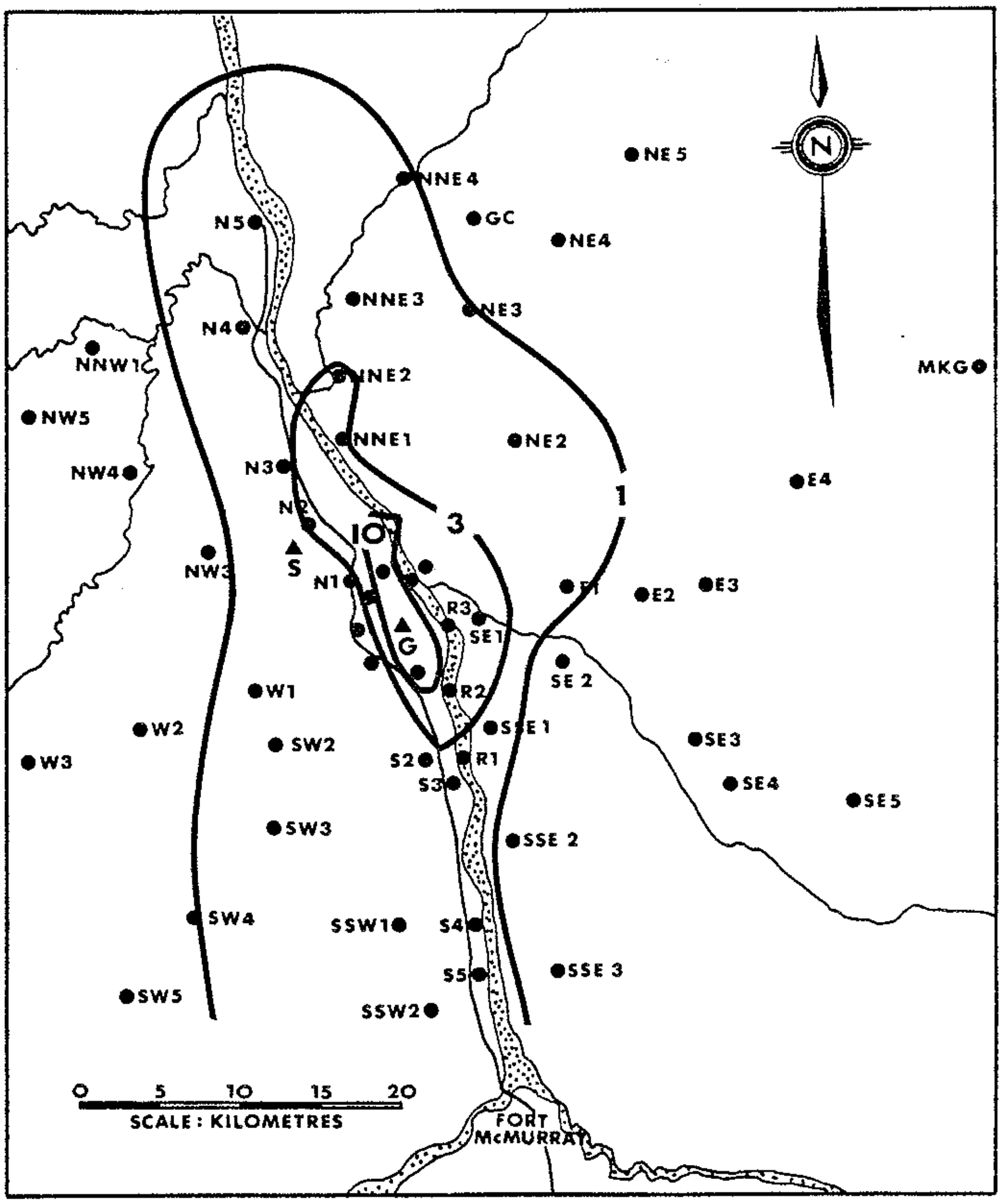

Figure 42. The spatial distribution of snowpack loading (mg/m^2) of insoluble vanadium in the study area on 10 January 1981.

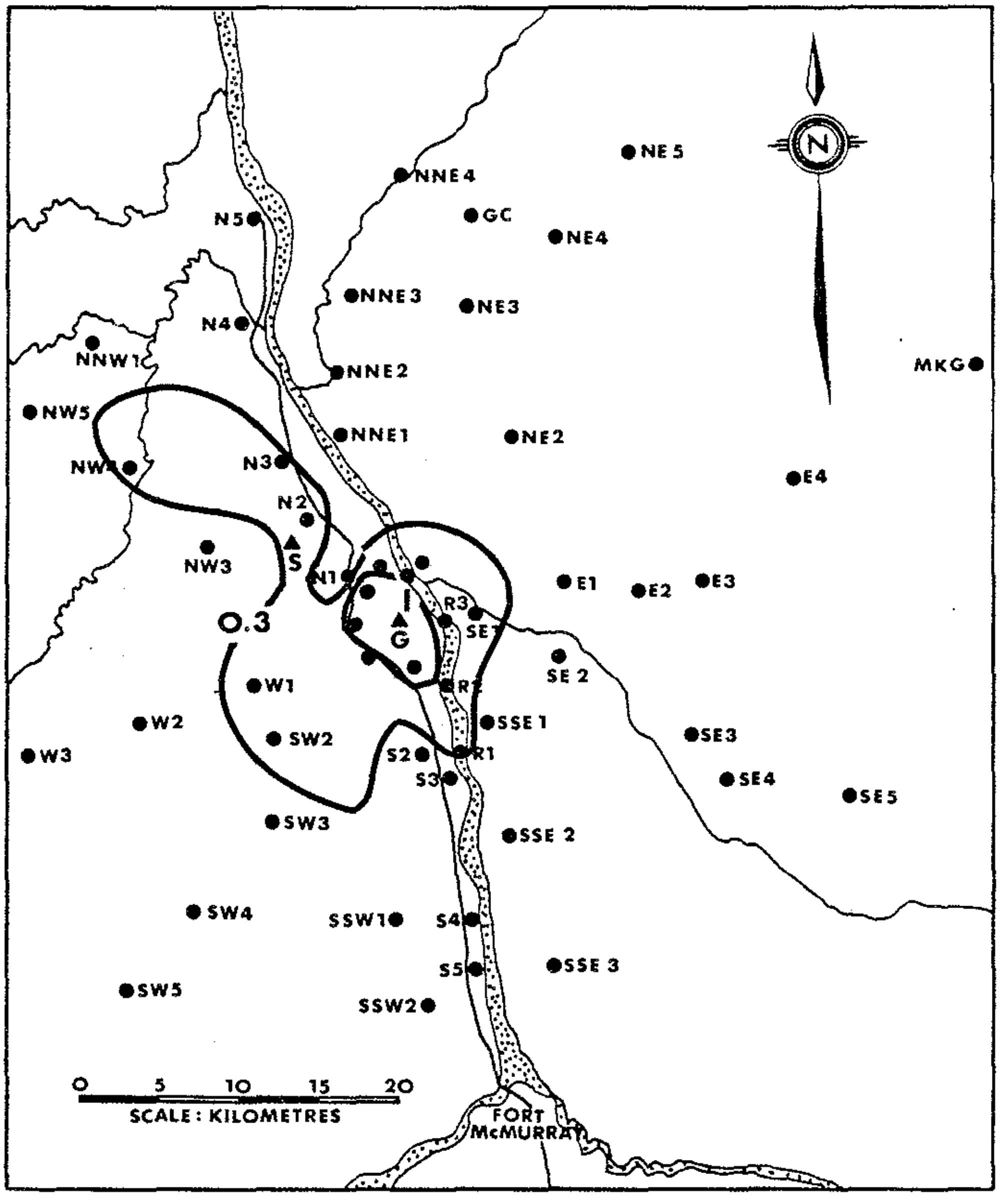

Figure 43. The spatial distribution of snowpack loading (mg/m^2) of insoluble manganese in the study area on 10 January 1981.

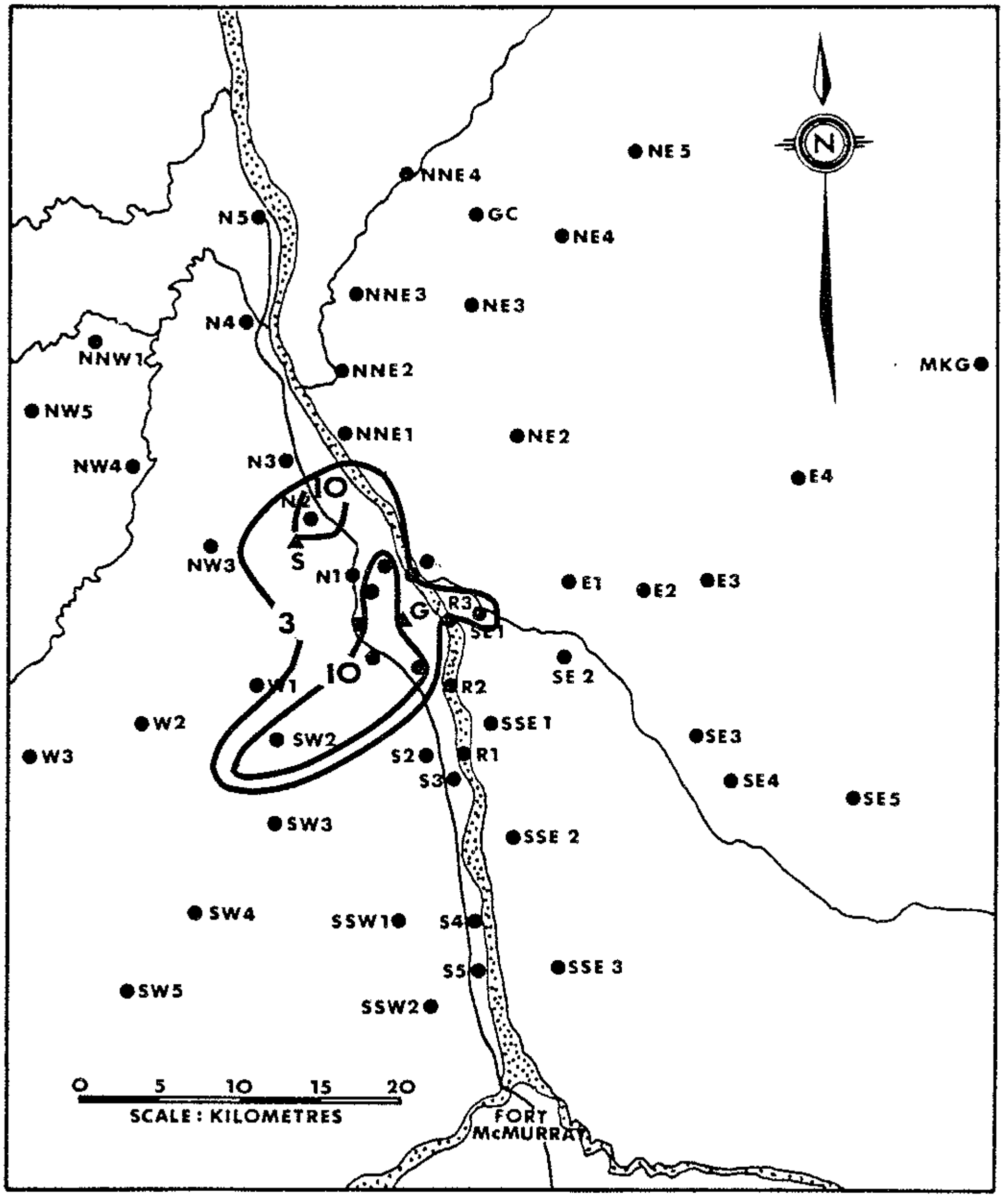

Figure 44. The spatial distribution of snowpack loading (mg/m^2) of insoluble titanium in the study area on 10 January 1981.

