EVALUATION OF THE SPATIAL AND TEMPORAL DISTRIBUTIONS OF SNOWPACK PARAMETERS IN THE SAINT JOHN RIVER BASIN

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ABSTRACT

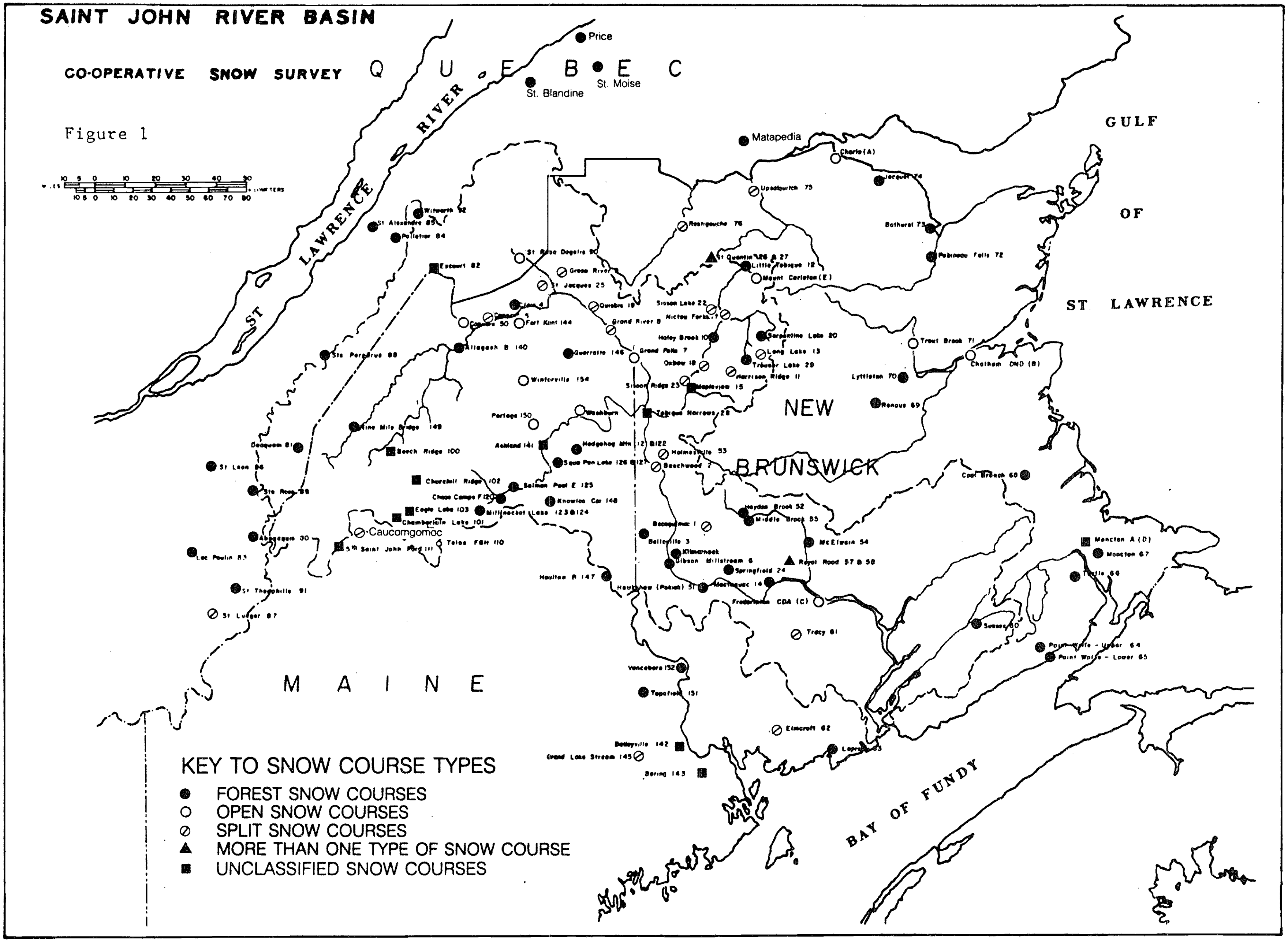
The spatial distributions of snow depth and snow water equivalent are known to be related to vegetative cover type and physiographic parameters such as elevation, slope and aspect. This paper examines some of these relationships for the Saint John River Basin. A number of objective techniques including multiple curvilinear regression and trend surface analysis are used to estimate snow water equivalent values for 100 km^2 grid elements within the basin. The snow courses were divided into forested and non-forested data sets and the models applied separately to each data set. The grid values, derived from each model, were used to calculate areally weighted snow water equivalent values for each of 56 sub-basins. This approach is being further extended by the inclusion of more accurate forest cover information derived from the analysis of satellite data.

Through this study it is hoped to evaluate the suitability of the current snow course network for flood forecasting in the Saint John River Basin.

INTRODUCTION

The accumulation of snow at a point and its subsequent ablation in the spring are affected by both regional and local factors. Large scale factors such as topographic relief, proximity to large open water bodies and predominant storm tracks affect the type and amount of precipitation at a point. These factors, through their influence on the regional climate, will also affect the rate of snowmelt in the spring. Because of the NW-SE orientation of the Saint John River Basin and the moderating effect on the climate of the Bay of Fundy more snow falls in the northern part of the basin and it melts more slowly. However, snow, once it has fallen, is also affected by local site conditions such as exposure and vegetation cover. Less snow tends to accumulate in open areas than in forested areas because of redistribution by the wind and accelerated melt in the spring due to increased insolation. The distribution of snow courses should reasonably reflect these regional and local factors as should the mapping technique used to interpolate between data points.

From information obtained from Peters and MacNeil (1975), the Fredericton Flood Forecast Centre (J.G. Devenney), and the Atmospheric Environment Service (B.E. Goodison), Trivett and Waterman (1979) examined the network of snow courses used to map the water equivalent of the snow cover in the Saint John River Basin during the "flood" season in the spring of each year. Generally speaking, the spatial distribution of snow courses is concentrated along the main stem of the Saint John River north of Fredericton and two of its tributaries, the Aroostook and the Tobique (Figure 1). The south-eastern portion of the basin south of Fredericton has very few stations. The north-eastern Quebec portion of the basin above St. Rose du Degelis is also conspicously blank. Geographically speaking, there are insufficient snow courses outside the basin to allow adequate mapping past the basin boundaries and too many concentrated along the above mentioned tributaries.



SAINT JOHN RIVER BASIN

Figure 1

Vegetation cover has a significant influence both on the accumulation of the snow cover and its depletion. The most significant factors are the redistribution of snow from fields and other open areas by wind scouring and the more rapid melting of snow in the fields due to increased insolation. Two survey sites, both having an open and forest snow course (Figure 2), were selected for comparison by Power et al (1980).

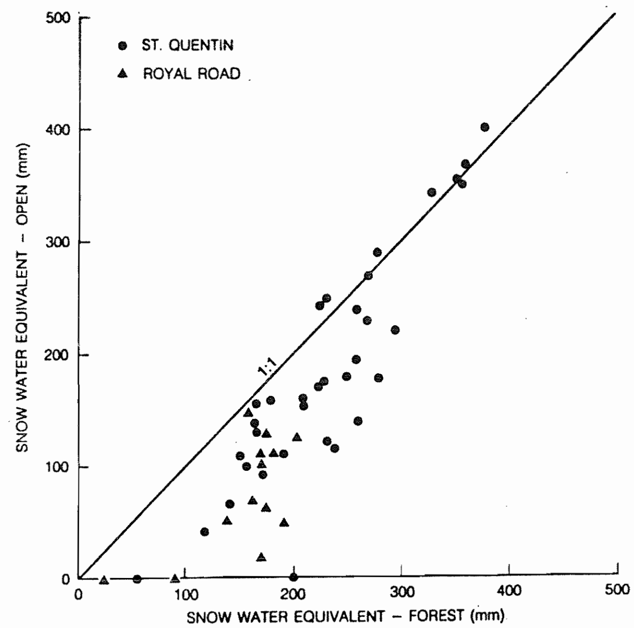


Figure 2 Comparison of snow water equivalent data from nearby open and forest snow courses in the northeast corner of the Saint John River Basin, St. Quentin, and the central portion of the basin, Royal Road (from Power, et al, 1980).

