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Summary of Ground-Based Snow Measurements for the Northeastern United States

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Abstract

Snow is an important resource for both communities and ecosystems of the Northeastern United States. Both flood risk management and water supply forecasts for major municipalities, including New York City, depend on the collection of snowpack information. Therefore, the purpose of this study is to summarize all of the snowpack data from ground-based networks currently available in the Northeast. The collection of snow-depth and snow water equivalent information extends back several decades, and there are over 2,200 active sites across the region. Sites are distributed across the entire range of elevations in the region. The number of locations collecting snow information has increased substantially in the last 20 years, primarily from the expansion of the CoCoRaHS (Community Collaborative Rain, Hail, and Snow) network. Our summary of regional snow measurement locations provides a foundation for future studies and analysis, including a template for other regions of the United States.

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Preface

This study was conducted for the U.S. Army Corps of Engineers Flood and Coastal Systems Research and Development Program under funding account U4376882, AMSCO 031398. The technical monitor was Dr. Ian Floyd, U.S. Army Engineer Research and Development Center, Coastal Hydraulics Laboratory (ERDC-CHL).

The work was performed by the Terrain and Ice Engineering Group (Dr. Meghan Quinn, lead) of the Remote Sensing / GIS Center of Expertise (Mr. David Finnegan, center director), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, the acting deputy director of ERDC-CRREL was Mr. Bryan E. Baker, and the director was Dr. Joseph L. Corriveau.

Additional work was performed by the River and Estuarine Engineering Branch (Mr. David May, chief) of the Flood and Storm Protection Division (Dr. Cary A. Talbot, chief), ERDC-CHL. At the time of publication, the deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty V. Wamsley.

COL Teresa A. Schlosser was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

The northeastern United States is a complex geographical region with elevations ranging from sea level to approximately 1,900 m* and land cover types varying from dense metropolitan areas to protected wilderness (Figure 1). Generally, this midlatitude region has four distinct seasons (Dupigny-Giroux et al. 2018), varying from cold, snowy winters to warm, humid summers. However, regional weather patterns can be locally influenced by latitude and mountainous topography. The National Centers for Environmental Information 1991–2020 U.S. Climate Normals (NCEI 2021a) found that mean annual surface air temperature across the Northeast varied from −1°C to 13°C during that period. Coastal regions in the Northeast tend to have less-extreme surface air temperatures due to moderation by the ocean (Huntington et al. 2009). Like air temperature, precipitation patterns show both temporal and spatial variability across the region. The Northeast 1991–2020 Climate Normals range between 81 and 216 cm/year with the greatest precipitation in mountains and in coastal Maine, New Hampshire, and Massachusetts (NCEI 2021a).

Along with most of the U.S., the annual mean temperature across the Northeast has risen in the past two decades. In the Northeast, temperatures have increased by approximately 0.5°C relative to the 1901–2000 average (NCEI 2021b). Climate change forecasts project that this trend will continue, with estimates of more than 2°C of warming on average by 2035 in the Northeast, two decades earlier than predictions of that level of warming globally (Dupigny-Giroux et al. 2018). Additionally, the NCEI 1991–2020 Climate Normals show a 5% to 10% increase in average annual precipitation relative to the 1901–2000 average (NCEI 2021b). Hayhoe et al. (2007) observed an increase in average annual precipitation of approximately 9.5 mm/decade in the proceeding century, with a possible reversal starting in the 1970s. Changes in precipitation vary spatially across the

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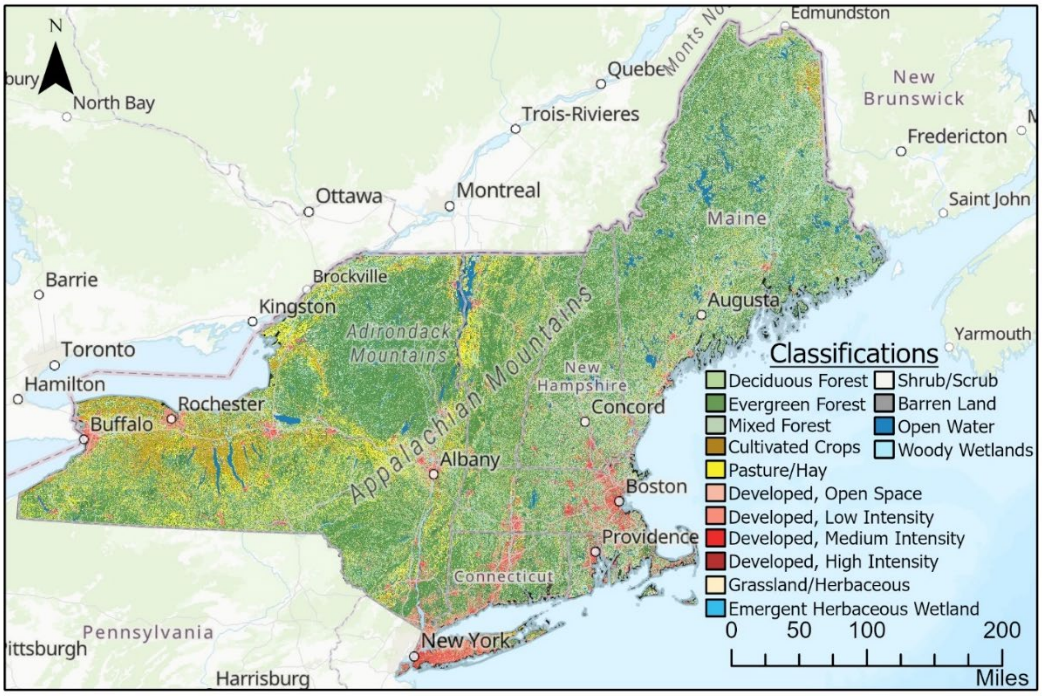
* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *U.S. Government Publishing Office Style Manual*, 31st ed. (Washington, DC: U.S Government Publishing Office, 2016), 245–252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

region, with larger changes in coastal regions and decreases in Connecticut and northern New Hampshire (Huntington 2009; NCEI 2021b)

Figure 1. Land cover types throughout the study area.



Subregional spatiotemporal variability in temperature and precipitation produces a range of different snowpack characteristics throughout the Northeast. For example, Cember and Wilks (1993) found the range of median total seasonal snowfall to be between 100 and 250 cm from south to north in New England.

Snow is important for many economic, social, and environmental activities in the Northeast. Winter recreation and tourism centers around snow-based activities, such as snowmobiling, snowshoeing, alpine skiing, and snowboarding. Snowmobiling, snowshoeing, and similar activities rely solely on natural snowfall and accumulation (Scott, Dawson, and Jones 2008). Snowfall events also affect the region's infrastructure. Winter storms compromise road safety and make driving more difficult, increasing crash rates (Khattak and Knapp 2001). Roofs can collapse due to snow loads that exceed the design capacity, as occurred in four different schools during the 2014–2015 winter (Bass and O'Rourke 2017). Snow also plays a significant role in ecological processes. When the snowpack is thin, soil and root systems more readily freeze, causing damage to sugar maple trees used for maple syrup production (Comerford et al. 2013). Additionally, a study conducted in Maine and Connecticut found that insulation from snow increased the overwintering survival rate of ticks (Linske et al. 2019).

Winter snowfall is important to the region's water resources. A useful metric for quantifying its importance to a region is the ratio between snow-derived runoff and total runoff. However, this is a challenging figure to calculate directly with the many physical processes that influence snowmelt. Most often, a proxy ratio is used as an approximation (e.g., snow water content divided by total precipitation or snow water content divided by total runoff). Kapnick and Delworth (2013) examined both ratios for the entire northern hemisphere; in New England, they found that in the southern lower elevations, snow might contribute as little as 10% to the annual runoff. In the northern, higher-elevation mountains, snow may contribute as much as 80% of the annual runoff. Similar studies in the area contain information on the ratio of snowmelt-season runoff to total runoff. One such study investigated the headwaters of the Hudson and other nearby rivers and found that the average snowmelt contribution was around 60% of the total annual runoff (Eschner 1982). Another study examined the entire drainage basin for the Androscoggin River (New Hampshire and Maine) over four years and found that snow accounted for up to 39%–57% of the annual flow volume (Oczkowski et al. 2006).

Major regional-scale flooding is typically caused by frontal systems approaching from the south and west or by tropical storms such as Irene, which produced severe flooding and economic damage in August of 2011. The extreme storm-induced flooding in the summer of 2011 partially overshadowed the widespread snowmelt and rain-on-snow-driven flooding in April of the same year. That flooding was caused by a moderately deep snowpack combined with higher temperatures and rainstorms (Suro, Roland, and Kiah 2015). While snowmelt and rain on snow may not be responsible for the largest floods on record, they are major contributors to high flow events in the Northeast. Villarini (2016) found a late winter to early spring date range for annual peak discharge at stream gages in the Northeast. The temporal distribution of peak discharges is tightly clustered in this range in northern parts of the region; however, in southern New England, the dates exhibit a bimodal distribution in spring or midsummer. This indicates a balanced influence between snowmelt and precipitation-only mechanisms on the date of annual peak flow (Villarini 2016). Berghuijs et al. (2016) show that the mean date of maximum annual flooding in the Northeast can be predicted by the date of peak snowmelt. In contrast, the maximum daily precipitation, daily excess precipitation (accounting for infiltration), or weekly precipitation are ineffective predictors of the maximum annual flood timing in the Northeast (Berghuijs et al. 2016).

Cho and Jacobs (2020) used snow water equivalent (SWE) products from SNODAS and the University of Arizona to demonstrate that snowmelt resulting from rain-on-snow events produces a runoff potential exceeding NOAA Atlas 14 precipitation-only estimates for 1- and 7-day durations at 25- and 100-year return intervals. The differences were greater for the 7-day durations, indicating that snowmelt processes become increasingly important relative to precipitation when evaluating extreme runoff over longer timescales. Projected changes in climate will affect SWE, promote earlier evapotranspiration leading to water supply losses, and accelerate the timing of spring runoff (Burns et al. 2007; Matonse et al. 2011).

To understand the full extent of these changes and to increase the accuracy of water resource forecasting, researchers will need in situ observations of the snowpack. Several studies have collected and performed analysis on snow data in the Northeast, but most used a subset of the available data (Cember and Wilks 1993; Hodgkins and Dudley 2006; Hayhoe et al. 2007; Campbell et al. 2010; Templer et al. 2017). In the Northeast, in situ snowpack datasets are inconsistent in specific variables observed, data collection methods, spatial distribution, and temporal resolution. Currently, there is no readily available compilation of all snow data records from the region.

1.2 Objectives

The overall purpose of this study was to summarize the ground-based snowpack datasets available for the Northeast. To address this, we implemented several specific objectives:

- Create summary information for the spatial distribution of the snow measurement locations across the states of Maine, New Hampshire, Vermont, New York, Connecticut, Massachusetts, and Rhode Island.
- Report the temporal metadata (periods of record [PORs] and resolutions) for the snowpack datasets.
- Identify measurement locations with long PORs.
- Summarize snow measurements by elevation range.

1.3 Approach

1.3.1 Metadata collection

We searched available snow-depth and SWE records within the Northeast region of the U.S.. The search included federal databases, state governments, nonprofits, universities, and separate research entities.

1.3.2 Inclusion criteria

To be included in this metadata summary, sources had to be

- measurements of either snow depth or SWE;
- located within the Northeast region of the U.S., defined as Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, and New York;
- part of a systematic program of regular snow data collection; and
- a "recent" dataset of active measurements with a POR ending between calendar year 2017 and the present.

We reviewed sources for snow-depth or SWE records and collected the metadata for each site in the record. Metadata collected was as follows:

- Source of the data
- Type of measurement when possible (manual, automated, etc.)
- Skill level of the data collector when possible (citizen scientist, trained volunteer, etc.)
- Temporal resolution, or frequency, of the measurement (daily, weekly, or biweekly [every other week])
- Station ID or name
- Longitude and latitude of the station
- First and last year of snow-depth collection
- First and last year of SWE collection

1.3.3 Analysis

The focus of our analysis was on sites that are active or recently active. We included in the study only ongoing datasets and those with a POR ending between 2017 and 2021. This criterion was used to include datasets with long records that may have stopped collecting recently. The only historical records with significant PORs that that we excluded were eleven WBAN

(Weather Bureau Army Navy) sites where daily snow measurements were discontinued around 2010.

Once we filtered the metadata to include recently active SWE or snow-depth-measurement sites in the Northeast, we grouped the data by network, POR, and state. A complete table of sites gathered in this review are available in the data file “Northeast Snow Metadata.xlsx,” downloadable at the same download location as this report: http://dx.doi.org/10.21079/11681/44122.

In section 2, we summarize the most common methods used to measure snow depth and SWE in the Northeast. This study also reports summary statistics for the record lengths, along with information about spatial and hypsometric distribution of the sites.

2 Measurement Methods

There are a variety of manual and automated methods used by researchers to measure snow depth and SWE. The methods vary by the needs of the group collecting the data and their resources. Here we summarize the common methods used to collect snow-depth and SWE data in the Northeast. Others have investigated the errors of each method (Johnson 2002).

2.1 Manual measurements

2.1.1 Snow measurement board, or snowboard

The snow measurement board (also referred to as a "snowboard") is a manual method of determining snow depth only (Figure 2). A snow measurement board is typically a 24 in. by 24 in. (61 cm by 61 cm) board (although exact dimensions vary) upon which snow-depth measurements are taken. The board should be leveled and cleaned before the start of the winter season. It should be located close to where all other weather measurements are taken (i.e., a weather station). Snow measurements on the board should be taken using a snow measurement stick, which is an easy-to-read ruler (in the U.S. it is marked in tenths of an inch). At the time of measurement, the observer drives the stick through the snow to the board and records the total depth of snow and ice (COOP [Cooperative Observer Program], n.d.).

Figure 2. Clean snowboard for recording snow depth.

2.1.2 Snow tube

The snow tube is a manual method of determining SWE. It involves taking a core sample of the snow on the ground. This is done using a snow tube or inverting a rain gage or other cylinder of known size and inserting it into the snow perpendicular to the ground (Figure 3). If the snow is shallow, it may be possible to slide something flat under the cylinder to ensure no snow escapes the coring. The snow tube containing the sample is then weighed, and the measurement is adjusted to account for the weight of the empty snow tube. With professional snow tube equipment, SWE is typically read directly from a scale marked in units of depth of liquid water, calibrated for a given snow tube diameter. If the measurement is made in units of mass, the value must be converted to depth using the density of water and the cross-sectional area of the tube. Alternatively, the sample could be melted in the tube (such as in a rain gauge) and the depth of water measured to determine SWE. If the cylinder is labeled with measurement markers, it can also be used to measure snow depth.

There are several types of snow tubes used in the Northeast, including the Adirondack and Federal snow-sampling tubes. The Adirondack sampler is a 3 in. inner diameter, 5 ft long tube often made of fiberglass with metal cutting teeth (Figure 4). The Federal snow tube has an inner diameter slightly larger than 1.5 in. and is typically made of aluminum (COOP, n.d.).

Figure 3. Snow coring. (Image reproduced with permission from Jessica Spaccio, Northeast Regional Climate Center [NRCC].)

Figure 4. Adirondack snow tube and scale used for snow-core sampling.
(Image reproduced with permission from Jessica Spaccio, NRCC.)

2.2 Automated measurements

2.2.1 Ultrasonic sensor

An ultrasonic snow-depth sensor is an automated method to measure snow depth. The sensor sends ultrasonic (higher frequency than audible soundwaves) pulses towards the ground and records the time it takes to receive a return signal. The sensor is mounted above a snow board and calibrated to ground height (Figure 5). When snow is on the ground, the distance between the sensor and the snow surface is measured, often with multiple pulses for error checking. The difference in height between the calibrated distance and the measured distance gives the depth of snow. The sensors commonly include a temperature probe to adjust for the measurements as a function of air temperature (Judd 2010).

2.2.2 Snow pillow

Snow pillows can be used to measure SWE at an automated station (Figure 6). Snow pillows are primarily flat polypropylene (plastic) bladders that contain a mixture of water and antifreeze. The pillows are 5–13 cm thick when filled and vary in surface area between 1 and 12 m^2, depending on the depth of the snowpack being measured. Deeper snowpacks require larger pillows to reduce the potential for uneven loading of the pillow. As snow falls onto the pillow, the increased fluid pressure in the pillow is measured by a transducer and converted into SWE (NRCS [Natural Resources Conservation Service] 2014).

Figure 5. Sonic sensor set above the snowboard. (Image reproduced with permission from NYS Mesonet 2021).

