

THE MAGNITUDE AND SIGNIFICANCE OF THE TERRESTRIAL SNOWPACK
AND WHITE ICE CONTRIBUTION TO THE PHOSPHORUS BUDGET
OF A LAKE IN THE CANADIAN SHIELD REGION OF THE KAWARTHA LAKES*

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ABSTRACT

The input of phosphorus, a limiting nutrient in freshwater lakes, from the melting of the terrestrial snowpack and white ice on the lake surface in early spring, was found to be significant.

It was found that the winter lake cover development could possibly be traced by analyzing the phosphorus concentrations in the column of lake ice at the peak ice season.

INTRODUCTION

General

Snow and ice melt during spring thaw has largely been ignored by limnologists when calculating phosphorus loading models for freshwater lakes. Notable exceptions to this are Schindler and Nighswander (1970), and Barica and Armstrong (1971).

Snow contains many impurities, one of which is the nutrient, phosphorus. Phosphorus in the air results mainly from fossil fuel combustion. Other sources of phosphorus are seen in Figure 1. Phosphorus is known to be the single most important nutrient controlling primary production and therefore the trophic status of a lake (Wetzel, 1975; Dillon and Rigler, 1975; Schindler et al., 1973). The natural source loading of phosphorus into lakes by rainfall is known to be significant (Armstrong and Schindler, 1971; Dillon and Rigler, 1975; Schindler et al., 1973). Schindler and Nighswander (1970) found that a significant amount of total dissolved phosphorus which originated in the snowpack was retained by Clear Lake after spring melt.

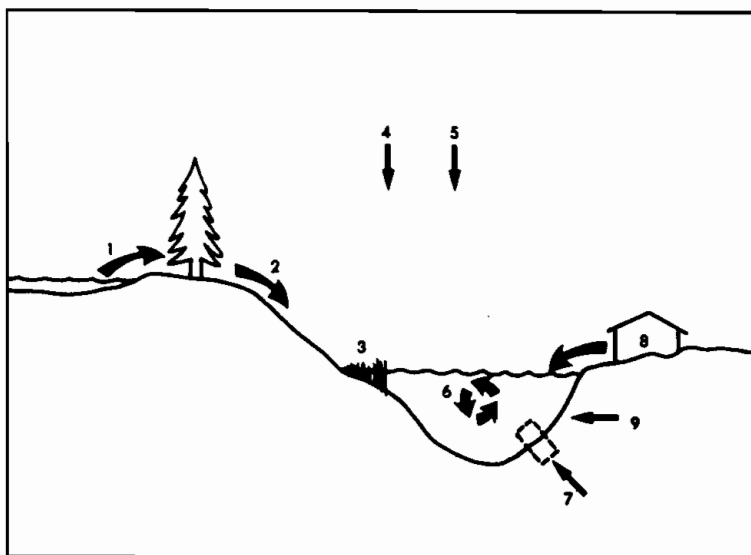
The purpose of this paper is to present a case for the inclusion of snow and ice data into the phosphorus loading model for lakes in the Canadian Shield of Central Ontario. The behaviour of phosphorus in white ice will be investigated as it pertains to white ice formation. The freeze-out process (Adams, 1976) will also be discussed.

Study Area

The field work for this paper was undertaken on the Coon Lake drainage basin during the winter of 1975-76. The basin is located approximately 6.4 kilometres north-east of the village of Burleigh Falls, Ontario. The precise location is found by using the military grid reference 223430 on the map:- Burleigh Falls, 31 D/9, 1:50,000, 1971.

* The basis of this paper is a Fourth Year thesis presented to Trent University (English, 1976). Mr. English is now at the University of Alberta.

Figure 1.
Sources of Phosphorus entering a Freshwater
Lake (not Including Snow and White Ice)



LEGEND

1. Input from first lake upstream.
2. Runoff - Includes: soil erosion; leaching of ground litter.
3. Aquatic (and terrestrial) vegetation.
4. Dry (atmospheric) fallout.
5. Precipitation.
6. Zooplankton and Phytoplankton 'cycle'
7. Sediment - under anaerobic conditions, release of phosphate from iron (ferric form).
8. Human input.
9. Input from: ground water seepage; bedrock.

This drainage basin was chosen because of its relatively small size (terrestrial basin area: 2.92 km²), accessibility and thus relative ease of accomplishing a considerable amount of field work in a short period of time. Coon Lake, a mesotrophic lake, (D.C. Lasenby, Trent University, 1975 personal communication), is supplied by five intermittent streams from swamps and two larger intermittent streams from Big Cedar Lake.

SNOWPACK

Measurement

Water equivalent of the snowpack was measured using a Mount Rose Snow Tube sampler (see Adams and Barr, 1974), at what was assumed to be the peak snow season. It was important to take these samples at the time of peak snow development, so that a true estimate of spring melt could be estimated. The catchment was divided into four areas, one area sampled per sampling date (Figure 2). Sampling points were selected on the basin using a simple computer program and using an overlay grid on the map of the catchment (Appendix A). At each sampling point, snow samples were obtained for total dissolved phosphorus analysis. This analysis involved employing a digestion technique using perchloric acid and ammonium hydroxide, a technique very similar to that used by Dillon and Rigler (1974).

Results

The mean water equivalents for each sampling area are shown in Table 1 as are the mean total dissolved phosphorus concentrations. The measurements for individual sites are given in Appendix B. The small differences occurring in the mean water equivalents between sampling areas can be partially attributed to climatic differences over the short period of time it took to sample the catchment. Other factors might be the small topographical and vegetational differences between the four sampling areas.