In years of very heavy snowfall, for example in 1977 when maximum snow water equivalents reached 400 mm, the snow cover water equivalent at both St. Quentin sites is very similar until late in the season when melt in the open site is proceeding at a faster rate than under the forest. It should be noted that in 1977 there was still a considerable amount of snow in the basin at the end of April which is the last snow survey date. In periods or places (e.g. Royal Road) with less snowfall, Figure 2 indicates that generally less snow accumulates in the open sites and it disappears earlier than in the forested sites. This fact must be taken into account when designing snow course networks and the subsequent mapping of the data.

Using detailed snow course descriptions, where available, and drawing on the personal knowledge of the FFC staff, the snow cover network was divided into three separate vegetation classes - forest, open and split. The class designated split includes snow courses that are partly forested and partly open such as courses which traverse an electric power transmission line.

Vegetation cover characteristics for the Saint John River Basin were available for the 10 km by 10 km UTM (Universal Transverse Mercator) grid system (Saint John River Basin Board Report No. 2, 1973). Information available for each grid included the percentage cover of sea, lake, forest, swamp, and open areas. For this study the swamp and open areas were treated as one class under the "open" designation. Both the sea and lake areas were excluded from any analyses.

Snow water equivalents for each vegetation class were estimated for each grid cell using one of the mapping techniques described in the next section. An average value for each grid cell was calculated by weighting the vegetation class estimates by their respective areas. Sub-basin averages were then calculated from the averaged grid cell snow water equivalents.

SNOW COVER MAPPING

In large basins like the Saint John River Basin, snow courses may essentially be considered as point data. Some form of interpolation scheme is necessary to extrapolate the information over the basin for calculation of the spatial averages for each sub-basin required by the flood forecasting model. The interpolation may be done manually by a skilled technician using conventional isoline analysis or it may be done by computer using one of a number of objective techniques. Three techniques were chosen as readily adaptable to the type of data under study: trend surface analysis, multiple regression analysis and nearest neighbour, or proximity analysis. These techniques were applied to the snow course data for each survey date. No attempt was made to generalize the relationships between snow cover and the physiographic data. Each survey date was treated as a unique event. Since it is not the purpose of this report to compare the techniques per se, they are only briefly outlined below. Further information may be obtained from Davis (1973) and Davis and McCullough (1975).

a) OPERATIONAL SNOW COURSE MAPPING

The various agencies in Maine, Quebec, and New Brunswick which collect snow course information send it by telephone to the Fredericton Flood Forecast Centre within several days of the survey dates. These data are coded onto cards and are analyzed by computer to calculate the following: the mean density of the snow along the survey; the length of the record averages (referred to as "normals") of snow water equivalent, snow depth and snow density; and the current data as a percentage of the "normal". Using selected long duration stations, mean snow water equivalent is calculated for the upper portion (above Beechwood) and the lower portion of the Saint John River Basin. Employing a shaded topographic underlay, an isoline map of snow water equivalent is prepared and the average for each sub-basin is estimated by eye. An isoline map of the percent of normal data is also prepared but without the use of the shaded topographic underlay. Since 1974 the U.S. National Environmental Satellite Service (NESS) has provided the Fredericton Flood Forecast Centre with snow line maps derived from NOAA satellite imagery. These maps were used as as an aid in evaluating the distribution of snow in data sparse areas especially late in the season as the snowline generally recedes to the north-west.

It is important to note that it is difficult to integrate subjectively the effects both of elevation and of cover type on the distribution of the snow course data. Since all data are given equal weight, open snow courses, which tend to have less snow and lose it more quickly, will distort the maps. Split snow courses are often used as a compromise, but the data should be reported separately for the forest and open segments of the course. The cover type of the snow courses assigned to each sub-basin during the mapping procedure should reflect the vegetation distribution within the sub-basin.

b) TREND SURFACE

Trend surface analysis assumes that the value of the mapped variable at a point in space can be segregated into a regional component and a residual component. The regional component results from large scale processes whereas the residual component is presumed to result from local factors affecting the variable being analysed.

The general form of the trend surface is as follows:

$$Y_i = f(x_i, y_i) + u_i \quad (1)$$

where Y_i = the observed value of the surface at the ith snow course

x_i = the x-axis coordinate of the ith snow course

y_i = the y-axis coordinate of the ith snow course

u_i = the residual at the ith snow course

f = some function which describes the spatial distribution of Y

A polynomial function of the form:

$$f(x_i, y_i) = (x_i + y_i)^n \tag{2}$$

where n = the degree of the polynomial (limited to the range 1 to 5)

was solved using the least square criteria to minimize the deviations giving

$$Y = b_o + b_1 x + b_2 y + b_3 x^2 + b_4 y^2 + b_5 xy \tag{3}$$

where Y = the estimated trend surface value

b_o to b_5 are the least squares coefficients in this case for a polynomial of degree $n = 2$

Once the coefficients are known the trend surface estimates of snow water equivalent for each grid cell can be calculated from its x and y coordinates.

c) MULTIPLE REGRESSION

In a similar manner the more familiar multiple regression analysis was applied to the snow course data set. The effect of elevation on the spatial distribution of snow course data was examined by including it as an independent variable available for selection by the step-wise multiple regression program.

The resulting equations were of the form:

$$Y = b_o + b_1 x + b_2 y + b_3 E \tag{4}$$

where E = elevation of the snow course

b_o to b_3 are the multiple regression coefficients

The squares and cubes of x, y and E were also included as independent variables in the multiple regression analysis. A second regression analysis was also done using the cross products of the independent variables (i.e. x.y, x.E and y.E) instead of the squares and cubes. The step-wise multiple regression program only included the most significant parameters in the final equation. Estimates of snow water equivalent for each grid cell were calculated using the x and y coordinates of the grid cell and its average elevation.

d) PROXIMITY ANALYSIS

In the proximity analysis, the snow water equivalent for each grid cell was calculated as the average of the nearby snow courses weighted by the distance of the snow course from the centre of the grid cell.

$$Y_n = \frac{\sum_{i=1}^{j} S_i \cdot \bar{d}_i^{k}}{\sum_{i=1}^{j} \bar{d}_i^{k}} \tag{5}$$

where Y_n = snow water equivalent of the nth grid

S_i = snow water equivalent of the ith snow course

d_i^{-k} = distance from grid n to snow course i raised to the power -k

j = the number of nearby stations used to calculate the average for the grid

SUB-BASIN AVERAGES

In addition to distributing the point snow course data over space by one of the previously described techniques, it is necessary to calculate sub-basin averages of snow water equivalent. A separate program, SNOSUB, which uses either gridded data from the trend surface program or the proximity analysis program or the multiple regression equation, maps the snow water equivalent for each grid cell separately by cover type. A weighted average snow water equivalent value for each cell is calculated using the area of each cover type in the cell. Up to four vegetation classes may be mapped in this way to determine the weighted average for the grid cell. Each grid, or a percentage thereof, is assigned to a sub-basin in order to calculate the sub-basin averages of the distributed snow course data. A composite map of the weighted grid cell data is printed along with the sub-basin averages of snow water equivalent and its corresponding volume.

COMPARISON OF TECHNIQUES

From the snow course information encoded on cards by the FFC, snow water equivalents were abstracted for 62 snow courses: 42 Forest, 12 Open and 8 Split. The three computerized distribution techniques were applied to all 62 snow courses as one data set and the sub-basin averages were compared to the "eye-ball" estimates supplied by the FFC. Although the FFC estimates are used as the control in this study, they are not considered to be the "true" or even best estimates of snow water equivalent in each sub-basin. Unfortunately there is no direct test to determine which technique is best. These techniques were also applied separately to the forest and open snow course data sets and the distributions were combined using SNOSUB to calculate sub-basin averages. Although this latter approach is not expected to reproduce the FFC sub-basin averages, the results are compared to the FFC values in order to evaluate the differences arising from the segregation of snow courses into vegetation classes.

a) SNOW COVER DISTRIBUTION WITH UNCLASSIFIED SNOW COURSES

Seven snow survey dates from 1977 were selected to test the three techniques because of their completeness relative to the 1976, 1978 and 1979 data sets. Each technique was applied separately to the data from each snow survey date. As Table 2 indicates, there is very little difference between the trend surface analysis and the multiple regression analysis in terms of the correlation coefficients (r) or the standard errors. The third degree trend surfaces (n = 3, Equation 2) are marginally better than the multiple regression surfaces. No comparable statistics are available for the proximity analysis.

