Snowpack to Streamflow:
Understanding how Snow Water Equivalent and Runoff are Changing in the Lake Superior Basin

By:

Patricia “Trece” Bye

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Environment and Sustainability at the University of Michigan

April 2025

Thesis Committee:

Andrew D Gronewold, Chair

Ayumi Fujisaki-Manome

Jamie L Ward, mentor

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Glossary of Terms

CGLRRM.................................... Coordinated Great Lake Regulation and Routing Model
CNBS ....Component Net Basin Supply
CSV..Comma-separated value
GCM ....General Circulation Models
GLERL...Great Lakes Environmental Research Laboratory
Great Lakes ....Laurentian Great Lakes
Lake Superior...Lake Superior of the Laurentian Great Lakes
LBRM ....Large Basin Runoff Model created by NOAA GLERL
NBS... Net Basin Supply
NCEI ....National Centers for Environmental Information
NOAA .... National Oceanic and Atmospheric Administration
R...R programming language
RNBS .... Residual Net Basin Supply
Runoff .... Basin Runoff
SWE ....Snow Water Equivalent
US .... United States of America
USACE ....United States Army Corps of Engineers

Abstract

The Laurentian Great Lakes (hereafter the Great Lakes) comprise the world's largest surface freshwater system. Over the past two decades, water levels in the Great Lakes have fluctuated drastically, reaching both record highs and lows. Accurate water level forecasting is critical due to the extensive ecosystem and millions of US and Canadian citizens that rely on this valuable resource. One of the most dominant variables for water supply in any freshwater system is surface runoff, which is directly impacted by precipitation amount, type, magnitude, and timing across the system's land surfaces. Lake Superior, the most upstream of the Great Lakes, receives the greatest amount of seasonal snowfall annually out of all the great Lakes. This snowfall affects both the timing and quantity of runoff into the Great Lakes system and impacts the water supply of the Great Lakes. In this study, I analyzed the patterns of snow water equivalent and its effect on surface runoff in the Lake Superior basin. My results indicate important changes in snow water equivalent and runoff patterns over time. Specifically, I found that, as of 1971, maximum seasonal snow water equivalent is occurring on average 12 days earlier in the spring season. I also found that maximum seasonal runoff is occurring earlier; however, the change in the timing of peak runoff occurred in 1983 and is found to now be on average 11 days earlier than it was before 1983. By advancing an understanding of these relationships and ensuring they are reflected in state-of-the-art modeling systems, I provided critical information for improving the skill of water level forecasts and preparing water managers and communities for future hydrologic changes, including those associated with climate change.

Introduction

The Laurentian Great Lakes (hereafter the Great Lakes) are the largest surface freshwater system in the world, holding roughly 20% of the earth's surface liquid freshwater (Gronewold et al., 2013; Hunter et al., 2015). Located in North America, the lakes act as a natural border between the United States and Canada (Méthot et al., 2015). The environmental climate of the Great Lakes is variable and unstable (Lofgren et al., 2002). Depending on the types of models used (and assumptions encoded within those models) to project future conditions under climate scenarios, water management practitioners (including those who run operational models) may find themselves evaluating a correspondingly largely divergent range of future water supply and water level scenarios. Operational water level forecasting for the Great Lakes typically provides guidance of upcoming conditions at shorter-time scale than climate time scale (e.g., from a few days, weeks, seasonal to annual). In other words, the forecast horizon for Great Lakes operational water supply modeling systems is relatively short (compared to the horizons practitioners usually consider when trying to account for climate change).

One conventional approach (which is employed in the Great Lakes operational forecasting systems) to approximate the water supply of any lake system is through calculating its net basin supply, or NBS which is typically defined as the sum of over-lake precipitation, runoff, lake evaporation (Fry et al., 2014; A. D. Gronewold & Rood, 2019; Kayastha et al., 2022). This formulation of NBS is often called component NBS (CNBS). However, in practice, especially on the Great Lakes, over-lake precipitation and evaporation are hard to accurately measure. Therefore, Great Lakes (and other large lake) water level forecasters will use residual NBS (RNBS) to forecast and monitor water supply (Gronewold et al., 2016; Gronewold & Rood, 2019). Residual NBS does not require knowledge of a lake's precipitation, evaporation, or runoff amounts, and calculates the change in water supply by measuring inflow to the lake, outflow of the lake and the overall water level change. For the Great Lakes specifically, these residual values are then used in the Coordinated Great Lakes Regulation and Routing Model (CGLRRM) to forecast water levels across the Great Lakes (Fry et al., 2020; Lofgren & Rouhana, 2016). While RNBS should equal CNBS in theory, uncertainty in individual NBS components drives differences in the final RNBS vs CNBS values. Since accurate NBS values are essential to both water level forecasting skill (based on the approach outlined above) and to understanding future changes in Great Lakes water levels, the individual components of NBS should also be well understood.

Due to the size of the Great Lakes basin and lakes (as seen in Figure 1), runoff, over-lake precipitation, and evaporation are each significant portions of the water balance (GLISA, 2021). This is unique for most freshwater systems around the world, in which precipitation and evaporation from the water surface are usually far less than the total amount of water entering through surface runoff.

Figure 1. Great Lakes (blue) and the basin boundary (green). Source: US Army Corps of Engineers, Detroit District.

Evaporation across Lake Superior typically peaks in the winter months, when water temperatures are much greater than the air temperatures directly above (Figure 2).

Precipitation across Lake Superior is generally uniform (especially when compared to other global freshwater systems) throughout the year, with a dip in the late winter months as seen in Figure 3 (GLISA, 2021). Runoff (especially into Lake Superior) peaks in the snowmelt season, which has historically occurred during spring months as seen in Figure 4.

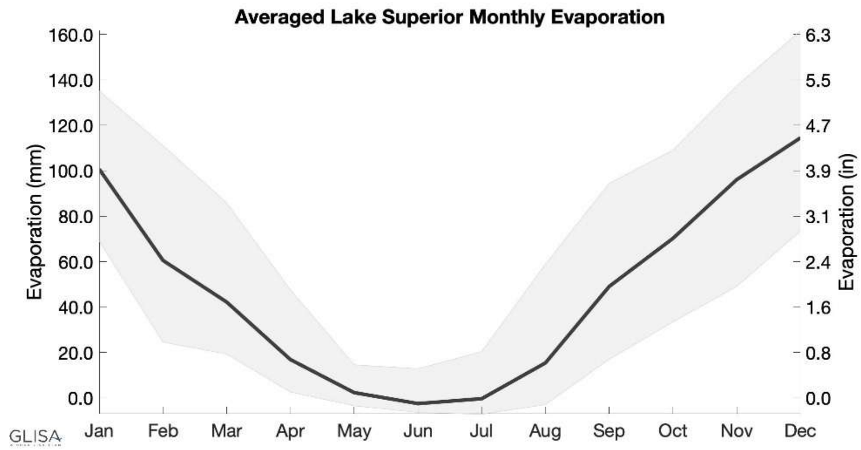

Figure 2. Monthly averaged lake evaporation for Lake Superior from 1940-2019. The grey band represents the range of historical monthly evaporation values while the black line is the long-term average. Graph obtained from the Great Lakes Integrated Science and Assessment Center (GLISA, 2021)

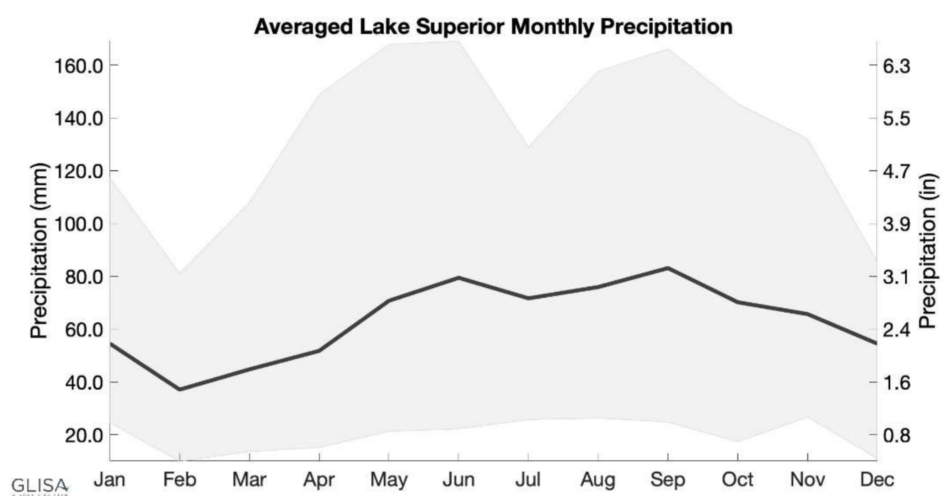

Figure 3. Monthly averaged over-lake precipitation for Lake Superior from 1940-2019. The grey band represents the range of historical monthly precipitation values while the black line is the long-term average. Graph obtained from the Great Lakes Integrated Science and Assessment Center (GLISA, 2021)

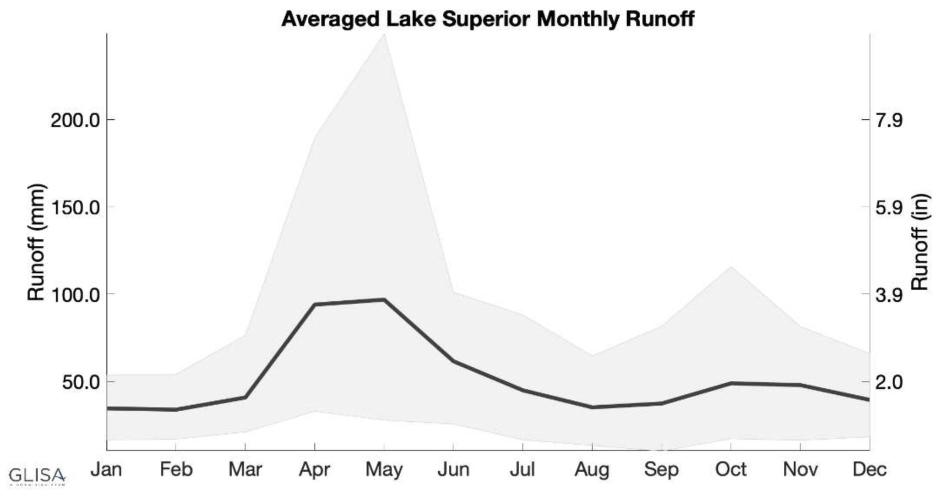

Figure 4. Monthly averaged runoff for Lake Superior basin from 1918-2019. The grey band represents the range of historical monthly runoff values while the black line is the long-term average. Graph obtained from the Great Lakes Integrated Science and Assessment Center (GLISA, 2025)

According to some studies, annual snowfall has decreased over the leeward side of the northern-most Great Lakes (i.e. Lakes Superior and Michigan-Huron) while total precipitation has also decreased in these areas (Baijnath-Rodino et al., 2018). However, other studies have shown increases in precipitation over time, especially over the past 5 to 10 years (Gronewold et al., 2013, 2016; Hunter et al., 2015). It is unclear, however, how trends in precipitation and snowfall, snow accumulation, and snowmelt collectively have propagated, and may propagate (respectively) into historical and potential future changes in the hydrological cycle. This gap in data and knowledge decreases forecastability and water management practices in the Great Lakes. Specifically, the key questions at the heart of this problem that, to date, have been unanswered, are (1) how has the timing and magnitude of snow water equivalent and runoff changed (if at all) in the past 60 years? And (2) to what extent are Great Lakes forecasting systems accounting for these changes (in historical simulations and forecasts)?

To address this knowledge gap and answer these questions, my thesis first compiles the current literature on historical estimates and forecasts of Great Lakes precipitation and runoff. It then introduces new research that analyzes snow and runoff relationships in the Lake Superior watershed using a combination of current regional modeling and novel statistical analysis tools.

Literature Review

Executive Summary

My review of the literature reveals a gap of research in Great Lakes snow to streamflow relationships. Overall, while it is established that runoff is significantly influenced by snowmelt (e.g., Deacu et al., 2012), the intricate and more subtle patterns and relationships that would inform seasonal and multi-decadal water supply forecasting are not fully developed in the literature. In addition, my literature review underscores the importance of understanding the influences of human activity and environmental processes on the water cycle of the Great Lakes, and how it is critical in regional decision making and forecasting.

Great Lakes Background

The Great Lakes are the largest surface freshwater system in the world (Gronewold et al., 2013, 2016; Hunter et al., 2015), containing roughly 20% of the Earth's unfrozen surface freshwater. The Great Lakes basin acts as a natural boundary, encompassing roughly 770,000 square kilometers; approximately one-third one-of that area comprises the surface water of the Lakes (Croley, 1990; Gronewold & Rood, 2019; Holman et al., 2012). This massive lake system encompasses two countries, including eight states in the United States of America, two Canadian provinces, and numerous tribal and sovereign nations. The Great Lakes are commonly defined as Lakes Superior, Michigan, Huron, Erie, and Ontario, and the large channels (rivers) that connect them. However, due to the size of the Straits of Mackinac that separate Lakes Michigan and Huron, those two lakes are hydrologically considered one lake and are collectively referred to as Lake Michigan-Huron. In addition, Lake St. Clair lies between the St. Clair River and the Detroit River, and is often considered one of the Great Lakes, particularly in water management and forecasting initiative.

