



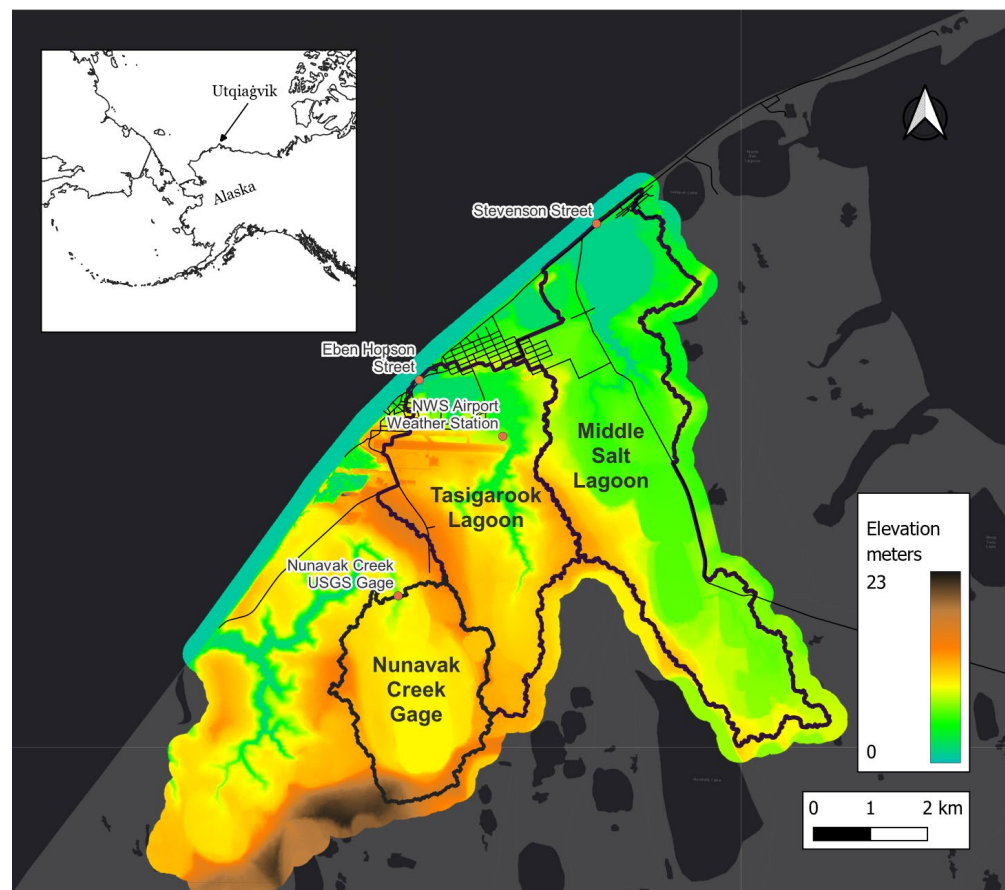
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Stage Frequency Analysis from Snowmelt Runoff near Utqiagvik, Alaska

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October 2023



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Stage Frequency Analysis from Snowmelt Runoff near Utqiagvik, Alaska

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Final Report

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Abstract

For the village of Utqiagvik, located at the North Slope of Alaska, a stone-armored revetment along the coastline is proposed to reduce coastal erosion. The inner drainage capacity of the revetment must be sufficient to handle seasonal runoff from snowmelt. For this effort, we investigated the snowmelt runoff and the hydraulic impact at the watershed outlet using numerical snow and hydraulic modeling of the study area. We validated the snow model results by comparing simulated snow water equivalent (SWE) values to field measurements. Additionally, the snow model was validated using satellite-based Moderate Resolution Imaging Spectroradiometer (MODIS) snow-covered area (SCA) products and time-lapse camera imagery during snowmelt. Our results indicate that the simulated SWE and snowmelt dates agree closely with measured values. The timing of modeled runoff onset was less accurate due to natural processes that delay snowmelt runoff such as snow dams and refreeze. The effect of the uncertainty from both runoff timing and volume was addressed with a Monte Carlo simulation of stage-frequency curves for the lagoons that receive snowmelt runoff. These stage-frequency curves can be used directly in the design of outlet, drainage or discharge structures for the proposed revetment.

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Preface

This study was conducted for the US Army Corps of Engineers (USACE) Alaska District: Joint Base Elmendorf-Richardson (JBER), under AMSCO Code 081818. The technical monitor was Ms. Rebecca Kloster, USACE Alaska District, Anchorage. SnowModel was approved by the Hydrologic Engineering Center (HEC) committee Member Representative for one time use for the Alaska District.

The work was performed by the Biogeochemical Sciences Branch (Mr. Nathan Lamie, chief) of the Research and Engineering Division and the Lidar and Wetlands Group (Dr. Elias Deeb, lead) and the Terrain and Ice Engineering Group (Dr. Meghan Quinn, lead) of the Remote Sensing/GIS Center of Expertise (RS/GIS CX), US Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. John W. Weatherly was acting division chief, and Dr. David Finnegan was RS/GIS CX director. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

We also want to acknowledge Ms. Patricia Nelson (CRREL-BSB) and Dr. Jewell Lund (formerly CRREL–Terrestrial Cryosphere Sciences Branch, and at time of publication, University of Wyoming) for providing some initial data analysis for this report. Additionally, a special thanks to two former CRREL employees Dr. Matthew Sturm (currently at University of Alaska, Fairbanks), and Dr. Christopher Hiemstra (currently at the United States Department of Agriculture), and Dr. Glen Liston (currently at Colorado State University) for collection of snow density and snow water equivalent values in the vicinity of the study area during past efforts.

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COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

1 Introduction

1.1 Background

High-latitude coastlines are experiencing erosion at an accelerated rate. In Utqiagvik (formerly Barrow), Alaska, flooding and erosion occur during severe coastal storms and are a threat to public health and safety. The city is situated on the coast of the Arctic Ocean on Alaska's North Slope (Figure 1). Located approximately 530 km north of the Arctic Circle, Utqiagvik (71°17'44"N; 156°45'59"W) with a current population of 4,927 (US Census Bureau 2020) is the northernmost incorporated place in the United States.* The Arctic coastal plain has low-relief terrain and is underlain by permafrost (material frozen for more than two consecutive years). The estimated maximum depth of permafrost is about 400 m (Brewer 1958) and the maximum thaw depth ranges from about 30 to 90 cm (Hinkel and Nelson 2003; Nelson et al. 1998). The landscape in the Utqiagvik peninsula includes about 50% of drained thaw-lake basins, and shallow thaw lakes occupy approximately 22% of the landscape (Hinkel et al. 2003).

The extreme latitude of Utqiagvik results in relatively cool short summers and long cold winters. The 1991–2020 climate normal for Utqiagvik (Barrow Post Rogers Airport, Alaska, USW00027502/Weather Bureau-Army-Navy [WBAN] 25702), as generated by the National Centers for Environmental Information, is shown in Figure 2. Annual average temperature for this 30-year period is -10.2°C with a high of 5.4°C (July) and low of -24.4°C (February). The total annual precipitation and snowfall normal is 137 mm and 116 cm, respectively. About 53% of the annual precipitation occurs during July through September (Figure 2).

Snowmelt makes up the majority of the annual runoff, though the fraction of available snow water equivalent (SWE) that is converted to runoff ranges significantly from estimates as high as 90%–100% (Brown et al. 1968; McCarthy 1994) to measurements following periods of drought as low as 33% (Douglas et al. 2017) and 29% (Liljedahl et al. 2017). The total annual snowfall for the 1991–2020 normal is approximately 166 cm and snow cover can last well into June and start as early as August (Figure 2).

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, <https://www.gpo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Figure 1. Project vicinity map including the coastline reach of concern.
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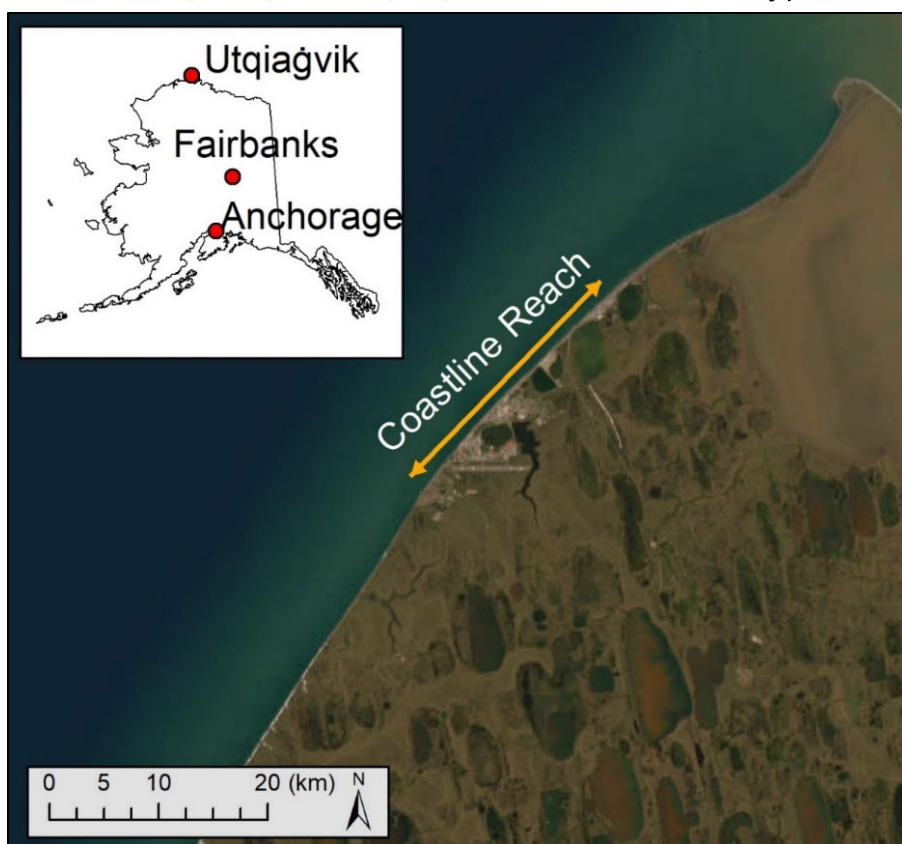
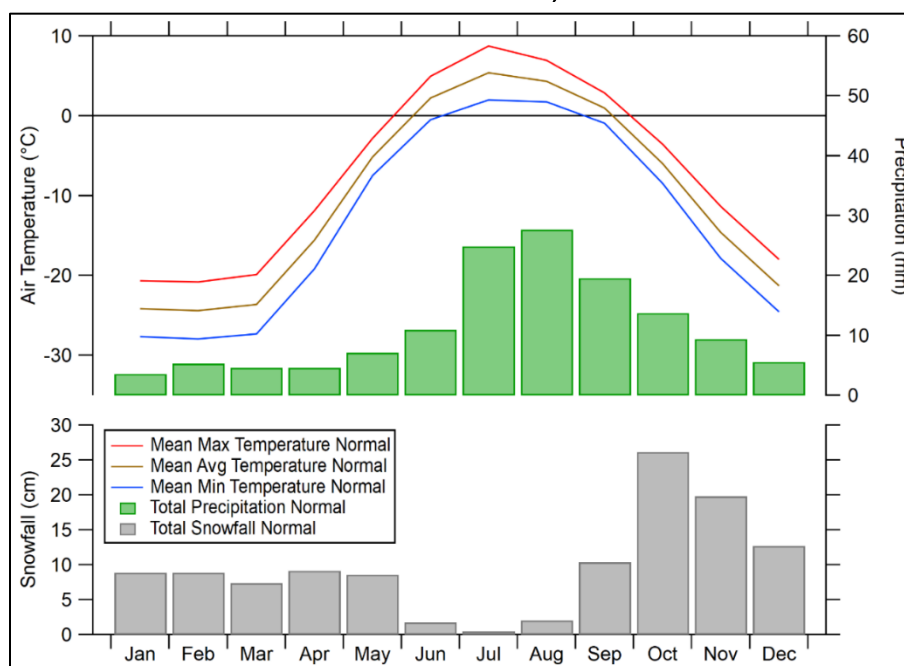


Figure 2. Monthly climate normal (1991–2020) at Utqiagvik Area, Alaska. (Data from NOAA 2021.)



Climate change is impacting Alaska more than any other state in the US and warming trends are approximately twice the rate of global estimates (Markon et al. 2018). The average air temperature for the North Slope, Alaska, has been warming at about 2.6 times the rate of the continental US (Markon et al. 2018). The consequence of this warming is a reduction in minimum sea ice extent between 10%–16% per decade since the 1980s (Markon et al. 2018). Because of the reduction in sea ice duration and extent, longer fetch lengths are occurring for open water wave generation. The consequence of reduced sea ice and longer fetch lengths is coastal erosion which has intensified for most of the Alaska coastline with estimates based on aerial photography from 1943 to 2003 for areas near city of Utqiagvik of approximately 0.3 m per year of shoreline reduction (USACE 2019). This erosion rate puts critical infrastructure at risk from storm events even under current climatic conditions. Melvin et al. (2017) project coastal erosion and damages to Alaska infrastructure will increase through the end of the 21st century as continued warming occurs.

It is within the context of increased coastal erosion for the North Slope that the US Army Corps of Engineers (USACE) Alaska District is planning to construct a coastal revetment in the city of Utqiagvik, Alaska. The rock revetment is along an approximately 5-mile length of Chukchi Sea coastline (Figure 1) and designed to reduce the risk of erosion from wave action that is threatening the community. The Alaska District's current design is primarily composed of a stone revetment that extends from the airport to the Naval Arctic Research Laboratory. The revetment will be placed against the bluff to the southwest of the city's water supply lagoon outlet with a berm structure in front of the lagoon. For the reaches where Stevenson Street runs along the coast, the design consists of an elevated road armored with stone on the seaward side. Besides protecting the city from the ocean, the design of the revetment must include consideration of interior drainage capacity to accommodate seasonal snowmelt runoff. A key concern is that the revetment could impede runoff discharge and cause interior flooding. To mitigate this risk, new outlet, drainage or discharge structures will be constructed to effectively pass snowmelt through to the ocean during the runoff period.

1.2 Objectives

The objective of this project is to estimate water stage frequency for both Middle Salt and Tasigarook Lagoons based on snowmelt runoff estimates into the lagoons. The stage frequency includes confidence bounds which can be used in a risk-based framework for hydraulic structure design by the Alaska District.

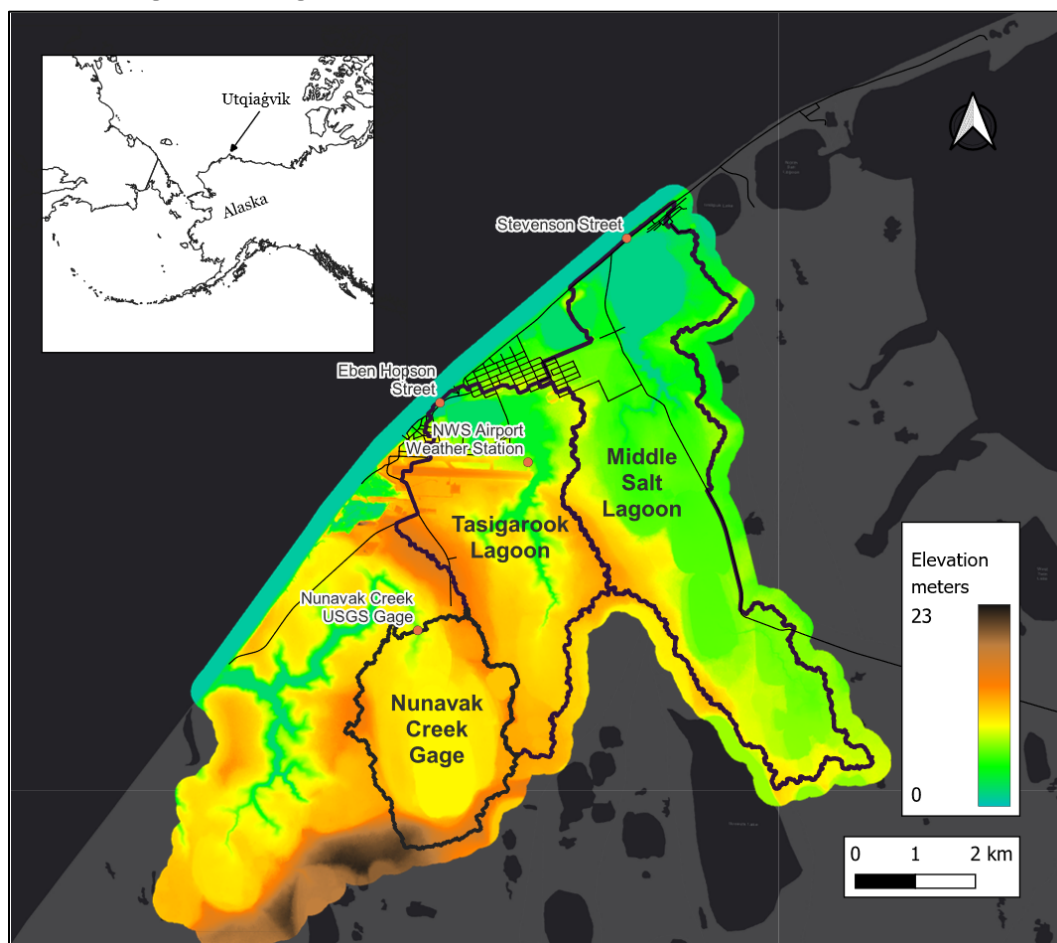
1.3 Approach

Due to the extreme environment of the North Slope Alaska as well as significant impacts based on inter-annual climate variability, several snow processes must be accounted for when estimating timing and volume of snowmelt. These processes include wind redistribution, formation of ice lenses (layers), and heat transfer through the snowpack. The approved model for USACE projects, Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS), currently cannot explicitly model snow redistribution or detailed layering (e.g., ice lenses) within the snowpack. While there is now a beta version of HMS which does have the option of using a full energy balance snowmelt method, at the start of this project the energy balance beta version was not available from HEC. For this reason, we chose SnowModel, a spatially distributed snow model that includes these and other physically-based snow processes (see Section 2.1 for more details). We conducted snowmelt runoff analysis using components of the HEC’s River Analysis System (HEC-RAS) model initialized with liquid water at soil surface (LWASS) grid output from SnowModel. The gridded RAS model was used to simulate snowmelt runoff processes which included routing runoff through the watershed using the 2D diffusion wave transform method. Runoff hydrographs to the lagoons were generated with the RAS model and used to calculate the stage-frequency curves. The annual series of modeled snowmelt volumes was combined with runoff hydrograph shape-dependent stage-volume curves to calculate the uncertainty in the stage-frequency estimates using a spreadsheet-based Monte Carlo simulation. The results of this analysis include flow rates, depths and velocities in the modeled domain which were used to generate statistics at desired locations from the results of multiple simulations.