Two dates in 1977 are examined in greater detail: March 15 was selected as representative of the time when snow water equivalent is near its maximum in the basin; and April 30 as severe test of the techniques when snow water equivalent is at its lowest value, snow cover is patchy, and often many snow courses fail to report. Unfortunately, snow water equivalent maps from the FFC were not available for visual comparison for the 1977 period.

For the March 15 period, the maps produced by all three techniques are very similar (Figure 3) with some minor differences. In the north west corner of the basin both the trend surface and multiple regression techniques tend to overestimate some of the grid cell values by 50-100 mm when compared to the proximity estimates. Along the Bay of Fundy the trend surface seems to reflect better the expected snow distribution in the highland areas. Both of these areas are data sparse and the seemingly better map produced by the trend surface may be fortuitous.

Table 1

The legends given below apply to all maps present in this report according to type.

Elevation Maps		Vegetation Maps		Snow Water Equivalent Maps	
Class Interval (metres)	Symbol	Class Interval % Area	Symbol	Class Interval (mm)	Symbol
0 - 49	1	0	0	-25*	
50 - 99	2	1 - 9	1	-25 - -2.5	-
100 - 149	3	10 - 19	2	-2.5 - 2.5	0
150 - 199	4	20 - 29	3	2.5 - 24	1
200 - 249	5	30 - 39	4	25 - 49	2
250 - 299	6	40 - 49	5	50 - 74	3
300 - 349	7	50 - 59	6	75 - 99	4
350 - 399	8	60 - 69	7	100 - 124	5
400 - 449	9	70 - 79	8	125 - 149	6
		80 - 89	9	150 - 174	7
		90 - 99	$	175 - 199	8
		100	+	200 - 224	9
				225 - 249	$
				250 - 274	A
				275 - 299	B
				300 - 324	C
				325 - 349	D
				350 - 374	E
				375 - 399	F
				400 - 424	G
				425 - 449	H
				450 - 474	I
				475 - 499	+
				500	

*Because both the multiple regression and trend surface techniques can produce large negative grid cell values, the -2.5 to -25.0 class interval was included in these maps. Values less than zero were not included in the calculation of sub-basin averages. Although grid cells with snow water equivalents less than -25 mm or greater than 500 mm are assigned the same symbol, there should be no confusion in interpreting the maps.

Figure 3 Comparison of Distributions of Snow Water Equivalent in the Saint John River Basin Using Unclassified Snow Courses

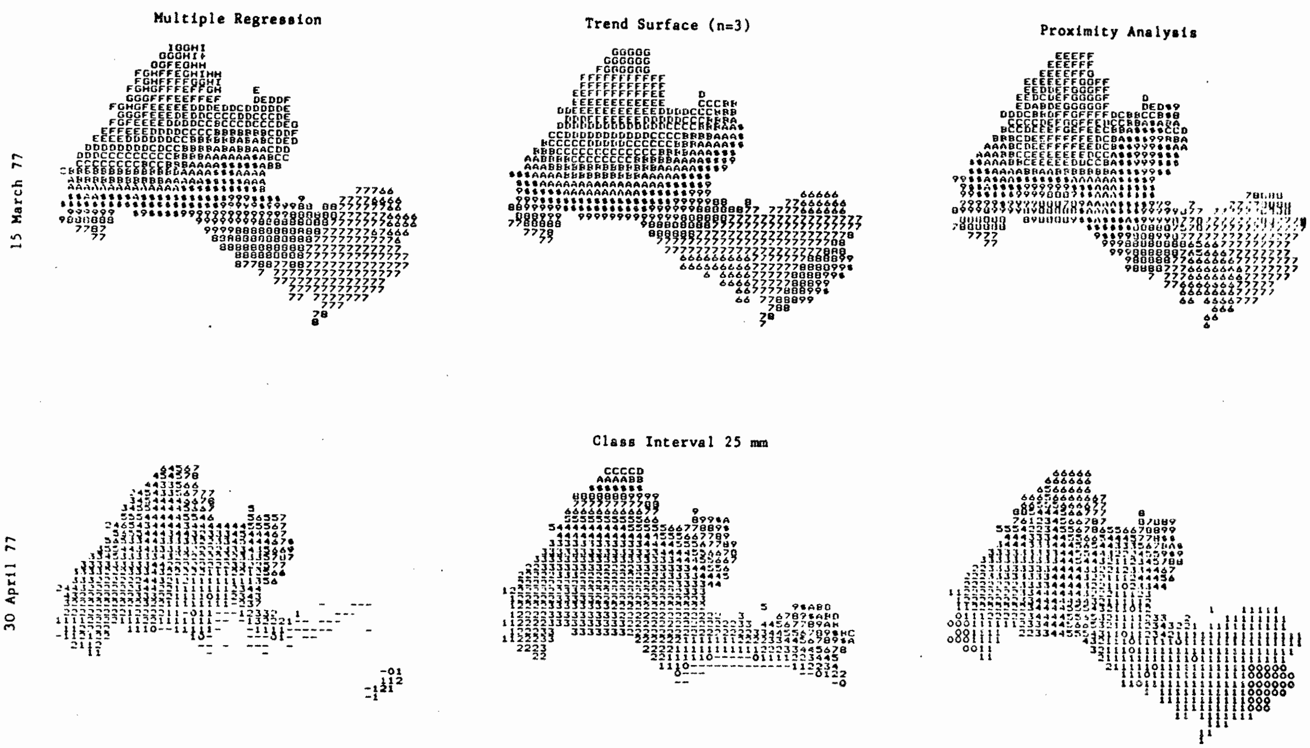


Table 2

Correlation coefficients (r) and standard errors (s.e.) for the multiple regression equations and trend surfaces generated from the 1977 snow water equivalent data combined data set (FOREST +OPEN +SPLIT).

a) Multiple Regression

Date	r	s.e.	Parameters
31 Jan	0.84	41	x,x.y,x.E,x
15 Feb	0.86	43	y,x.y,x.E,x
28 Feb	0.87	48	y,x.y,x.E
15 Mar	0.83	52	y,x.y,x,x.E
31 Mar	0.81	55	y,x.E
15 Apr	0.78	73	y,x.E
30 Apr	0.84	46	x.E,y,y.E

b) Trend Surface

	FIRST DEGREE		SECOND DEGREE		THIRD DEGREE	
Date	r	s.e.	r	s.e.	r	s.e.
31 Jan	0.81	43	0.84	39	0.86	36
15 Feb	0.84	44	0.86	40	0.91	32
28 Feb	0.86	48	0.86	46	0.91	37
15 Mar	0.77	56	0.83	49	0.86	45
31 Mar	0.80	55	0.81	53	0.87	45
15 Apr	0.77	72	0.80	67	0.85	60
30 Apr	0.74	54	0.79	49	0.83	45

The snow water equivalent maps produced for the end of April are more dissimilar and reflect how well the three techniques cope with missing data (Figure 4). The number of snow courses reporting in April was reduced to 38 from the 55 which reported for the March 15 period. The snow courses which are most frequently missing are those in Maine along the Aroostook and the ones in New Brunswick east of the basin. Although the correlation coefficients and standard errors are virtually identical for the multiple regression and trend surface analyses, the multiple regression map better reflects the data in Figure 4. The trend surface map shows larger values than the multiple regression map in the area north of Fredericton to Perth-Andover and in the area north-east of Sussex. The proximity analysis tends to produce a smooth surface when six snow courses are used ($j = 6$, $k = 2$ in Equation 5) to calculate the value for each grid. This tends to produce small, but non-zero values, for grids even through the nearest snow course station may indicate no snow.

