SNOW DISTRIBUTION, MELT AND RUN-OFF CHARACTERISTICS OF AN INTER-DRUMLIN SWALE

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Within Canada numerous areas of distinctive hydro-meteorologic character can be recognized. Within each of these regions the solution of water-based problems can be approached on a sub-regional basis. The Peterborough Drumlin Field can be identified as a distinctive physiographic sub-region within the more densely populated area of Ontario. In order to investigate the snow distribution, melt and run-off characteristics of this sub-region a typical interdrumlin swale was selected. Utilizing a grid snow course and standard climatological station instrumentation, melt rates using generalized snowmelt equations were compared to snow tube measurements. Melt rates from both methods were then extrapolated over the study catchment and tested against streamflow data. Large differences between the predicted and actual flows observed during the initial stages of the melt were seen to decrease during the latter stages and large lag periods were observed. It is suggested that these characteristics are typical of the drumlinized till plain topography found in the study area and that they are a function of the recharging of the inter-drumlin wetlands.

Introduction: Regionalization of Water Problems

Within Canada the demand for water per capita is within a fairly narrow range; unfortunately, the supply is much more areally variable. Thus areas of overall water deficiency as well as water sufficiency and even areas having excess run-off are created. The importance of available run-off is brought out by D. Cass-Beggs (1969):

> "The problem of water supply in Canada is the control and redistribution of run-off according to the needs and location of her increasing population. The supply factor in the supply and demand relationship is the available run-off."

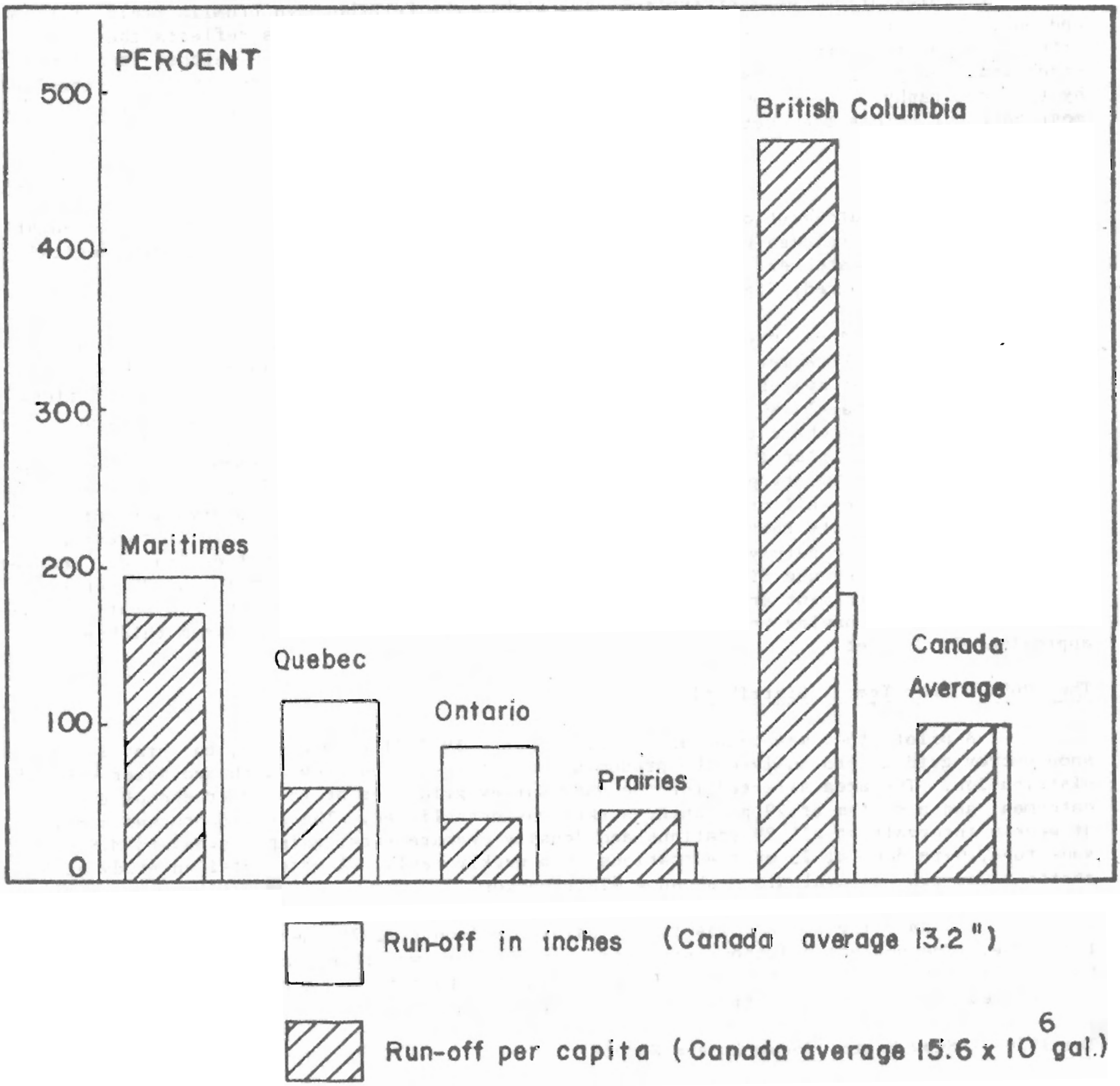
Available run-off has also been used as a basis for the regionalization of water problems. W.R.D. Sewall (1969) refers to this as the geographical incidence of the problem and views it as one of the five classifications for the various water problems. Such regionalization can operate at a variety of scales, from very local and relatively minor drainage problems to provincial water scarcity problems and to international pollution of lakes and rivers.

On a provincial scale a tremendous difference in run-off per capita figures exists. D. Cass-Beggs has used the run-off per-capita ratio as a measure of water scarcity on this provincial scale (Figure 1). At one extreme Ontario and the Prairie provinces are well below the national average at .35 and .39 of the average respectively. At the other extreme British Columbia has more than 4 times the national average.

This provincial regionalization appears to be a sound framework from which to tackle national problems. The solution of provincial problems must logically come from within the province and therefore a number of sub-regions should be identified. Davar (1972) has suggested the regionalization of snowmelt prediction. Within the Ontario region one such proposed sub-region could be the Peterborough Drumlin Field.

The Peterborough Drumlin Field Hydrologic Sub-Region

Recognized as a distinct physiographic region by Chapman and Putnam (1966), the Peterborough Drumlin Field covers some 1750 square miles between the Oak Ridges inter-lobate moraine and the Canadian Shield. Climatically, as represented by the city of Peterborough, the region is transitional between that of the north shore of Lake Ontario and that of the Canadian Shield to the north, having a mean temperature of 43.8°F and 23.7" of rain and 65.5" of snow. Hydrologically its major rivers and streams form a system of drainage



Run-off per capita for settled areas as a percent of Canadian average.

Figure 1

flowing into the Trent Canal system, the major west-east drainage system flowing through southern Ontario, Figure 2.

The area surrounding the city of Peterborough is recognized by Chapman and Putnam as representing the most typical area within the Peterborough Drumlin Field,(Fig. 3 and 3a). The occurrence of forested areas lying between the drumlins reflects the orientation of the drumlins at S25W, and corresponding to the forested patches is a lower order drainage pattern consisting of wetland areas connected by streams strongly controlled by the topography. These lower order streams drain into higher order streams which for the most part cut across the overall trend of the topography.

The Study Catchment

A study catchment of some 125 acres (0.51 km^2) was selected as being representative of the lower order drainage basins. The existence of the Trent University climatological station within the catchment selected, provided the basis for the meteorological instrumentation required, Figures 4 and 4a.

