Snow Accumulation and Climate
Over the Grand Lake Catchment, Newfoundland

C.E. BANFIELD
Department of Geography
Memorial University of Newfoundland
St. John's, Newfoundland A1B 3X9, Canada

ABSTRACT

Late-winter snow cover over the Grand Lake catchment on the island of Newfoundland was analysed for the period 1934-1990, with the objective of examining its sensitivity to winter temperature and precipitation. Snow depth and water equivalent were obtained from annual snow survey records and compared with corresponding temperature and precipitation series from nearby climatological stations. Mean winter temperature exhibited a general warming trend until the mid-1950's followed by shorter oscillations through to the present. Winter snowfall and the snowfall/rainfall ratio showed considerable short-term variability throughout. Thus, over the period as a whole the depth and water content of the late-winter snow blanket were strongly correlated with mean winter temperature and winter rainfall, but not with winter snowfall. Within the basin variations in snow conditions are influenced by site elevation, distance inland and the overall character of winter weather.

INTRODUCTION

The winter climate of Newfoundland is conditioned by the proximity of the province (particularly the island portion) to the northwest Atlantic Ocean, with its two contrasting current systems, and to the climatological mean location of the Arctic frontal zone and associated storm tracks through the region (Banfield, 1983). The overall character of the winter weather, including the relative amounts and frequencies of snowfall and rainfall and the duration of sub-freezing periods, is strongly dictated by the behaviour of this frontal zone. Considerable variability in winter conditions can occur, inter-annually and at longer time scales, with implications for the duration and depth of the snow cover. Currently, this is of vital concern for hydrological engineers within the province, given the significance of the spring runoff for hydro-power production and flood regulation. In addition, impacts on regional snow cover of any climatic changes that may arise from escalating atmospheric "greenhouse gas" levels will require appropriate analysis, pending improved regional resolution of the climate predictive models. Within these contexts the aim of this work is to analyse the sensitivity of the late-winter snow cover to prior winter weather indices for the Grand Lake watershed on the island of Newfoundland, based on the record of its annual snow survey for the period 1934-1990.

THE GRAND LAKE CATCHMENT AND THE ANNUAL SNOW SURVEY

The Grand Lake catchment in western Newfoundland is one of the largest on the island, with a natural watershed area of 4,800 km^2 (Figure 1). Grand Lake, with a mean surface elevation of 85m, occupies a tenth of the catchment area; owing to its depth (up to 300m) it remains mostly free of ice cover during all but the coldest winters. Near-vertical cliffs rise up to 500m from its southern shores. Altitudes reach 650-700m between Hind's Lake and Little Grand Lake. Relief is lower in the northeast, where shorelines are much less steep. Logging by paper companies has removed substantial sections of the natural forest; dense tree cover occurs mainly on the steeper lake shores and in stream valleys. The altitudinal tree limit varies with exposure to wind but is generally at approximately 400-500m. Most of the uplands bear a mixture of shrubs, dwarf trees and /or heath vegetation, or are rocky and barren (Damman, 1983; Meades, 1983). Such variations in ground cover will affect accumulation and retention of snow and ultimately the watershed runoff regime.

The hydro-electric power potential of the watershed was recognised early this century. Since the completion of the Main Dam and generating plant in 1925, Deer Lake Power Company Limited (DLPC) has supplied power to domestic and industrial users in western Newfoundland; total installed capacity is 125,000 KW. Since 1977, however, almost all of the power produced has been required by the pulp and paper mill at Corner Brook. Thus, in order to produce an annual forecast of the spring runoff for planning hydro production and flood regulation, an annual snow survey has been undertaken by DLPC during the second half of March since 1926 (Green, 1965).

The snow survey sites were selected by DLPC with the objective of sampling the major physical sub-divisions within the catchment, based upon topography and annual precipitation regime. However, site density has been limited by available resources and accessibility (Figure 1). Sections of the catchment are not adequately represented, such as the high terrain to the east of Grand lake and the summit area of Glover Island. Additional sites were incorporated in the early 1930's, and climatological observations at two nearby stations began in 1933. Consequently this study utilises data from nine survey sites operated during 1934-1990, together with sites 9 and 10 which commenced in 1940 (the site numbers are those used by DLPC).