Managing Great Lakes' water supply and ecosystem health has put strain on many communities and organizations (Hall, 2006). More than 35 million people reside in the Great Lakes region, and this number continues to grow (Méthot et al., 2015). Tensions continue to rise around water quality issues and water quantity extremes, along with social issues such as economics, rights, and policy (Powers, 2023). These tensions lead to discussions about what the future of the Great Lakes, both politically and environmentally, will look like (Gronewold et al., 2024).

Politically and economically, the Great Lakes are a hub for manufacturing, international trade, shipping, agriculture, and innovative research and development (Hall, 2006). The lakes also attract tourists, and are used for recreational activities such as boating, hunting, and fishing, as well as other economic, social, and cultural activities (Hall, 2006). The Great Lakes are primarily governed by the Great Lakes Compact (Great Lakes - St. Lawrence River Basin Water Resources Compact, 2008), which is an agreement between the states and provinces that contain a portion of the Great Lakes basin (Gronewold et al., 2024). While many positive outcomes have resulted from the implementation of the Great Lakes Compact, society and climate are changing rapidly and threaten the continued efficacy of the agreement (Powers, 2023). Understanding the impacts of climate change is critical to the continued health and growth of the Great Lakes and the surrounding communities.

Future climate projections for the Great Lakes region are highly variable (Lofgren et al., 2002; Xue et al., 2022). Climate scientists have attempted to model long-term trends in climate and lake conditions. Projections depend on the type of model used, how it represents specific climate processes and interactions over various spatial scales, and how model output is pre- and post-processed to conduct analyses. As a result of these factors, Great Lakes' water level and climate projections remain uncertain (Lofgren et al., 2002). One statistical framework on a regional model demonstrated that an increase in long-term water levels is likely to occur for the Great Lakes (Kayastha et al., 2022; VanDeWeghe et al., 2022). However, a long-term decrease is also a possibility using coupled Global

Circulation Models and Regional Climate Models (Croley, 1990; Seglenieks & Temgoua, 2022).

Over-lake precipitation, over-lake evaporation, and basin-wide runoff are the three primary components that contribute water level supply and variation in the Great Lakes. Contributions of both precipitation and runoff increase the water supply while evaporation reduces the water supply (Deacu et al., 2012). Precipitation, in the context of the Great Lakes net basin supply (NBS), includes liquid precipitation over lake (including melted snow from the lake surface). Evaporation includes water phase change over the lake surface, where positive evaporation results in lake water being transferred to the atmosphere as water vapor. A negative evaporation value can also occur which indicates condensation over the lake surface. Runoff is defined as water that moves to the lake from the drainage basin via lateral streamflow. Runoff results from over-land precipitation, regardless of the water phase, and is enhanced during the spring when snowmelt occurs. In the past few decades, water level fluctuations have increased dramatically (Gronewold et al., 2021; Gronewold & Rood, 2019). Record low water levels were observed in the late 1990's to near 2010 (Gronewold & Stow, 2014), followed immediately by a drastic increase in water levels and subsequent record high levels in 2018-2020 (Kayastha et al., 2022). The timing of the NBS components defines the long-term stabilization of the Great Lakes water levels. A disruption in the magnitude or timing of each component could influence lake long-term levels (Ehsanzadeh et al., 2013).

In light of their importance for understanding and projecting long-term lake levels, studies presenting historical estimates and long-term projects of NBS components show wide variability. Some general circulation models (GCMs) indicate a decrease in basin runoff (Lofgren et al., 2002). However, regional climate model (RCM) ensembles indicate increased future runoff in the Great Lakes region (Kayastha et al., 2022). While this difference is justified by the bias and uncertainties that come with global circulation and regional climate models, it emphasizes the need for further work. In addition, GCMs may not be offering accurate information over the Great Lakes region due to biases the hydrometeorological cycle, and the inability of GCMs to accurately resolve the lakes themselves (Briley et al., 2021; Gronewold et al., 2018; Kayastha et al., 2022)

Runoff in the Great Lakes

Due to the high surface area of the land surface within the Lake Superior basin, runoff contributes a large amount of the water supply (Gronewold & Rood, 2019), especially during the early spring when snowmelt is abundant (Croley, 1990). Snowmelt is especially important for runoff around the upper Great Lakes (i.e., Lake Superior and Lake Michigan-Huron). As snow melts, much of the melted water reaches the lake without having the opportunity to infiltrate the surrounding soil. Snow water equivalent (SWE) is defined as the product between the depth and the bulk density of a given snowpack (Winkler et al., 2021). In other words, it is the amount of water a snowpack contains in a vertical field (Egli et al., 2009; Yao et al., 2018). Studies have evaluated the impact of climate variability on snowfall and precipitation patterns over the Great Lakes basin (Baijnath-Rodino et al., 2018; Suriano et al., 2019), but the connection between snow properties, such as SWE, and runoff patterns in the Great Lakes Basin is not well-established.

Byun et al., (2019) conducted research using a combination of downscaling GCMs and historical reanalysis to better understand how Midwest US streamflow could respond to global climate change by 2080. They found that future peak streamflow could increase by 10-30% in most regional watersheds. At the same time, Byun et al. (2019) projected that winter and spring precipitation would also increase by 30% during the spring months by 2080.

The Great Lakes Runoff Intercomparison Project (GRIP), initiated at the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory, analyzes model performance for simulating runoff in the Great Lakes region (Fry et al., 2014; Mai et al., 2021, 2022). The GRIP initiative, which has now advanced through four phases, found that hydrological models in the Great Lakes region tended to perform better when Snow Water Equivalent (SWE) was incorporated along the way (Mai et al., 2022). Furthermore, GRIP found that SWE's performance differs regionally, with Lake Superior having the best results in the Great Lakes (Mai et al., 2022).

Precipitation and Snow in the Great Lakes Basin

Precipitation patterns are extremely influential to the overall Great Lakes water supply and NBS. Spring runoff is dominantly impacted by regional snowmelt. In order to understand the impact of snow on streamflow and water levels, the SWE metric is used.

Future impacts of snowfall over the Great Lakes basin are widely variable. The SWE data itself has biases that can further exaggerate historical and future simulations. Measuring snow characteristics is difficult, and snow varies drastically across an area, making observations somewhat uncertain (Kochendorfer et al., 2022; Kunkel et al., 2009). Snow data can be variable and SWE measurements were not always calculated. For example, historical SWE estimates are based on the assumption of a 10-to-1 ratio, where every 10 inches of snow measured in a column is assumed to equate to 1 inches of water (Kunkel et al., 2009). However, the ratio can vary (e.g. 12-1 is used for newer and lighter snow), and the assumption becomes a source of uncertainty.

Further, future SWE scenarios vary depending on changes in SWE calculation methods. Using a global climate model, Byun et al., 2019 determined that maximum SWE would decrease 50% over the Great Lakes and would occur about 15 days earlier in the upper Midwest (Byun et al., 2019).

Summary of Literature Gap Analysis and Thesis Rationale

My literature review indicates there is a need for additional historical analysis of SWE and runoff patterns, especially their connection through time. This analysis is needed to advance modeling and forecasting capabilities on the Great Lakes. This study aims to do just that. As the literature reveals, SWE has a direct impact on runoff. It is clear that accurate prediction of SWE and its processes are needed for accurate water level modeling. Great Lakes water level modeling needs additional SWE and runoff analysis (Gronewold et al., 2016; Mai et al., 2022; VanDeWeghe et al., 2022). Here, I provided insight into these SWE-runoff processes that can inform future improvements to operations.

As forecasters are always looking for ways to improve Great Lakes' water level forecasts, snow has become a major consideration to these improvements. Current regional snow forecasts tend to focus on both the timing and quantity of snow properties (fresh snowfall, snowpack, SWE, etc.). In the historical record, however, total snowfall amounts, SWE accumulation, and other related variables are available, but only at daily, monthly, or seasonal temporal resolutions. This study will address missing analysis of historical characteristics including the timing and magnitude of peak SWE and runoff. Understanding these relationships have proven to strengthen water supply management in the Western United States (Heldmyer et al., 2021; Henn et al., 2016; Wrzesien et al., 2019). In applying a similar framework to the Great Lakes, I hope to also improve regional water supply forecasting skill.

SWE is vastly different across the entire Great Lakes basin as is seen in Figure 5. However, it's known that SWE does particularly well in the models if focused solely on Lake Superior (Mai et al., 2022). I used data produced by the Large Basin Runoff Model to examine the temporal and magnitude relationships between SWE and runoff around Lake Superior and uncover how these relationships have changed over the simulated period (see Methodology for more information). In addition, the Great Lakes Runoff Intercomparison Project (Mai et al., 2022) indicates that SWE evaluation for the Large Basin Runoff Model (LBRM) is somewhat limited. However, SWE tends to be more accurate on a larger scale in the LBRM, not focusing on smaller basins but on a larger geographic scale (Shin et al., 2024). It is also important to note that LBRM tends to perform better on longer time scales (i.e., monthly vs daily). Given the goals of understanding specific timing trends of both SWE and runoff, I chose to use daily data while understanding its limitations and biases.

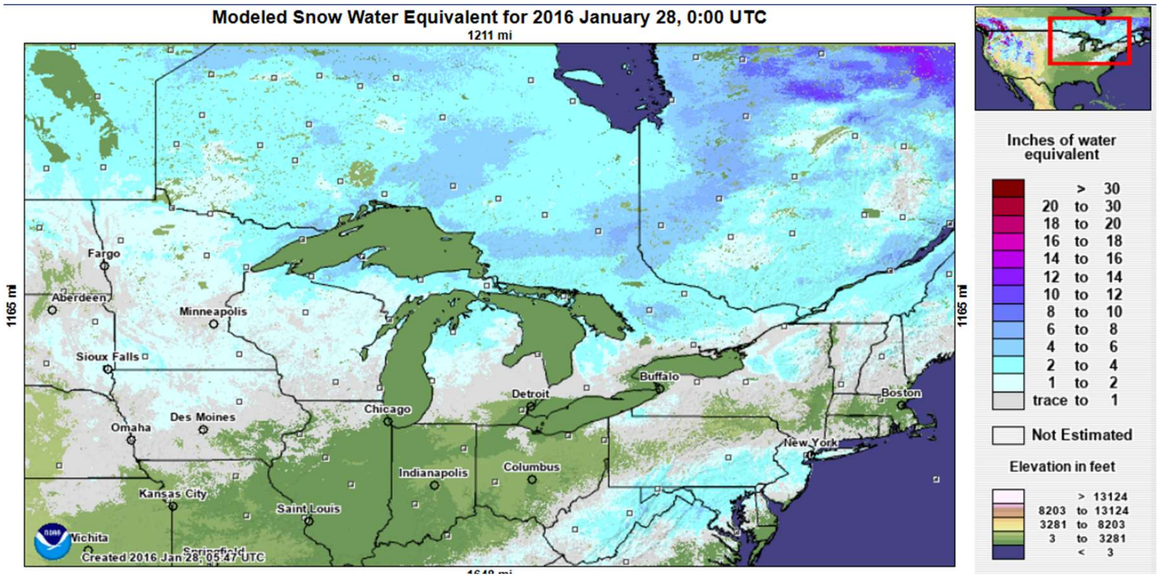

Figure 5 Modeled SWE for January 28, 2016. Darker blues indicate higher values of SWE. Green areas have no measurable snow. Obtained from NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC, 2025)

Methodology and Data Manipulation

Study Area

The geographical domain of this study is the Lake Superior Basin. As was mentioned in the literature review section, Lake Superior is the northernmost lake of the Great Lakes and contains three thousand cubic miles of freshwater, as seen in Figure 6 (*Lake Superior*, n.d.). As the most upstream lake, Lake Superior's outflow propagates through the entire Great Lakes system. A schematic of the depth and size of the lakes is shown in Figure 6 (Gronewold et al., 2013).