The study area covers one complete inter-drumlin swale. It is drained by a third order stream (Strahler Classification) which has two second order streams draining into it from adjacent swales of similar shape, size, vegetation and other characteristics. The area is approximately 40 per cent forested. The drumlin sides are generally open pasture, but forested where the slopes are very steep. Cedar (Thuja occidentalis), Elm (Ulmus Americanus), Poplar (Populus tremuloides), and Maple (Acer saccharum) are the major tree species found. Twenty per cent of the swale is considered swampland by virtue of its flooded condition over all or most of the year. The Otonabee Region Conservation Authority's Land Use Report suggests that 32 per cent of the Peterborough Drumlin Field is forested, based on a 20,000 acre survey. The total percentage of swampland is not estimated. However, by deduction from land use figures given, it is estimated to be between 15 and 20 per cent. The soils of the catchment are Otonabee loam on the drumlin slopes and organic peat and muck in the lower areas, having been developed upon a calcareous till of a minimum thickness of approximately 20 feet.

The 1969-70 Snow Year: Distribution

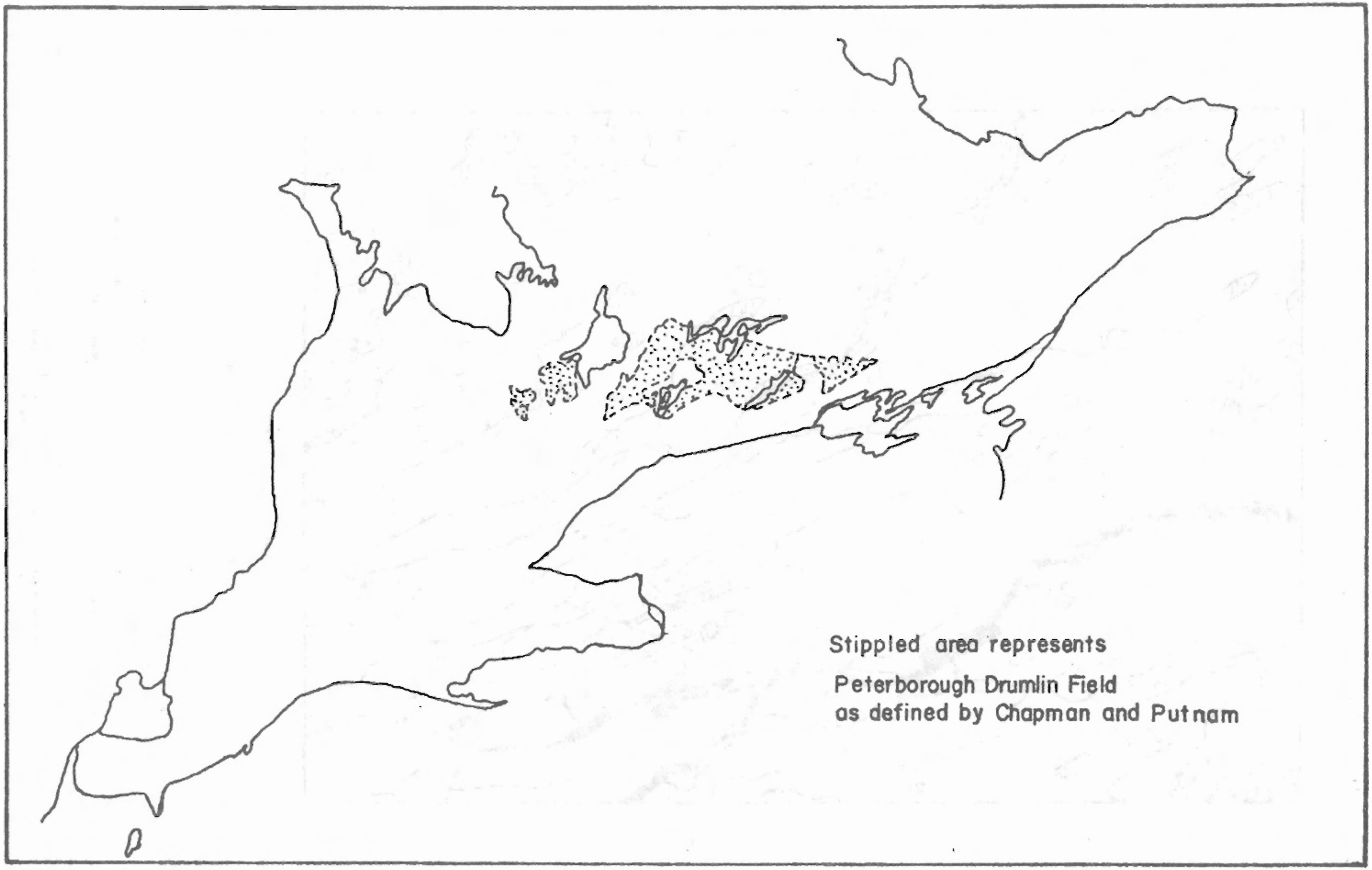
A pilot study was undertaken, prior to the 1970-71 snow season, to establish a snow survey grid and to analyse the predominant factors in the snow depth and water equivalent distribution. The area selected for the snow survey grid lies at the lower end of the catchment and a system of 29 permanent stakes was established. The snow depth was sampled at weekly intervals at all 29 stations and density measurements, using a standard M.S.C. snow tube, were done at 12 of the stations on a weekly basis. A more detailed study at 86 stations was done to evaluate peak snow distribution.

The sampling pattern was tested using Morrison's (1970) nearest neighbour analysis technique. The nearest neighbour statistic for the grid was found to be 1.93, well above Morrison's critical value of 1.25. Thus the sampling pattern was accepted as representative of the area within the grid, Figures 5,6,7,8,9,10,11.