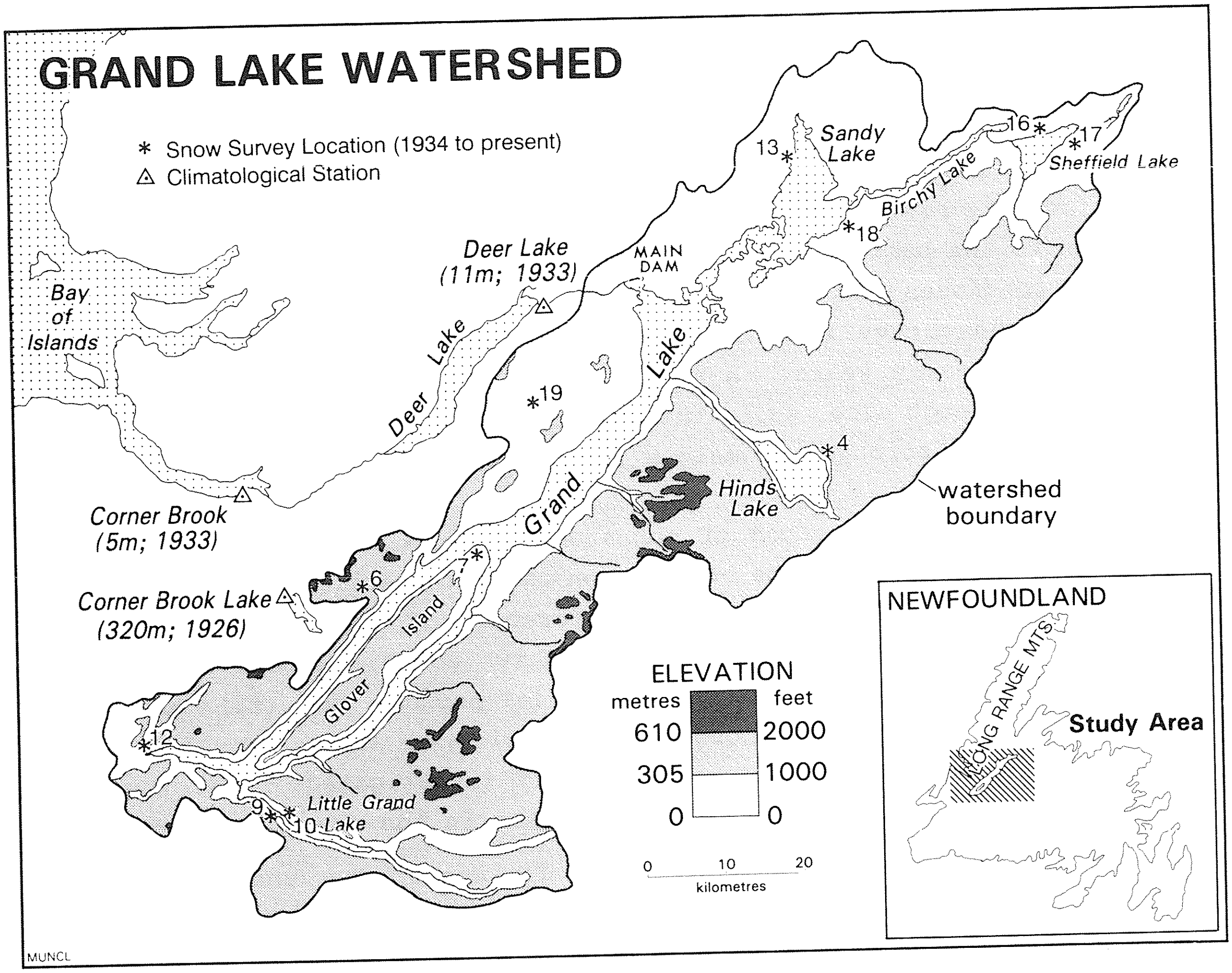

Figure 1. Grand Lake Watershed, showing snow survey sites and climatological stations used for this study.

The design of the snow courses differs from that adopted for Canadian Atmospheric Environment Service (AES) operational snow surveys (Atmospheric Environment Service, 1973). Occasional very strong winds during winter would cause excessive drifting over larger, more open courses, such as used by AES. Thus, in order to minimise this problem, most DLPC survey sites consist of three separate, near-circular small clearings occurring within an approximately level, natural forest area of 1000-2000m^2. Clearing diameter ranges from approximately 15-25m, with most surrounding tree heights 5-10m. The one exception is site 6 which occupies an upland valley having only scattered tree cover. Some sites have had to be moved short distances to make way for logging activity. It is recognised that this type of clearing configuration could result in "snow trapping" and that resulting snow depths and densities are unlikely to be representative of the windswept high elevations above the tree line.

Over the past four years the survey has utilised a Water Survey of Canada snow sampler having metric water equivalent graduation. Previously the Mount Rose sampler was used. Samples are taken away from the edge of the clearing and the base of the tube is checked for evidence of ground contact. If particularly resistant ice crusts are encountered then incremental samples are taken to the base of the snow pack. At each of the three site clearings sampling continues until three identical water equivalent readings are observed. The survey is normally completed in three days, though it took longer in the early years. A mean depth, water equivalent and density is determined for each site, using the information from all samples except those considered to be strongly anomalous for the site.

By applying the "method of sub-areas" to the survey results, a value representing the total volume of water on the catchment, in the form of snow, is determined by DLPC. Subsequently a forecast of total runoff for April 1 through June 15 is prepared, by including two additional estimates, namely (i) normal total precipitation for this period and (ii) groundwater contribution. Evaporation losses are considered small for this period, although this term has yet to be thoroughly investigated. Over the period 1934-1990 the calculated mean volume of water in the snow blanket has averaged 57% of the observed total runoff for April 1 to June 15, and 25% of the annual catchment yield. The mean error in the spring runoff forecast following the snow survey has averaged 13% (standard deviation 10%).

CLIMATIC CONDITIONS

Contemporary climatological data are restricted to three locations, all of which are just outside the catchment (Figure 1). Unfortunately the upland Corner Brook Lake record (operated by the Corner Brook Paper Company) does not clearly discriminate between snowfall and rainfall; however its long term mean total precipitation for the winter season (December through March) is 94% of that for the low-lying AES network station in downtown Corner Brook. Thus total precipitation over the western limits of the study area for these four winter months is estimated to average 400-450mm. The record for Deer

Lake, operated by DLPC for the AES network, is considered to be reasonably representative of the lowest sections of the northeastern part of the study basin (i.e. the Sandy Lake area). Here, winter precipitation is about two thirds of that at Corner Brook (Atmospheric Environment Service, 1982). This suggests that a climatological zone of maximum precipitation, produced by the combined influence of prevailing winds, the Gulf of St. Lawrence and the Long Range Mountains axis, lies through the southwestern extremity of the catchment, with a definite "rain shadow" effect over the central and northeastern sections.