When comparing the sub-basin averages produced by computer interpolation with the FFC estimates for all snow survey dates in 1977 (Table 3), the trend surface and proximity techniques seem to simulate better the manual isoline analysis than does the multiple regression approach. The multiple regression technique, produces similar sub-basin estimates of snow water equivalent to the trend or proximity techniques for very high water values around 400 mm but consistently exceeds the FFC estimates at lower snow water equivalents. Since the number of snow courses reporting in each snow survey period varies, the comparisons given in Table 3 should be considered as a guide only.

Considering the more limited data set used to produce the computerized maps, and considering the lack of other aids, such as satellite derived snow-line maps or first hand knowledge to massage the data, it is encouraging that these techniques performed as well as they did. The effort required to produce the sub-basin averages for the flood forecast model would be considerably reduced if one of these computerized techniques were to be adopted operationally.

Table 3

Sub-basin averages of snow water equivalent derived from trend surface, multiple regression and proximity analysis are compared using linear regression to the FFC sub-basin estimates obtained from isoline analysis for all snow survey periods in the years 1976 to 1977.

Model	Intercept mm	Slope	Correlation Coefficient	Standard Error
Trend Surface (3)*	13.3	0.99	0.96	33
Multiple Regression	56.4	0.89	0.89	54
Proximity Analysis (3)**	11.8	1.00	0.94	39
Proximity Analysis (6)	7.4	1.02	0.95	35

* Third degree trend surface

** Brackets indicate the number of nearest snow courses used

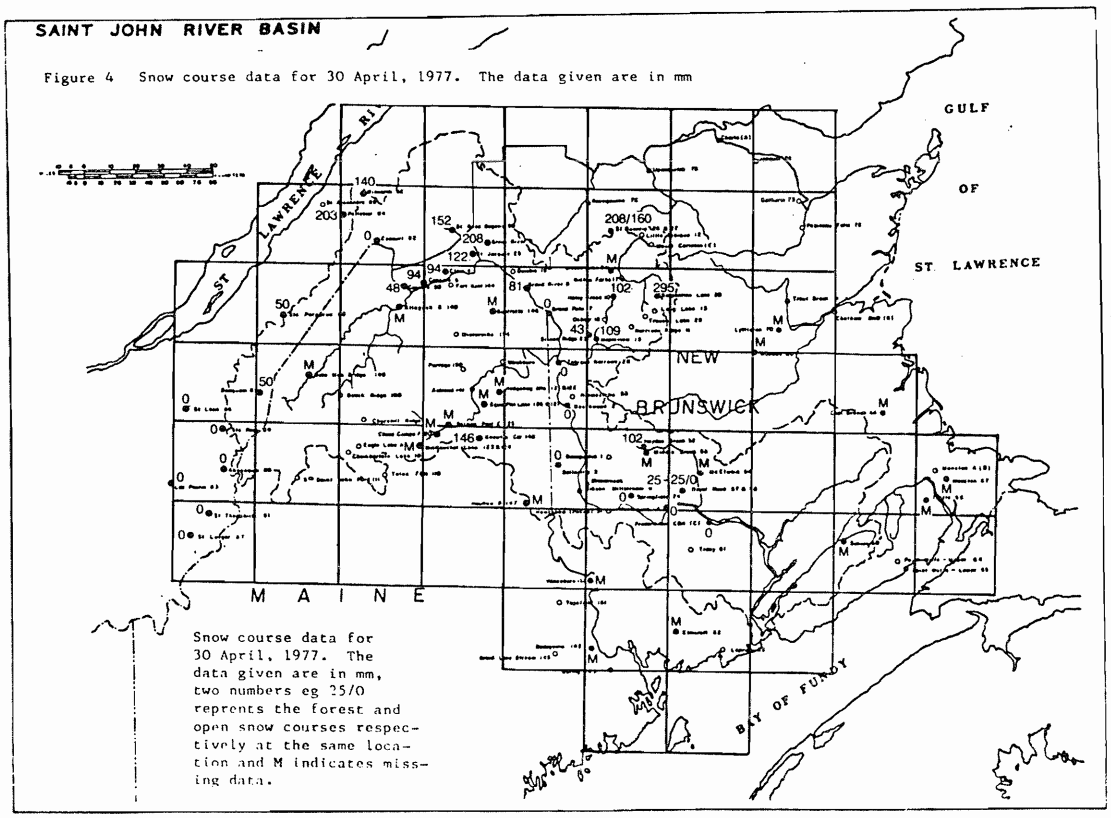


Figure 4 Snow course data for 30 April, 1977. The data given are in mm

Table 4

Correlation coefficients (r) and standard errors (s.e) for the multiple regression equations and trend surfaces generated from the 1977 snow water equivalent data classified by vegetation type - FOREST and OPEN.

a) Multiple Regression

	FOREST			OPEN		
Date	r	s.e.	Parameters	r	s.e.	Parameters
31 Jan	0.89	26	y.E,E,x.y	0.88	46	y,x,E^2
15 Feb	0.90	31	$y.E,E_2$	0.88	45	y,x,E^2
28 Feb	0.88	41	y.E,E	0.92	51	y,x,E^2
15 Mar	0.79	47	y,y.E,E	0.92	46	x,y
31 Mar	0.84	46	y,y.E,E	0.92	49	x,y.E,x.E
15 Apr	0.74	75	y,x.E	0.91	54	y,x,E^2
30 Apr	0.89	41	x.E,y	0.88	50	y,x

b) Trend Surface

	FOREST			OPEN		
Date	r	s.e.	Degree	r	s.e.	Degree
31 Jan	0.86	28	3	0.86	40	1
15 Feb	0.90	29	3	0.85	40	1
28 Feb	0.90	35	3	0.91	42	1
15 Mar	0.82	42	3	0.93	38	1
31 Mar	0.87	39	3	0.84	53	1
15 Apr	0.86	54	3	0.88	52	1
30 Apr	0.87	40	3	0.89	37	1

b) SNOW COVER DISTRIBUTION WITH CLASSIFIED SNOW COURSES

Segregating the snow courses into forest and open vegetation classes gives a slight increase in the correlation coefficients for both the trend surface and the multiple regression analysis (Table 4). Snow water equivalent maps for the forest and open cover classes are given in Figure 5 and 6 for March 15 and April 30, respectively. Each of the three computer techniques produces essentially similar distributions for the forest cover type in the upper part of the basin. The major difference in the forest distribution is along the Bay of Fundy where the trend surface values overestimate the others by 125 to 150 mm. With respect to the open class the trend surface over-estimates the other techniques by a similar amount in the northwestern part of the basin. Both the trend surface and the multiple regression maps exhibit a strong gradient, with snow water equivalent values decreasing to the south-east more rapdily than might be realistic. This is rather hard to confirm since there are no open snow courses south of Fredericton and Royal Road, both of which indicate snow water equivalents around 100 mm.

Differences between the three techniques are more apparent in the maps for April 30 (Figure 6). Both the trend surface and multiple regression surface forest maps indicate that, in the north central part of the basin from Ashland to Edmunston, the grid values are underestimated (see input data mapped in Figure 4). The trend surface over-estimates along the northern border of the basin and it is especially serious in the Sussex area. This problem results from the distribution of missing stations in the northeast area.