The 1970-71 Snow Year: Snowmelt and Runoff

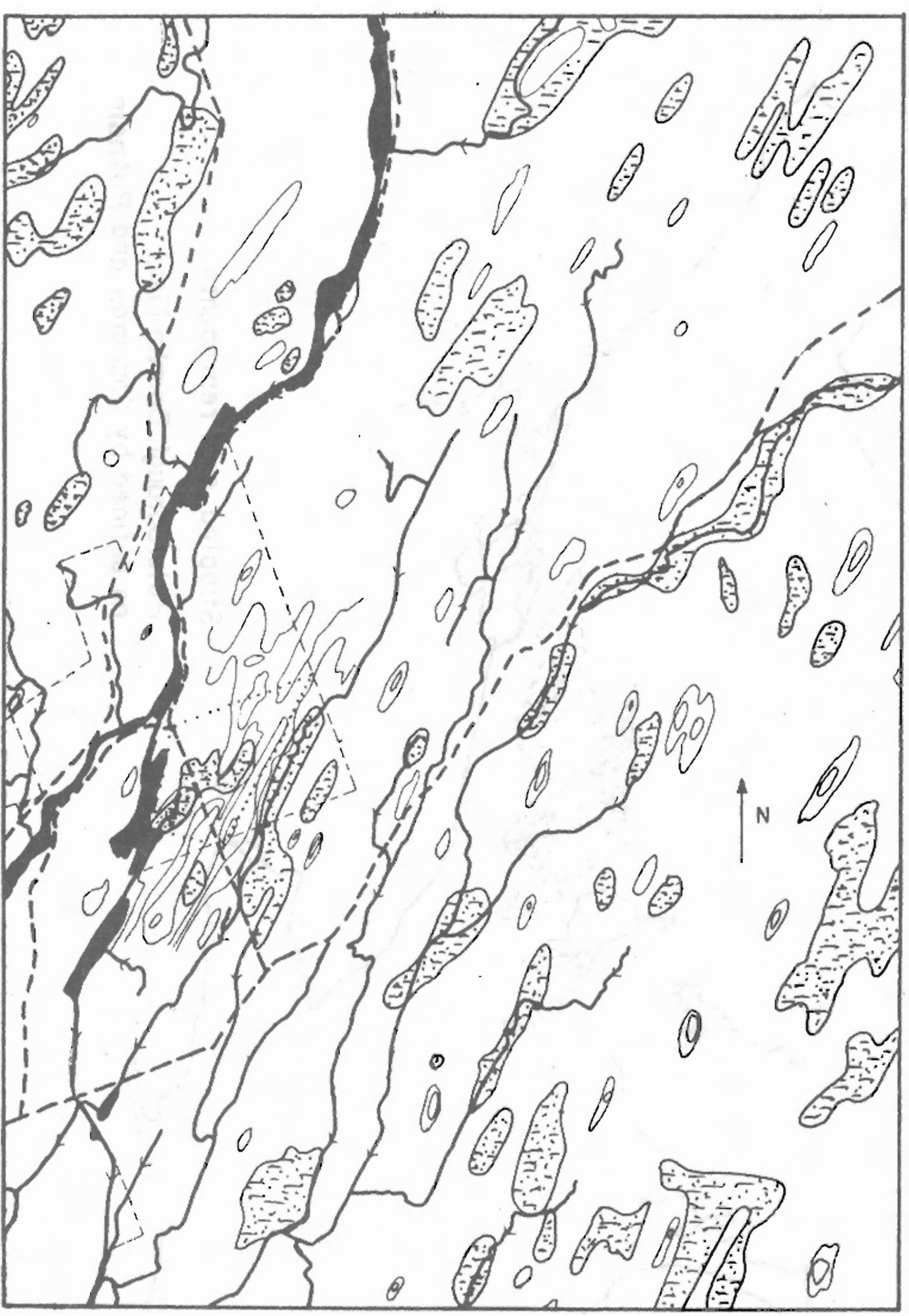
The 1970-71 snow year was used as a test year to study the melt and run-off characteristics of the study catchment with a view to establishing some basic generalizations concerning the run-off of the lower order catchments within the Peterborough Drumlin Field. Specifically the study took place during a 12 day period during which the most active melt was occurring.

The study was designed to test techniques for measuring melt and to look at the run-off characteristics of the inter-drumlin swale. The generalized snowmelt equations developed by the U.S. Corps of Engineers (1956) were employed with appropriate basin modifications. The calculated melt from this method was compared to snow tube measurements of melt which were done at the outset of the 12 day period, at the mid-point and at the end.



Stippled area represents
Peterborough Drumlin Field
as defined by Chapman and Putnam

Figure 2



DRAINAGE AND TOPOGRAPHY

OF THE STUDY AREA AND SURROUNDINGS

LEGEND

Wetland

Drumlin crest

Stream with direction of flow

Peterborough city limits

Boundary of study catchment

Major road

0 1000 metres

Scale 1:50,000

THE STUDY CATCHMENT

LEGEND

Catchment boundary

stream with direction of flow

● 1 stream gauging station

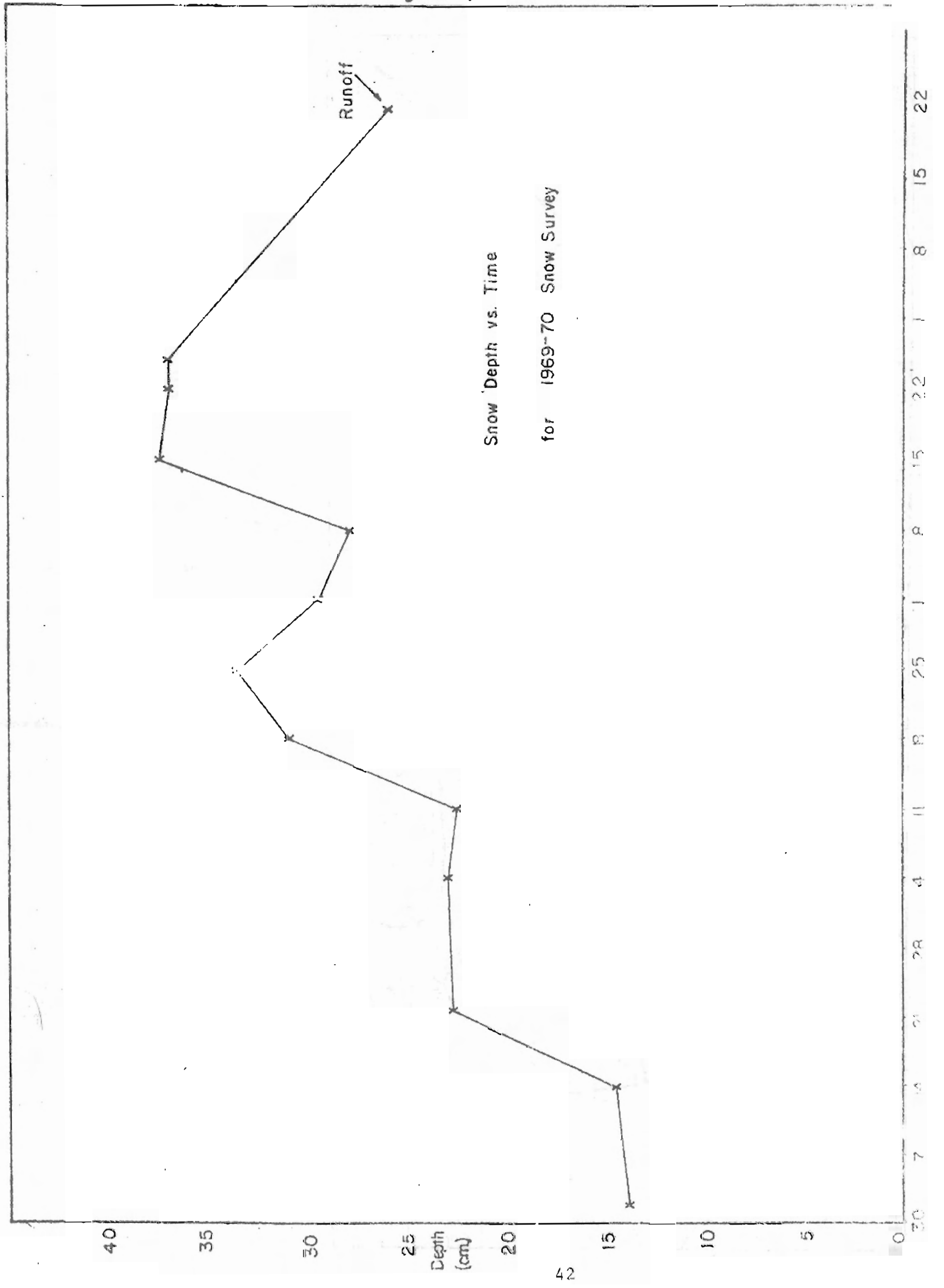
boundary of forested area

☐ Trent University Climatological station

x show measurement site

0 400' Scale

Figure 5


Snow Depth vs. Time
for 1969-70 Snow Survey
Runoff
Depth (cm)
40
35
30
25
20
15
10
5
0
30
7
14
21
28
4
11
18
25
1
8
15
22
1
8
15
22