During the four winter months (1951-1980) snowfall averaged 75% of total precipitation at Corner Brook, 69% at Deer Lake and 73% at Buchans (20km SE of Hinds Lake, at 276m); therefore, it is likely to be 80-90% at the highest elevations of Grand Lake catchment. There is a noticeable reduction in snowfall for February, despite the fact that this is normally the coldest month. This is attributed to a preponderance of colder, drier air masses as ice cover extends over the Gulf of St. Lawrence and the principal winter storm tracks move further to the east of the study area. The climatological mean period of maximum snow depth on the ground is early March for Corner Brook and Deer Lake and about the third week of March at Buchans (Potter, 1965). It is likely to be late March or early April over the highest terrain of Grand Lake catchment.

The analysis of the historical winter climate-snow cover relations will rely upon the temperature, snowfall and rainfall data from the Corner Brook and Deer Lake stations, whose sites have been permanent since 1933. Whilst these data will not be fully spatially representative of the Grand Lake catchment area in an absolute sense, they should be adequate for examining the general temporal variations in these climate parameters over this particular region of Newfoundland.

THE HISTORICAL RECORD OF SNOW COVER AND WINTER CLIMATE, 1934-1990

Mean snow depth, density and water equivalent for late March

The average depth of snow at the time of the survey, over the 57-year period, ranges from 62cm at the northeastern shore of Glover Island (site 7) to 123cm 15km to the west at Valley of the Lakes (site 6) (Figure 2). Elevation and distance inland from the Gulf of St. Lawrence exert a joint control over this value. Increased elevation (as at sites 4, 6 and 19) results in fewer and shorter winter melt periods and can add an orographic component to some snowfall events, depending upon accompanying winds and thermal stability. In addition, during onshore west and northwest winds, moisture from the Gulf of St. Lawrence serves to intensify snow squalls over western sections of the catchment. Consequently although melt periods would be relatively more frequent in the southwestern valleys near sites 9, 10 and 12, the average depth is greater there than at the same elevation at Sandy Lake (sites 13 and 18), since the latter area is in the "snow shadow" zone from the Long Range Mountains during W-NW airstreams.

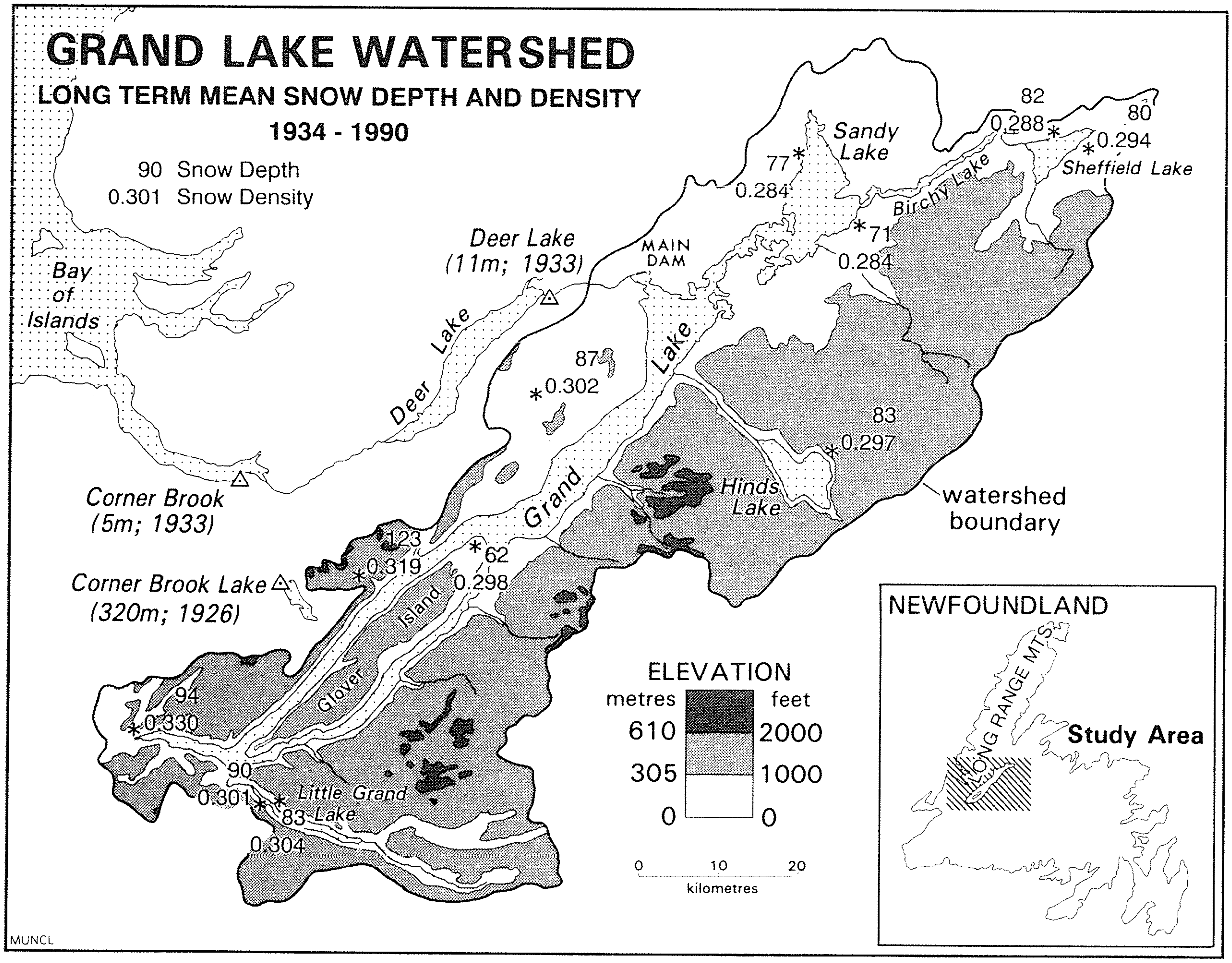

Figure 2. Long-term mean snow depth and density at snow survey sites (1934-1990).