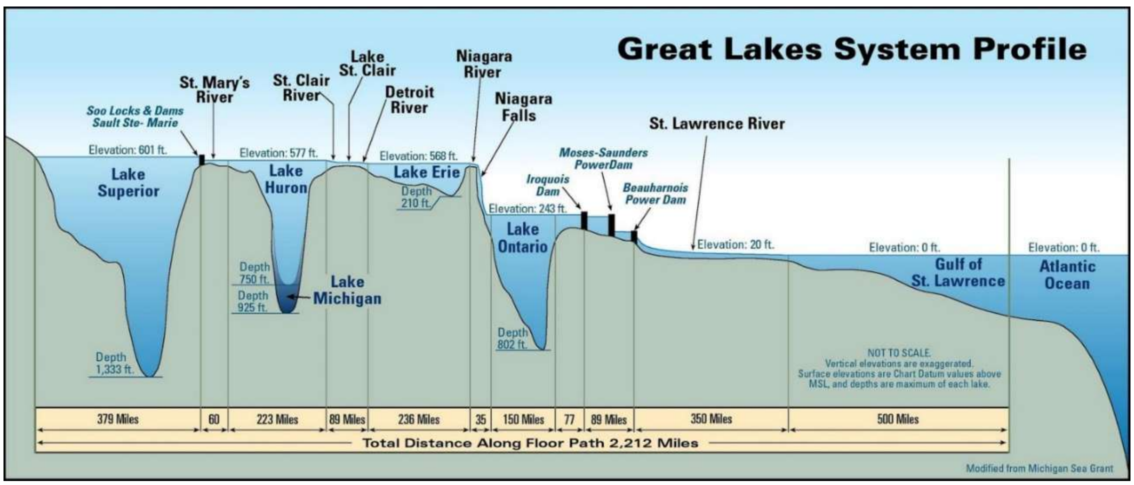

Figure 6. Monthly averaged runoff for Lake Superior basin from 1918-2019. Graph obtained from the Great Lakes Integrated Science and Assessment Center (GLISA, 2021)

On average, Lake Superior's basin receives roughly 929mm, or 36.5in of precipitation per year (Holman et al., 2012). This precipitation, in conjunction with the annual runoff and evaporation, determines the overall water supply for the lake.

Data

Snow Water Equivalent (SWE) and runoff are the two hydrometeorological variables examined in this work. As mentioned in the literature review, SWE is the primary source of basin runoff in the spring during snowmelt. Runoff, in turn, has waterfalling effects on the water supplies of the downstream lakes.

First, SWE is a major indicator of the amount of water on a basin's land surface because it defines the amount of liquid water sitting on the land surface if air could be removed from the snowpack's pore space. Using a standard 10:1 ratio, this would indicate that if there were 10 inches of snow on the ground, it would melt down to one inch of water. While this is a set standard, actual ratios vary significantly based upon atmospheric conditions (Taheri & Mohammadian, 2022). As snow falls, it accumulates and presses the snow beneath it down, decreasing the snow-liquid ratio (i.e., time-varying snow density). For the purposes of this study, the liquid amount of any snow on the ground, not just fresh snow, is considered the SWE and is a direct measurement of how much total liquid water is on the land surface.

The second variable analyzed is basin runoff, or, as called in this study, runoff. Runoff is one primary component of Net Basin Supply (NBS) and has historically peaked during the spring season in the Great Lakes due to snowmelt (Croley, 1990; GLISA, 2021). Runoff occurs throughout the year as a result of surface rainfall, snowmelt, and a combination. The relationship between surface runoff and SWE is examined in this study, to determine if SWE can be a potential indicator of runoff patterns within Lake Superior.

Data within this study are based on historical SWE and runoff values simulated by the region's commonly used land-surface model, the Large Basin Runoff Model (LBRM). The LBRM is a well-established water supply model that has been used in the Great Lakes region for both operational and experimental purposes (Kayastha et al., 2022; Shin et al., 2024). This rainfall-runoff model was developed by the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and has since been used as a component for many other hydrometeorological models, including the Great Lakes Season Hydrological Forecasting System, which is used operationally by the US Army Corps of Engineers (USACE) (Deacu et al., 2012; GLISA, 2021; Gronewold et al., 2016). While the LBRM may not be the most accurate model to explain runoff dynamics in the Great Lakes (Mai et al., 2022; Shin et al., 2024), its operational use is appealing to the study.

The most up-to-date version of LBRM is used in the study. This update incorporates the Clausius-Clapeyron relationship to better capture the surface energy balance (Kayastha et al., 2022). The Clausius-Clapeyron equation describes the relationship between water vapor and air temperature. This equation identifies that as air temperature increases, the capacity to hold water vapor increases exponentially, informing the rate of evapotranspiration over land. Adding the Clausius-Claperyon relationship into LBRM's code is critical for modeling evapotranspiration over the Great Lakes (Lofgren & Rouhana, 2016). For the purposes of this study, the LBRM was calibrated by USACE prior to any runs, and USACE's original parameterizations are used (Shin et al., 2024). LBRM uses daily rainfall, as well as daily maximum and minimum air temperatures as input for each Great Lakes sub-basins as are described in Shin et al. (2024).

After the model is run, the SWE and runoff variables are interpolated using Theissen polygon-based weighting (Shin et al., 2024). This method involves partitioning an area into polygons such that each edge of the polygon is equidistant to the nearest basin data point (Han & Bray, 2006). The meteorological station data used is from the Global Historical Climatology network - daily and is operated by the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI). LBRM's Lake Superior sub-basin map is shown in Figure 7.

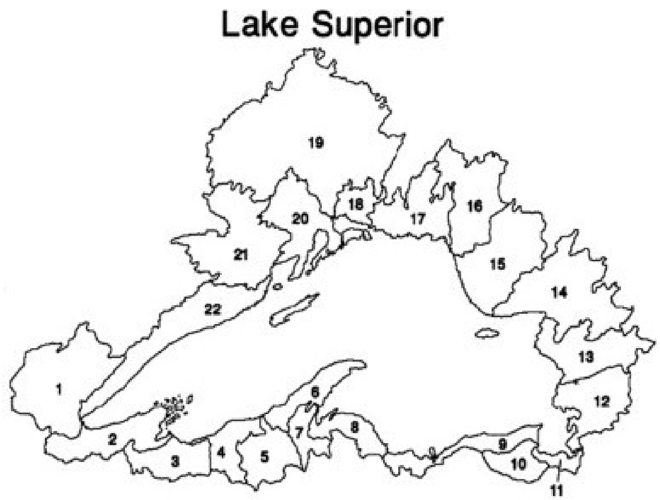

Figure 7. Lake Superior basin from LBRM based on NOAA GLERL historical delineation. Lake Superior includes 22 sub-basins (Hunter et al., 2015).

For this study, simulated LBRM data is acquired from Shin et al. 2024) and includes daily SWE and runoff values from 1960 – 2020. The data was transferred into two separate comma-separated value (CSV) files that contained the SWE and runoff amounts, respectively, for each Lake Superior sub-basin as well as a weighted mean for the entire lake basin.

I used the open-source R programming language and its associated tools and packages to analyze LBRM output and create figures (R Core Team, 2023). Unless otherwise noted, all LBRM data is stored in CSV files.

Data Processing

I calculated weighted averages using Microsoft Excel. The size of each sub-basin is built into the LBRM, and the weighted calculation is completed using these areas. SWE data is read into R using the read.csv function and formatted dates as mm/dd/yyyy.

An established "snow year" is used in this project because the typical January - December calendar year splits the winter season. Given that SWE accumulates and is observed in the winter, it spans over multiple years (i.e., Figure 8). For this study, each snow year starts on July 1 and ends on June 30 of the following year. For consistency, the snow year is referred to as the year it starts in. For example, a winter season of 2018-2019, as seen in Figure 8, would have a snow year of July 1, 2018 to June 30, 2019 and would be referred to as "snow year 2018". The snow year calculator was done in R by appending the month January - June months to the end of the prior July - December months.

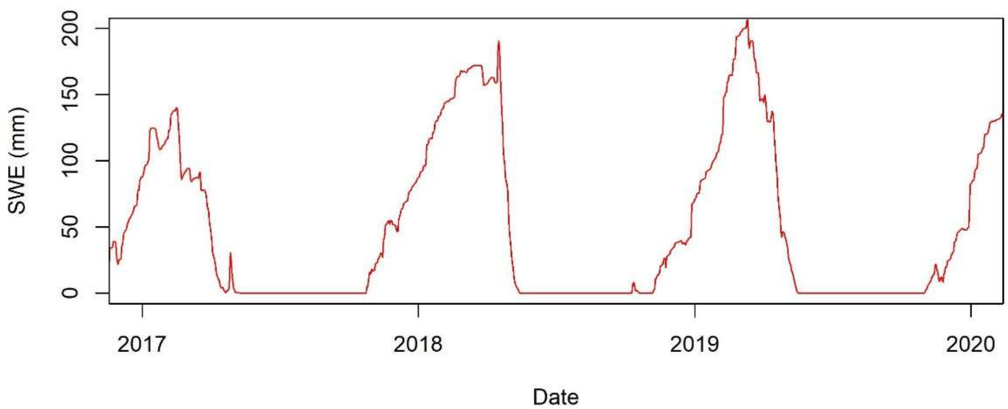

Figure 8. SWE time series for Lake Superior basin-based on LBRM simulated output

Within each snow year, I was most interested in maximum SWE and runoff, along with their corresponding dates. Figure 9 demonstrates the basic relationship between SWE and runoff. To simplify variable comparison, the timing of data is presented as "days since July 1" for each snow year, which was calculated by counting the number of days after July 1 that the maximum SWE or runoff occurs. To simplify the data, a new data frame is created that contains the snow year, date of maximum SWE (or runoff), the days since July 1 and the amount of the SWE (or runoff). This data set then becomes the primary data set for analysis.

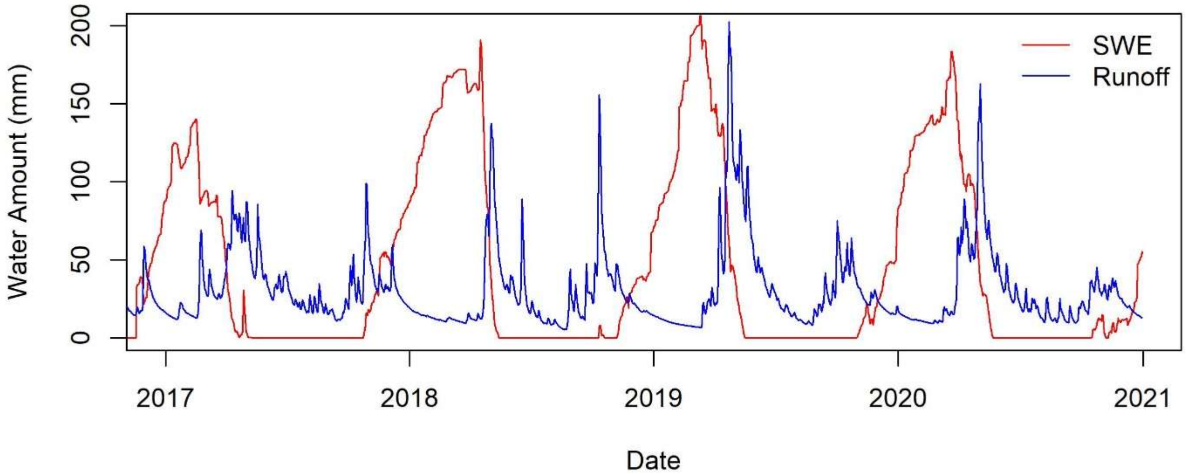

Figure 9. SWE and runoff time series for Lake Superior basin based on LBRM simulated output.

Understanding Snow Water Equivalent Dynamics

Considering the importance of the relationship of Snow Water Equivalent (SWE) on the water supply cycle, I began to answer the question about how Lake Superior basin SWE has changed during the 1960-2020 historical study period. While the information that can be obtained from one singular data set is immense, here, I focused on the timing and magnitude of maximum SWE. The maximum is defined as the sole day that SWE peaks for each snow year. Specifically, I was interested in the date that it occurred and its magnitude at that time. The same maximum metric is the focus for runoff data.

Maximum Snow Water Equivalent Timing

In this section I examined the timing and magnitude trends of Snow Water Equivalent (SWE) during the simulated historical period. By extracting the magnitude and timing of the maximum SWE from the Large Basin Runoff Model (LBRM) data set, I evaluated changes in the historical period.

The snow year, described in the methodology section, is on the x-axis while the days since July 1 are on the y-axis. On plots where the entire historical run is used, snow years 1959-2019 are plotted. Only up to 2019 is plotted as this snow year includes spring 2020, the final year of data. Figure 10 displays historical maximum SWE timing for each snow year as dots. Each dot’s placement indicates its timing relative to July 1, while its color indicates the maximum SWE magnitude. Lighter (darker) colors indicate less (more) SWE on the ground (color bar on the right).