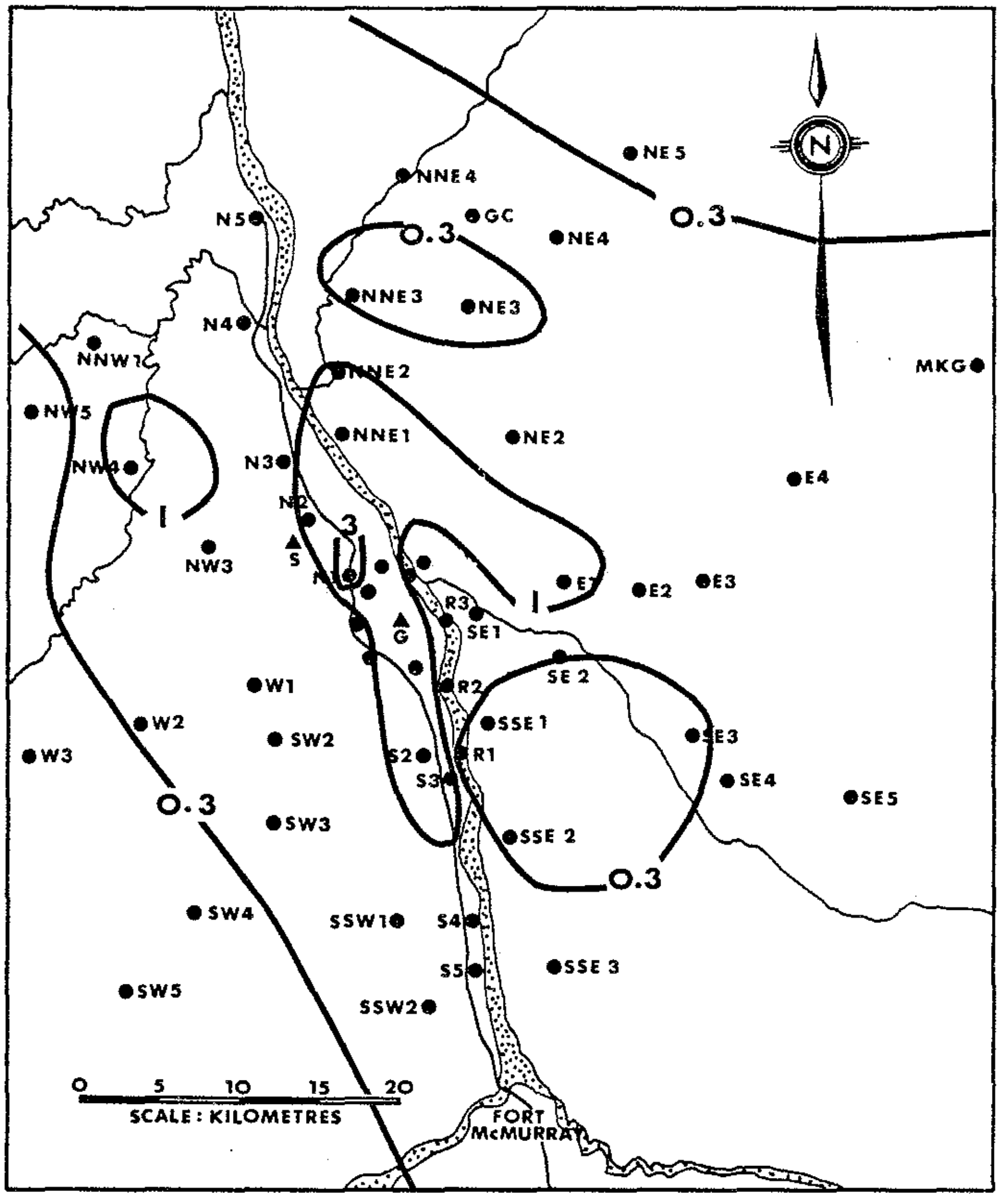

Figure 45. The spatial distribution of snowpack loading (mg/m2) of soluble aluminum in the study area on 10 January 1981.

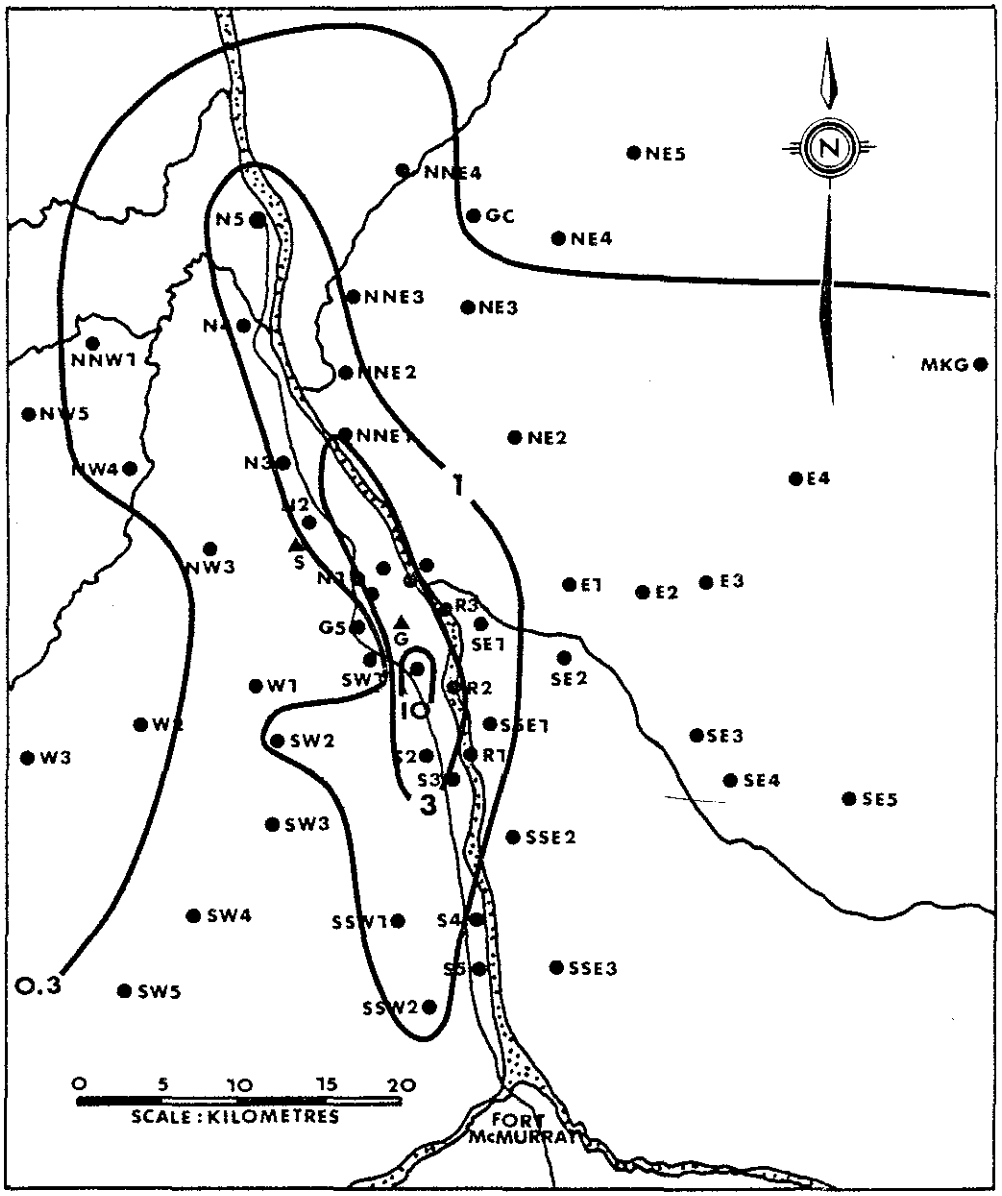

Figure 46. The spatial distribution of snowpack loading (mg/m^2) of soluble vanadium in the study area on 10 January 1981.

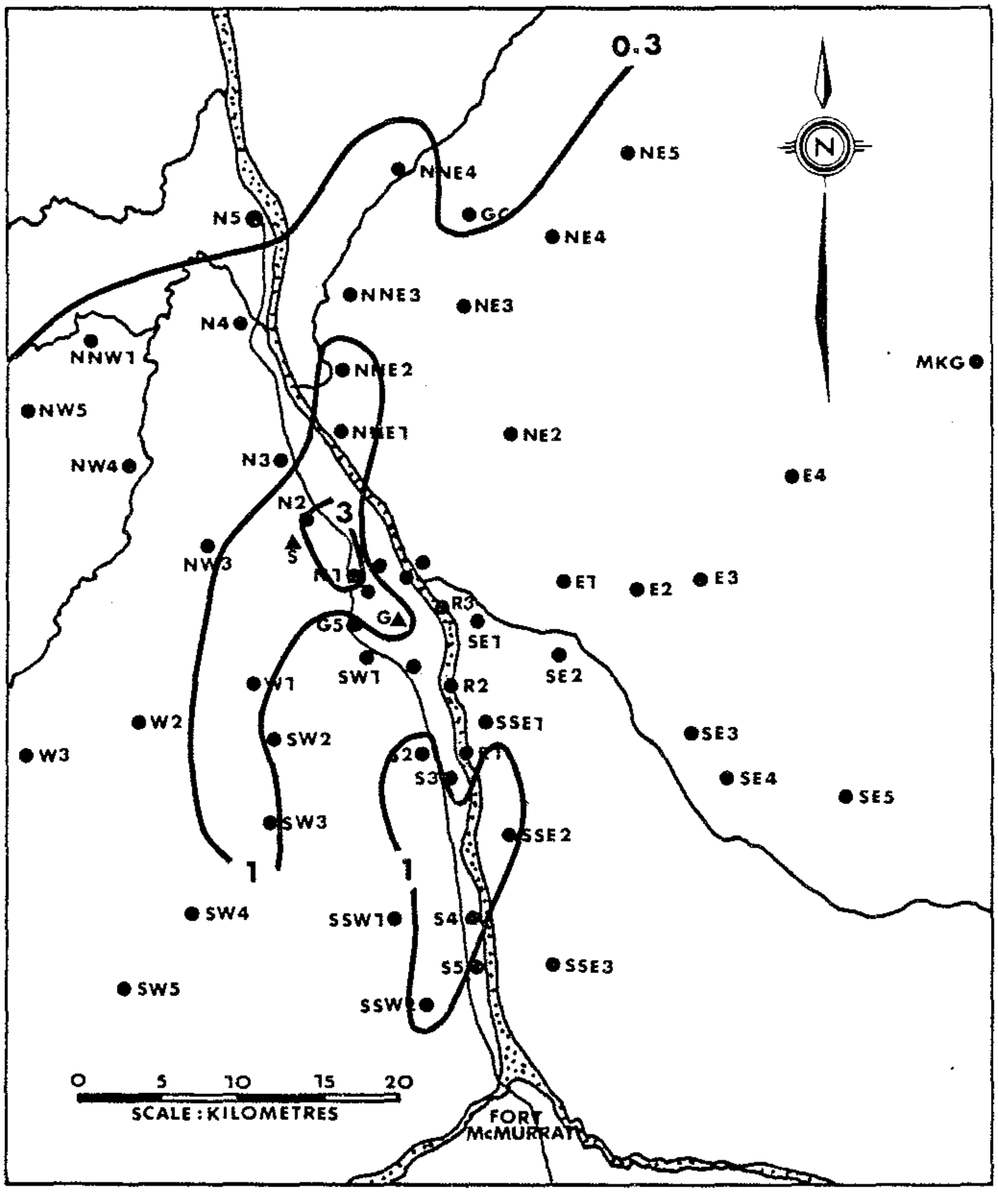

Figure 47. The spatial distribution of snowpack loading (mg/m^2) of soluble iron in the study area on 10 January 1981.

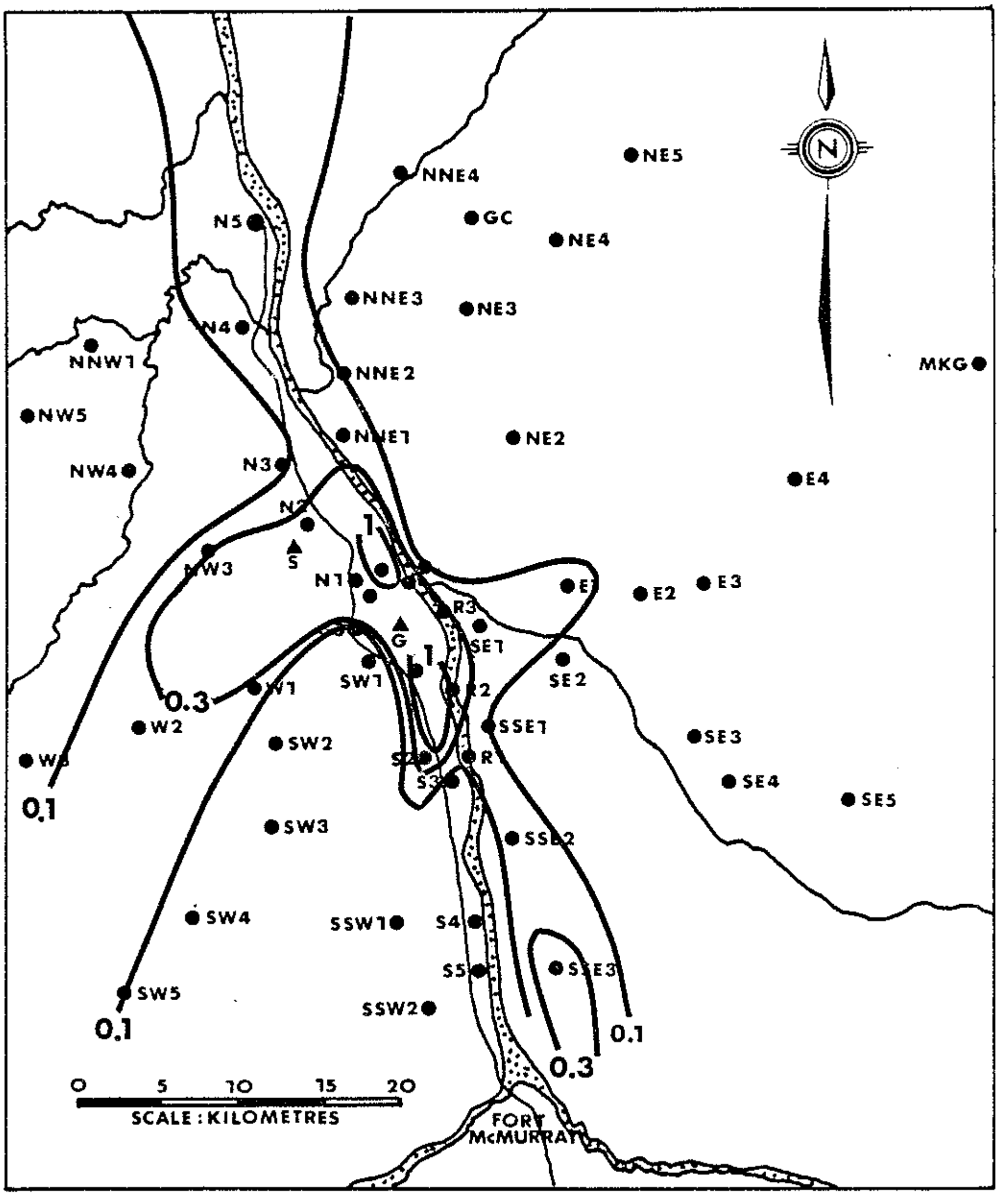

Figure 48. The spatial distribution of snowpack loading (mg/m^2) of soluble nickel in the study area on 10 January 1981.

