Preliminary Analysis of Historical Snow Data Using a Geographic Information System

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Abstract:

Historical snow data have been analyzed using geographic information systems software to determine the magnitude and distribution of maximum observed equivalent water content of snowpack for the State of Maine. Data from 131 sites with as much as 80 years of record were used to generate a map of maximum equivalent water content. Maximum water contents ranged from 6 to 10 inches (150 to 250 millimeters) along the coast to a high of more than 18 inches (450 millimeters) in mountainous areas of eastern New Hampshire and western Maine. These maximum water contents were generally more than 2-5 times the average equivalent water contents of snowpack reported by earlier investigators. Preliminary trend analysis of annual maximum observed equivalent water contents at sites with near-continuous record indicate peak values in the period 1950-70 with decreasing values since 1970.

Introduction:

The depth and water content of the snowpack have been measured at selected sites in Maine for more than 80 years. This information on snow depth and equivalent water content has been collected by electric-power utilities, water-power companies, pulp and paper companies, and the U.S. Geological Survey (USGS) in cooperation with the State of Maine. In 1991, the USGS and the Maine Geological Survey began a compilation of all historical snow-survey data for the State.

This paper presents preliminary results of an analysis of historical snow-survey data to determine the areal characteristics of the maximum observed equivalent water content of snowpack observed for the State. In addition, these maximum values were graphically compared with the average water content in snowpack for the period 1941-65 as reported in Hayes (1972), and a preliminary analysis of long-term trends in annual maximum observed equivalent water content of snowpack was undertaken for selected sites with more than 10 years of record.

Sources of data and database development:

The primary sources of snow-survey data used in this report and the approximate period of record for each source are:

Union Water Power Co.	1910-present
Kennebec Water Power Co.	1926-present
Bangor Hydro-Electric Co.	1930-present
U.S. Geological Survey	1941-present

A database was developed for each site in the historical records. The data include site name, identification number, location (latitude and longitude), elevation, and source. A separate database for the snow-survey data includes the site identification number, date of measurement, average snow depth, and average equivalent water content. Both databases were developed using Borland's **dBase** database software and an IBM-compatible personal computer. (Note: The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.)

Once the data were stored in the database, several quality-assurance checks of the data were performed. Site identification numbers, dates, and measurements were cross-referenced to eliminate

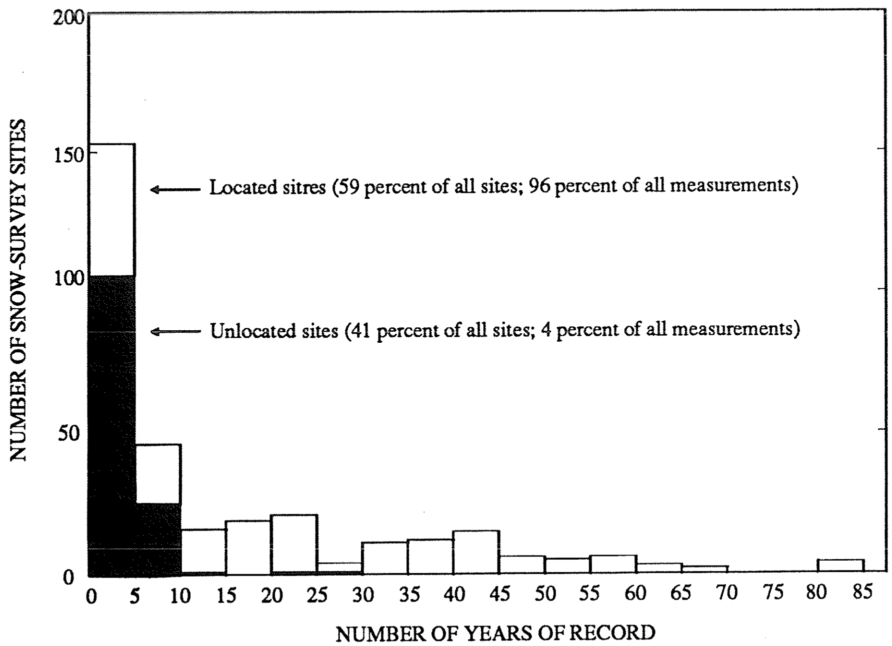

Figure 1. Histogram of number of located and unlocated sites, grouped by the number of years of record per site. Although locations are known for only 59 percent of the sites, 96 percent of the measurements in the database are at located sites.

duplicate entries; this was possible because data from USGS files included some data obtained from the utilities and paper companies prior to this effort. Average snow depths, average equivalent water contents, and calculated snow densities (equivalent water content divided by snow depth) were screened for unreasonable values, and anomalous entries were checked. Site locations were plotted on a State map to verify that locations stored in the database agreed with locations on original source maps.