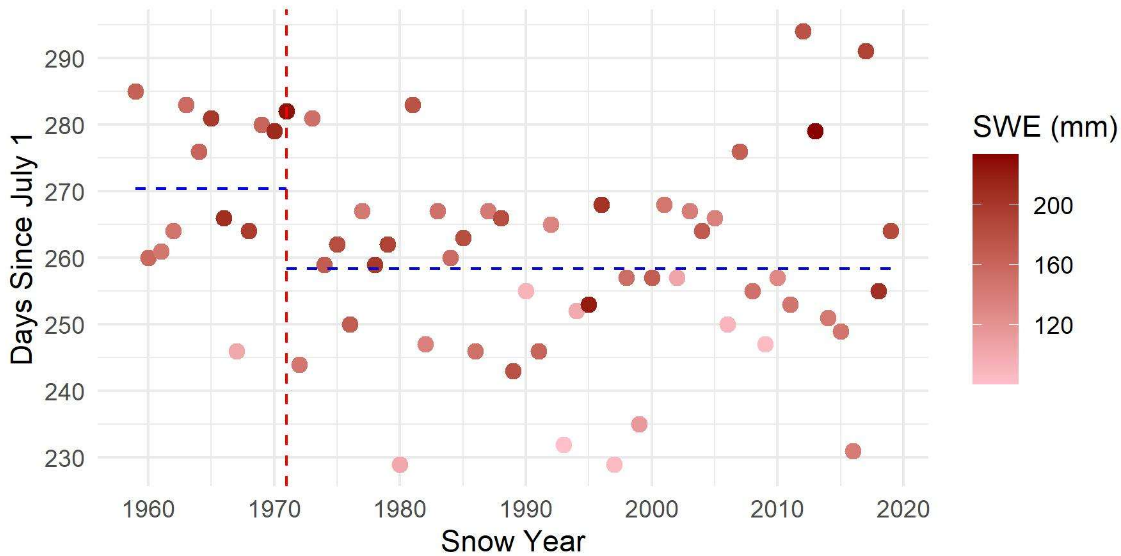

Figure 10. Timing of maximum SWE (days since July 1) and magnitude from LBRM over Lake Superior basin. Shading of each point represents the magnitude of the SWE. A changepoint is labeled at 1971 with the mean SWE timing before and after drawn

I performed a changepoint analysis to the data to better understand how SWE timing and magnitude have changed in the historical record. R's "changepoint" function (Killick & Eckley, 2014) detects changes in the mean of a univariate time series. Specifically, it identifies a point where there is a significant change in the mean values of a data set. I used the binary segmentation method that examines the entire data set and attempts to identify one single changepoint. After finding one changepoint, the process is repeated on each of those segments (Killick & Eckley, 2014). This process continues until no more changepoints are detected in the data set. While multiple change points were found in the SWE dataset, changepoints after the first only occurred within the last 5 years, indicating there may be a regime shift happening in the 2010s. However, for the purposes of this study, only the first and primary changepoint was used. For LBRM SWE, the changepoint was found in 1971 Figure 10. After finding the changepoint, mean SWE was calculated before and after 1971. In Figure 10, the changepoint is shown as a vertical red dashed line, while the means on either side of the changepoint are shown as horizontal blue dashed lines.

I then begin to decipher how maximum SWE timing and magnitude compare before and after the 1971 changepoint. In the earlier regime, the average SWE timing was 270 days since July 1, or March 28. After 1971, the maximum SWE occurs earlier in the winter. Specifically, average maximum SWE occurred 258 days after July 1, or on March 16th. Based on these results, average SWE occurred 12 days earlier after 1971.

From 1971 and onward, there is more variability in both the timing and the magnitude of maximum SWE. The year when the maximum SWE happened later than all the other years was in 2013. This maximum SWE was 294 days since July 1 (April 21). Contrastingly, the earliest maximum SWE occurred in both 1980 and 1997 on February 15, or 229 days since July 1.

In snow years 2012, 2017, and 1963, the maximum SWE occurred late in the season. These also had high SWE magnitudes with amounts ranging from 160mm to 200mm, or 6-8 inches of water. In contrast, the years when the maximum had little water, less than 120mm, occurred earlier in the spring season. Therefore, the timing of the maximum SWE does correlate with its magnitude. Further, the most variation in the maximums occurs within the last five years of the simulated historical period.

SWE Yearly Distribution

While understanding the trends of the maximum SWE values is vital to understanding SWE more generally, I must also understand how the yearly accumulation and melting of snow differentiate between years. Here, I looked at what seasonal SWE distribution looks like for each snow year in the LBRM historical simulation.

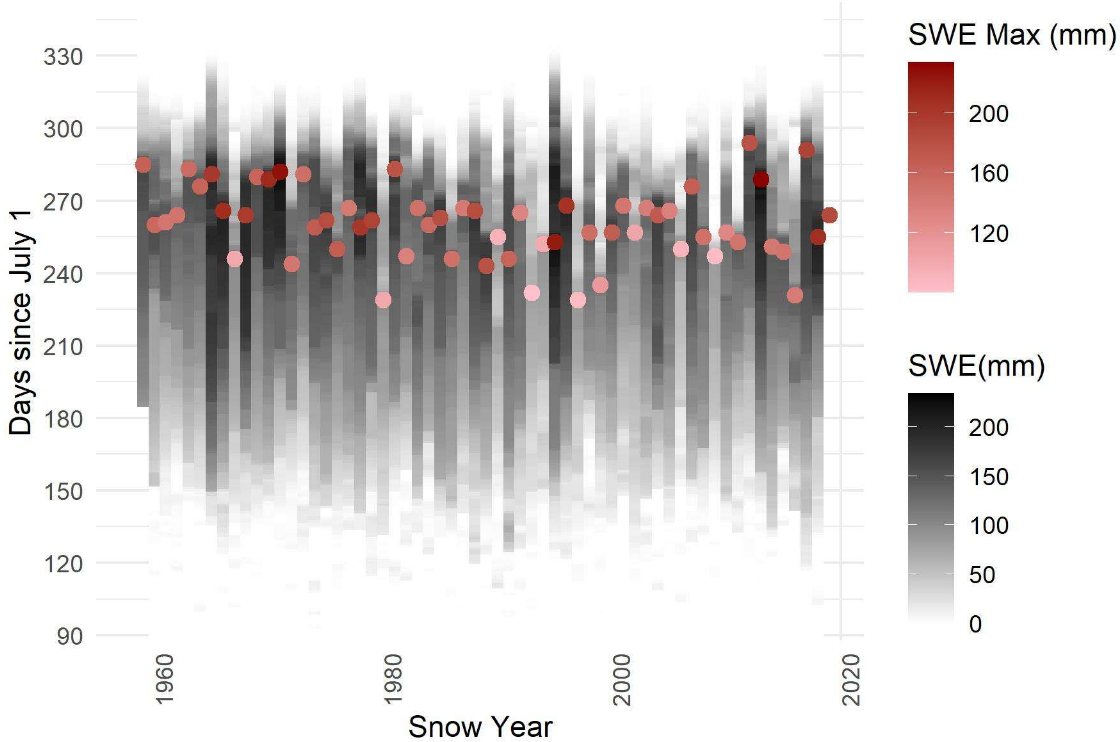

Figure 11. Timing of maximum SWE (days since July 1) and magnitude from LBRM over the Lake Superior basin. Shading of each point represents the magnitude of the SWE. Gray color-bar represents magnitude of yearly SWE distribution for the entire simulated period.

Figure 11 describes the yearly variation in SWE throughout the historical simulation. Each year is represented by a single column in the graph. The gradient represents the amount of SWE each day of the snow year and is referenced to the number of days since July 1. The colored red points placed on top represent the day maximum SWE occurred and are colored in respect to the magnitude of that maximum. The darker the black and white bar, the more SWE.

As shown in Figure 9, snow events and melting events often occur many times during a winter season. This is apparent in years like 1965 and 1979, which correspond to episodic darkening and lightening of the SWE color bar throughout the winter season (Figure 11). An in-depth analysis of this phenomenon will be discussed next.

Unique Years

A variety of LBRM snow years exhibit unique SWE seasonal evolution, especially in terms of maximum SWE and its timing. A few examples include years exhibited sudden snow accumulation or melt (such as years 1997 or 2004), years that had relatively early or late maximum SWE timings, or years where maximum SWE was either extraordinarily high or low. In this section, I highlighted and describe some of these cases.

Individual snow years are plotted to look like data presented in Figure 11, allowing the reader to better discern within-season SWE variation and changes. To further understand the meteorological conditions, data from the NOAA National Center for Atmospheric Research (NCEI) products are used (NOAA NCEI, 2025). Here, winter months include November through March. The regional data encompasses all the Great Lakes basin within United States political boundaries. Since most of the analysis done in this section will be based on comparing the year in question to long-term averages of meteorological conditions, data focused only on the US is sufficient. There is a lack of reliable data that contains accurate and coordinated from the US and Canadian boundaries of the Great Lakes region, which is currently a point of research by numerous international efforts (Hong et al., 2022). For these reasons, meteorological conditions are focused on the US side.

Within the first SWE regime, the 1967 snow year is an outlier. During winter 1967, LBRM simulates earlier SWE onset than all other pre-1971 years (by almost 15 days). In addition, this is also the only snow year in the first regime where the maximum SWE magnitude is less than 140 mm, with the maximum SWE of 110 mm occurring on March 2, 1968.

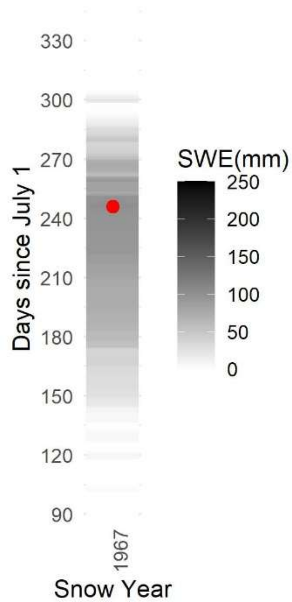

Figure 12. SWE distribution from LBRM for the snow year 1967. Gray color bar spans the entire range of SWE values across all years. The red dot indicates the maximum SWE for the snow year.

For some context on climate at the time, the total precipitation for November – March was 10.07 inches, or about 250mm, which is close to average for the region. The temperature statistics for the year were also average spanning the entire year.

1967 is of particular interest due to the maximum SWE occurring so early in the season (at least for the first regime). Shortly after the maximum SWE, the Great Lakes region experienced a spike in precipitation. However, as temperatures also rose significantly during this time, it is probable that an increase of rain-on-snow events occurred, causing snowmelt. What could have been a later maximum SWE turned into a melting and re-snow event. Rain on snow events trigger an interesting dynamic, because the liquid precipitation melts the snow, but leads to runoff from both snow and rainfall sources (López-Moreno et al., 2021; Wayand et al., 2015). In addition, it is very hard to quantify the rain vs snow contributions during these events (Wayand et al., 2015). However, this relationship is outside the scope of this study.

Snow year 1995 is of particular interest because snowfall was heavy and lasting (i.e., the corresponding SWE bar is dark for most of the snow year). The maximum SWE of 221 mm occurred 253 days after July 1 on March 11th, 1996. This SWE magnitude is the third highest, with only snow years 1971 and 2013 being higher (226mm and 233mm, respectively).

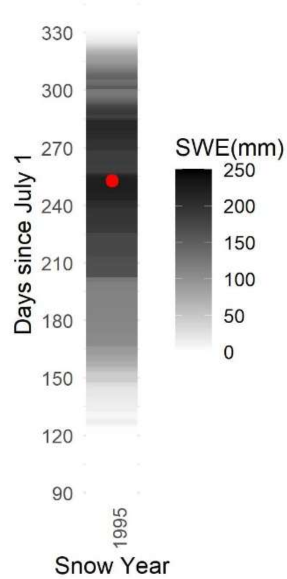

Figure 13. SWE distribution from LBRM for the snow year 1995. Gray color bar spans the entire range of SWE values across all years. The red dot indicates the maximum SWE for the snow year.

Despite enhanced SWE, basin-wide precipitation was close to average, with almost 11 inches, or 280 mm, of precipitation occurring between November 1995 and March 1996. However, it is important to remember that this is a basin-wide average and does not only focus on Lake Superior.

Air temperatures during this snow year were below average, with the average high temperature being below freezing. This air temperature drop is a strong indicator that much more precipitation fell as snow vs rain during the 1995 snow year, directly impacting the snow patterns seen. In addition, SWE distribution for this year does not have many melting points before the maximum SWE occurs, further supporting the hypothesis that air temperature played a large role in the evolution of SWE during the season.

In snow year 1997, I saw sudden melting after the maximum SWE occurs on February 15, 1998 (229 days after July 1, 1997). This contrasts many of the other yearly distributions, as seen in Figure 11, where the snow gradually melts after maximum SWE occurs. Corresponding SWE produced by LBRM is 85mm, which was the third lowest maximum in the study period. Notably, basin precipitation was marginally above average and temperatures during this period were also above freezing for much of the season, especially after January 1998. This temperature and precipitation fit well with the distribution seen as rising temperatures would cause rapid melt after the maximum. Furthermore, these above average temperatures and increased precipitation indicate that winter-time rainfall is at a higher frequency. In addition, a strong El Niño event was occurring during the winter season.

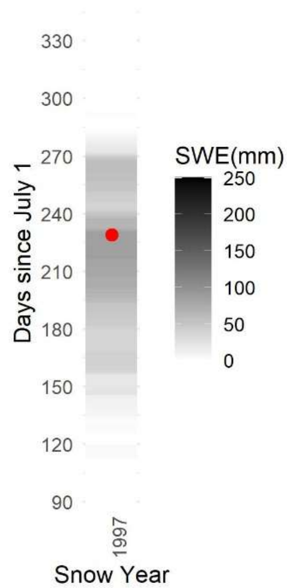

Figure 14. SWE distribution from LBRM for the snow year 1997. Gray color bar spans the entire range of SWE values across all years. The red dot indicates the maximum SWE for the snow year.

Both snow years 2004 and 2006 are of interest not because of when the SWE maximum occurred or what the maximum was, but because of the SWE pattern leading up to the maximum. Both of these years had early snowfalls in the winter season, with measurable SWE and snow on the ground in mid-October.