The decision as to which interpolation technique to use depends to a large extent on the spatial distribution of the input data. The proximity analysis will cope with missing data without grossly distorting the distribution surface. It does so by extending the influence of each snow course over a much larger area. There will still be a tendency to over-estimate late in the season since snow courses with little or no snow

Figure 6 Comparison of Distributions of Snow Water Equivalent in the Saint John River Basin for Forest and Open Vegetation Classes - 30 April 1977

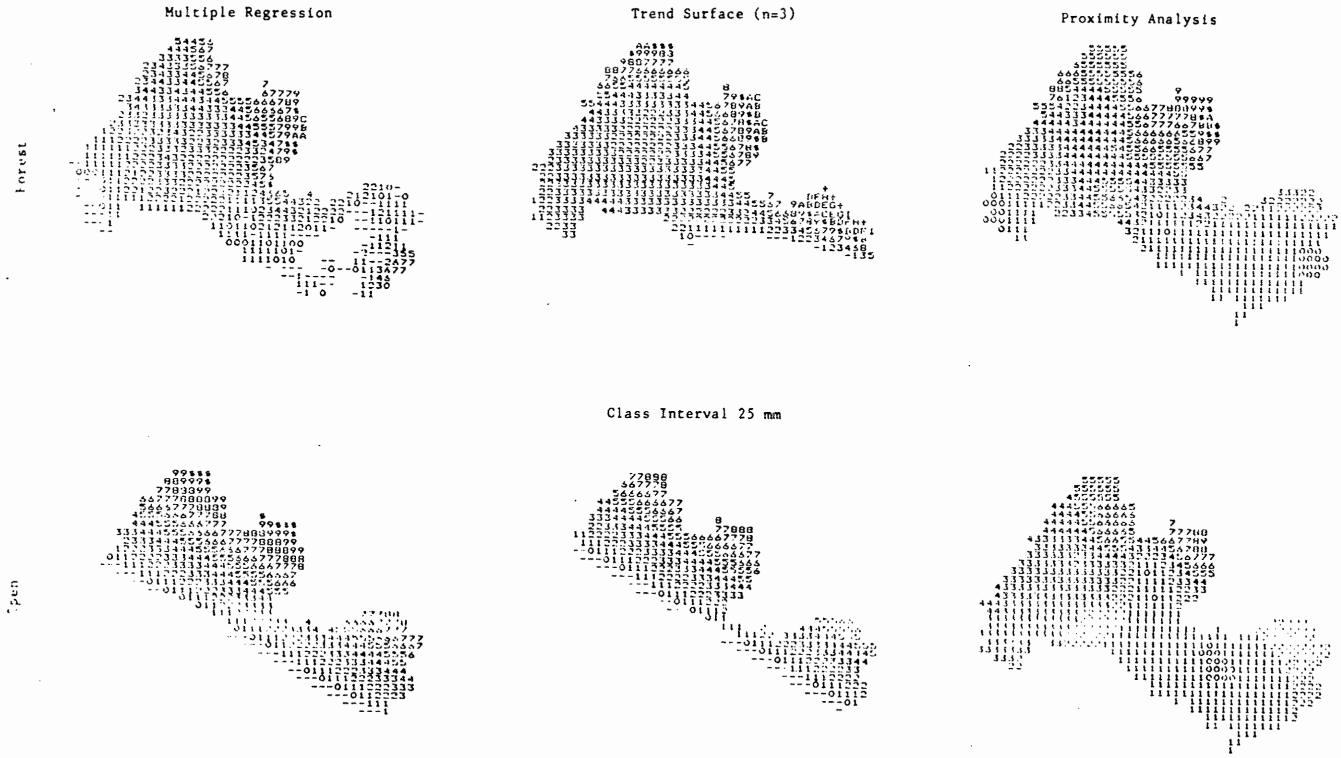


Figure 5 Comparison of Distributions of Snow Water Equivalent in the Saint John River Basin for Forest and Open Vegetation Classes - 15 March 1977

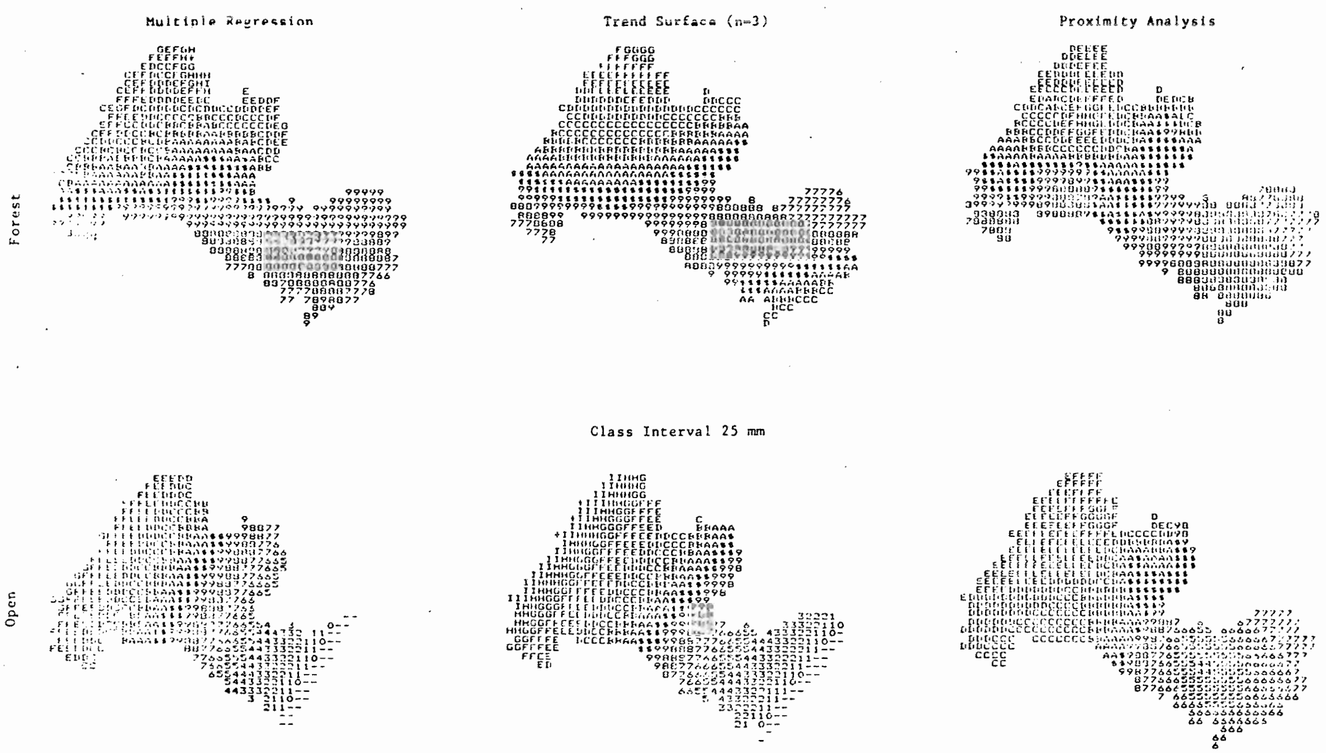


Table 5

Sub-basin averages of snow water equivalent, weighted by the area of forest and open area in each sub-basin are compared through linear regression to the FFC sub-basin averages derived from isoline analysis.for four survey dates in March and April, 1977. The type of analysis applied to the forest and open data sets are indicated in brackets.

Model	Intercept mm	Slope	Correlation Coefficient	Standard Error
Forest - (TR) Open - (TR)	39.6	1.02	0.93	42
Forest - (MR) Open - (MR)	16.7	0.97	0.95	37
Forest - (PR3) Open - (PR3)	-11.0	1.09	0.94	40
Forest - (PR6) Open - (PR6)	1.0	1.03	0.92	44
Forest - (TR) Open - (PR3)	13.3	1.02	0.93	43
Forest - (TR) Open - (PR6)	-27.6	1.03	0.93	43

TR - 3rd degree trend surface

MR - multiple regression

PR3 - proximity analysis with 3 nearest neighbour and the inverse of the distance cubed

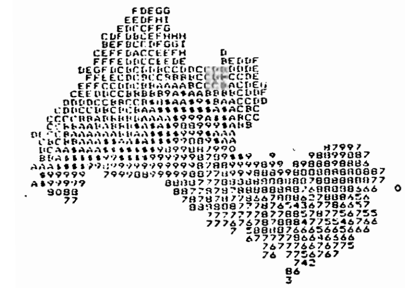
PR6 - proximity analysis with 6 nearest neighbour and the inverse of the distance squared

are probably the ones that fail to report thereby extending the influence of the northern snow courses to the southern part of the basin. However without an adequate spatial distribution of snow courses, both the trend surface and multiple regression surfaces can become seriously distorted outside the boundaries defined by the reporting network. This problem can occur with the open class network throughout the flood forecasting season (due to its limited size) and to the forest class network near the end of the flood forecast season, due largely to stations failing to report. It is for precisely this reason that the program SNOSUB does not require the same interpolation technique to be applied to each vegetation class. As Table 5 indicates the multiple regression technique when applied to both vegetation classes is marginally better at reproducing the FFC isoline estimates. Because the forest class is the dominant vegetation class in terms of areal coverage and because of the limited number and distribution of the open snow courses, the success of any of the interpolation techniques, when compared to the FFC isoline sub-basin estimates of snow water equivalent, is determined by the distribution of reporting snow courses. This can be confirmed by comparing the distribution of "forest" snow water equivalent in Figure 5 and 6 with the corresponding distributions produced by combining the areally weighted forest and open grid values given in Figure 7 to 12.