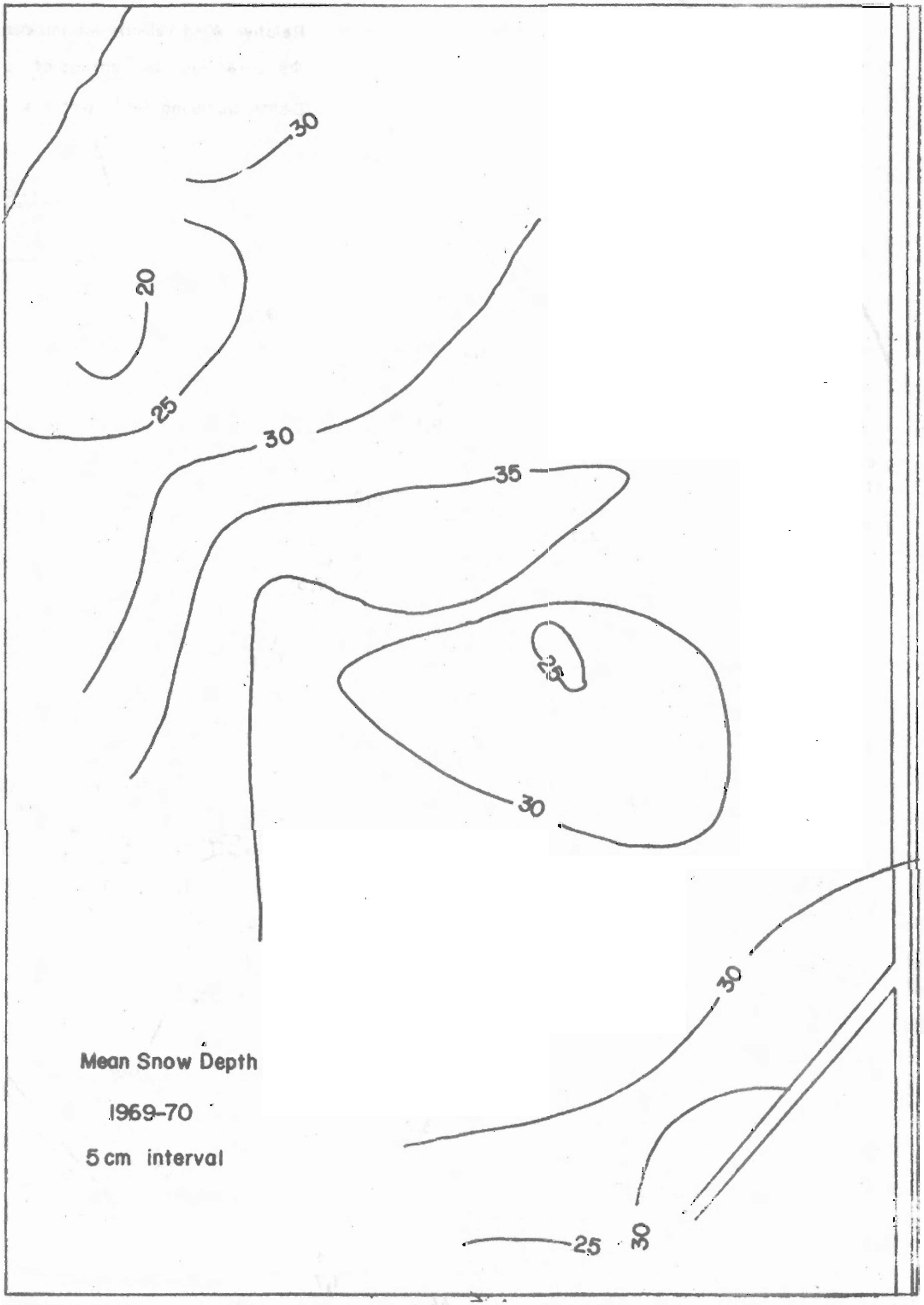

30
20
25
30
35
25
30
30
25
30
Mean Snow Depth
1969-70
5 cm interval

Figure 6

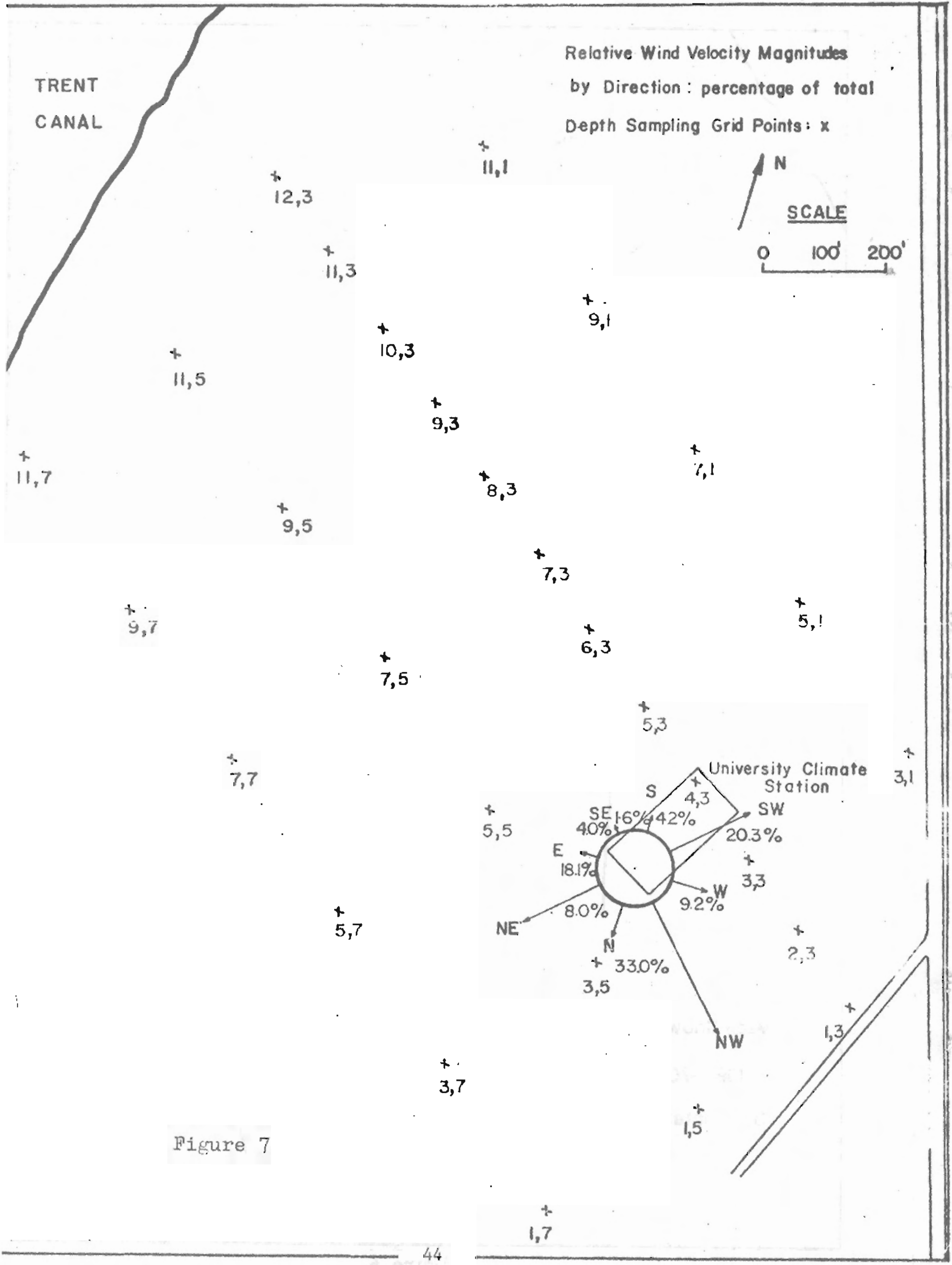

TRENT
CANAL
Relative Wind Velocity Magnitudes
by Direction : percentage of total
Depth Sampling Grid Points : x
N
SCALE
0 100' 200'
11,1
12,3
11,3
9,1
10,3
11,5
9,3
7,1
11,7
8,3
9,5
7,3
5,1
9,7
6,3
7,5
5,3
3,1
7,7
University Climate Station
S
4,3
SW
SE
1.6%
4.2%
4.0%
5,5
20.3%
E
18.1%
3,3
W
9.2%
8.0%
5,7
NE
N
33.0%
2,3
3,5
1,3
NW
3,7
1,5
1,7