Table 1

Mean Water Equivalence and Mean (Total Dissolved) Phosphorus Concentrations at Each Snow Area

| <u>Snow Area</u> | <u>Mean Water Equivalent</u> | <u>Mean Total Dissolved Phosphorus Concentration (mg/L)</u> |
|------------------|------------------------------|---|
| North (12 sites) | 16.08 cm | .0163 |
| East (20 sites) | 15.33 cm | .0509 |
| West (19 sites) | 14.08 cm | .0974 |
| South (9 sites) | 14.38 cm | .0414 |

The following equation was formulated to express the phosphorus loading into Coon Lake from each snow sampling area:-

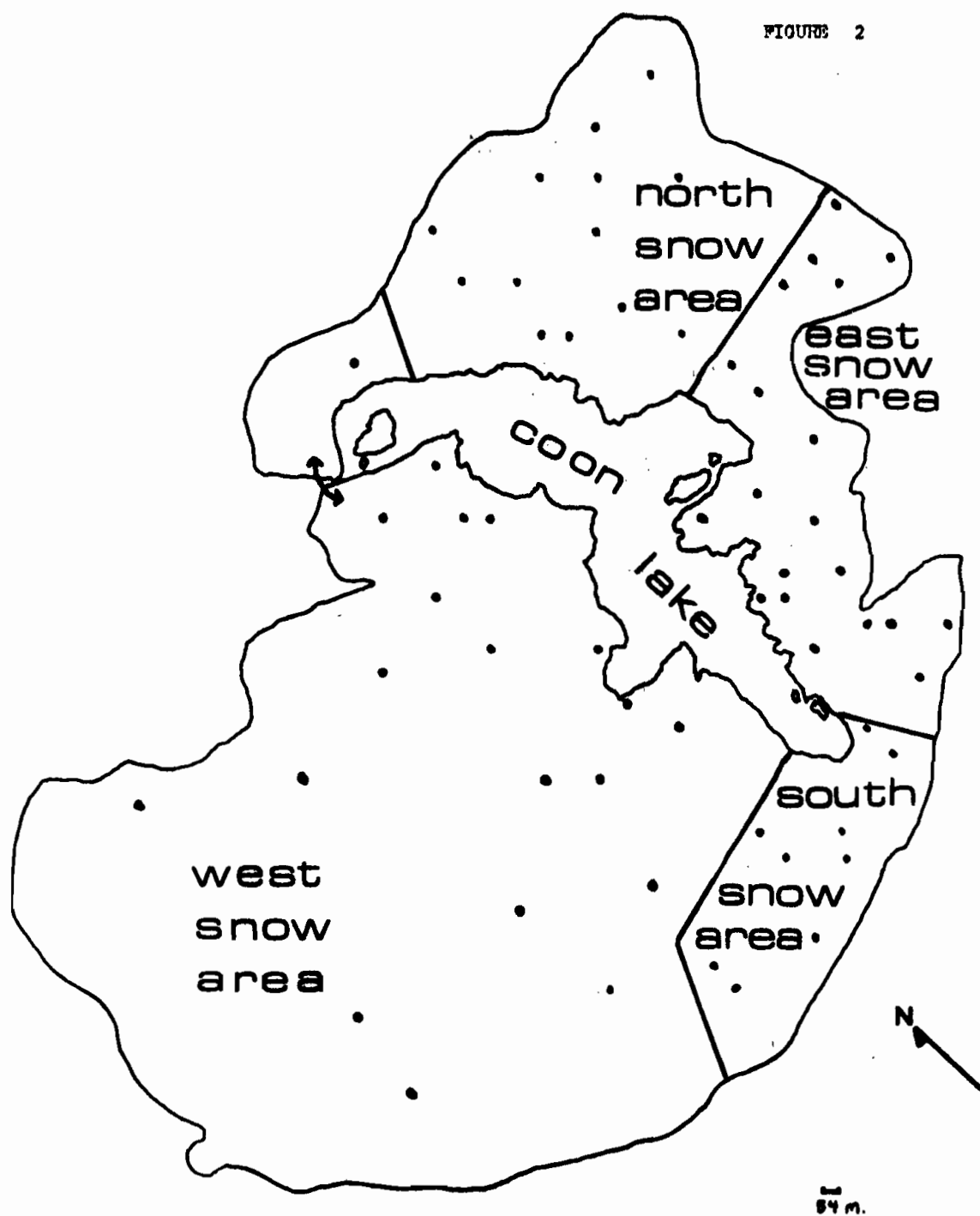
$$J_s = \frac{A_e \times \bar{x}H_2O_e \times \bar{x}TDP_c \times .33}{A_o}$$

where

- A_e = area of sampling area (m²)
- $\bar{x}H_2O_e$ = mean water equivalence of snowpack (m)
- $\bar{x}TDP_c$ = mean total dissolved phosphorus concentration (mg/L)
- .33 = a constant, the fraction of phosphorus from terrestrial basin reaching the lake after the retention factor of .67 (see Schindler and Nighswander, 1970)
- A_o = surface area of the lake (m²)
- J_s = total dissolved phosphorus loading from the snowpack which enters the lake (mg/m²)

Table 2 shows the loading of total dissolved phosphorus into Coon Lake from each sampling area. Once the phosphorus has entered the lake from the melting snowpack,

FIGURE 2



Snow Sampling Sites

Schindler and Nighswander (1970) found that 80% would be retained by the lake, 20% would be drained out of the lake during early spring.

Table 2

Loading of Phosphorus into Coon Lake from Each Sampling Area*

$$J_S = \frac{A_e (m^2) \times \bar{x}H_2O_e (m) \times \bar{x}TDP_c (mg/L) \times .33}{A_o (m^2)}$$

Substituting in the equation for each snow area:

North Snow Area : $J_S = 3.66 \text{ mg/m}^2$

East Snow Area : $J_S = 8.17 \text{ mg/m}^2$

West Snow Area : $J_S = 73.41 \text{ mg/m}^2$

South Snow Area : $J_S = 3.74 \text{ mg/m}^2$

Total Loading of (Total Dissolved) Phosphorus from
Snow Areas = 88.98 mg/m^2

* before retention factors taken into consideration.