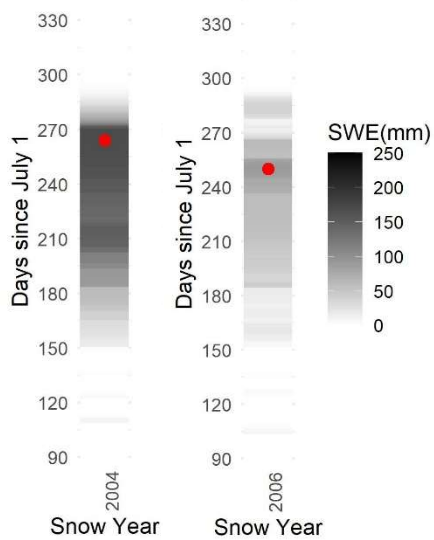

Figure 15. SWE distribution from LBRM for the snow year 2004 and 2006. Gray color bar spans the entire range of SWE values across all years. The red dot indicates the maximum SWE for the snow years.

The air temperatures during these two winters, and especially the early winters, were different. In 2004, they were close to the normal level for October, with highs in the upper 50s degrees Fahrenheit. Snow year 2006 had a slightly lower temperature in October, but within near normal range.

Looking at all winter months (November – March) across the basin, air temperatures for both snow years are normal for the regime after 1971. These temperatures, averaging high 20s degrees Fahrenheit for November through March, are higher than average in comparison to the first regime of the simulation period. That being said, I hypothesized that a single event caused these early snowfalls. In addition, it is likely that these early snowfalls have a large-scale impact on overall SWE patterns, since there is complete melting in the following days.

Snow year 2009 is of particular interest because melting occurred very quickly, and the Lake Superior basin remained almost SWE-free for the rest of the winter. The maximum SWE occurred 247 days after July 1 or March 5, 2010, with a magnitude of 83mm. This makes it the second lowest maximum SWE, with only snow year 1993 smaller. However, in 2009, there was a sudden decrease in SWE, indicating rapid melting that did not occur in 1993.

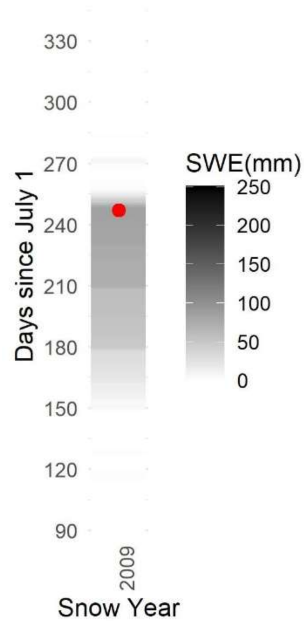

Figure 16. SWE distribution from LBRM for the snow year 2009. Gray color bar spans the entire range of SWE values across all years. The red dot indicates the maximum SWE for the snow year.

Temperatures for snow year 2009 were above average for the second regime in the historical simulation period. There were no abrupt monthly-resolved temperature changes over these months.

However, precipitation was the third lowest from November – March for the period. Very little precipitation occurred between January and March, which matches results shown in Figure 16. Precipitation with warmer temperatures did occur at the end of March and early April, indicating that sudden warming and rain-on-snow could be a major contributor to melting directly after the maximum.

Understanding Runoff Dynamics

Runoff is one of the major components of net basin supply (NBS) (Deacu et al., 2012; Gronewold et al., 2016; Mai et al., 2022). Many studies show how influential runoff is to Lake Superior water supply (Gronewold et al., 2013). However, past studies show that the models are unable to effectively capture the relationship between the two (Mai et al., 2022). To address these unknowns, I completed a historical simulation analysis of the timing and magnitude of maximum runoff to begin the analysis process. As with my SWE analysis, I defined the maximum runoff magnitude as the sole day that runoff peaks for each snow year. From this singular point, I am interested in the date when it occurred and its magnitude at that time. This yearly data is the primary focus for the study. The snow year was applied to the data by the process described in the methodology section.

Unique to the runoff data set, some of the maximum runoff events happened in late fall. Since these events were not directly related to snowmelt, they are removed from the dataset. I did not look at the second highest runoff event in these years to keep the data set uniform.

Maximum Runoff Timing

Similar to what was done for SWE, Figure 17 describes the timing and magnitude of runoff in Lake Superior. A changepoint analysis was once again performed and is represented by a vertical red dashed line while the means on either side are represented by a horizontal blue dashed line.

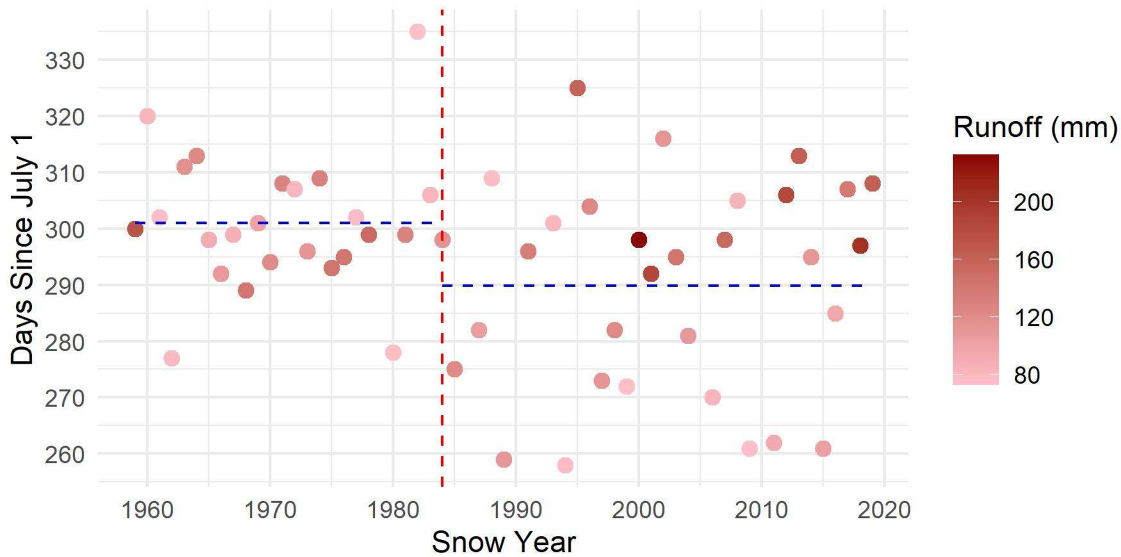

Figure 17. Timing of maximum runoff (days since July 1) and magnitude from LBRM. Shading of each point represents the magnitude of the Runoff. A change point is labeled at 1983 with the mean Runoff timing before and after drawn

The changepoint analysis indicates that a runoff mean-based regime shift occurred in the snow year 1984. The mean runoff time for the 1959-1984 data record is 301 days since July 1, or April 28 of the subsequent year. The mean runoff time for the 1984-2019 snow years is 290 days, or April 17. This means that the average timing of peak runoff is 11 days earlier in the spring season after 1984.

Before the changepoint (snow years 1959-1984), the range of days was 276 days since July 1 (April 3) at the earliest and 340 (June 6th) days at the latest. Both of these are outliers. The majority of maximum runoff dates lie between 288 days and 313 days, exhibiting roughly 25 days of variability. In addition, runoff maximums are lower (contain less water) before the regime shift.

After the 1984 snow year, the timing and amount of runoff becomes more variable. Maximum runoff occurs as late as 325 days since July 1 (May 22) in 1995 and as early as 258 (March 15) in 1994. In comparison to the outliers seen before 1984, these extremes are not outliers after the changepoint. This means that since 1985, maximum runoff timing variability is 68 days, over twice what is seen prior to the runoff regime shift. In addition, the range of magnitudes also increases to include maximum runoff values over 220mm in one monthly average. The range in magnitude before 1984 is 73 mm to 172 mm, or 100 mm. After 1984, the runoff range extends to 179 mm, spanning from 5 mm to 233 mm.

Runoff Yearly Distribution

While understanding that maximums are critical to understanding how runoff is changing historically, understanding how these maximums also fit into the yearly story matter as well. Here, I looked at Large Basin Runoff Model (LBRM) yearly runoff evolution.

Figure 18 displays the historical patterns of maximum runoff timing. Each dot on Figure 18 describes the maximum runoff in a given snow year. The placement on the graph indicates its timing in relation to July first while its color indicates the maximum amount of runoff. Lighter colors indicate less runoff on the ground while darker colors indicate more runoff. The difference between high and low values is a uniform color bar.

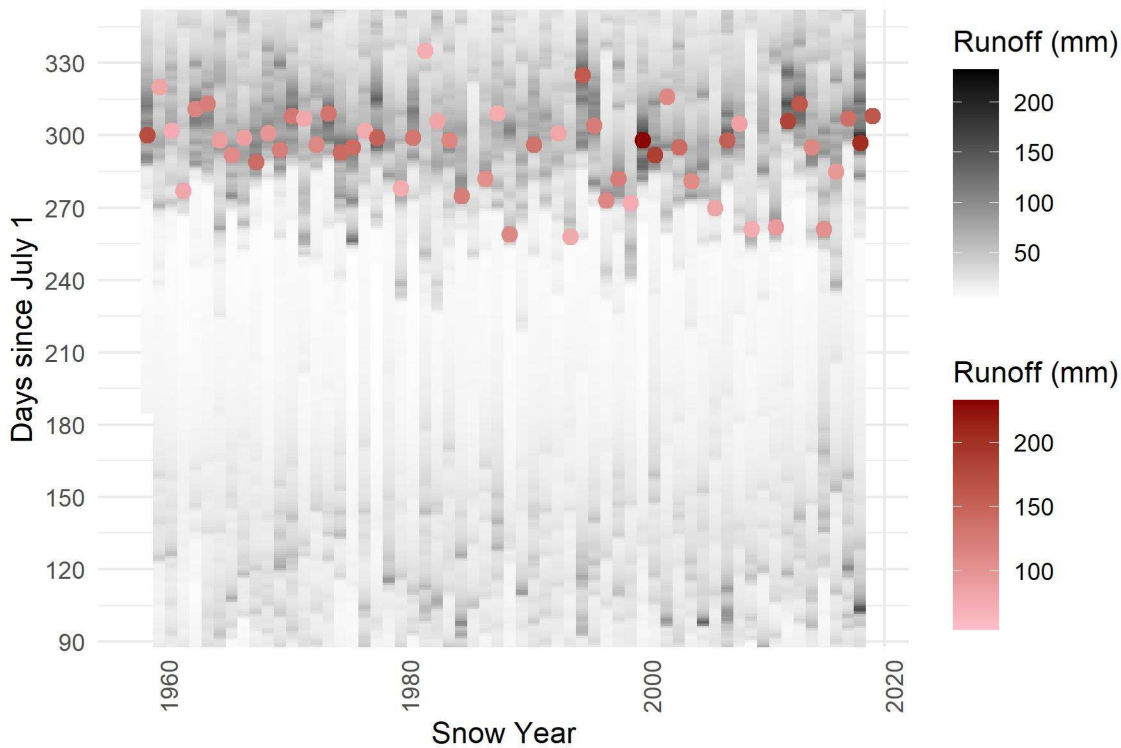

Figure 18. Timing of maximum runoff (days since July 1) and magnitude from LBRM. Shading of each point represents the magnitude of the runoff. Gray color-bar represents magnitude of yearly runoff distribution for the entire simulated period

The most noticeable feature in Figure 18 is the white space in the middle of the graph. This white space depicting low runoff occurs during months below freezing, when precipitation often accumulates as solid snow, dramatically decreasing runoff into the lake as is seen in the SWE distribution in **Error! Reference source not found.**11. In addition, ice formation during the winter on rivers, streams, inland lakes, and Superior shores decreases the amount of runoff entering the lake.

Maximum runoff (i.e., colored dots) occurs after winter minimum runoff, which indicates that the maximum runoff, in most cases, happens after snowmelt in the spring season. Enhanced runoff occurring on earlier dates can likely be attributed to heavy rain events.

Unique Years

A variety of years throughout the runoff distribution are of particular interest. Here, I examined a few years. This analysis is a mirror image of the analysis done for SWE in section Understanding SWE Dynamics, Unique Years. A description of the methods used here can be found in that section.

Both snow year 1962 and 1980 have early maximum runoffs during the first regime. The maximums occur 277 and 278 days after July 1: April 4 and 5, respectively. Their maximums are also lower than average runoff during the first regime, totaling 79 mm and 75 mm, respectively.

