Effects of Temperature and Snowfall on Winter Low Flows in New England

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ABSTRACT

The influence of winter climatic variability on magnitudes of winter low-flow events was examined by statistical analysis of hydrologic and climatic data for thirteen river basins in MA, NH and VT. Magnitudes of winter low-flow events respond primarily to variations in winter precipitation. However, the response is modified by temperature and snowfall influences which depend on the local winter temperature regime.

INTRODUCTION

Although annual low-flow events in New England occur primarily in the summer months, an understanding of winter low flows is important in the assessment of winter water supply, water quality and aquatic habitat (Melloh, 1990). Winter low-flow events occur during prolonged spells of cold, dry weather when water input from rainfall or snowmelt is limited.

Melloh (1990) examined how winter low flows vary between the Upland and White Mountain physiographic regions of New Hampshire. Otherwise, previous studies in the region have concentrated on annual low-flow events. Dingman (1978) showed that low flows in New Hampshire and Vermont are significantly related to mean basin elevation. Lawlor (1990) used multiple regression analysis to estimate low-flows from basin characteristics, such as drainage area and geology, in New Hampshire and Vermont.

Previous work, then, has focussed on the spatial variability of low-flow characteristics. This study examines how magnitudes of winter low-flow events in New England respond to winter climatic variations. An understanding of the influence of winter temperatures and snowfall may lead to an improved understanding of the nature of winter low-flow events. The influence of climatic variability on the timing of low-flow events is not addressed in this paper, but the possibility that differences in timing of occurrence may in turn affect the magnitudes of low-flow events is understood.

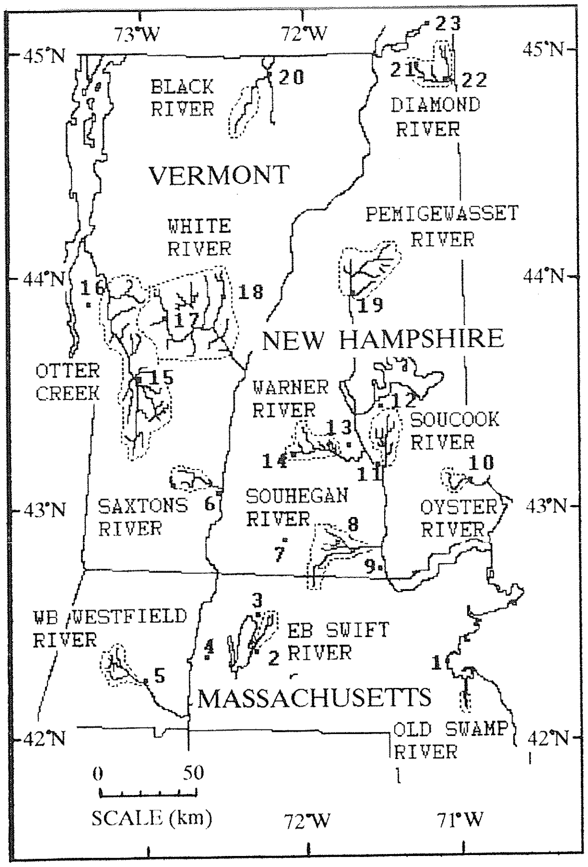
ANALYSIS METHODOLOGY

The methodology is based on statistical analysis of historical records of winter climatic and hydrologic data for thirteen drainage basins selected from Vermont, New Hampshire and Massachusetts (Figure 1, Table 1).

Calculation of Variables

Climate stations for each basin analysis were selected based on proximity to the basin, and length and completeness of records. For each winter season (defined as December 1 to April 30), mean temperature (TEMP), total precipitation (PRECIP) and total snowfall (SNOW) were calculated from National Climatic Data Center daily records of maximum and minimum temperature, precipitation, and snowfall.

