Student Paper Prize

An Improved Method of Predicting Snowpack Water Equivalent

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ABSTRACT

A method for predicting snowpack water equivalent (SWE) was developed for New York and New England using variables available at National Cooperative Observer (Co-Op) collection sites. Summary of the day statistics from National Weather Service Offices (NWSO) were used to create statistical regression models. These equations were successfully tested on Co-Op snow survey data. A new variable, Maxinrow, the number of consecutive days with a maximum temperature less than freezing, proved slightly superior to degree-day variables. The models will allow the ground-based snowmelt data network to increase from 15 NWSOs and a handful of research sites to over 500 locations in the Northeastern United States at virtually no additional expense to prospective users.

INTRODUCTION

In New England and New York, spring floods, agricultural water supplies, and reservoir levels are problems where snowmelt plays an important seasonal role. Efforts at forecasting water quantities by predicting snowmelt range from simple degree-day models (Kuz'min,1961) to multiple regression (U. S. Army Corps of Engineers {USACOE}, 1956, Garstka et al., 1958) involving elaborate arrays of collection sites. Although Zuzel and Cox (1975) found temperature alone, if necessary, to be an adequate predictor, precipitation, relative humidity, wind, and snowpack water equivalent (SWE) are the minimum parameters needed for the various multivariate approaches to snowmelt prediction. More recently these point collection techniques have been superceded, in part, by gamma radiation detection overflights (Carroll & Carroll, 1989) and satellite-based remote sensing (Dozier,1987).

Despite the trend toward more complex techniques there is still a place for point measurements. Ground based observations could be used to verify remote sensing techniques, and to continue providing primary input into models determining basin snowmelt characteristics (e.g.; Anderson, 1973 and Fleming, 1975). One of the main problems with point measurements is simply the small number of observing sites where sufficient data for predicting snowmelt is recorded. An increase in the number of these locations could significantly improve the accuracy of the prediction models.

Buttle and Xu (1988) demonstrated that a simplified but effective method for calculating snowmelt in Southern Ontario was to observe SWE from one day to the next. If no precipitation fell the difference in SWE was simply snowmelt. Although this neglected sublimation of and evaporation from the snowpack, those events were considered to be inconsequential, at least on a daily basis. Presently, only National Weather Service Offices (NWSO), of which there are 15 in New York and New England, and a few research locations actually determine SWE on a daily basis.

Volunteers with the National Cooperative Observer Program (Co-Op), an underutilized network composed of approximately 250 sites in New York and 250 sites in New England, do not melt the snowpack on a regular basis, but do record daily precipitation, snowfall and temperatures. It would be worthwhile to add information from this network into the dataset used by snowmelt researchers.

The purpose of this investigation was to develop a method for predicting SWE from NWSO data, using only predictors available at Co-Op stations. The resulting models could then be applied to Co-Op data, thereby augmenting the sampling network and providing additional snowmelt information for concerned interests.

THE EQUATIONS OF SNOWMELT

The starting point for all snowmelt research is the snowpack energy balance equation (after Kuz'min, 1961 and Fleming, 1975),

1) $W_r + W_k + W_e + W_s + W_h + W_b = 0$

where all units are in Joules/m^2-day and

W_r = radiative heat transfer
W_k = sensible heat transfer with the atmosphere
W_e = latent heat transfer with the atmosphere
W_s = soil heat transfer
W_h = heat transfer which changes snow temperature
W_b = heat expenditure to melt snow (or freeze water)

If the heat expenditure to melt snow (W_b) is brought over to one side of the equation, the sum of the other terms, if positive, indicates heat available for melting snow.

The data at Co-Op sites do not directly measure the components of the energy equation. These circumstances require any model developed to rely heavily on the water balance approach,

2) $SWE_{end} - SWE_{initial} = S + R - M - Sub - Evap$

where all values are in inches and

SWE = values of the water equivalent at specific times

S = new snow

R = rain

M = snowmelt (the water expressed at the bottom of the pack)

Sub = sublimation from the snowpack

Evap = evaporation of the melted snow in the pack

Neglecting sublimation and evaporation leaves the simple relationship involving precipitation input, melt, and the corresponding change in SWE, as demonstrated by Buttle and Xu (1988).