7.2 THE SPATIAL DISTRIBUTION OF THE MEASURED SNOWPACK LOADINGS ON 20 FEBRUARY 1981

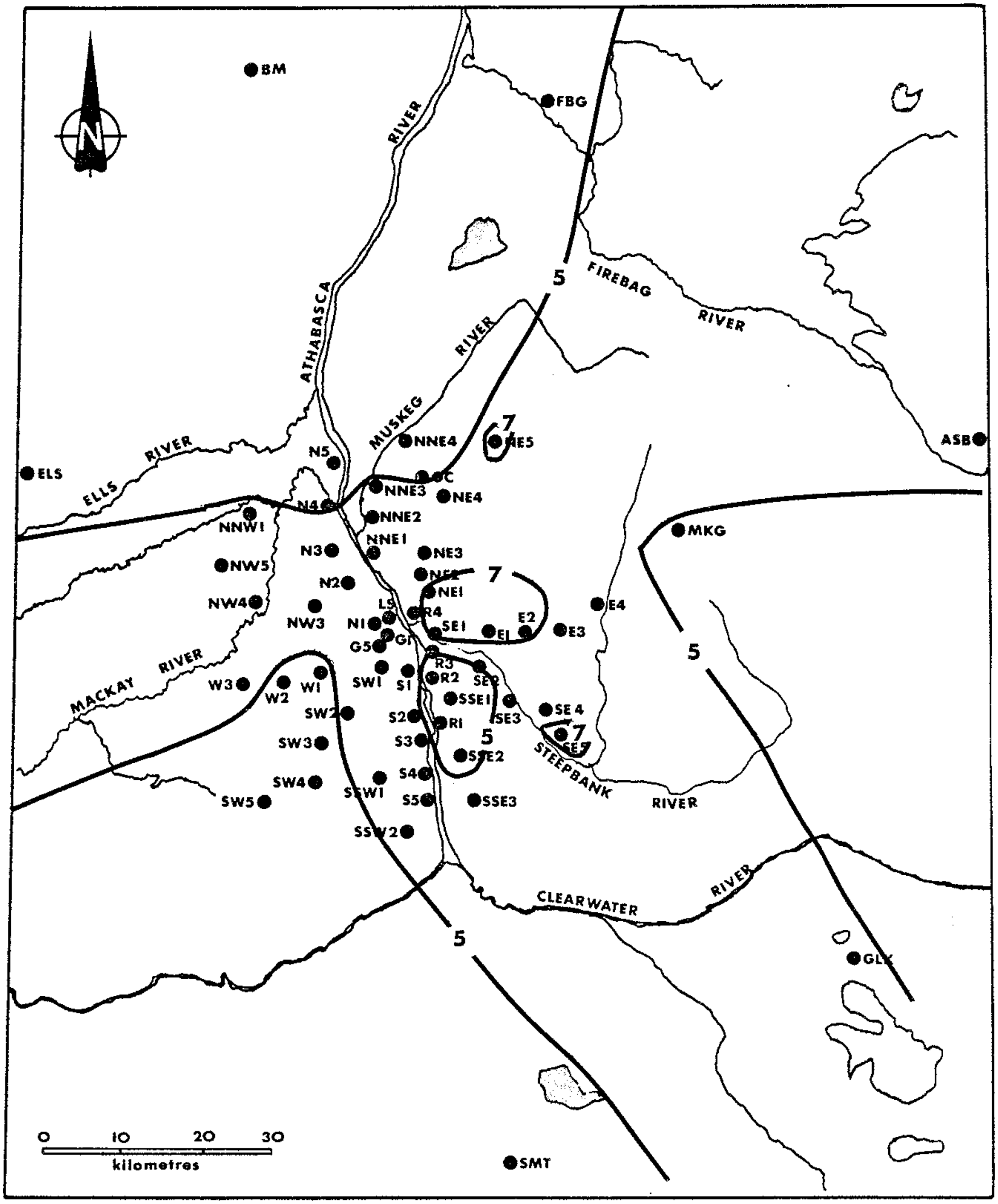

Figure 49. Spatial distribution of snowpack pH on 20 February 1981.

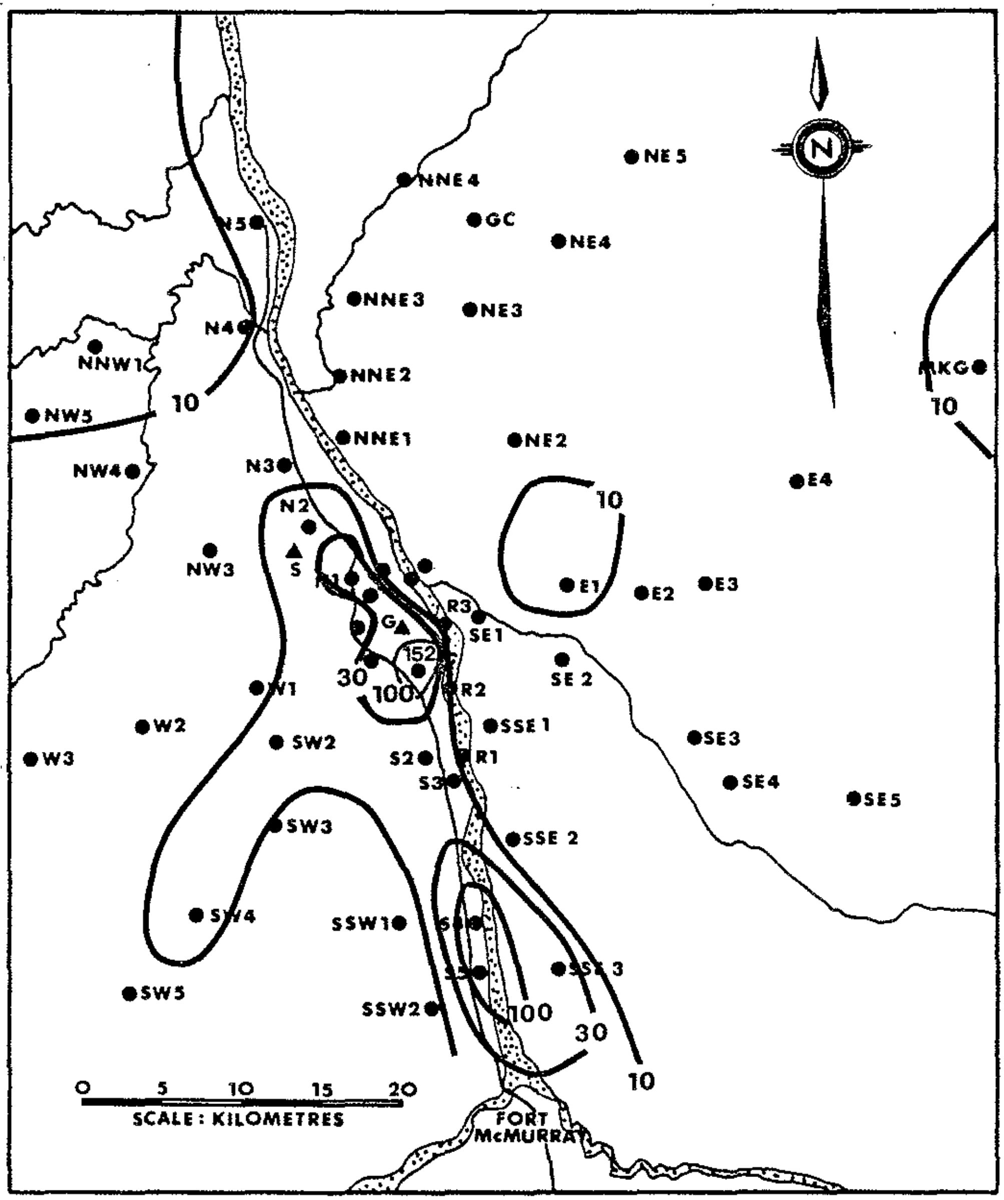

Figure 50. Spatial distribution of Cl^- snowpack loading (mg/m^2) on 20 February 1981.

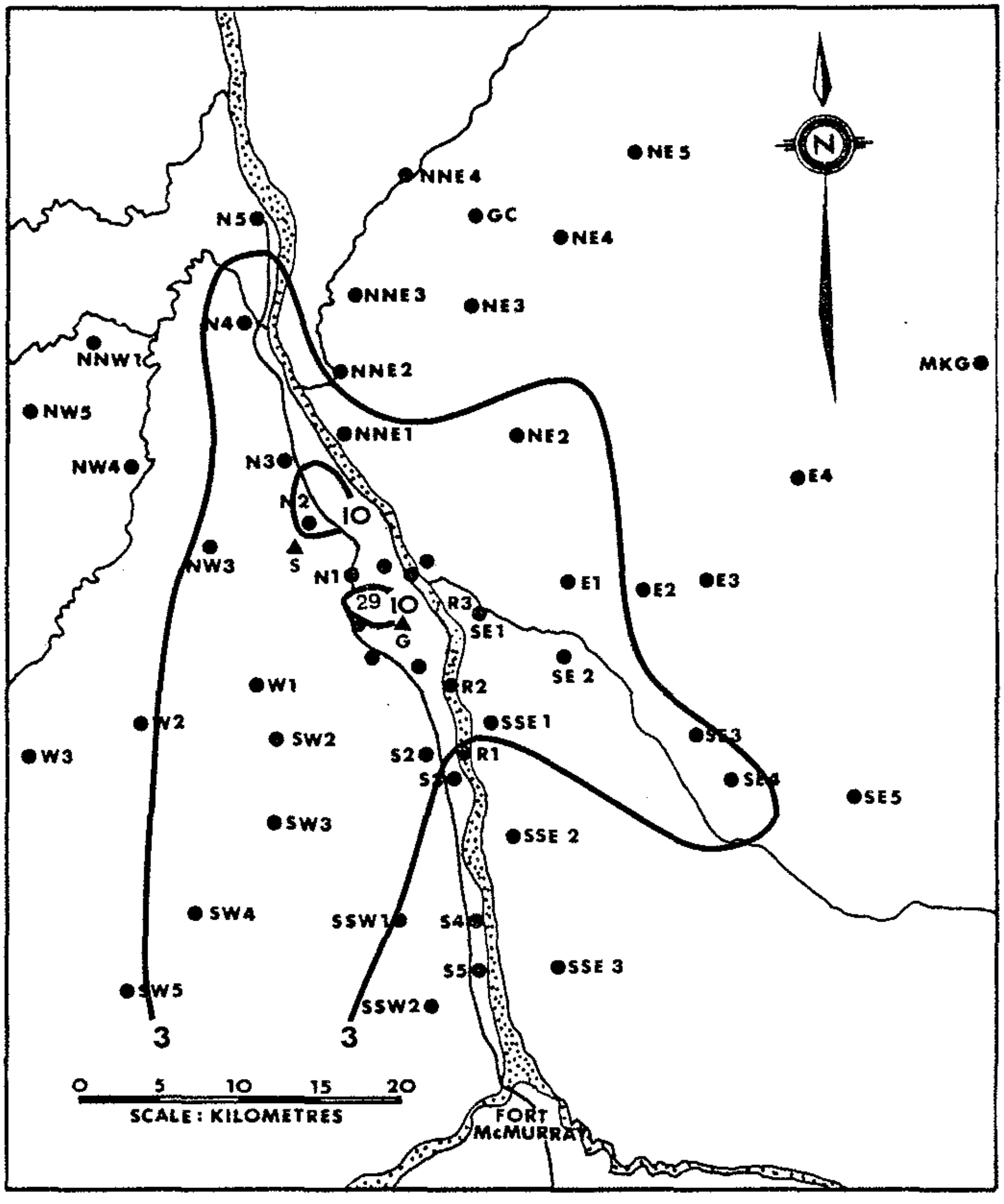

Figure 51. The spatial distribution of NH_4^+-N snowpack loading (mg/m^2) on 20 February 1981.