The minimum average 7-day flow (Q7) calculated from USGS records of mean daily discharges over the period beginning January 1 and ending April 30 was taken to represent each winter season low flow. The beginning of the period is delayed one month relative to the climatic variable



Climate Stations:
(T=TEMP, P=PRECIP, S=SNOW)

1. Boston, MA (TPS)
2. Hardwick, MA (TPS)
3. Petersham, MA (PS)
4. Amherst, MA (T)
5. Knightville Dam, MA (TPS)
6. Bellows Falls, VT (TPS)
7. Peterborough, NH (T)
8. S. Lyndeborough, NH (PS)
9. Nashua, NH (T)
10. Durham, NH (TPS)
11. Concord, NH (TPS)
12. Lakeport, NH (TPS)
13. Blackwater Dam, NH (TPS)
14. Bradford, NH (PS)
15. Rutland, VT (TPS)
16. Cornwall, VT (TPS)
17. Rochester, VT (PS)
18. Chelsea, VT (TPS)
19. Woodstock, NH (TPS)
20. Newport, VT (TPS)
21. Dixville Notch, NH (P)
22. Errol, NH (P)
23. First Conn. Lake, NH (TS)

Figure 1. Selected river basins and climate stations

Table 1. Selected gaging stations and periods of record for analysis

USGS #	Station Name	Period of Record	Exc.(*)	Climate Stations
4296000	Black River, Coventry, VT	1960-89		20
1052520	Diamond River, Wentworth, NH	1949-89		21,22,23
1174500	EB Swift River, Hardwick, MA	1949-89	54,58,82,85,87	2,3,4
1105600	Old Swamp R., S. Weymouth, MA	1967-89		1
4282500	Otter Creek, Middlebury, VT	1952-86	57,58,59,61	15,16
1073000	Oyster River, Durham, NH	1952-88	59,64,74,81	10
1075000	Pemigewasser R., Woodstock, NH	1949-76		19
1154000	Saxtons R., Saxtons River, VT	1952-82	58,62,63	6
1089000	Soucook River, nr. Concord, NH	1953-84	79,81	11,12
1094000	Souhegan River, Merrimack, NH	1950-76		7,8,9
1191000	WB Westfield R., Huntington, MA	1952-86	56,58,61,74,83,84	5
1086000	Warner River, Davisville, NH	1948-78		13,14
1144000	White River, West Hartford, VT	1950-89		17,18

(*) winter seasons are excluded if daily streamflow record are rated by USGS as "poor" or if climatic data records are inadequate

Otter Creek flows are subject to slight regulation; other streamflows are unregulated definitions in order to minimize effects of antecedent conditions.

Analysis

Two statistical techniques were used to identify possible relationships between Q7 and the climatic variables:

1. regression analysis of Q7 against the three climatic variables; and
2. a split-sample analysis, to compare values of Q7 among different winter climatic scenarios.

Regression analysis

Possible relationships between Q7 and climatic variables were initially identified by examination of scatterplots and Spearman rank correlation coefficients. This was followed by multiple regression analysis to identify relationships between Q7 and combinations of climatic variables.

Split-sample analysis

For each river basin, a minimum Euclid-distance clustering algorithm (Balling and Lawson, 1982) identified groups of winters having similar climatic characteristics e.g. above average temperature, average precipitation, below average snowfall. Oneway analysis of variance (ANOVA) and Scheffe simultaneous 95% confidence intervals (Bowerman and O'Connell, 1990) identified significant differences (at the 0.05 level) between group mean values of TEMP, PRECIP, SNOW and Q7. In some cases, the validity of ANOVA was questionable owing to unequal variances of dependent variables among winter groups and this analysis was supported by a non-parametric version (Kruskal-Wallis and Mann-Whitney U tests; Hollander and Wolfe, 1973).

Results from the split-sample analysis were compared with those obtained from the regression analysis.

RESULTS AND DISCUSSION

Results from regression analysis indicate that the magnitudes of winter low-flow events are primarily a function of winter season precipitation. Effects of temperature and/or snowfall are significant only in the Otter Creek, Black River, West Branch Westfield River, and East Branch Swift River basins. However, the results of the split-sample analysis suggest that temperature and snowfall influences might be important in other basins, and that these influences are not uniform throughout the region, but depend on the local mean winter temperature regime. The discussion will thus focus on the results of the split-sample analysis. Several low-flow responses to winter climatic variability are suggested in Table 2.