Presently (June 1992), the database is still under development. This continued development reflects the number of sources of data and the difficulty in working with historical data as much as 80 years old. Results presented in this paper are preliminary and subject to revision.

Summary of the database:

As of June 1992, the database contained approximately 15,000 measurements made at 323 snow-survey sites. Approximately 96 percent of the measurements were at located sites (189 sites or 59 percent of all sites), and 94 percent of the measurements were at located sites with more than 10 years of record (120 sites or 37 percent of all sites). While the percentage of located sites with more than 10 years of record appears low (37 percent), the bulk of the measurements in the database (94 percent) were at sites with well documented locations and with more than 10 years of record.

The number of located and unlocated sites grouped by the number of years of record at each site is shown in figure 1. Most unlocated sites (sites which could not be located accurately enough to plot on a map) had less than 10 years of record; these sites were either abandoned after several years of measurement or measured only once.

The distribution of located snow-survey sites in Maine and adjacent New Hampshire, Quebec, and New Brunswick is shown in figure 2. The areal distribution is good; however, most located sites are at elevations less than 2,000 feet (610 meters). Hayes (1972) noted that average water contents taken from his map for points in excess of 2,000 feet (610 meters) in elevation should be used with caution.

Geographic information systems (GIS):

Use of geographic information systems (GIS) technology is integral to the present and planned future analysis of the historical snow-survey data. GIS technology permits the rapid examination of the spatial relations between point, line, and polygon (areal)

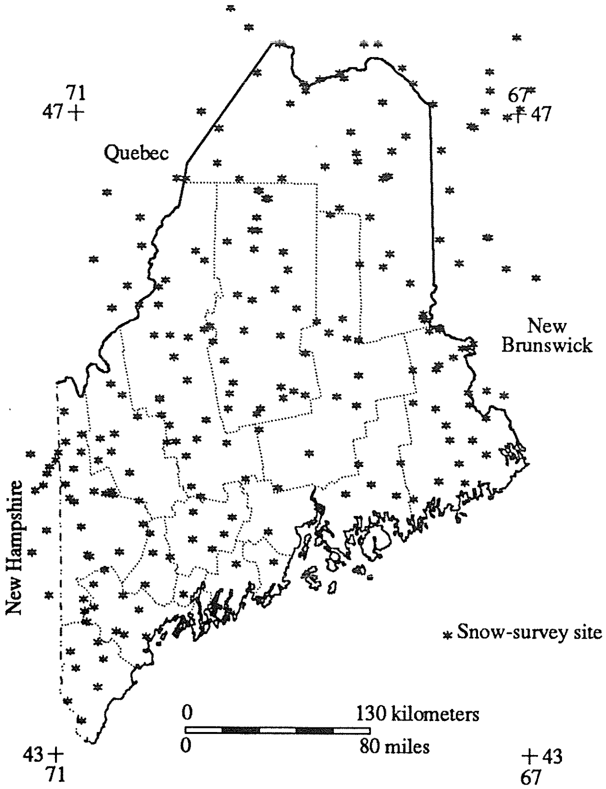

Figure 2. Location of snow-survey sites.