Analysis of the remaining snow course data, 1976 to 1979, was restricted to the proximity analysis which was applied separately to the forest and open data sets and to the trend surface which was applied only to the forest data set. Sub-basin averages were calculated in two ways: a) the forest and open proximity distributions were combined using SNOSUB and b) the forest trend surface distributions and the open proximity distributions were combined using SNOSUB. The proximity analysis was chosen because, conceptually, it more closely resembled the FFC isoline analysis. The trend surface technique was only applied to the forest data set because of the limitations of the open network discussed previously. Of the two, the trend surface technique is the preferred since it filters out

Figure 7 Multiple Regression
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

SAINT JOHN BASIN MAP
15-MAR-77



BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	355	864.9
2	334	808.8
3	334	833.7
4	353	498.6
5	263	618.7
6	305	363.5
7	308	337.5
8	337	889.3
9	386	463.3
10	333	246.8
11	381	385.7
12	382	105.9
13	283	148.4
14	359	104.9
15	319	490.0
16	341	504.2
17	325	409.8
18	336	552.9
19	283	383.6
20	305	313.7
21	305	86.8
22	304	93.9
23	199	83.7
24	174	84.4
25	199	104.8
26	187	231.7
27	166	158.9
28	193	115.9
29	176	87.9
30	175	37.8
31	168	46.0
32	187	83.7
33	163	86.9
34	173	42.4
35	184	90.1
36	174	28.8
37	152	19.2
38	202	301.9
39	181	51.3
40	165	8.3
41	161	96.7
42	169	244.6
43	166	24.5
44	163	19.3
45	192	338.9
46	179	155.1
47	151	201.1
48	183	89.8
49	175	318.6
50	148	30.9
51	137	69.2
52	151	37.6
53	163	87.8
54	128	125.8
55	132	165.2
56	127	15.4

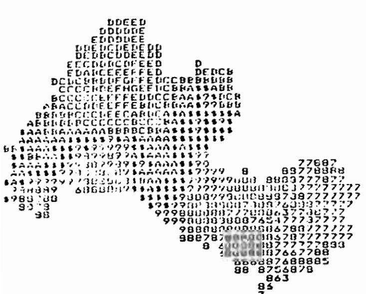
Figure 9 Trend Surface
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

SAINT JOHN BASIN MAP
15-MAR-77

BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	240	814.9
2	299	746.2
3	250	810.3
4	342	482.8
5	284	669.4
6	312	271.7
7	331	244.3
8	363	958.6
9	361	433.8
10	339	260.2
11	308	423.6
12	292	109.7
13	280	147.4
14	263	122.4
15	328	509.0
16	355	534.2
17	264	481.0
18	285	469.7
19	253	253.2
20	240	294.8
21	234	98.9
22	220	93.1
23	233	98.0
24	206	97.4
25	201	105.6
26	205	254.5
27	191	67.5
28	188	135.6
29	188	93.8
30	187	40.6
31	181	49.6
32	190	85.1
33	176	94.0
34	180	44.0
35	183	89.4
36	174	28.8
37	163	20.6
38	187	279.4
39	177	50.0
40	172	8.6
41	138	112.0
42	203	294.3
43	174	26.0
44	176	20.8
45	157	277.6
46	172	149.4
47	141	187.9
48	154	75.8
49	173	315.5
50	175	36.5
51	174	87.7
52	203	50.4
53	220	118.3
54	165	165.0
55	199	140.4
56	196	23.3

Figure 11 Proximity Analyses
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

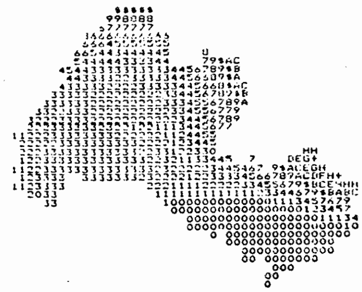
SAINT JOHN BASIN MAP
15-MAR-77



BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	232	786.3
2	288	717.5
3	226	733.3
4	313	441.9
5	303	712.0
6	353	307.8
7	378	278.2
8	334	883.6
9	357	428.6
10	380	291.1
11	310	425.7
12	267	100.4
13	249	131.5
14	252	117.6
15	313	476.2
16	327	475.6
17	279	509.2
18	278	458.2
19	230	230.0
20	232	285.2
21	248	105.0
22	231	96.7
23	258	108.6
24	236	111.7
25	213	112.2
26	238	294.7
27	209	74.0
28	201	134.4
29	189	94.2
30	174	42.0
31	169	51.9
32	194	86.3
33	184	98.3
34	191	46.8
35	196	75.8
36	181	30.0
37	174	21.9
38	197	293.9
39	178	[illegible]
40	178	[illegible]
41	182	109.2
42	180	[illegible]
43	174	28.6
44	173	20.5
45	176	310.6
46	178	154.5
47	149	190.5
48	171	84.1
49	171	311.4
50	168	35.1
51	164	82.7
52	168	41.7
53	187	100.5
54	166	162.9
55	158	194.4
56	145	17.4

Figure 10 Trend Surface
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

SAINT JOHN BASIN MAP
30-APR-77



BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	48	162.8
2	59	148.7
3	59	172.0
4	88	125.0
5	39	93.6
6	43	37.8
7	54	40.0
8	128	339.6
9	103	123.7
10	95	50.3
11	72	100.1
12	90	33.9
13	104	54.8
14	61	28.8
15	57	102.6
16	49	102.6
17	30	69.2
18	218	350.7
19	149	148.9
20	110	135.0
21	43	18.3
22	67	28.4
23	30	13.0
24	27	13.2
25	12	5.5
26	30	7.5
27	0	0.0
28	4	0.0
29	0	0.0
30	0	0.0
31	0	0.0
32	18	8.4
33	0	0.0
34	0	0.5
35	27	13.5
36	12	2.1
37	0	0.0
38	87	130.3
39	26	7.6
40	0	0.0
41	0	0.0
42	0	0.0
43	0	0.0
44	0	0.0
45	363	639.9
46	42	37.0
47	92	122.7
48	389	190.8
49	120	219.6
50	0	0.0
51	0	0.0
52	0	0.0
53	0	0.0
54	21	30.0
55	0	0.0
56	0	0.0

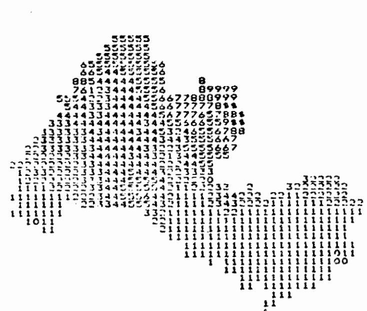
Figure 8 Multiple Regression
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

SAINT JOHN BASIN MAP
30-APR-77

BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	3	11.7
2	41	104.1
3	34	111.5
4	71	100.7
5	57	134.3
6	62	54.0
7	79	58.6
8	91	240.2
9	126	151.9
10	90	69.1
11	90	123.6
12	100	37.6
13	106	56.1
14	68	31.9
15	32	71.7
16	40	83.7
17	49	89.9
18	170	280.3
19	120	128.8
20	98	120.7
21	46	19.7
22	87	36.8
23	26	11.3
24	12	6.1
25	59	31.0
26	14	17.5
27	3	1.3
28	3	3.4
29	5	2.6
30	10	2.2
31	4	1.3
32	25	11.4
33	6	3.5
34	12	3.0
35	35	17.9
36	15	2.5
37	0	0.1
38	68	102.1
39	10	2.9
40	0	0.0
41	0	0.6
42	0	3.2
43	1	0.2
44	1	0.3
45	20	35.4
46	10	8.7
47	6	8.5
48	22	10.8
49	8	16.0
50	0	0.0
51	8	4.1
52	0	0.0
53	0	0.0
54	47	46.0
55	12	15.6
56	0	0.0

Figure 12 Proximity Analyses
Sub-basin averages of snow water equivalent and accompanying distribution map calculated from forest and open grid cell values weighted by the respective areas.