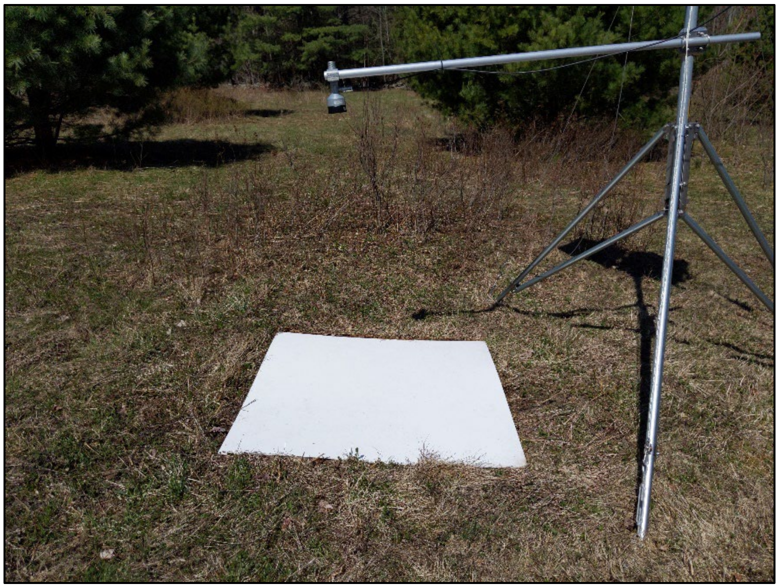
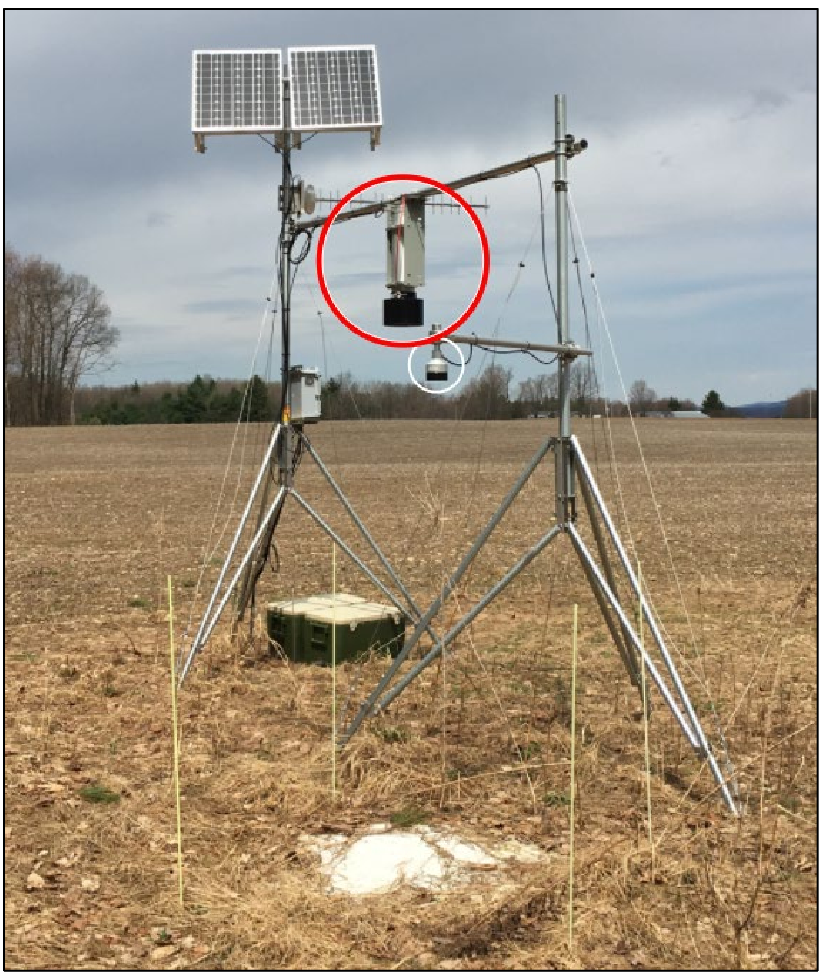


Figure 6. Snow pillow and depth sensor set up for an automated weather station. (Image reproduced from NRCS 2022. Public domain.)

2.2.3 Gamma-radiation sensors

SWE can also be measured indirectly by taking advantage of naturally occurring gamma radiation emitted by radioactive elements in the soil. National Weather Service (NWS) gamma measurements have been made for several decades from aircraft (Carroll 2001). Campbell Scientific and Hydro Quebec developed a terrestrial-based sensor used by the New York State (NYS) Mesonet network. The Campbell Scientific CS725 is a passive, noncontact gamma-radiation spectrometer tailored for use in measuring SWE. The CS725 sensor measures the energy associated with gamma rays emitted from Potassium 40 (^{40}K) and Thallium 208 (^{208}Tl), which are the most abundant radioactive elements found in soil. The sensor is typically installed 3 m or more above the ground and calibrated to the natural gamma-ray energy levels at a given site without snow present (Figure 7).

Figure 7. CS275 SWE sensor circled in *red*. SR50A acoustic snow-depth sensor circled in *white*. (Image reproduced with permission from NYS Mesonet 2021.)



When snow accumulates between the soil and the sensor, water in the snowpack degrades or completely absorbs some of the gamma rays. The degree to which the gamma ray's energy is attenuated by the snow is used to estimate SWE beneath the sensor. The presence of trees or wooden objects can impact the performance of the sensor due to naturally occurring potassium and thallium in wood (Campbell Scientific 2021).

The CS725 has a specified accuracy of ±15 mm for SWE between 0 and 300 mm and ±15% for SWE between 300 and 600 mm. The sensor provides continuous data; however, the instrument estimates a daily SWE measurement using the results of a histogram of gamma-radiation energy levels collected over a 24-hour window (Campbell Scientific 2021).

3 Available Datasets

3.1 Federally managed datasets

3.1.1 Global Historical Climate Network

Maintained by NOAA's NCEI, the Global Historical Climate Network (GHCN) daily record is a worldwide database of over 107,000 surface stations collecting daily temperature, precipitation, and snow records maintained (Menne et al. 2012). The database contains records from a number of individual meteorological networks:

- Community Collaborative Rain, Hail, and Snow (CoCoRaHS) Network
- U.S. Cooperative Observer Program (COOP)
- World Meteorological Organization
- U.S. Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL)
- Weather Bureau Army Navy (WBAN)

Jones and Daly (2019) provide a detailed description of the sources of snow data in the GHCN. Snow depth and SWE are reported for some stations in the GHCN, with approximately 15,000 stations across the U.S. reporting both values. Snow depth and SWE are reported in terms of depth to the whole millimeter and tenth of a millimeter, respectively (Jones and Daly 2019).

3.1.1.1 Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS)

The CoCoRaHS Network is a volunteer-based observer network sponsored by NOAA and the National Science Foundation. Observers are typically not formally trained. Snow measurements are made manually with a ruler to the nearest 0.5 in (1.3 cm) (Jones and Daly 2019). SWE measurements are made once a week (typically on a Monday) using a 4 in. (10.2 cm) diameter rain gauge or a plastic pipe to collect a snow core from the total depth of snow on the ground. The core is melted to determine the depth of liquid water in the sample, which is reported to the nearest 0.25 mm (0.01 in) (Jones and Daly 2019).

3.1.1.2 National Weather Service Cooperative Observer Program (COOP)

NWS cooperative weather observing stations are locations where weather data is collected by trained volunteers, institutions, or government agencies using equipment that NWS typically provides. COOP station snow depths are recorded in whole inches, and SWE is reported in hundredths of an inch (NWS 2017). COOP snow-depth measurements are recorded daily, and SWE measurements are taken at least weekly (NWS 2013).

3.1.1.3 Weather Bureau Army Navy (WBAN)

The WBAN network contains data collected by the U.S. Weather Bureau, Air Force, Navy, and Army stations. Data collection began in 1961. The WBAN network consists of federal weather stations and airports where weather data is collected. As Jones and Daly (2019) describe, the *Federal Meteorological Handbook No. 1* (NOAA 2019) specifies the accuracy of snow data collection, which is by whole inch for snow depth and tenth of an inch for SWE. The data are transmitted in a METAR (Meteorological Terminal Aviation Routine Weather Report) along with other weather observations.

3.1.1.4 Soil Climate Analysis Network (SCAN)

The Soil Climate Analysis Network (SCAN) is a USDA automated soil climate monitoring network maintained by NRCS. The network was established in 1991 and records data every hour (also summarized daily). SCAN provides data for natural resource monitoring, such as drought tracking, climate change, watershed health monitoring, and flood risk assessment (NRCS National Water and Climate Center 2017). Snow depth is recorded every hour using ultrasonic depth sensors accurate to the millimeter. SWE is measured using a snow pillow and pressure transducer. Sensors are located across the U.S., Puerto Rico, and the Virgin Islands. The stations are centered in agricultural areas, where they measure soil conditions at various depths, weather variables such air temperature and wind speed, and snowpack variables such as depth and SWE.

Within our study area, there are four SCAN sites: Mount Mansfield, Vermont; Lye Brook, Vermont; Mascoma River, New Hampshire; and Hubbard Brook, New Hampshire (Figure 8). Recent damage by bears to the Mount Mansfield and Mascoma River snow pillows has interrupted the records at those sites; however, the NRCS plans to restore the SWE measurement functionality at these sites in the future (Meredith Albers, NRCS, pers. comm., 21 September 2021).

Figure 8. SCAN monitoring station at Mount Mansfield, Vermont. (Image reproduced with permission from Meredith Albers, NRCS.)

3.1.2 U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers–New England District (USACE NAE) measures snow depth and SWE on a biweekly basis in the winter months for the Connecticut, Merrimack, Housatonic, Thames, and Blackstone River basins. Kissock (2019) provides a detailed description of the snow data collection activities of USACE NAE. Snow data is collected by individual project offices biweekly between January and April. Currently, there are 93 snow survey locations where snow depth and SWE are measured using federal samplers. The data record began in 1961 with a small number of USACE project locations that has grown over the years. The data are posted to a publicly available web page. These data are also submitted to NOAA to model snowpack density in the Northeast for use in a variety of projects, such as water supply management, flood risk assessment, and dam safety monitoring.

The USACE Buffalo (LRB) and Baltimore (NAB) districts also collect snow data in cooperation with the Northeast Regional Climate Center (NRCC) at Cornell University. Section 3.3.4 describes the data collected by those districts.

3.1.3 Sleepers River Research Watershed

Sleepers River Research Watershed in Vermont has weekly snow-depth and SWE measurements beginning in 1960. Measurements were initiated by the Agricultural Research Service and then continued by NWS, the U.S. Army Cold Regions Research and Engineering Laboratory, and finally by the USGS. Measurements are currently taken at nine snow courses, and a tenth course was stopped in 2017. Snow depth and SWE were originally collected using federal samplers but were replaced by Adirondack samplers in 1967. Both parameters are measured and reported weekly (Chalmers et al. 2019).

The continuous monitoring of this site allows for a good-quality long-term record of snow depth in the forested watershed. The snowpack measurement record is used to study the impact of changes in snowpack to streamflow, groundwater levels, and soil moisture.

3.2 State-managed datasets

3.2.1 Maine Cooperative Snow Survey

The Maine Cooperative Snow Survey is managed by the State of Maine River Flow Advisory Commission. Maine Cooperative collects snow depth and SWE for Maine to predict spring flooding and includes the following cooperating partners (Maine River Flow Advisory Commission 2010):

- Allagash Wilderness Waterway
- Brookfield Renewable Energy Group
- Cobbossee Water District
- Great River Hydro, LLC

- Maine Environmental Science Academy–Fryeburg
- Maine Forest Service
- Maine Geological Survey
- National Weather Service Forecast Office, Caribou
- National Weather Service Forecast Office, Gray
- Nestle Poland Spring Water Company
- New Brunswick Environment and Local Government
- SAPPI Limited
- USGS, New England Water Science Center, Maine Office
- University of Maine, School of Earth and Climate Sciences

Station periodicity (temporal resolution of measurements) varies significantly, with some stations surveyed biweekly and some surveyed only once per year. Observations have increased from an average of one measurement per year in the early twentieth century to an average of five measurements per year in the twenty-first century. The median number of observations per year at a site in the network is three.

Observers submit data to the Maine Geological Survey and USGS for quality control and recording. These data are also submitted to NWS for their flood forecasting. Snow-depth and SWE measurements are collected by observers using standard federal snow-sampling tubes on north-facing slopes. Observers average 10 readings at the site and report depth and SWE to the nearest half inch (Maine River Flow Advisory Commission 2010; USGS 2016).

Some of the survey locations are coincident with NWS monitoring locations included in the GHCN. However, the Maine Cooperative Snow Survey measurements are not recorded in the GHCN records and, therefore, our study treated these records from coincident locations as separate stations. The Maine Cooperative Snow Survey dataset contained approximately 250 snow measurement sites that meet the criteria of this study, including locations in New Hampshire and western New Brunswick.

3.2.2 Massachusetts Department of Conservation and Recreation

The Massachusetts Department of Conservation and Recreation (MA DCR) Division of Water Supply Protection collects snow surveys at the Wachusett and Quabbin Reservoirs as part of their watershed and reservoir water-quality management. Snow cores are taken at each measurement site six times, and the snow depth and SWE values are each averaged into a single value per measurement location. Sampling occurs weekly during the winter season (Division of Water Supply Protection 2020). There are six survey locations in the Wachusett Reservoir and six in the Quabbin Reservoir that meet the criteria for this study.

3.2.3 New Hampshire Department of Environmental Services

The New Hampshire Department of Environmental Services (NH DES) Dam Bureau maintains 18 snow-sampling sites across the state that meet the criteria for this study. Snow cores are taken by trained employees of the Dam Bureau using snow tubes and scales. Measurements of snow depth and SWE occur biweekly during the winter season. Records go back to 1950 for some sites. The data are used to determine snow melt runoff for the subsequent spring and inform operation decisions for the larger, state-owned dams (Nancy Baillargeon, NH DES, pers. comm., 30 August 2021).

3.2.4 New York City Department of Environmental Protection

The New York City Department of Environmental Protection (NYC DEP) collects snow-depth and SWE data in the watersheds east and west of the Hudson River (Horton 2018). These data are used to model water stored as snowpack and to inform NYC DEP reservoir operations. Snow depth and SWE have been collected biweekly using snow cores since 1965. Additionally, snow pillows were installed in 2009 that collect snow depth and SWE at hourly intervals. Eighty-two snow-core sampling sites and twelve snow-pillow sites matched the criteria for this study.

3.3 Other datasets

3.3.1 Great River Hydro

Great River Hydro owns several dams along the Connecticut River and collects monitoring snow-depth and SWE data at their reservoirs. They have 18 active monitoring sites in Vermont and New Hampshire with records starting in 1979.

3.3.2 Harvard Forest

Harvard Forest, Massachusetts, is a research location managed by Harvard University. An automated snow-pillow station within the forest has collected daily SWE (reported in millimeters) from 2009 to 2020 for research in watershed ecology. Snow-depth data are not currently reported at the site (Boose 2021).

3.3.3 Hubbard Brook Experimental Forest

In 1955, the USDA established Hubbard Brook Experimental Forest, a 7,800-acre hardwood forest in the White Mountain National Forest in New Hampshire (Hubbard Brook Ecosystem Study, n.d.). Data collected at Hubbard Brook is used to study the response of ecosystem structure, composition, and function to disturbances both natural and anthropogenic, including changing atmospheric chemistry, climate, biota, and landscape template (USDA Forest Service, Northern Research Station, 2020). Since the site was established, snow depth and SWE have been measured at the site using snow cores. Snow surveys are conducted weekly at five separate locations within the forest. The current procedure uses a 1.485 in. inner diameter Mt. Rose snow tube for measurements. This allows for a one-to-one conversion from ounces of snow in the tube to inches of SWE.

3.3.4 Northeast Regional Climate Center

NRCC at Cornell University maintains snow survey records and maps for New York. Surveys are manually conducted biweekly for the winter season. The surveys collect snow depth and SWE, which are used to develop snowpack maps for New York State. Partner organizations collect measurement using various snow coring techniques, and the following subsections describe these further (Jessica Spaccio, pers. comm., 27 August 2021).

3.3.4.1 Brookfield Power NY Glens Falls

Brookfield Power NY Glens Falls (NMP-S) observers use a 3 in. diameter fiberglass snow tube to record snow depth and SWE.

3.3.4.2 Hudson-Black Reg District (Watertown)

Hudson-Black Reg District (Watertown) observers use an Adirondack snow tube to record snow depth and SWE. Three samples are taken within a 100 ft radius of the official measurement site. The samples are averaged and reported as the final measurement.

3.3.4.3 New York State Canal Corporation

The NYS Canal Corporation observers use a Brecknell Electro Sampson scale with an Adirondack snow tube to record snow depth and SWE. The tube is 5 ft long with a 3 in. inner diameter and a 40-tooth cutter to drive through snow and ice layers. The average of two measurements is taken as the final value at each site.