Snow densities lie in a fairly narrow range between typical values quoted for wind-toughened snow and hard wind slab (McKay and Gray, 1981) (Figure 2). In general values increase with greater mean depth due to greater compaction and settling. The 57-year mean snow density for all sites may be compared with a value predicted from the equation of Bilello (1967) for average density of a "dry snow cover" in a given climatic region of N.

America, which is:

$$Q = 0.152 - 0.0031T + 0.019W$$

where Q = average seasonal snow cover density (g cm^{-3})

T = average air temperature for season of snow cover (assumed <0 deg C)

W = average wind speed for season of snow cover (m sec^{-1})

For the Grand Lake catchment the snow cover season is taken to be December through March; T is estimated at -6.5^0C and W at 7 m s^{-1} (allowing for variability in elevation). The resulting value for Q of 0.305 is close to the observed catchment mean density (for late season) of 0.300.

Snow water equivalent exhibits moderate variability over the period of record, as expressed by the coefficient of variation (CV). CV is slightly higher (0.38 - 0.42) at the southwestern valley sites (nos. 9, 10 and 12), where the main spring melt period normally begins a little earlier, than over the northeastern sector of the basin (CV 0.35 - 0.38). Variability in water equivalent is greater at site 7 (CV 0.52); this may be partly due to (i) a localised moderation in winter air temperatures at site 7 due to the nearby open water of Grand Lake, giving rise to more frequent slight thaws during milder winters, and (ii) exposure to stronger winds off the lake.

Historical record of winter climate and snow cover variables

For the purposes of this study the winter period is defined as December 1 to March 31; hence the winter value for each climate variable is determined as the average (or total) of the four monthly values (e.g. mean air temperature, total snowfall, mean snowfall/rainfall ratio). Each winter record refers to the average of values for the Corner Brook and Deer Lake stations.

Figure 3 illustrates the relation between short-period fluctuations and trends in mean winter temperature (TW) and the corresponding ratio of winter snowfall to winter rainfall (S/R), using five-year moving averages. The correlation between winter temperature and year is slightly positive but not significant (r = 0.12; n = 57). From the start of the record until the first half of the 1950's decade there is an overall warming trend which is mostly concentrated into the early and latter segments of this period. A period of high inter-annual variability followed until the early 1960's, including the mildest winter of the record (1958) and three of the coldest. Following a second temperature peak in the late 1960's a significant if short-lived cooling trend characterised the early years of the 1970's.

However the last two decades have also produced contrasting trend directions as the mild early 1980's were succeeded by a continuing cooling trend. Overall, the principal oscillations in winter temperature for this area are similar to those reported elsewhere in eastern Canada over the past four decades (Berry, 1991). Since the precipitation data used to determine the S/R ratios are from AES climatological stations, the original observed depth of snowfall was converted to millimetres of water equivalent using a constant density of 0.10. Over most of the record the direction of the short-term trends of S/R opposes the temperature trends, as may be anticipated over this range of temperatures. However, different periods may experience similar S/R despite significant differences in mean winter temperature, such as the mid-1950's and early 1970's. The correlation between the individual yearly values of TW and S/R is not significant (r = -0.27; n = 57).

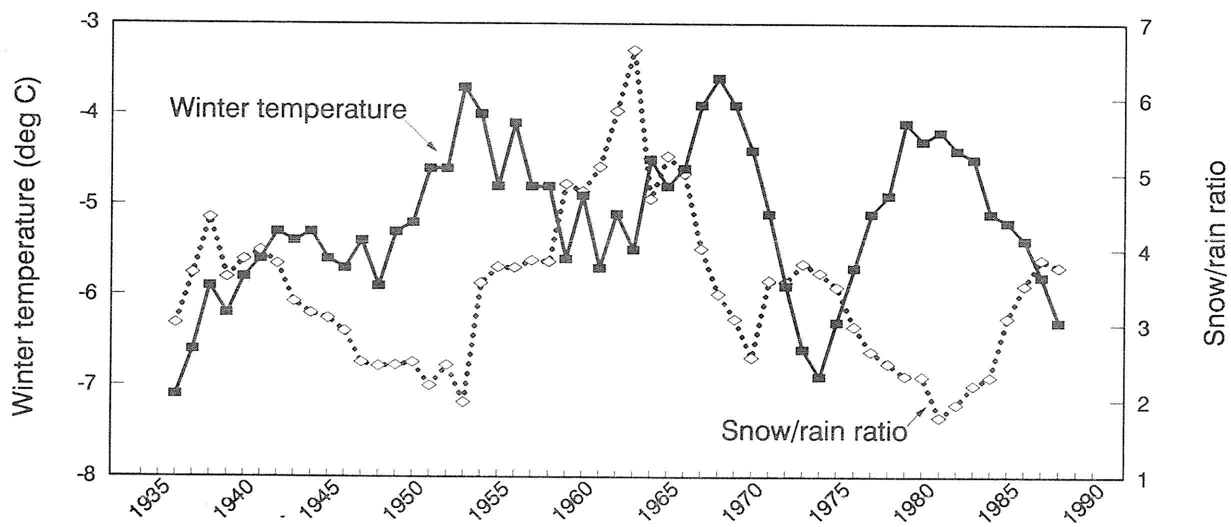

Figure 3. Historical mean winter temperature and winter snowfall/rainfall ratio for Corner Brook-Deer Lake, 1934-1990 (five year moving averages, centered on year 3).