SAINT JOHN BASIN MAP
30-APR-77



BASIN NUMBER	SNOW WATER EQUIVALENT DEPTH (mm)	VOLUME (mil cu m)
1	25	86.8
2	65	163.4
3	54	175.0
4	81	115.3
5	83	197.3
6	81	70.9
7	85	62.8
8	100	265.6
9	112	135.3
10	98	75.7
11	114	157.7
12	126	47.4
13	121	64.1
14	73	34.1
15	94	209.7
16	87	182.0
17	65	119.1
18	203	334.4
19	125	125.1
20	103	126.8
21	45	19.4
22	49	20.6
23	38	16.3
24	19	9.0
25	27	14.4
26	34	42.5
27	10	3.7
28	12	8.4
29	7	3.2
30	10	2.7
31	10	2.1
32	11	8.1
33	3	4.6
34	3	1.9
35	23	10.9
36	11	2.0
37	2	0.7
38	43	72.8
39	19	8.4
40	10	3.5
41	12	7.2
42	14	21.2
43	15	2.3
44	15	1.9
45	32	57.3
46	19	13.7
47	15	20.9
48	17	8.3
49	11	21.6
50	14	3.1
51	12	6.2
52	14	3.2
53	16	8.6
54	9	8.3
55	11	14.5
56	12	1.5

the "noise" in the data set; that is, the deviation of individual snow courses from the regional trend is considered to be due to some local influence.

Two parts of adjacent sub-basins were selected to compare the FFC estimates of mean snow water equivalents derived from isoline maps with those derived from the two previously discussed objective techniques. One sub-basin of each pair is predominantly forested whereas the other contains a significant amount of open areas. Sub-basins #3 and #5 are in the north-western part of the Saint John River Basin in the State of Maine (Figure 13). Sub-basin #3 is in an area previously identified (Trivett and Waterman, 1980) as one with few snow courses due to its inaccessability. Sub-basins #17 and #20 are in the central part of the basin. Sub-basin #20 also borders a very large data sparse area.

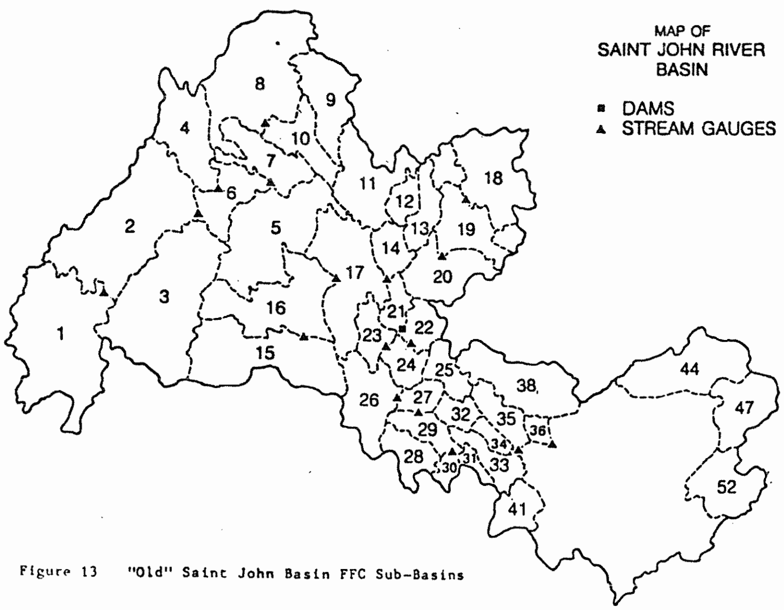


Figure 13 "Old" Saint John Basin FFC Sub-Basins

It is worth noting here that, whereas the operator producing the isoline map may draw upon secondary sources, such as snow cover maps derived from satellite data (Schneider, 1977) or personal knowledge, to complement his snow course data base, the proximity analysis extends the area of influence of the nearest reporting snow courses to cover the data sparse area. The trend surface on the other hand uses the regional trend to extrapolate into the data sparse area. When the data sparse area occurs near the boundaries defined by the reporting network, all three of the above techniques can lead to serious errors in the estimates of snow water equivalent for the nearby sub-basins.

As expected both the trend surface and proximity techniques tend to underestimate the FFC sow water equivalent estimates in the "open" sub-basin #5 and #20 (Figures 14 and 15) and to deplete the snow in these sub-basins sooner. This observation supports the proposal to segregate snow courses according to cover type before mapping. With some notable exceptions the snow water equivalent estimates from the proximity analysis agree more closely with the FFC estimates, whereas those from the trend surface analysis tend to underestimate the FFC values. These exceptions occurred primarily in years 1976 and 1979 and can be traced to two possible sources of error. Firstly, for snow survey periods where the reporting network is reduced in number and, in particular, where the missing stations are mainly in one segment of the basin, the trend surface may become seriously distorted, especially near the boundaries of the basin. The proximity analysis will extend the "area of influence" of the reporting stations far beyond

Figure 14 Comparison of FFC isoline sub-basin averages of snow water equivalent with trend surface and proximity estimates for two northern sub-basins.

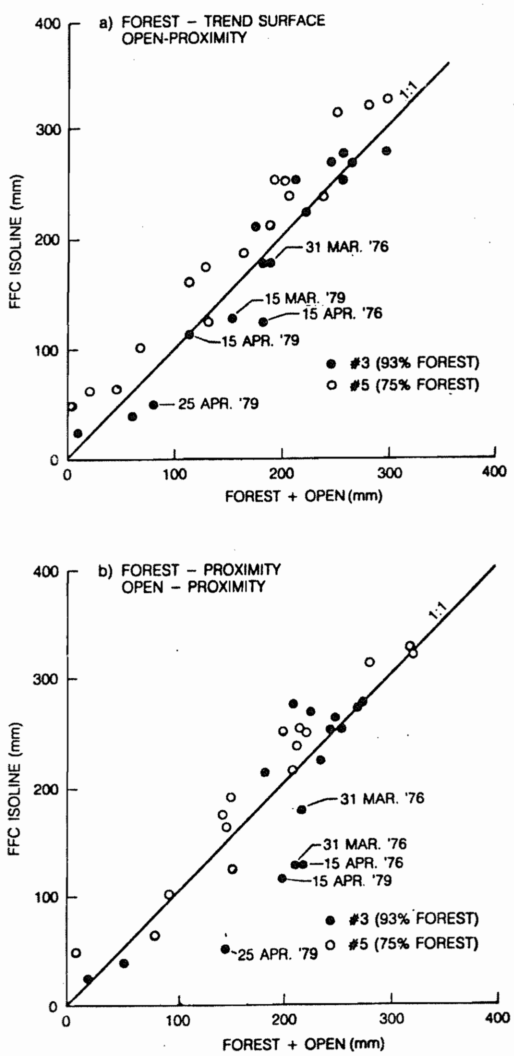
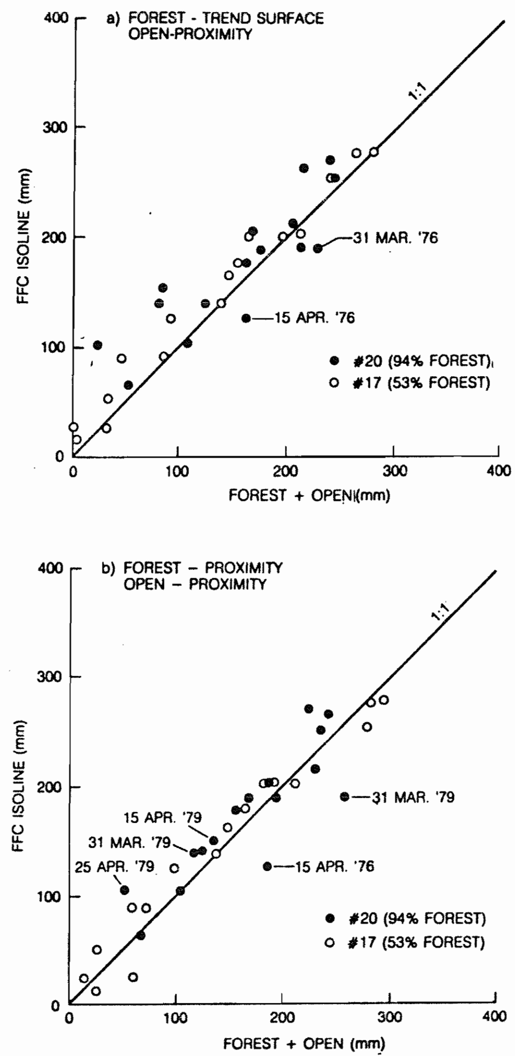


Figure 15 Comparison of FFC isoline sub-basin averages of snow water equivalent with trend surface and proximity estimates for two central sub-basins.