Because of the ability of rain to both enter and melt the snowpack, separate equations have been developed which predict snowmelt during rain on snow events. One example (after USACOE, 1956) is

3) $M = (0.00695\ °F^{-1})\ (T_r - 32)\ P_r$

where

M = melt in inches

T_r = temperature of the rain (°F)

P_r = precipitation in inches

MODEL DEVELOPMENT

A) Data Preparation

National Weather Service Offices have included SWE in their daily climate data summaries since the early to mid 1950's. Maximum and minimum air temperatures, snowfall, and precipitation are reported for the midnight to midnight period, the depth of the snowpack is measured every morning at 7:00 a. m. E.S.T. (12:00 UTC), and reported if greater than two inches (5 cm), and the SWE is measured at 1:00 p. m. E.S.T. (18:00 UTC).

Figure 1 shows the location of the 15 National Weather Service Offices in New York and New England. Table 1 describes the length of record used in this study for each NWSO.

Schmidlin (1990), investigating several NWSOs in Indiana and Ohio, described some problems with these datasets ranging from typographical errors to physically impossible values. For this work obvious keypunch errors were corrected, while lapses in continuity or logic caused the entire observation to be omitted. These lapses typically involved dramatic changes in SWE not justified by additional snowfall or rainfall, or by temperature extremes. Removed observations amounted to a very small percentage of the 30 to 35 year datasets. As a worst case, 3 of 138 days with greater than two inches of snow on the ground at LaGuardia Airport in New York City were omitted from 33 years of January observations.

Because the purpose of this work was to predict the amount of SWE, it was important not to consider any predictors whose daily values could be affected by events occurring after the afternoon SWE measurement. For example, the maximum temperature for a given day probably occurs after the SWE measurement. The preceding

Figure 1. National Weather Service Offices (NWSOs) in New York and New England.

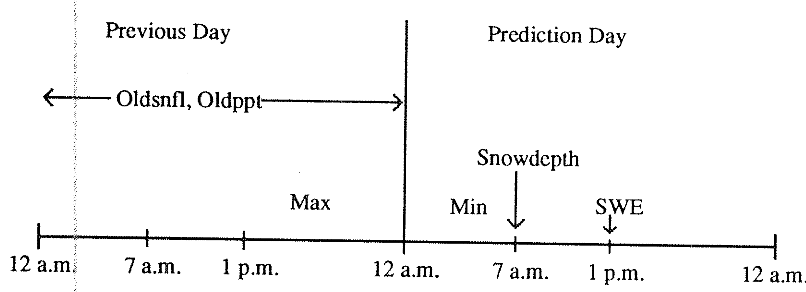

Figure 2. NWSO timing of observations.

Table 1. National Weather Service Offices and their length of record used for this work.

NWSO	Length of Dataset
Albany, NY	1952-1986
Binghamton, NY	1952-1986
Boston, MA	1953-1986
Bridgeport, CT	1952-1986
Buffalo, NY	1952-1986
Burlington, VT	1952-1986
Caribou, ME	1952-1986
Concord, NH	1952-1986
Hartford, CT	1954-1986
LaGuardia - NYC, NY	1952-1986
Portland, ME	1953-1986
Providence, RI	1953-1986
Rochester, NY	1953-1986
Syracuse, NY	1952-1986
Worcester, MA	1959-1986

day's maximum temperature was, therefore, included in the initial predictor list. Figure 2 shows the timing of these and other variables.

The 6 hour window where snowdepth could change after being measured and before SWE is determined introduces a potential source of error into the model. The measured snowdepth, however, still precedes the SWE measurement and may be used as a predictor. Since snowfall and precipitation can occur in the eleven hours between the SWE measurement and midnight they could not be used to predict SWE on the same date. To ensure the purely predictive nature of a model, it was decided to use the preceding 24 hour precipitation (Oldppt) and snowfall (Oldsnfl) amounts, and the morning snowdepth as possible predictors of the afternoon SWE.

The U. S. Army Corps of Engineers (1956) and Garstka et al. (1958) used such variables as relative humidity and wind in their regression analyses. Since these variables are not measured at Co-Op stations, an attempt was made to create variables which could furnish some extra information to a prospective model. For example, many researchers have reported daily snowmelt as a function of cumulative degrees greater than a base temperature. Conversely, cumulative degree days less than a ceiling temperature could provide a measure of the cold content of the snowpack, indicating the heat required to raise the snowpack to the freezing point and then to ripen, or satisfy the free water holding capacity of the snow.

For this work cumulative melting degree days (Cummdd) were calculated for days when the maximum temperature exceeded 32° F. The cold indicator was named Maxinrow, or the number of consecutive days when the maximum temperature was less than 32° F. Similar variables for minimum and mean temperature were developed, for consecutive cold days and also for warm days. Hotmax was the number of consecutive days with a maximum temperature greater than 32° F.