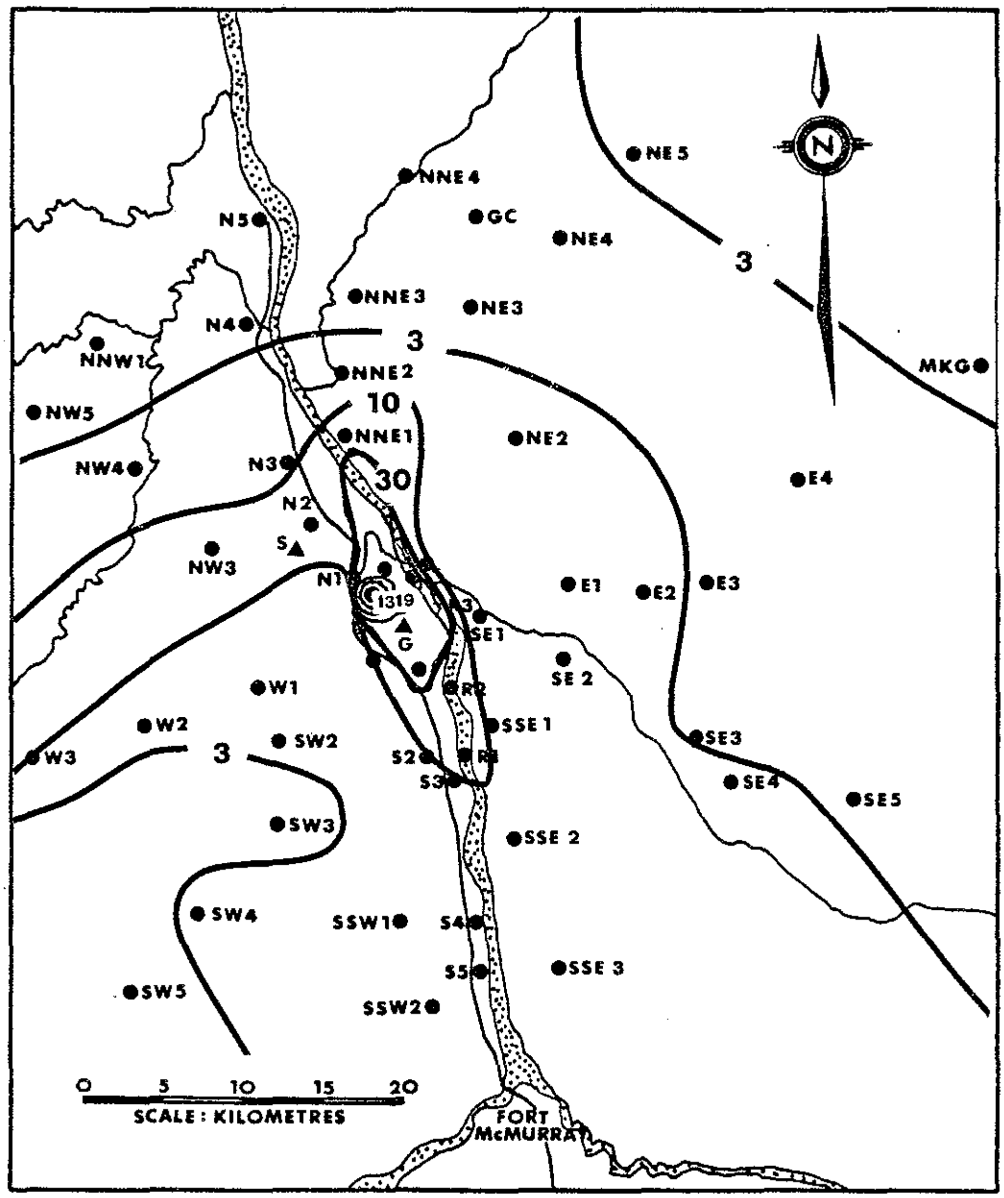

Figure 52. The spatial distribution of K^+ snowpack loading (mg/m^2) on 20 February 1981.

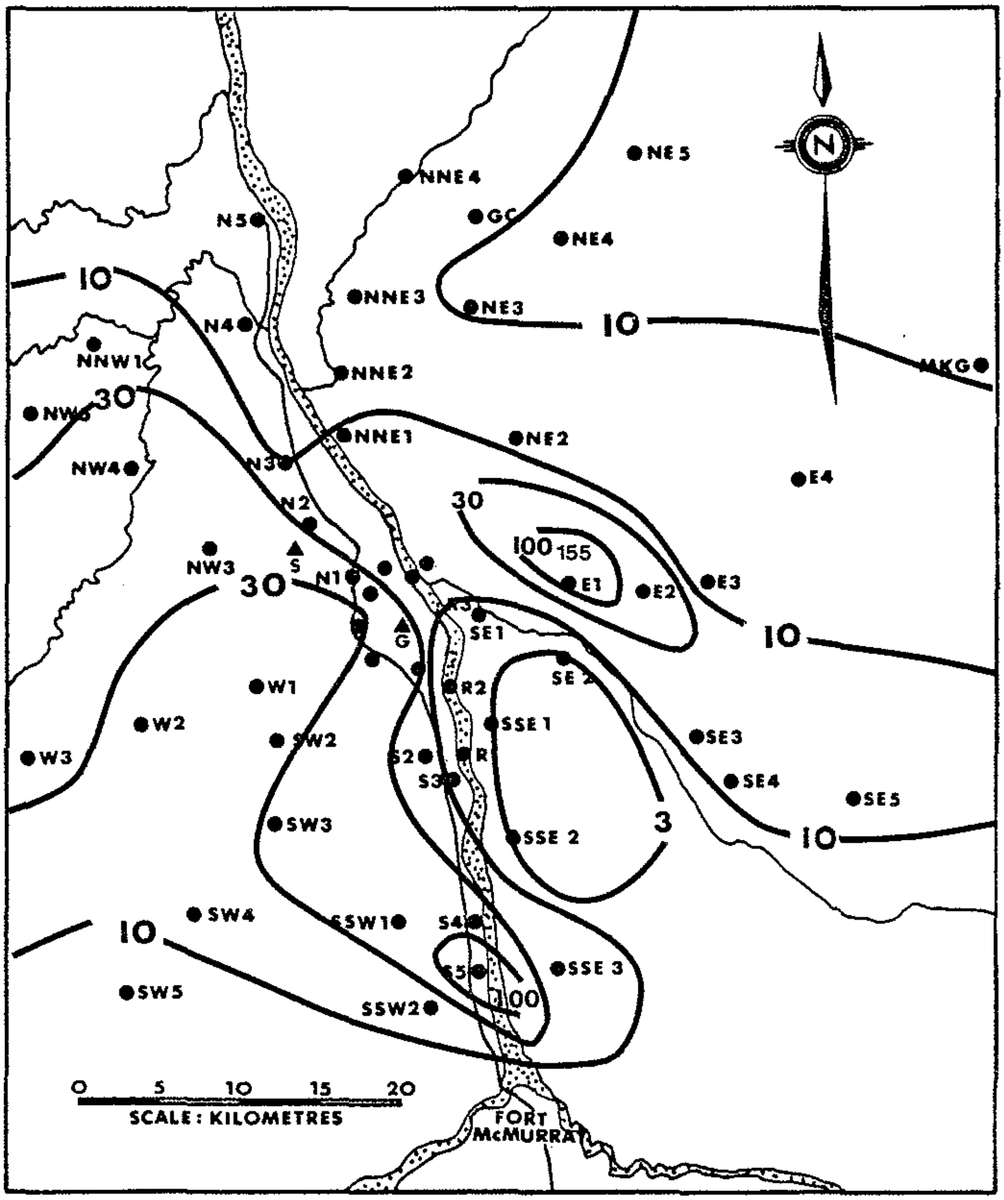

Figure 53. The spatial distribution of Na^+ snowpack loading (mg/m^2) on 20 February 1981.

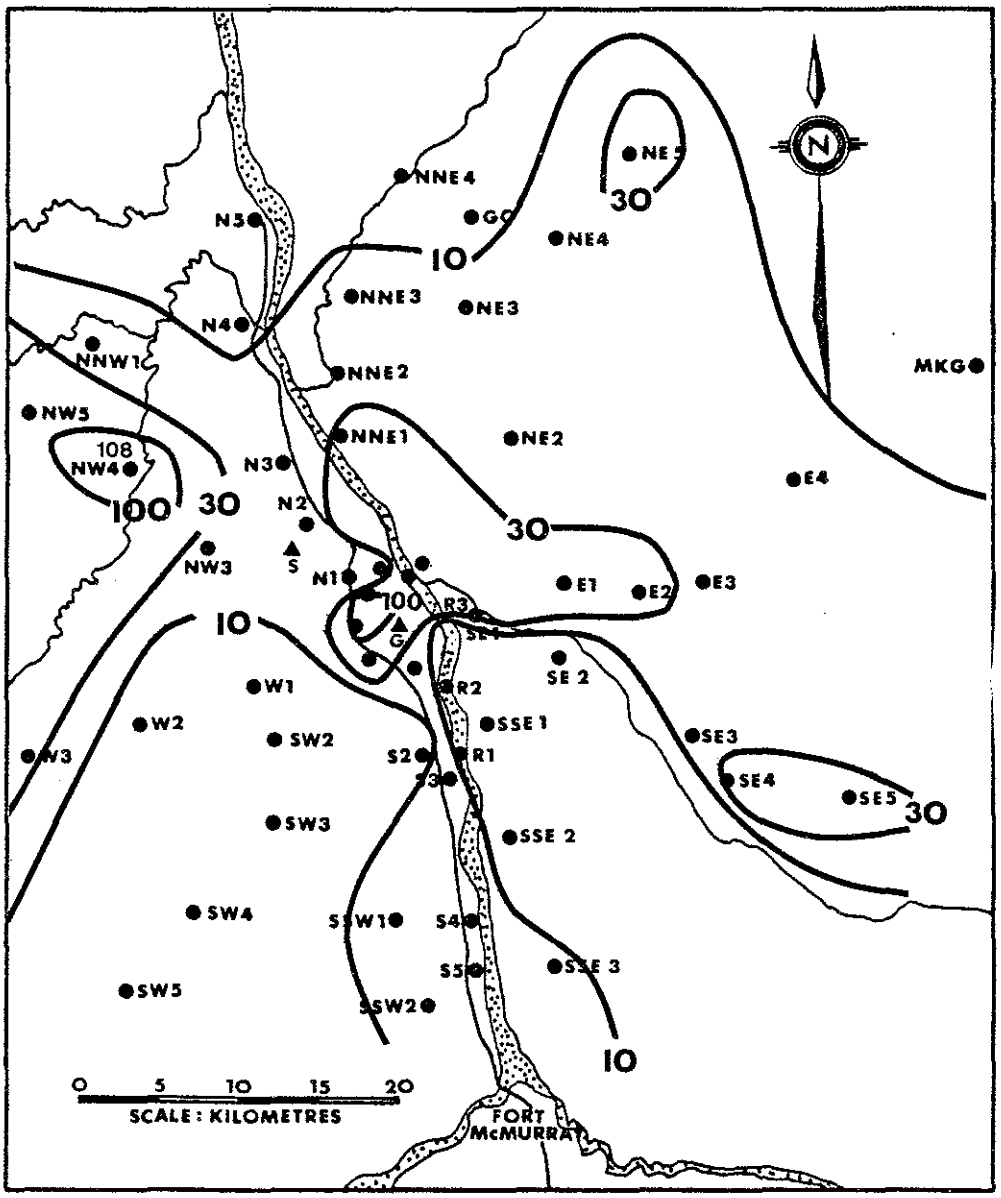

Figure 54. The spatial distribution of Mg^{++} snowpack loading (mg/m^2) on 20 February 1981.

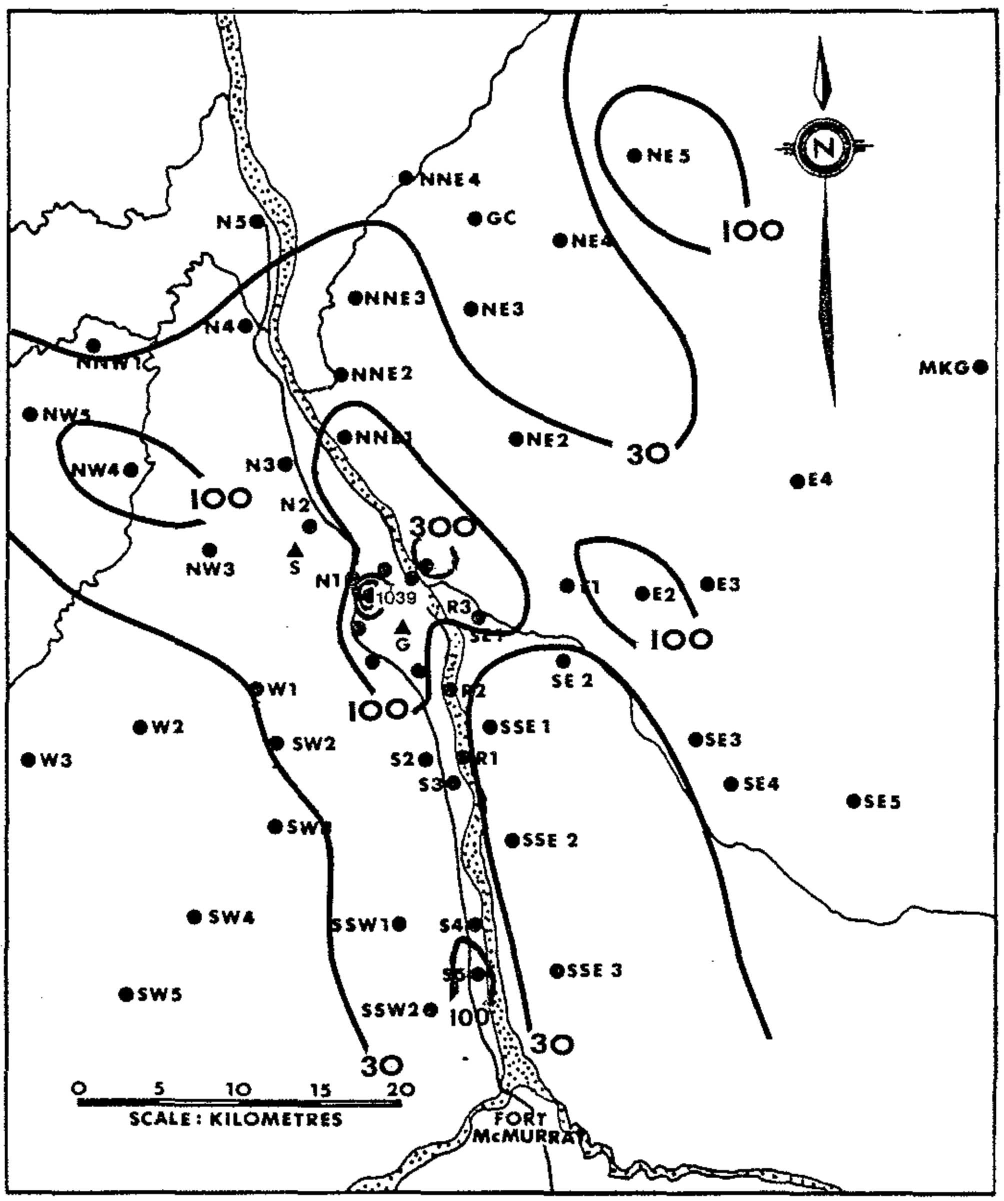

Figure 55. The spatial distribution of Ca^{++} snowpack loading (mg/m^2) on 20 February 1981.