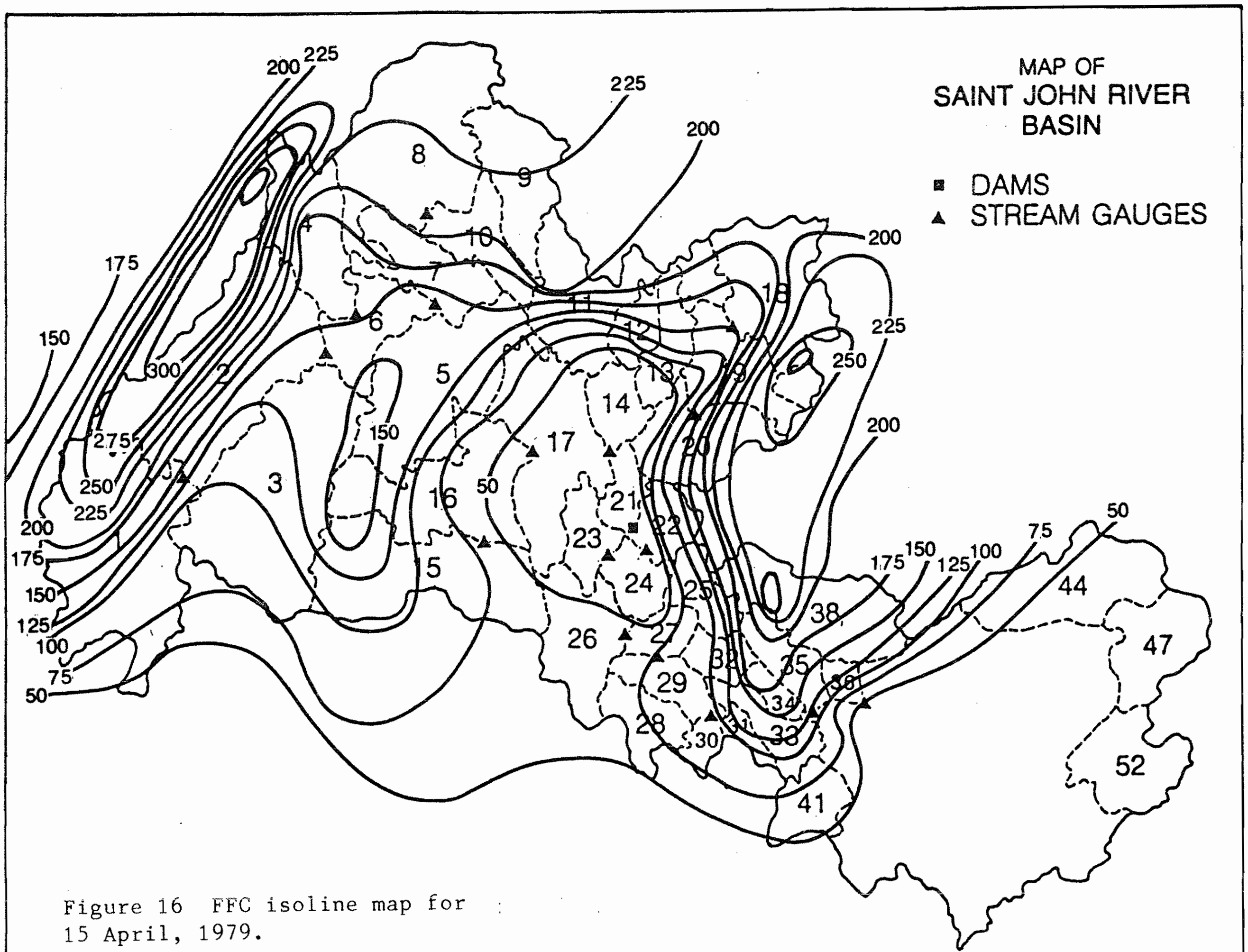


Figure 16 FFC isoline map for 15 April, 1979.

what could feasibly be considered "representative". Secondly, in cases where the FFC isoline map exhibits large gradients over short distances (see Figure 16) it is very difficult to estimate the sub-basin averages by eye.

SUMMARY

The division of snow courses into vegetation classes is considered to be essential. Figure 2 clearly indicates the problems that will arise if vegetation cover is not taken into account. To do so using the manual isoline analysis would require a level of mapping skills possessed by few people. Snow courses classified as SPLIT should have the data for their open and forest segments reported separately.

The trend surface analysis shows considerable promise as a mapping tool. It is easily implemented and the products are easily interpreted by the operational hydrologist. It is especially suited to snow survey data considering the problems in selecting the snow survey location and its "representativeness" of the surrounding area.

Both the multiple regression and the proximity analysis place more emphasis on the individual survey points and for that reason are less suitable for mapping snow course data.

Regardless of the mapping technique used it is essential that the input data not be geographically biased; that is to say, that the location of snow survey sites be uniformly, though not necessarily regularly, distributed over the basin. It is also important that there be sufficient snow survey sites outside the basin boundaries to allow the snow water equivalents to be correctly mapped to the basin boundaries.

As might be expected the major problem in using any computerized mapping technique occurs in the late spring when snow cover is patchy. Accordingly, the next major step in this study will be the incorporation of snow cover from satellite information into the grid system. Since the FFC is already distributing temperature and precipitation on a grid basis (Trivett, 1977) to calculate sub-basin averages, it would now seem feasible to incorporate a snowfall/snowmelt procedure to update the snow water equivalents between survey periods.

REFERENCES

Davis, J.C. (1973): Statistics and data analysis in geology, John Wiley and Sons, Inc.

Davis, J.C. and McCullough, M.J. (1975): Display and analysis of spatial data, Nato Advanced Study Institute, Pub. John Wiley and Sons, Inc.

Peters, J.E. and MacNeil, C.F. (1975): Catalogue of historical data and real-time data available at Fredericton, New Brunswick, WMO Saint John River Basin WWW Study, Task Force No. 1.1.

Power, J.M., Merry, C.M., Trivett, N.B.A. and Waterman, S.E. (1980): Snowpack estimation in the Saint John River Basin, a paper presented at the International Symposium of Remote Sensing of Environment.

Saint John River Basin Board (1973): Hydrology of the Saint John River Basin, Report No. 2, Inland Waters Directorate, Environment Canada, Halifax, Nova Scotia.

Schneider, S.R. (1977): Operational satellite assessment of snow cover and river ice in the Saint John River Basin, WMO Saint John River Basin WWW Study, Task Force Report No. 6.2.

Trivett, N.B.A. (1977): The application of grid square analysis to daily precipitation in a real-time flood forecast environment. WMO Saint John River Basin WWW Study, Task Force Report No. 3.12.

Trivett, N.B.A. and Waterman, S.E. (1979): A preliminary appraisal of the Saint John River Basin snow course survey network, a report submitted and presented to the Saint John Basin Flood Forecasting Technical Sub-Committee.

Trivett, N.B.A. and Waterman, S.E. (1980): Saint John River Basin snow course network: distribution and mapping, unpublished report, Hydrometeorology Division, Atmospheric Environment Service Downsview, Ontario.