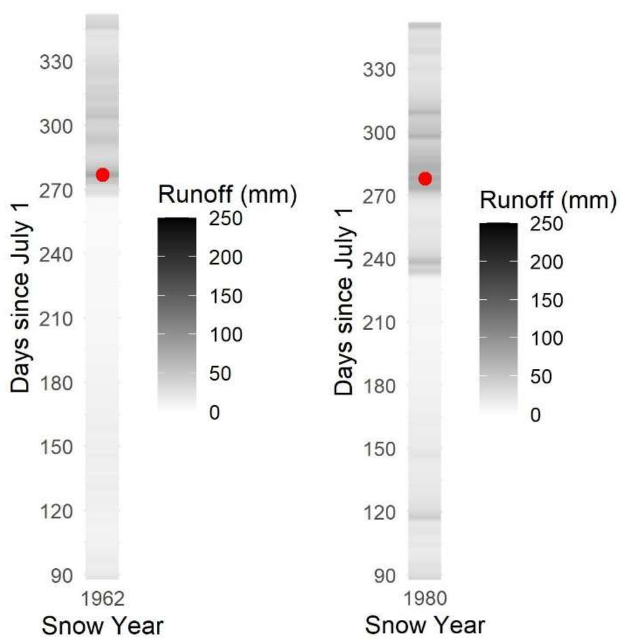

Figure 19. Runoff distribution from LBRM for the snow years 1962 and 1980. Gray color bar spans the entire range of runoff values across all years. The red dot indicates the maximum runoff for the snow year.

Although precipitation was low between November and March of the 1962 snow year, 1980 snow year precipitation was average. Precipitation was especially low in February with less than 25 mm (or one inch) being recorded for snow year 1962.

Air temperatures were lower than average and close to average for 1962 and 1980, respectively. In snow year 1962, by March average air temperatures were above freezing. In the snow year 1980, air temperatures increased quickly during the spring in comparison to 1962. Given the variability of 1962 with low precipitation and temperatures, it makes sense that the maximum runoff would occur earlier in the season and have a lower magnitude. While this situation is also seen in 1980, Figure 19 indicates that runoff was high later in the season too, but the earliest rise in runoff happened to be the greatest.

Shortly after snow year 1980 having an early maximum runoff, the latest maximum runoff in the historical simulation period occurred on June 1 or 335 days after July 1 in the 1982 snow year. Notably, there were other episodes of enhanced runoff earlier in the snow year.

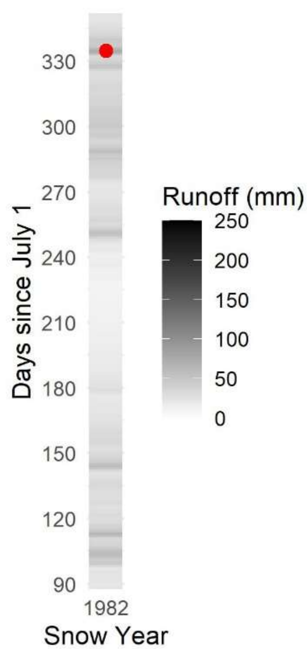

Figure 20. Runoff distribution from LBRM for the snow year 1982. Gray color bar spans the entire range of runoff values across all years. The red dot indicates the maximum runoff for the snow year.

Precipitation this year was high (over 60 mm for the month of February) for the first regime and near-normal for years after 1984. Precipitation saw a dramatic spike in May 1983, potentially being the primary contributor maximum runoff.

Temperatures during this time were also near- to above-average. Snowmelt may have been a driver for those earlier surges in runoff but, given the considerable precipitation in May 1983, primary runoff could have come from rainfall.

Snow year 1994 is of particular interest because it has the earliest maximum runoff for the entire simulation period, which occurred 258 days after July 1 (March 16) Its magnitude is 76 mm, which is the 9 lowest maximum runoff magnitude in the data record.

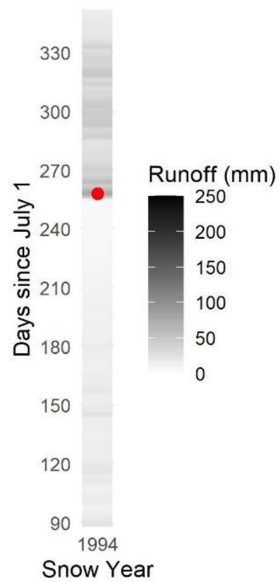

Figure 21. Runoff distribution from LBRM for the snow year 1994. Gray color bar spans the entire range of runoff values across all years. The red dot indicates the maximum runoff for the snow year.

Precipitation this year was average and did not have any abrupt peak in March. The temperature, however, was higher than average for the winter months, including March. Given the somewhat low maximum runoff and the steady runoff that follows, a springtime melt probably initiated this surge causing a relative spike in runoff, which, then was followed by an average runoff pattern in the later spring months. Figure 21 shows that a gradual runoff pattern once snow has melted and the maximum spike is reached is common. This is also seen in Figure 22.

Snow year 2000 is noteworthy because it contains the largest maximum runoff of 233 mm. This large maximum occurred 298 days after July 1, or on April 25, 2001. It also appears that this was the last large runoff peak during this season.

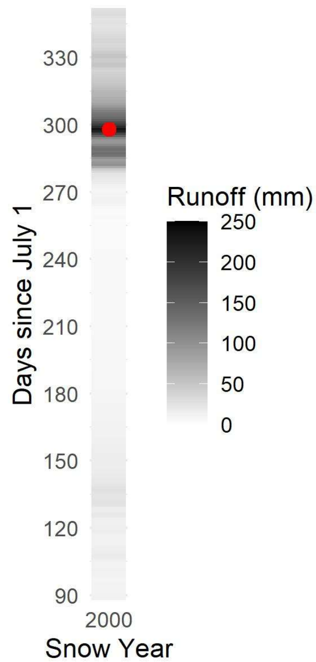

Figure 22. Runoff distribution from LBRM for the snow year 2000. Gray color bar spans the entire range of runoff values across all years. The red dot indicates the maximum runoff for the snow year.

Interestingly, precipitation and air temperatures from November through March were lower than average. Precipitation did increase in the spring months, which is normal for the basin. Air temperatures spiked in March but were not extraordinary for this time of year.

The Interaction Between Snow Water Equivalent and Runoff

In this section, I tie together SWE and runoff. So far, I have concluded that regime changes occur in the simulated time period. Furthermore, these changes do not occur at the same time as SWE and runoff. I have also explored some of the most critical years for snow and runoff on Lake Superior. Here, I discuss the delay between regime shifts in SWE and runoff, the delay between maximum SWE and maximum runoff, and what SWE and runoff comparisons in the unique years look like.

Delay Between Maximum Snow Water Equivalent and Runoff

I have established that maximum SWE occurs before maximum runoff in most cases. How does maximum runoff timing relate to maximum SWE timing in the Large Basin Runoff Model (LBRM) data record? To answer this question, I subtracted SWE “days since July 1" from the same for runoff. In Figure 23, the red and blue vertical dashed lines depict SWE and runoff changepoint years, respectively. These regime shifts correspond to changepoint findings in the sections Understanding Runoff (SWE) Dynamics. Overall, I did see some slight changes in the average lag times between maximum SWE and runoff when averages are taken before SWE’s changepoint (1971), between the changepoints (1971 – 1983), and after runoff’s changepoint in 1983. The average lag before 1971 and after 1983 is about 30 days, or one month between the peaks. This, however, rises to about 40 days after SWE’s changepoint but before runoffs. This further justifies that in 1971, SWE did undergo a change that caused the maximum to occur about 10 days earlier in the season. Runoff didn’t go through this change until 1983, when I saw the lag return to its original month-long delay.

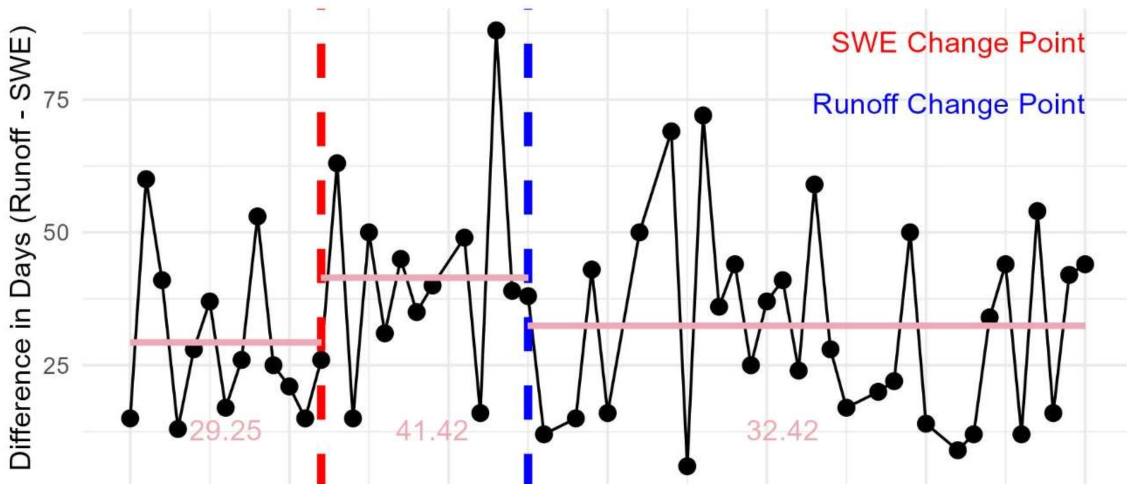

Figure 23. Lag between maximum SWE and Runoff. Maximum runoff day (days since July 1) subtracted from maximum SWE day. Previously calculated change points for maximum SWE and runoff as vertical lines (red and blue respectively). Pink lines represent average lag.

In the snow year 1994, the maximum SWE and runoff had the shortest delay of six days. Further, the years directly before and after had the second and third largest delays of 69 and 72 days respectively. The largest delay is in the snow year 1982, with 88 days occurring between maximum SWE and runoff.

Unique Years to Compare

In the previous sections on SWE and runoff, unique years were based solely on SWE or runoff. Here, I look at how each of these stand-out years looked for both SWE and runoff. Do noteworthy SWE patterns correspond to unusual or abrupt changes in runoff?

Snow year 1962 was of interest in my runoff results because of its early peak timing (277 days or on April 3). At this time, SWE was near average and experienced a typical rise and decline of snow amounts. Precipitation and air temperature were low during the winter months. Overall, SWE was average, and runoff was on the lower side of average.

Snow year 1967 year was singled out because peak SWE occurred abnormally early (246 days or March 2) for the first SWE regime. Runoff during this time follows the normal rise and fall. There were a few instances where runoff increased about a month and a half before the peak. Both temperature and precipitation were average this winter.

The winter of 1980-81 was similar to snow year 1962 in that peak runoff timing was much earlier than others in its timing regime. Corresponding SWE timing and magnitude were earlier and just below average. However, unlike the colder and drier conditions of 1962, temperatures and precipitation were average and even increased sharply, which may have been the cause for a sudden early runoff. The two graphs (listed in appendix A) match up with a melting event, causing abrupt runoff, with the maximum runoff occurring later (April 4) after more snow had accumulated. This first rush of melting occurred around 240 days after July 1 (February 26) and the second around 270 days, or March 28.

Snow year 1982 SWE and runoff were both unique. This year was highlighted due to it having the latest maximum runoff, occurring on May 31. The weather was close to average in the beginning of winter, but as temperatures rose in February and March, precipitation spiked. Both the runoff and the SWE are not unusually high, though. The SWE record indicates times of melting and re-accumulation that match with runoff pulses in the spring. Given the seemingly slower melt, the maximum spike in runoff may have been more attributed to a springtime rain event. Additionally, this year had a strong El Niño.

Snow year 1994 was of interest because it exhibited the earliest maximum runoff in the entire simulation period. Similar to the patterns seen in 1962 and 1980, maximum runoff occurred during the first seasonal runoff peak. In addition, SWE decreased quickly after its maximum (March 9) and was almost immediately converted to the recorded maximum runoff. The maximum SWE was almost 100mm, with 75% of that going directly into runoff. While it was not the shortest delay between SWE and runoff, the pattern is definitely clear that snow melted directly into runoff.

One of the standout years for SWE was snow year 1995. The high maximum SWE magnitude (221 mm) and long-lasting snowpack are of particular interest. While precipitation was somewhat average (about 40 mm), warm air temperatures (around 25 degrees Fahrenheit) led to a persistent snowpack, corresponding to continued accumulation instead of experiencing sporadic melt periods. The large maximum of SWE corresponds to high maximum runoff (158 mm), which occurs on the second-latest day in the data set (May 20).

Snow year 1997 is an anomalous year because melting occurs shortly after maximum SWE is recorded. In many other years, I saw that sudden melt events occur just before strong runoff episodes. There is a small signal here between maximum SWE and runoff but not as strong as other places. In addition, the maximum runoff occurs after almost all of the snow has melted. The runoff maximum spikes and then is gradual and has similar patterns to those found in the fall. Additionally, there was not strong snow accumulation for a long time. The darkest part of the graph (not even a large amount of SWE) is only about 40 days long, indicating that this may not have been a snowy year. Temperatures were warmer, less SWE was recorded, but precipitation was generally average.

I highlighted snow year 2000 because the largest maximum runoff of 232 mm was recorded. Interestingly, precipitation was close to normal (40 – 50 mm) for a majority of the season. The SWE time series does not depict sudden melt close to the time of maximum runoff. Additionally, SWE's maximum is higher than average but is not the highest I have analyzed.