Using the snow survey data for the eleven sites previously identified (Figure 1), an historical record of mean snow depth and water equivalent for the catchment has been constructed (Figures 4 and 5). In 1958, the mildest winter of the record, the survey was not carried out due to insufficient snow cover. For this year an estimate of mean depth (5cm) and water equivalent (1.25cm) are determined from examination of the observed spring runoff and spring precipitation, using a density of 0.25. The most distinct feature of the depth and water equivalent records is the overall strong decline in the amounts from the beginning of the period until the second half of the 1950's, followed by a partial recovery into the early 1960's. Subsequently, over the past 25 years, there have been more frequent reversals in the direction of the five-year moving averages, with the rising and falling limbs each lasting 5 to 7 years. Figure 5 also compares the five-year moving average of water equivalent with that of winter temperature. Peaks in water equivalent generally occur at times of reduced winter temperature, and vice-versa, although again this is less clearly demonstrated during the past two decades. For the period as a whole the yearly values of these two elements exhibit a significant negative correlation (r = -0.49; n = 57).

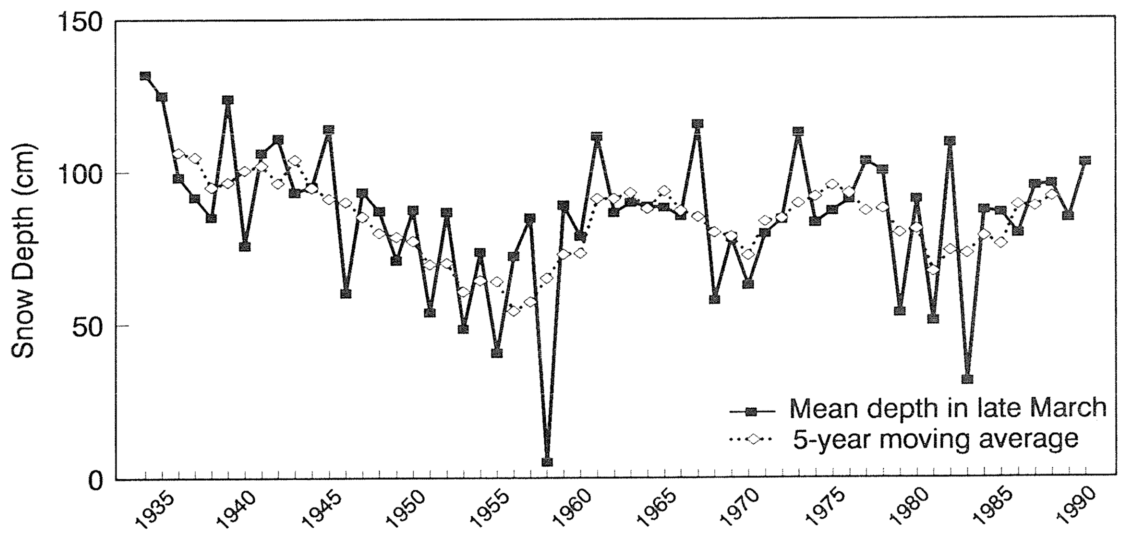

Figure 4. Historical record of mean depth of snow at time of annual snow survey, 1934-1990.

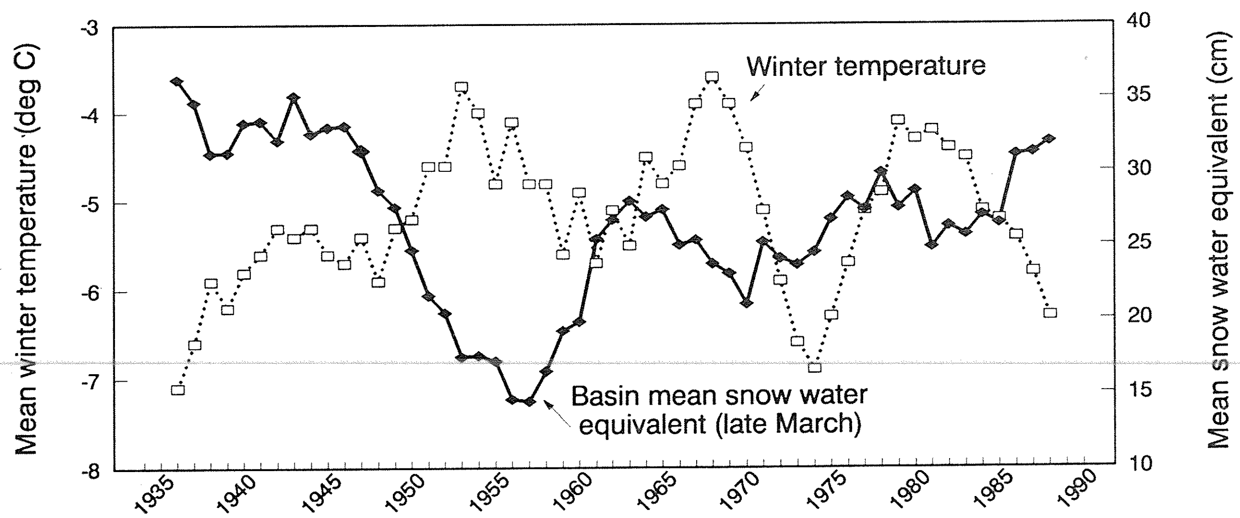

Figure 5. Historical record of mean water equivalent of snow (at time of annual snow survey) and mean winter temperature, 1934-1990 (five-year moving averages, centered on year 3).