2 Methods

Because of the extreme environment in the Arctic, we needed to apply state-of-the-art physical models to estimate the hydraulic impacts of snowmelt on the coastal revetment. Our modeling approach included simulating and validating snowmelt runoff using a physically based numerical snow model (Sections 2.1–2.2). The snowmelt runoff from that model was subsequently used as an input to a hydraulic model (Section 2.3). These results were used to perform a Monte Carlo stage frequency analysis for the outlets of Middle Salt Lagoon and Tasigarook Lagoon (Section 2.4). Our study domain encompassed a larger region including the Middle Salt Lagoon, Tasigarook Lagoon, and Nunavak Creek watersheds (Figure 3). The expanded study domain is a result of streamflow data limitations, which is discussed in Section 2.3.

Figure 3. Utqiagvik location map where watersheds are outlined in *black*.



2.1 Snow modeling

This work uses SnowModel (Liston and Elder 2006a), a state-of-the-art, spatially distributed, snow-evolution modeling system designed for application in all landscapes, climates, and conditions where snow occurs. It is an aggregation of three submodels; EnBal (Liston and Hall 1995; Liston et al. 1999) calculates surface energy exchanges and snowmelt; SnowPack-multilayer (ML) (Liston and Hall 1995; Liston and Mernild 2012) is a snowpack model that simulates snow depth and water-equivalent evolution; and SnowTran-3D (Liston and Sturm 1998; Liston et al. 2007) accounts for snow redistribution by wind. Coupled with SnowModel is an atmospheric model (MicroMet; Liston and Elder 2006b) that is used to provide the required meteorological forcings. The modeling suite requires air temperature, relative humidity, wind speed and direction, and precipitation data. Known relationships between meteorological variables and the surrounding landscape (primarily topography) are used to distribute those variables over a landscape in physically plausible and computationally efficient ways.

SnowModel is designed to run on grid increments of 1 m to 200 m and temporal increments of 10 min to 1 day. They can be applied using much larger grid increments (up to tens of kilometers) if the inherent loss in fine scale information (Liston 2004) does not risk the resolution needed for the application of which the output will be used. Simulated processes include snow precipitation; blowing-snow redistribution and sublimation; interception, unloading, and sublimation within forest canopies; snow-density evolution; and snowpack ripening and snowmelt. The modeling system incorporates first-order physics required to simulate snow evolution within each of the global snow classes (i.e., Ice, Tundra, Taiga, Warm Forest [or Alpine], Prairie, Maritime, and Ephemeral) defined by Sturm et al. (1995).

We performed snow modeling simulations from 1 September 1981 through 31 August 2021, using hourly time steps. Our modeling domain of about 179 km² (12,450 m by 14,400 m; 30 m grid cells) included the Tasigarook Lagoon, Middle Salt Lagoon, and Nunavak Creek watersheds (Figure 4). We used the 2015 North American Land Change Monitoring System (NALCMS, <http://www.cec.org/north-american-land-change-monitoring-system/>) land cover which can automatically be downloaded through scripts in

SnowModel (see Figure 5), and topography was derived from the *North Slope Borough LiDAR Technical Data Report* (QSI 2019).

Figure 4. Study site boundary for the snow modeling shown with delineated watersheds, terrain elevation, and ground-based monitoring sites.

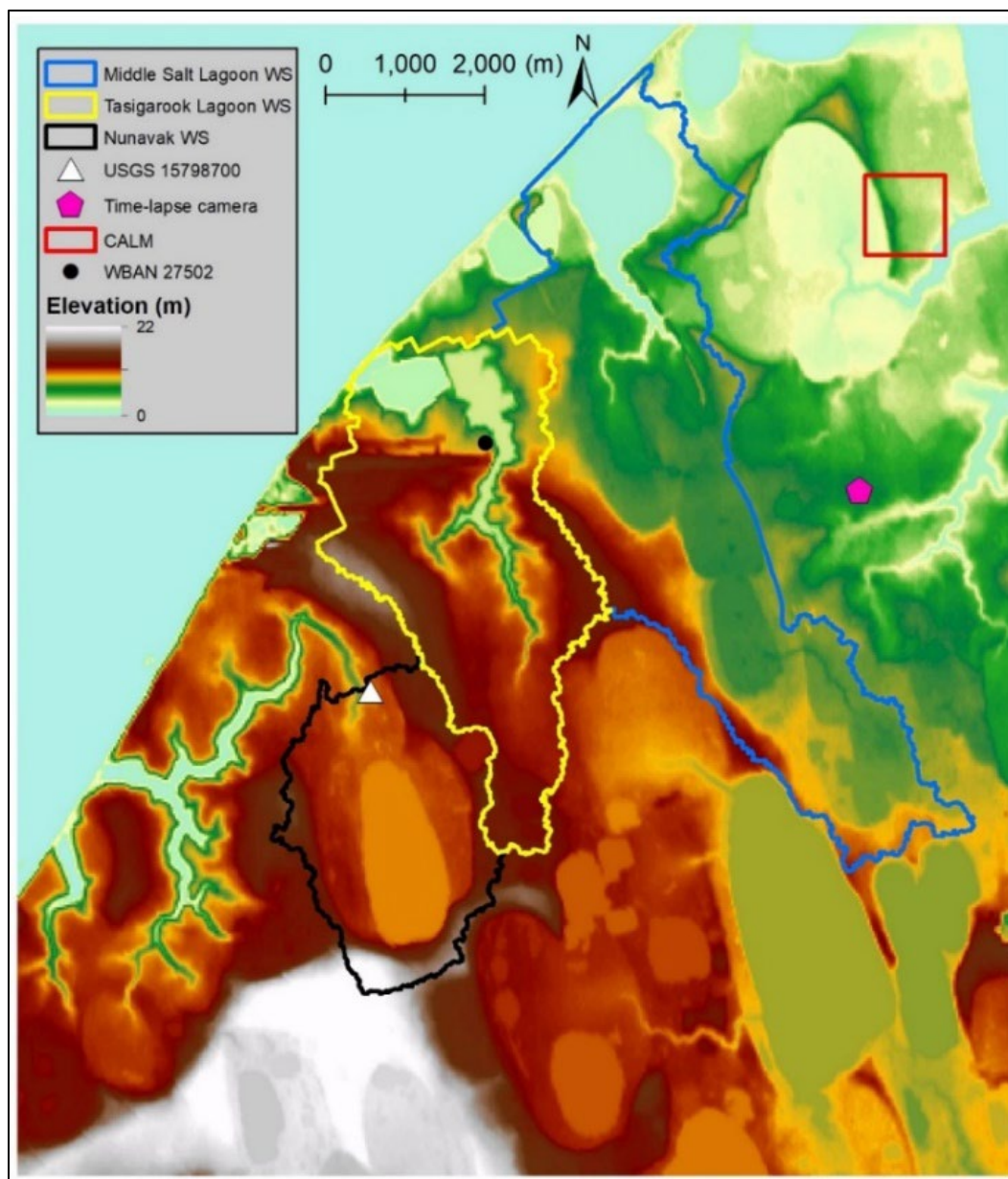
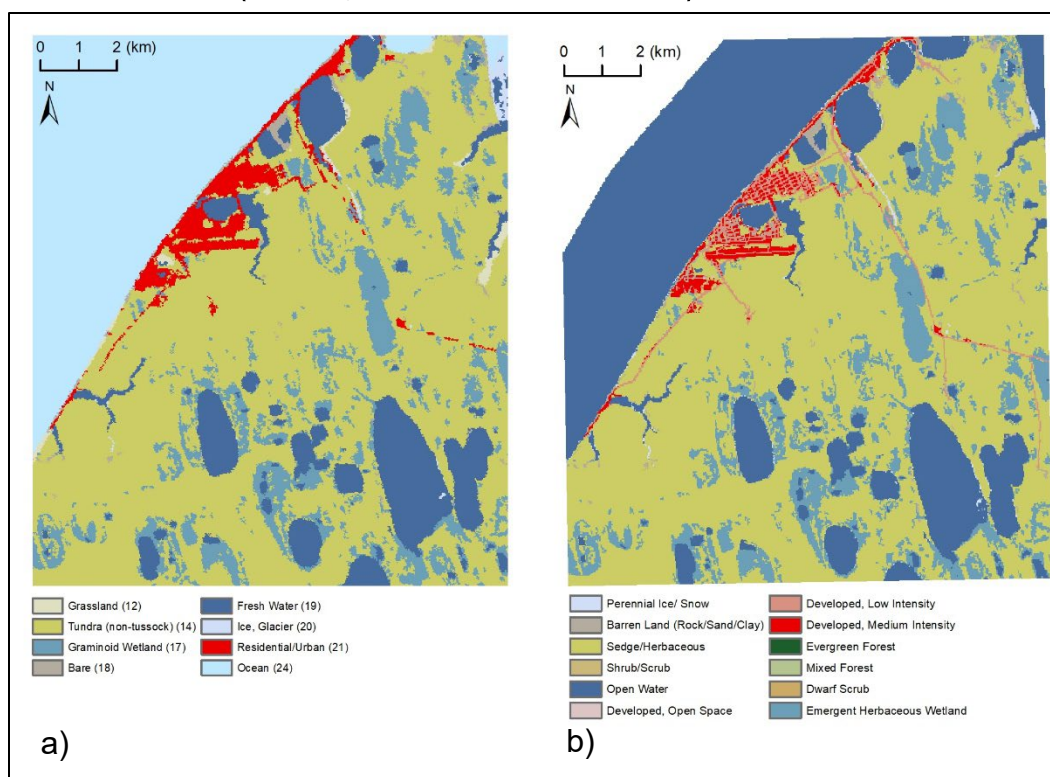


Figure 5. Land cover classes (a) for SnowModel simulations North American Land Change Monitoring System (NALCMS) and (b) Hydrologic Engineering Center–River Analysis System (HEC-RAS; national land cover database) simulations.



As a forcing dataset for the SnowModel simulations, we used air temperature, wind velocity and direction, and relative humidity from the Wiley Post-Will Rogers Memorial Airport (latitude 71.28703°, longitude -156.73938°; WBAN 27502). Accurate precipitation measurements in the Arctic are extremely difficult. Liljedahl et al. (2017) reported an underestimation of total winter precipitation measurements between 2.8 to 4.3 times the reported amount at the meteorological station in Utqiagvik (WBAN 27502). To account for this, we investigated reanalysis datasets to replace precipitation measurements at the meteorologic station. McCrystall et al. (2021) reported that the fifth generation European Centre for Medium-Range Weather Forecast v5 (ERA5) produces the best precipitation estimate for Arctic environments. As an example illustrating the difference in precipitation, a comparison of meteorological station and ERA5-Land (Muñoz Sabater 2019), a downscaled version of ERA5 (Hersbach et al. 2020), accumulated precipitation for water years 1982 to 1986 (Day 1 = 1 October) is shown in Figure 6. For 1982 to 2021, the correction factor (ERA5 precipitation / WBAN 27502) ranged from 1.2 to 7.8 with an average of 3.1 (Figure 7). This corresponds to the underestimation range of precipitation

measurements reported by Liljedahl et al. (2017). Therefore, we chose the ERA5-Land precipitation as the more representative precipitation for the forcing dataset in the snow modeling effort.

Figure 6. Comparison of accumulated precipitation of European Centre for Medium-Range Weather Forecast v5 (ERA5)-Land (*blue line*) and meteorological station data (*red line*, WBAN 27502) for water year (WY) 1982–1987 at Utqiagvik, Alaska.

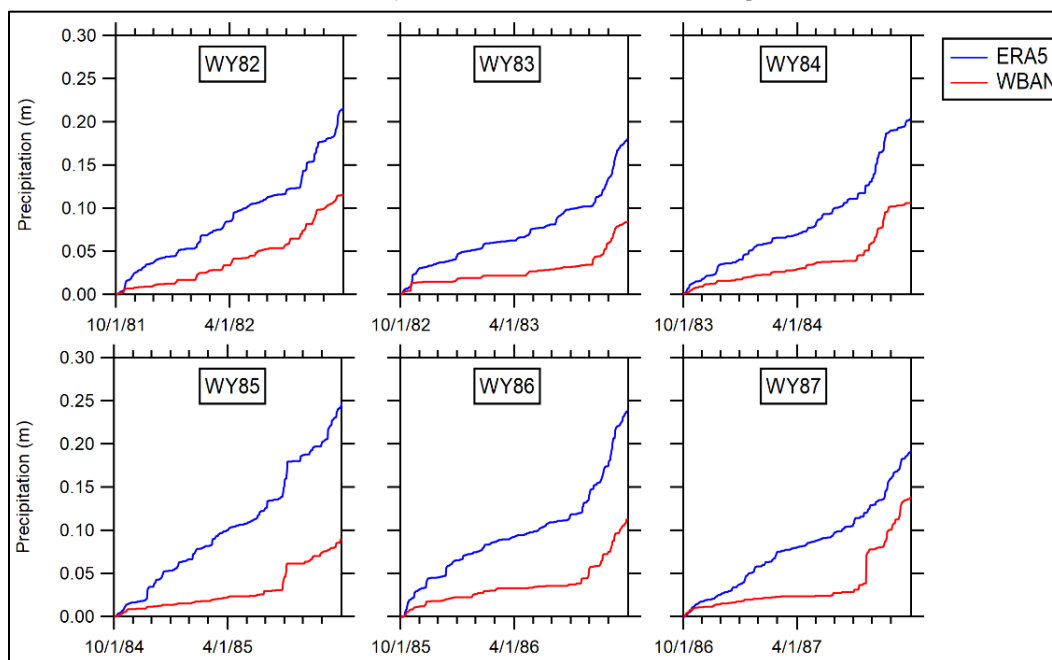
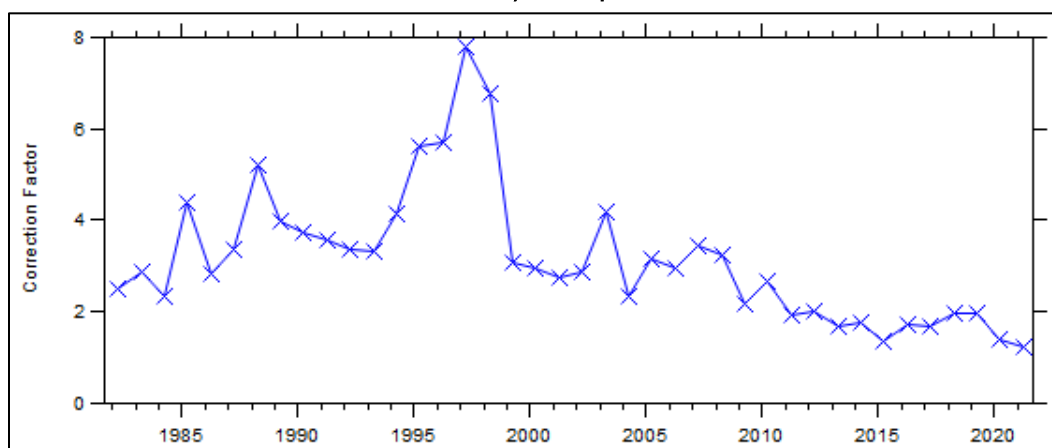


Figure 7. Correction factor of precipitation between ERA5 and meteorological station (WBAN 27502) on 1 April.