ICE

General

Two aspects of lake ice were studied. The first was simply the measurement of white ice volume at peak ice year and sampling of the white ice to determine a mean total dissolved phosphorus concentration contained in it. The phosphorus loading from the white ice could then be calculated. The white ice was measured for phosphorus as I was interested in the atmospheric contribution and white ice includes a considerable amount of winter precipitation, although flooding of the snow cover on the lake by lake water was noted. The development of the winter lake cover is covered in detail by Adams and Jones (1970) and Jones (1970).

The other aspect of lake ice which was investigated was the behaviour of phosphorus in the white ice layer. This involved measuring the ice cover development over the winter and recording phosphorus concentrations at various sites on the lake during the winter.

Results

Table 3 illustrates the mean total dissolved phosphorus concentrations in white ice at peak ice season.

Table 3

Mean Total Dissolved Phosphorus Concentrations at Peak Ice Year
in the White Ice

| | |
|----------|---------|
| Hole #7* | .0492** |
| Hole #6 | .0418 |
| Hole #5 | .0312 |
| Hole #4 | .0951 |
| Hole #3 | .0420 |
| Hole #2 | .0791 |
| Hole #1 | .1084 |

* all Holes are shown in Figure 4;

** all measurements in mg/L.

The following equation was formulated to express the phosphorus contribution from white ice:

$$J_{wi} = \frac{d \times D \times A_{owi} \times \bar{x}TDP_c}{A_o}$$

where J_{wi} = total dissolved phosphorus loading from white ice (mg/m^2)
 d = mean thickness of white ice (m)
 D = density of white ice (Gaitskhoki, 1970) = .8765
 A_{wi} = areal extent of white ice (m^2)
 \bar{xTDP}_c = mean total dissolved phosphorus concentration (mg/L)
 A_o = surface area of lake (m^2).

Table 4 indicates phosphorus loading from white ice.

Table 4

White Ice Contribution

Mean phosphorus contribution = .0639 mg/L
Mean thickness of white ice
at peak ice year = .2806 m
White ice density
(after Gaitskhoki, 1970) = .8765
Areal extent of white ice = 346900 m^2

Calculation of Phosphorus Loading:

$$J_{wi} = \frac{d \times D \times A_{wi} \times \bar{xTDP}_c}{A_o}$$

J_{wi} (loading of total dissolved phosphorus into
Coon Lake from white ice) = 15.72 mg/m^2

DISCUSSION ON SNOWPACK AND WHITE ICE LOADING

Prologue

Awareness of the importance of phosphorus and the concept of phosphorus loading in an ecosystem is relatively new. The modelling concept appeared in the 1960's when Vollenweider (1968) produced an input-output model for lake phosphorus. In 1975, Dillon and Rigler became the first to include a precipitation coefficient in a phosphorus loading model. They arrived at the figure of 75 $\text{mg}/\text{m}^2/\text{year}$ for precipitation loading and included it in their equation for evaluating the natural phosphorus supply to a lake.

$J_n = (Ad.Es) + 75 .A_o$ (mg/yr)
where Ad = the terrestrial catchment in m^2
 Es = export coefficient from the soil
 A_o = area of the lake in m^2

Vollenweider and Dillon (1974) recognized that the precipitation input was very significant and could possibly account for the majority of the phosphorus input in some areas, especially those in which man has little influence. They did not, however, take the precipitation factor into account in their model. There was, at the same time, growing awareness of the importance of precipitation in the phosphorus loading regimes of freshwater lakes (Holmes and Hendrian, 1974; Schindler and Nighswander, 1970; Armstrong and Schindler, 1971; Barica and Armstrong, 1971; Likens and Bormann, 1974; and Rigler, 1975).

Magnitude

The accumulation of winter precipitation in the study area represents approximately 21.0% of the annual precipitation (D.R. Barr, Trent University, 1975, personal communication). What makes this accumulated precipitation important is that, in the spring, it melts and runs off into the lake in a relatively short period of time. Theoretically, therefore, this sudden input at breakup will include 20% of the phosphorus loading from precipitation for the year. Vollenweider (1968: 14) stated that "...there are no seasonal fluctuations in loading rate of phosphorus." Evidence from the field study on Coon Lake suggests otherwise, as the snowpack and white ice make a large contribution in a short period of time. The input from the terrestrial snowpack and white ice results in a total

loading factor of 35.48 mg/m^2 of total dissolved phosphorus (see Figure 3). This represents an 82.67% increase in total dissolved phosphorus in Coon Lake.

It seems evident from the data collected on Coon Lake that the input of total dissolved phosphorus from accumulated winter precipitation should be investigated and perhaps included in the phosphorus loading regimes for lakes in the Canadian Shield region of Central Ontario.

WHITE ICE FORMATION, PHOSPHORUS CONCENTRATION RELATIONSHIPS

Figure 4 illustrates the vertical distribution of the total dissolved concentrations in white ice for Coon Lake at peak ice. The differences apparent in the phosphorus concentration in columns of white ice can be attributed partially to the mode of white ice formation.

Briefly, the white ice formation history followed:

- a) slow formation up until approximately the 11th of January, 1976;
- b) a slushing period for the greater area of the lake;
- c) slushing focussed in the north-west arm of the lake;
- d) at peak ice season, slushing only evident in a small area of the north-west arm of the lake.

The lake followed a brief cycle of: a) stability (early ice formation); b) instability (weight of snow on ice; flooding); and, finally c) stability achieved again at peak ice season.

Phosphorus readings taken at seven sites on the lake at peak ice season, indicate a lower total dissolved phosphorus concentration in the white ice in the north-west arm, where slushing was most pronounced. The mean phosphorus concentration in this area of the lake was $.0407 \text{ mg/L}$; almost exactly one-half the mean concentration found in the other areas of the lake which experienced only a minor period of slushing prior to January 25. This higher mean concentration for the other areas of the lake was $.0812 \text{ mg/L}$. This could possibly be attributed to the fact that lake water played a greater role in the formation of white ice in the north-west arm of the lake. The phosphorus concentration of lake water at the surface of the lake at peak ice season was $.0285 \text{ mg/L}$.