Table 2. Influence of temperature and snowfall on low-flow magnitudes

SNOW/TEMP Influence on Q7	*Basins*	*Mean Winter Temperatures (°C)*	
		*Average **	*Range **
None	Old Swamp R.	2.2	1.0 -> 3.5
	Oyster R.	-0.6	-2.0 -> 1.0
	Souhegan R.	-1.3	-2.0 -> 0.0
Higher Q7 possible with lower TEMP and/or higher SNOW	WB Westfield R.	-1.7	-3.5 -> 1.0
	Otter Creek R.	-1.7	-3.5 -> 1.0
	Soucook R. #	-1.9	-3.5 -> 0.0
	Warner R. #	-2.3	-3.5 -> 0.0
	EB Swift R.	-0.2~	-2.0 -> 3.5~
Higher Q7 with higher TEMP and/or lower SNOW	Saxtons R. #	-2.2	-3.5 -> 0.0
	White R. #	-4.9	-8.0 -> -2.0
	Pemigewasset R. #	-2.6	-3.5 -> 0.0
Higher Q7 with higher TEMP	Black R.	-4.6	-8.0 -> -2.0
	Diamond R.	-8.0	-11.0 -> -5.5

* average and range of mean winter temperatures for period of record indicated in Table 1
# suggested by results but not statistically significant
~ temperature data from Amherst, MA at lower elevation

Results from six of the basins are presented as examples. Results of the split-sample analyses for these six basins are given in Table 3 and scatterplots of Q7 against total winter precipitation are shown in Figure 2.

Old Swamp River, MA

Differences in mean values of Q7 clearly correspond to differences in mean values of precipitation (Figure 2(a), Table 3(a)). Comparison of Groups 1 and 3 suggests that for a given average precipitation, differences in mean temperature and snowfall have no effect on the average value of Q7. The Oyster River and Souhegan River basins show similar behavior.

West Branch Westfield River, MA

While precipitation is the most influential climatic variable, split-sample analysis (Figure 2(b), Table 3(b)) shows its effect on Q7 to be modified by influences of temperature and snowfall.

Groups 1 and 2 are similar in terms of temperature and snowfall. The higher average precipitation of Group 2 (by 34%) translates to a 64% higher average Q7.

Groups 2 and 4 provide a different comparison. Average Q7 for Group 2 is 95% higher despite the non-significant difference in mean precipitation (+15%). However, Group 2 winters have significantly higher snowfall (+152%), suggesting that the fraction of precipitation that falls as snow can significantly affect low flows. The comparison of Groups 2 and 3 supports this. Group 3 has significantly higher precipitation (by 25%), but is warmer, on average, by 2.2°C, with 34% less snowfall. Average values of Q7 are not significantly different.

Higher low flows can be supported by cooler temperatures and a greater fraction of precipitation in the form of snow. This effect is also suggested by the split-sample analysis for the Soucook River (Figure 2(c), Table 3(c)). Groups 1 and 2 have similar mean values of precipitation, but Group 1 winters are significantly colder, on average, with significantly higher snowfall. Group 1 winters tend to have higher low flows, although the Group 1 average is not significantly higher (+39%) than that of Group 2.

Similar results were obtained from the analyses of Otter Creek, Warner River and East Branch Swift River.

White River, VT

No apparent relationship with either temperature or snowfall was suggested by regression analysis. There is considerable scatter in the Q7 values, even within groups (Figure 2(d)) and large differences in both average precipitation and average temperature are required to produce a significant difference in average Q7 (Groups 2 and 4). A similar precipitation difference accompanied by a much smaller temperature difference (Groups 2 and 3) results in a smaller difference in average Q7 (Table 3(d)). The importance of variations in temperature and snowfall is not clear, but there are indications that higher low flows are favored by higher temperatures and a lower snowfall fraction of precipitation. This is also the case for the Pemigewasset River and Saxtons River basins.