Snowdepth and temperature information for the day before the day of the prediction were included in the predictor list to investigate if previous information about the snowpack and temperature conditions would be useful. Table 2 gives a list of potential predictors used in model development.

B) Exploratory Model Building and Final Models

Binghamton, NY was arbitrarily selected to be the first station used in model development. January days were used which did not follow a day when rain fell. Rain on snow days amounted to approximately 5% of all observations and were reserved for later analysis. Half of the remaining data were reserved for use in verification of the model. These were simply alternate observations in the dataset.

The initial predictor list was reduced with a stepwise selection procedure (p. 430 ff., Neter et al., 1985) using SWE as the dependent variable. The variable selection procedure initially yielded snow depth (Snowdepth), Maxinrow, yesterday's snowfall (Oldsnfl), and yesterday's precipitation (Oldppt) as predictors for Binghamton.

Standardized residual analysis of the multiple regression results was used to determine if errors were normally

Table 2. Potential predictors used in model building.

Predictor	Abbreviation
Maximum temperature	Max
Minimum temperature	Min
Mean temperature {(Max + Min)/2}	Mean
Previous day's precipitation	Oldppt
Previous day's snowfall	Oldsnfl
7:00 a.m. snow depth	Snowdepth
Square root of snow depth	Sqrtsndp
Cumulative melting degree days (the running total of (Max - 32°F.),for successive days with Max > 32°F.)	Cummdd
Consecutive days with Max < 32°F.	Maxinrow
Consecutive days with Max > 32°F.	Hotmax
Consecutive days with Min < 32°F.	Mininrow
Consecutive days with Min > 32°F.	Hotmin
Consecutive days with Mean < 32°F.	Meaninrow
Consecutive days with Mean > 32°F.	Hotmean
Previous maximum temperature	Oldmax
Previous minimum temperature	Oldmin
Previous mean temperature	Oldmean
Previous snow depth	Olddepth
Max - Min	Range

Table 3. January models for 15 NWSOs in New York and New England. The dependent variable is sqrtSWE.

dataset	r-squared (%)	RMSE	constant	snowdept	sqrtsndp	maxinrow	oldsnfl	oldppt
Albany	75.1	0.204	0.156	0.028	0.284	-0.005	-0.078	0.524
Binghamton	64.4	0.239	0.143	0.037	0.295	-0.014	-0.073	0.398
Boston	75.0	0.176	0.123	0.021	0.303	-0.020	-0.057	0.426
Bridgeport	62.9	0.155	0.425	0.067	0.023	-0.017	-0.046	0.261
Buffalo	71.6	0.272	0.210	0.036	0.231	-0.012	-0.054	0.299
Burlington	67.8	0.223	-0.007	0.000	0.383	-0.007	-0.049	0.295
Caribou	64.9	0.341	-0.221	-0.025	0.586	-0.007	-0.043	0.427
Concord	47.3	0.333	-0.745	-0.110	1.027	0.001	-0.053	0.411
Hartford	58.2	0.243	-0.195	-0.046	0.637	-0.012	-0.049	0.248
LaGuardia NYC	85.7	0.081	-0.044	-0.005	0.350	-0.004	-0.051	0.549
Portland	66.8	0.306	0.134	0.020	0.353	-0.031	-0.060	0.280
Providence	43.5	0.181	0.116	-0.028	0.394	0.010	-0.039	0.235
Rochester	59.1	0.245	-0.154	-0.024	0.551	-0.011	-0.064	0.563
Syracuse	55.2	0.263	-0.053	-0.006	0.422	0.002	-0.076	0.668
Worcester	62.6	0.223	0.299	-0.004	0.302	-0.009	-0.046	0.350

distributed or whether transformations of the variables would be necessary (p. 111 ff., Neter et al., 1985). Residual plots indicated increasing variance of predicted SWE as snowdepth increased. This suggested the need for a transformation of SWE. A test after Box and Cox (p. 225 ff., Draper & Smith, 1981) indicated a square root transformation would make the variance nearly constant, thereby making the root mean squared error (RMSE) representative of the entire data range. Rerunning the selection procedure using the square root of SWE (sqrtSWE) produced the same predictors, but yielded curvature in the residuals when plotted against snowdepth. This implied the need for an additional predictor term, and the square root of snowdepth (sqrtSndp) was added to the model. The resulting regression yielded normally distributed residuals with essentially constant variance.