White ice formation in the areas which received little slushing was caused mainly by snow melt (during periods of thaw), and/or rainfall mixing with the snow present on the lake surface at isolated periods during the winter. Total dissolved phosphorus concentration in rainfall is known to be higher than the $.0280 \text{ mg/L}$ registered at the black ice/water interface (D. Lasenby, 1975, personal communication); and the phosphorus concentration in the snow was found to be approximately $.0588 \text{ mg/L}$. Therefore it can be assumed that the higher concentrations found in the non-slushing areas of the lake are due to the mode of formation, melting snow and rainfall.

In those areas of the lake which slushed, slushing occurred in two stages. The first was the initial flooding of the snow cover, which, during the period of initial flooding (January 25) averaged 30.0 cm in the north-west arm of the lake and 14.99 cm in the areas experiencing only minor slushing. The second stage of the slushing is shown in Figures 5 and 6. This stage will be labelled "enclosed slushing", as the slush is covered completely by a thin layer of white ice. In some cases a white ice layer existed beneath the slushing layer, giving the appearance of a sandwich: white ice (at the surface), then slush (freezeout process), and under the slush a thin layer of white ice. Adams (1976) discusses the possibilities of freezeout existing in the formation of white ice during slushing periods. The freezeout implies a higher concentration of total dissolved phosphorus in the "slush" (below the thin white ice layer) than in the white ice itself. Results for phosphorus analysis in these enclosed slush formations tend to agree with what Adams (1976) has postulated. For example, analysis of the white ice and the slushing layer (under the white ice) for January 25, for two sites in the north-west arm of Coon Lake, indicates a higher phosphorus concentration in the "freezeout zone".

Figure 3

**FLOW CHART ILLUSTRATING
PHOSPHORUS TRANSPORT AND RETENTION
PREDICTION DURING SPRING MELT
ON THE COON LAKE DRAINAGE BASIN**

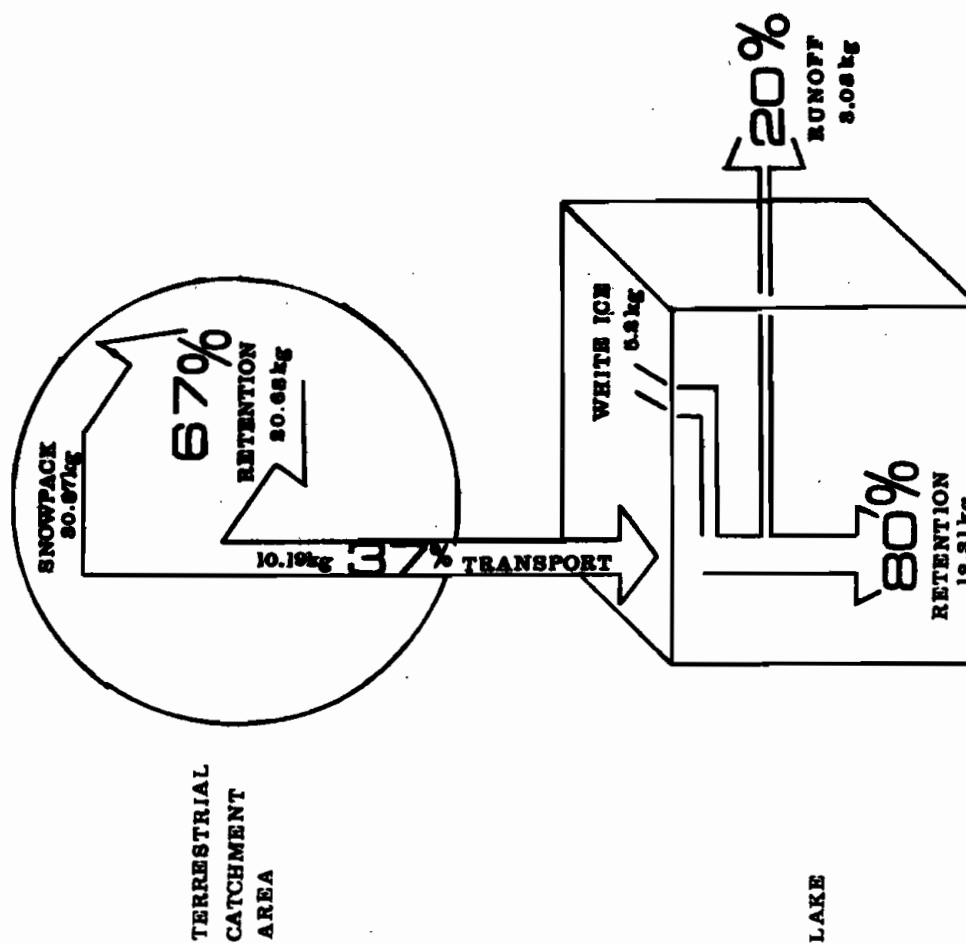
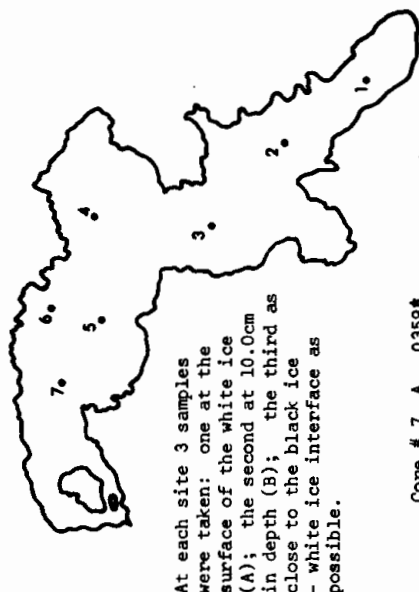