3.3.4.4 New York State Department of Environmental Conservation

The NYS Department of Environmental Conservation observers use an Adirondack snow tube and mechanical scale to record snow depth and SWE. Data collection begins with several (more than 10) depth measurements made on the way to the sampling location. At the snow course site, the scale is then set up with one to two measurements taken at the scale, and no fewer than two taken in each cardinal direction in a line away from the scale. Based on snowpack consistency, more snow-depth and SWE measurements may be collected. Temperature is noted at 1 m above the snowpack surface.

3.3.4.5 Trenton Falls Operators

Trenton Falls Operators observers use an Adirondack snow tube to record snow depth and SWE. Each observation site is sampled three to five times within an approximately 10 m square area. The samples are averaged and reported as the final measurement.

3.3.4.6 U.S. Army Corps of Engineers, Buffalo and Baltimore Districts

USACE LRB and NRB observers use a snow tube and mechanical scale to measure snow depth and SWE.

3.3.5 New York State Mesonet

The NYS Mesonet, operated and maintained by the University of Albany, is a network of weather stations across the state of New York. The State of New York and the Department of Homeland Security and Emergency Services established the network in 2014 to act as an early warning weather detection system. Snow data collected by the NYS Mesonet are inputs to snowpack models used to develop flood warnings (NYS Mesonet 2021). Several subnetworks within the NYS Mesonet collect snow data: the Snow Network, the Standard Network, and the Thruway Micronet.

3.3.5.1 Snow Network

The NYS Snow Network is series of 21 automated weather stations across the Adirondacks, Tug Hill, and Catskills (NYS Mesonet 2021). Snow depth and SWE are measured using sonic and passive gamma-radiation sensors, respectively. The snow depth is collected every 5 minutes and SWE every 6 hours.

3.3.5.2 Standard Network

The NYS Standard Network is a series of 126 automated weather stations spaced approximately equidistant across New York's 62 counties. Each Standard Network site contains a 30 ft tower centered on a 33 ft by 33 ft plot of land. The stations measure surface temperature, relative humidity, wind speed and direction, precipitation, solar radiation, atmospheric pressure, soil moisture and temperature, and snow depth every 5 minutes (NYS Mesonet 2021). Snow depth is measured using a sonic sensor and snowboard. The University of Albany collects, quality controls, and archives data and then disseminates it to users.

3.3.5.3 Thruway Micronet

The Thruway Micronet is composed of 12 stations along New York's major roads. Each station measures air temperature, snow depth, relative humidity, wind speed, and wind direction (NYS Mesonet 2021). Snow depth is measured using a sonic sensor and snowboard. The network is used to gain information about roadway conditions.

4 Summary of Available Data

We filtered all locations with SWE and snow-depth measurements by the first decade of record. We then plotted these records on a cumulative scale from the earliest decade of record (1880) to the current decade of record (2020). We have not fully evaluated the continuity of each time series for missing data. We used only the beginning and ending dates for our summary.

There are 2,549 snow-depth locations and 1,612 SWE locations in U.S. networks for the Northeast with data extending to at least 2017. PORs ranged from 1 year to 138 years across all considered data. Collection methods ranged from citizen volunteer efforts to automated stations, and collection frequency varied from daily to annually.

Very few snow-depth records and no SWE records date back into the nineteenth century. The earliest SWE record is from 1906, which allows for more than a century of data at this location. More than half of the stations in our study were established on or after 2000, allowing for only a 20-year POR at these sites.

Table 1 lists by state and network all stations considered. Table 2 shows the measurement methods, observer skill, and periodicity (temporal scale) of snow sampling for each network. We organized the networks by operational entity (federal, state, or other) and then divided the GHCN network into three groups—the CoCoRaHS, COOP, and WBAN networks—because each network has different sampling methods and schedules.

Table 1. Total number of snow-depth and SWE measuring stations in the Northeast by measurement type.

State	Network	Number of Stations	
		Snow Depth	SWE
All States	All Networks	2549	1612
	GHCN	1678	855
	CoCoRaHS	1275	760
	COOP	381	93
	WBAN	22	2
	Great River Hydro	18	18
	SCAN	4	4
	USACE NAE	93	93

Table 1 (cont.). Total number of snow-depth and SWE measuring stations in the Northeast by measurement type.

State	Network	Number of Stations	
		Snow Depth	SWE
Connecticut	GHCN	170	106
	CoCoRaHS	149	100
	COOP	19	6
	WBAN	2	0
	USACE NAE	14	14
Maine	GHCN	194	82
	CoCoRaHS	131	80
	COOP	60	1
	WBAN	3	1
	Maine Cooperative	250	251
Massachusetts	GHCN	394	207
	CoCoRaHS	338	179
	COOP	55	28
	WBAN	1	0
	Harvard Forest	0	1
	MA DCR	12	12
	USACE NAE	28	28
New Hampshire	GHCN	131	60
	CoCoRaHS	84	51
	COOP	44	9
	WBAN	3	0
	Great River Hydro	8	8
	Hubbard Brook	5	5
	NH DES	18	18
	SCAN	2	2
	USACE NAE	29	29
New York	GHCN	592	298
	CoCoRaHS	418	252
	COOP	163	45
	WBAN	11	1
	NRCC	229	230
	NYC DEP Cores	82	82
	NYC DEP Pillows	12	12
	NYS Mesonet	138	21

Table 1 (cont.). Total number of snow-depth and SWE measuring stations in the Northeast by measurement type.

State	Network	Number of Stations	
		Snow Depth	SWE
Rhode Island	GHCN	57	38
	CoCoRaHS	49	35
	COOP	7	3
	WBAN	1	0
Vermont	GHCN	140	64
	CoCoRaHS	106	63
	COOP	33	1
	WBAN	1	0
	Great River Hydro	10	10
	Sleepers River	10	10
	SCAN	2	2
	USACE NAE	22	22

Table 2. Collection methods for snow depth and SWE by network.

Data Source	Network	Collection Method	Collector Skill	Periodicity
Federal	CoCoRaHS (GHCN)	Manual	Trained Volunteer	Snow Depth Daily / SWE Weekly
	COOP (GHCN)	Manual	Trained Volunteer	Snow Depth Daily /SWE Weekly
	WBAN (GHCN)	Automated	NA[a]	Every 6 hr
	Sleepers River	Manual	Professional	Weekly
	SCAN	Automated	NA	Hourly
	USACE NAE	Manual	Professional	Biweekly
State	Maine Cooperative	Manual	Trained Volunteer	Varies
	MA DCR	Manual	Professional	Weekly
	NH DES	Manual	Professional	Biweekly
	NYC DEP Cores	Manual	Professional	Biweekly
	NYC DEP Pillows	Automated	NA	Hourly
Other	Great River Hydro	Manual	Professional	Biweekly
	Harvard Forest	Automated	NA	15 min
	Hubbard Brook	Manual	Professional	Weekly
	NRCC	Manual	Trained Volunteer	Biweekly
	NYS Mesonet	Automated	NA	Hourly

[a] Not applicable

4.1 Period of record

Table 3 shows the POR mean, median, minimum, and maximum values for snow depth and SWE for each network. The largest portion of sites within the GHCN are CoCoRaHS; however, the locations have a median POR of 5 years only. In contrast, WBAN sites have the longest median record length but have only 22 locations across the Northeast. The largest state-operated network is the Maine Cooperative Snow Survey, which has a median record length of approximately 45 years.

Table 3. Snow-depth and SWE period of record (POR) statistics.

Data Source	Network	Snow-Depth POR (years)					SWE POR (years)				
		N	Mean	Median	Min	Max	*N*	Mean	Median	Min	Max
All Data	All Networks	2549	25.7	11	1	138	1612	24.6	11	1	116
Federal	GHCN	1678	17.7	7	1	138	855	6.3	5	1	70
	CoCoRaHS	1275	6.5	5	1	15	760	5.9	5	1	15
	COOP	381	48.9	38	2	138	93	8.0	9	2	13
	WBAN	22	74.4	76.5	14	110	2	69.5	69.5	69	70
	Sleepers River	10	44.8	40	36	63	10	44.8	40	36	63
	SCAN	4	20.5	21	18	22	4	20.0	20	18	22
	USACE NAE	93	35.4	31	22	61	93	35.4	31	22	61
State	MA DCR	12	31.2	31.5	9	52	12	31.2	32	9	52
	Maine Cooperative	250	45.3	42	1	116	251	45.1	42	1	116
	NH DES	18	53.6	64	4	72	18	53.6	64	4	72
	NYC DEP Cores	82	57.0	57	57	57	82	57.0	57	57	57
	NYC DEP Pillows	12	10.3	10	5	13	12	10.3	10	5	13
Other	Great River Hydro	18	43	43	43	43	18	43	43	43	43
	Harvard Forest	0	-	-	-	-	1	13.0	13	13	13
	Hubbard Brook	5	53.2	57	29	67	5	53.2	57	29	67
	NRCC	229	52.1	56	1	84	230	51.8	50	1	84
	NYS Mesonet	138	5.9	6	4	7	21	4.0	4	4	4

Figure 9 and Figure 10 plot the number of stations with snow-depth and SWE measurements, respectively, against POR. We omitted from the plots networks that include only a few stations (e.g., Harvard Forest). Long data records of both snow depth and SWE are available from the Maine Cooperative and NRCC networks, which steadily added sites over the past century. The NYC DEP and the USACE snow data collection efforts began in the 1960s, although the bulk of USACE measurements start in the 1980s. In the past 15 years, SWE data collection at COOP sites has increased substantially, and the creation of the CoCoRaHS network has dramatically increased the number of snow-depth and SWE data collection sites.

Figure 9. Cumulative number of snow-depth-measurement locations with a given POR. Plot includes only datasets with 10 or more locations.

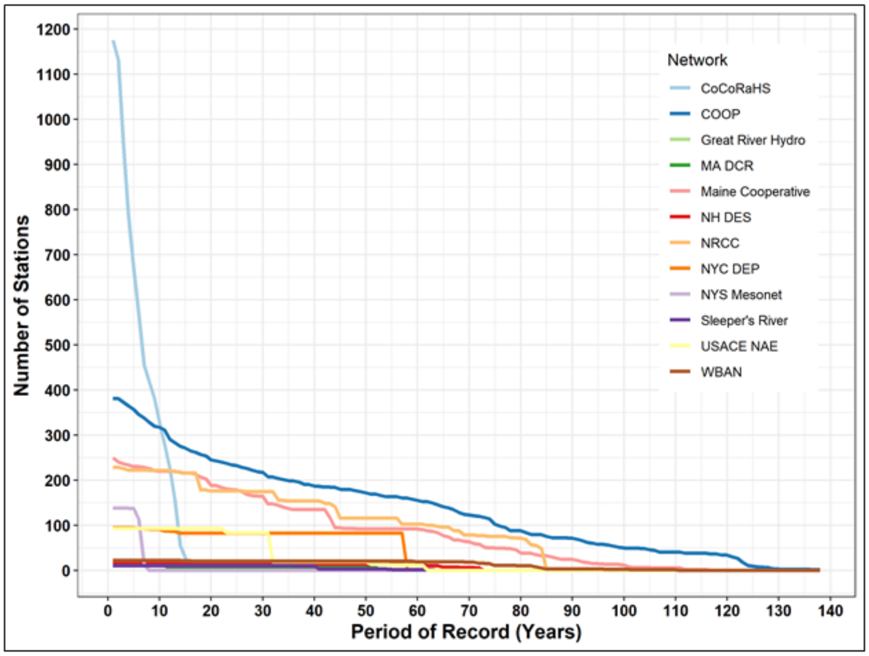


Figure 10. Cumulative number of SWE measurement locations within a given POR. Plot includes only those datasets with 10 or more locations.

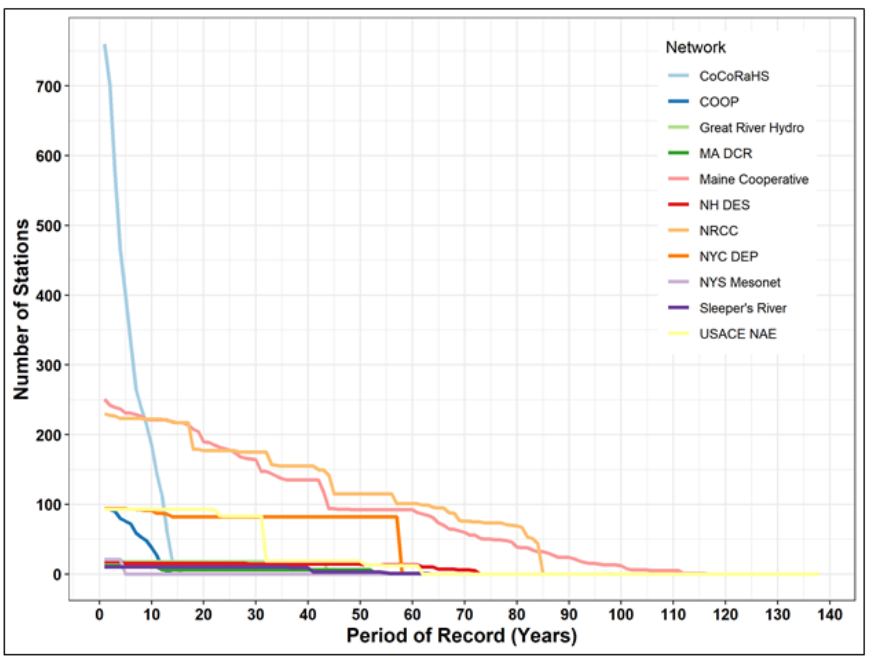
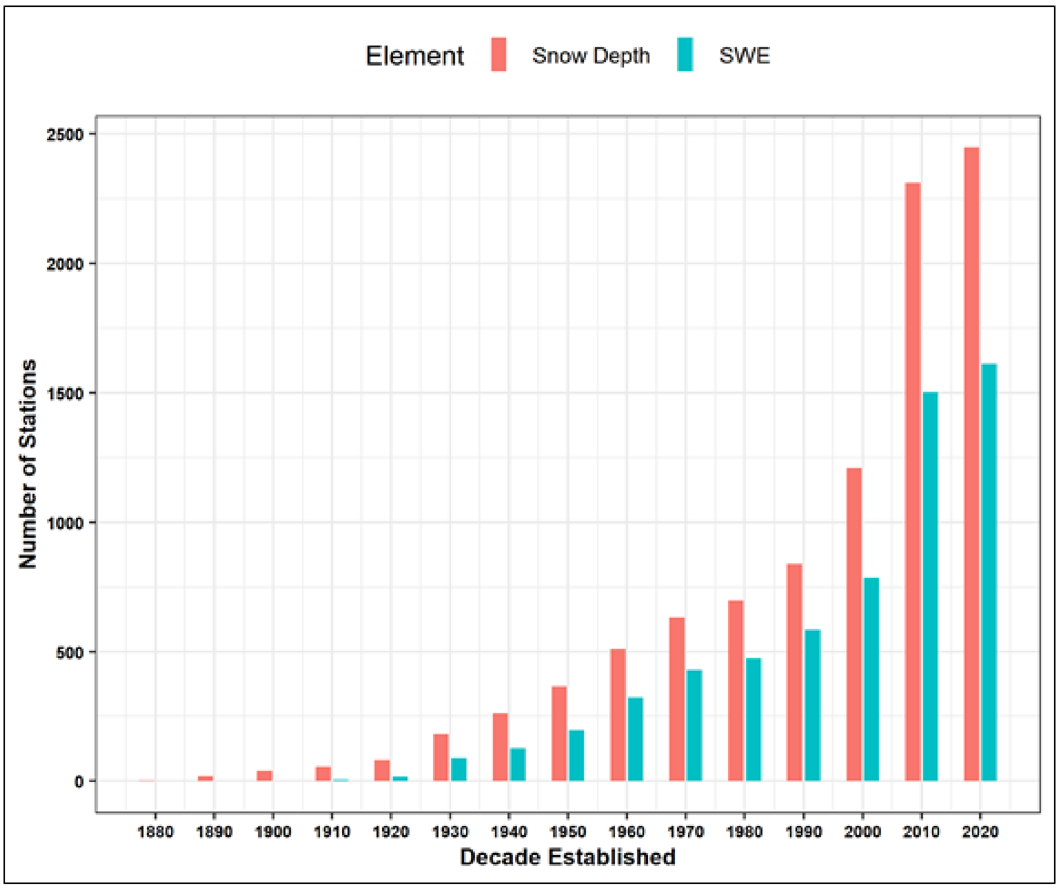


Figure 11 shows the cumulative number of snow-depth or SWE stations established by decade for the Northeast. When we evaluated the total number of sites across the Northeast, there were a small number of snow-depth collection sites established in the 1880s. In contrast, the earliest SWE records occur after 1900. The total number of sites have increased substantially in the last 20 years, indicating that there is increased value and use of snow data for numerous social, environmental, and economic activities.