Figure 7

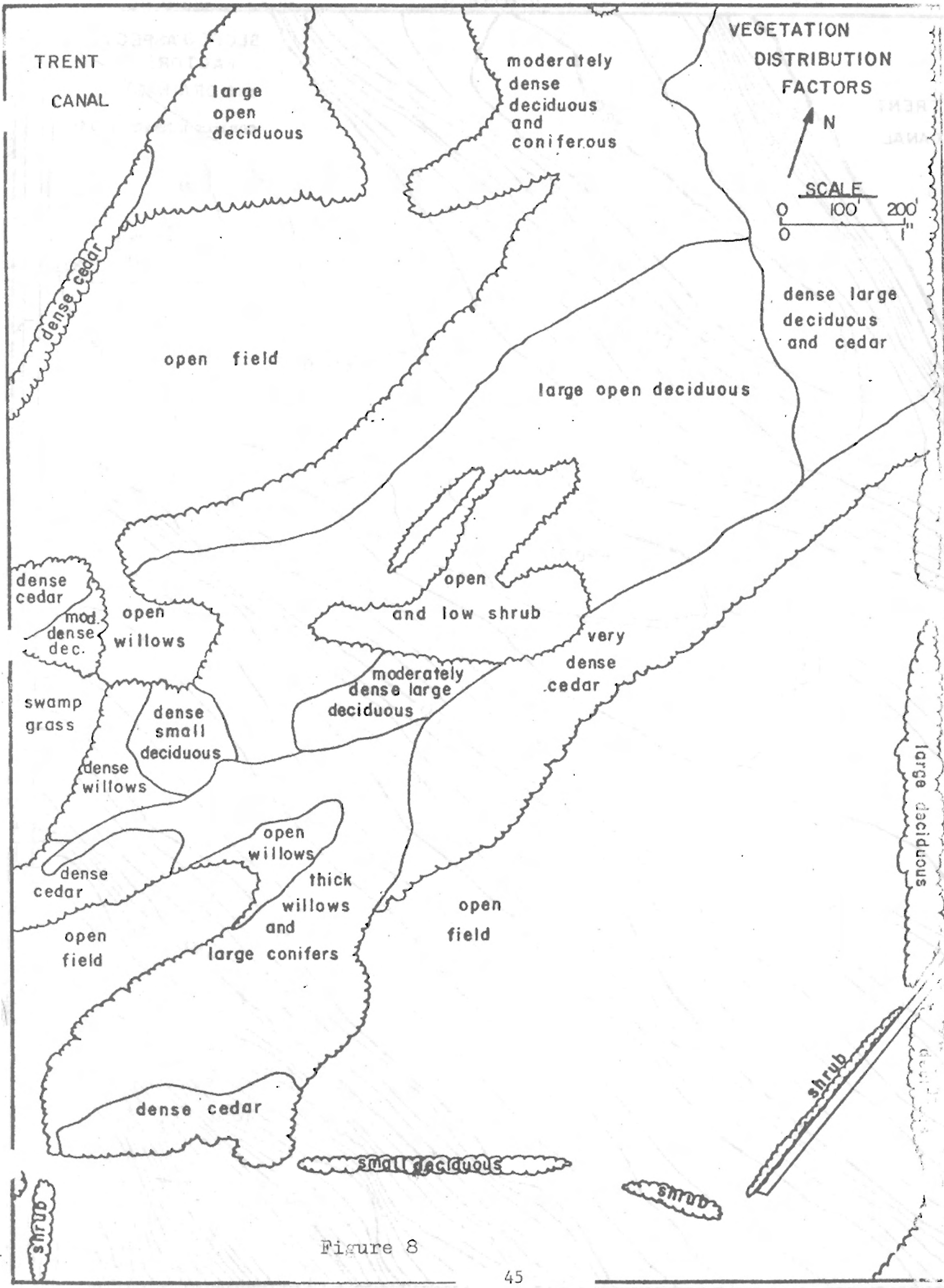