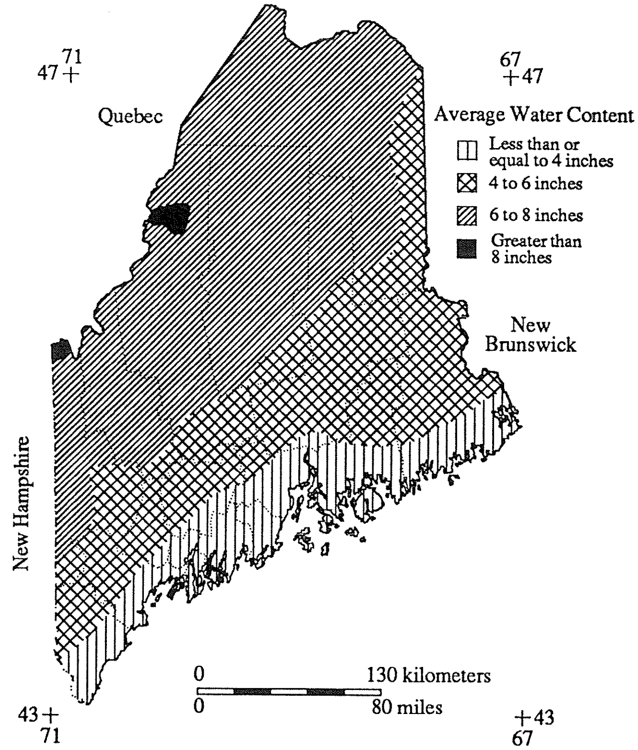

Figure 3. Average water content of snowpack in Maine on March 1, based on measurements made during 1941-1965. (Modified from Hayes (1972), fig. 1.)

data. In this case, the observed equivalent water content of snowpack at a snow-survey site is point data.

The GIS software **ARC/INFO**, developed by Environmental Systems Research Institute of Redlands, California, was used for analysis and presentation of the data. Two software packages within **ARC/INFO** were particularly important in the analysis of the data: **TIN** (Triangular Irregular Network), which was used to convert the point data to a smoothed contour map, and **GRID**, which was used to convert the contour maps to rectangular gridded data sets and to compare the results.

Preliminary analysis of snow-survey data:

The average equivalent water content of snowpack in Maine on March 1, based on measurements made during the period 1941-1965, is shown in figure 3. This map was produced by digitizing the contour lines from Hayes (1972) and grouping the resulting areas into the ranges shown. The general trend toward increasing water content away from the coast is the result of a decline in the moderating influence of coastal effects and an increase in elevation. The effects of elevation are not obvious on Hayes' map; in addition to having few data at elevations above 2,000 feet (610 meters), the data analysis technique used by Hayes also "smoothed" the effects of elevation.

The maximum observed equivalent water content of snowpack in Maine based on the data from the USGS database is shown in figure 4. The sites used to construct figure 4 are shown in figure 5. The map was constructed as follows:

1) A program was written to identify the highest value measured at each site during the period of record. These maximum values occur in March or April with very few exceptions, confirming figure 2 of Hayes (1972), which shows that the average date of maximum water content of the snowpack ranges from early March along the coast to late March in northern Maine.

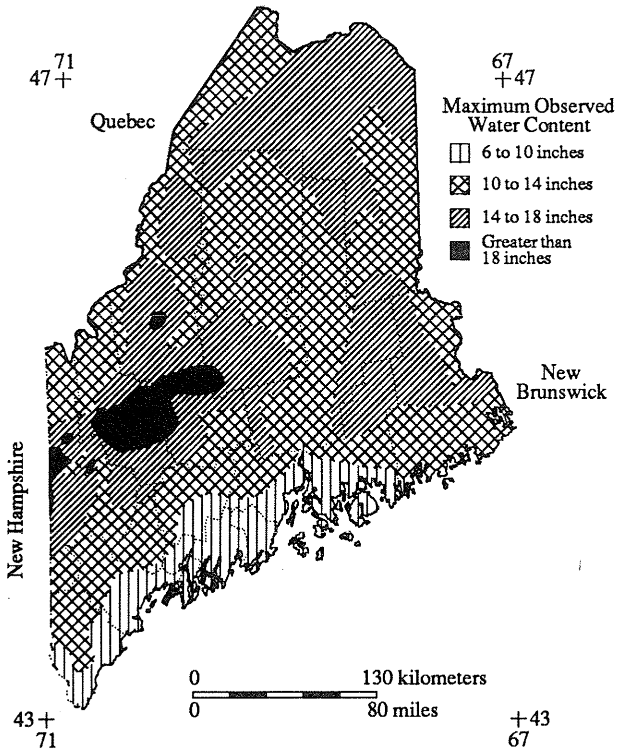

Figure 4. Maximum observed equivalent water content of snowpack in Maine, based on measurements for the periods of record for individual snow-survey sites in the database.