The calibrated model was verified with the reserved half of the dataset. RMSE and the coefficient of multiple correlation (R^2) were compared for the two dataset halves. Since both were within 5% of one another the halves were combined, regression analysis was rerun, and the result was the final model for January days with snow on the ground except those preceded by a day with rain. The same predictor variables were used for all 15 New York and New England stations, with separate parameter estimates for each station. At this point 15 models for January existed. Table 3 shows the equation, the RMSE, and the R^2 for each station using January as an example. The R^2 indicates that between 44% and 87% of the variation in sqrtSWE was described by the models. Models using the same variables were also developed for December and February, with virtually the same range for R^2 and RMSEs.

Slope and intercept models with dummy variables is a method which can be used to group many stations and test whether one parameter estimate per variable is suitable for all stations in the group (p. 339, Neter et al., 1985). This analysis can create a family of parallel lines with separate intercepts for each station, when the intercepts are the only parameter estimates which differ between stations. If successful, the result is one model with more general application possibilities than the individual station models.

Groups were subjectively formed which encompassed stations sharing geographic and topographic similarities, and are outlined in figure 3. The main groups checked included Coastal (Portland, Boston, Providence, Bridgeport, LaGuardia-New York City), Mountain (Caribou, Concord, Burlington, Albany, Worcester, Hartford), and Western New York (Buffalo, Rochester, Binghamton, Syracuse). The 15 stations were also combined into a Total group. As an example, table 4 shows R^2, RMSE, station intercepts, and the parameter estimates for the January mountain group. Rain on snow days are included by adding a correction factor to the calculation.

The procedure was repeated for the other winter months of December and February, and individual and grouped models were developed. Grouping across months (January and February, and also the three winter months of December, January and February) resulted in two additional sets of models. Table 5 shows the three month winter model for all 15 stations. This grouping procedure not only creates separate intercepts for each station, but also correction factors for month, and for those 5% of all observations which followed a day where rain fell on snow. More than 70% of the variation in sqrtSWE is still being described by the model.

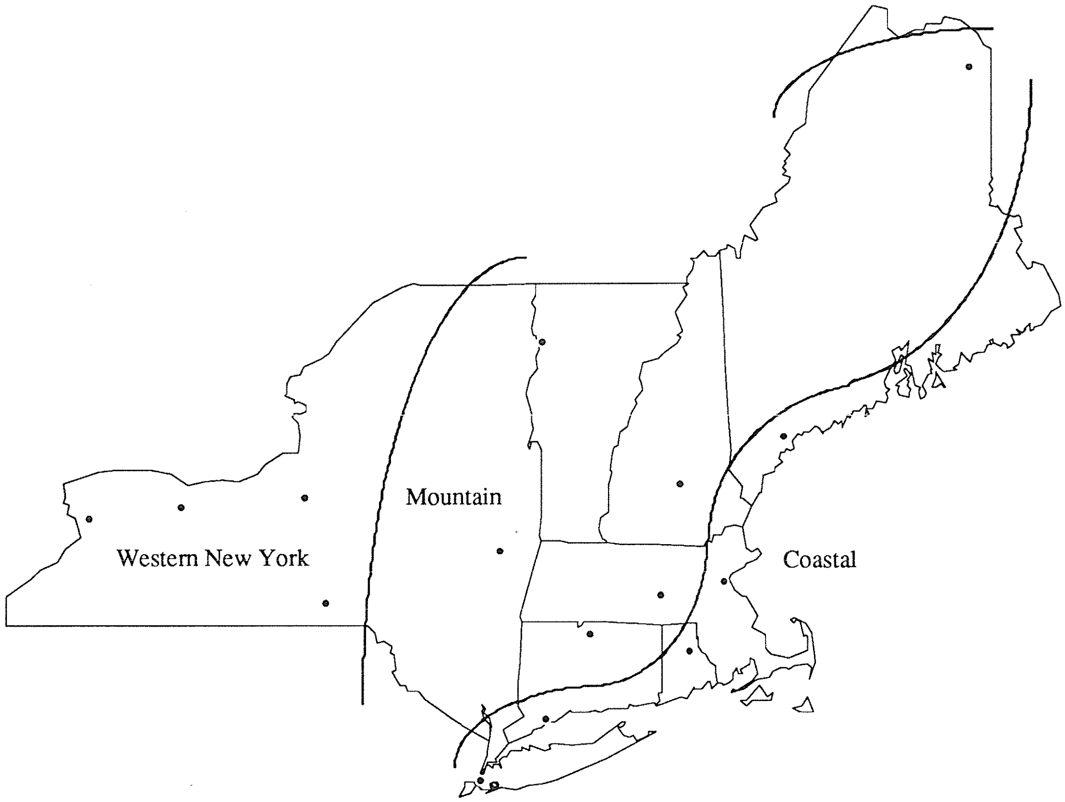

Figure 3. Divisions for grouping NWSOs.