Figure 11. Cumulative number of snow-depth and SWE observation locations in the Northeast.



4.2 Spatial distribution of snow measurement sites

The GHCN is a commonly used, spatially distributed network of ground observations for meteorologic data (Figure 12). CoCoRaHS has the highest spatial density of sites where either snow depth or SWE are measured. While CoCoRaHS has numerous sites in the study area, there is an increased chance of measurement error or inconsistency because it is run entirely by citizen volunteers. In addition, the CoCoRaHS network has only been in existence for a relatively short period of time; even sites with the longest PORs have less than 20 years of data (Figure 9). In comparison, the COOP is federally managed and supported by trained volunteers taking measurements at consistent times and locations, which allows for a more reliable record. The COOP network has the second highest data density of the GHCN network. While many COOP network sites have been in existence for a century or more, SWE data collection started only recently at some sites, and the longest PORs are less than 15 years (Figure 10). The WBAN network is entirely automated and has long PORs with well-regulated data, but it has very few stations available.

Figure 13 shows the spatial distribution of Maine snow measurement sites where either snow depth or SWE were available. It includes data from GHCN and the Maine Cooperative Snow Survey. The Maine Cooperative Snow Survey network includes locations outside the Maine political boundary in New Hampshire and New Brunswick, Canada, which are not included in any other dataset in this report. Some sites in the Maine Cooperative network are colocated with GHCN locations, but the snow-core data collected at those sites are distinct from the routine data.

The spatial distribution of snow data collection sites in New Hampshire and Vermont includes data from the GHCN, NRCS SCAN, USACE NAE, NH DES, Great River Hydro, Hubbard Brook Experimental Forest, and Sleepers River Research Watershed (Figure 14). To avoid redundancy, Figure 14 does not show the snow course sites in the Maine Cooperative network that lie within New Hampshire.

The snow data collection sites in Massachusetts, Connecticut, and Rhode Island include information from the GHCN, USACE NAE, MA DCR, and Harvard Forest networks (Figure 15). The GHCN locations are evenly distributed throughout all three states. The USACE NAE sites, which are used for water management purposes, are concentrated in watersheds where flood risk management is a key consideration. The MA DCR locations have limited spatial extents because the snow data is primarily used for Wachusett and Quabbin Reservoirs.

The spatial distribution of sites in New York includes several networks that are unique to that state. In addition to the GHCN data, New York also has information from the NRCC, NYC DEP, and the NYS Mesonet networks (Figure 16). Some sites in the NRCC network are colocated with GHCN, but data collected at those sites are reported separately and have slight differences for coincident time periods. Due to the size of the state and variety of networks, New York has the most snow data collection locations within the study area.

Snow data measurement locations in the Northeast have PORs ranging from over 100 years to less than 5 (Figure 9 and Figure 10). For many engineering or scientific investigations, a reasonably long record is required to perform robust statistical analyses. We have highlighted those locations with at least a 20-year snow-depth record and SWE record in Figure 17 and Figure 18, respectively.

Figure 12. Current observation locations in the GHCN. Locations are split by data source (CoCoRaHS, COOP, and WBAN). Only those locations with snow-depth or SWE measurements, or both, are shown.

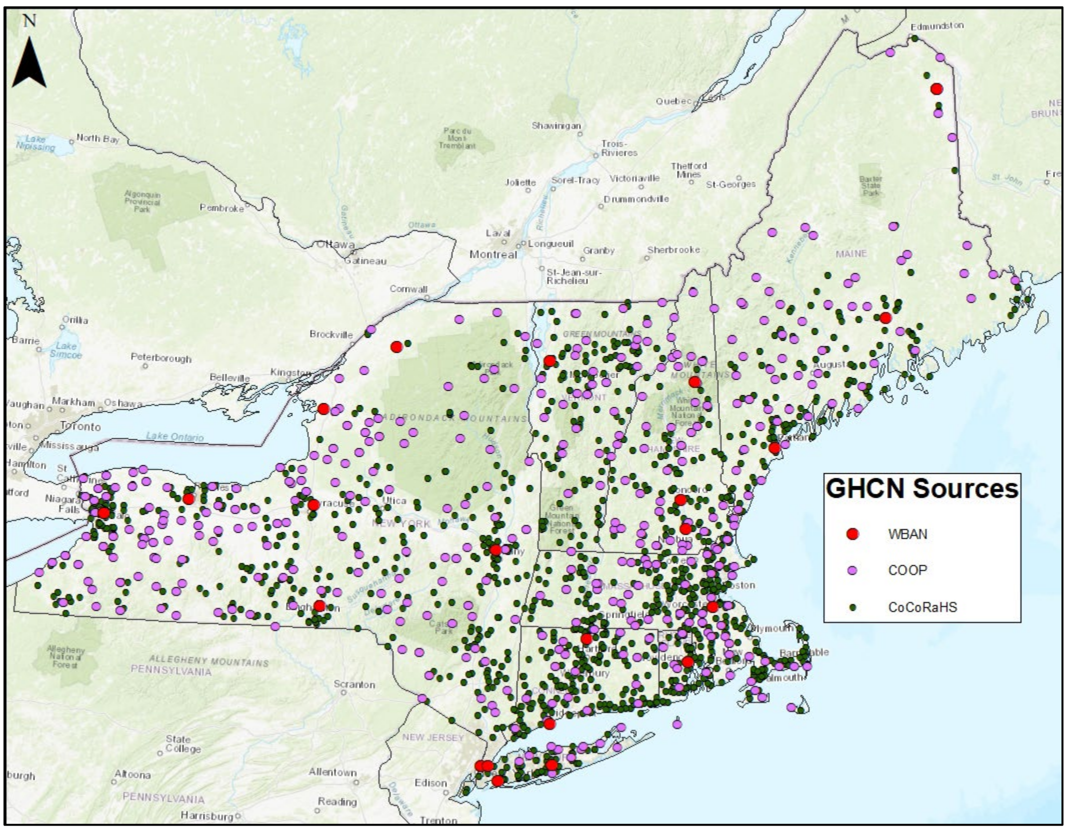


Figure 13. Current snow observation locations in Maine with snow-depth or SWE records continuing to 2017 or later. Maine Cooperative also contains data in New Hampshire and New Brunswick, Canada.

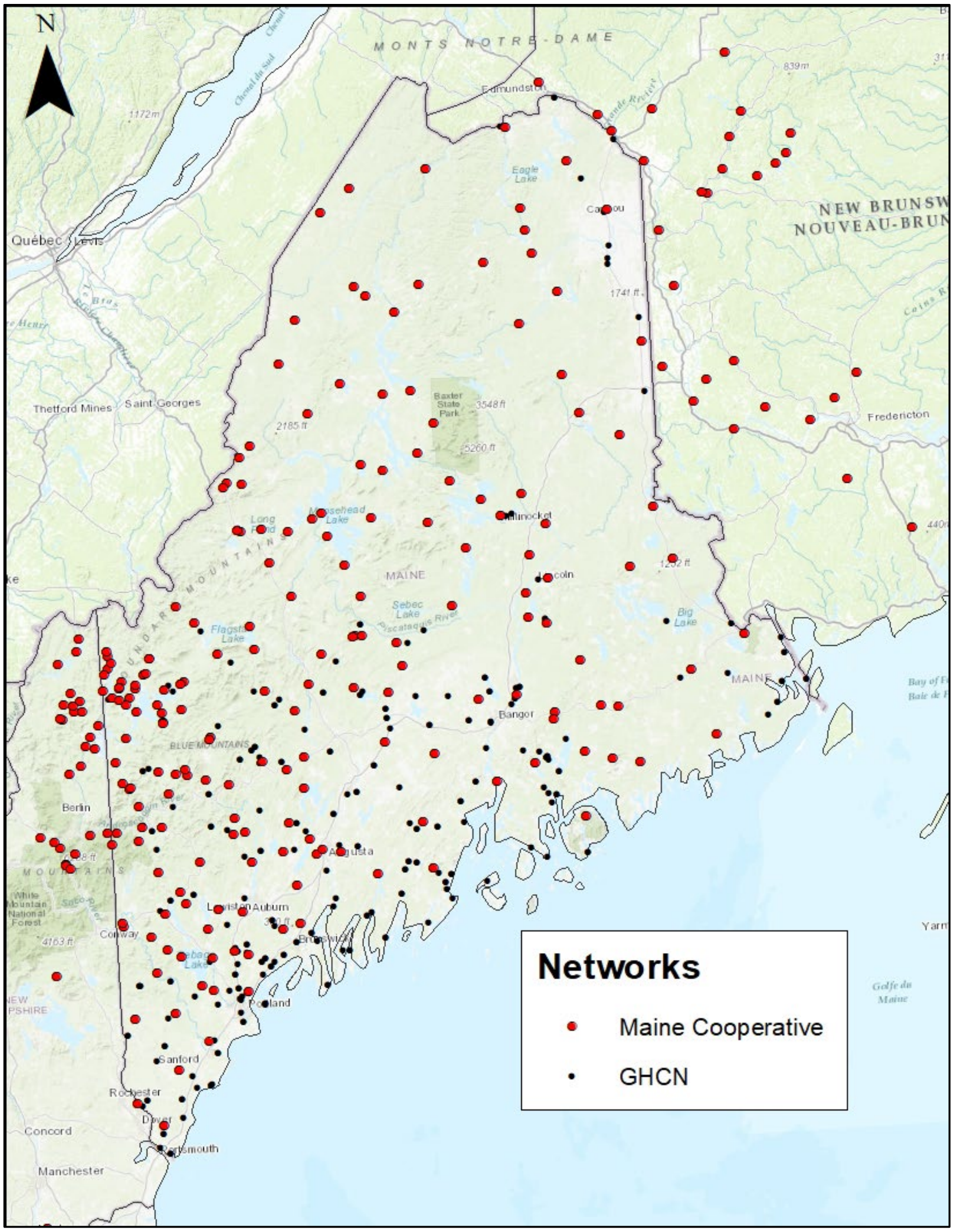


Figure 14. Current snow observation locations in New Hampshire and Vermont with snow-depth or SWE records.

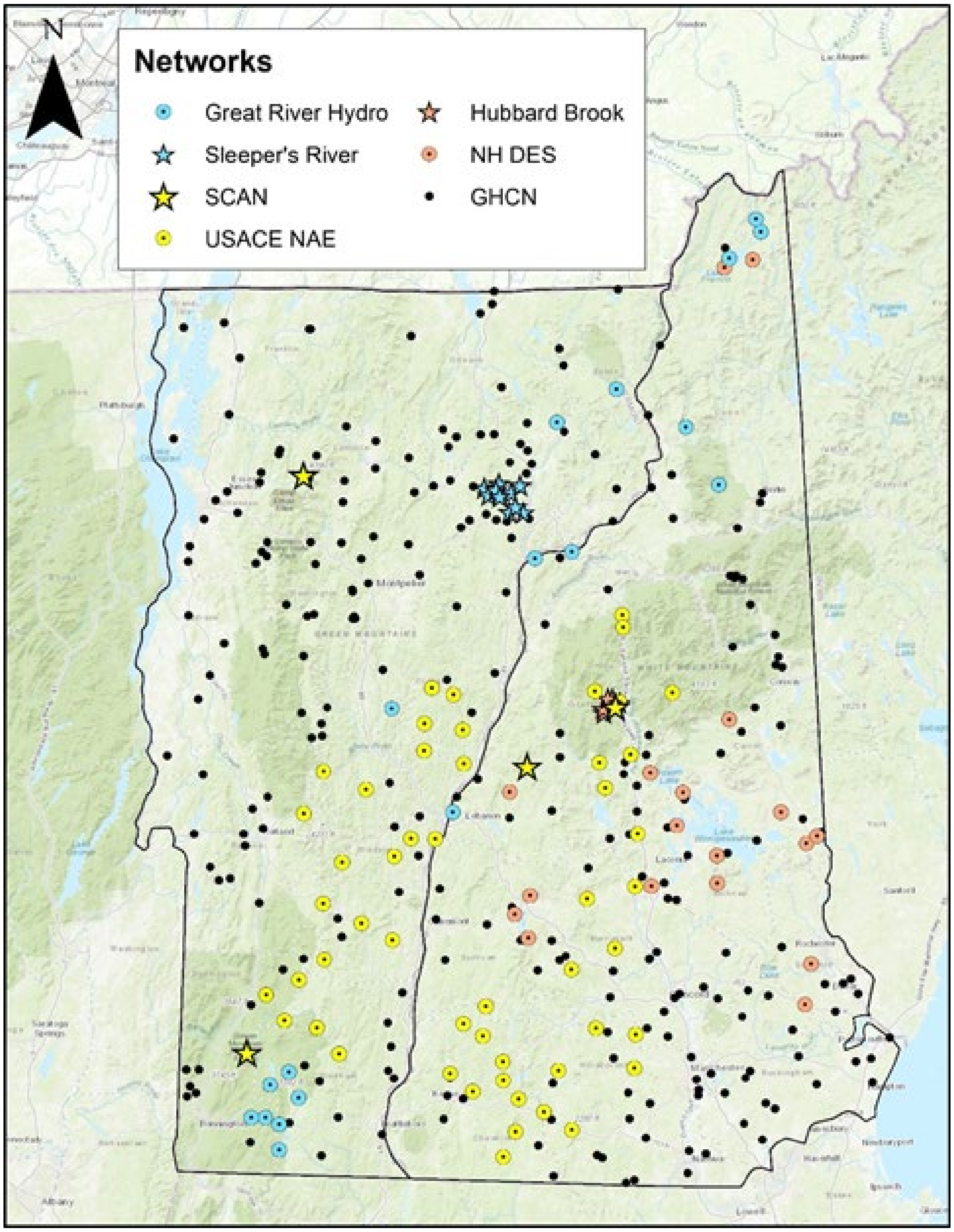


Figure 15. Current snow observation locations in Massachusetts, Connecticut, and Rhode Island with snow depth or SWE.

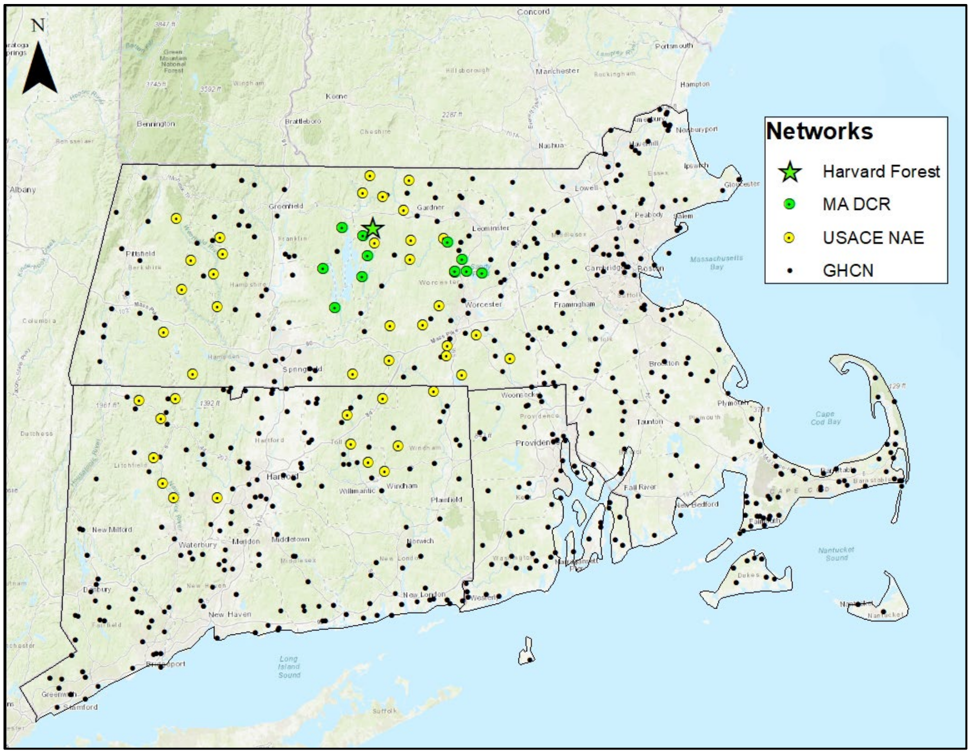


Figure 16. Current snow observation locations in New York with snow-depth or SWE records.