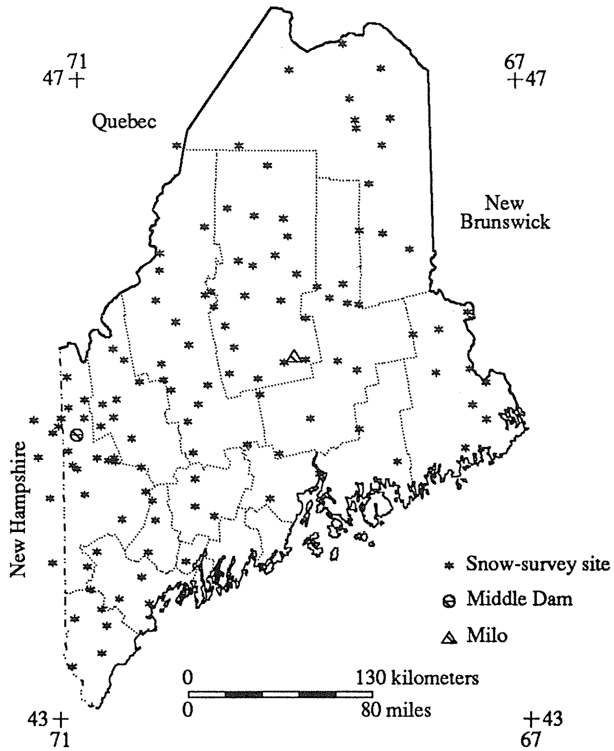

Figure 5. Location of snow-survey sites used to construct figure 4. In general, only sites with more than 10 years of record including the heavy snowfall years 1958, 1963, and 1969 are included. The Middle Dam and Milo sites discussed in the text are also shown.

2) These values were used with the site locations and the **ARC/INFO TIN** package to produce a contour map of maximum observed equivalent water content of snowpack.

3) Analysis of the highest value at each site showed that most of these values occurred during the winters of 1958, 1963, and 1969. Many of the sites that had highest values in other years were not sampled during these three heavy snow years. Sites with highest values in years with three or fewer highest values Statewide were individually evaluated. Comparisons of these maximum values were made with nearby sites and with previously published maps of snow-water content for the three heavy snow years. Sites with maximum values that did not agree with other historical data were dropped from the data set. At most of these sites the records did not extend back to 1969.

4) The revised data set was used to produce the final map of maximum observed equivalent water content of snowpack shown in figure 4. The locations of the 131 sites included in the revised data set are shown in figure 5.

In the revised data set, 17 winters are represented among the 131 measurements; 83 percent of the maximum measurements occurred in the heavy snow years 1958, 1963, and 1969. The areal distribution of sites used for figure 4 shows a bias towards the headwaters of the major rivers. These are areas where hydroelectric power companies and paper companies have maintained long-term snow-survey programs. This concentration of sites is similar to the concentration of sites on the Hayes (1974) average water content map.