SIGNIFICANCE OF WINTER TEMPERATURE AND PRECIPITATION FOR LATE-MARCH SNOW COVER

Given the climate of this catchment the variance in snowpack depth and water equivalent in late March should be strongly controlled by weather factors during the previous winter months, which exert varying degrees of influence during earlier and later parts of the season. The historical record described above will form the basis for a statistical analysis of the significance of air temperature and precipitation variables for late March snow conditions and the ensuing spring runoff.

Firstly, correlations between these variables are tabulated for (a) the full winter period (December through March) and (b) February-March, based upon the records for 1934-1990 (Table 1). It is notable that mean temperature is significantly correlated with rainfall but not with snowfall, for both periods. The records indicate that a wide range of snowfall is possible with mean winter temperatures of approximately -4.0 to -8.0^{0}C. Temperature and the snowfall/rainfall ratio are significantly correlated only for February-March. Neither the depth nor the water equivalent of the snowpack in late March is significantly associated with the amount of snowfall during the winter. However, the highly significant relation between temperature and rainfall for December-March results in both these elements being strongly correlated with depth and water equivalent. Snow depth is more strongly correlated with the weather variables than is water equivalent. Finally, the rainfall for December-March is the only individual winter weather variable to show a significant association with observed spring runoff.

In order to specify further the magnitude of the principle winter weather effects multiple regression analyses were undertaken for the December-March and February-March periods, with the snow depth and water equivalent as dependent variables. Table 2 summarises the results of the stepwise multiple regression analyses. Tests of normality and constancy of variance were reasonably well satisfied for the included variables. Mean temperature and total rainfall for December-March are identified as having the most significant influence over both depth and water equivalent. When snow depth is the dependent variable, winter temperature is associated with the greatest portion of its variance (39%), with winter rainfall accounting for a further 16%. With water equivalent as the dependent variable, however, the rainfall is entered at step 1 (R^2 =.25), since it has a marginally higher correlation with water equivalent than temperature does (Table 1). The exclusion of winter snowfall as a significant factor suggests that although several heavy winter snowfalls may increase snowpack volume considerably during the course of the winter, their net effect by late March is inconsistent since in some years significant thaw events intervene. However, winters that are clearly warmer than normal are usually characterised by quite frequent episodes of above-freezing weather (invariably accompanied by rain) so that, barring a very heavy late-winter snowfall, the snowpack would remain shallow. When only the February-March weather data are included, temperature becomes the only significant predictor variable, but the R^2 values are less than for the December-March analysis.

Table 1. Pearson correlation coefficients between winter weather variables, late-March snow cover and spring runoff over the Grand Lake catchment.

(a) WEATHER VARIABLES AVERAGED FOR DECEMBER THROUGH MARCH

	RAIN-FALL	SNOW-FALL	S/R RATIO	SNOW DEPTH	SNOW W E	SPRING RUNOFF
TEMP	.41**	-.13	-.27	-.63**	-.49**	-.20
RAIN		-.07	-.72**	-.62**	-.50**	-.38*
SNOW			.43**	.22	.12	.15
S/R				.40*	.27	.18
DEPTH					.91**	.63**
W E						.67**

** p = 0.001; * p = 0.01

(b) WEATHER VARIABLES AVERAGED FOR FEBRUARY AND MARCH

	RAIN-FALL	SNOW-FALL	S/R RATIO	SNOW DEPTH	SNOW W E	SPRING RUNOFF
TEMP	.39*	-.30	-.37*	-.55**	-.36**	-.16
RAIN		-.33*	-.55**	-.37*	-.19	-.07
SNOW			.50**	.14	.03	.09
S/R				.15	.02	-.03
DEPTH					.91**	.63**
W E						.67**

Table 2. Stepwise multiple regression analyses between late-March snow cover and winter weather variables, Grand Lake catchment.

Independent variables:
Mean temperature (TEMP); Total rainfall (RAIN);
Total snowfall (SNOW); Snowfall/rainfall ratio (S/R)

A. FOR DECEMBER THROUGH MARCH:

1. Dependent variable: MEAN SNOW DEPTH (Late March)

	Variable In	Mult. R	R^2	Sig F	Beta In
STEP 1	TEMP	.63	.39	.000	-.63
STEP 2	RAIN	.74	.55	.000	-.44

2. Dependent variable: MEAN SNOW WATER EQUIVALENT (Late March)

	Variable In	Mult. R	R^2	Sig F	Beta In
STEP 1	RAIN	.50	.25	.005	-.50
STEP 2	TEMP	.59	.34	.006	-.34