2.2 Snow model validation

Because of the extremely remote location environment of our study site, there are limited physical measurements of SWE and snowmelt runoff. Consequently, to account for this deficiency of available data, we used several methods to validate the snow modeling effort. As a part of this validation, we used snow depth measurements from the Circumpolar Active Layer Monitoring (CALM) program and SWE measurements from the SnowNet field campaigns. Snow depth (h_s) is related to SWE (Equation 1),

$$SWE = h_s \frac{\rho_b}{\rho_w}, \quad (1)$$

where

ρ_b = the bulk density and
 ρ_w = the density of water.

We compared these measurements to simulated SWE from SnowModel. Additionally, we used remote sensing measurements which included the Terra Moderate Resolution Imaging Spectroradiometer (MODIS) snow-covered area (SCA) product and observed snowmelt date from time-lapse camera imagery to validate our simulated snowmelt dates.

We also evaluated other remote sensing methods for estimating snowpack properties (e.g., spatial distribution of depths and melt timing); however, they did not provide additional context in validating SnowModel results. These included satellite-based stereophotogrammetry (e.g., Maxar Worldview), existing airborne lidar acquisitions, and a time-series of satellite-based radar observations (e.g., from European Space Agency Sentinel-1 products). Processing artifacts of the initial stereophotogrammetric results in this relatively flat terrain did not produce reliable digital surface models of the shallow snowpack found around Utqiagvik, Alaska. Similarly, the timing and extent of existing airborne lidar acquisitions did not match necessary requirements for comparison with SnowModel scenarios. Finally, the 3 and 6 day repeat orbits of the Sentinel-1 satellite radar time-series failed to capture the dynamic snowmelt signal at this study location as it pertained to comparison with the SnowModel snowmelt timing.

2.2.1 Cold Regions Research and Engineering Laboratory (CRREL) field campaigns (SnowNet)

Cold Regions Research and Engineering Laboratory (CRREL) has performed several field campaigns in Utqiagvik, Alaska. For the snow model validation, we used SWE measurements from water year (WY) 2008, 2009, and 2011 SnowNet field campaigns (Table 1). During the late season CRREL field campaigns, snow densities varied between 321 kg/m³ and 326 kg/m³.

Table 1. Snow water equivalent (SWE) and snow density for Cold Regions Research and Engineering Laboratory (CRREL) field campaigns.

—	December 2007	March 2008	April 2008	November 2008	December 2008	January 2011
<i>n</i>	15	20	42	7	34	29
Min SWE (m)	0.044	0.055	0.059	0.009	0.025	0.021
Max SWE (m)	0.088	0.085	0.240	0.013	0.196	0.180
Average SWE (m)	0.071	0.139	0.156	0.017	0.082	0.084
Average snow density (kg/m ³)	227	321	326	104	311	288

2.2.2 Circumpolar Active Layer Monitoring (CALM)

The CALM program was established in the early 1990s to observe spatial variability of long-term observation of active layer thickness (Brown et al. 2000). The Utqiagvik CALM site (1 km by 1 km) is located east of the project boundary watershed and about 6 km east of the Wiley Post–Will Rogers Memorial Airport (Figure 8). At the end of the winter season, when maximum snow depth is expected, snow depths were measured at 121 points (every 100 m) between 1995 and 2015, and 2019 (Figure 9). The average snow depth for all years was 39 cm with an average minimum of 30 cm and an average maximum of 53 cm. Snow depths ranged from 1 cm (1999) to 146 cm (2008).

Unfortunately, SWE and snow density were not measured during the CALM field campaign. In 2008 and 2009, Liljedahl et al. (2017) measured snow densities of 320 kg/m³ at nearby sites. During the CRREL field campaigns average snow densities at the end of winter season were between 288 kg/m³ and 326 kg/m³ (see Section 2.2.1). A commonly used snow density when converting snow depth to SWE is 300 kg/m³, and in the absence of more detailed data this value was adopted.

Therefore, during our snow model validation, we used a snow density of 300 kg/m^3 when converting the CALM snow depth measurements to SWE using Equation 1.

Figure 8. CALM grid and time-lapse camera locations.

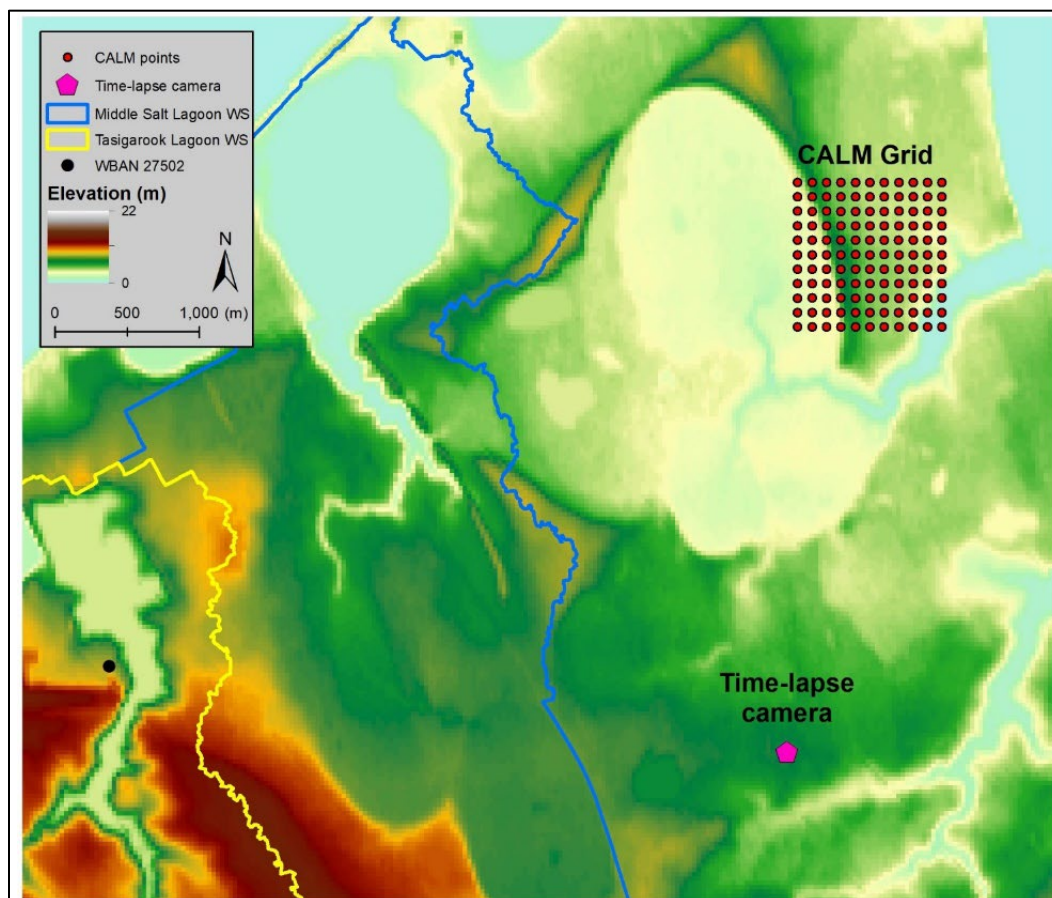
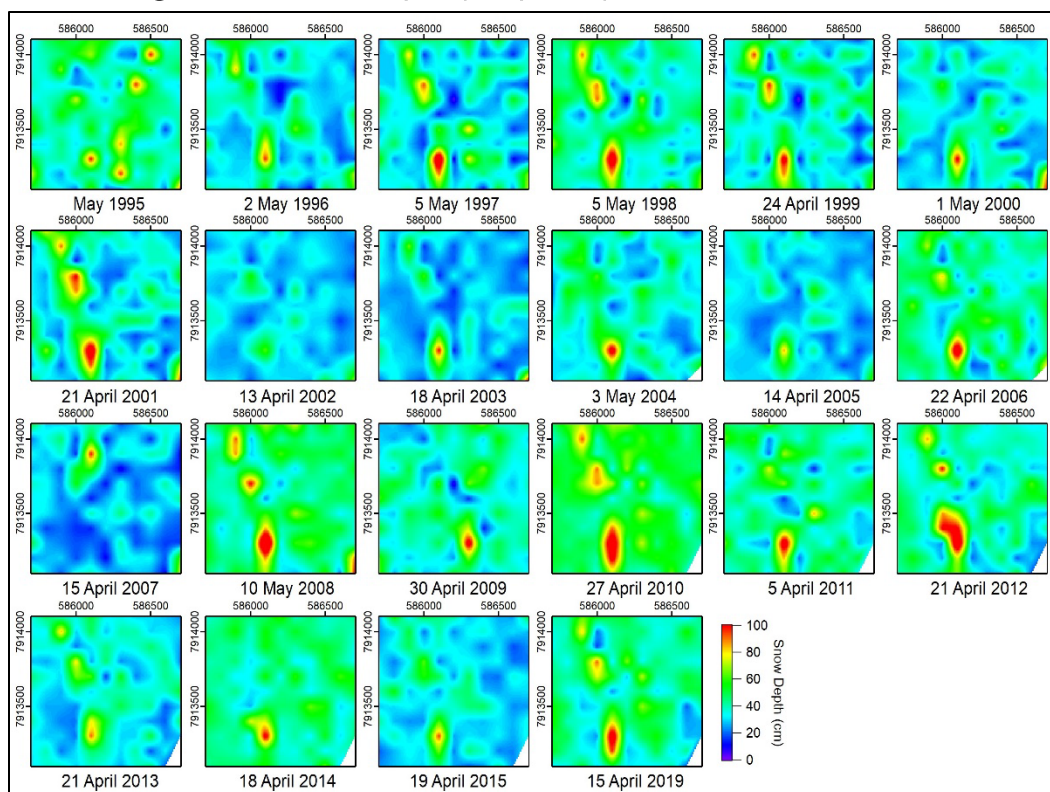


Figure 9. CALM snow depths (interpolated) from 1995–2015 and 2019.



2.2.3 Time-lapse camera

Timing of snowmelt was also further enhanced by looking at historical time-lapse camera images. An automated camera network to monitor canopy phenology (<https://phenocam.nau.edu/webcam/>) was initiated in 2007 spanning northeastern United States and Canada (Seyednasrollah et al. 2019). In 2015, a time-lapse camera was installed in Utqiagvik, and this camera operated until 2019 (Milliman et al. 2019). The camera in Utqiagvik is located in the southeast portion of the snow model domain (Lat 71.280075, Lon -156.609149, elevation 5 m; Figure 8).

2.2.4 Terra Moderate Resolution Imaging Spectroradiometer (MODIS) snow-covered area (SCA) product

SCA depletion curves were derived from the MODIS on the Terra satellite at the CALM grid and the time-lapse camera sites (Figure 10). Terra's Level 3 Daily Snow Cover or MOD10A1 (Hall and Riggs 2016) provides a daily estimation of fractional snow-covered area (fSCA) based on an empirical relationship with the normalized difference snow index (NDSI):

$$NDSI = \frac{G-SWIR}{G+SWIR}, \quad (2)$$

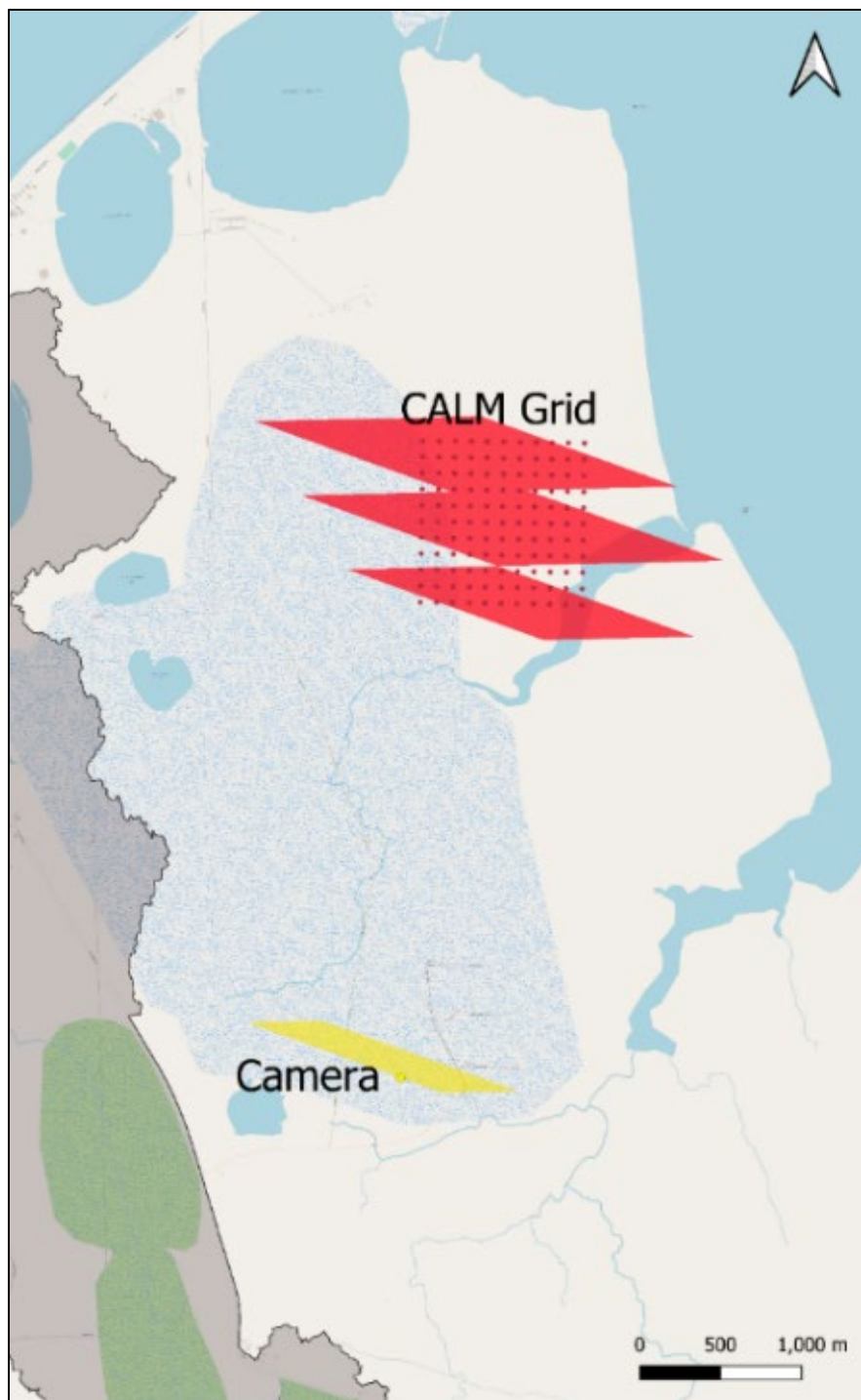
where

G = the spectral reflectance of a green band (500 nm, MODIS Band 4) and

$SWIR$ = the spectral reflectance of a shortwave infrared band (1640 nm, MODIS Band 6).

The method was particularly well suited to this environment because of the lack of vegetation and can identify snow on all surfaces including frozen lakes. To mitigate the impact of clouds on the daily SCA estimation, pixels identified as clouds in the MOD10A1 were replaced by the most recent, previous cloud-free FSCA value (Hall et al. 2019). FSCA was then summed over the area of interest for each day of the period of record (2002–2021). Calculated depletion curves for the CALM grid are represented as areas based on the nominal pixel size (463.3 m). Though the actual footprint is somewhat larger at Utqiagvik's latitude, the disparity can be ignored as the timing and rate of ablation is of primary concern. Additionally, lack of solar illumination early in the calendar year results in erroneously low estimations of SCA; however, these conditions exist prior to the onset of melt and can also be ignored.

Figure 10. Moderate Resolution Imaging Spectroradiometer (MODIS) tiles at the CALM grid (*red*) and time-lapse camera (*yellow*) sites.



2.3 Hydrological modeling

There are two primary watersheds in Utqiagvik, a 19.8 km² basin draining to the Middle Salt Lagoon and a 12.8 km² basin draining into a complex of small dams and lagoons above the Tasigarook Lagoon (Figure 3). Both lower lagoons are directly adjacent to the ocean and the alignment of the proposed revetement. In late May or early June of each year, the annual snowpack melts in what is typically a roughly two-week ablation and runoff period (McCarthy 1994; Braddock and McCarthy 1996). The meltwater makes its way to the lagoons where it is partially retained by sand berms on the beach constructed to prevent seawater from entering the lagoons, which are then breached and the meltwater is released to the ocean.

The average annual runoff from both snowmelt and rainfall was reported to be approximately 110 mm (Dingman 1980). Snowmelt makes up the majority of the annual runoff, though the fraction of available SWE that is converted to runoff ranges significantly from estimates as high as 90%–100% (Brown et al. 1968; McCarthy 1994) to measurements following periods of drought as low as 33% (Douglas et al. 2017) and 29% (Liljedahl et al. 2017).