Black River, VT

Q7 is significantly correlated with precipitation, but regression analysis showed temperature and snowfall together to explain more of the total variance of Q7.

Groups 2 and 4 are similar with regard to temperature and the significant corresponding difference in Q7 can be attributed to differences in precipitation. Average precipitation for Group 4 is 33% higher than that of Group 3, but Groups 3 and 4 have similar average values of Q7. The average temperature of Group 4 is lower by 2.1°C, suggesting that lower temperatures can negate the effect of higher precipitation. In the low temperature regime of this northern basin, the fraction of precipitation that falls as snow is not affected, but water input from snowmelt is likely to be inhibited. Comparison of Groups 2 and 3 suggests that for a given precipitation average, higher average temperatures alone may result in higher average low flows. Higher low flows are thus favored by increased precipitation combined with higher average temperatures.

Diamond River, NH

To a certain extent, the response of low flows to climatic variations is similar to that of the Black River basin. Significant differences in average values of Q7 are explained by differences in average precipitation and the effect of increased precipitation may be enhanced when accompanied by higher temperatures. Groups 1 and 4 have similar average precipitation but Group 4 winters are significantly cooler. Average Q7 of Group 4 is not significantly different from the Group 2 and Group 3 averages. However, the comparisons of Groups 1-4 and Groups 2-3 suggest that temperature increases alone

Table 3. Split-sample analysis of winter groups

(a) Old Swamp River, MA

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
TEMP (deg. C)	2.2	1.6	2.3	3.1		1-2,1-3,2-3
PRECIP (cm.)	48.2	54.8	30.4	54.0		1-2,2-3
SNOW (cm.)	99.3	137	56.4	73.9		1-2,1-3
Q7 (cu. m/s)	0.11	0.12	0.07	0.14		1-2,2-3

(b) West Branch Westfield River, MA

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
# TEMP (deg. C)	-1.7	-2.4	-2.3	-0.1	-1.1	1-3,2-3
# PRECIP (cm.)	45.1	36.3	48.6	60.6	42.9	1-2,1-3,2-3,3-4
SNOW (cm.)	132	167	157	104	66.3	1-3,1-4,2-3,2-4
Q7 (cu. m/s)	1.84	1.46	2.40	2.25	1.23	1-2,2-4

(c) Soucook River, NH

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
TEMP (deg. C)	-1.9	-2.7	-1.7	-2.7	-0.4	1-2,1-4,2-3,2-4,3-4
PRECIP (cm.)	36.5	30.5	28.2	40.5	47.4	1-3,1-4,2-3,2-4
SNOW (cm.)	168	199	134	204	125	1-2,1-4,2-3,2-4
Q7 (cu. m/s)	1.30	1.21	0.87	1.39	1.71	2-4

(d) White River, VT

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
TEMP (deg. C)	-4.9	-5.6	-3.7	-4.7	-6.6	all comparisons
PRECIP (cm.)	38.5	42.3	49.3	32.2	33.3	1-2,1-3,1-4,2-3,2-4
SNOW (cm.)	191	244	202	163	198	1-3
Q7 (cu. m/s)	11.1	12.0	13.9	10.1	8.11	2-4