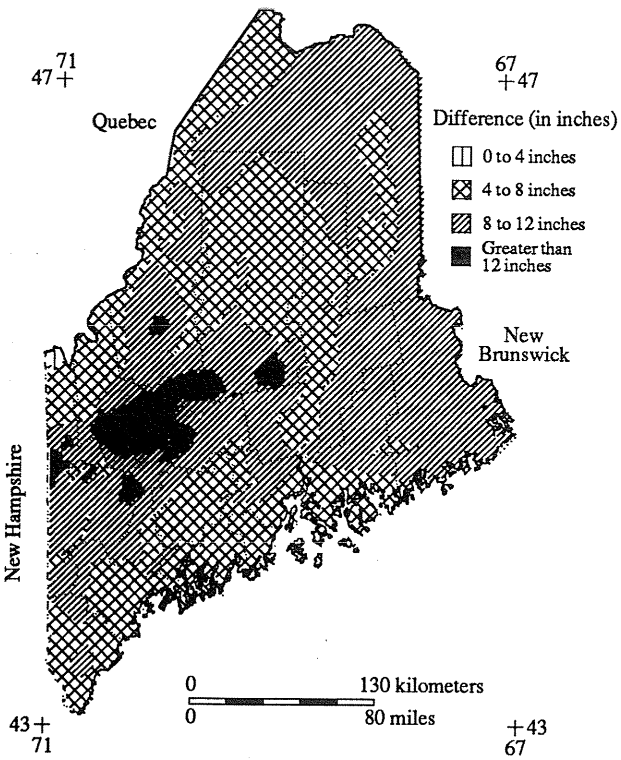

Figure 6. Difference between the maximum observed equivalent water content of snowpack (figure 4) and average snowpack water content (figure 3).

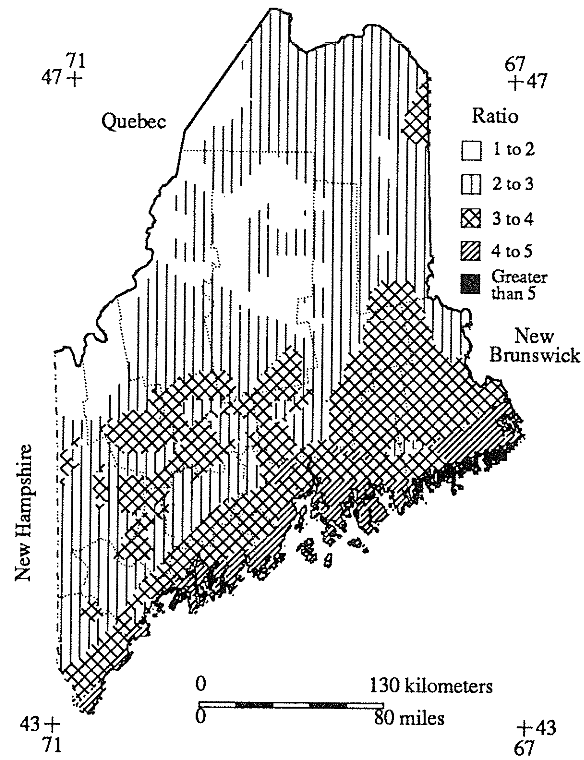

Figure 7. Ratio of the maximum observed equivalent water content of snowpack (figure 4) and average snowpack water content (figure 3).

The same general trend of increasing water content away from the coast seen in figure 3 can also be seen in the maximum observed equivalent water content map (figure 4). This trend is modified by a broad area of increased observed maximum equivalent water content centered on mountainous area of eastern New Hampshire and western Maine. This elevation control is more obvious in the maximum observed equivalent water content map (figure 4) than in the average water content map (figure 3) because of the different techniques used in producing the maps. Contouring for figure 4 was based on individual sites; Hayes determined the water content at 15-minute intersections of latitude and longitude on annual snow-survey maps for the period 1941-65, computed the 25-year average at the intersections, and contoured the average values. Also, the period of record for Hayes' map did not include 1969, the year with the largest number of highest values in the data set. Comparably high values of maximum observed equivalent water content are not shown in the high elevations of north-central Maine because of the lack of data in this part of the State.

As an example of the utility of GIS software in examining spatial relations between different data sets, the **ARC/INFO GRID** package was used to generate two rectangular gridded data sets: one from the average water equivalent content map and one from the maximum observed equivalent water content map. These data sets consist of a series of grid cells with a value of equivalent water content assigned to each cell based on zones on the original map. The gridded data sets were registered to each other so that grid cell values could be compared rapidly.

A map showing the difference (in inches) of equivalent water content between the maximum observed snowpack water content and average snowpack water content is shown in figure 6. The technique and the period of record used to generate the Hayes' map and the maxmum observed equivalent water content map are different. The results of the comparison would differ if an average water content map for March 1 were produced from the entire period of record or if the actual average values at the individual sites were contoured.

The difference between maximum and average snowpack water content ranges from less than 4 inches (100 mm) in the northwestern corner of the state to more than 12 inches (300 mm) at higher elevations (mountainous areas of eastern New Hampshre and western Maine). The pattern in figure 6 is very similar in form to the maximum observed equivalent water content map. This is not surprising as it was already noted that the method used to produce the Hayes (1972) map smoothed the effects of elevation.