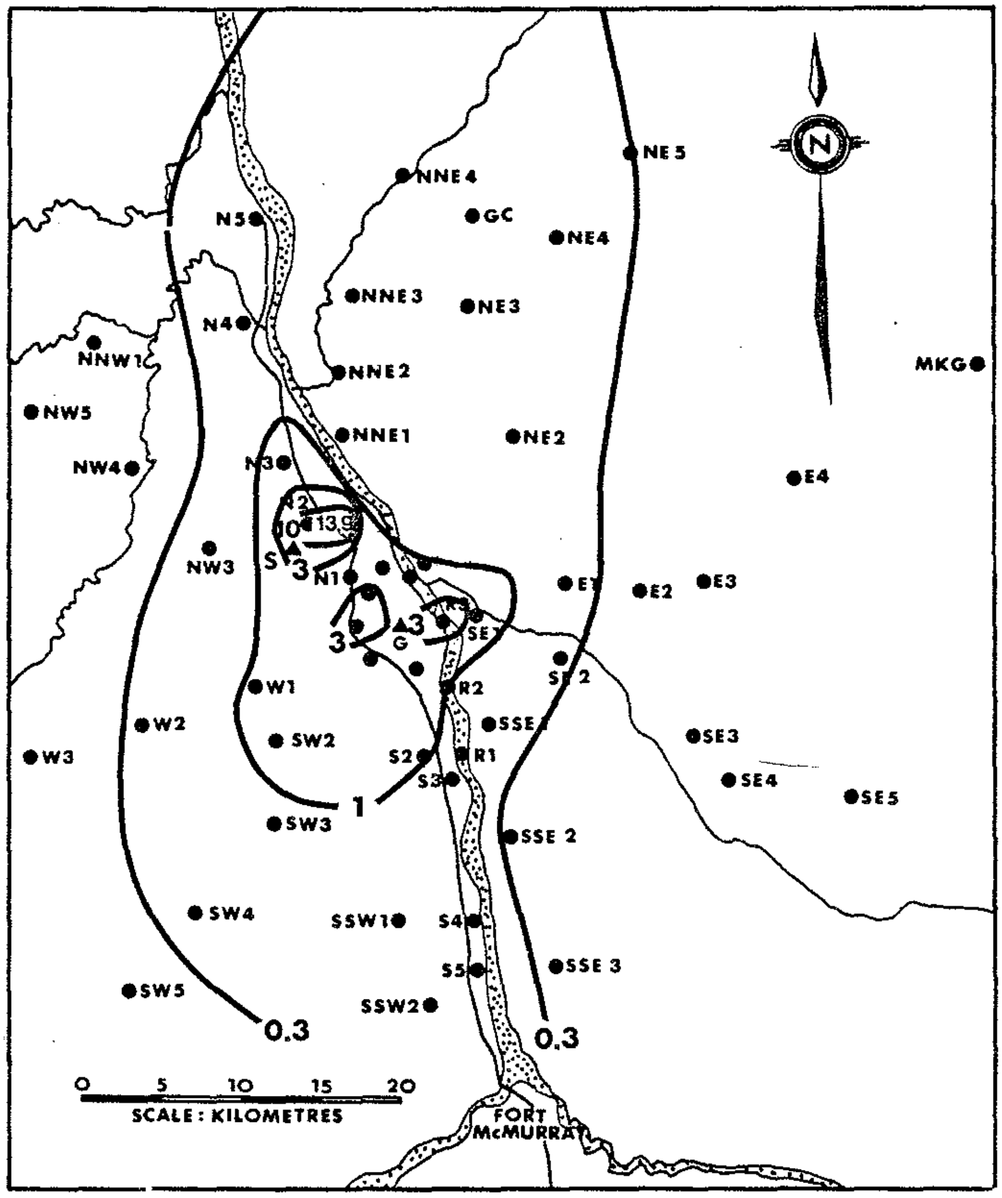

Figure 56. The spatial distribution of total insoluble metal loading (g/m2) on 20 February 1981.

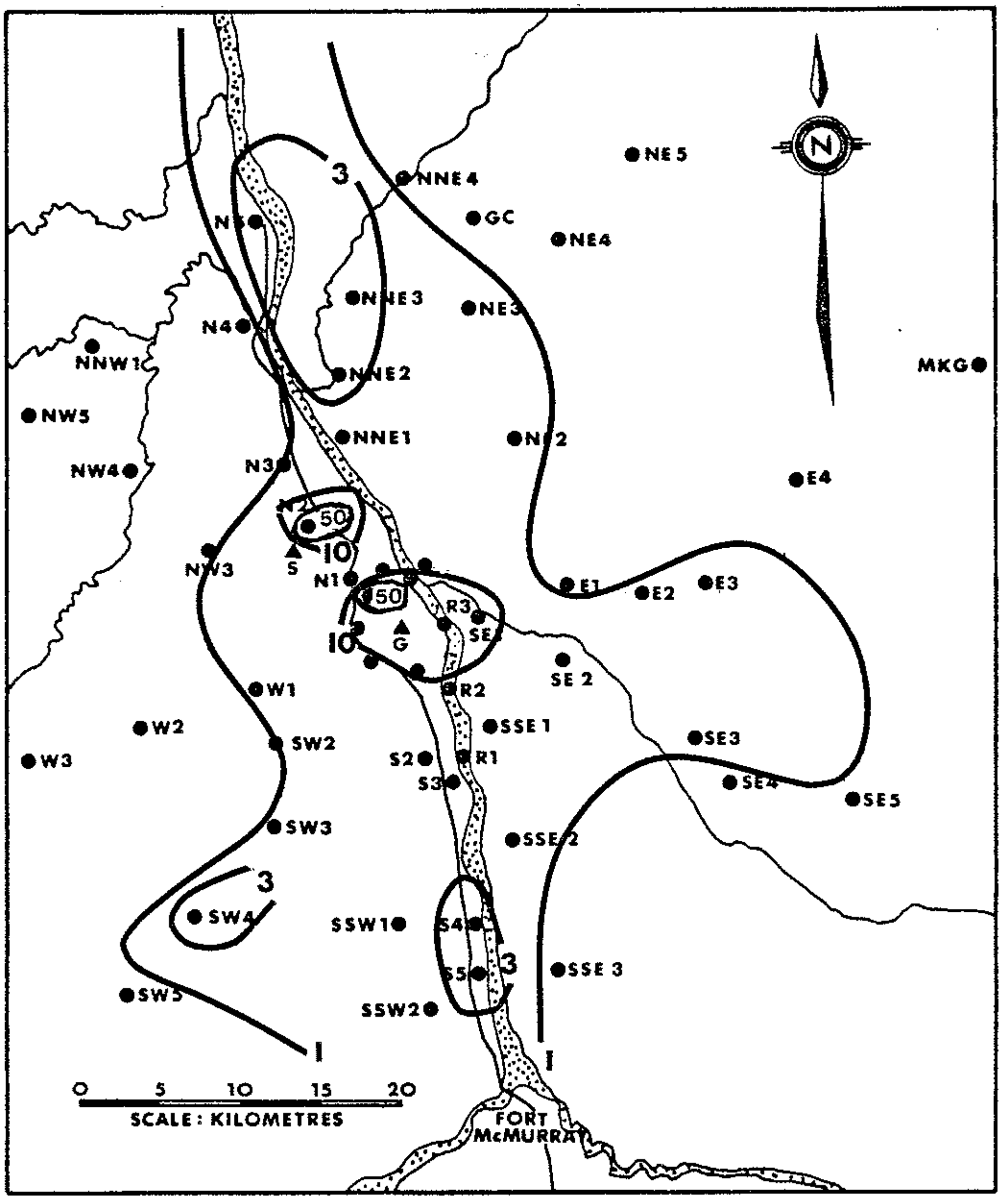

Figure 57. The spatial distribution of insoluble titanium loading (mg/m^2) on 20 February 1981.

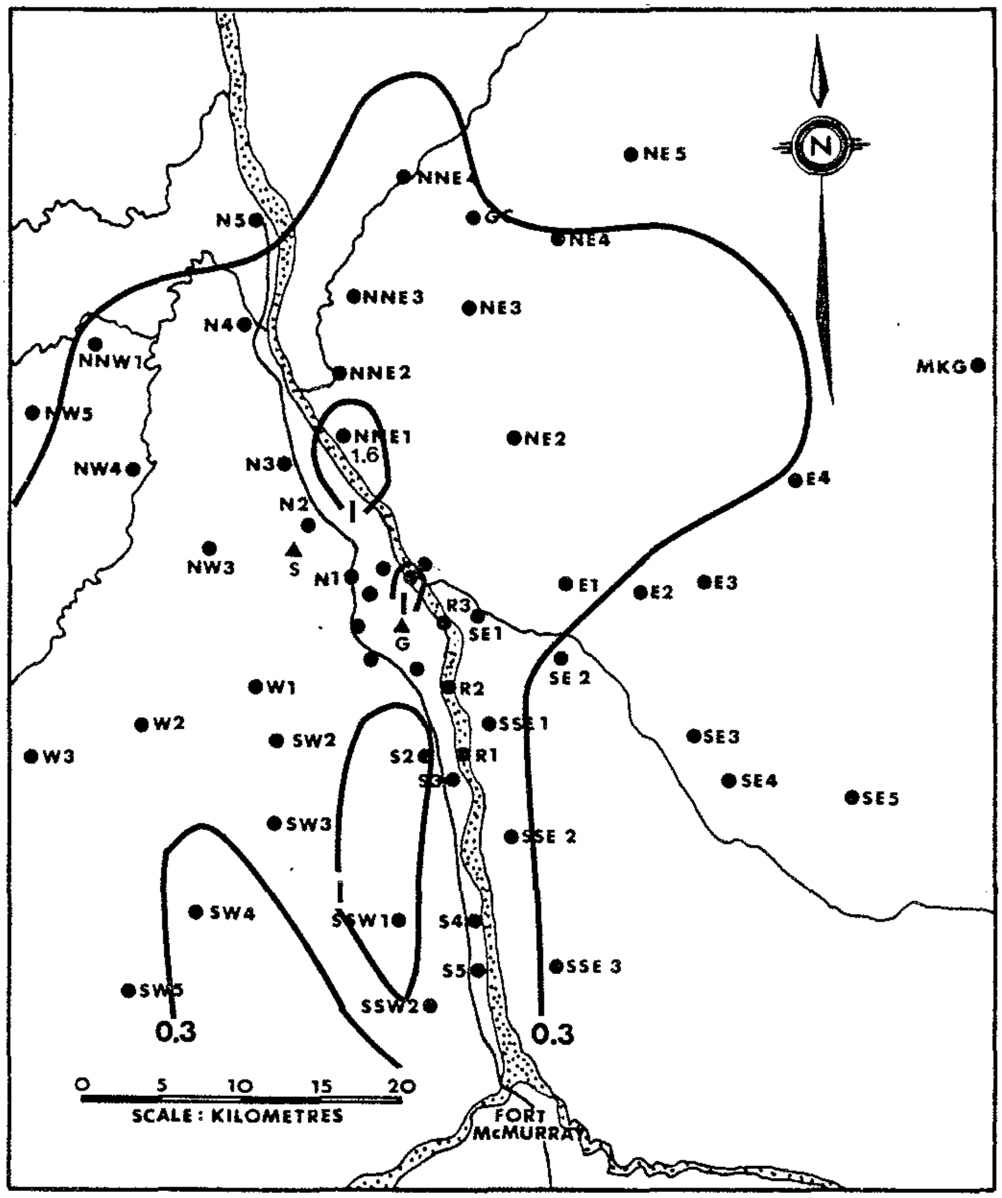

Figure 58. The spatial distribution of soluble aluminum loading (mg/m2) on 20 February 1981.