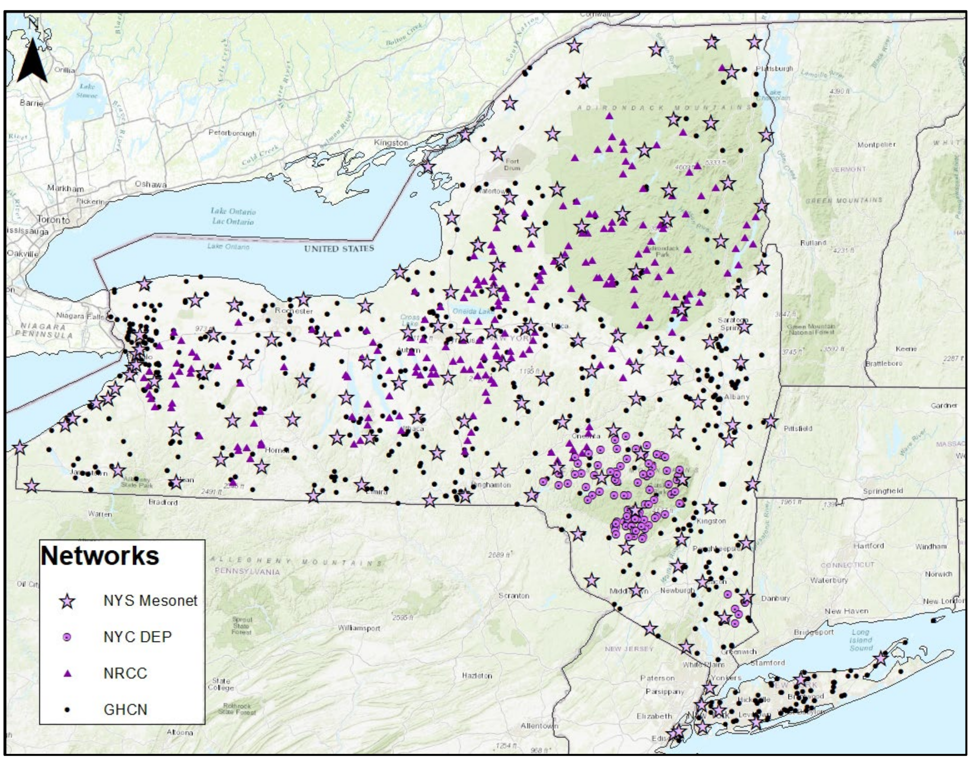


Figure 17. Snow-depth observation locations with 20 or more years of record.

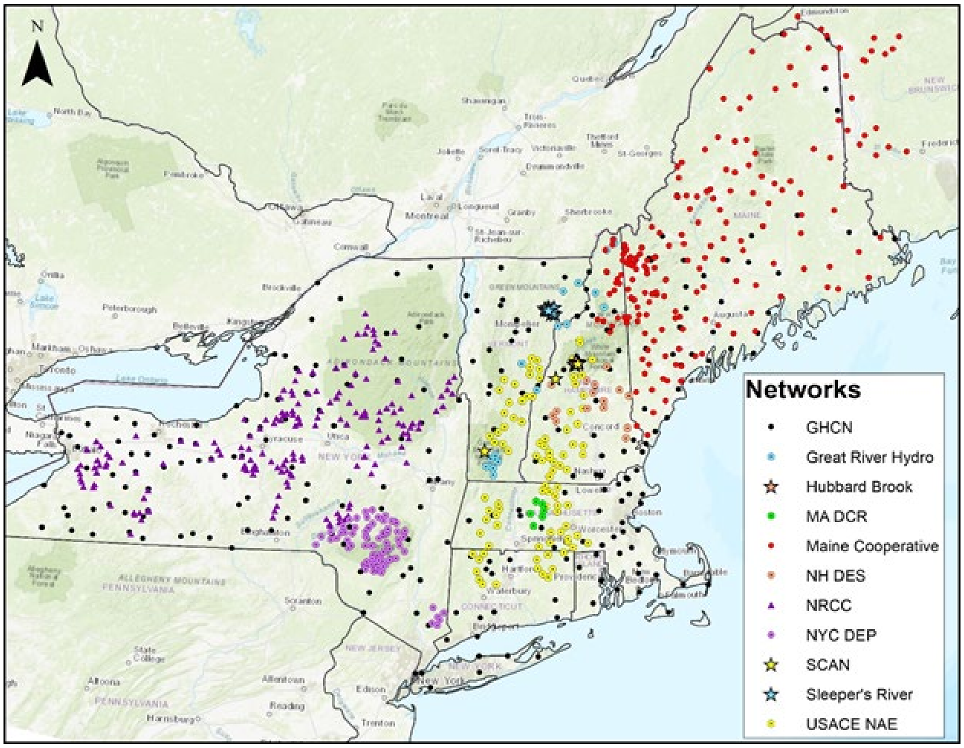
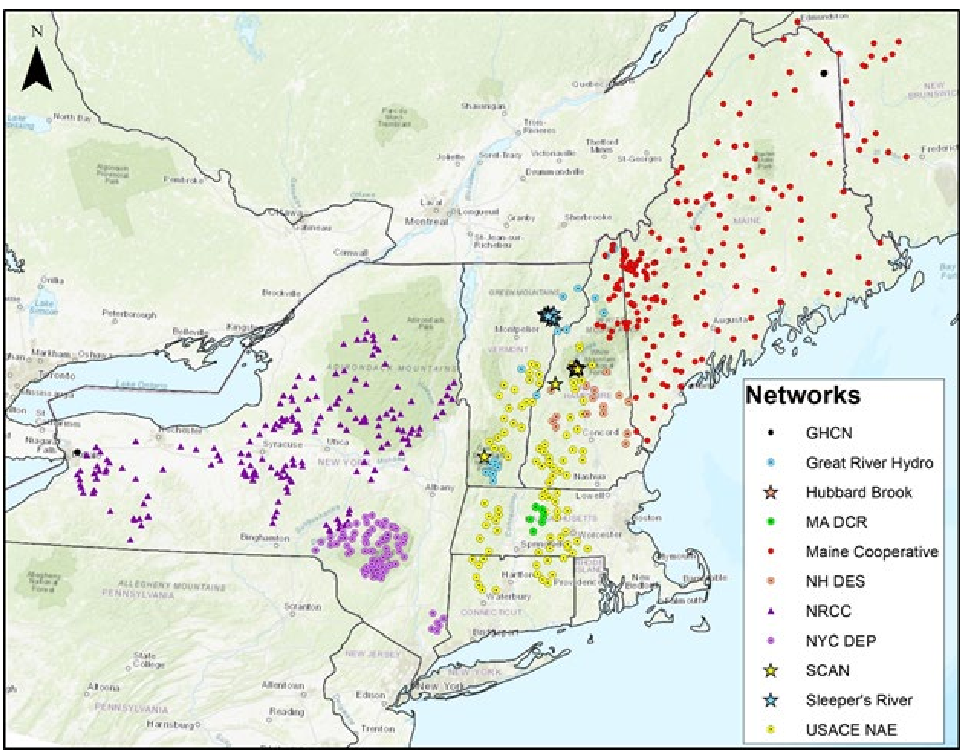


Figure 18. SWE observation locations with 20 or more years of record.



Many measurement sites collect data other than snow depth and SWE. In the GHCN, all partner organizations (CoCoRaHS, COOP, and WBAN) are also collecting weather data such as precipitation and temperature. Harvard Forest is a research site for Harvard University and tracks other observations in addition to precipitation and temperature, such as forest health and water quality. Those observations may not be made at the exact same location as the SWE measurements but are representative of the wintertime conditions in the area. The Hubbard Brook Ecosystem Study also tracks data for other variables, such as streamflow, in addition to precipitation and temperature. The NYS Mesonet tracks other weather observations, such as relative humidity, wind speed and direction, precipitation, solar radiation, atmospheric pressure, and soil moisture and temperature, as part of its early weather warning system for New York State. The SCAN network tracks additional observations focused on soil health along with precipitation, temperature, wind, and solar radiation.

Sleepers River has many other observations available to complement their snow course data, though observations may not be colocated. However, the meteorological data collected at Sleepers River is often used with the snow measurements for scientific analysis. The other networks discussed in our study do not include measurements of climate variables but may have weather stations nearby.

4.3 Temporal resolution of snow measurements

While all snow data have value, the temporal resolution of snow measurements is an important piece of metadata that may dictate the utility of a particular source for analysis. For example, weekly snow course data may be sufficient for the development of snow loads, provided the collection includes data points at peak SWE; but the development of melt factors for use in runoff hydrology typically requires at least daily data. This section explores the variation in temporal scales at which snow data are collected in the Northeast.

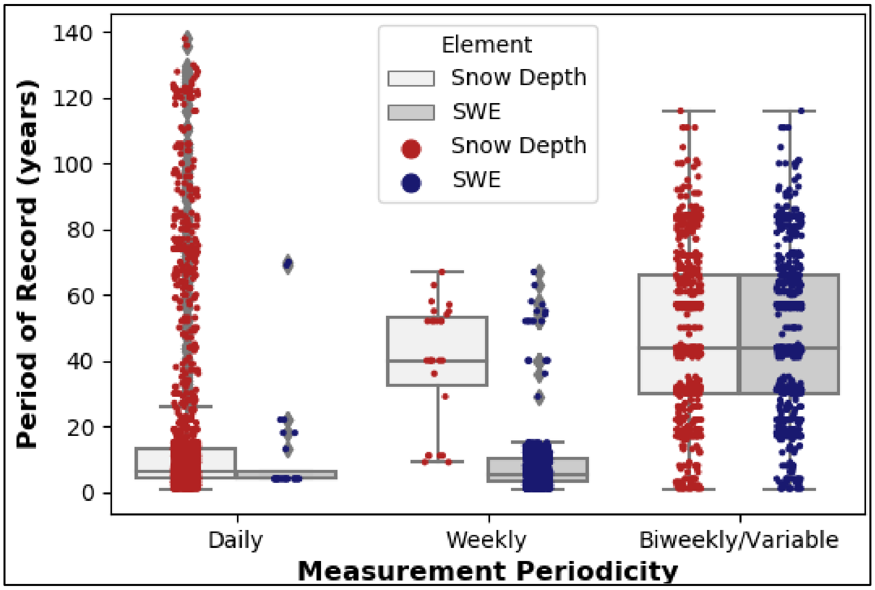
Most snow data in the Northeast are collected once per week or more frequently (Table 4). Because snow depth is easier to measure, there are significantly more stations that collect depth versus SWE, especially on a daily and weekly basis (Table 4 and Figure 19). The vast majority of stations that collect only snow depth are a subset of volunteer run COOP and CoCoRaHS sites. Sites where data are collected on a biweekly or variable frequency are primarily formal snow course sites where snow cores are collected by trained professionals and both snow depth and SWE are available.

The separation of measurements by periodicity is based on the metadata description of the individual networks and not on an analysis of the actual data collected at each site. For example, CoCoRaHS volunteers are asked to collect snow depth daily and SWE weekly. Therefore, in the exploratory analysis below, we assume stations in that network follow that guidance. In reality, there are sometimes significant variations in recording intervals versus the metadata values at individual stations across the various networks. Therefore, the periodicity summary below is a high-level overview based on available metadata only, subject to future refinement from more in-depth analysis of time series data at each station.

Table 4. Total number of snow-depth and SWE locations in the Northeast by periodicity.

State	Frequency of Data Availability	Number of Stations	
		Snow Depth	SWE
All States	Daily	1832	40
	Weekly	18	880
	Biweekly/Variable	690	692
Connecticut	Daily	170	0
	Weekly	0	106
	Biweekly/Variable	14	14
Maine	Daily	194	1
	Weekly	0	81
	Biweekly/Variable	250	251
Massachusetts	Daily	394	1
	Weekly	12	219
	Biweekly/Variable	28	28
New Hampshire	Daily	133	2
	Weekly	5	65
	Biweekly/Variable	55	55
New York	Daily	742	34
	Weekly	0	297
	Biweekly/Variable	311	312
Rhode Island	Daily	57	0
	Weekly	0	38
	Biweekly/Variable	0	0
Vermont	Daily	142	2
	Weekly	10	74
	Biweekly/Variable	32	32

Figure 19. POR at stations that collect snow-depth or SWE data, or both, at daily, weekly, and biweekly or variable intervals.



4.3.1 Daily data

Sources of daily snow data in the region include COOP, CoCoRaHS, WBAN, SCAN, NYC DEP pillows, Harvard Forest, and the NYS Mesonet. All of these sources collect both daily depth and SWE data except for COOP and CoCoRaHS stations, which collect only snow depth on a daily basis. Daily snow data are the most valuable for analyses where changes over short timescales (days) are of interest, such as those that concern snowmelt and rain-on-snow processes.

There is a long history of collecting daily snow-depth data at COOP and WBAN sites with some records extending over 100 years (Figure 20). The distribution of snow-depth collection sites is throughout the region; however, there are a limited number of sites in parts of upstate New York and Maine (Figure 21). While the number of sites collecting SWE data at daily and subdaily intervals has increased dramatically in the past 20 years, there are a limited number of sites with long SWE records (Figure 22). The WBAN sites in Buffalo, New York, and Caribou, Maine, provide the longest daily SWE records. Several other WBAN sites in the region have data until around 2010 when they were discontinued. Because this study focuses on documenting recently active sites (Appendix A), it excludes many WBAN sites with older daily SWE data, including at least 11 sites with more than 50 years of record. NRCS SCAN sites established in New Hampshire and Vermont in the early 2000s provide the next longest daily SWE records. In the past 10 years, the build-out of the NYS Mesonet and NYC DEP snow pillows has dramatically increased the availability of high-temporal-resolution SWE data in New York.

Figure 20. Daily snow-depth and SWE data.

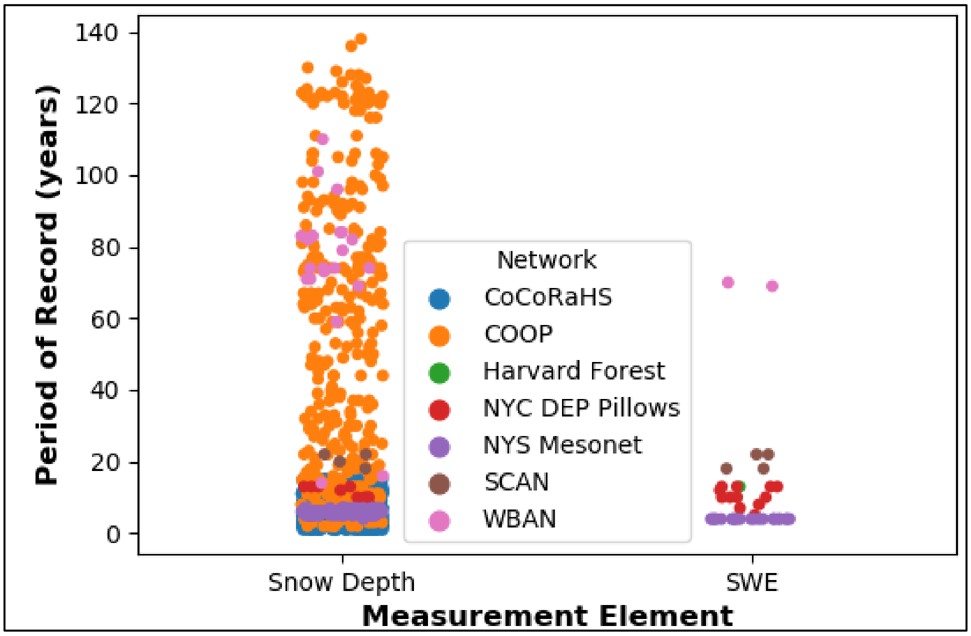


Figure 21. Spatial distribution of daily snow-depth records.