2004 is highlighted because there was a bout of early winter snowfall. I also observed sudden melting that led to direct runoff. Were these small snowfall events observed in the runoff record? In fact, I saw evidence of these events; the first snow event (mid-October) was more delayed behind runoff than the second event (early November), but small surges of runoff can be seen (Appendix A) in parallel with the early snow events. Temperatures were generally close to average (mid 20 degrees Fahrenheit) throughout the winter but had a warmer start.

2006 was shown for the same reason as 2004: an early snow event. The two early snow events in 2006 are easier to observe in the runoff time series. A darker line (more runoff) appears at about 110 days (October 19) in the runoff distribution where the snowfall event happened around 105 days (October 14). In addition, a smaller and slightly more delayed event occurs around 125-130 days. Air temperatures and precipitation were normal. That being said, there is no reason to believe that these events had long term impacts on runoff given the near normal runoff pattern.

Most snow melted in late winter for snow year 2009. By March 1, there was no observed SWE across the entire basin, and only small snow events happened later. Maximum runoff occurred two weeks later, likely an impact this abrupt melt event. Temperatures were generally warmer than average and corresponded to lower-than-average precipitation. There was a spike in warm precipitation in early March indicating that this rapid melt, sudden runoff spike sequence was in response to a rain-on-snow event.

Conclusion

The results above indicate that within the last 60 years, the Lake Superior basin has undergone changes that impacted both snow and, in turn, runoff pattern. These changes, quantified and described in the previous sections, are summarized here, detailing the most prominent and significant findings.

Findings

Changepoint analyses demonstrate that the timing of peak daily Snow Water Equivalent (SWE) in the Lake Superior basin became earlier in the season as the Large Basin Runoff Model (LBRM) simulation progressed. Specifically, I found that 1971 represents the most significant change in SWE timing, and that the mean peak SWE occurred on March 28 before 1971 and March 16 after 1971. Furthermore, when analyzing additional changepoints, the 1971 changepoint remained and additional changepoints were identified in the late 2010s. This indicates that a possible changepoint occurred within the last 5 years of the study. A repeat study could be done in 10 years to see if the changepoint held true, similar to (Venumuddula et al., 2024)'s work where the authors did a repeat study (Ji et al., 2019) while expanding on the time period to evaluate the continuation or change of trends. They worked on ice cover in the Great Lakes, but the methodology for expanding the time period would be valuable.

The timing of SWE not only changed based on its mean value before and after 1971, but in its variability during 2010-2020. From snow year 1959 to 2009, the range in maximum SWE timing was generally within 25 days, apart from a low outlier (i.e., earlier timing) roughly every 10 years. This outlier generally occurred 15-20 days earlier than the standard timing range. However, this pattern changes in the 2010s. The range becomes much more drastic, ranging from 294 days (April 21) on the high end to 249 days (March 7) on the lesser end (excluding the lowest outlier which occurs in the 10-year outlier pattern). This range of 45 days indicates that something has changed in those last 10 years.

However, further work would have to be completed in at least 10 years in the future to determine the impacts of this variability.

In addition to timing variability, SWE maximum volumes became more variable after 1971 changepoint, the maximum SWE magnitude ranged 108 mm (100 mm – 208 mm) before 1971, including outliers near 1971. When this year/volume is not included, the SWE volume range narrows to 66mm. After the 1971 changepoint, SWE magnitudes vary 154 mm (list lowest and highest amounts here) Both the highest and lowest magnitudes occur during the last 30 years of the study period (2013 and 1993, respectively).

Like SWE, peak daily runoff timing became progressively earlier during the LBRM simulation study period. I found that the mean timing of peak runoff changed from April 28 to April 17 in 1984. Unlike SWE's changepoint, the changepoint function could not identify addition significant changepoints after 1984. As of now, it is unclear if considerable changes would occur if this study was repeated after 10 years.

Runoff timing variability was sizable. Before 1984, the timing ranged 64 days, with much of the data being within 25 days of each other. However, this range increased to 68 days after 1984 with no outliers, more than doubling the previous segment's range if outliers are not included. Given the data set, there is no indication that this pattern would have an additional changepoint during the simulated period, but further work would be necessary to justify this conclusion.

Runoff magnitude variability also increases after the 1984 changepoint. Before 1984, the runoff volume ranged from 73 mm to 172 mm over 100 days. However, the second highest runoff magnitude is 151 mm which would lower the total range of magnitudes significantly. After 1984, the runoff range extends to 179 mm, with lowest and highest values recorded as 5 mm to 233 mm, respectively.

Maximum SWE and runoff do not occur at the same time; however, I can understand their relationship by looking at the delay between maximum SWE and runoff.

Broken into three segments, 1959-1971, 1971-1984, 1984-2020, I saw that the mean delay times of each of these segments differs slightly. Before 1971 and after 1983, the average delay (or lag) time between the maximum SWE and maximum runoff is 30 days, or about a month. From 1971 to 1983, or during the time when SWE had undergone its change, but runoff had not, the lag increased to 40 days. This is further indicating that maximum SWE timing shifted about 10 days earlier after 1971, and that the 10-day early shift in maximum runoff caused the delay to go back to pre-1971 time of approximately 30 days.

These results are important for furthering the understanding of Lake Superior snow and water supply dynamics. Furthermore, this study leaves gaps and questions that could be answered in future studies. Here, I discuss what the limitations of the study are, and what can be done in the future to further this work.

Limitations of Research

One major limitation of this study is the bounds and biases that are set by the Large Basin Runoff Model (LBRM). As noted in previous studies, the LBRM is not the strongest model for snow prediction (Mai et al., 2022; Shin et al., 2024). However, I used the LBRM because it outputs SWE and runoff, making an analysis of snow-runoff relationships around Lake Superior possible. In addition, LBRM's SWE shortcomings, there are several parameters and boundary conditions that can be manipulated depending on what the research question is. However, as previously stated, the operational parameters and boundary conditions were used for the data production of this work (Shin et al., 2024). Other parametrization and boundary conditions may change SWE or runoff results, which could alter the results presented here.

Another limitation of this research is geographic scope. I used one basin wide weighted-average value to conduct the entirety of the analysis. A more precise measurement, at the sub-basin level, that was then compared and analyzed across all sub-basins, would provide a more wholistic story across the basin. Due to the limitations of time in this case, the broader, basin wide average, was used in this study.

Future Work

A vast range of work could be done to further the scope, scale, and implications of the work completed in this study. Some suggestions are below.

It is my hope that this research can be expanded beyond using average values for Lake Superior. A similar study could be completed on the remaining Laurentian Great Lakes and other large lakes that are heavily impacted by snowmelt. Expanding the research to more comprehensively involve sub-basins of these lakes would also have impactful results as it would allow specific location-based relationships between SWE and runoff to be uncovered.

In addition, this study focuses on the second half of the 20th century. Using an expanded historical data set would help identify additional regime changes and could further the story of how snow is changing in the region. A caveat of extending the analysis earlier into the 20th century is that the data would have to be simulated beyond where there are observations for the LBRM (Fry et al., 2020; Hunter et al., 2015). In this case, a different type of modeling would have to be used.

Understanding the historical patterns in snow and runoff is important to expand scientific knowledge of the Great Lakes' hydrologic history. However, as scientists learn more about past relationships, they should also try to understand future SWE-runoff relationships. Forecasts of snow and runoff, along with other essential variables, are being projected by various researchers (Kayastha et al., 2022; Xue et al., 2022). Completing a similar study on projections would not only help identify relationships, but it would also help operational scientists make decisions for public information, water management, and local decision making.

Snowmelt is not the only contributor to runoff in the Great Lakes basin. Furthermore, snowmelt does not have a linear relationship to runoff. There are other variables that affect the snow and runoff relationship, including, but not limited to, soil moisture, temperature (specifically air temperature anomaly), and wind. Understanding how and the extent to which these variables interact with runoff and what their relationship would bolster the current understanding of regional SWE-runoff relationships. It would be helpful not only to modelers or forecasters, but also to the industries of farming, construction, transportation, conservation, among others.

The model used in this study was the LBRM, an operational model used in the Great Lakes region. Although well informed, LBRM has limitations as described in the methodology and literature review section. The use of other hydrometeorological models, such as Weather Research and Forecasting Hydrology Model, or a combination of multiple models, could reveal a variety of things such as spatial distribution. Using different models, and comparing the results, would capture intermodal variability, and thus characterize uncertainty, similar to what has been done in the Great Lakes Runoff Intercomparison Project (Fry et al., 2014; Mai et al., 2021, 2022).

The inspiration and funding for this work came from the Bipartisan Infrastructure Law Seasonal to Annual Water Level Forecasting project focused on forecasting advancements in the Great Lakes region. It is my hope that this work will be able to provide additional insight for model programmers and scientists at the National Oceanic and Atmospheric Administration and the Cooperative Institute for Great Lakes Research. As the newest model for Great Lakes water levels is established, it is my intention to make sure the snow to runoff process is better understood, especially as it relates to the Large Basin Runoff Model.

Political and Social Implications

The Laurentian Great Lakes have brought together people for generations. These natural resources are important, and the work that happens to keep the lakes healthy and safe must continue. In addition, many people rely on forecasters (both water and weather) to get information on what the lakes will look like so that they can make decisions for their work and recreation. Decision makers, such as water boards, county officials, recreational companies, tourism, navigation, and others need accurate and substantial information on what the lake conditions will be in the near future. With a broad understanding of snow and runoff dynamics, forecasters can better inform the public.

For example, this work has demonstrated that runoff is becoming more interannually variable both in its Lake Superior-wide timing and volume. Knowing this, communities can prepare for a wider range of water level possibilities. Given that not all communities have the means to prepare for all contingencies related to water timing and volume in their community, this information could provide insight into how they are allocating their own resources effectively.

This study set out to understand the historical relationship between SWE and Runoff. My results demonstrate that both the timing and magnitude of runoff are becoming earlier and more variable after 1984. In addition, SWE is becoming earlier and more variable in magnitude, but the timing variable is only of special note in the last 10 years of the simulated period. Furthermore, the pattern of delays between SWE and runoff further showcase the 10-day shift in both maximum SWE and runoff, even as they occurred during different years. This relationship continues to be important to understanding the relationship between snowpack and runoff in the Lake Superior basin. I suggest repeating this study in 10-15 years to determine if these regimes change.

Acknowledgements

This work was funded in part by the Cooperative Institute for Great Lakes Research under the grant titled: development of next generation prediction system for Great Lakes Water Levels and Lake Management Decisions (award #NA22OAR4320150). This work was also presented at a variety of academic conferences. Funding for these conferences, including registration, travel, lodging, and meals, was funded by Bipartisan Infrastructure Law project and grant at the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory and the Global Center for Transboundary Waters (National Science Foundation Grant #2330317), and the University of Michigan. The data set from the historical run of the Large Basin Runoff Model was created by Satbyeol "Joy" Shin. Shin was a post-doctoral fellow working at the University of Michigan Cooperative Institute for Great Lakes Research at the time this was created. An analysis of her data set can be found in (Shin et al., 2024).

Primary advisement and mentorship for this study is by Andrew D. Gronewold. The committee for this thesis includes Andrew D. Gronewold and Ayumi Fujisake-Manome at the University of Michigan. Other influential mentors include Jamie L Ward (Cooperative Institute for Great Lakes Research and the US Army Corps of Engineers – Detroit) and Lauren Fry (National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory) and Deanna Fielder (US Army Corps of Engineers – Detroit). Jamie Ward was irreplaceable with her advice during the formation of the thesis ideas, planning, research, and writing/editing. I cannot thank you enough Jamie for all your support. To all the mentors above, your immense knowledge is beyond compare. I've learned so much from our discussions and the opportunity to be part of this scientific community.

This work greatly benefitted from the never-ending support of family, friends, and colleagues at the University of Michigan and beyond. Special thanks to the members, former and current, of SEAS-Hydro. Drew Gronewold, you've inspired me, pushed me, and helped me become the researcher and scientist I am. Thank you for taking a chance on

me two years ago. Thank you for your continuous support of my career and education and your patience with me. Guneet, you were my rock in the GCTW room. I don't know what the writing process would have looked like with your complete support and compassion. Thank you.

I'd like to thank a few special people in my life, who have supported and loved me. Abby, my dear wife. Your unconditional love and support have been my backbone through this process. Without knowing what came next, you celebrated my acceptance into graduate school, married me, and moved away from home. All so that I could follow my dreams. I could not have done this with you by my side. You have taught me how to take a step back and slow down to enjoy the moment. Thank you for never giving up on me, even when I was giving up on myself. Thank you for always being by my side even when I would be working late and most likely very crabby the next day. Thank you for taking care of me when I struggled to take care of myself. I hope to be as much of a wife to you as you are to me. I love you forever, come what may.

Mom, Dr. Jo Hopp, you taught me what a scientist is. You also taught me to persevere, to be brave, to know there is always a solution, and to always learn. You were my first and forever inspiration as the kind of scientist and teacher I want to be. I flew Mom, and I enjoyed my flight. Dad, you listen to my dreams and took me to DC and went with me on every crazy school fieldtrip. You showed me what commitment to education and family looks like at the same time – and how to smile and be goofy throughout the process. Zachary, Toby, and Ryann, you are the best siblings I could have asked for. You taught me that I can work in loud environments. I know that we will always have each other's back, no matter what. Thank you for supporting me and taking care of Mom and Dad when I was the first to leave home.