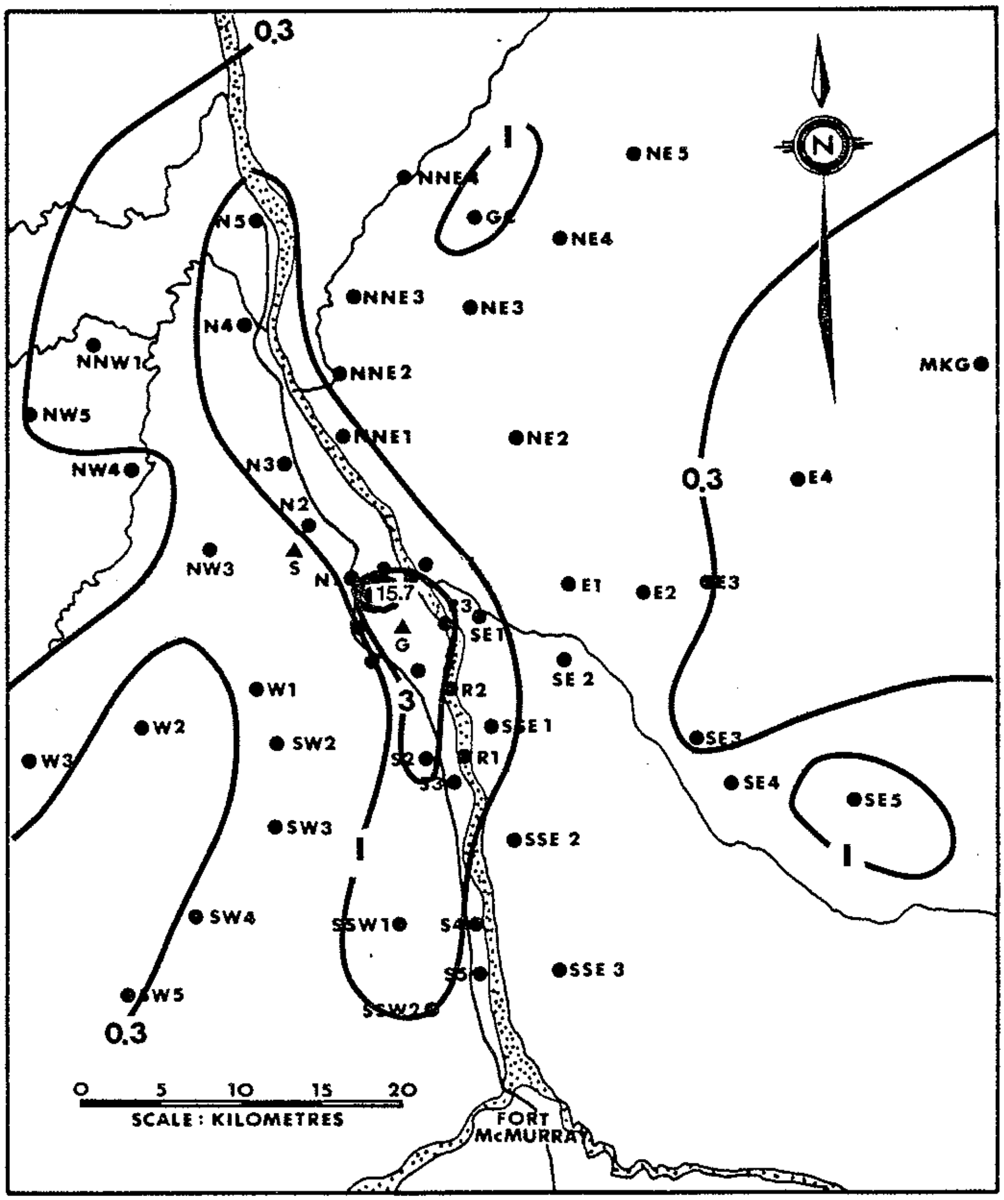

Figure 59. The spatial distribution of soluble vanadium loading (mg/m^2) on 20 February 1981.

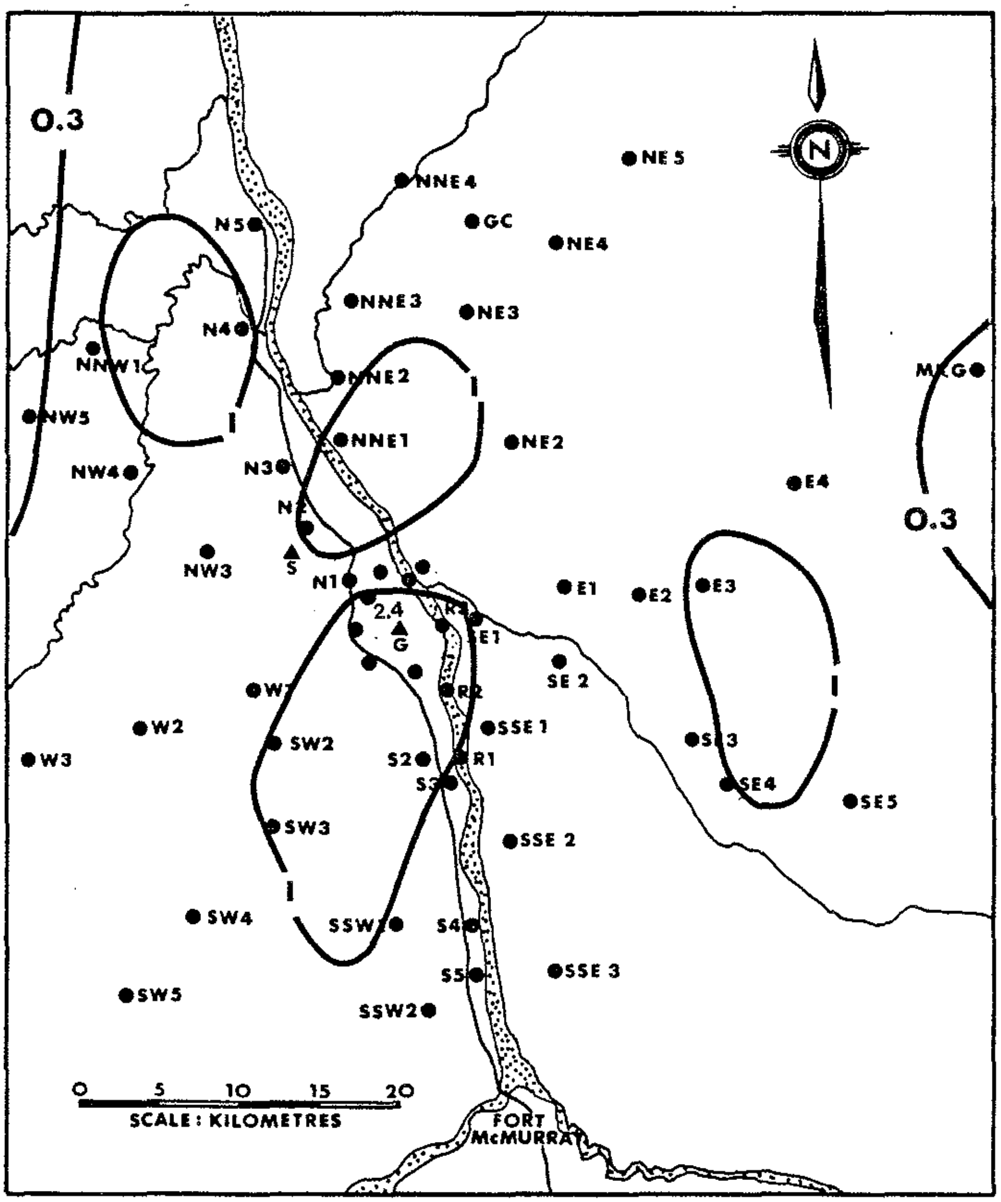

Figure 60. The spatial distribution of soluble iron loading (mg/m2) on 20 February 1981.

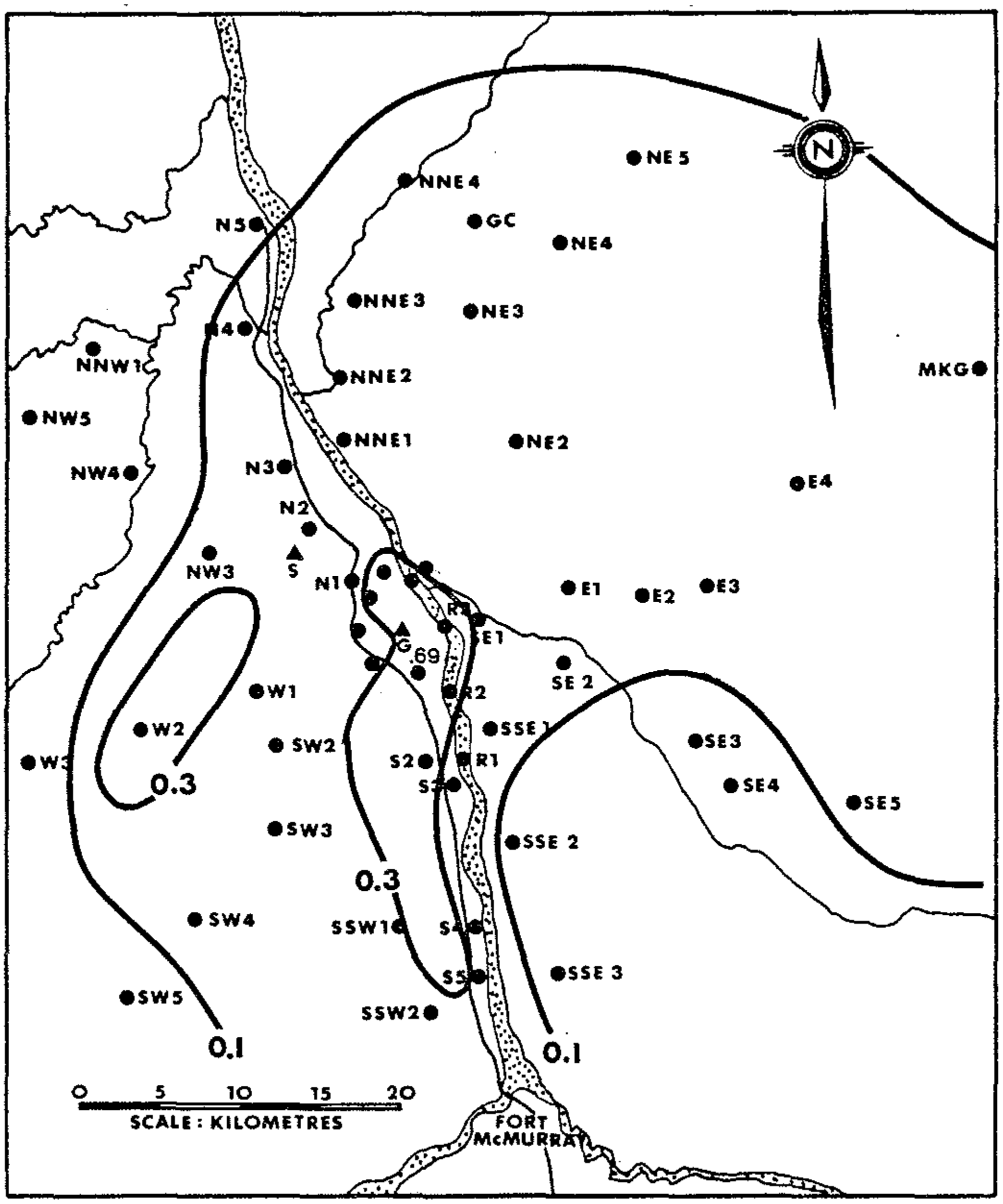

Figure 61. The spatial distribution of soluble nickel loading (mg/m^2) on 20 February 1981.

7.3 THE SPATIAL DISTRIBUTION OF THE DIFFERENCE IN CONTAMINANT LOADINGS BETWEEN THE JANUARY 1981 AND 1978 SNOWPACK SURVEYS

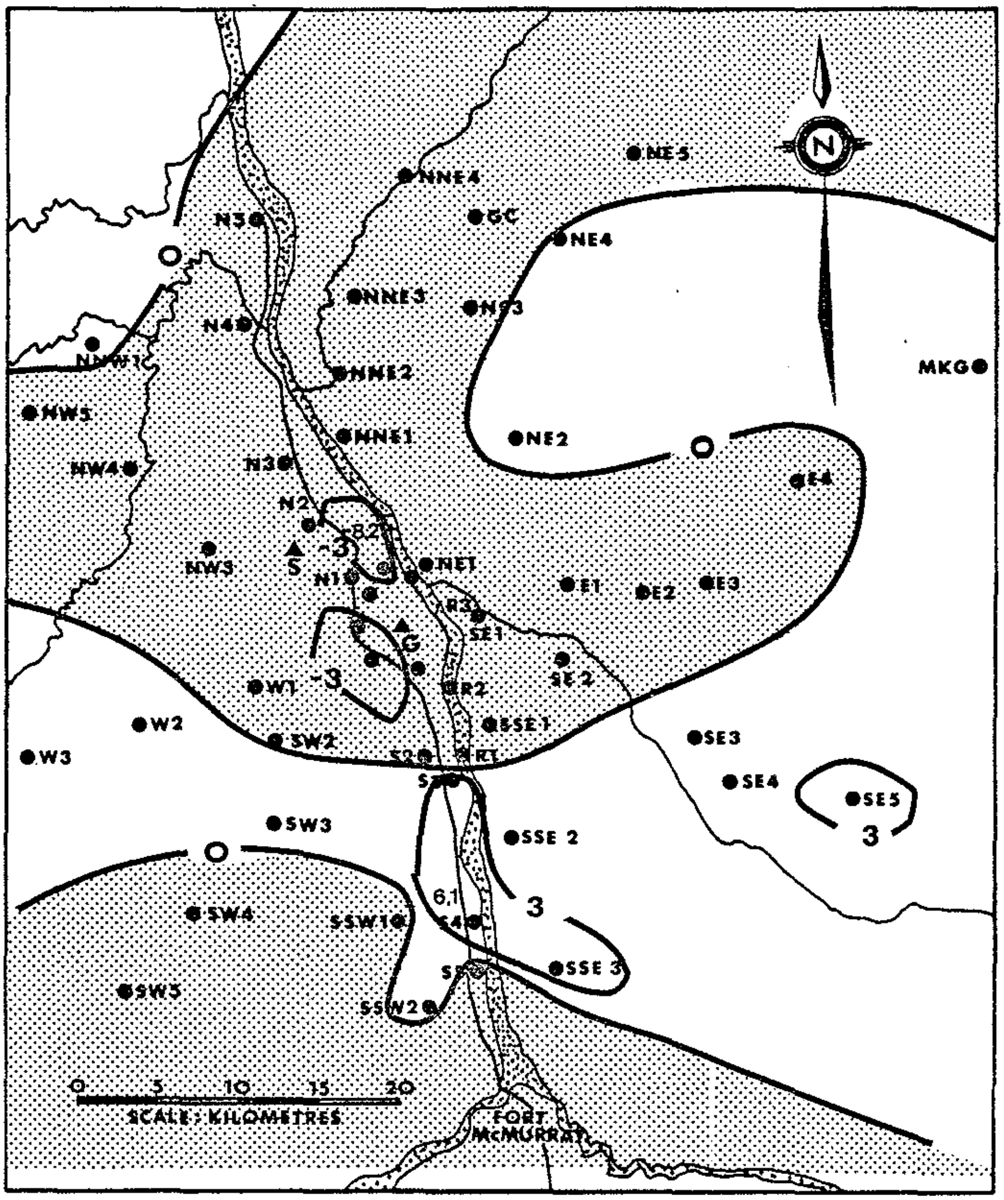

Figure 62. Difference in NO_3^--N loadings (mg/m^2) between the January 1978 and 1981 snowpack surveys. Shading indicates areas of decreased loading.