Table 4. January mountain grouping, showing station intercepts, parameter estimates, rain on snow correction factor, and statistics, including probability of a greater t-ratio.

Intercept	Estimates	s.e.estimate	t-ratio	pr of > t
Albany	0.039	0.032	1.200	0.232
Burlington	-0.076	0.033	-2.330	0.020
Caribou	0.116	0.033	3.520	0.000
Concord	0.085	0.034	2.500	0.013
Hartford	0.036	0.032	1.120	0.262
Worcester	-0.033	0.033	-1.010	0.314
Variable				
snowdepth	-0.009	0.003	-3.230	0.001
sqrtsndp	0.433	0.020	22.130	0.000
maxinrow	-0.007	0.001	-8.420	0.000
oldsnfl	-0.047	0.003	-13.560	0.000
oldppt	0.307	0.030	10.260	0.000
rain on snow	0.070	0.021	3.320	0.001

r-squared = 0.688 RMSE = 0.287 n=4259

Table 5. Winter total grouping, showing station intercepts, parameter estimates, rain on snow correction factor, and statistics, including probability of a greater t-ratio. The model is for February data, with corrections for December and January. As an example, the model for Binghamton in January would be SqrtSWE = 0.038 - 0.013 * Snowdepth + 0.492 * Sqrtsndp - 0.008 * Maxinrow - 0.053 * Oldsnfl + 0.316 * Oldppt - 0.099. If rain had fallen on the day before the prediction, add 0.122.

Intercept	Estimates	s.e.estimate	t-ratio	pr of > t
Albany	-0.001	0.015	-0.080	0.940
Binghamton	0.038	0.015	2.590	0.010
Boston	-0.021	0.016	-1.320	0.188
Bridgeport	-0.102	0.017	-5.880	0.000
Buffalo	-0.009	0.015	-0.600	0.550
Burlington	-0.087	0.015	-5.840	0.000
Caribou	0.087	0.015	5.940	0.000
Concord	0.071	0.015	4.710	0.000
Hartford	-0.014	0.015	-0.900	0.367
LaGuardia-NYC	-0.175	0.019	-9.060	0.000
Portland	0.088	0.015	5.970	0.000
Providence	-0.043	0.016	-2.620	0.009
Rochester	0.062	0.015	4.210	0.000
Syracuse	-0.074	0.015	-4.930	0.000
Worcester	-0.103	0.015	-6.780	0.000
Variable				
snowdept	-0.013	0.001	-10.490	0.000
sqrtsndp	0.492	0.008	58.660	0.000
maxinrow	-0.008	0.000	-19.350	0.000
oldsnfl	-0.053	0.001	-37.300	0.000
oldppt	0.316	0.012	26.340	0.000
Correction for				
December	-0.201	0.005	-39.460	0.000
January	-0.099	0.005	-21.520	0.000
rain on snow	0.122	0.010	12.790	0.000

r-squared = 0.721 RMSE = 0.281 n=21176

MODEL VERIFICATION ON INDEPENDENT DATA

A) Data Preparation

The New York observers in the National Cooperative Observer Program take daily observations of maximum and minimum temperature, precipitation, snowfall, and depth of the snowpack. These volunteers also participate in a periodic snow survey under the auspices of the Northeast Regional Climate Center. Beginning the first Monday in January, and at 28 day intervals through February, followed by 14 day intervals into May, the observers determine the SWE. Twenty-two stations (see figure 4 and table 6) with at least 20 years of data were chosen for verification to ensure samples large enough for statistical analysis.