The ratio of the maximum observed equivalent water content of snowpack to the average equivalent water content of snowpack is shown in figure 7. In this case, there is a regular trend from ratios of 1 to 2 along the Maine-Quebec border to ratios more than 5 along eastern coastal Maine. There is some evidence of an elevation bias in the distribution of ratios in the range 3 to 4. The marked trend in ratio of maximum observed to average equivalent water content implies that there is much more variability in equivalent water content of snowpack in coastal regions than in interior regions.

Meterological factors affect the trend in the ratio of the maximum observed equivalent water content of snowpack to the average equivalent water content of snowpack as follows: The path of a low-pressure center responsible for Maine's northeast coastal storms controls the location of a rain-snow line that is typically oriented subparallel to the coast. When this line is located well inland, the coastal areas are on the warm side of the front and all the coastal precipitation is in the form of rain. When this line is located offshore, all of the State is on the cold side of the front and all precipitation is in the form of snow. This rain-snow line seldom extends far enough inland to produce rain in the northern parts of the state or at higher elevations. In contrast, however, it may be located far enough offshore to produce major accumulations of snow in the coastal zone (a condition that generates Maine's classic "Nor'easter" blizzards). Because most inland precipitation is in the form of snow, the maximum observed equivalent water content of snowpack is closer to the average equivalent water content of snowpack. Because coastal precipitation is more evenly divided between rain and snow, the maximum measured equivalent water content of snowpack along the coast may be much higher than the long-term average equivalent water content of snowpack.

In addition to the comparison of the maximum observed snowpack equivalent water content map produced in this study with the average equivalent water content map produced by Hayes (1972), the trend of annual maximum water contents for a limited number of sites with near-continuous long-term records was also examined. These sites are surveyed primarily by the Union Water Power Company, Kennebec Water Power Company, and Bangor Hydro-Electric Company, and most of these sites are located in the headwater regions in the State. Data collection at USGS sites was suspended in the 1970s because of budget constraints and was only recently resumed.

Plots of annual maximum observed equivalent water content of snowpack over time for two sites -- Middle Dam (surveyed by the Union Water Power Company) and Milo (a USGS site) -- are shown in figure 8. The data points are shown by crosses; the dark solid line in each graph is a 7-year moving mean of the data; the long dashed line is a 2nd-order-regression line fit to the data points; and the dotted lines are the 95-percent confidence interval for the regression line. The plots, running averages, and regressions, and confidence intervals were all generated by the program **SigmaPlot** developed by Jandel Corporation, and are preliminary at this time.

Considering the significant amount of scatter in the data points, a linear regression might justifiably be used to model the data. A succession of recent winters with below average snowfall in Maine combined with the low maximum observed equivalent water content of snowpack at Middle Dam (and other headwater sites) suggested that a linear model was not adequate. In order to smooth the data, a series of plots showing 3-year, 5-year, 7-year, and 9-year moving means were produced for several headwater sites with near-continuous long-term records. A broad maximum in the moving means in the period 1950-70 was observed for each of the sites for each of the four averaging intervals; the 7-year moving mean in figure 8 is shown as an example. Based on the trends of the moving means, a 2nd-order regression was fit to the raw data and plotted on figure 8. A 2nd-order regression is the simplest regression that **qualitatively** duplicates the trend observed in the moving means; higher order regressions did little to improve the fit to the data.

The plot for Milo is included to illustrate the effects of missing data for the period from the mid-1970s to the late-1980s. Although the data for the 2nd-order regression suggest decreasing maximum