B. FOR FEBRUARY AND MARCH ONLY

1. Dependent variable: MEAN SNOW DEPTH (Late March)

	Variable In	Mult. R	R^2	Sig F	Beta In
STEP 1	TEMP	.55	.30	.000	-.55

2. Dependent variable: MEAN SNOW WATER EQUIVALENT (Late March)

	Variable In	Mult.R	R^2	Sig F	Beta In
STEP 1	TEMP	.36	.13	.006	-.36

EXAMPLES OF CONTRASTING SNOW COVER CONDITIONS

As indicated earlier, winter weather characteristics for this area are very sensitive to the behaviour and location of major regional frontal zones and storm tracks. Some measure of the possible contrasts in seasonal atmospheric ciculation features is afforded by maps of the monthly mean surface pressure pattern for February. Figure 6 illustrates the situation for three contrasting winters, including an indication of the extent of seaice in the Gulf of St. Lawrence. Accompanying each map are indices of temperature (TW) and precipitation (RW, SW, and S/R) for December-March at Corner Brook/Deer Lake, the late-March mean snow depth and water equivalent as a fraction of the 57-year mean (D/MEAN D, WE/MEAN WE) and the late-March mean snow density.

Snow depth and water equivalent for 1984 were very close to the long-term mean. The mean surface pressure gradient for January and February was fairly weak and indeterminate and the majority of cyclones took a SW to NE path over or near the island of Newfoundland. Precipitation was well above normal; consequently, although snowfall was fairly heavy (possibly related to open water in the Gulf) this was counteracted by slightly above-normal temperature and considerable rainfall.

The circulation pattern in 1981 was unusual, especially for February. Most cyclones arrived from the SSW and arctic outbreaks were few. As a result snow depth and water equivalent were well below normal, owing to the significant positive temperature anomaly and low snowfall/rainfall ratio. Frequent thaws and rainfalls probably contributed to the relatively higher snow density.

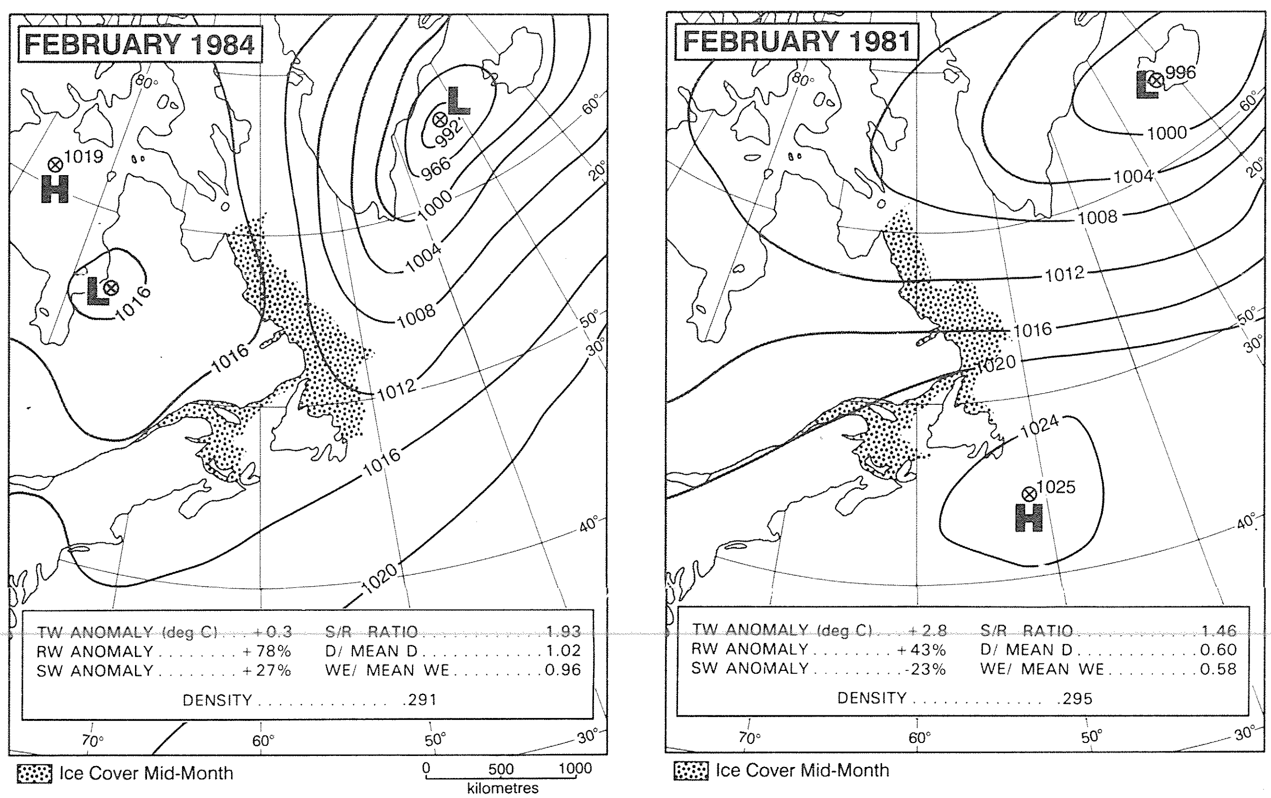

Figure 6. Mean surface air pressure pattern for February and associated indices of winter weather and late-March snow cover for Grand Lake area: (a) 1984, (b) 1981,