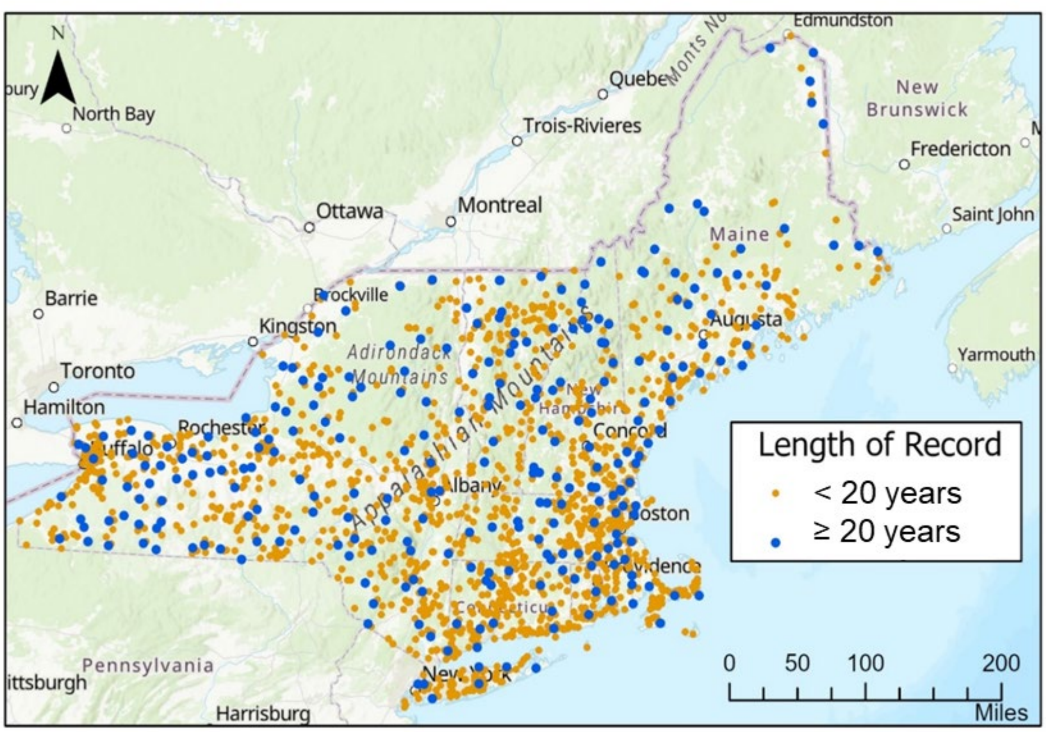
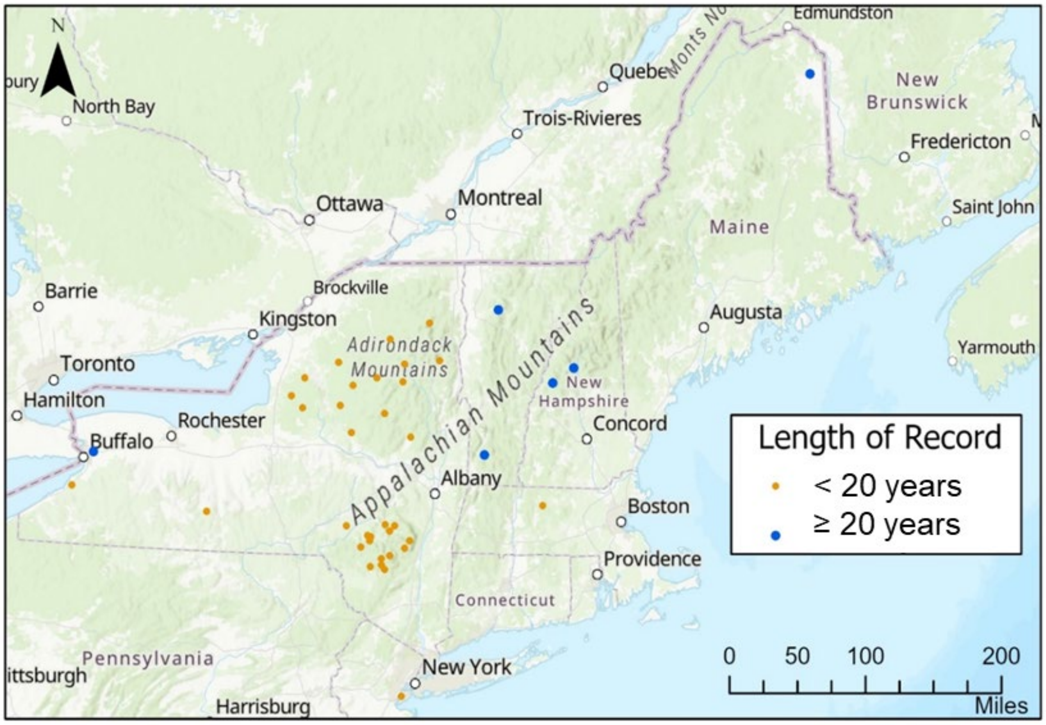


Figure 22. Spatial distribution of daily SWE records.



4.3.2 Weekly data

Sources of weekly snow data in the region include COOP, CoCoRaHS, Sleepers River, MA DCR, and Hubbard Brook snow courses. The guidance for CoCoRaHS volunteers is to collect SWE data once a week; but snow-depth data is generally collected at those sites more frequently, typically daily or after snow events. Because of the popularity and widespread public participation in the CoCoRaHS program, the weekly snow data category is dominated by sites in this network. CoCoRaHS is relatively young, however, and all stations in the dataset have a POR of less than 20 years. Some COOP stations report SWE weekly, while others report it semidaily. However, it is not clear if these are all measured values or derived from precipitation or snow-depth values.

The other stations with weekly data are formal snow course collection efforts at Sleepers River Research Watershed, the Wachusett and Quabbin reservoir watersheds (MA DCR), and Hubbard Brook Experimental Forest. Most of these sites have PORs of over 50 years. The exception is the Wachusett Reservoir watershed snow collection, which began in 2011 (Figure 23). The weekly reporting of snow depth is generally limited to only a few watersheds (Figure 24), while weekly reporting of SWE is more widely dispersed throughout the region (Figure 25). Again, the CoCoRaHS network makes up the majority of the SWE locations.

Figure 23. Weekly snow-depth and SWE data.

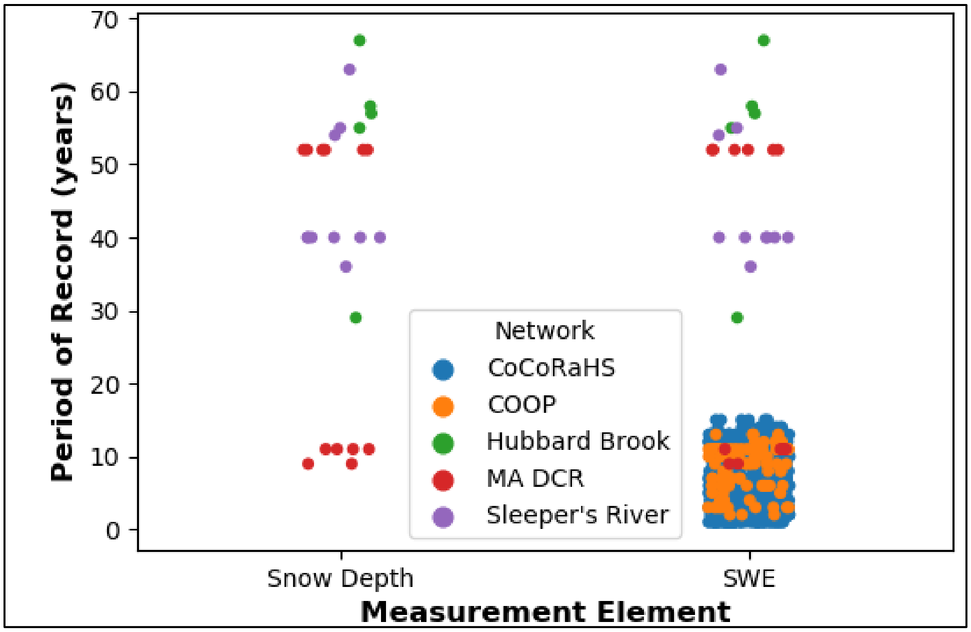


Figure 24. Spatial distribution of weekly snow-depth records.

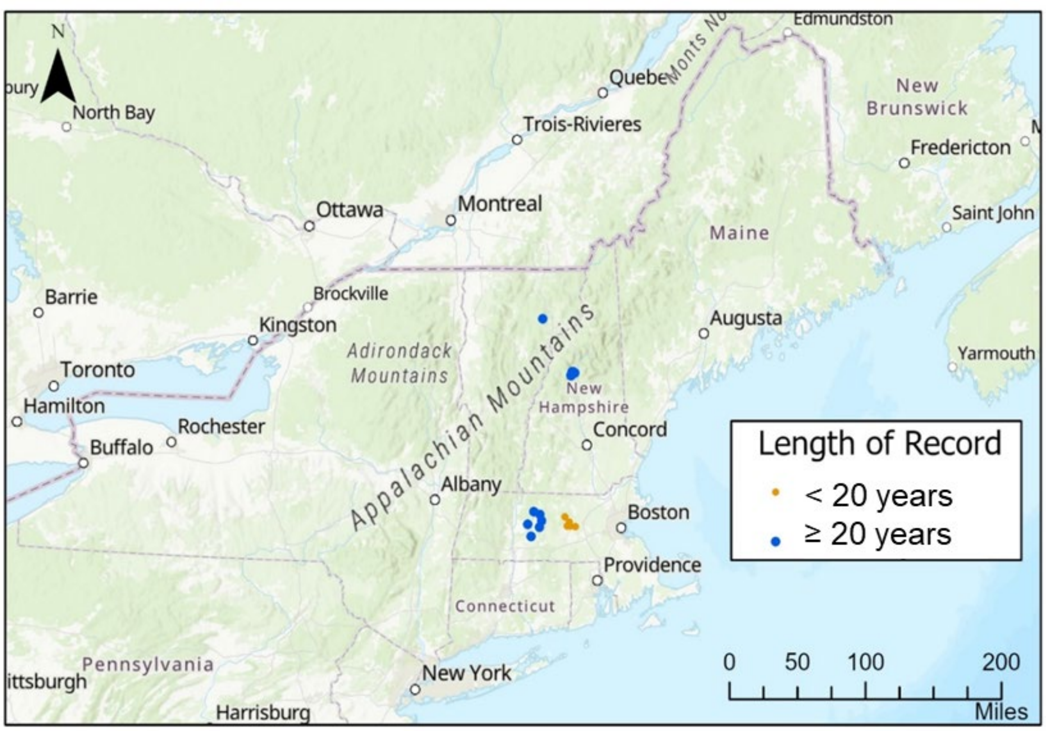
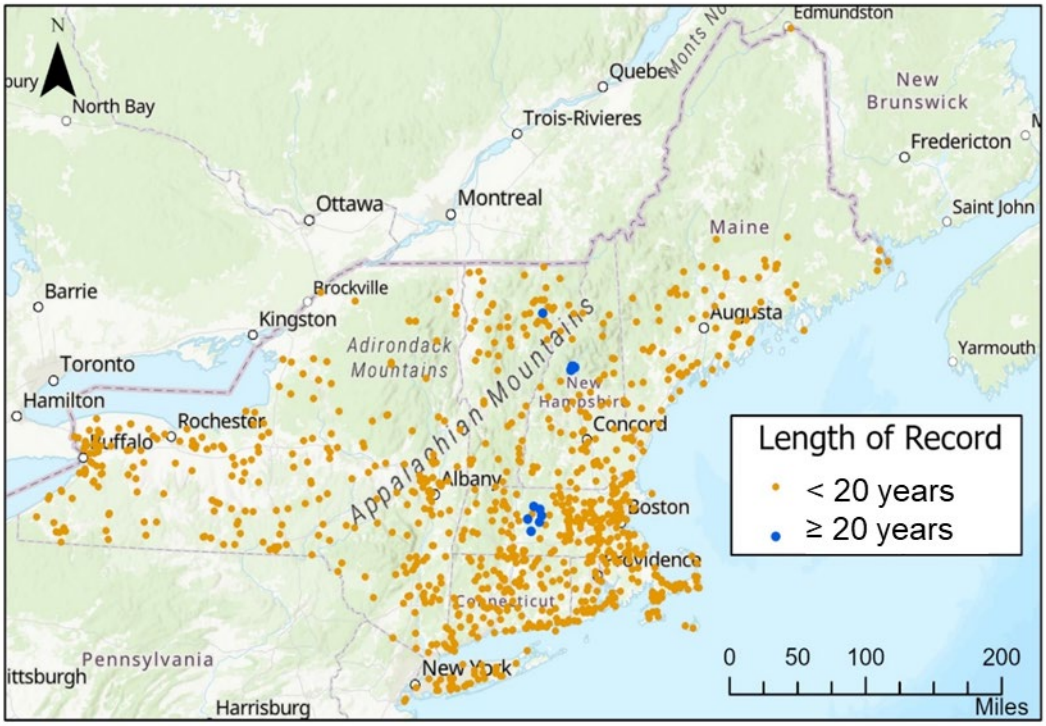


Figure 25. Spatial distribution of weekly SWE records.



4.3.3 Biweekly and variable data

Sources of data that are collected either biweekly or at variable intervals include the Maine Cooperative Snow Survey, USACE NAE, NH DES, NYC DEP Cores, and the NRCC snow courses. These networks are all formal snow course collection efforts, many of which are continuing to grow, resulting in significant variation in the POR (Figure 26). Some of the oldest records are from the Maine Cooperative and the NRCC snow courses. In general, these sites use manual snow measurements, which provide both snow depth and SWE. Therefore, the distribution of sites with more than 20 years of data for snow depth (Figure 27) is very similar to the SWE locations (Figure 28).

Figure 26. Biweekly or variable snow-depth and SWE data.

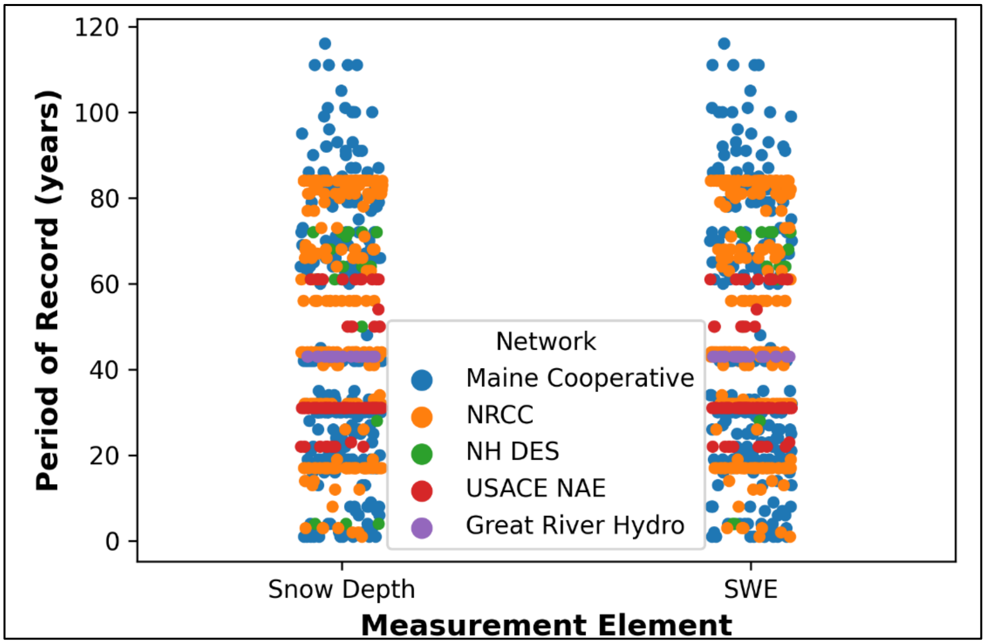


Figure 27. Spatial distribution of biweekly or variable snow-depth records.