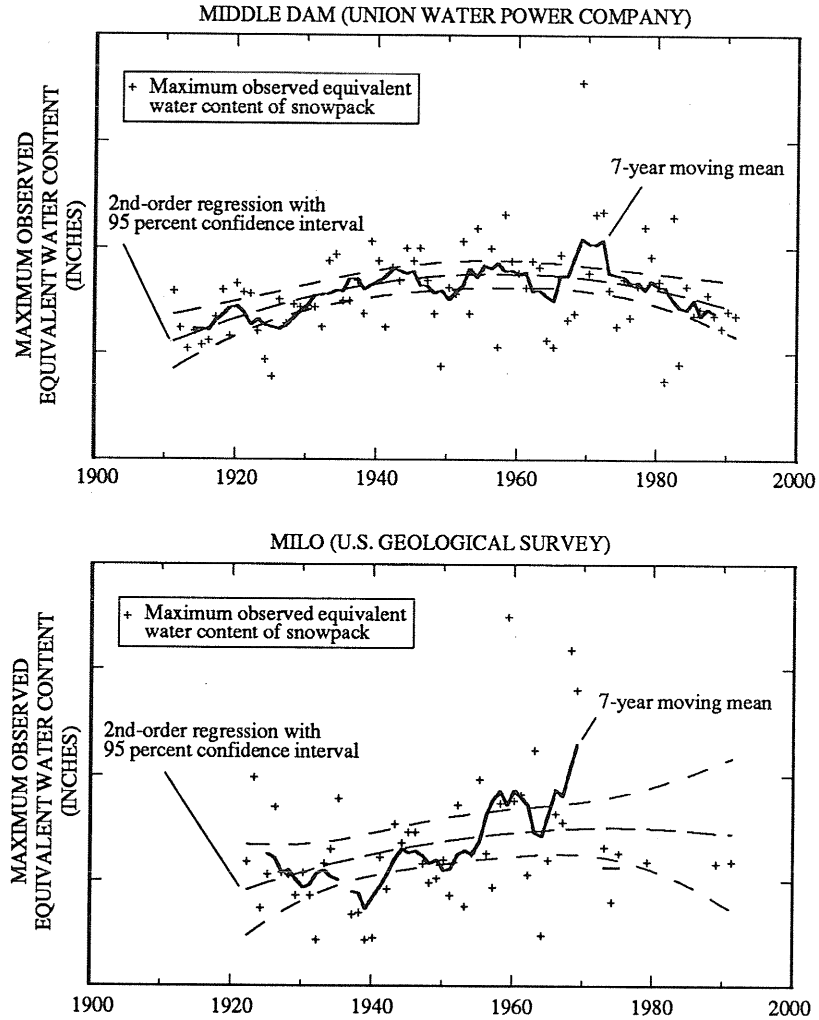

Figure 8. Preliminary trend analysis of maximum observed equivalent water content of snowpack for the Middle Dam and Milo, Maine, snow-survey sites.

observed equivalent water contents in the 1980s and 1990s, the regression confidence intervals are ambivalent, allowing for possible continued increase in maximum observed equivalent water content (at least in a statistical sense). Most of the sites in central and southern Maine are USGS sites, and this missing record will be a problem when assessing whether the trend for the maximum observed equivalent water content of snowpack observed at headwater sites is true for coastal sites as well.

Addition data needed and future studies:

The first priority for additional work is to complete collection and entry of all historical data into the database. Additional data from several utilities and power companies in northern and eastern Maine are needed to supplement present data.

Because of the different technique used to generate the Hayes (1972) map of average equivalent water content, plans are to generate a map of average equivalent water content using the **ARC/INFO TIN** package and site-specific average data for the period of record at selected sites. This map would be more directly comparable to the maximum observed equivalent water content map (figure 4) than the Hayes map. The average equivalent water content for several different time periods (for example 1941-65, 1951-75) may also be examined to investigate further the spatial and temporal trends in average equivalent water content of snowpack.

Studies are also planned to examine the possible use of record extension techniques used by the USGS Water Resources Division for their stream-gaging records to fill in missing snow-survey data at the USGS sites in central and southern Maine. The large variability in the ratio of maximum water content to average water content and the lack of long-term index stations in these areas may be a complicating factor in these efforts.

Finally, current snow-load maps by the Building Officials and Code Administratiors International (1990) show snow loads with a 50-year recurrence interval. Few field data were readily available to develop these maps for Maine. Using the newly available historical snowpack data for Maine, future studies are planned to investigate the statistical distribution of the maximum water equivalent data and use appropriate frequency distributions to determine 50-year maximum snowpack water contents for individual sites and produce a state map similar to the empirical maximum equivalent water content map presented in this report.

References:

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Hayes, G.S., 1972, Average water content of snowpack in Maine: U.S. Geological Survey Hydrologic Investigations Atlas HA-452, scale 1:1,000,000.