Nonna and Nonno, my grandparents. You taught me the importance of never giving up, following my dreams, and to know that family will always be there. I know from you that when things got a little shaky, I always had my Nonna and Nonno in my back pocket. And I'll always remember that Nonna and Nonno love Trece. Dr. and Mrs. Soper, well, you both helped raise me. You taught me how to see compassion and love in every scenario. You taught me to always walk into a room smiling and to hug with emotion.

Carrie and Steve, thank you for being so supportive of my education. Thank you for visiting Ann Arbor, helping us move, and loving me as your own. You are wonderful in-laws to have.

To my professors at the University of North Dakota, thank you for offering a new freshman a research position and trusting me to be a teaching assistant for ATSC110. You've inspired me, supported me, encouraged me, and frankly put up with me. Thank you for pushing me further in my studies and career. Cassidy, Lauren, Lucas, Matt, and Nathan: You all made my education experience the best it could have been. What a group to go through UND AtSci with. Thank you for those long nights doing projects, the countless equations on the board, and a group I can still talk to. There is something special (and maybe a little strange) about us six – and I'll never forget that.

Artemis: My first service dog. You were there from when I was accepted into Michigan to submitting this thesis. You came to class, lab, meetings, events, conferences, presentations, and so much more. You laid on my legs when I wrote, and you told me when I needed to take breaks. You taught me to slow down, to go on crazy adventures, to remember to take breaks, and to always come back home at the end of day. You goofy little girl… we did it.

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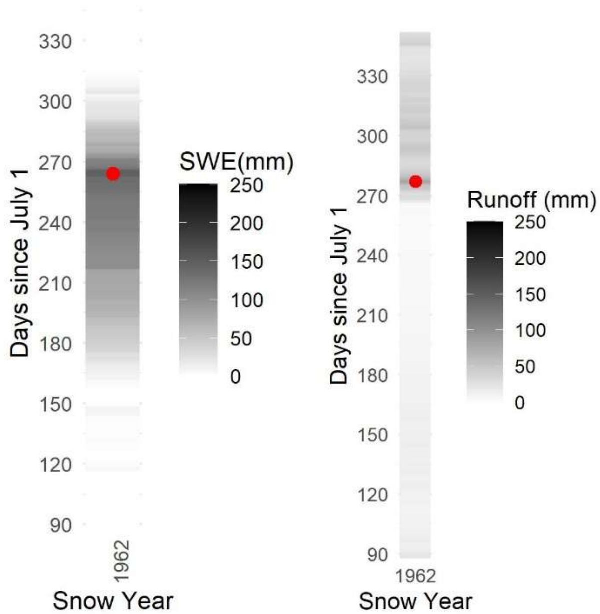
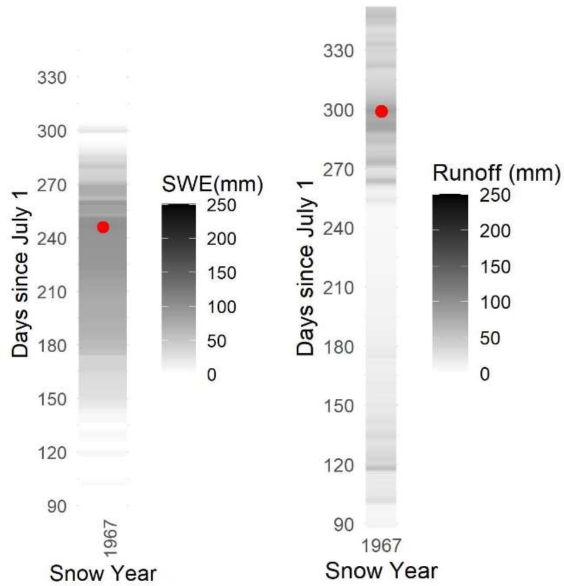
Appendix

Appendix A: Unique Year Complete Graphs

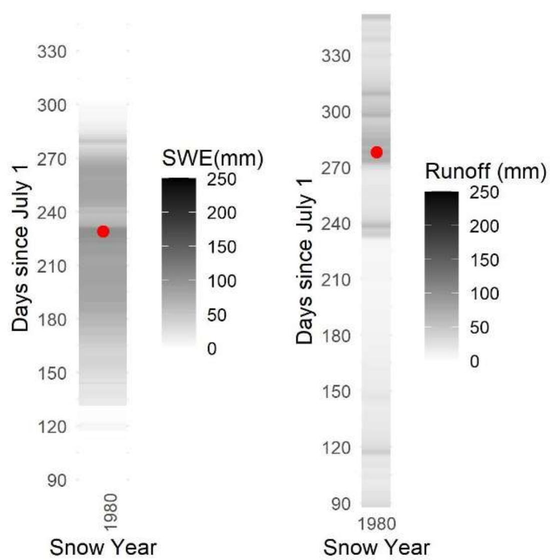
Snow Year 1962



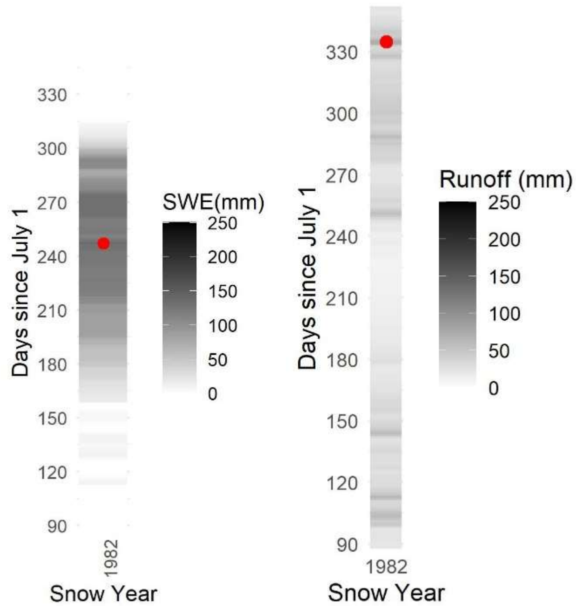
Snow Year 1967



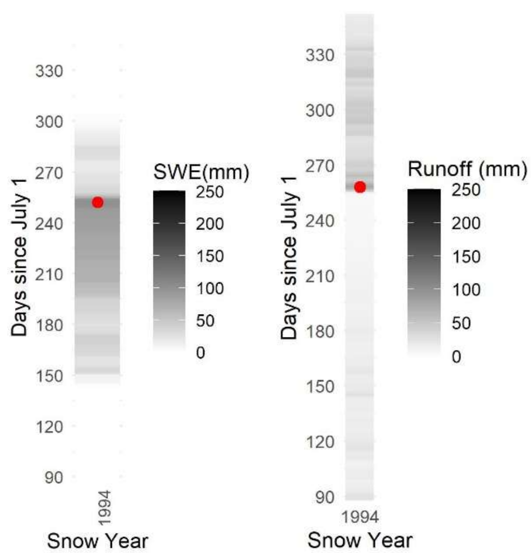
Snow Year 1980



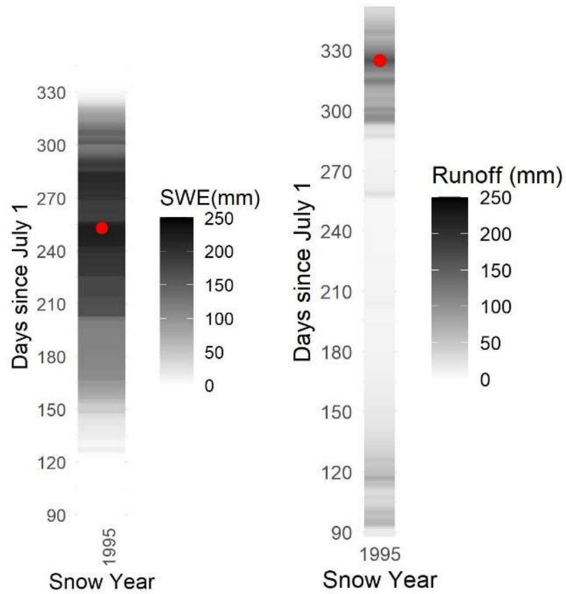
Snow Year 1982



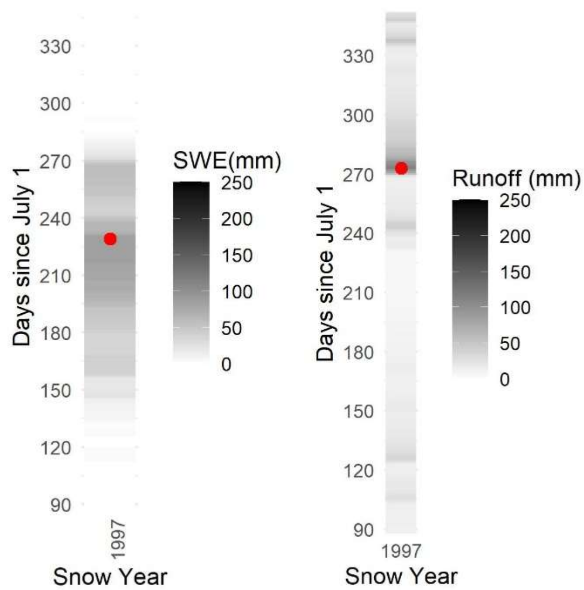
Snow Year 1994



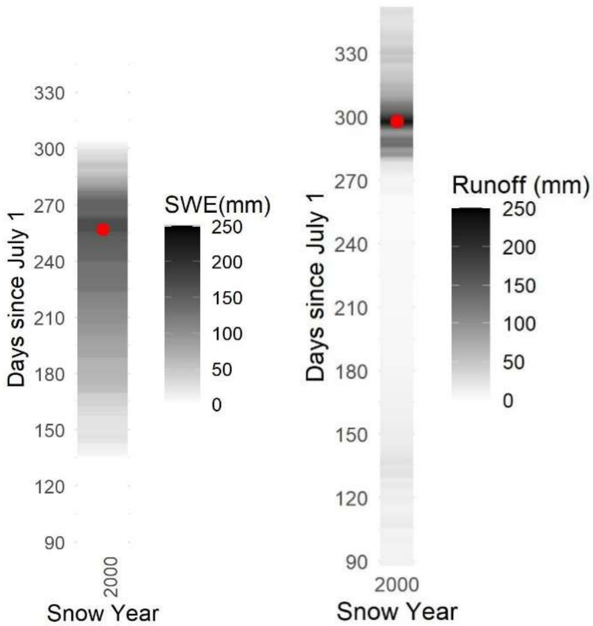
Snow Year 1995



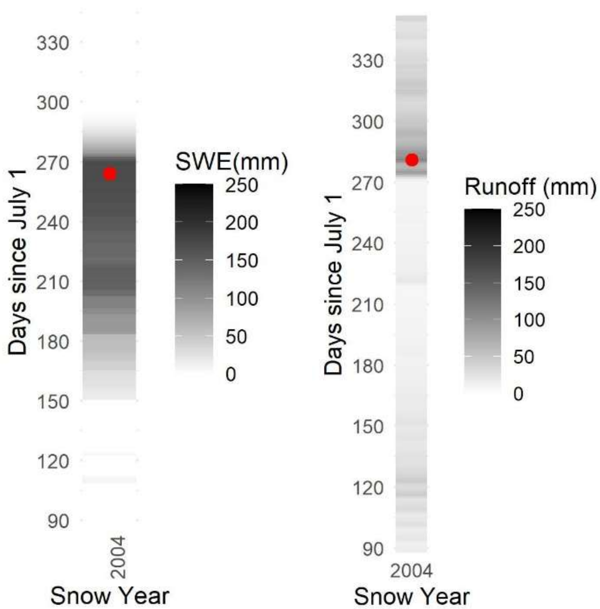
Snow Year 1997



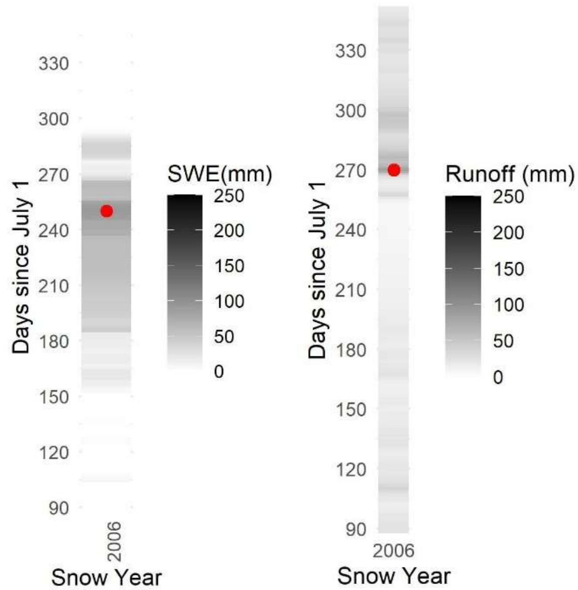
Snow Year 2000



Snow Year 2004



Snow Year 2006



Snow Year 2009