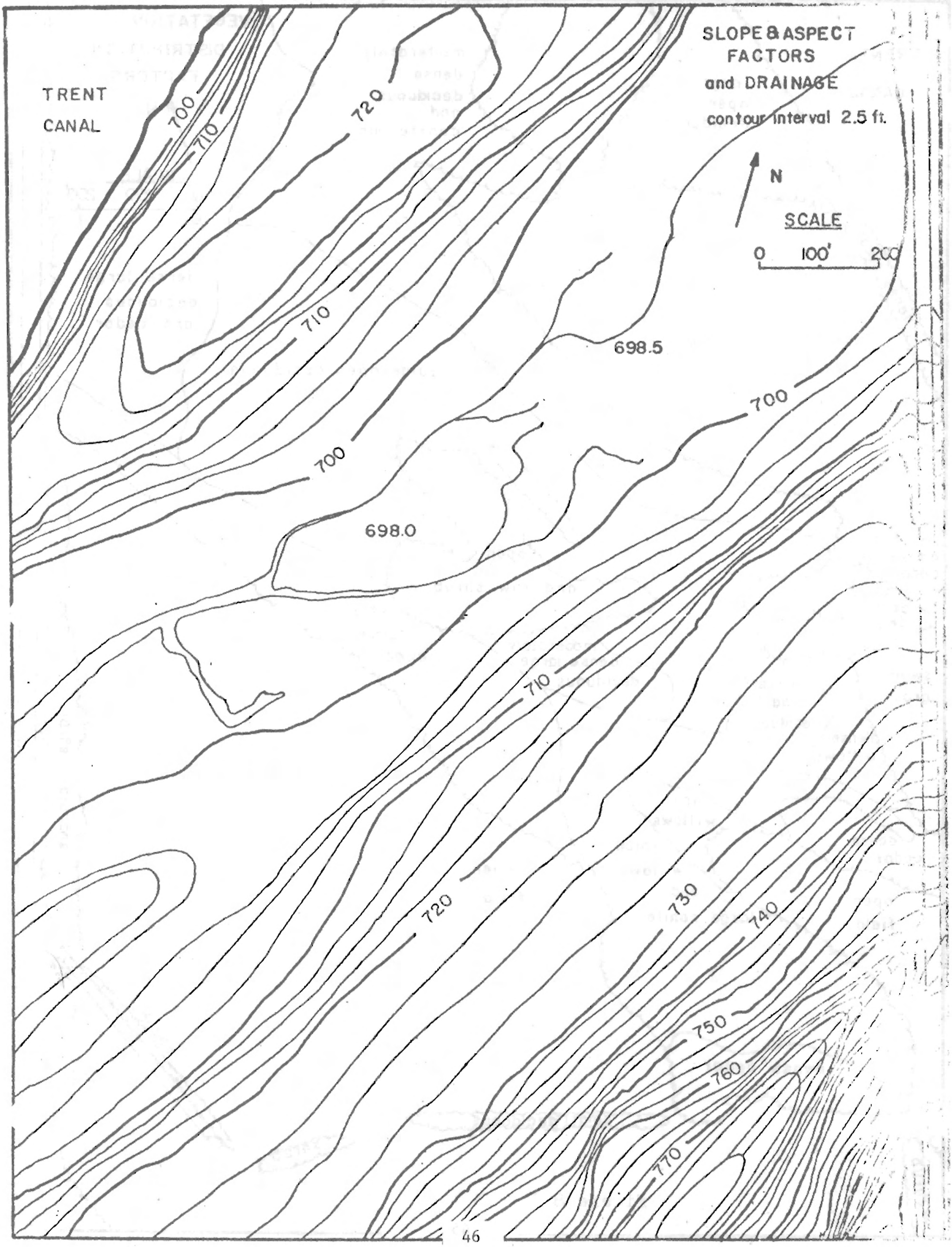
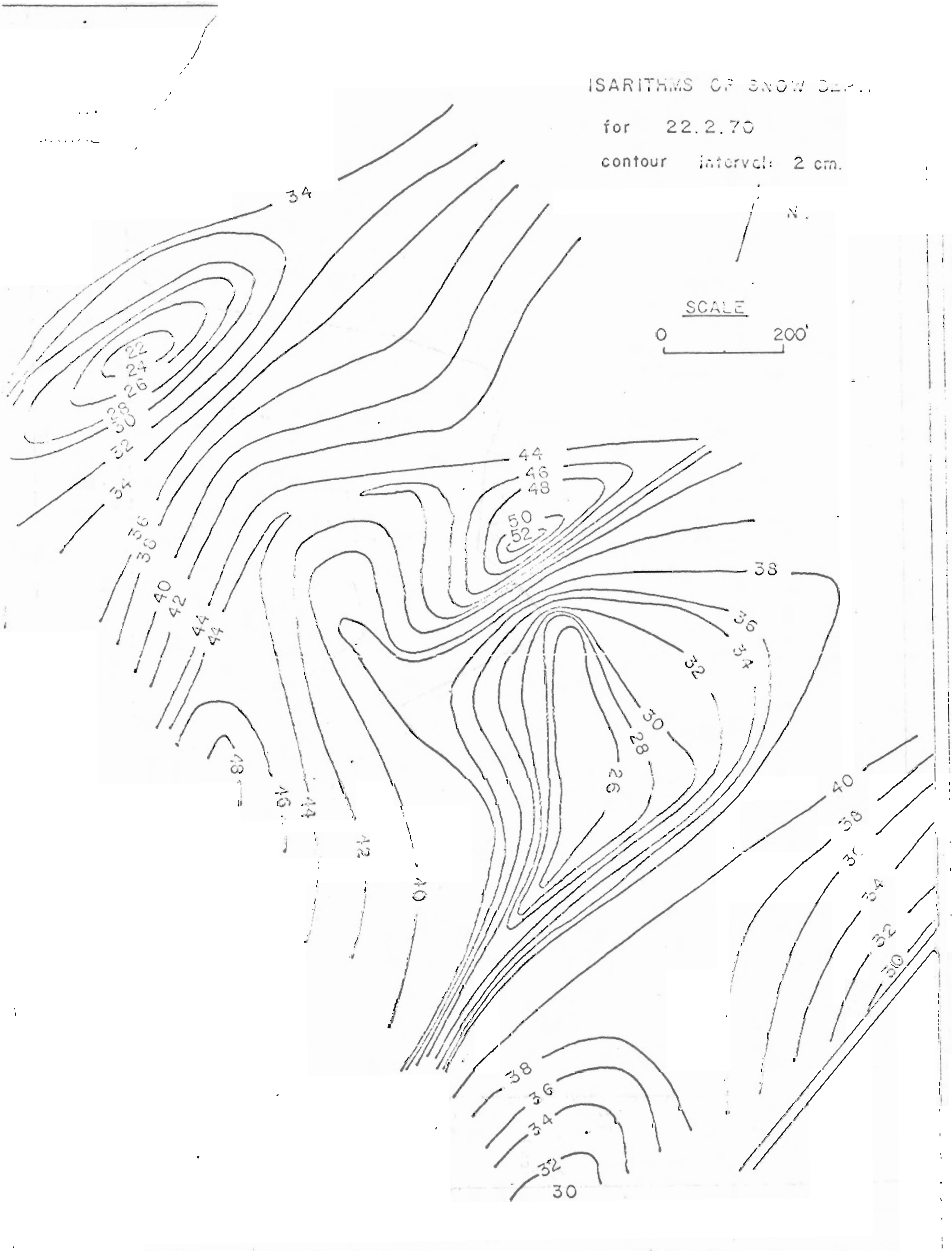