Snowmelt runoff can be delayed by small scale processes like snow-damming, meltwater storage in snowpack, and refreeze. While these processes are common in many regions that experience snowmelt, they are amplified in low gradient, extremely cold arctic regions (Schramm et al. 2007; Pohl et al. 2005; Kane et al. 1991). Common hydrologic modeling approaches used elsewhere typically ignore these processes with limited consequence. However, in the arctic, snow-damming resulting from runoff collecting in snow-filled channels can delay runoff onset on the order of days and weeks (Schramm et al. 2007). The formation of snow dams is a very local process that is currently not implemented in common snowmelt runoff modeling software and would be difficult to reasonably parameterize. Some attempts have been made to numerically simulate snow dams, but existing models are at the scale of a single dam (Xia and Woo 1992) and not suitable for application at the watershed scale. This reality makes it extremely challenging to accurately calibrate and validate runoff models when modeled runoff peaks may be days or even weeks earlier than observations.

2.3.1 Snowmelt runoff model

The HEC-RAS (version 6.1) was used to route the snowmelt runoff calculated by SnowModel. The model was selected to address several specific modeling constraints. First, the region's low gradient terrain includes the presence of many vegetated drained thaw lake basins (Liljedahl et al. 2017) and exhibits a "fill-and-spill" behavior of runoff progression (Douglas et al. 2017). Shallow depressions must fill with runoff to a level that exceeds some local grade control before entering a successive depression, creating complex flow paths. In some cases, portions of watersheds can be deranged having no clearly defined drainage network (Stuefer et al. 2017). Some of the water during snowmelt fills depressions in the terrain (i.e., water does not contribute to runoff), and when the depressions are filled, most water results in runoff (Dingman 1980). Second, the gridded runoff timeseries from SnowModel includes spatial variability resulting from wind redistribution of snow and topographic effects in the energy balance calculations. The runoff routing model must include both fine spatial topographic detail and the ability to incorporate spatially varied melt inputs to capture the complexity of the region's hydrology.

We used the HEC-RAS 2D diffusion wave approximation to the shallow water equations (DSW) to simulate runoff in a mesh model domain. DSW is appropriate for shallow, friction and gravity controlled flows (HEC 2016b) such as runoff. The relatively high-resolution (0.46 m horizontal) lidar derived terrain data (QSI 2019) allowed the model to capture some of the complex topography including dry lakes and shallow depressions that control flow patterns and provide depressions that hold meltwater during runoff.

The modeling domain included the Nunavak Creek watershed above the US Geological Survey (USGS) gage, and both the Tasigarook Lagoon and Middle Salt Lagoon watersheds (Figure 3).

HEC-RAS allows users to define a spatially variable precipitation boundary condition which is applied to the modeling mesh. We used this feature to define the snowmelt or LWASS timeseries as the model's hydrologic boundary condition. While we are using the precipitation boundary condition in HEC-RAS for convenience, the input is actually the total runoff produced by SnowModel, which includes snowmelt and liquid precipitation from rain-on-snow events. Network Common Data Form

files of the *roff* variable produced by SnowModel were converted to the HEC Data Storage System format using a Python script and assigned as a meteorological precipitation boundary condition. Terrain roughness values (i.e., Manning’s roughness value, Table 2) were selected from the range suggested by HEC (USACE 2022) which are tied to land use classification in the 2016 National Landcover Database (Dewitz 2021) (Figure 5). Despite different land cover products being used within SnowModel and HEC-RAS configurations (NALCMS versus National Land Cover Database [NLCD]), both products are derived from approximately the same satellite imagery (2015 and 2016 Landsat 30 m spatial resolution). Moreover, as can be seen in Figure 5, the actual land cover for our study area shows no significant differences between the two products.

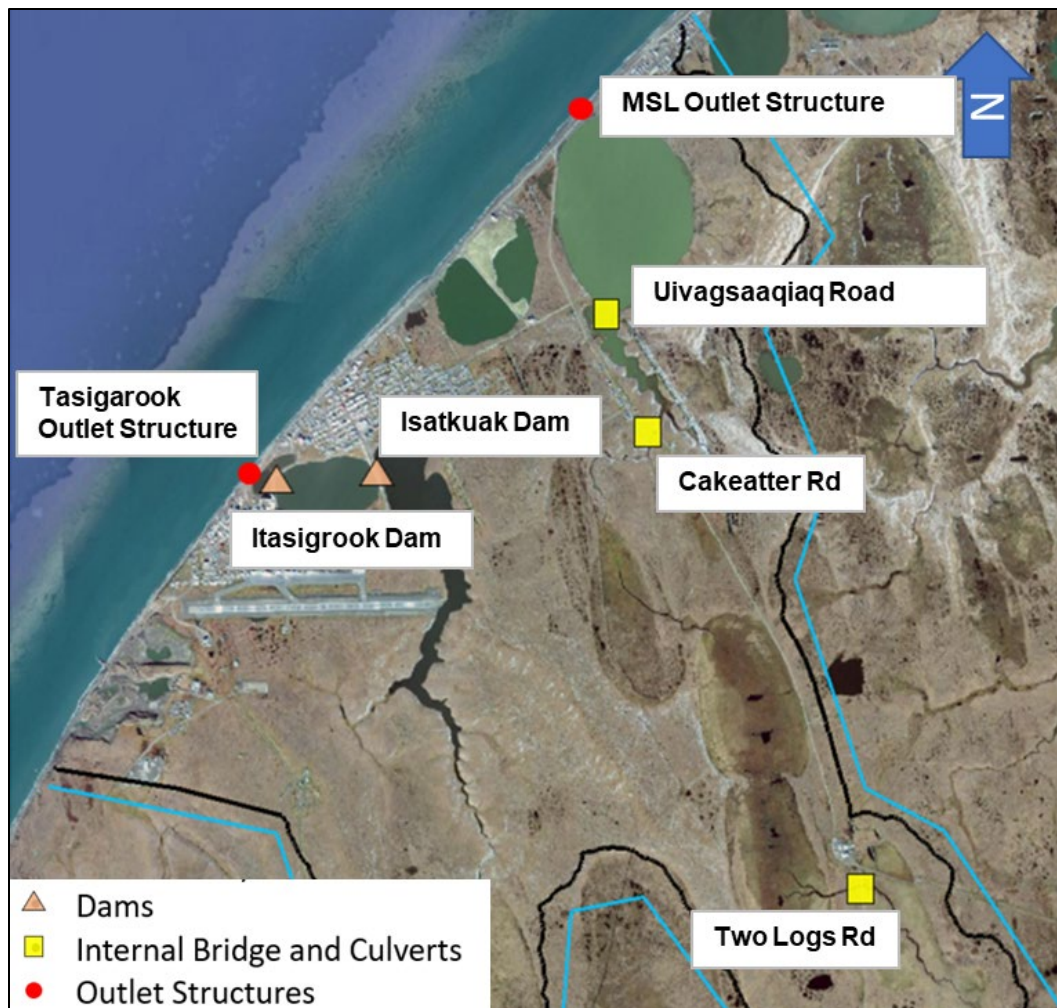
Table 2. Manning’s roughness values used for the Hydrologic Engineering Center–River Analysis System (HEC-RAS) model.

NLCD Landcover Classification	Manning’s Roughness Value
NoData	0.04
Sedge-Herbaceous	0.04
Open Water	0.035
Emergent Herbaceous Wetlands	0.06
Developed, Open Space	0.035
Developed, Low Intensity	0.08
Developed, Medium Intensity	0.12

2.3.2 Hydraulic structures

The watersheds include several hydraulic structures including road culverts and small earthen dams (Figure 11) which were included in the model domain.

Figure 11. Hydraulic structures in Middle Salt Lagoon and Tasigarook Lagoon watersheds.



2.3.2.1 Outlet Structures

Outflow from both the Middle Salt Lagoon and the Tasigarook Lagoon are regulated by outlet structures. The outlet structure for the Middle Salt Lagoon is a pair of wooden box culverts beneath Stevenson Street leading to the beach (Figure 12). The outlet structure on Tasigarook Lagoon is a row of 7 box culverts (Figure 13).

Figure 12. Middle Salt Lagoon outlet structure. (Image from Corps of Engineers, Pacific Ocean, Alaska District [CEPOA]. Public domain.)



Figure 13. Tasigarook Lagoon outlet structure. (Image from CEPOA. Public domain.)



2.3.2.2 Dams

There are two small dams in the Tasigarook Lagoon watershed. The lower Itasigrook Dam, which is directly upstream from the Tasigarook Lagoon, forms the Lower Isatkoak Lagoon. Outflow from the dam is passively controlled by a sheet pile weir spanning approximately 23.3m (Figure 14).

The Itsatkuag Dam is directly upstream and forms the Upper Isatkoak Lagoon which is also the city water supply. Outflow from this dam is controlled by a row of 11 corrugated metal pipe (CMP) arch culverts (Figure 15).

Figure 14. Itasigrook Dam spillway crest. (Image from CEPOA. Public domain.)



Figure 15. Itsatkuag Dam outlet structures. (Image from CEPOA. Public domain.)



2.3.2.3 Bridges and culverts

There are three culvert crossing locations in the Middle Salt Lagoon watershed. The most downstream structure at Uivagsaaqiaq Road, consisting of three elliptical culverts spans the upper end of Middle Salt Lagoon. There are two CMP culverts under Cakeatter Road and two culverts under Two Logs Road. Details of the structures, their dimensions, and the source of information are included in Table 3.

Table 3. Hydraulic structures in the HEC-RAS model.

Structure Type	Description	Number	Dimensions	Source Data (RAS Element)
Outlet Structures	—	—	—	—
Tasigarook Lagoon	Box Culverts	7	Unknown	Composite rating curve from dam safety inspection report (Coleman 2016b) (rating curve)
Middle Salt Lagoon	Wooden Box Culverts	2	1.5 m × 1.5 m	Estimate from photo (culverts) in Figure 12.

Table 3 (cont.). Hydraulic structures in the HEC-RAS model.

Structure Type	Description	Number	Dimensions	Source Data (RAS Element)
Dams	—	—	—	—
Itasigrook Dam	Sheetpile Weir	1	23.3 m	Engineering Drawing from dam safety inspection report (Coleman 2016b) (weir)
Isatkaug Dam	CMP Arch Culverts	11	1.1 m × 0.7 m (W × H)	Labeled photo in Coleman (2016a) (culverts)
Culverts	—	—	—	—
Uivagsaaqiaq Road	Aluminum Ellipse	3	4.5 m × 3.2 m (W × H)	Engineering Drawing (Reynolds 2018) (culverts)
Cakeatter Road	CMP Culverts	2	1.5 m diameter	Estimated (culverts)
Two Logs Road	CMP Culverts	2	1.2 m diameter	Estimated (culverts)

2.3.2.4 Bathymetry

Bathymetric data for the lakes was estimated using best available information. Data for Middle Salt Lagoon were derived from some incidental depth measurements made during a geotechnical drilling project (Dilley 2008). Depths and storage assumptions for the lagoons above the Tasigarook Lagoon were based on information from a dam safety Periodic Inspection Report (Coleman 2016b).

2.3.3 Snowmelt runoff calibration and validation

While there is a long history of scientific instrumentation in the region, there are no long-term runoff discharge measurements or lagoon stage records available to validate model simulations to in the study area. A formerly operated USGS stream gage (No. 15798700) on Nunavak Creek operated between 1972 and 2004. This gage is directly adjacent to the study area and provided the only long-term source of runoff data for model calibration.

Comparing simulated runoff to measured discharge at the Nunavak Creek USGS gage (Figure 3), provided a method for calibrating snow accumulation and ablation from SnowModel. The watershed area above the gage is approximately 7.5 km² which is similar in scale to Middle Salt Lagoon and Tasigarook watersheds. Runoff in the basin is partially regulated by Lake Emaiksoun, which is around 1.8 km² in area. Flows recorded at the Nunavak Creek gage were made manually by USGS staff for the ascending limb, then a new datum was set at the stilling well

recorder for the rest of the season (Matt Schellekens, pers. comm.).* Our calibration effort focused on runoff volumes rather than the usual peak timing and magnitude approaches. The calibrated models were then applied to the Middle Salt Lagoon and Tasigarook Lagoon watersheds.

2.4 Stage frequency and uncertainty analysis

The end products of this study were stage-frequency curves for two lagoons adjacent to the proposed coastal revetment. The Tasigarook and Middle Salt Lagoons (Figure 3) were both included in the HEC-RAS model, and simulations of runoff included routing through them and their existing outlet structures.

A key challenge of this study was quantitatively dealing with the impact of snow dam processes on the stage-frequency curves for the subject lagoons. While we could extract peak stages from the lagoons from our simulated runoff results from each year, snow dams and refreeze were not directly modeled and the stages did not necessarily represent the peak stage for that specific year. To address this, we estimated the stage-frequency curves using two different methods. The first method was volume-driven, using the modeled runoff results from the SnowModel and HEC-RAS workflow. The second was a simple but conservative peak-flow driven method which made use of transposed peaks from the adjacent Nunavak Creek gage record.

2.4.1 Volume driven method

We developed a novel method to obtain stage-frequency curves by separating our analysis into three parts (Figure 16). First, we developed runoff volume-frequency curves which were insensitive to the delay processes. Second, we developed stage-volume curves for each watershed using a generalization of runoff responses as a function of melt intensity observed in the simulated results. Last, we combined the curves to obtain peak stage-frequency curves for each lagoon using a Monte Carlo analysis to capture uncertainty in both the runoff volume-frequency curve and the stage-volume curves. The general workflow to develop stage-frequency curves is shown in Figure 17.

* 3 February 2022 Supervisory Hydrologist, United States Geological Survey, Fairbanks Alaska.

Figure 16. Example iteration of Monte Carlo simulation combination of bootstrapped fit volume-frequency curve combined with a randomly selected stage-volume curve transfer function to obtain a single updated stage-frequency curve.