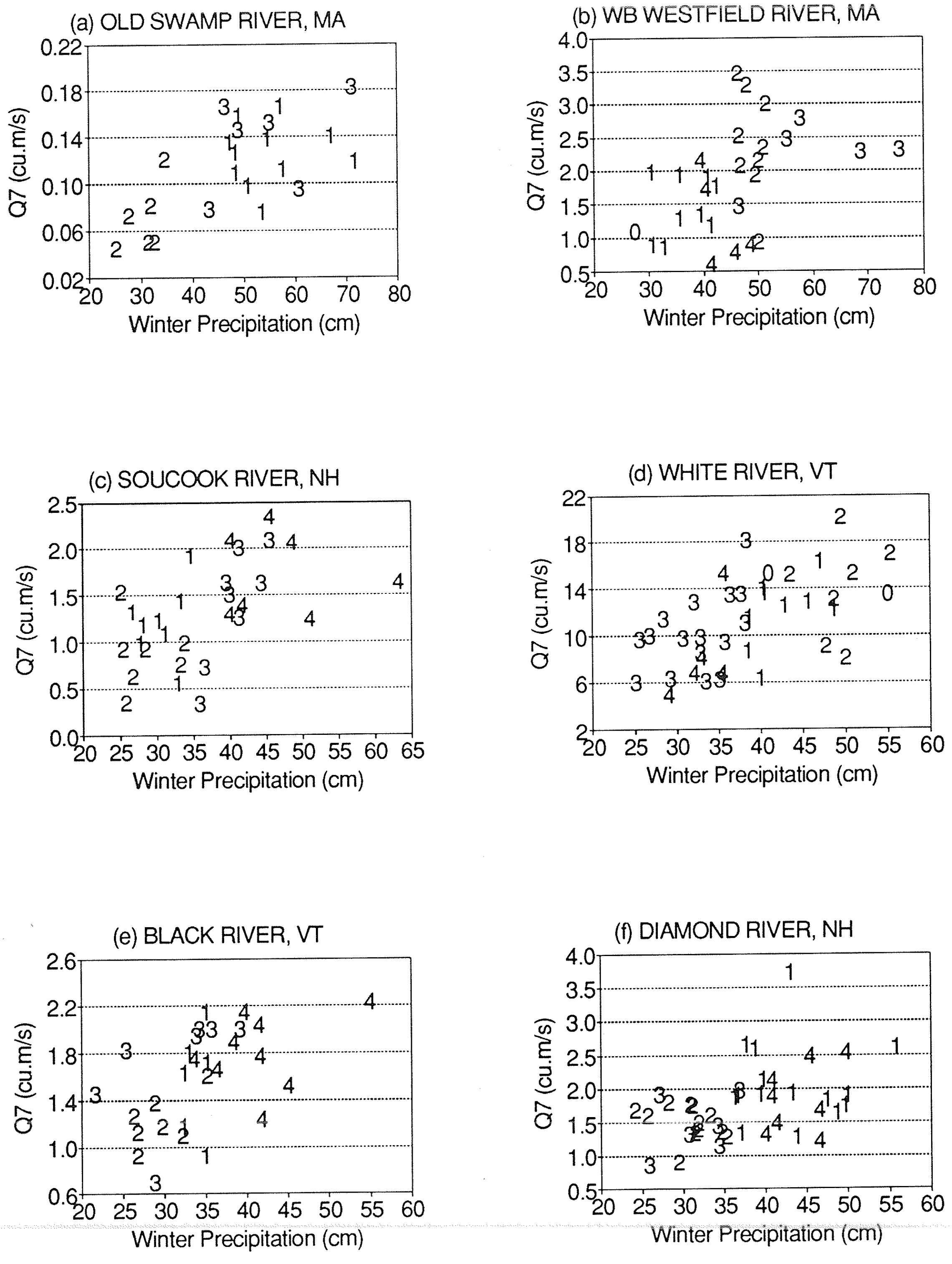
(e) Black River, VT

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
# TEMP (deg. C)	-4.6	-4.4	-5.1	-3.3	-5.4	2-3,3-4
# PRECIP (cm.)	34.8	33.7	29.2	31.1	41.3	2-4,3-4
SNOW (cm.)	225	226	181	200	272	2-4,3-4
Q7 (cu. m/s)	1.65	1.56	1.22	1.69	1.86	2-4

(f) Diamond River, NH

	Overall	*Winter Group Mean Values*				*Means Sig. Different*
	Mean	*1*	*2*	*3*	*4*	*at 0.05 level*
# TEMP (deg. C)	-8.0	-6.5	-7.6	-10.6	-9.6	1-3,1-4,2-3,2-4
PRECIP (cm.)	37.8	43.0	30.5	31.4	43.8	1-2,1-3,2-4,3-4
SNOW (cm.)	358	361	312	328	447	1-4,2-4,3-4
Q7 (cu. m/s)	1.76	2.06	1.58	1.45	1.84	1-2,1-3