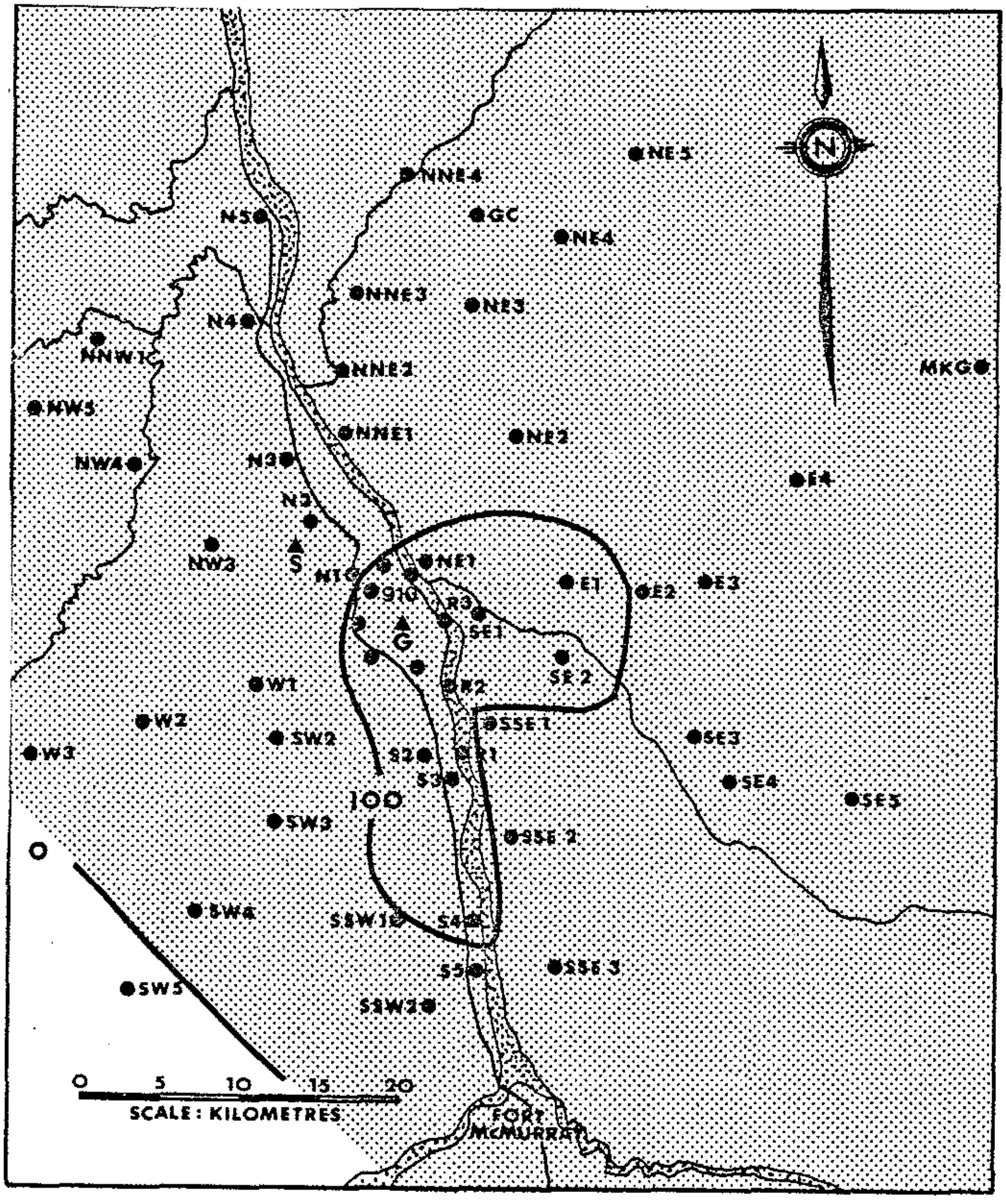

Figure 63. Difference in Al loadings (mg/m2) between the January 1978 and 1981 snowpack surveys. Shading indicates areas of decreased loading.

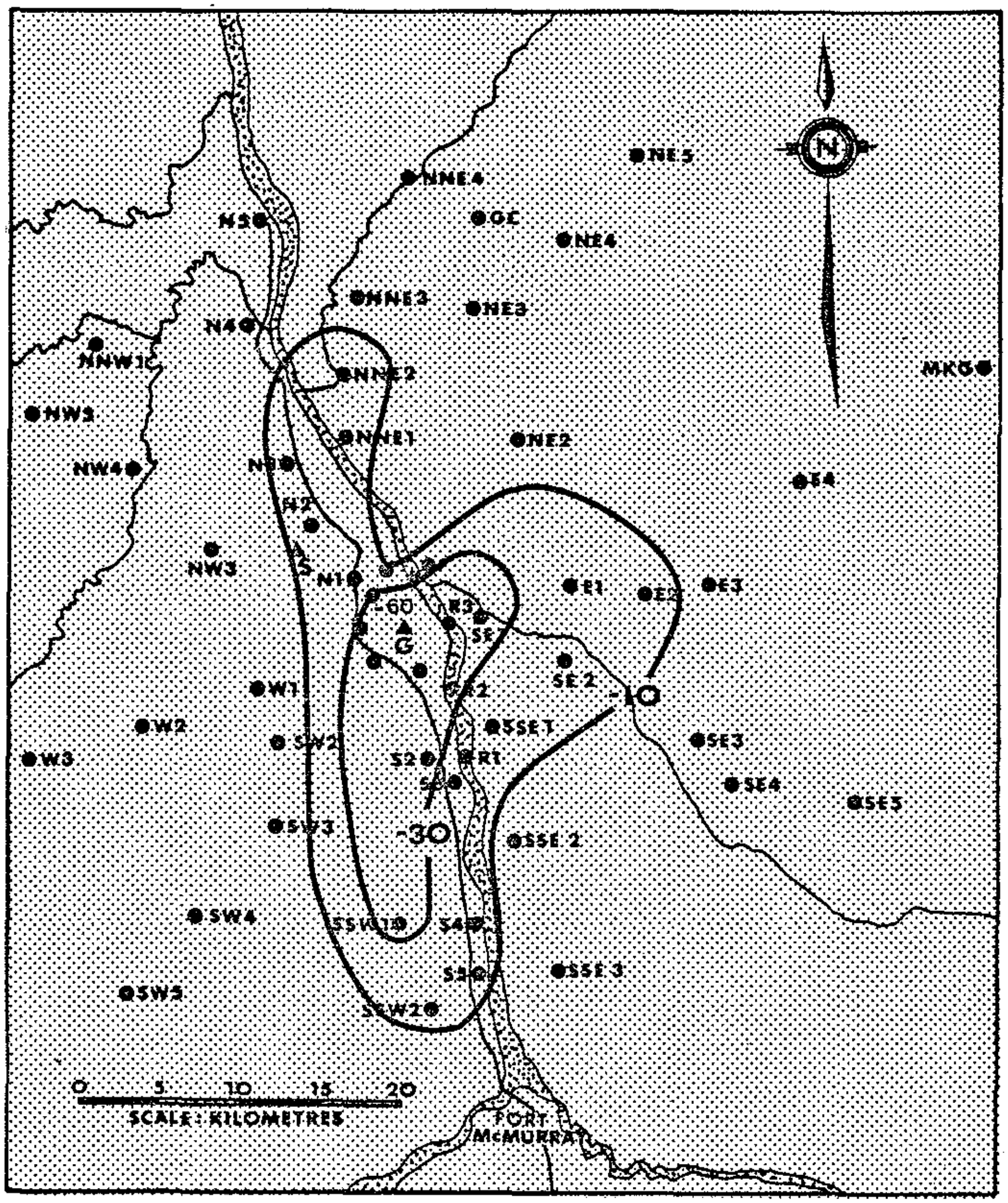

Figure 64. Difference in Vanadium loadings (mg/m^2) between the January 1981 and 1978 snowpack surveys. Shading indicates areas of decreased loading.

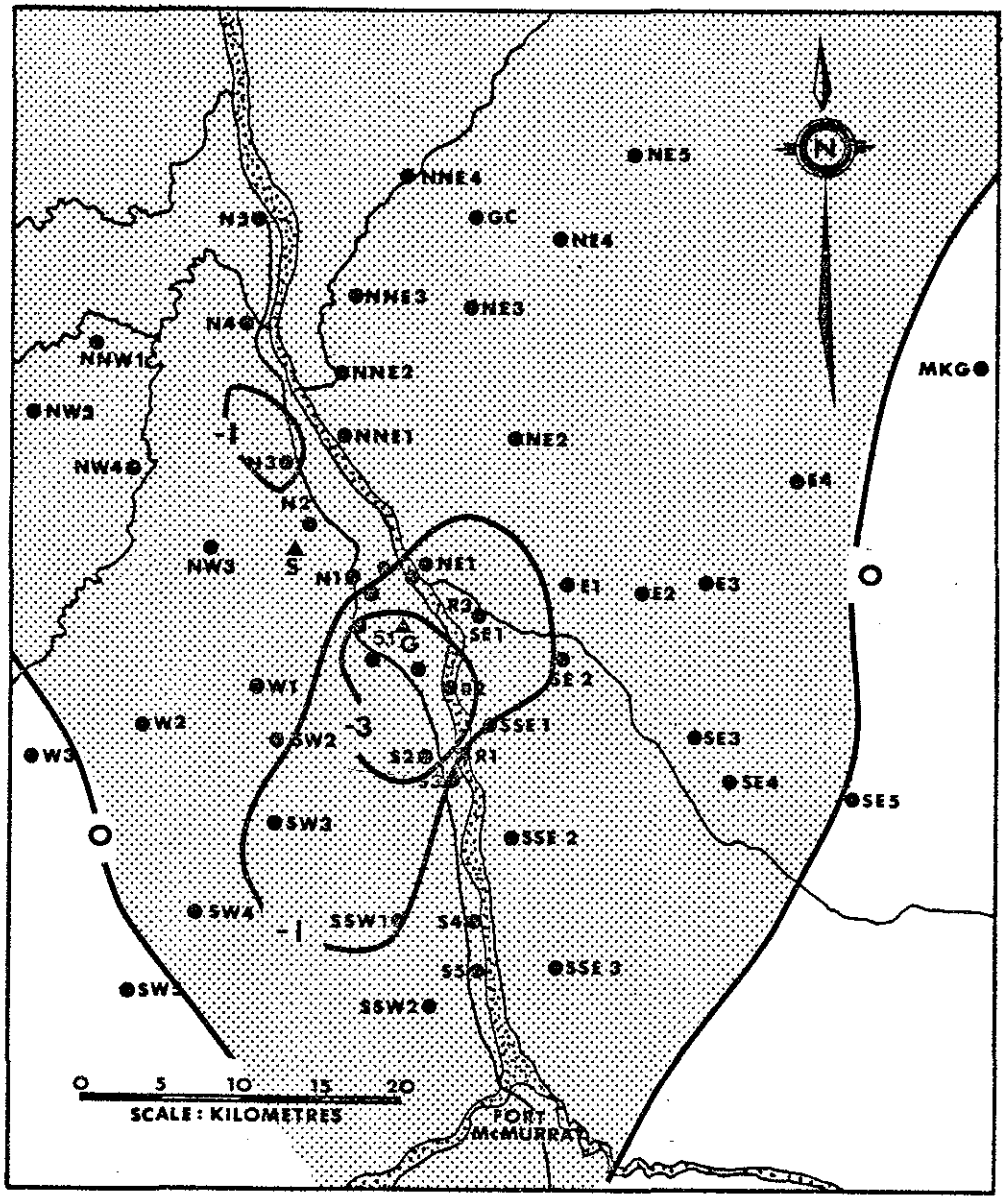

Figure 65. Difference in Manganese loadings (mg/m^2) between January 1978 and 1981 snowpack surveys. Shading indicates areas of decreased loading.

8. LIST OF AOSERP RESEARCH REPORTS

Report	Project	Reference
1	PM	Alberta Oil Sands Environmental Research Program. 1976. First annual report, 1975. Alberta Oil Sands Environmental Research Program. AOSERP Report 1. 58 pp.
2	AF 4.1.1	Kristensen, J., B.S. Ott, and A.D. Sekerak. 1976. Walleye and goldeye fisheries investigations in the Peace-Athabasca Delta--1975. Prep. for the Alberta Oil Sands Environmental Research Program by LGL Ltd., Environmental Research Associates. AOSERP Report 2. 103 pp.
3	HE 1.1.1	McVey, W.W. 1976. Structure of a traditional baseline data system. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Population Research Laboratory. AOSERP Report 3. 26 + 266 pp.
4	VE 2.2	Stringer, P.W. 1976. A preliminary vegetation survey of the Alberta Oil Sands Environmental Research Program study area. Prep. for the Alberta Oil Sands Environmental Research Program by Intraverda Plant Systems Ltd. AOSERP Report 4. 108 pp.
5	HY 3.1	Strosher, M.T. and E. Peake. 1976. The evaluation of wastewaters from an oil sand extraction plant. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Environmental Sciences Centre (Kananaskis). AOSERP Report 5. 103 pp.
6	PM	Patterson, R. and A.M. Lansdown. 1976. Housing for the north--the stackwall system; construction report--Mildred Lake tank and pump house. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Manitoba, Faculty of Engineering, Northern Housing Committee. AOSERP Report 6. 36 pp.
7	AF 3.1.1	Jantzie, T.D. 1977. A synopsis of the physical and biological limnology and fishery programs within the Alberta oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Renewable Resources Consulting Services Ltd. AOSERP Report 7. 73 pp.