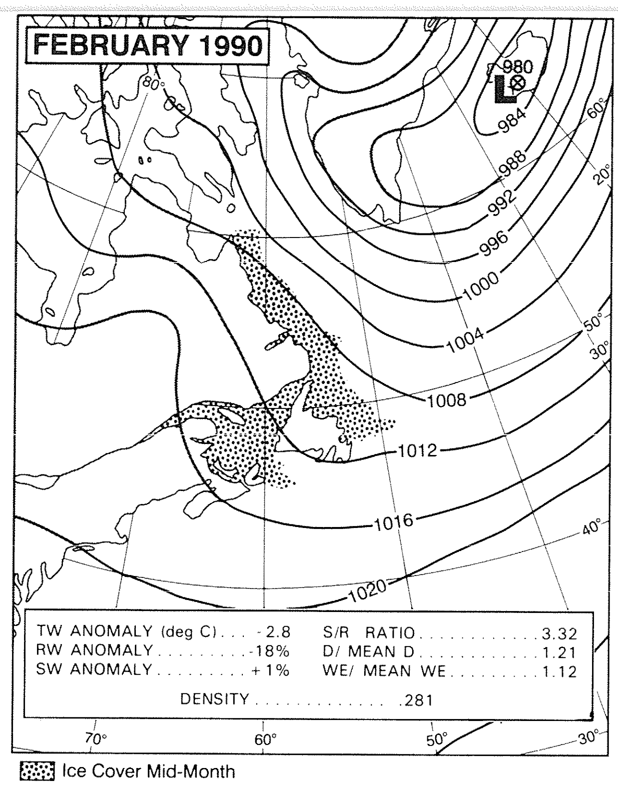

Figure 6 (c) 1990.

In contrast, the winter of 1990 was one of the coldest of the past 50 years. The circulation pattern favoured more frequent continental arctic air incursions, especially in February and March. Interestingly, snowfall was less than in 1984, perhaps partly due to heavy ice in the Gulf. However the infrequent winter thaws allowed little wasteage of the snowpack and, owing to the "drier" nature of most snowfalls, mean density was lower and the positive anomaly in water equivalent was less than that for depth.

CONCLUSION

The record of annual late-winter snow survey data for the Grand Lake catchment during 1934-1990 reveals several distinct oscillations between periods of increasing and decreasing depth and water equivalent. Most prominent amongst these was the decline from the early 1940's until the mid 1950's, followed by the recovery through the early 1960's. Most recently, snowpack volume has been generally increasing since a minimum in the early 1980's. Both depth and water equivalent for late March have shown a significant inverse relation to the mean temperature of the preceding four winter months. However, winter snowfall is not a significant predictor of depth or water equivalent, due to its weak association with winter mean temperature. Hence, this study confirms that, for this area, the snowpack water equivalent in late March will normally contribute a significant, major component of the ensuing runoff volume during the period April 1 - June 15. Consequently, if sufficiently reliable seasonal forecasting of air temperature, rainfall and snowfall can be achieved in future, useful approximations of late-winter snowpack water equivalent, and hence spring runoff, could be generated.

Future analysis of relations between snow cover, climate and weather for this basin should be enhanced with the current deployment by DLPC and the province of several remote data collection platforms. However further work is required on means of improving the estimates of catchment snow water content and ensuing spring runoff volume.

ACKNOWLEDGMENTS

Mr. Carl S. Stratton, Chief Engineer with the Deer Lake Power Company Limited, kindly provided the annual snow survey records and enabled me to accompany the 1991 snow survey. Historical climatological data were provided by Mr. Stuart Porter, Scientific Services Officer with A.E.S. at St. John's. Staff at the Memorial University of Newfoundland Cartographic Laboratory produced the maps.

REFERENCES

Atmospheric Environment Service. 1982. Canadian Climate Normals; Volume 3: Precipitation (1951-1980); Environ. Can., Toronto, Ont.

Atmospheric Environment Service. 1973. Snow Surveying. 2nd Ed. Environ. Can., Toronto, Ont.

Banfield, C.E. 1983. Climate. In Biogeography and Ecology of the Island of Newfoundland (G. Robin South, ed.), 37-106. Vol. 48 of Monographiae Biologicae (J. Illies, ed.); Dr. W. Junk, Publishers, The Hague-Boston-London.

Berry, M.O. 1991. Recent temperature trends in Canada. The Operational Geographer, 9 (1): 10-14.

Bilello, M.A. 1967. Relationships between climate and regional variations in snow-cover density in North America. Physics of Snow and Ice (H. Oura, ed.), Proc. Int. Conf. Low Temp. Sci., Hokkaido Univ., Sapporo, Japan, Vol. 1, Part 2, 1015-1028.

Damman, A.W.H. 1983. An ecological sub-division of the Island of Newfoundland. In Biogeography and Ecology of the Island of Newfoundland (G. Robin South, ed.), 163-206. Vol. 48 of Monographiae Biologicae (J. Illies, ed.); Dr. W. Junk Publishers, The Hague-Boston-London.

Green, M.G. 1965. Thirty-five Years Experience in the Use of Snow Surveys in the Operation of a Major Hydroelectric Plant in Newfoundland. Eastern Snow Conference, Proceedings of the 1965 Annual Meeting.

McKay, G.A. and D.M. Gray. 1981. The Distribution of Snowcover. In Handbook of Snow: Principles, Processes, Management and Use, (D.M. Gray and D.H. Male, ed.); chapter 5, 153-190.

Meades, W.J. 1983. Heathlands. In Biogeography and Ecology of the Island of Newfoundland (G. Robin South, ed.), 267-318. Vol. 48 of Monographiae Biologicae (J. Illies, ed.); Dr. W. Junk Publishers, The Hague-Boston-London.

Potter, J.G. 1965. Snow Cover. Canada, Dept. of Transport, Meteorological Branch; Climatological Studies Number 3.