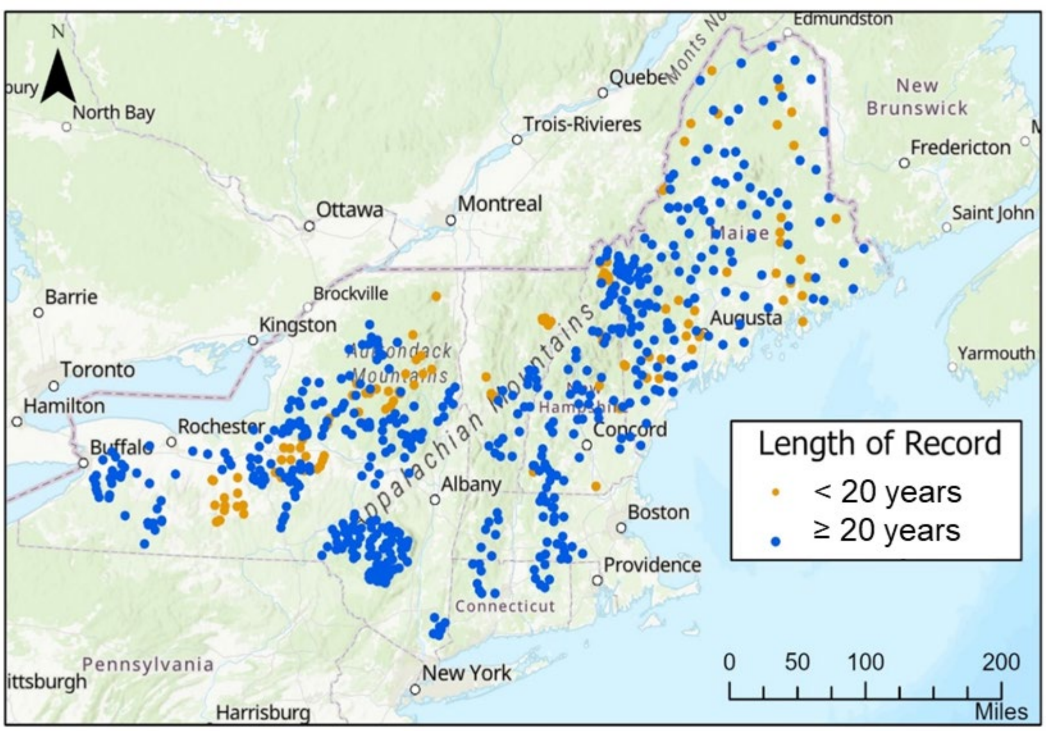
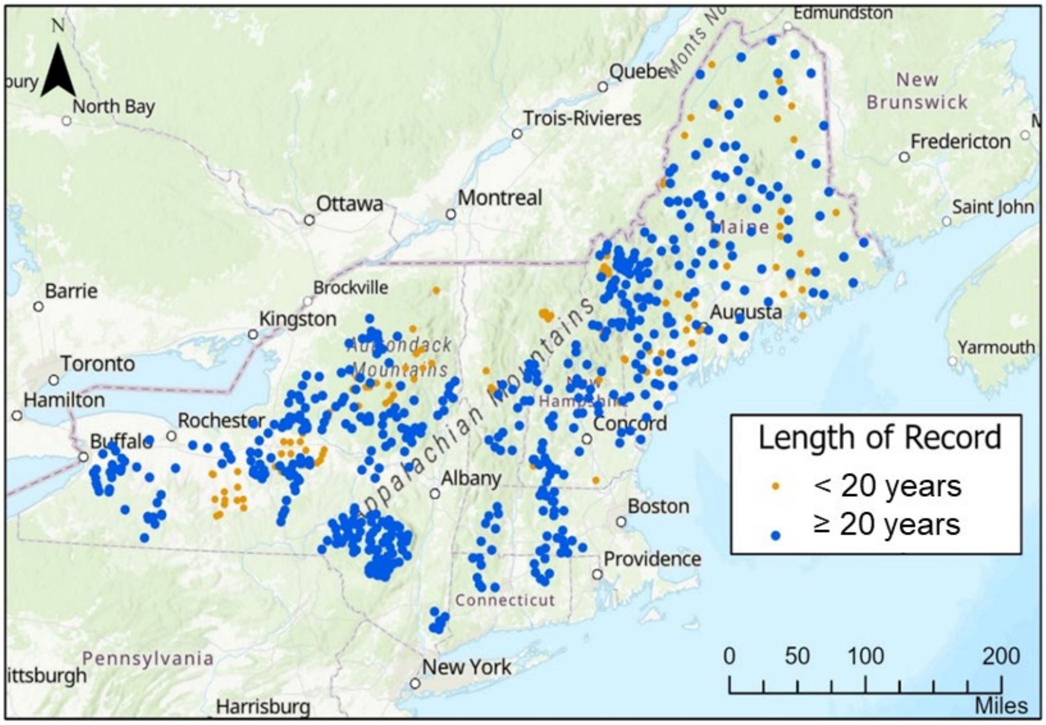


Figure 28. Spatial distribution of biweekly or variable SWE records

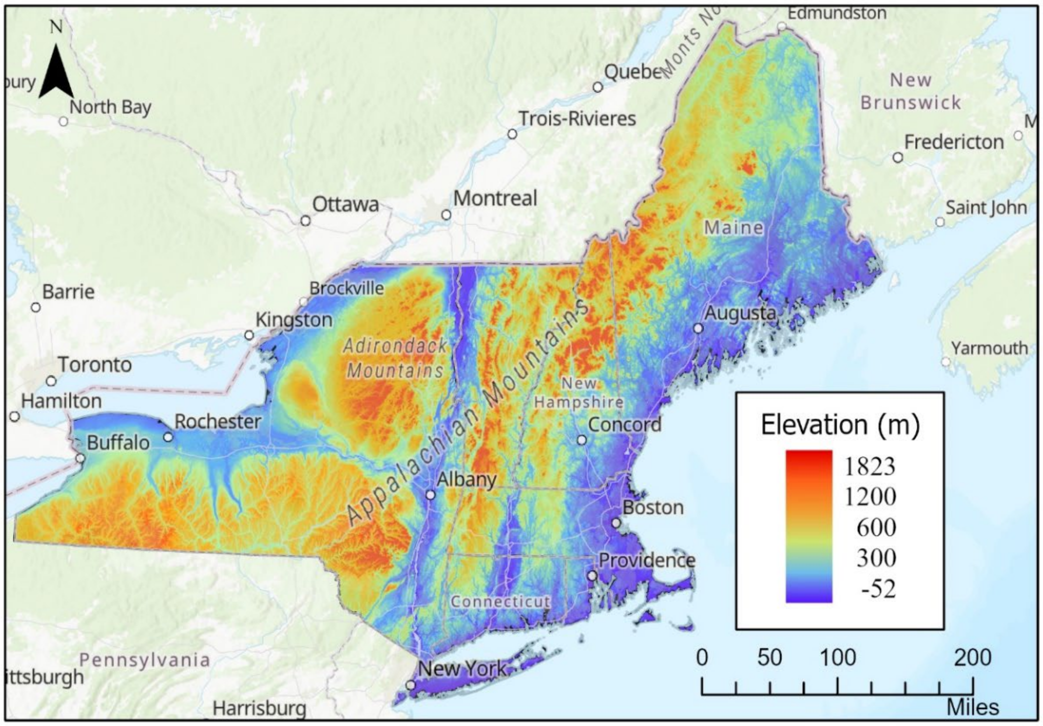


4.4 Distribution of observation sites by elevation

The landscape of the Northeast exhibits substantial topographic variation, bounded to the east by the Atlantic Ocean, to the west by the Great Lakes Ontario and Erie, with a spine formed by the northern terminus of the Appalachian Mountains running through the center of the region (Figure 29).

To investigate the elevational distribution of snow measurement sites in the Northeast, we extracted elevations from the USGS National Elevation Dataset (NED) 1/3 arc-second DEM (digital elevation model) at the latitude and longitude associated with each station. Many stations include elevation data in their metadata; however, many do not, and several contain what appear to be erroneous values. Therefore, for consistency, we used the NED-derived value for each site in the following analysis.

Figure 29. Elevation throughout the study area (three quarries along the Hudson River contribute to the negative elevations).



In general, ground-based weather observations tend to be biased to lower elevations near population centers (Brasnett 1999). In the Northeast, we find that both snow-depth and SWE observations are distributed across a broad band of elevations, with the predominant number of sites at lower elevations, tapering off to very few stations above 800 m (Figure 30). While this may partially confirm a bias toward stations at lower elevations, the distribution is similar to the overall elevation distribution across the region (Figure 31), with some underrepresentation in the 200–600 m elevation band. This is probably due to a combination of the large number and broad spatial distribution of CoCoRaHS sites, which are typically at people's homes, providing a more uniform sample of low to medium elevations, and the large number of formal snow course sites located at higher elevations in New York and Maine.

When looking at sites that collect data at daily, weekly, or biweekly or variable intervals, obvious patterns of elevation distribution emerge. Daily snow-depth data is biased towards very low elevations while the very sparse daily SWE measurements are uniformly distributed across elevations between 300 and 700 m (Figure 32; Figure 34). With some exceptions, daily snow-depth data is dominated by COOP and CoCoRaHS stations, which tend to be near population centers at lower elevations. The more recent addition of NYS Mesonet, NYC DEP snow pillows, and SCAN sites has increased the availability of daily or subdaily snow-depth and SWE data at higher elevations (Figure 33; Figure 34). Weekly SWE measurements are predominately made at COOP and CoCoRaHS sites (Figure 33; Figure 35), which are again biased towards lower elevations, while higher elevations in the region tend to be represented by biweekly or variable data collection sites. This is likely because the biweekly and variable data are collected at formal snow courses by groups (USACE-NAE, NRCC, and NYC DEP) who are interested in characterizing snow conditions in watersheds or regions where snow is an important factor for runoff, and these areas tend to be at higher elevations (Figure 33; Figure 36).

Figure 30. Distribution of snow observations sites by elevation.

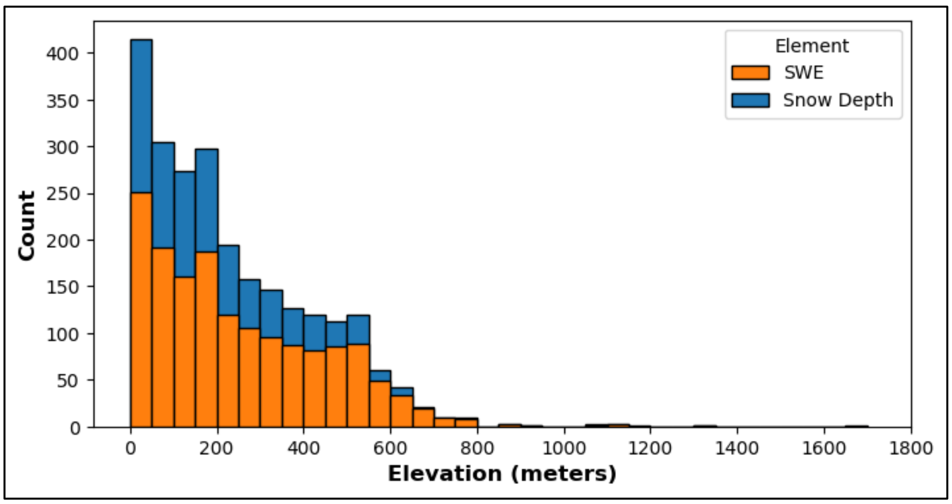


Figure 31. Elevation distribution of all topography across the Northeast. Elevations values counted from the USGS NED 1/3 arc-second DEM reduced using 300 m pixels.

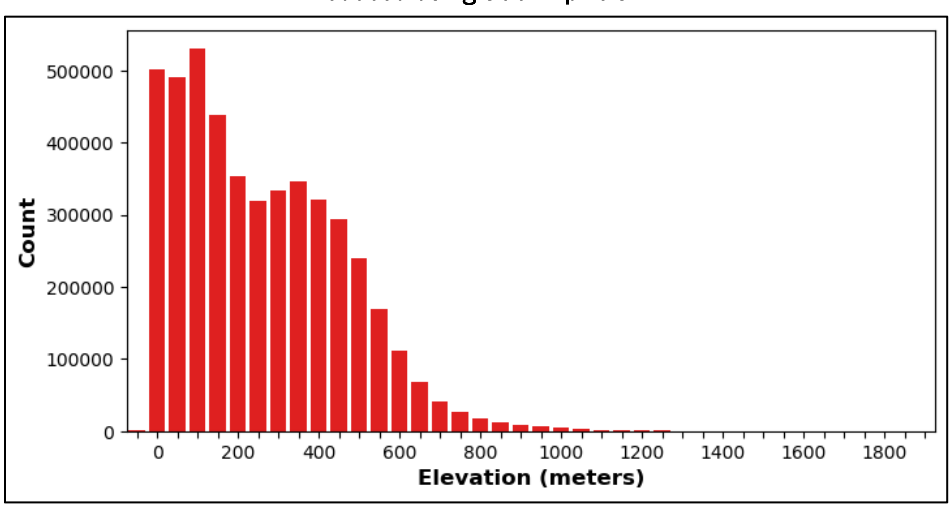


Figure 32. Distribution of snow observation sites by elevation, categorized by periodicity of measurement.

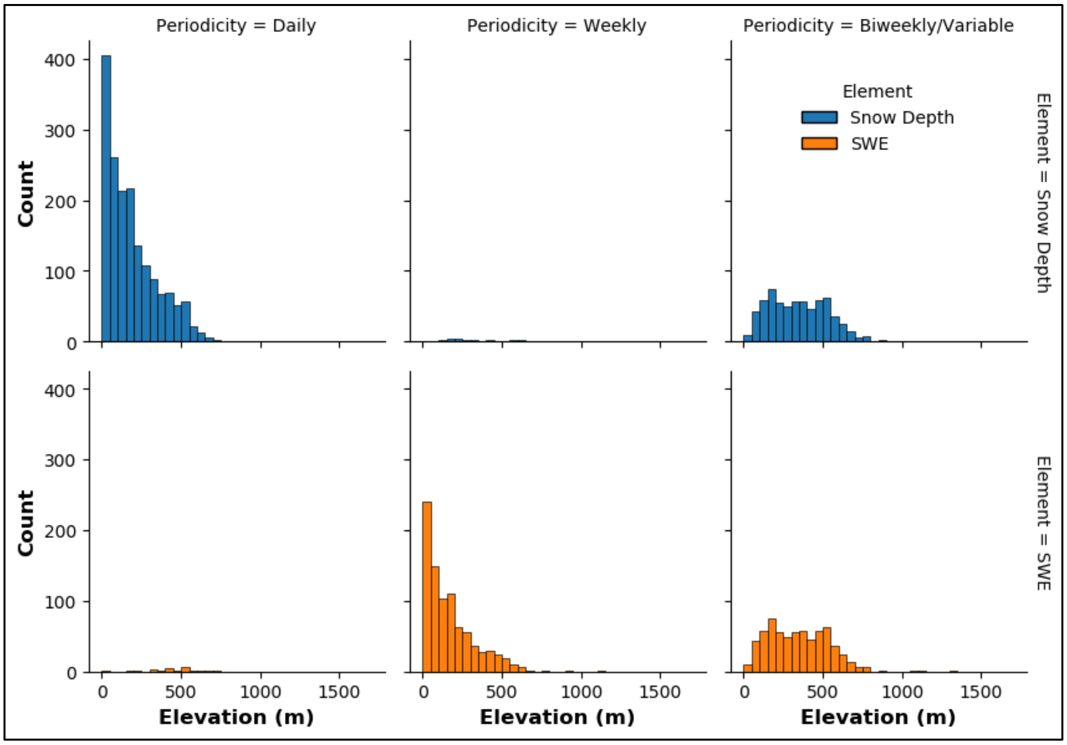


Figure 33. Distribution of snow observation sites by elevation, categorized by network.

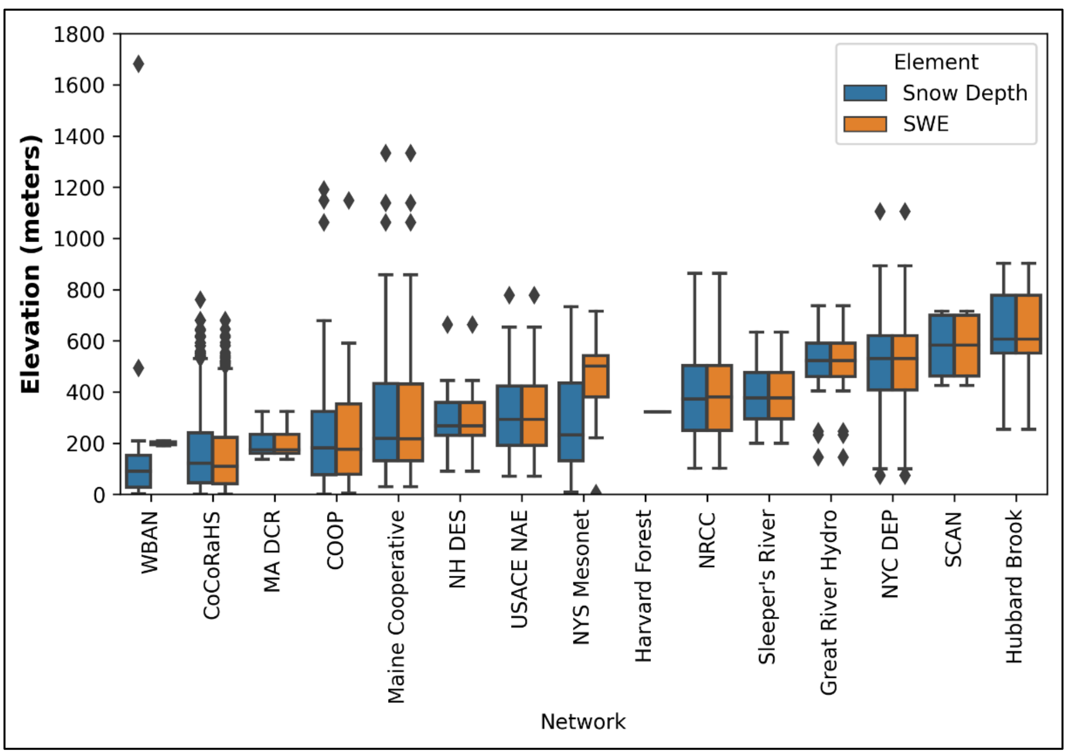


Figure 34. Elevation distributions of daily snow measurement sites categorized by network name.