# indicates variable is significantly autocorrelated (lag 1); significance tests might be affected


(a) OLD SWAMP RIVER, MA

(b) WB WESTFIELD RIVER, MA

(c) SOUCOOK RIVER, NH

(d) WHITE RIVER, VT

(e) BLACK RIVER, VT

(f) DIAMOND RIVER, NH

Figure 2. Relationship of Q7 with winter precipitation. Numeric symbols represent winters belonging to the split-sample groups indicated in Table 3. The symbol 0 indicates a winter not associated with one of the identified groups.

do not appear to affect low flows. The influence of climatic variations is thus limited by the overall temperature regime of this northern basin.

CONCLUSIONS

Magnitudes of winter low-flow events are primarily a function of winter precipitation. However, the response of winter low flows to variations in precipitation is modified by temperature and snowfall influences which depend on the local winter temperature regime.

In southern and coastal river basins, e.g. Old Swamp River, where mean winter temperatures generally exceed -2°C, variations in temperature and snowfall have no significant effect on low flows. Precipitation that falls as snow has the same net effect as precipitation that falls as rain.

Farther inland, e.g. West Branch Westfield River, where the lower end of the mean winter temperature range is below -3°C, results suggest that higher low flows can be promoted by cooler temperatures and a higher snowfall fraction of precipitation. Temperatures during the coolest winters are evidently still high enough for regular water input from snowmelt.

In the north of the region, higher low flows are favored by higher winter temperatures. In the two extreme northern basins (Black River and Diamond River), this appears to result from increased water input from snowmelt. However, farther south, e.g. the White River, increased precipitation as rain as opposed to snow may also be important.

These conclusions have an important implication in the context of global climate change in that the effect of warmer winter temperatures on winter low flows will depend on the current winter temperature regime. Furthermore, there appears to be an upper limit to the positive influence of temperature on low flows (assuming no change in precipitation). Beyond this limit, further temperature increases may actually result in decreasing low flows until the effects of temperature are no longer significant.

This study, based on bulk seasonal climatic variables, comprises a preliminary examination of the response of winter low flows to climatic variations. The temperature and snowfall influences suggested by these results will be investigated further in a more detailed follow-up study, which will also take into consideration the temporal distributions of precipitation, temperature and snowfall throughout the winter season. The possibility of a negative temperature and/or positive snowfall influence, within a certain temperature range, certainly requires further examination, first to verify that this response is indeed real, and if so, to identify the mechanism by which it occurs. For instance, increased precipitation as snow as opposed to rain may provide more effective maintenance of baseflow in winters when the total precipitation is accounted for by a few large storms, rather than smaller, more frequent storms. Assuming an adequate potential rate of snowmelt, the meltwater released by the snowpack is a source of daily water input between storms. In winters when a large snowpack accumulates, ground frost development may be inhibited also, allowing infiltration and groundwater recharge to occur for a greater portion of the winter.

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References

Balling, R.C. Jr., and M.P. Lawson, 1982, "Twentieth century changes in winter climatic regions", Climatic Change 4, 57-69

Bowerman, B.L., and R.T. O'Connell, 1990, "Linear statistical models: An applied approach", PWS-KENT Publishing Company, Boston

Dingman, S.L., 1978, "Synthesis of flow-duration curves for unregulated streams in New Hampshire", Water Resources Bulletin, 14(6), 1481-1502

Hollander, M., and D.A. Wollfe, 1973, "Nonparametric statistics methods", John Wiley and Sons, New York

Lawlor, S.C., 1990, "Estimation of low-flows from basin characteristics in New Hampshire and Vermont", MS Thesis, University of New Hampshire

Melloh, R.A., (1990), "Analysis of winter low-flow rates in New Hampshire streams", C.R.R.E.L. Special Report 90-26