8 AF 1.2.1 Machniak, K. 1977. The impact of saline waters upon freshwater biota (a literature review and bibliography). Prep. for the Alberta Oil Sands Environmental Research Program by Aquatic Environments Ltd. AOSERP Report 8. 258 pp.

9 ME 3.3 Croft, B.R., A. Lamb, and R.N. Dawson. 1977. A preliminary investigation into the magnitude of fog occurrence and associated problems in the oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Stanley Associates Engineering Ltd. AOSERP Report 9. 87 pp.

10 HE 2.1 Millar, J.F.V. 1977. Development of a research design related to archaeological studies in the Athabasca Oil Sands area. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Saskatchewan. AOSERP Report 10. 69 pp.

11 AF 2.2.1 Flannagan, J.F. 1977. Life cycles of some common aquatic insects of the Athabasca River, Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Freshwater Institute. AOSERP Report 11. 20 pp.

12 ME 1.7 Mercer, J.M. and R.B. Charlton. 1977. Very high resolution meteorological satellite study of oil sands weather: "a feasibility study". Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Department of Geography. AOSERP Report 12. 44 pp.

13 ME 2.3.1 Davison, D.S., C.J. Fortems, and K.L. Grandia. 1977. Plume dispersion measurements from an oil sands extraction plant, March 1976. Prep. for the Alberta Oil Sands Environmental Research Program by Intera Environmental Consultants Ltd. AOSERP Report 13. 195 pp.

14 none

15 ME 3.4 Denison, P.J. 1977. A climatology of low-level air trajectories in the Alberta oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Acres Consulting Services. AOSERP Report 15. 118 pp.

16	ME 1.6	Barge, B.L., R.G. Humphries, and S.L. Olson. 1977. The feasibility of a weather radar near Fort McMurray, Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Research Council, Atmospheric Sciences Division. AOSERP Report 16. 72 pp.
17	AF 2.1.1	Lutz, A. and M. Hendzel. 1977. A survey of baseline levels of contaminants in aquatic biota of the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Freshwater Institute. AOSERP Report 17. 51 pp.
18	HY 1.1	Loeppky, K.D. and M.O. Spitzer. 1977. Interim compilation of stream gauging data to December 1976 for the Alberta Oil Sands Environmental Research Program. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Water Survey Branch. AOSERP Report 18. 257 pp.
19	ME 4.1	Walmsley, J.L. and D.L. Bagg. 1977. Calculations of annual averaged sulphur dioxide concentrations at ground level in the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Atmospheric Environment Service. AOSERP Report 19. 40 pp.
20	HY 3.1.1	Strosher, M.T. and E. Peake. 1978. Characterization of organic constituents in waters and wastewaters of the Athabasca Oil Sands mining area. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Environmental Sciences Centre (Kananaskis). AOSERP Report 20. 71 pp.
21	PM	Alberta Oil Sands Environmental Research Program. 1977. Second Annual Report, 1976-77. Alberta Oil Sands Environmental Research Program. AOSERP Report 21. 62 pp.
22	PM	Smith, S.B., ed. 1979. Alberta Oil Sands Environmental Research Program Interim Report covering the period April 1975 to November 1978. Prep. by A.S. Mann, R.A. Hursey, R.T. Seidner, and B. Kasinska-Banas. AOSERP Report 22.

23	AF 1.1.2	Lake, W. and W. Rogers. 1979. Acute lethality of mine depressurization water to trout-perch and rainbow trout: Volume I. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Environment, Water Control Branch. AOSERP Report 23. 44 pp.
24	ME 1.5.2 ME 3.5.1	Fanaki, F., R. Mickle, M. Lusis, J. Kovalick, J. Markes, F. Froude, J. Arnold, A. Gallant, S. Melnichuk, D. Brymer, A. Gaudenzi, A. Moser, and D. Bagg. 1979. Air system winter field study in the AOSERP study area, February 1977. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 24. 182 pp.
25	ME 3.5.1	Bottenheim, J.W. and O.P. Strausz. 1977. Review of pollutant transformation processes relevant to the Alberta oil sands area. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Hydrocarbon Research Centre. AOSERP Report 25. 166 pp.
26	AF 4.5.1	Bond, W.A. and K. Machniak. 1977. Interim report on an intensive study of the fish fauna of the Muskeg River watershed of northeastern Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Department of Fisheries. AOSERP Report 26. 137 pp.
27	ME 1.5.1	Fanaki, F., compiler. 1978. Meteorology and air quality winter field study in the AOSERP study area, March 1976. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 27. 249 pp.
28	VE 2.1	Turchenek, L.W. and J.D. Lindsay. 1978. Interim report on a soils inventory in the Athabasca Oil Sands area. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Research Council, Soils Division. AOSERP Report 28. 100 pp.
29	ME 2.2	Shelfentook, W. 1978. An inventory system for atmospheric emissions in the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by SNC Tottrup Services Ltd. AOSERP Report 29. 58 pp.

30 ME 2.1 Strosher, M.M. 1978. Ambient air quality in the AOSERP study area, 1977. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Environment, Pollution Control Division. AOSERP Report 30. 74 pp.

31 VE 2.3 Thompson, M.D., M.C. Wride, and M.E. Kirby. 1978. Ecological habitat mapping of the AOSERP study area: Phase I. Prep. for the Alberta Oil Sands Environmental Research Program by Intera Environmental Consultants Ltd. AOSERP Report 31. 176 pp.

32 PM Alberta Oil Sands Environmental Research Program. 1979. Third Annual Report, 1977-78. Alberta Oil Sands Environmental Research Program. AOSERP Report 32. 114 pp.

33 TF 1.2 Nowlin, R.A. 1978. Relationships between habitats, forages, and carrying capacity of moose range in northern Alberta. Part I: moose preferences for habitat strata and forages. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Recreation, Parks and Wildlife, Fish and Wildlife Division. AOSERP Report 33. 63 pp.

34 HY 2.4 Allan, R. and T. Jackson. 1978. Heavy metals in bottom sediments of the mainstem Athabasca River system in the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Freshwater Institute. AOSERP Report 34. 72 pp.

35 AF 4.9.1 Griffiths, W.H. and B.D. Walton. 1978. The effects of sedimentation on the aquatic biota. Prep. for the Alberta Oil Sands Environmental Research Program by Renewable Resources Consulting Services Ltd. AOSERP Report 35. 86 pp.

36 AF 4.8.1 Jones, M.L., G.J. Mann, and P.J. McCart. 1978. Fall fisheries investigations in the Athabasca and Clearwater rivers upstream of Fort McMurray: Volume 1. Prep. for the Alberta Oil Sands Environmental Research Program by Aquatic Environments Ltd. AOSERP Report 36. 71 pp.

37 HE 2.2.2 Van Dyke, E.W. and C. Loberg. 1978. Community studies: Fort McMurray, Anzac, Fort MacKay. Prep. for the Alberta Oil Sands Environmental Research Program by Applied Research Associates Ltd. AOSERP Report 37. 195 pp.

38	VE 7.1.1	Green, J.E. 1979. Techniques for the control of small mammal damage to plants: a review. Prep. for the Alberta Oil Sands Environmental Research Program by LGL Ltd., Environmental Research Associates. AOSERP Report 38. 111 pp.
39	ME 1.0	Longley, R.W. and B. Janz. 1979. The climatology of the Alberta Oil Sands Environmental Research Program study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Atmospheric Environment Service. AOSERP Report 39. 102 pp.
40	WS 3.3	Beltaos, S. 1979. Mixing characteristics of the Athabasca River below Fort McMurray--winter conditions. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Research Council, Transportation and Surface Water Engineering Division. AOSERP Report 40. 110 pp.
41	AF 3.5.1	Sprague, J.B., D.A. Holdway, and D. Stendahl. 1978. Acute and chronic toxicity of vanadium to fish. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Guelph. AOSERP Report 41. 92 pp.
42	TF 1.1.4	Todd, A. 1978. Analysis of fur production records for registered traplines in the AOSERP study area, 1970-75. Prep. for the Alberta Oil Sands Environmental Research Program by Alberta Recreation, Parks, and Wildlife. AOSERP Report 42. 17 pp.
43	TF 6.1	Phillips, W., D. DePape, and L. Ewanyk. 1979. A socioeconomic evaluation of the recreational use of fish and wildlife resources in Alberta, with particular reference to the AOSERP study area. Volume 1: summary and conclusions. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Department of Rural Economy. AOSERP Report 43. 116 pp.
44	VE 3.1	Malhotra, S.S. and P.A. Addison. 1979. Interim report on symptomology and threshold levels of air pollutant injury to vegetation, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 44. 13 pp.

45 VE 3.3 Malhotra, S.S. 1979. Interim report on physiology and mechanisms of air-borne pollutant injury to vegetation, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 45. 38 pp.

46 VE 3.4 Addison, P.A. and J. Baker. 1979. Interim report on ecological benchmarking and biomonitoring for detection of air-borne pollutant effects on vegetation and soils, 1975 to 1978. Prep. for the Alberta Oil Sands Environmental Research Program by Canadian Forestry Service, Northern Forest Research Centre. AOSERP Report 46. 40 pp.

47 TF 1.1.1 Cook, R.D. and J.O. Jacobson. 1979. A visibility bias model for aerial surveys of moose on the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Interdisciplinary Systems Ltd. AOSERP Report 47. 28 pp.

48 HG 1.1 Schwartz, F.W. 1979. Interim report on a hydrogeological investigation of the Muskeg River basin, Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Alberta, Department of Geology. AOSERP Report 48. 104 pp.

49 WS 1.3.3 Hartland-Rowe, R.C.B., R.W. Davies, M. McElhone, and R. Crowther. 1979. The ecology of macrobenthic invertebrate communities in Hartley Creek, northeastern Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Department of Biology. AOSERP Report 49. 144 pp.

50 ME 3.6 Denison, P.J., T.A. McMahon, and J.R. Kramer. 1979. Literature review on pollution deposition processes. Prep. for the Alberta Oil Sands Environmental Research Program and Syncrude Canada Ltd. by Acres Consulting Services Limited and Earth Science Consultants Inc. AOSERP Report 50. 264 pp.

51 HY 1.3 Warner, L.A. and M.O. Spitzer. 1979. Interim compilation of 1976 suspended sediment data for the AOSERP study area. Prep. for the Alberta Oil Sands Environmental Research Program by Environment Canada, Water Survey of Canada. AOSERP Report 51. 59 pp.

52 ME 2.3.2 Davison, D.S. and K.L. Grandia. 1979. Plume dispersion measurements from an oil sands extraction plant, June 1977. Prep. for the Alberta Oil Sands Environmental Research Program by Intera Environmental Consultants Ltd. AOSERP Report 52. 209 pp.

53 HY 3.1.2 Strosher, M.T. and E. Peake. 1979. Baseline states of organic constituents in the Athabasca River System upstream of Fort McMurray. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Environmental Sciences Centre (Kananaskis). AOSERP Report 53. 71 pp.

54 WS 2.3 Nix, P.G., J.W. Costerton, R. Ventullo, and R.T. Coutts. 1979. A preliminary study of chemical and microbial characteristics of the Athabasca River in the Athabasca Oil Sands area of northeastern Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by Chemical and Geological Laboratories Ltd., Microbios Ltd., and Xenotox Services Ltd. AOSERP Report 54. 135 pp.

55 HY 2.6 Costerton, J. and G.G. Geesey. 1979. Microbial populations in the Athabasca River. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Calgary, Department of Biology. AOSERP Report 55. 65 pp.

56 AF 3.2.1 Giles, M.A., J.F. Klaverkamp, and S.G. Lawrence. 1979. The acute toxicity of saline groundwater and of vanadium to fish and aquatic invertebrates. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Freshwater Institute. AOSERP Report 56. 216 pp.

57 LS 2.3.1 Thompson, M.D. 1979. Ecological habitat mapping of the AOSERP study area (supplement): Phase I. Prep. for the Alberta Oil Sands Environmental Research Program by Intera Environmental Consultants Ltd. AOSERP Report 57. 45 pp.

58 AF 2.0.2 Lock, M.A. and R.R. Wallace. 1979. Interim report on ecological studies on the lower trophic levels of Muskeg rivers within the Alberta Oil Sands Environmental Research Program study area. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada. AOSERP Report 58. 105 pp.

59	TF 3.1	Gilbert, F.F., S.A. Brown, and M.E. Stoll. 1979. Semi-aquatic mammals: annotated bibliography. Prep. for the Alberta Oil Sands Environmental Research Program by the University of Guelph, Department of Zoology. AOSERP Report 59. 167 pp.
60	WS 1.1.1	Neill, C.R. and B.J. Evans. 1979. Synthesis of surface water hydrology. Prep. for the Alberta Oil Sands Environmental Research Program by Northwest Hydraulic Consultants Ltd. AOSERP Report 60. 84 pp.
61	AF 4.5.2	Machniak, K. and W.A. Bond. 1979. An intensive study of the fish fauna of the Steepbank River watershed of northeastern Alberta. Prep. for the Alberta Oil Sands Environmental Research Program by Fisheries and Environment Canada, Freshwater Institute. AOSERP Report 61. 196 pp.
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