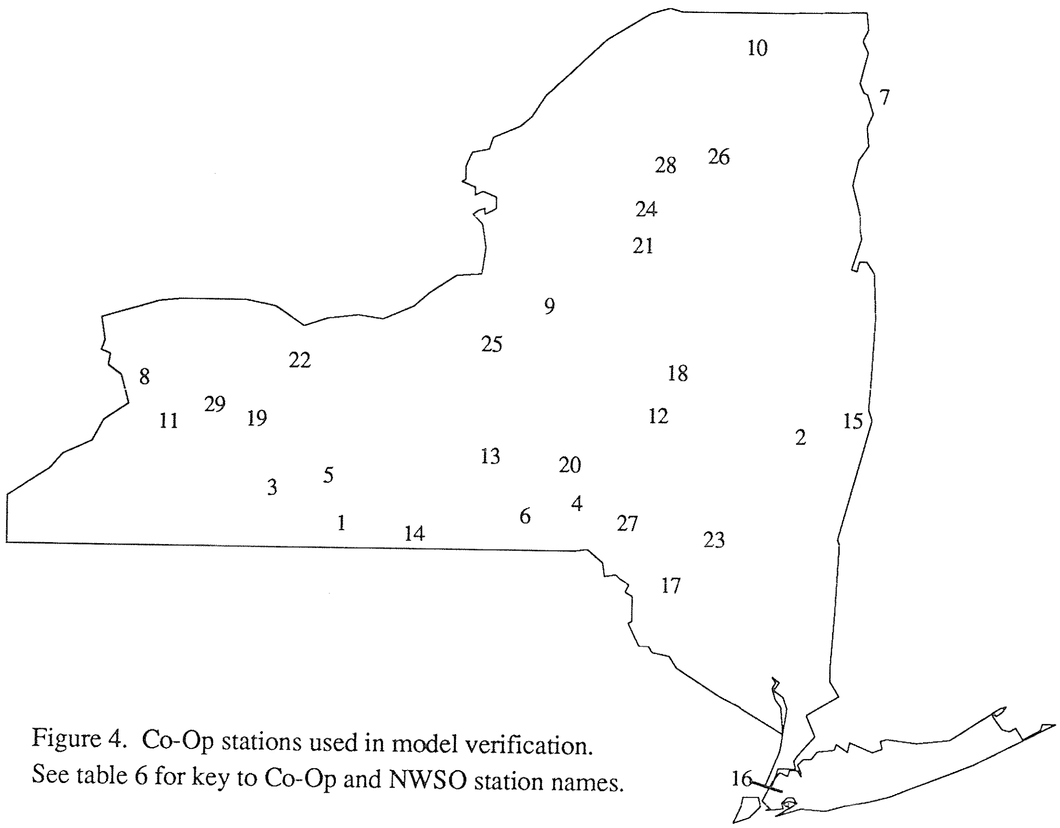

Figure 4. Co-Op stations used in model verification.
See table 6 for key to Co-Op and NWSO station names.

Table 6. National Cooperative Observer stations with their years of snow survey data and National Weather Service Offices in New York and Vermont used in verification studies. The identification numbers correspond to those in figure 4.

Station	Years of Record	Station	Years of Record
1. Addison	1948 - 1986	15. Grafton	1952 - 1984
2. Albany	(NWSO)	16 La Guardia - New York City	(NWSO)
3. Alfred	1938 - 1990	17. Liberty	1942 - 1990
4. Bainbridge	1938 - 1990	18. Little Falls	1937 - 1985
5. Bath	1954 - 1990	19. Mount Morris	1955 - 1986
6. Binghamton	(NWSO)	20. Norwich	1938 - 1990
7. Burlington, Vermont	(NWSO)	21. Old Forge	1937 - 1990
8. Buffalo	(NWSO)	22. Rochester	(NWSO)
9. Camden	1942 - 1986	23. Slide Mountain	1941 - 1990
10. Chasm Falls	1939 - 1980	24. Stillwater Reservoir	1937 - 1990
11. Colden	1965 - 1990	25. Syracuse	(NWSO)
12. Cooperstown	1941 - 1990	26. Tupper Lake - Sunmount	1937 - 1990
13. Cortland	1948 - 1990	27. Walton	1941 - 1980
14. Elmira	1947 - 1990	28. Wanakena	1937 - 1990
		29. Warsaw	1955 - 1990

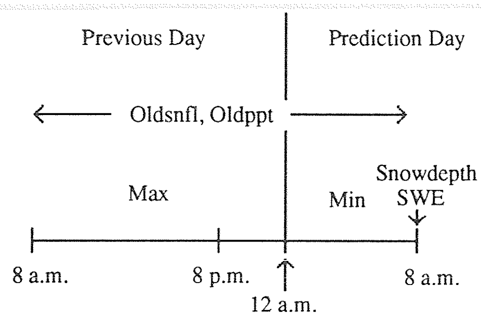

Figure 5. Co-Op station timing of observations

All observations at these stations are taken at the same time of day, usually in the morning. Oldsnfl and Oldppt are for the 24 hours immediately preceding the SWE and snowdepth measurement. Therefore, there is no timelag as is the case with the NWSO observations, and errors due to this source of lost information are eliminated. Figure 5 illustrates the timing of data collection at Co-Op sites. It should be compared with the discontinuity of data collection at NWSO sites in figure 2.