Figure 4
Total Dissolved Phosphorus Concentrations
in Vertical Ice (White Ice) Columns at Peak Ice Year



| | | |
|----------|---|--------|
| Core # 7 | A | .0359* |
| | B | .0578 |
| | C | .0539 |
| Core # 6 | A | .0481 |
| | B | .0293 |
| | C | .0484 |
| Core # 5 | A | .0188 |
| | B | .0644 |
| | C | .0104 |
| Core # 4 | A | .1718 |
| | B | .0662 |
| | C | .0474 |
| Core # 3 | A | .0550 |
| | B | .0585 |
| | C | .0132 |
| Core # 2 | A | .1056 |
| | B | .0735 |
| | C | .0582 |
| Core # 1 | A | .1645 |
| | B | .1446 |
| | C | .0160 |

* all readings in mg/L

Figure 5

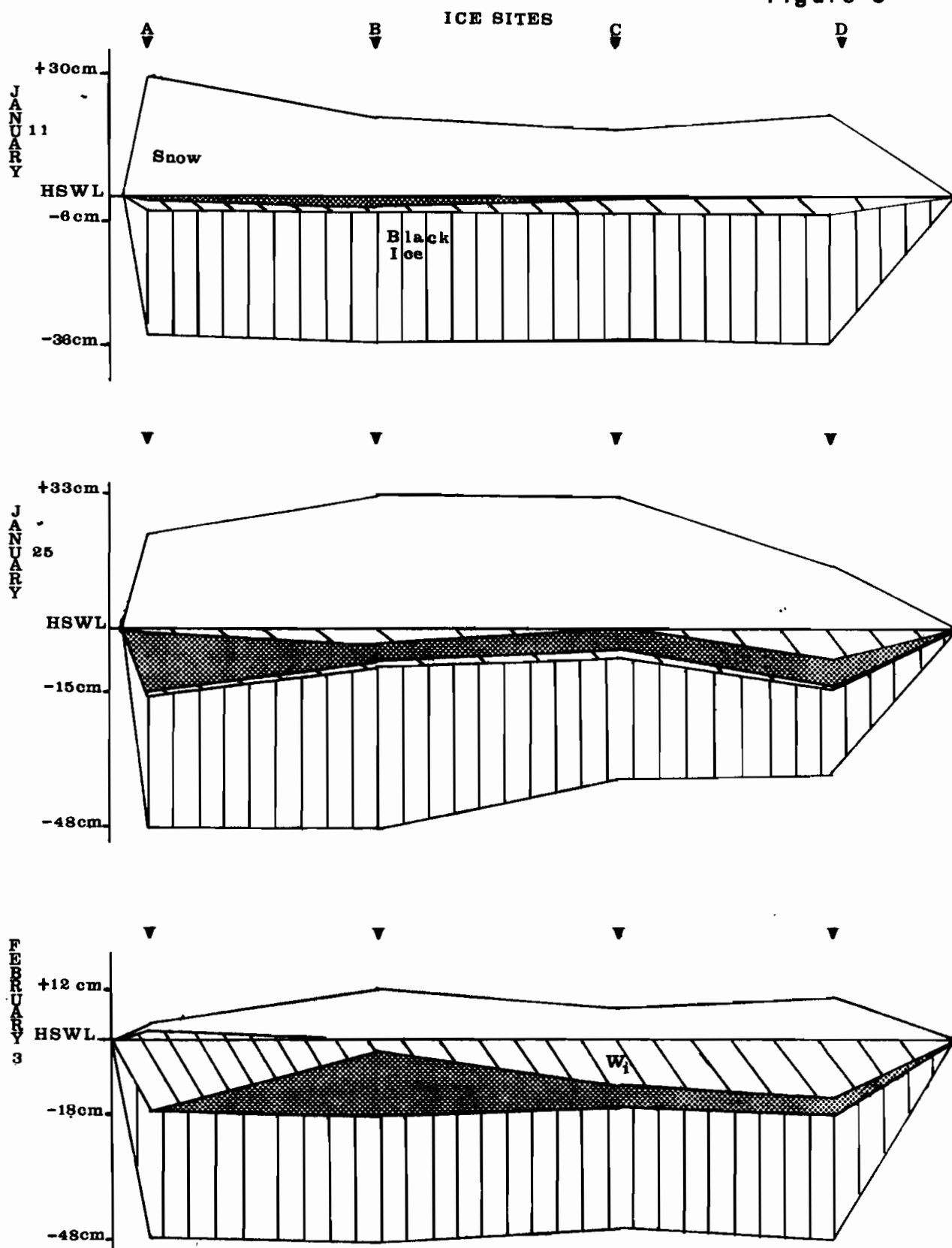
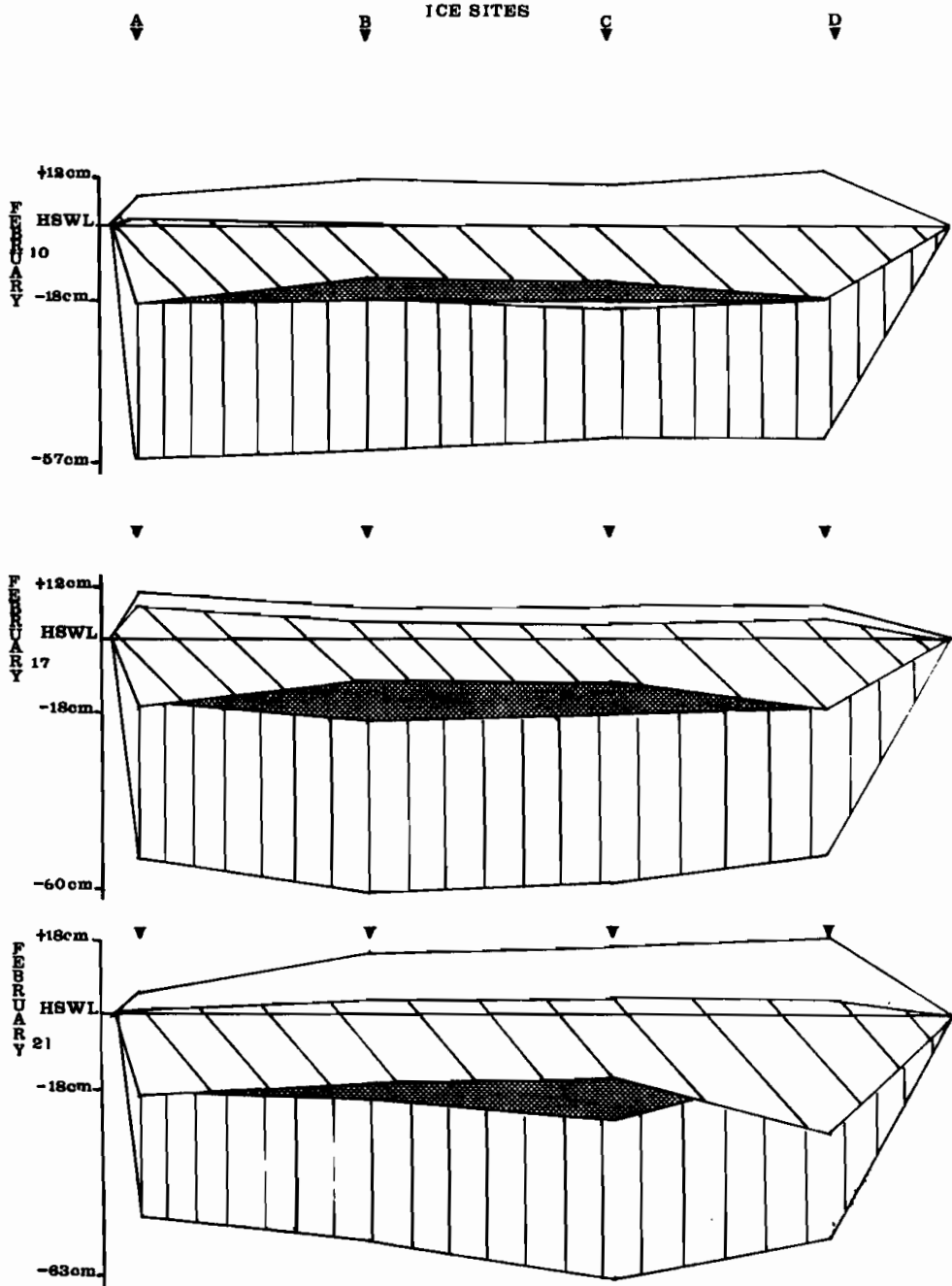