VEGETATION DISTRIBUTION FACTORS
N
SCALE
0
100'
200'
0
1"
TRENT CANAL
large open deciduous
moderately dense deciduous and coniferous
dense cedar
open field
dense large deciduous and cedar
large open deciduous
dense cedar
mod. dense dec.
open willows
open and low shrub
very dense cedar
moderately dense large deciduous
swamp grass
dense small deciduous
dense willows
open willows
dense cedar
thick willows and large conifers
open field
open field
large deciduous
dense cedar
small deciduous
shrub
shrub
shrub

Figure 8

Figure 9


TRENT
CANAL
SLOPE & ASPECT
FACTORS
and DRAINAGE
contour interval 2.5 ft.
N
SCALE
0
100'
200
700
710
720
710
698.5
700
700
698.0
710
720
730
740
750
760
770



ISARITHMS OF SNOW DEP

for 22.2.70

contour interval: 2 cm.

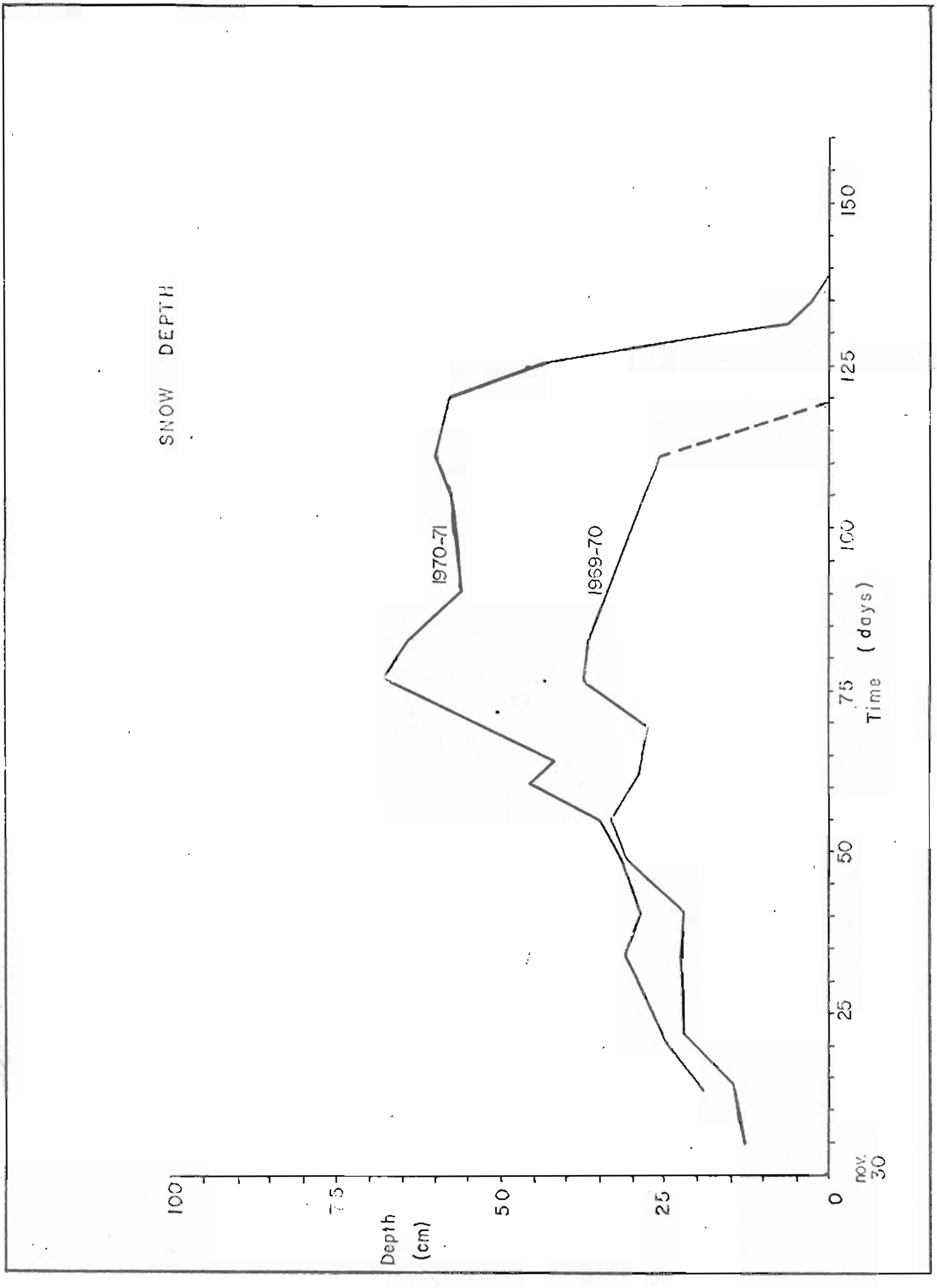

SNOW DEPTH
1970-71
1969-70
Depth (cm)
100
75
50
25
0
Time (days)
nov. 30
25
50
75
100
125
150

Figure 11

A brief outline of the components used in the melt equations is shown in Figures 12 and 12a. The two methods agree within 9 per cent over the 12 day period.

Part two of the study was designed to test both the representativeness of the sample grid to the entire 125 acre catchment and the standard M.S.C. snow tube measurement technique. The snow melt data as derived from the grid measurements was extrapolated over the entire catchment to yield an estimated total run-off from snowmelt. This estimated run-off was then compared to actual stream flow during the study period. A gauge was set up at each of the two input points to the study basin and a third gauge was established near the outlet of the catchment. The difference in flow between the input and the output was the actual available run-off from snowmelt. The snow tube and melt equation methods agree to within 11 and 17 per cent respectively of the actual stream flow. These differences, in view of the instrumentation and assumptions employed, Figures 13 and 13a, are quite acceptable. The percentage errors during the early and latter portions of the melt differ considerably and warrant some comment. The snow tube method and melt equation methods differed from the actual flow by 45.3 and 67.6 per cent respectively during the period March 30 to April 4, 1971. During the period April 4 to April 11, 1971 the differences had been reduced to 2.6 and 1.6 per cent respectively.

This large initial difference appears to stem from the recharging of the wetland by the initial run-off. As the wetland storage capacity nears maximum, more of the run-off can then enter the stream. Thus near the end of the snowmelt the differences become progressively less. It also appears that there may be an abnormally long lag period occurring in this catchment. Unfortunately the records end on April 11, 1971 due to a broken control dam which makes this speculative.

Soil moisture measurement, using the gravimetric method, were made during the summer months following a rain, (greater than ½"/24 hours), to evaluate field capacity, and then again prior to the melt period. Figure 14 illustrates the corporative results which indicate that the soil was greater than or equal to field capacity prior to the melt, throughout the basin. In addition it was found that 95 % of the basin had no frost present in the soil, due to the extremely heavy snow accumulation which provided insulation against low air temperatures.

During the melt period, overland flow was observed throughout the area immediately to the south-east of the wetland area, through sample points (5,1), (5,3), (5,5) and (5,7) and up slope to approximately the 720-725 ft. contour. In addition ponded water was observed in an area near point (3,1) and throughout a slight depression following the 735 ft. contour.

These measurements and observations suggest that during the snow melt period the variable contributing area or partial area appears to play an important part in the melt water - ground water - stream flow-over land flow interrelationship in this catchment. This is obviously linked to the variable error in predicted vs. actual flow throughout the melt and the hypothesized extended lag.

An additional error in the method can be found in that, between the melt and stream flow stages infiltration and evapotranspiration are processes acting on the run-off. While no quantitative evidence is available from this catchment, Erickson and McCorquodale (1966) found 8% evaporation losses for their simulation of the Manicouagan River basin and estimated infiltration losses at 0.057 inches per day. Infiltration as a source of error has been discounted. If evaporation from snow surfaces is further discounted as insignificant during the study period (since there were only 14 hours during which there was sufficient energy to produce sublimation), then the only other loss remaining is evaporation from open water surfaces. The use of Meyer's (1915) mass transfer equation yields a possible loss of 0.073 inches or 1.2% of the total melt, due to evaporation from open water surfaces. This correction then reduces the differences between the snow tube and melt equation methods and the stream flow values to 9.3 and 15.9 per cent respectively.

Conclusions

The effect of the interdrumlin wetlands upon the groundwater - overland flow-

	Date	Ii	a	v	Pr	S	$\bar{T}$	$\bar{D}$	M	%	Aw
P.M.	30,3	190	81	5.0	-	-	29	17	.211	100	.211
	31,3	515	70	4.0	-	-	28	22	.461	100	.461
	1,4	110	63	6.1	-	-	36	30	.337	100	.337
A.M.	2,4	240	70	6.2	.35	-	37	29	.049	100	.049
P.M.	2,4	240	70	6.2	-	-	37	29	.328	100	.328
	3,4	115	81	5.5	-	.02	32	26	.201	100	.201
	4,4	490	70	4.3	-	.05	26	19	.234	100	.234
	5,4	550	63	4.0	-	-	28	21	.586	100	.586
	6,4	560	60	3.3	-	-	27	16	.669	100	.669
	7,4	570	58	6.3	-	-	32	15	.959	97	.954
	8,4	580	56	4.0	-	-	30	23	.702	85	.595
	9,4	400	54	7.2	-	-	39	25	.609	74	.451
	10,4	555	52	4.8	-	-	33	21	.991	57	.565
A.M.	11,4	560	50	4.5	-	-	34	27	.404	50	.202

Calculated Melt	6.076
Actual Melt from Snow Tube	5.600
Measurements	.476-diff.

$\frac{.476}{5.600}$ x 100 = 8.5% difference

Figure 12

Clear Weather Melt Equation:

$$M = k' \ (1 - f) \ (4 \times 10^{-3} Ii) \ (1 - a) + k(8.4 \times 10^{-3} v)$$
$$(2.2 \times 10^{-1} T'a + 7.8 \times 10^{-1} T'd) + f(2.9 \times 10^{-2} T'a) + 2 \times 10^{-2}$$

Melt Equation for Periods of Rain:

$$M = (2.9 \times 10^{-2} + 8.4 \times 10^{-3} kv + 7 \times 10^{-3} Pr) \times (T'a) + (1 - f) \ (7 \times 10^{-2}) + 2 \times 10^{-2}$$

(Modified after Findlay [1966][13])

M = melt in inches/day

k' = short wave radiation melt coefficient. It equals 1 for horizontal basins and when north and south facing slopes are equal in area. The latter is assumed to hold for the study catchment.

f = percentage of study area forested. For the grid area f = .44 (44%)

Ii = incident solar radiation (ly/day). This component was derived from duration of bright sunshine data using the Hamon, Weiss and Wilson method (1954).[20]

a = albedo of the snow cover. This was derived from the graphical relationship of albedo to time during the melt season as presented in Snow Hydrology.[18]

k = a basin constant which assesses the effect of forest on wind speed.