B) Verification Results

For verification, Maxinrow was calculated for the Co-Op stations. Equations from geographically proximate NWSOs (e.g.; Buffalo for Colden, Albany for Grafton) were used at each station. If the Co-Op site was between NWSOs, verification was attempted with the equations for both stations, or, in the case of Old Forge, those for Syracuse, Albany, and Burlington. When the grouped equations were tested, the intercept for the nearest NWSO was used. Percentages of model described variation were calculated. RMSE was also determined, and standardized residuals were plotted against snowdepth for each location to determine any bias or weakness in the models.

All stations in Western and Central New York exhibited no problems, indicating very good response to the models. RMSEs were very similar to those of the exploratory data. Adirondack stations, however, exhibited uniform underprediction with Burlington or Albany models. Investigation of January and February minimum temperatures revealed more affinity between Adirondack stations and Caribou than with Albany or Burlington. Applying the Caribou model to these Co-Op sites solved most of the problem. The beginning of a tendency toward underprediction was only evident when the actual SWE exceeded 4 inches in January and 6 inches in February. Table 7 shows the NWSO whose models best describe each Co-Op site, and corresponding R^2 and RMSE.

Table 7. Co-Op stations and preferred NWSO models, with representative model described variation and RMSE.

Station	January preferred models	January described variation	January RMSE	February preferred models	February described variation	February RMSE
Addison	Buffalo	0.66	0.22	Buffalo	0.55	0.27
Alfred	Buffalo	0.59	0.21	Buffalo	0.56	0.28
Bainbridge	Binghamton	0.80	0.18	Binghamton	0.79	0.21
Bath	Buffalo	0.81	0.17	Buffalo	0.47	0.23
Camden	Syracuse	0.68	0.28	Caribou	0.69	0.40
Chasm Falls	Caribou	0.74	0.20	Caribou	0.80	0.23
Colden	Rochester	0.80	0.19	Rochester	0.76	0.33
Cooperstown	Syracuse	0.67	0.22	Syracuse	0.66	0.27
Cortland	Syracuse	0.69	0.23	Syracuse	0.79	0.24
Elmira	Binghamton	0.76	0.17	Binghamton	0.67	0.23
Grafton	Caribou	0.78	0.19	Caribou	0.90	0.13
Liberty	Caribou	0.69	0.22	Caribou	0.78	0.19
Little Falls	Caribou	0.73	0.16	Caribou	0.76	0.21
Mt. Morris	(bad data)	-.--	-.--	Buffalo	0.59	0.26
Norwich	Albany	0.33	0.28	Albany	0.79	0.22
Old Forge	Caribou	0.66	0.30	Caribou	0.43	0.38
Slide Mountain	Caribou	0.74	0.31	Binghamton	0.73	0.42
Stillwater	Caribou	0.72	0.26	Caribou	0.53	0.33
Tupper Lake	Caribou	0.73	0.20	Caribou	0.61	0.32
Walton	Caribou	0.71	0.23	Caribou	0.77	0.22
Wanakena	Caribou	0.70	0.23	Caribou	0.67	0.36
Warsaw	Buffalo	0.78	0.24	Rochester	0.79	0.18

Table 8. Maxinrow correlated with mean snowpack density

Station	December	January	February
Albany	-0.438	-0.434	-0.257
Binghamton	-0.269	-0.465	-0.408
Boston	-0.475	-0.545	-0.316
Bridgeport	-0.574	-0.494	-0.402
Buffalo	-0.501	-0.393	-0.222
Burlington	-0.494	-0.401	-0.418
Caribou	-0.422	-0.461	-0.479
Concord	-0.496	-0.304	-0.024
Hartford	-0.554	-0.406	-0.495
LaGuardia NYC	-0.448	-0.524	-0.238
Portland	-0.384	-0.456	-0.311
Providence	-0.403	-0.167	-0.396
Rochester	-0.322	-0.403	-0.402
Syracuse	-0.354	-0.318	-0.247
Worcester	-0.437	-0.465	-0.295