Figure 6



| | | |
|--------------|-----------------|-----------|
| Ice Hole 'O' | White Ice | .045 mg/L |
| | Freezeout Water | .054 mg/L |
| Ice Hole 'H' | White Ice | .053 mg/L |
| | Freezeout Water | .072 mg/L |

At peak ice season, when these "slushing" areas in the north-west arm had completely frozen, phosphorus concentrations indicated a higher concentration layer of phosphorus at the level which the final "enclosed slush" layer froze.

For example,

| | | |
|-------------|--|------------|
| Ice Hole #7 | - A (surface) | .0359 mg/L |
| | - B (10-15 cm from surface) | .0578 mg/L |
| | - C (just above black ice/white ice interface) | .0539 mg/L |
| Ice Hole #5 | - A (as above) | .0188 mg/L |
| | - B " " | .0644 mg/L |
| | - C " " | .0104 mg/L |

The "B" level indicated for ice holes #5 and #7 is the approximate location of the last slush layer which froze in the vertical white ice column. The concentrations for the "B" levels are substantially higher in ice hole #5 and somewhat higher in ice hole #7.

Briefly, the phosphorus concentrations in white ice appear to depend upon the mode of formation of the white ice. This data indicates that if a lake experiences much slushing as a result of depression by snow weight and thermal expansion, the resulting white ice will have a relatively low mean total phosphorus concentration. Conversely, and theoretically, if one samples the column of white ice at peak ice for phosphorus concentrations, the results should spell out the mode of ice formation, without having previous knowledge of the ice cover formation. For example, see Figure 7.

The curve in Figure 7 would indicate a period of slushing, as the higher concentrations of phosphorus in the mid area of the ice column would most likely result from the freezeout process subsequent to refreezing of slush. A bimodal peak might indicate two periods of significant slushing. The concentrations of the phosphorus in the white ice core could indicate the mode of slushing. If the concentration of phosphorus is high, then most likely the slushing resulted from a thaw, or rainfall. If the concentrations in the slushing area are low, then more than likely the mode of formation would be flooding by lake water.

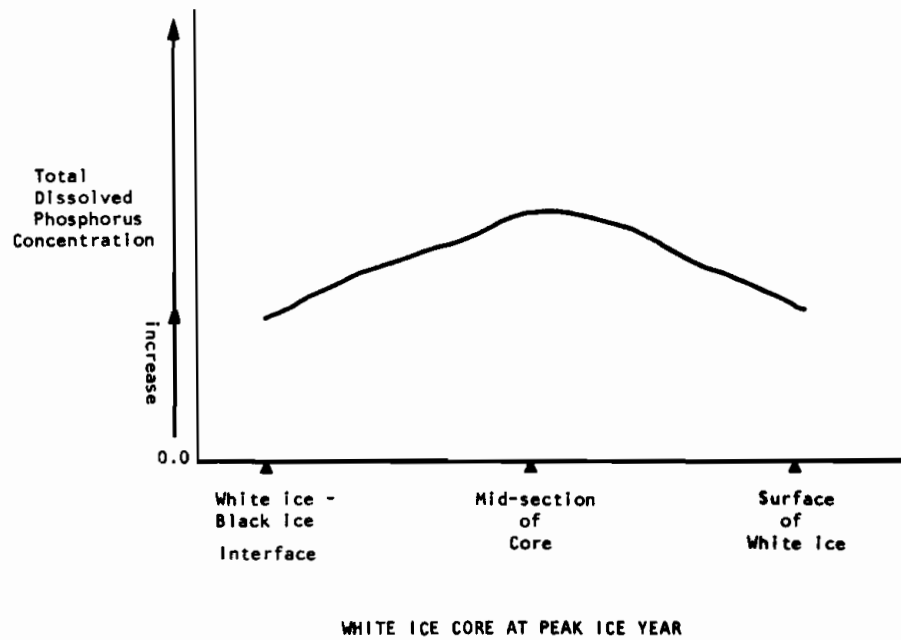
If indeed the freezeout process is applicable (as it appears to be), then the history of ice formation on a lake surface may be traced by chemical analysis of the ice layers for nutrients (or some other chemical property). This, of course, means more work is needed in the field and laboratory.