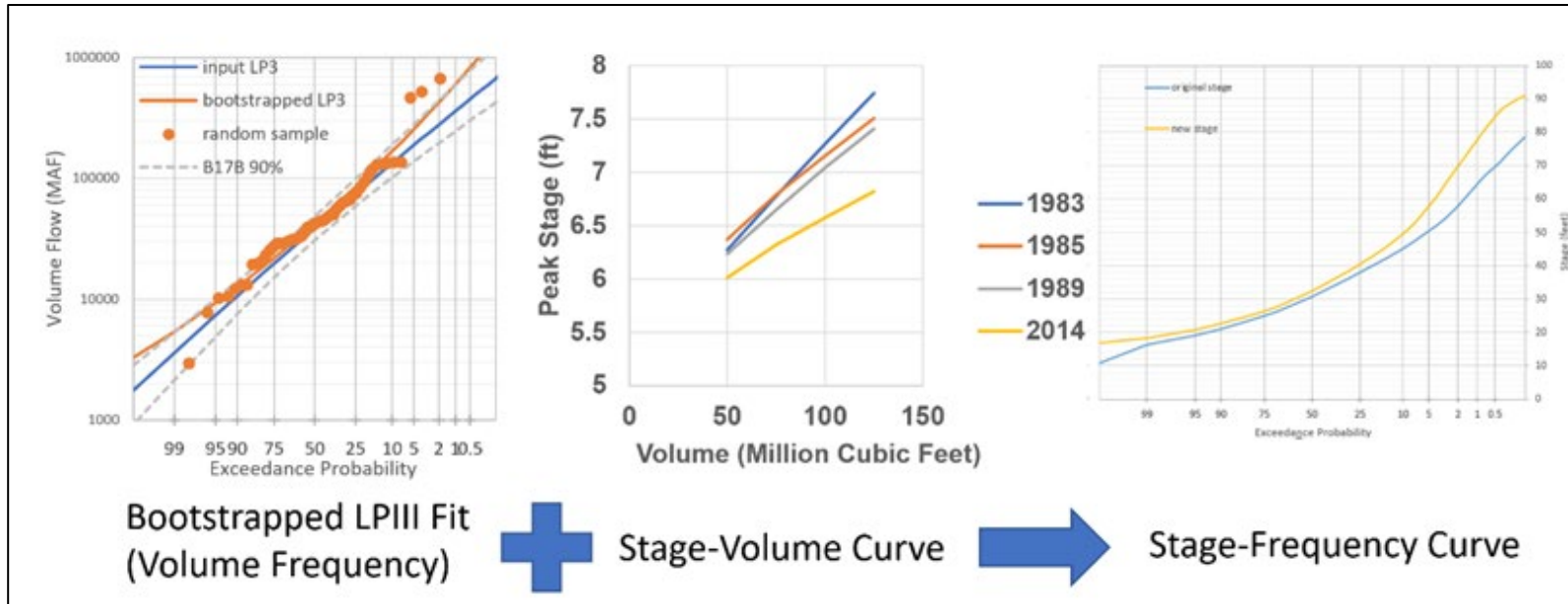
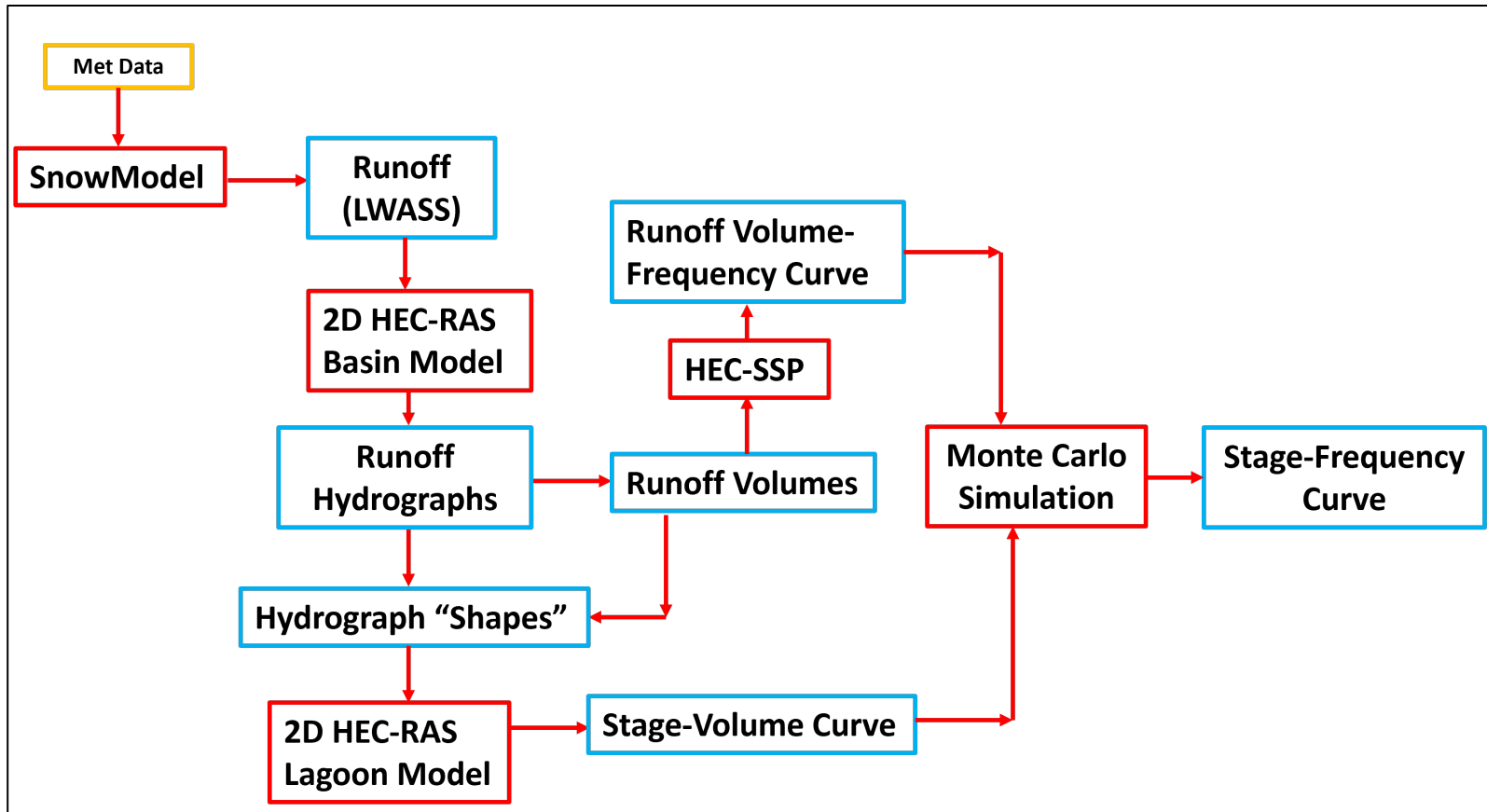


Figure 17. Schematic of a method to develop stage-frequency curves for lagoons.



2.4.1.1 Volume frequency curves

We compiled the annual maximum series of melt runoff volumes from the simulated results, based on a sliding 35-day window to capture the melt period. The selection of a 35-day window ensured that most of the runoff was captured for any given year, although the melt period was typically only 2–3 weeks in duration. The runoff volume annual maximum series was fit with a log-Pearson Type III (LP3) probability distribution using Bulletin 17C methods to obtain a volume-frequency curve for each lagoon watershed using the Statistical Software Program (SSP) produced by HEC.

2.4.1.2 Stage volume curves

Next, we investigated the effect of snow dams on runoff response to develop a generalized approach to accounting for the process of snow dam filling and breaching. Xia and Woo (1992) describe in detail how snow dams fail due to erosion from seepage or overflow. The breach progression depends on the energy inputs and the rate of melt. For example, if melt is gradual, reservoirs may fill slowly and erode the dam thermally resulting in a gradual release of meltwater in the basin. On the other hand, if meteorological conditions cause a rapid melt, the dams may overtop and breach from the erosive forces of the flowing water over their crests. Overtopping dams tend to cause a rapid cascading failure progression as upstream breaches lead to failures of dams lower in the basin (Xia and Woo 1992). From this we surmise that, while snow damming and breaching processes may delay the onset of runoff, the basin response is still strongly tied to the rate of melt; gradual melt will result in a moderated release of runoff over a longer time span, while rapid melt will produce a shorter event with a distinct period of peak flow.

From our sample of 40-year simulation results, we identified distinctive patterns of runoff hydrograph shapes that represent a range of different runoff responses driven by the meteorological conditions. The patterns generally represented years with

1. a sudden rapid melt with the majority of runoff occurring in just a few days,
2. a moderate period of melt ramping up to a single peak over the course of nearly a week,

3. a two-peaked response where early melt from solar radiation was followed by a second peak a few days later driven by sensible heat as the air temperatures warmed above freezing, and
4. a low and slow response with small diurnal peaks spanning over two weeks.

From these shapes, four different simulation years with distinct runoff hydrograph shapes were identified and normalized by volume. These normalized hydrographs encode the runoff response of each basin as a function of the intensity of the melt period without the need to consider the specific date of onset which is not important for developing stage-volume curves.

To develop peak stage-volume curves for each lagoon, the normalized hydrographs were scaled to a range of volumes coinciding with the range of the runoff volume-frequency curves. The scaled hydrographs were hydraulically routed through the lagoons with the HEC-RAS model to determine peak stage, and thus peak stage-volume curves were calculated for each of the four runoff patterns.

Two scenarios were simulated using this method. Tasigarook is a small lagoon with limited storage, and thus requires discharge through the outlet structure to prevent overtopping of Eben Hopson Street, even for relatively small runoff volumes. In contrast, Middle Salt Lagoon has a storage capacity sufficient to store some runoff without breaching the sand berm on the beach. Peak stage-volume curves were developed for both lagoons assuming the existing outlet structures were fully open allowing free discharge (scenario 1), and for the additional case where the Middle Salt Lagoon outlet remained closed, and runoff was stored without release (scenario 2). For scenario 2, where the outlet of Middle Salt Lagoon is closed, the peak stage-volume curve is insensitive to the runoff timing and is therefore a single curve regardless of the shape of the input hydrograph.

2.4.1.3 Stage-probability curves

A stage-probability curve can be created by combining the discharge-probability and stage-discharge curve, assuming the probabilities for a given volume-stage pair are equal. However, this approach does not account for the uncertainty that exists within the volume-frequency curve, computed from 40 years of simulated data, or the variations in the stage-volume relationship because of the hydrograph shape. To estimate the

stage-frequency curve including the uncertainty surrounding the curves, a Monte Carlo analysis was performed by first using parametric bootstrapping of volumes from the LP3 volume-frequency curve to estimate a new LP3 distribution based on those peak flows or volumes, and pairing the new LP3 curve with a randomly selected peak stage-volume curve to produce a peak stage-frequency curve for each lagoon. This process was repeated numerous times until the expected 1% annual exceedance probability (AEP) converged to an error tolerance of 2%. This process is described in EM 1110-2-1619 (USACE 1996) and implemented in the HEC Flood Damage Assessment (FDA) software (HEC 2016a). However, instead of computing a damage-probability curve, as HEC-FDA ultimately does, a stage-probability curve is created.

Discharges can be computed for the LP3 distribution at selected exceedance probabilities using the following equation (IACWD 1982):

$$\text{Log } Q = \bar{X} + KS, \quad (3)$$

where

- Q = the selected discharge quantile for a given exceedance probability,
- $\bar{X}$ = the mean log-discharge estimate,
- S = the standard deviation of log-discharge, and
- K = the deviate, a function of the skew coefficient and given exceedance probability.

The moments (mean, standard deviation, and skew) computed from Bulletin 17C are the values used for the mean and standard deviation, and skew. The K value is computed from the following Wilson-Hilferty approximation (useful from skew -1 to 1):

$$K = \frac{2}{G} \left[\left[\left(K_n - \frac{G}{6} \right) \frac{G}{6} + 1 \right]^3 - 1 \right], \quad (4)$$

where

- K_n = the standard normal deviate and
- G = the skew coefficient.

The parametric bootstrap begins by randomly sampling standard normal deviate values for K_n which then can be used to compute a discharge value.

The random sample size is the number of years from the simulated record generating a new set of peak annual maximum flows or 35-day annual maximum volumes. This sample represents a single realization drawn from the initial LP3 curve. The LP3 moments are computed from the sampled volumes to generate a new peak or volume frequency curve reflecting the uncertainty from the gage record. This Monte Carlo process was scripted and performed in Microsoft Excel.

The four flow-stage relationships together represent the uncertainty in that relationship. The likelihood of each of them occurring for a realization was assumed to be equal at 25%. This assumption could be further refined with more detailed observational data about the melt-out behavior of the basin, but based on the sparse data available each distinct pattern was assumed to have equal probability. For each new volume frequency curve, one of the four volume-stage curves was independently selected to transform the volumes to stages to generate a single stage-frequency curve. This method of transforming volumes to stages assumes the probability associated with each 35-day volume is the same probability as the matched stage (1% AEP 35-day volume = 1% AEP stage value). The bootstrap and volume-stage transform process is repeated 40,000 times for a total of 40,000 stage-frequency curves at each location.

Convergence testing is a way of determining whether a Monte Carlo simulation has enough realizations to produce accurate results. The following approach was used to check for convergence:

$$\left| \frac{z_{1-\alpha/2} S}{\bar{X} \sqrt{N}} \right| = \% \text{ error} \leq \% \text{ error tolerance}, \quad (5)$$

where

- $z_{1-\alpha/2}$ = the edge of a confidence interval around the expected value for a given α ,
- S = the standard deviation of the metric,
- $\bar{X}$ = the mean of the metric, and
- N = the sample size.

α was set at 10% (setting confidence intervals at 90%) and the error tolerance was set at 2%.

2.4.2 Peak-flow driven method

A Monte Carlo analysis was also used to calculate the uncertainty in the stage-frequency curves for the peak flow driven method. In this case, the input curves to the analysis were peak-flow-frequency curves. The annual maximum series of peak flows from the Nunavak Creek gage were transposed to the Tasigarook Lagoon and Middle Salt Lagoon watersheds (Figure 3) using a drainage area ration approach. The peak flow for Middle Salt Lagoon (Q_{MSL}) was calculated using the following equation:

$$Q_{MSL} = Q_{NUN} \left(\frac{A_{MSL}}{A_{NUN}} \right)^{0.8266}, \quad (6)$$

where

- Q_{NUN} = the peak flow at the Nunavak Creek gage,
- A_{MSL} = the area of Middle Salt Lagoon watershed, and
- A_{NUN} = the area of the and Nunavak Creek watershed.

The exponent accounts for the nonlinear scaling of peaks flows to watershed area and was based on values for the North Slope from Curran et al. (2003). The same approach was used to create an annual series of peak flows for the Tasigarook Lagoon watershed. The annual maximum series were fit with aLP3 probability distribution using Bulletin 17C methodologies in HEC-SSP.

The peak-flow-frequency curves were converted to stage-frequency curves using stage-flow curves derived from the HEC-RAS model. A range of steady state flows were run through each watershed model, and the resulting stage in each of the lagoons was recorded to create a series of flow-stage pairs which were converted into stage-flow curves. The Monte Carlo analysis proceeded in a similar fashion as outlined in the volume driven method to generate stage-frequency curves with uncertainty. The simulations were run with both outlet structures open (Scenario 1).

3 Modeling Results

3.1 Snow modeling and validation

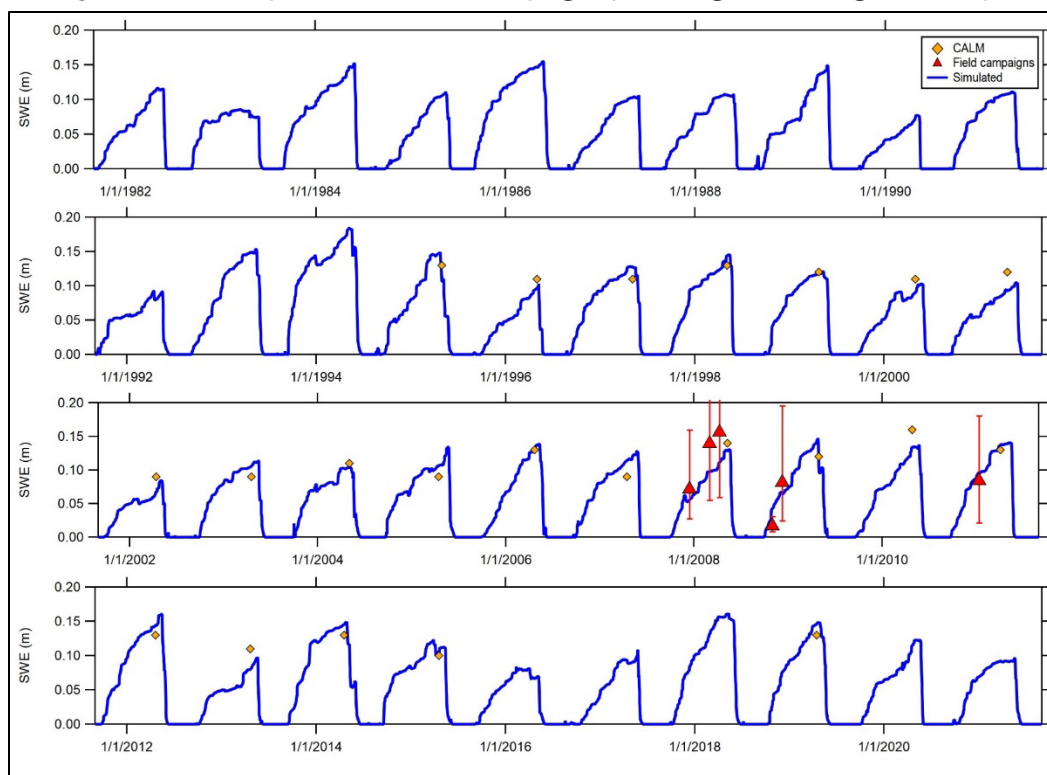
Snow modeling and snow model validation was carried out by comparing simulated SWE to observed SWE (converted from snow depth measurements) at the CALM site and SWE measurements from CRREL field campaigns. Additionally, we compared simulated SWE depletion dates with MODIS SCA at the CALM and time-lapse camera sites. We also evaluated simulated snowmelt dates and compared these dates to the imagery at the time-lapse camera site.

3.1.1 Snow model snow water equivalent (SWE) validated to CALM and CRREL field campaign measurements

Figure 18 shows the simulated SWE at the CALM site for WY 1982–2021. During the calibration phase of the snow modeling effort, it was noticed that, even though we had used the ERA5-Land precipitation as the forcing parameter, the SWE was still slightly below the observed SWE at the CALM site. Therefore, we corrected the precipitation with several different factors. In the end, we used a correction factor of 1.4 which resulted in simulated SWE that corresponded closer to the CALM SWE values than when no additional correction factor was applied. By correcting the precipitation with this value, the resulting correction factor was still within the precipitation factors reported by Liljedahl et al. (2017) (see Section 2.1).

In general, the snowmelt occurs in June. The maximum simulated SWE for the 40-year simulation varies from 0.077 to 0.18 m. The highest SWE was for WY94. During most years, SWE aligns well with the measured SWE at the CALM site. It is likely that the difference in simulated and measured SWE is because of the simplified conversion of snow depth to SWE using a constant snow density of 300 kg/m³. The simulated SWE is within the range of the CRREL field campaign measurements collected at a nearby site (see WY 2008, 2009, 2011 in Figure 18). Note that the distribution of SWE values during the CRREL field campaigns vary greatly confirming the complexity of the extreme environment in this area.

Figure 18. Simulated snow water equivalent (SWE; *blue line*), field measurements at CALM (*yellow diamonds*), and CRREL field campaigns (*red triangles including error bars*).



3.1.2 Snow model validated to MODIS and time-lapse camera

Figure 19 shows the SCA depletion curves from the MODIS imagery at the CALM and time-lapse camera sites (Figure 10). The depletion curves snowmelt dates occur at the CALM site in June. The earliest and latest year where snowmelt occurred were 2002 and 2018, respectively. At the time-lapse camera site, the time series was shorter (2015–2019), and the year when the earliest snowmelt occurred was in 2016.