DISCUSSION

The physical role of the predictors is clear for all except Maxinrow. Whereas Snowdepth, Sqrtsndp, Oldsnfl, and Oldppt are either components or related to components in the water balance of the snowpack, Maxinrow is unusual. It is highly correlated with cumulative freezing degree days (the running total of 32° F. - maximum temperature, for consecutive days with the maximum temperature less than freezing). A consistent negative correlation between Maxinrow and the mean density of the snowpack shows that lower mean snowpack density occurs with larger values of Maxinrow. Table 8 illustrates this trend for the 15 NWSOs in the three winter months. This holds whether the mean density is calculated over the time period equal to Maxinrow, or over the period of measurable snowcover if less than Maxinrow. Although the correlations are not statistically significant, high mean densities never occur with high values of Maxinrow. This points to Maxinrow as a weak guide to snowpack ripeness. For most of the stations and months Maxinrow consistently serves to reduce the SWE. If Maxinrow equals zero then the square root of SWE may be that of a ripe or nearly ripe snowpack. If Maxinrow is non-zero the resulting water content is possibly being corrected for non-ripeness. Maxinrow may, therefore, also be describing a component of the snowpack water balance.

The predictive role of Maxinrow was compared with that of the traditional degree-day term, Cummdd. When Cummdd was substituted for Maxinrow, the models consistently showed lower R^2 by as much as 4% and higher RMSE. Thus Maxinrow appears to be at least a slight improvement as a predictor over the degree-day approach.

The range of R^2 values for January models is typical for all three winter months. Variation is probably in part due to differences in station climatologies. Concord, for example, has the lowest R^2 and is influenced by warm, moist coastal storms, colder systems moving up the Ohio Valley and across the Great Lakes, and cold Canadian outbreaks. Caribou, being influenced primarily by the colder systems, may have less variation as a result. Another explanation may be measurement technique (SWE determination by weighing, melting, or estimating) and possible differences in accuracy as described by Schmidlin & Edgell, (1989). Further examination of this problem could lead to model improvements and is recommended.

CONCLUSIONS

The results of these verification studies show that even the most general model is successful at describing more than 70% of the variation in sqrtSWE. Since no knowledge of previous SWE is required for this approach, it appears that this work successfully fills a gap in the data network by allowing daily cooperative observer data to be used in calculating the SWE with reasonable accuracy. It is hoped that these equations will be used in the Northeastern United States and adjacent Canadian provinces, and cautiously tested on other regions. The possible upper limit of 4 inches of actual SWE in January and 6 inches in February before underprediction begins should be noted when using the models for areas of deep snowcover.

The network of stations supplying snowmelt information in New York and New England can be expanded from 15 NWSOs to over 500 sites at virtually no cost to prospective users, enabling these results to be readily incorporated into systems requiring knowledge of SWE and snowmelt.

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LITERATURE CITED

Anderson, E. A., National Weather Service River Forecast System - Snow Accumulation and Ablation Model, NOAA Technical Memorandum NWS Hydro-17, U. S. Department of Commerce, Washington, D. C., November, 1973, 219 pp.

Buttle, J. M. & F. Xu, Snowmelt Runoff in Suburban Environments, Nord. Hydrol. 19: 19-40, 1988.

Carroll, S. S., & T. R. Carroll, Effect of Uneven Snow Cover on Airborne Snow Water Equivalent Estimates Obtained by Measuring Terrestrial Gamma Radiation, Water Resour. Res. 25: 1505-1510, 1989.

Dozier, Jeff, Recent Research in Snow Hydrology, Rev. of Geophys. 25:153-161 1987.

Draper, N. R. & H. Smith, Applied Regression Analysis, 2nd ed., John Wiley & Sons, New York, 1981.

Fleming, G., Computer Simulation in Hydrology, Elsevier Environmental Science Series, New York, 1975.

Garstka, W. U., L. D. Love, B. C. Goodell & F. A. Bertle, Factors Affecting Snowmelt and Streamflow, U. S. Bureau of Reclamation, 189 pp., 1958.

Kuz'min, P. P., Melting of Snow Cover. (1961) Israel Program for Scientific Translations, 1972.

Neter, J., W. Wasserman, & M. H. Kutner, Applied Linear Statistical Models, 2nd edition, Irwin, Homewood,IL, 1985.

Schmidlin, T. W., A Critique of the Record of "Water Equivalent of Snow on the Ground" in the United States, J. Appl. Meteorol. 29:1136-1141 1990.

Schmidlin, T. W. & D. J. Edgell, Observations on the Measurement of Shallow Snow Covers, Preprints, 6th Conference on Applied Climatology, Charleston, SC, 1989

U. S. Army Corps of Engineers, Snow Hydrology, Summary Report on Snow Investigations, 437pp., 1956.

Zuzel, J. F. & L. M. Cox , Relative Importance of Meteorological Variables in Snowmelt, Water Resour. Res. 11: 174-176, 1975.