CONCLUSION

Snowpack and White Ice Phosphorus Loading

The sudden influx of winter precipitation in the Coon Lake catchment into the lake itself appears to be significant as far as phosphorus loading is concerned (English, 1976). Rodin and Bazilevich (1969) refer to the autumnal "pulse" of deciduous leaves onto the forest floor, and subsequent large input of nutrients (via leaching) into the soil. The spring input of melting snow and ice into the lake is similar to Rodin and Bazilevich's example in the sense that large amounts of nutrients are involved in both cases. The leaching of the leaves revitalizes the seasonal nutrient depletion in the soil, while the influx of melting precipitation in the spring adds to the nutrient budget of the freshwater lake, providing for the demands of the lake ecosystem. The presence of algal blooms on Coon Lake and other freshwater lakes (W.P. Adams, Trent University, 1975, personal communication) during spring melt have often been attributed solely to light reaching the lake

Figure 7.
Phosphorus Concentrations along
a core of White Ice at Peak Ice Year



surface during candling and breakup of the lake ice. Since phosphorus is the limiting nutrient for freshwater lakes, it seems that the algal bloom on Coon Lake (witnessed by the author, R. Heron and D.R. Barr) could partially result from phosphorus input from the melting terrestrial snowpack and the white ice.

White Ice/Phosphorus Relationship

The behaviour of phosphorus in the white ice appears to react to a set of physical thermodynamic laws which are little understood. Adams (1976) postulates the freeze-out process as being of importance. This study appears to back up this postulation; however, freezeout is far from being understood.

To paraphrase W.P. Adams (1976: 90), the detailed biological effects of the individual major components of the lake cover, and the terrestrial snowpack, have received relatively little attention. This is quite remarkable, especially in Canada with our large number of lakes and substantial annual snowfall.

Acknowledgements

My thanks are extended to David Lasenby, Douglas Barr, Richard Heron, Wayne Wilson, Mrs. Marley Waiser and my father, James English, who edited this paper.

I would especially like to thank Dr. W.P. Adams for his valuable criticism and encouragement of this project.

Finally, I wish to thank Mrs. R.M. Kennedy who typed this paper.