The simulated snowmelt date aligns close to the SCA depletion snowmelt date from the MODIS imagery at the CALM and time-lapse camera sites (Figure 20). This is another validation of how the snow model is representing the actual snowmelt processed.

Time-lapse camera images from 2015–2019 (Appendix A) were also used to validate the snow model simulations. We used this dataset to compare observed and simulated snowmelt dates. Snowmelt varies spatially on the landscape and, at the time-lapse camera site, the time from onset of melt to completely snow-free is typically about three weeks (Table 4). This melt time-period is similar as reported by McCarthy (1994), and Braddock and

McCarthy (1996). In general, the simulated snow-free date aligns with the snowmelt dates.

Figure 19. Snow-covered area (SCA) depletion curves (in square kilometers) at the (a) CALM and (b) time-lapse camera sites.

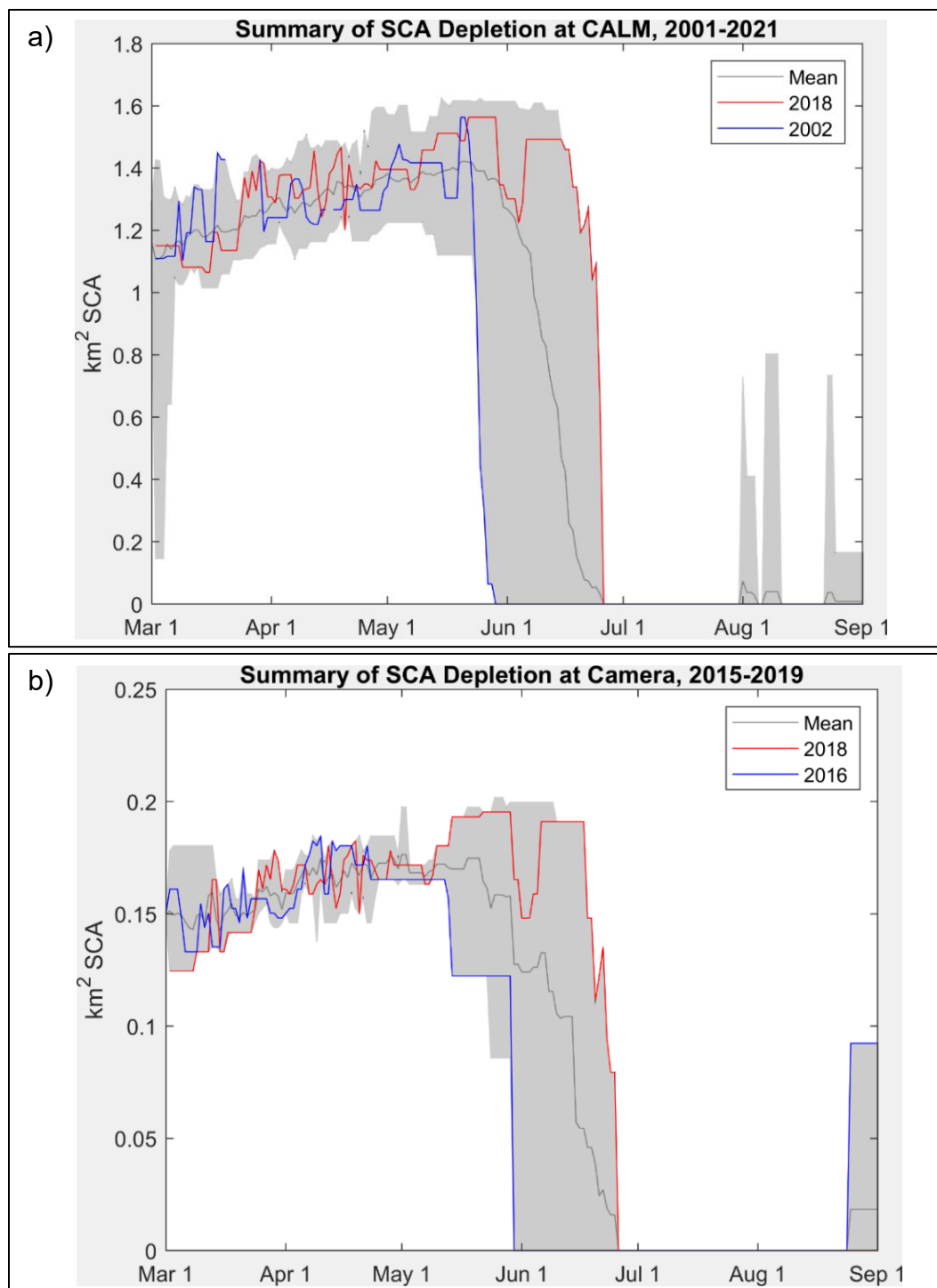


Figure 20. Modeled SWE (blue line) comparison to MODIS SCA at the camera (gray line) and CALM (black line) sites for WY 2002–2021.

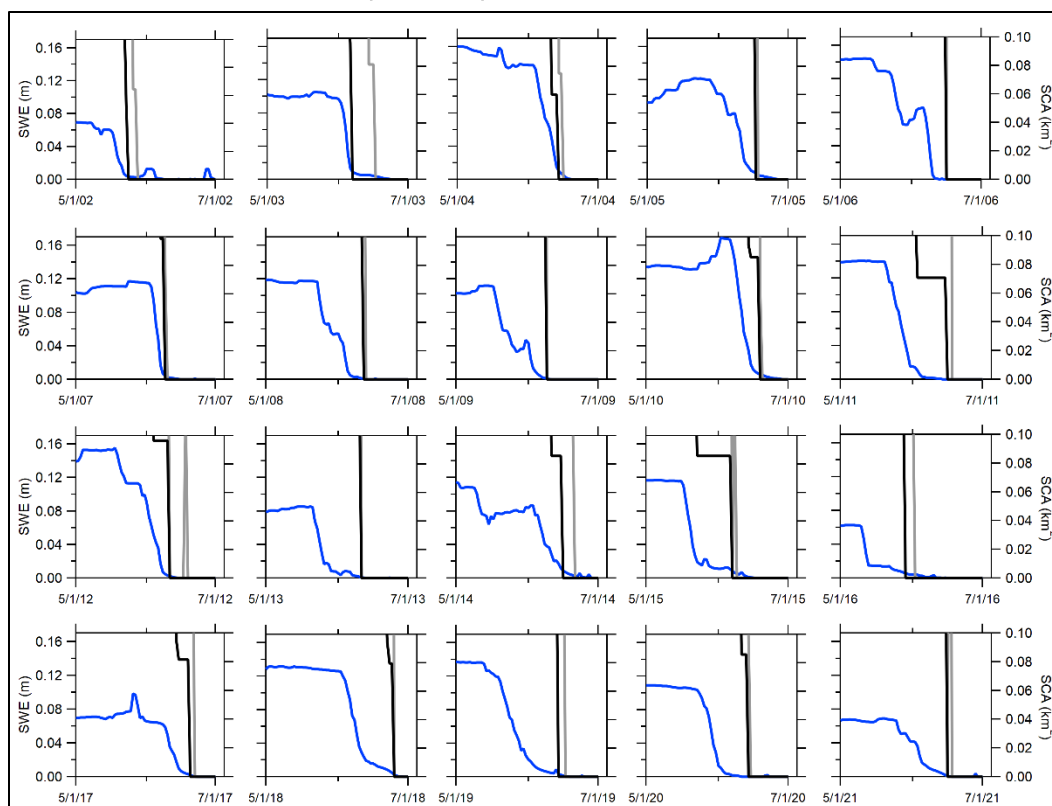


Table 4. Comparison of snowmelt dates from the time-lapse camera and snow model.

WY	Time-lapse camera: snowmelt onset to snow free dates	Simulated: snow free date
2015	18 May–10 June	12 June
2016	11 May–7 June	6 June
2017	1 June–22 June	18 June
2018	7 June–29 June	1 July
2019	1 June–19 June	17 June

3.2 Snowmelt runoff modeling and Stage Frequency Analysis

Snowmelt runoff modeling and validation was carried out by first simulating runoff in the Nunavak Creek watershed using the runoff from SnowModel routed through the HEC-RAS 2D model. We then compared the results to the USGS streamflow record available.

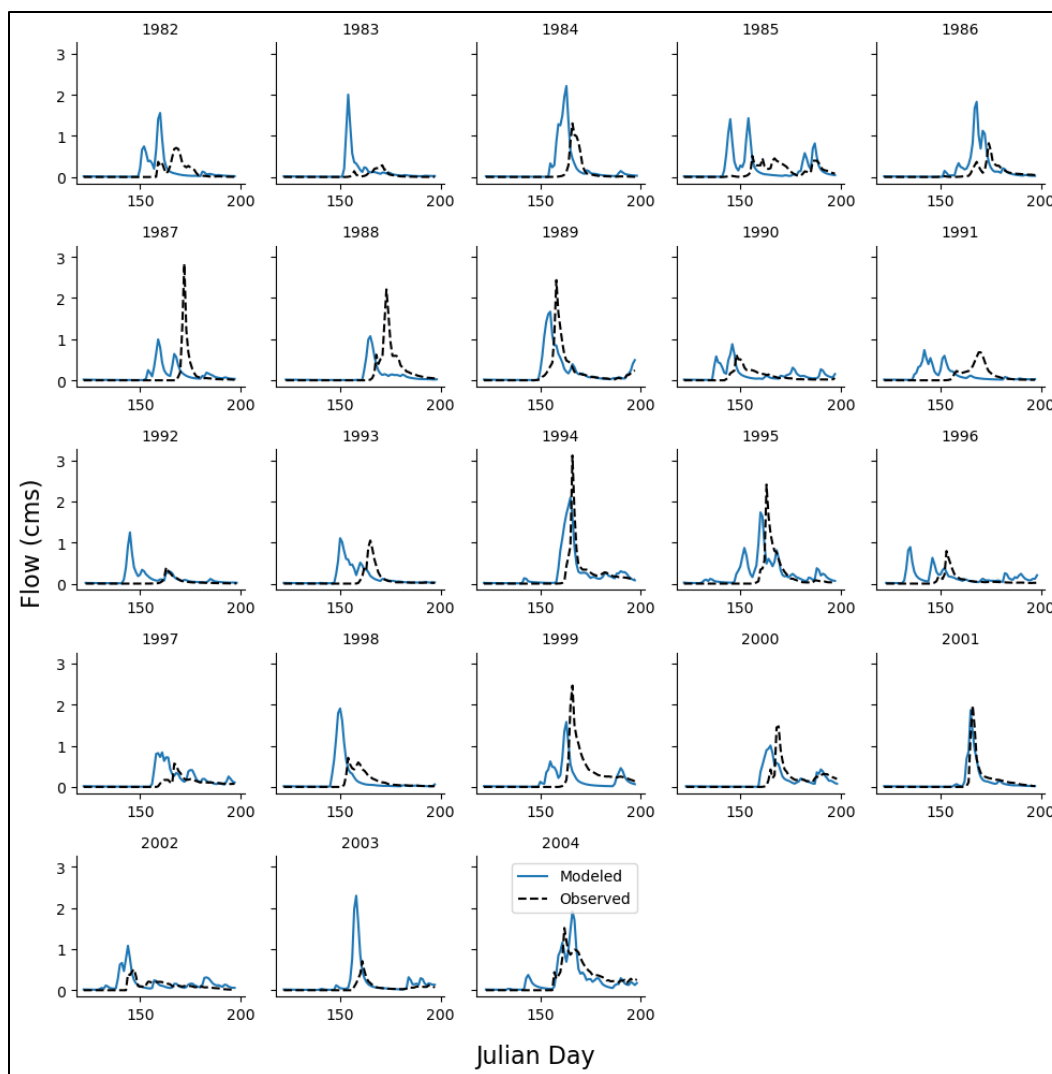
3.2.1 Hydrologic modeling

3.2.1.1 Nunavak Creek watershed

The modeled runoff hydrographs computed with HEC-RAS at the Nunavak Creek gage location generally did not match the observed hydrographs well (Figure 21). Modifications to the roughness parameters changed the runoff peak timing on the order of hours while the difference between the observed and modeled peaks were typically on the order of days or weeks, limiting the effectiveness of traditional hydraulic model calibration methods.

The snow ablation model captures the effects of water storage as melt moves vertically through the snowpack, but because it is decoupled from the runoff routing model, it does not directly handle snowmelt storage of meltwater after it reaches the soil surface. Other models attempt to capture the effects of runoff storage in the snowpack, but because of the dominant impacts of snow-damming, these models still miss the timing of runoff onset by several days (Schramm et al. 2007). Instead of viewing our model as a precise simulation of the runoff process, an unattainable goal with currently available methods, we consider it as a tool to capture the effects of spatially varied melt and terrain effects such as storage in dry lakes, albeit with runoff unimpeded by intermediate snow storage, refreeze and snow-damming. In the absence of these delaying processes, simulated runoff will tend to begin at concentrated locations lower in the basin earlier than observations. Simulated peaks may be larger or smaller than observations. However, as the lack of attenuation due to snow dams during a rapid melt period may cause an earlier high peak. Therefore, storage behind snow dams can slowly accumulate during a milder melt period and still produce a large peak from a sudden breach.

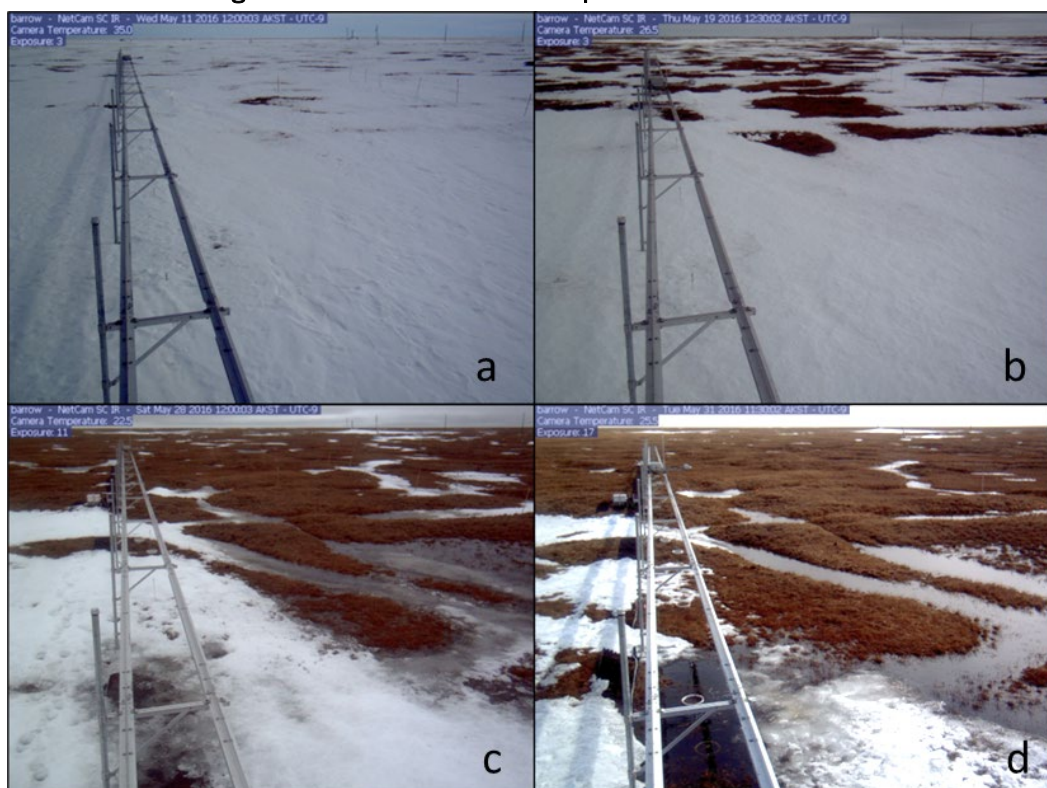
Figure 21. Runoff hydrographs modeled (*blue line*) and observed (*black dashed line*) at Nunavak Creek for WY 1982–2004.



We reviewed measurements of terrain albedo made at the NOAA Global Monitoring Laboratory station (<https://gml.noaa.gov/aftp/data/radiation/baseline/brw/>), just outside the study area and found that for the period WY 1998–2004 runoff at Nunavak Creek typically did not begin until the albedo had decayed to around 0.3 and the air temperature was above freezing. This suggests that while the arrival of longer periods of sunlight increases the incoming shortwave solar radiation and triggers melt, the meltwater is held locally on the landscape even after the snow melts sufficiently to expose the low albedo terrain (Figure 22). The exposed land absorbs much more energy than the surrounding snow creating a positive feedback loop that encourages further melt and terrain exposure (Dingman 1980). In some years (e.g., 1989 and 1995) runoff did not occur until the average

daily air temperature was above 0°C indicating that availability of sensible heat from the air may sometimes be necessary to allow ponded and partially frozen melt water to mobilize.