$k = 1 - 0.7f \quad \therefore \quad k = 0.608$ for the study basin

v = mean wind speed at a height of 10 m. This was derived from 1 m. mean wind speeds and extrapolated to 10 m. using the power relationship over a snow cover developed by Longley (1970).[21]

T'a = the air temperature difference between the screen and the snow surface assumed to be at 32 F.

T'd = the difference between the dewpoint temperature and the snow temperature assumed to be at 32 F.

Pr = daily rainfall in inches

8.4×10^{-3} = convection-heat of vaporization coefficient

4×10^{-3} = theoretical melt coefficient for absorbed short-wave radiation

2.2×10^{-1} = effective weight of air temperature in producing convection-condensation melt

7.8×10^{-1} = effective weight of dewpoint temperature in producing convection-condensation melt

2.9×10^{-2} = net long-wave radiation melt coefficient

2×10^{-2} = assumed melt caused by ground heating

7×10^{-3} = rainfall melt coefficient

7×10^{-2} = short-wave radiation melt coefficient during period of rainfall

S = snowfall (inches of water)

$\overline{T}$ = average temperature (°F)

$\overline{D}$ = average dewpoint temperature (°F)

% = percentage of basin snow covered

Aw = available water

Figure 12a

1200 hrs
Mar 30
to
1200 hrs
Apr. 4

Gauge site 1 - area under curve = 59.7-4.5 (base flow correction)

Gauge site 2 + 3 - area under curve = 43.7

1 - (2 + 3) = 11.5 squares.

Note: base flow
assumed to
= .25 q. secs

1 sq = $4.32 \times 10^4 ft^3$

∴ discharge = $11.5 \times 4.32 \times 10^4 = 4.97 \times 10^5 ft^3$

1200 hrs
Apr. 4
to
1200 hrs
Apr. 11

Gauge site 1 area under curve = 171.1 - 7.0 (base flow correction)

Gauge site 2 + 3 area under curves = 120.3

1 - (2 + 3) = 43.8 sqs

∴ discharge = $43.8 \times 4.32 \times 10^4 = 1.89 \times 10^6 ft^3$

From Snow Tube Measurements and extrapolation

1200 hrs
Mar. 30
to
1200 hrs
Apr. 4

1.52" melt x $7.98 \times 10^8 in^2 = 1.21 \times 10^9 in^3$

$1.21 \times 10^9 in^3 \times 1.728 \times 10^3 ft^3/in^3 = 7.02 \times 10^5 ft^3$

1200 hrs
Apr. 4
to
1200 hrs
Apr. 11

4.2" melt x $7.98 \times 10^8 in^2 = 3.35 \times 10^9 in^3$

$3.35 \times 10^9 in^3 \times 1.728 \times 10^3 ft^3/in^3 = 1.94 \times 10^6 ft^3$

Differences between "calculated" and "actual" melts

1200 hrs Mar 30 to 1200 hrs Apr 4: $7.02 \times 10^5 - 4.97 \times 10^5 = 2.25 \times 10^5$

$$\frac{2.25 \times 10^5}{4.97 \times 10^5} \times 100 = 45.3\% \text{ difference}$$

1200 hrs Apr 4 to 1200 hrs Apr 11: $1.94 \times 10^6 - 1.89 \times 10^6 = 0.05 \times 10^6$

$$\frac{0.05}{1.89} \times 100 = 2.6\% \text{ difference}$$

1200 hrs Mar 30 to 1200 hrs Apr 11: $2.64 \times 10^6 - 2.39 \times 10^6 = .25 \times 10^6$

$$\frac{.25}{2.39} \times 100 = 10.5\%$$

Figure 13

From Generalized Melt Equation and Extrapolation

1200 hrs Mar. 30 to 1200 hrs Apr. 4	$1.80'' \times \text{melt} \times 7.98 \times 10^8 \text{in}^2 = 1.44 \times 10^9 \text{in}^3$ $1.44 \times 10^9 \text{in}^3 / 1.728 \times 10^3 \text{ft}^3/\text{in}^3 = 8.33 \times 10^5 \text{ft}^3$
1200 hrs Apr. 4 to 1200 hrs Apr. 11	$4.256'' \text{ melt} \times 7.98 \times 10^8 \text{in}^2 = 3.40 \times 10^9 \text{in}^3$ $3.4 \times 10^9 \text{in}^3 / 1.728 \times 10^3 \text{ft}^3/\text{in}^3 = 1.97 \times 10^6 \text{ft}^3$

Difference between Melt Equation and "Actual"

1200 hrs Mar. 30 to 1200 hrs Apr. 4: $8.33 \times 10^5 - 4.97 \times 10^5 = 3.36 \times 10^5$

$$\frac{3.36}{4.97} \times 100 = 67.6\%$$

1200 hrs Apr. 4 to 1200 hrs Apr. 11: $1.97 \times 10^6 - 1.89 \times 10^6 = .03 \times 10^6$

$$\frac{.03}{1.89} \times 100 = 1.6\%$$

1200 hrs Mar. 30 to 1200 hrs Apr. 11: $2.80 \times 10^6 - 2.39 \times 10^6 = .41 \times 10^6$

$$\frac{.41}{2.39} \times 100 = 17.1\%$$

Storage by inter-drumlin wetland

from difference between snow tube and "actual" = $2.5 \times 10^5 \text{ft}^3$ = 10.5% of potential

from difference between generalized melt equations and "actual" = $4.1 \times 10^5 \text{ft}^3$ = 17.1% of potential

Average difference = $3.3 \times 10^5 \text{ft}^3$

= 13.8% of potential runoff

Figure 13a

stream flow regime of the drumlin field region appears to be of major significance. An evaluation of these interrelationships in a detailed fashion will add greatly to the understanding of the behaviour of the timing, quantity and regime of snow melt run-off. The strength of the generalized melt equations in their application to this characteristically drumlinized landscape of south-central Ontario has been demonstrated. Utilizing basic meteorological parameters and a simple grid snow course this technique has been seen to provide relatively good predictions of snow melt. In order to improve this predictiveness a more detailed knowledge of the influence of the interdrumlin wetlands must be acquired.

Acknowledgments

I would like to thank Dr. W.P. Adams for his support and guidance, Mr. Doug Barr for his assistance and to all the others in the Dept. of Geography, Trent University, who helped in so many ways. The assistance of Mr. Hardy Granberg, Dept. of Geography, McGill University, and my wife, Heather, in proofreading this paper is also acknowledged. The National Advisory Committee for Geographical Research, Canada and the National Research Council, Canada aided this work financially.

Soil Moisture Readings

Station Number	Percentage Soil Moisture		Percentage Difference (Percentage [a] - Percentage [b])
	(a) 28,2,71	(b) 27,7,71	
1,3	17.6	18.2	- .6
2,5	31.3	11.4	+19.9
3,1	17.4	15.6	+ 1.8
3,7	35.5	28.7	+ 6.8
4,1	19.7	11.8	+ 7.9
4,3	32.4	19.5	+12.9
4,5	28.7	22.3	+ 6.4
4,11	20.6	7.0	+13.6

Figure 16

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