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APPENDIX A

Computer Program for Selecting "Random" Coordinates on Grid Map, Pictured:-

```

Operation:-          100  C=0, B=0, M=0, G=0
                     110  C=INT ( 45 * RND(1) ) +1
                     120  ;"C=";C
                     130  M=M+1
                     140  IF M= 50 THEN 160
                     150  GOTO 110
                     160  B=INT ( 35*RND (1))+1
                     170  ;"B=";B
                     180  G=G+1
                     190  IF G=50 THEN 210
                     200  GOTO 160
                     210  END

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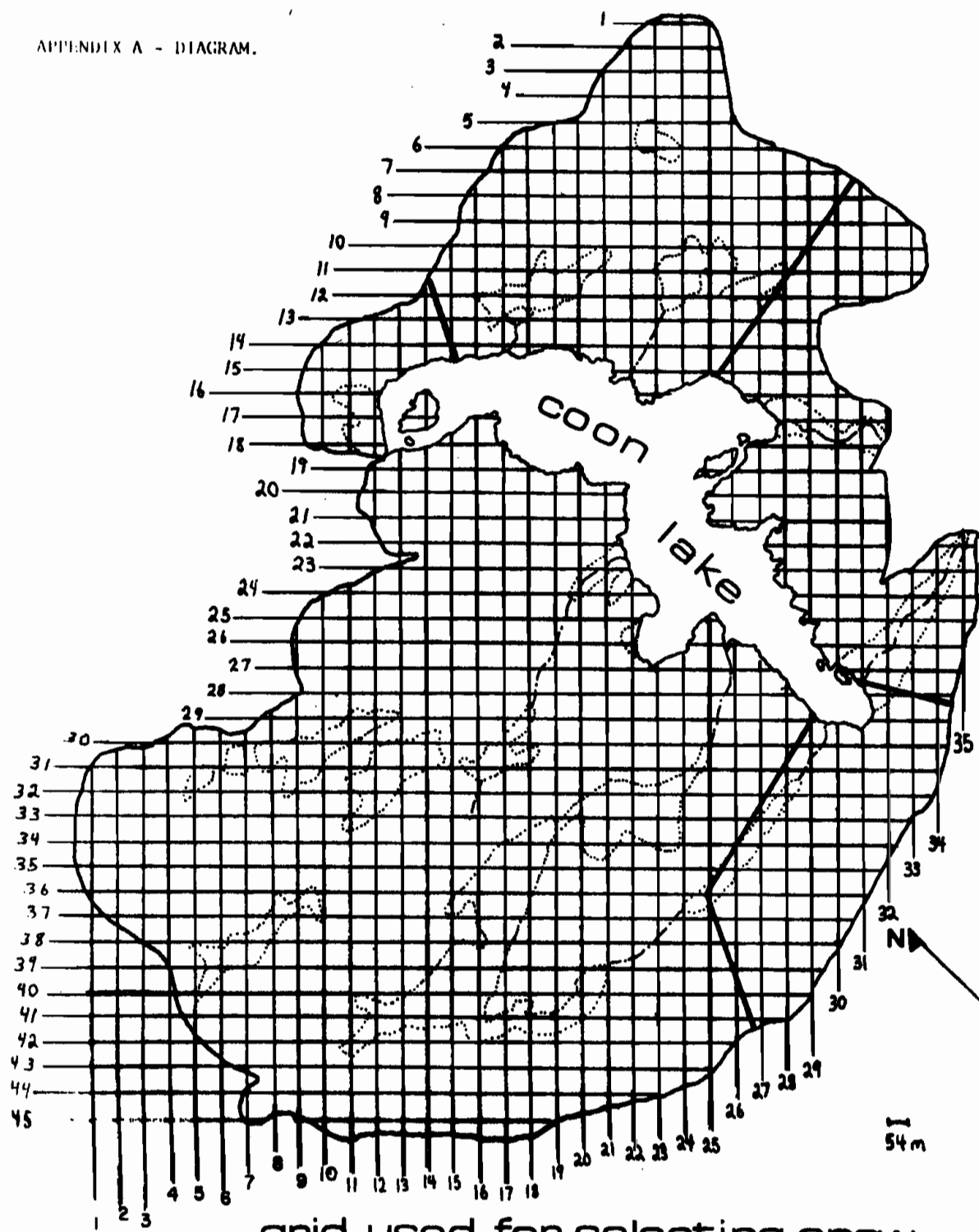
Brief Description:- The coordinates along the abscissa are numbered 1 to 35, the ordinate, 1 to 45. The program above simply prints out 50 numbers, randomly selected in the function: $B = \text{INT}(35 * \text{RND}(1)) + 1$, then it prints out 50 numbers randomly selected from the same function, however changed to accommodate the 45 numbers of the ordinate. These two sets of 50 numbers are then matched up, giving readings for both the ordinate and abscissa on the grid map. The sampling sites were found by using compass and pacing the distances.

APPENDIX B

West Snow Area:

| <u>Site</u> | <u>Water Equivalent (cm)</u> | <u>Total Dissolved Phosphorus Concentration (mg/L)</u> |
|-------------|----------------------------------|--|
| 1 | 14.48 | no sample |
| 2 | 8.89 | .1555 |
| 3 | 9.65 | .0243 |
| 4 | 10.92 | .1316 |
| 5 | 17.78 | .1085 |
| 6 | 10.92 | .0995 |
| 7 | 13.46 | .1366 |
| 8 | 16.26 | no sample |
| 9 | 15.49 | .1316 |
| 10 | 11.18 | .1190 |
| 11 | 16.50 | .0809 |
| 12 | 18.80 | .0895 |
| 13 | 13.97 | .0900 |
| 14 | 13.30 | .1280 |

APPENDIX A - DIAGRAM.



grid used for selecting snow sites, using computer program

Appendix B - West Snow Area (cont'd...)

| <u>Site</u> | <u>Water Equivalent (cm)</u> | <u>Total Dissolved Phosphorus Concentration (mg/L)</u> |
|------------------------|----------------------------------|--|
| 15 | 17.02 | .0468 |
| 16 | 13.46 | .1008 |
| 17 | 14.99 | .0750 |
| 18 | 17.78 | .0699 |
| 19 | 12.70 | .0200 |
| Mean | 14.08 | .0974 |
| Standard Deviation | 2.89 | |
| Standard Error of Mean | .66 | |

East Snow Area:

| | | |
|------------------------|-------|-----------|
| 1 | 11.20 | .0232 |
| 2 | 12.70 | .0335 |
| 3 | 14.48 | .0274 |
| 4 | 11.68 | .0410 |
| 5 | 17.29 | .0107 |
| 6 | 13.97 | .0700 |
| 7 | 17.02 | .0270 |
| 8 | 15.75 | .1574 |
| 9 | 15.22 | .0366 |
| 10 | 22.10 | .0565 |
| 11 | 16.00 | .0339 |
| 12 | 15.49 | .0817 |
| 13 | 14.73 | .0438 |
| 14 | 11.43 | .0619 |
| 15 | 15.24 | .0462 |
| 16 | 18.29 | no sample |
| 17 | 19.30 | .0480 |
| 18 | 19.56 | no sample |
| 19 | 10.16 | .0673 |
| 20 | 14.99 | no sample |
| Mean | 15.33 | .0509 |
| Standard Deviation | 3.06 | |
| Standard Error of Mean | .68 | |

North Snow Area:

| | | |
|------------------------|-------|-----------|
| 1 | .76 | .0170 |
| 2 | .22 | no sample |
| 3 | 17.78 | .0390 |
| 4 | 17.78 | .0180 |
| 5 | 14.73 | .0025 |
| 6 | 15.49 | no sample |
| 7 | 13.21 | .0040 |
| 8 | 17.27 | no sample |
| 9 | 16.26 | .0153 |
| 10 | 16.00 | .0224 |
| 11 | 14.48 | .0118 |
| 12 | 19.05 | no sample |
| Mean | 16.08 | .0163 |
| Standard Deviation | 1.73 | |
| Standard Error of Mean | .49 | |

South Snow Area:

| | | |
|---|-------|-------|
| 1 | 11.94 | .0354 |
| 2 | 16.00 | .0520 |

Appendix B - South Snow Area (cont'd...)

| <u>Site</u> | <u>Water Equivalent (cm)</u> | <u>Total Dissolved Phosphorus Concentration (mg/L)</u> |
|------------------------|----------------------------------|--|
| 3 | 14.99 | .0490 |
| 4 | 11.18 | .0455 |
| 5 | 8.89 | .0454 |
| 6 | 17.78 | .0300 |
| 7 | 16.51 | .0330 |
| 8 | 17.78 | .0400 |
| 9 | 14.41 | .0420 |
| Mean | 14.38 | .0414 |
| Standard Deviation | 3.11 | |
| Standard Error of Mean | 1.04 | |