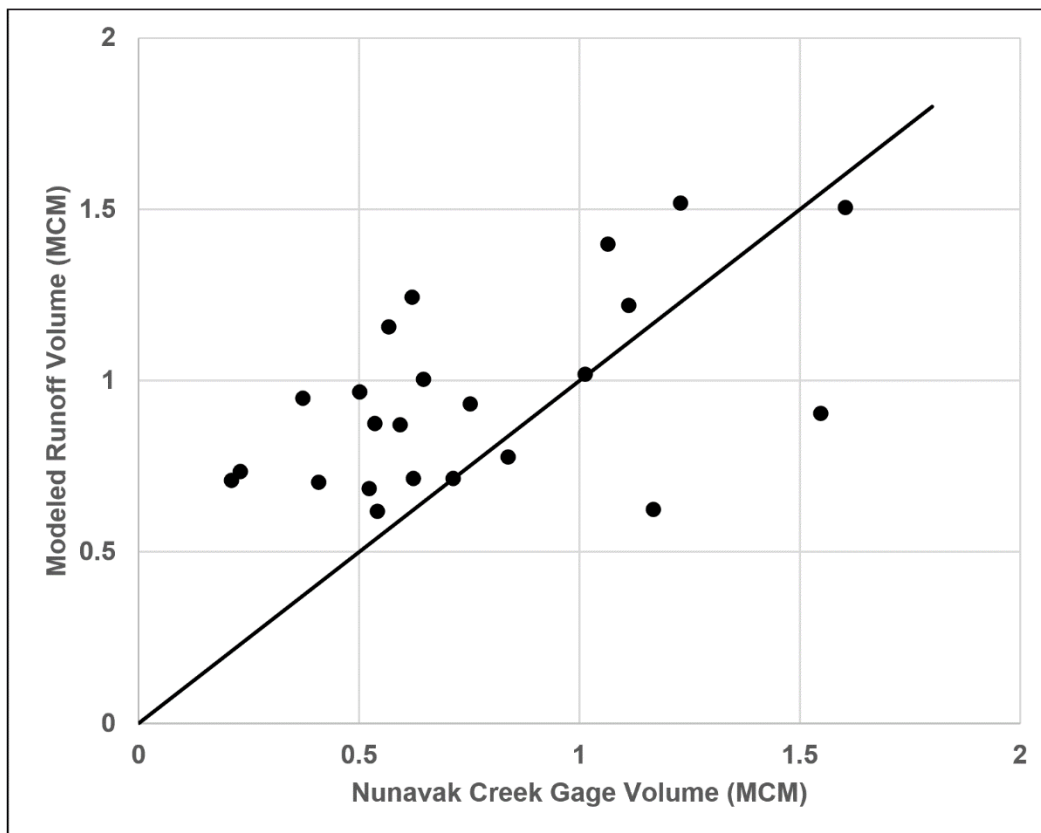
Figure 22. Progression of snowmelt and runoff in 2016 at Barrow Phenocam/time-lapse camera (<https://phenocam.nau.edu/webcam/sites/barrow/>; Milliman et al. 2019; Seyednasrollah et al. 2019). The panels depict conditions throughout May (a) 11 May: small patches of exposed terrain (b) 19 May: expanding snow-free areas (c) 28 May: majority of snow melted, ponded and frozen water in troughs, and (d) 31 May: ponded water has mostly melted but a significant amount remains in depressions on the terrain.



The maximum 35-day volumes of modeled runoff tended to be higher than the observed volumes (percent bias: 25.8%) (Figure 23). This indicates that the volume of input melt minus losses to storage on the modeled terrain is larger than the observed runoff. The consistent bias toward model overestimation of volume is likely in part because of the conservative limitation of losses during the runoff process. Others have noted significant infiltration losses tied to antecedent dry soil conditions (Douglas et al. 2017; Liljedahl et al. 2017), but unfortunately their observational period does not overlap with the Nunavak Creek gage record for comparison. Without a quantitative estimation of historic soil moisture conditions to calculate infiltration losses, the only losses we included in the volume estimates were terrain-based losses from standing meltwater

stored in landscape depressions. This assumption is expected to result in conservatively larger runoff volumes. The terrain storage was calculated using fine spatial resolution of the underlying terrain digital elevation model (DEM, 0.46 m) coupled with the subgrid resolution storage calculations that HEC-RAS employs.

Figure 23. Nunavak Creek maximum 35-day runoff volumes modeled versus observed (1982–2004).



3.2.1.2 Middle Salt Lagoon and Tasigarook Lagoon watersheds

The same model parameters used in the Nunavak Creek HEC-RAS model were applied to the watersheds of Middle Salt Lagoon and Tasigarook Lagoon for the period 1982–2021. There are no recorded flow or lagoon stage data in these watersheds to compare the results with directly. Based on the model results and comparison in the Nunavak Creek watershed, we expect similar issues with runoff delay in these results. We also expect that by conservatively assuming the only losses are those from runoff stored on the terrain that the volumes of runoff calculated by the HEC-RAS model are similarly larger than actual volumes as discussed in the Nunavak Creek section.

While the modeled peak stages in the lagoons could be used to directly calculate stage-frequency curves, there is considerable uncertainty in the timing of the inflows from runoff which ultimately would introduce uncertainty into the calculated peak stages that would be difficult to quantify. To avoid this issue, we extracted the volumes (nontime dependent) from each year of these simulations and built an annual series of volumes as an input to the volume driven stage-frequency method.

3.2.2 Volume driven method

3.2.2.1 Volume frequency curves

The 35-day volume frequency curves, which are the key input to the volume driven stage-frequency curve method (Section 2.4.1), were estimated using HEC-SSP. The annual maximum 35-day runoff volumes were extracted from the simulated HEC-RAS results from 1982–2021 for both Middle Salt Lagoon and Tasigarook Lagoon (Table B-1, Appendix B). Values range from 1.4 MCM (2016) to 3.0 MCM (2004) and from 0.8 MCM (1988, 2016) to 1.9 MCM (1994) for Middle Salt Lagoon and Tasigarook Lagoon, respectively.* The simulated annual maximum values were treated as the systematic record. No other historical information was included for the analysis. Regional skew was excluded as discussed in the peak flow frequency analysis, below, and the Hirsh-Stedinger plotting position method was used for visually comparing the analytical fit.

The Multiple Grubb-Beck (MGB) low outlier test identified 19 potentially influential low flood observations at Middle Salt Lagoon while the MBG tests identified no outliers at Tasigarook Lagoon. MGB is a generalized low outlier test that can identify multiple potentially influential low floods in the dataset. These identified values could have a large influence on the upper end of the flood frequency curve. The Grubbs-Beck Critical Value was computed as 2.05 MCM/s, meaning values up to the critical value were identified as influential low flows. Censoring the potentially influential low flood observations at Middle Salt Lagoon slightly improved the fit between the analytical curve and plotted values at the lower probability region (upper end of the frequency curve); however, censoring the potentially low flood observations came at the expense of a reduced fit at the higher probability ranges (lower end of the frequency curve). The MGB test did not identify potentially influential low floods at Tasigarook Lagoon.

* MCM: Million cubic meters.

Additionally, the analytical curve appears only slightly closer to the plotted values at the low probably frequencies; therefore, censoring was not performed in the analysis and the annual maximum volumes were treated all the same. A comparison of frequency results with and without outlier volumes for the 35-day volume frequency for Middle Salt Lagoon is shown in Figure 24a, and Figure 24b and Figure 24c shows the 35-day volume frequency curves computed for Middle Salt Lagoon and Tasigarook Lagoon.

Figure 24. The 35-day volume frequency for Middle Salt Lagoon comparing frequency results with and without outlier volumes (a). The curve with outliers is shown in *green* while the curve with no outliers is shown in *red*. The 35-day volume frequency curve computed in HEC-Statistical Software Program (HEC-SSP) for Middle Salt Lagoon (b) and Tasigarook Lagoon (c).

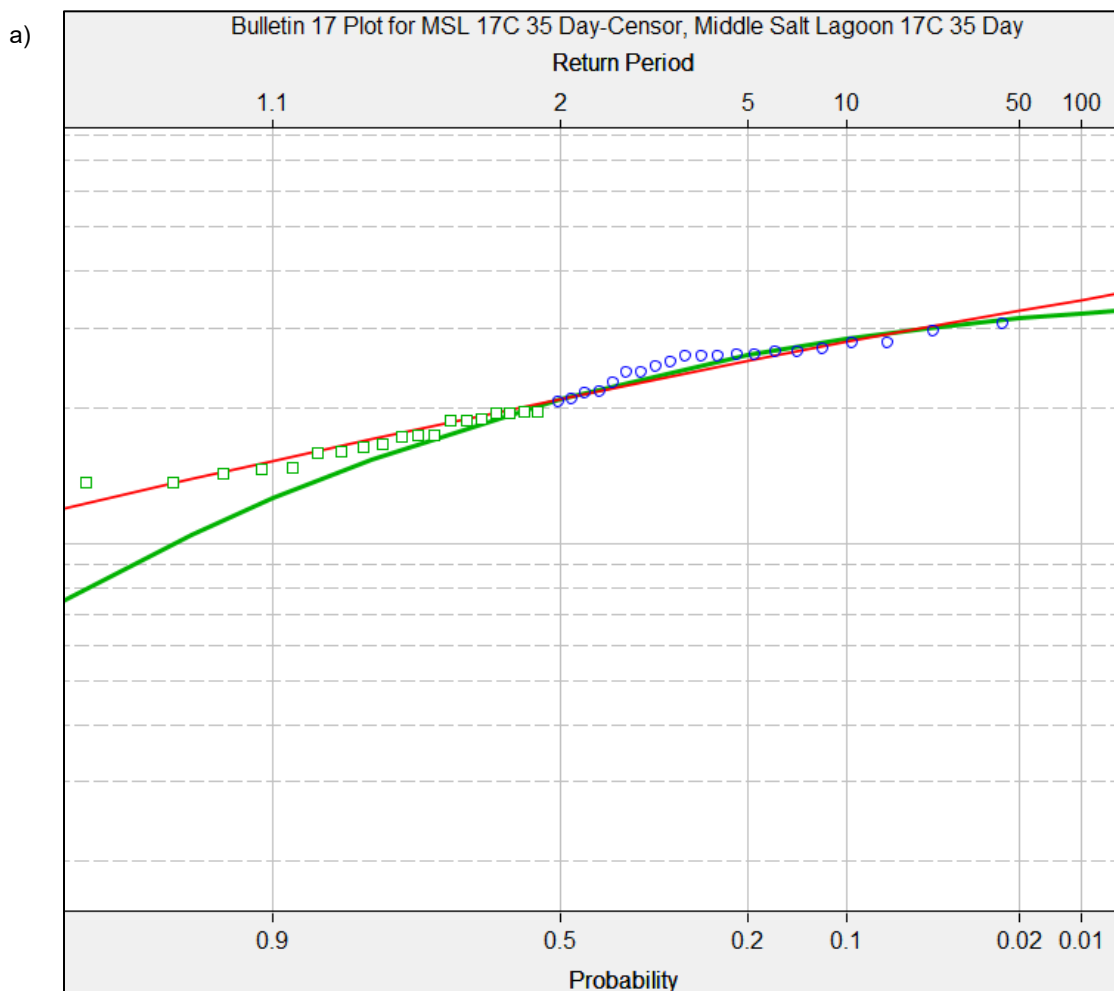
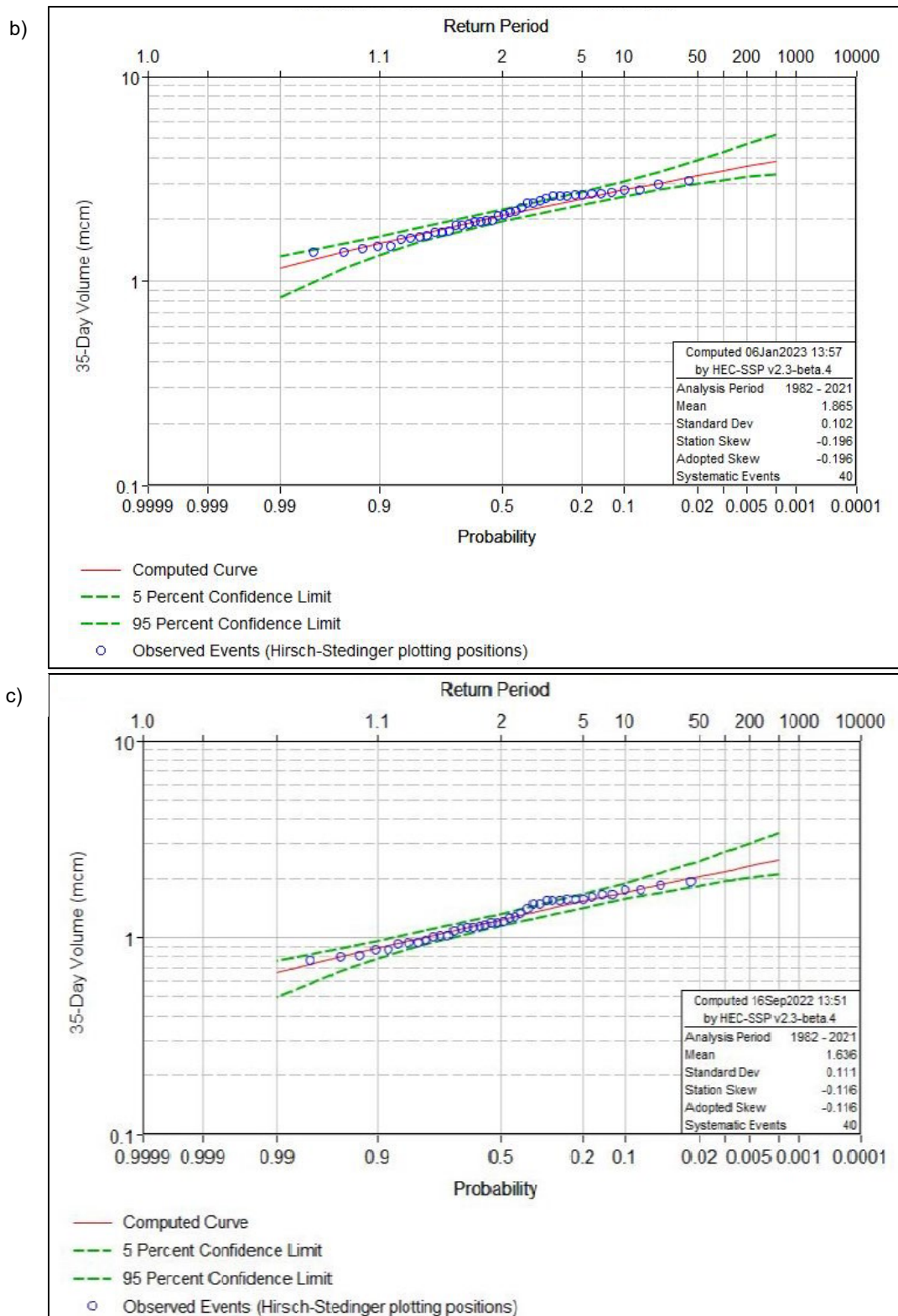


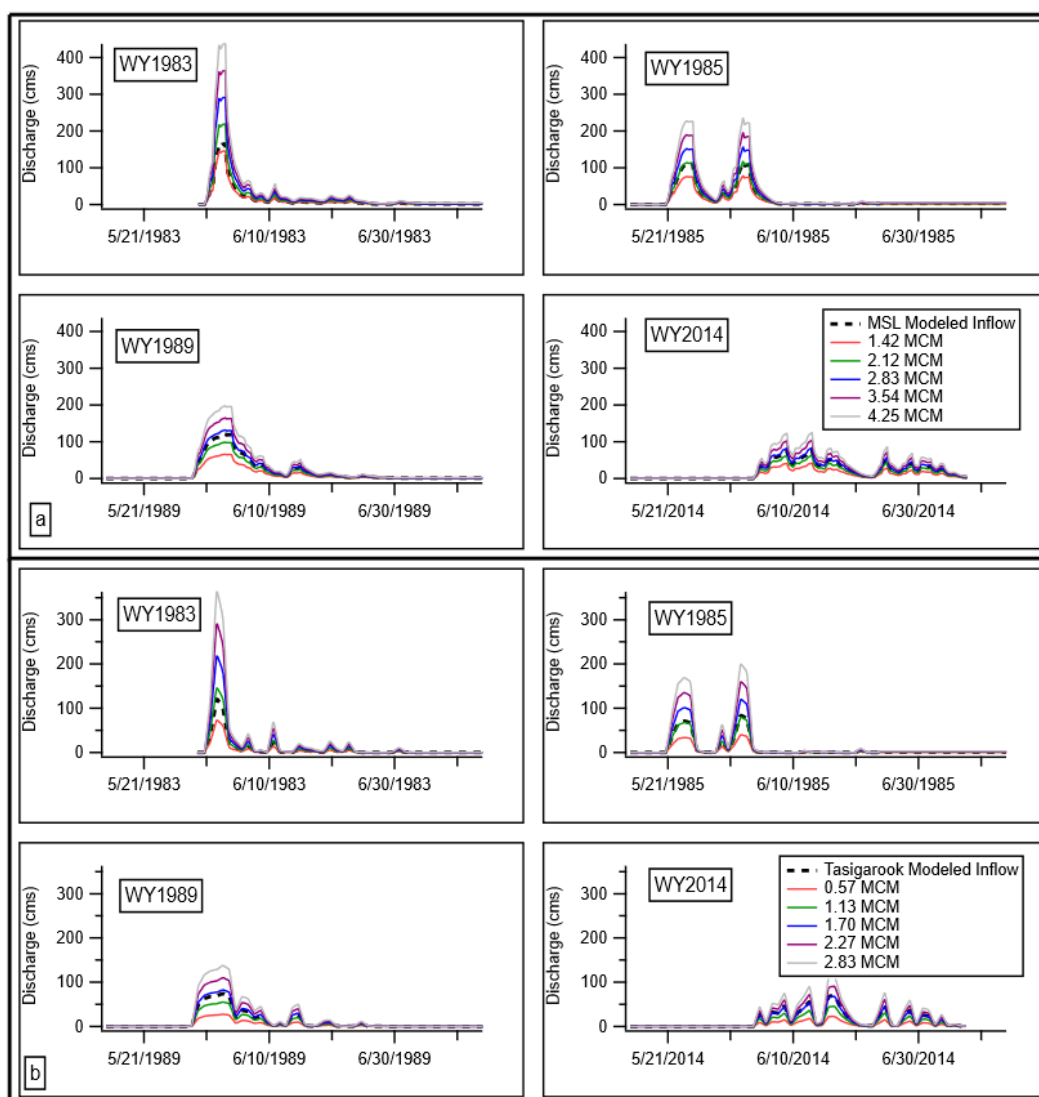
Figure 24 (cont). The 35-day volume frequency for Middle Salt Lagoon comparing frequency results with and without outlier volumes (*a*). The curve with outliers is shown in *green* while the curve with no outliers is shown in *red*. The 35-day volume frequency curve computed in HEC-Statistical Software Program (HEC-SSP) for Middle Salt Lagoon (*b*) and Tasigarook Lagoon (*c*).