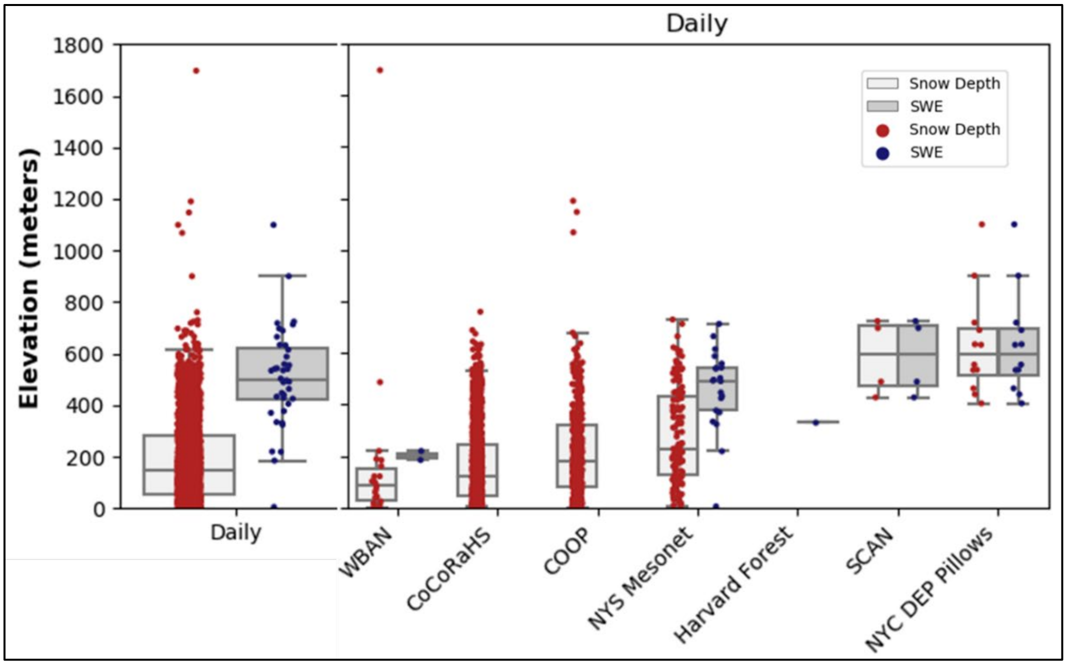


Figure 35. Elevation distributions of weekly snow measurement sites categorized by network name.

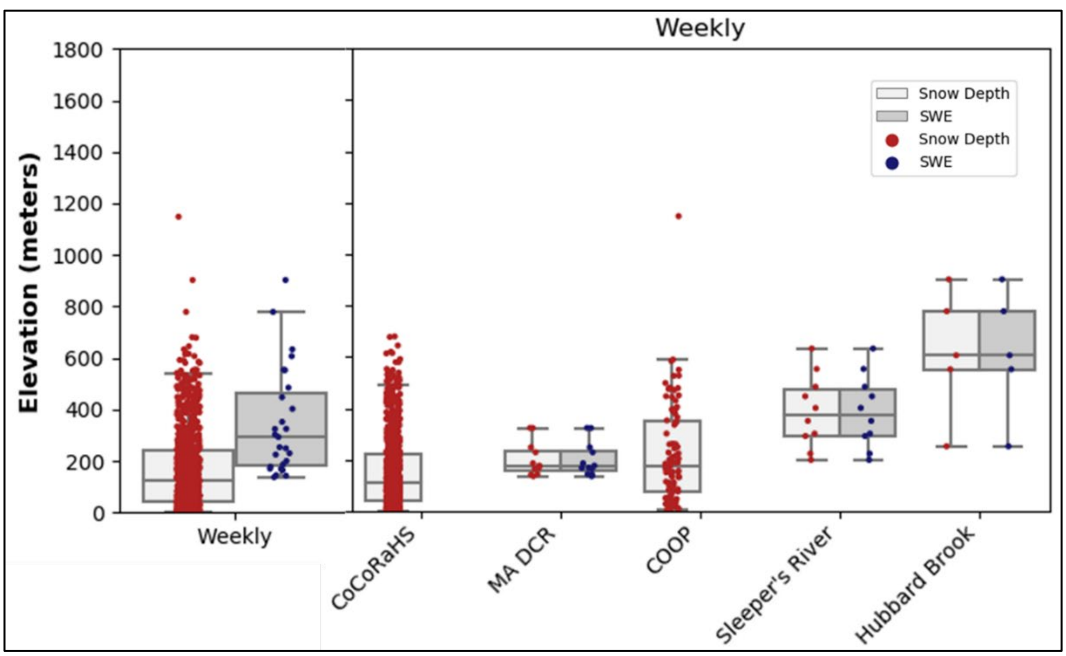
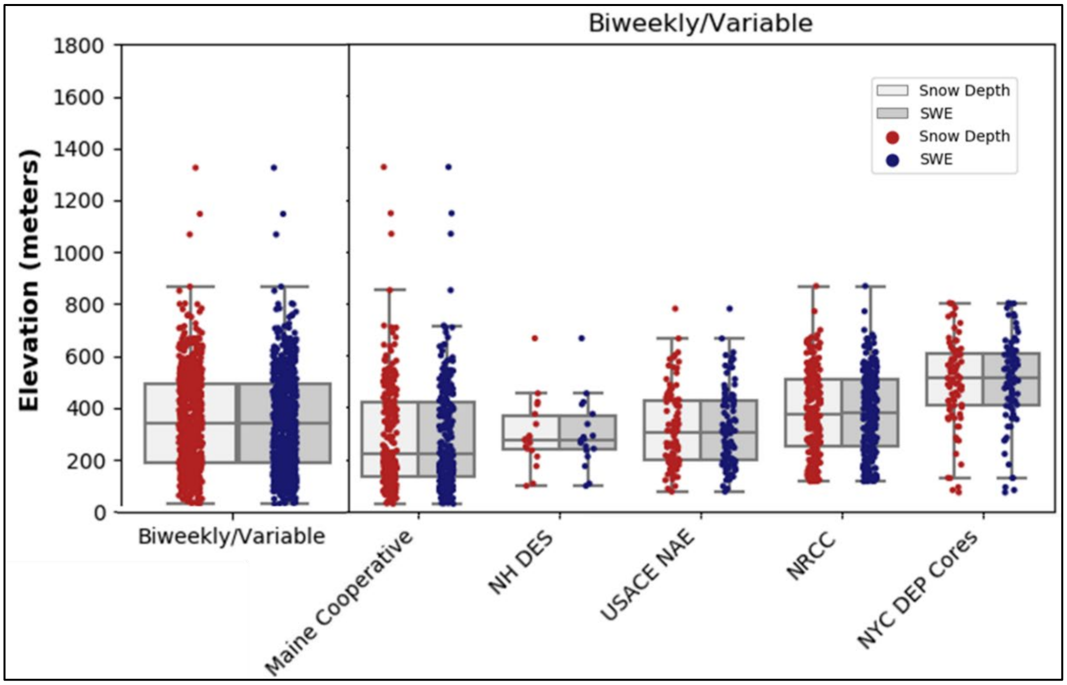


Figure 36. Elevation distributions of biweekly or variable snow measurement sites categorized by network name.



5 Conclusions

There are over 2,200 active or recently active sites where SWE or snow-depth data, or both, are collected in the Northeast. Snow measurements are collected by a broad variety of individuals and groups with varying levels of experience and motivation. The oldest records, which date back well over 100 years, are from snow-depth measurements collected at COOP sites and in Maine around dam projects (now cataloged by the Maine Cooperative Snow Survey). The NRCC records include several active snow course sites with over 80 years of record. The number of active sites included in the NRCC records has been gradually growing over the past century, punctuated by step increases as government agencies interested in water management established formal snow course programs (e.g., USACE, NH DES, MA DCR, and NYC DEP). Furthermore, the development of automated sensors has allowed for a recent increase in valuable daily or subdaily SWE measurements (e.g., NYS Mesonet, NRCS SCAN, and NYC DEP snow pillows); however, their spatial coverage is biased to New York with the exception of SCAN sites, which cover four locations in Vermont and New Hampshire.

The citizen-science-driven CoCoRaHS network has caused a dramatic increase of new sites collecting snow-depth and SWE records, starting around 2006. There are more than 1,200 CoCoRaHS observation locations in our study area that have records ending in 2017 or later. While the CoCoRaHS network provides large quantities of data, it also lacks data continuity. Each observation location is maintained by a single volunteer and is not usually continued when that volunteer stops providing data. However, the spatial density of this dataset is likely to be valuable in filling in the voids present in professionally measured snow data coverage across the Northeast.

Several research areas in the region collect snow data over a small spatial extent but often in coordination with other meteorological or environmental sensors (Harvard Forest, Sleepers River, and Hubbard Brook). Sleepers River and Hubbard Brook both have collection sites with over 40 years of record.

The spatial distribution of the sites varies by state and network. New York has the greatest number of locations where snow measurements are taken, while Rhode Island has the fewest. In general, the total number of sites is proportional to the geographic size of the state and the state population.

Across the entire region, there is on average one station measuring snow depth and one measuring SWE for every 112 and 178 km^2 of land area, respectively. Rhode Island, Connecticut, and Massachusetts are small but densely populated states that have one snow-depth station per 54 km^2 and one SWE station per 69 km^2. For other states in the study region, the density of snow observation sites tracks with population density. For example, snow depth and SWE measurements in New York are 116 and 190 km^2, respectively, with New Hampshire at 125 and 203 km^2, Vermont at 137 and 244 km^2, and Maine at 180 and 240 km^2.

Sites are distributed across the entire range of elevations in the region. Much of the data are biased towards lower elevations where people live and work. The vast number of CoCoRaHS sites, typically collected at people's homes, contributes to that bias. Agencies collecting snow data for water management purposes tend to collect data at higher elevations. There is an underrepresentation of snow data for areas in the elevation band between approximately 300 and 600 m.

There are a variety of snow-depth and SWE data available in the Northeast that could be useful in future studies related to snowmelt, flood prediction, climate change, and economic impacts of changes in snow accumulation and melt patterns. In this review, we sought to identify and summarize metadata for the various sources of snow data in the region. While the data contained in the GHCN are well known and widely used, we describe a number of additional datasets to consider when conducting snow-related analyses in the Northeast. The datasets have varying POR, measurement methods, periodicity (temporal scale), and spatial density (spatial scale).

Additional work will be necessary to analyze the quality of the time series data and to perform quality control processes. Some next steps include

- a full review of ground station time series data to identify gaps and other issues in the records,
- identifying nearby meteorological stations that can provide supplementary temperature and other time series data, and
- identifying and reviewing snow data from bordering provinces of Canada.

Most snow data are collected for water supply, flood forecasting, and road and driving conditions. The networks with long historical records are used primarily for water management activities and extend to the higher elevations. While water management and public safety are often the motivating reason for collecting snow data, many other economic and ecological activities utilize this information. The value of snow data is apparent by the dramatic increase in collection sites that have been initiated during the last decade. Our summary of ground-based snow sites in the Northeast is the first such effort in the region. It provides a single reference for currently available information used by water managers, researchers, and the public for a variety of activities in the region. By referring to our summary, future studies and analyses can spend less time gathering potential data sources while also maximizing the use of available snow data.

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Appendix A: Dataset Auditing

A.1 GHCN

The Global Historical Climate Network (GHCN) daily record is database of daily temperature, precipitation, and snow records maintained by NOAA's National Centers for Environmental Information (NCEI). In the study area, the GHCN contains more than 1,500 observation locations of mixed measurement type, record length, and measurement frequency. Inspection of the GHCN found many records that

- consisted of single or a few unconnected measurements,
- contained large data gaps, or
- reported zero values that did not match other records in area.

For these reasons, we audited the GHCN records by

- plotting the daily snow-depth and SWE data for the period of record (POR),
- visually inspecting the POR plots for discrepancy from the site metadata, and
- updating the metadata to better represent the available daily data.

Records were edited in the following circumstances:

- The start year in the metadata record did not match the actual start of data collection.
- The plot showed a data gap of greater than 50% of the total POR.
- The end year in the metadata record did not match the actual end year of data collection.

We considered some years unusable and removed them from the study in the following cases:

- The record contained two or fewer actual measurements.
- The reported values were zero, which was inconsistent with the surrounding data.
- The actual data collection stopped prior to 2018.

We found some records with a long POR (greater than 50 years) that had large data gaps. To keep from losing potentially valuable records, the POR was assumed to start at the initial collection point and end at the final collection year. Table A-1 lists these stations.

Table A-1. GHCN records with long PORs that also contain large data gaps.

ID	Name	Element	Start Year	End Year	POR	State	Source
USC00174927	MADISON	Snow Depth	1893	2020	128	ME	Coop
USC00303087	FULTON	Snow Depth	1900	2021	13	NY	Coop
USC00309389	WHITEHALL	Snow Depth	1932	2021	17	NY	Coop
USC00301152	CANANDAIGUA 3 S	Snow Depth	1942	2021	12	NY	Coop
USC00305673	CATTARAUGUS	Snow Depth	1948	2021	6	NY	Coop
USC00306867	PULASKI	Snow Depth	1948	2021	8	NY	Coop
USW00094790	WATERTOWN INTL AP	Snow Depth	1949	2019	2	NY	WBAN
USC00302169	DOWNSVILLE DAM	Snow Depth	1959	2021	13	NY	Coop

A.2 NRCC

The Northeast Regional Climate Center (NRCC) at Cornell University maintains snow survey records and maps for New York. Jessica Spaccio at NRCC provided a list of key partner organizations and their sampling methods (pers. comm., 27 August 2021). One of these organizations is the New York City Department of Environmental Protection (NYC DEP), which summarizes their snow-core and snow-pillow surveys by watershed. Each watershed contains multiple survey points that are averaged into a single point for the NRCC network. Since data from the individual NYC DEP sites were included in the report separately, we did not include the averaged sites from the NRCC record (Table A-2).

Table A-2. NRCC observation points removed from the study.

ID	Name	First Year of Record	Last Year of Record	Reason for Removal
86K	CROTON WATERSHED	2000	2021	Summary of NYC DEP
72L	EAST BRANCH DELAWARE	2000	2021	Summary of NYC DEP
84K	ESOPUS WATERSHED	2000	2021	Summary of NYC DEP
71L	NEVERSINK WATERSHED	2000	2021	Summary of NYC DEP
85K	RONDOUT WATERSHED	2000	2021	Summary of NYC DEP
95J	SCHOHARIE WATERSHED	2000	2021	Summary of NYC DEP
73L	WEST BRANCH DELAWARE	2000	2021	Summary of NYC DEP

The NRCC has also recently begun collecting data from a small number of sites in Vermont that matched the criteria of this study. These sites were not included in the study because they

- were individual snow course sites at Sleepers River, Vermont (duplicates of this dataset), or
- were part of an undocumented study in the Green Mountain National Forest, Vermont.

Acronyms and Abbreviations

CoCoRaHS	Community Collaborative Rain, Hail, and Snow
COOP	Cooperative Observer Program
DEM	Digital Elevation Model
GHCN	Global Historical Climate Network
MA DCR	Massachusetts Department of Conservation and Recreation
METAR	Meteorological Terminal Aviation Routine Weather Report
NA	Not Applicable
NCEI	National Centers for Environmental Information
NED	National Elevation Dataset
NH DES	New Hampshire Department of Environmental Services
NRCC	Northeast Regional Climate Center
NRCS	Natural Resource Conservation Service
NWS	National Weather Service
NYC DEP	New York City Department of Environmental Protection
NYS	New York State
POR	Period of Record
SCAN	Soil Climate Analysis Network
SNOTEL	Snowpack Telemetry
SWE	Snow Water Equivalent
USACE	U.S. Army Corps of Engineers
USACE LRB	USACE Buffalo District
USACE NAB	USACE Baltimore District
USACE NAE	USACE New England District
WBAN	Weather Bureau Army Navy

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14. ABSTRACT
Snow is an important resource for both communities and ecosystems of the Northeastern United States. Both flood risk management and water supply forecasts for major municipalities, including New York City, depend on the collection of snowpack information. Therefore, the purpose of this study is to summarize all of the snowpack data from ground-based networks currently available in the Northeast. The collection of snow-depth and snow water equivalent information extends back several decades, and there are over 2,200 active sites across the region. Sites are distributed across the entire range of elevations in the region. The number of locations collecting snow information has increased substantially in the last 20 years, primarily from the expansion of the CoCoRaHS (Community Collaborative Rain, Hail, and Snow) network. Our summary of regional snow measurement locations provides a foundation for future studies and analysis, including a template for other regions of the United States.

15. SUBJECT TERMS
Hydrology, New England, Northeastern States, Snow, Snow Depth, Snow--Measurement, Snowmelt, Snowpack, Snow Water Equivalent, SWE

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