3.2.2.2 Stage volume curves

Simulated runoff hydrographs from the years 1983, 1985, 1989 and 2014 were selected to represent the range of runoff shapes that the basin could experience based on meteorological conditions. The hydrographs were normalized to the modeled 35-day volume for each year then scaled to a range of runoff volumes spanning the volume-frequency curve (Figure 25).

Figure 25. Example scaled snowmelt runoff hydrograph shapes for the (a) Middle Salt Lagoon watershed and (b) Tasigarook Lagoon watershed. Model flow hydrograph (*broken black line*) is the unscaled modeled runoff hydrograph.

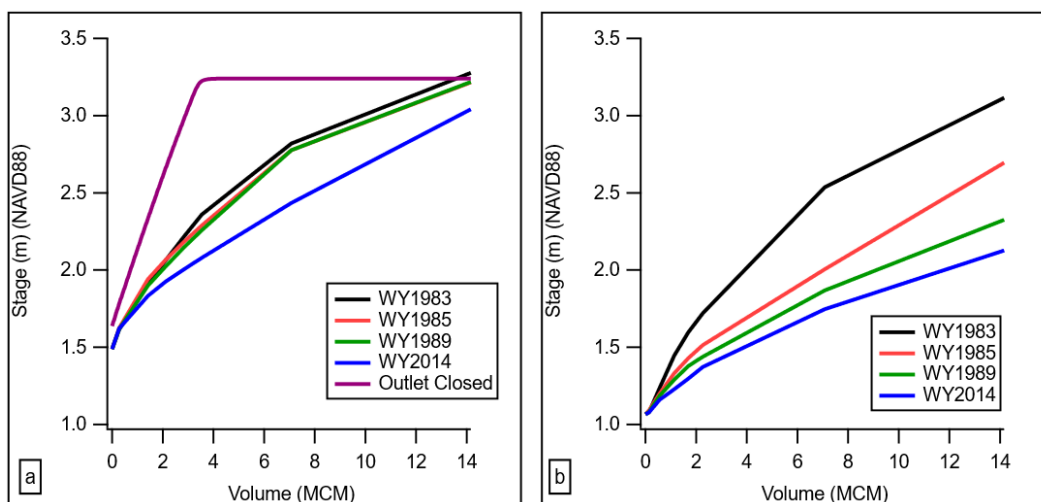


The scaled hydrographs were then routed through the HEC-RAS model of the lagoons, which are controlled by existing outlet structures. Peak stages

from each run were extracted from the lagoon stage hydrographs and used to construct stage-volume curves for each hydrograph shape (Figure 26).

The single-peaked shape from 1983, representing a rapid melt, produced the highest stages as inflows greatly exceeded the outlet capacity, while the gradual melt-out of the 2014 shape produced the lowest stages.

Figure 26. Stage-volume curves for (a) Middle Salt Lagoon and (b) Tasigarook Lagoon for different inflow hydrograph shapes.

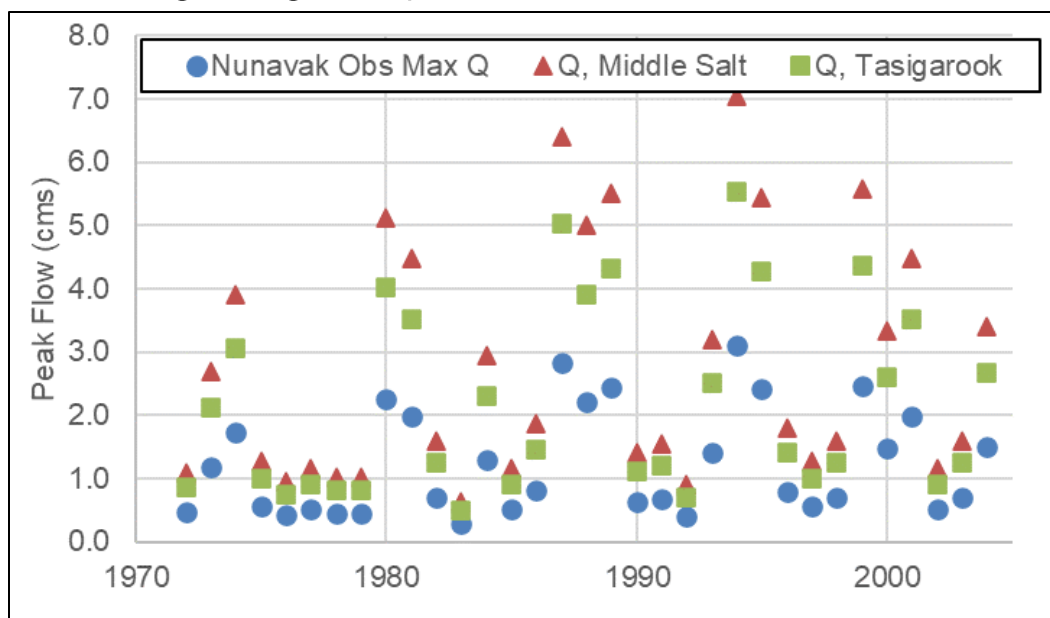


3.2.3 Peak driven method

3.2.3.1 Peak flow frequency curves

The annual maximum peak flows that are the key input to the peak flow driven stage-frequency curve approach (Section 2.4.2) were derived from transposing annual peak flows from the Nunavak Creek gage (Figure 27). The transposed peak flow annual series from 1972 to 2004 were input into HEC-SSP version 2.3 to compute peak flow frequency curves for Middle Salt Lagoon and Tasigarook Lagoon.

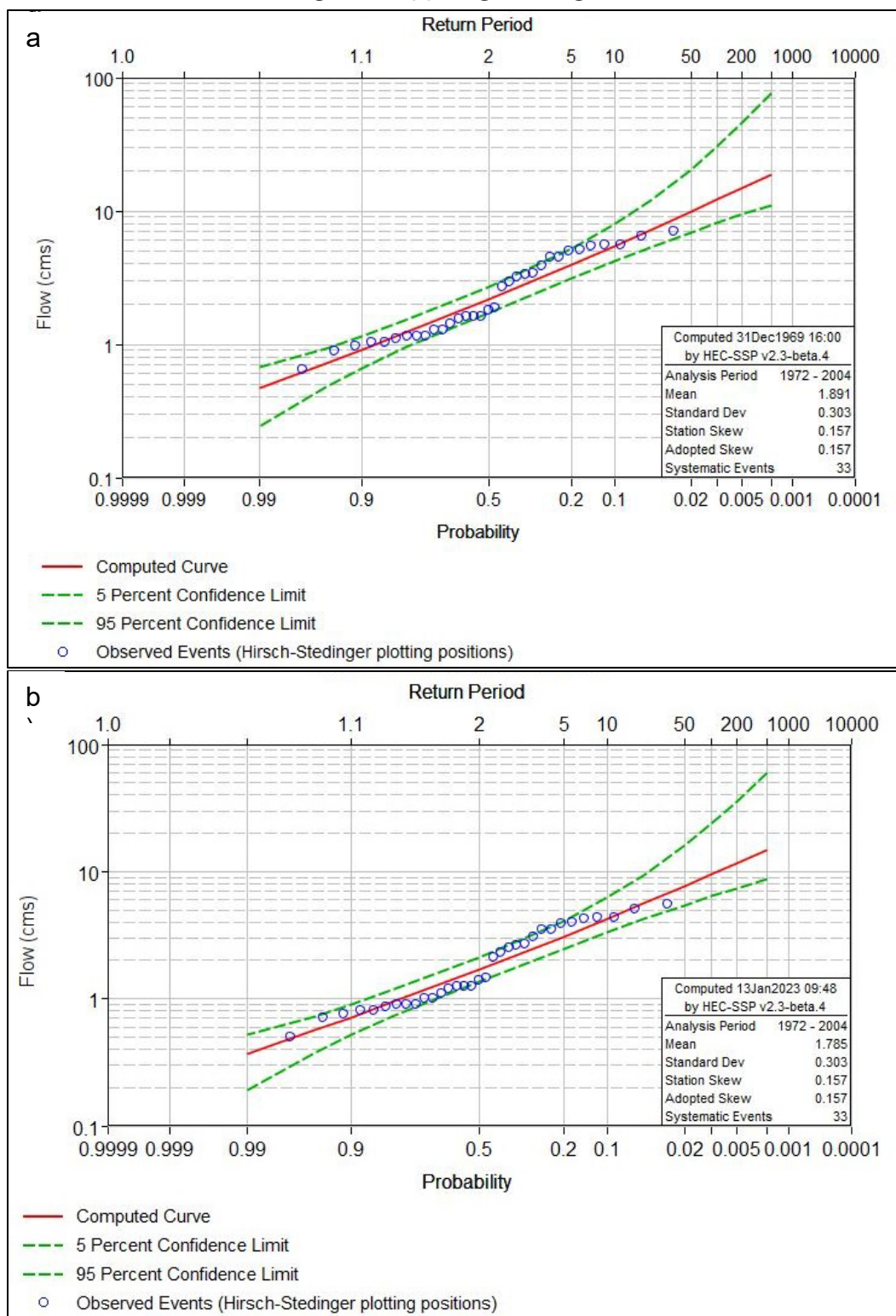
Figure 27. The annual maximum peak flows (Q) in Middle Salt Lagoon and Tasigarook Lagoon transposed from Nunavak Creek from 1972 to 2004.



HEC-SSP (HEC 2022) can use Bulletin 17-C methodology (England et al. 2019) for computing peak and volume frequency curves, which involves fitting an LP3 distribution to annual maximums using the expected moments algorithm. The perception threshold, which reflects the range of discharges that could be perceived and recorded by the gage, was set to a range from zero to infinity for the systematic period. No other historical information was included for the analysis. Regional skew was excluded as recommended by Curran et al. (2016) for areas of Alaska outside the regional skew study due to the low density of gages. The Hirsch-Stedinger plotting position (Stedinger et al. 1993) was used as a nonparametric technique for visually comparing the fitted curve as recommended in Bulletin 17C. The MGB low outlier test did not identify any potentially influential low flood observations at Middle Salt Lagoon or at Tasigarook Lagoon.

No further corrections were applied to the peak flows. When plotting the peak values against the computed LP3 curve, the LP3 curve does not appear to fit the plotted values well. A cursory review of the peak values suggests there could be some serial correlation to the dataset, which was not removed at the time of the analysis. Any consideration using the peak flow frequency curve should revisit the peak data and correct for any trends. Figure 28 shows the peak flow frequency curves at Middle Salt Lagoon and Tasigarook Lagoon.

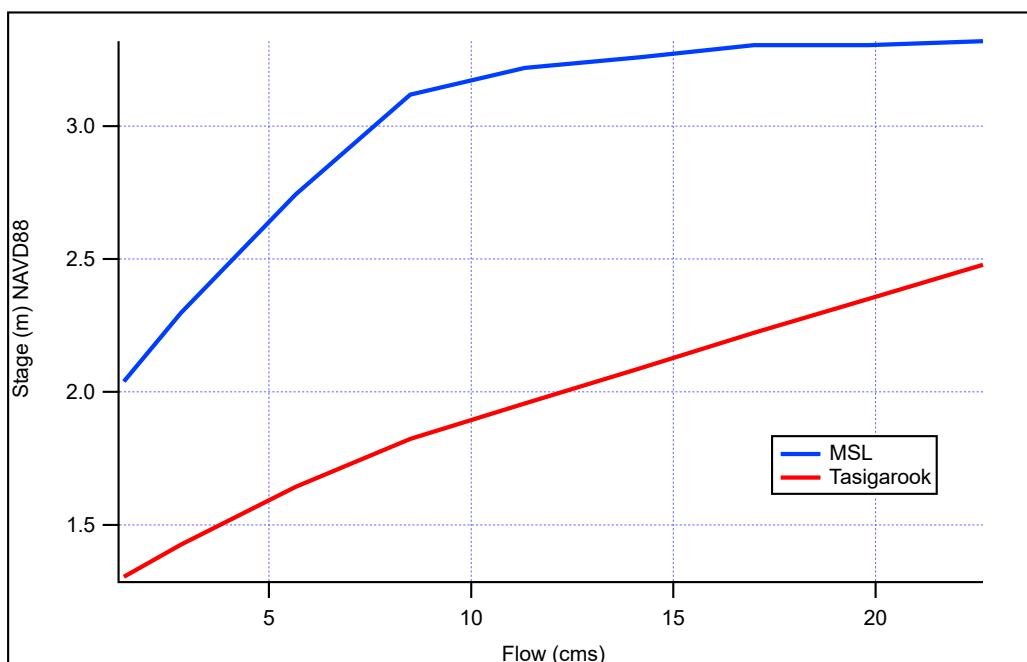
Figure 28. Peak flow frequency curve computed in HEC-SSP for (a) Middle Salt Lagoon and (b) Tasigarook Lagoon.



3.2.3.2 Stage peak flow curves

The peak-flow-frequency curves were used to create stage frequency curves via a single stage-flow curve for each lagoon (Figure 29). The curves were constructed by selecting the peak stage in each lagoon for a given steady state flow rate applied to the HEC-RAS model of each lagoon, with the outlet structures open.

Figure 29. Stage-peak flow curves for Middle Salt Lagoon and Tasigarook Lagoon for steady-state flows through the lagoons with the outlet structures open.



3.2.4 Stage-Frequency Curves

Stage frequency curves were constructed for each lagoon with both the volume driven method and the peak flow driven method.

A complete summary of the five stage frequency curves developed is listed in Table 5.

Table 5. Summary of stage frequency curves inputs and locations.

Annual Series	Transfer Function	Middle Salt Lagoon	Tasigarook Lagoon
35-Day Duration Volume	Stage-Volume Peak stage from dynamic flow 4 curves for 4 year-shapes <i>Outlets Open</i>	X	X
	Stage-Volume Peak stage from dynamic flow 4 curves for 4 year-shapes <i>Outlet Closed</i>	X	—
Peak Flow	Stage-Peak Flow Steady-state peak flow run through <i>Outlets Open</i>	X	X

The bootstrapped LP3 fit was obtained for each iteration of the Monte Carlo simulation by parametrically bootstrapping the volume or peak flow frequency curve for each watershed. This step produced a unique volume-frequency (or peak flow-frequency) curve for each iteration capturing the uncertainty in the volume (or peak flow) annual series based on the length of the data series. This unique LP3 fit was combined with either a randomly selected stage-volume curve (Figure 26) or the corresponding stage-peak flow curve (Figure 29) for the given lagoon. This combination yielded a single unique stage-frequency curve for each realization of the Monte Carlo simulation. The expected stage-frequency curve along with the median and 90% confidence limits were computed from the 40,000 iterations. This number of 40, iterations were simulated for the Monte Carlo to ensure the 1% AEP expected value converged within our tolerance.

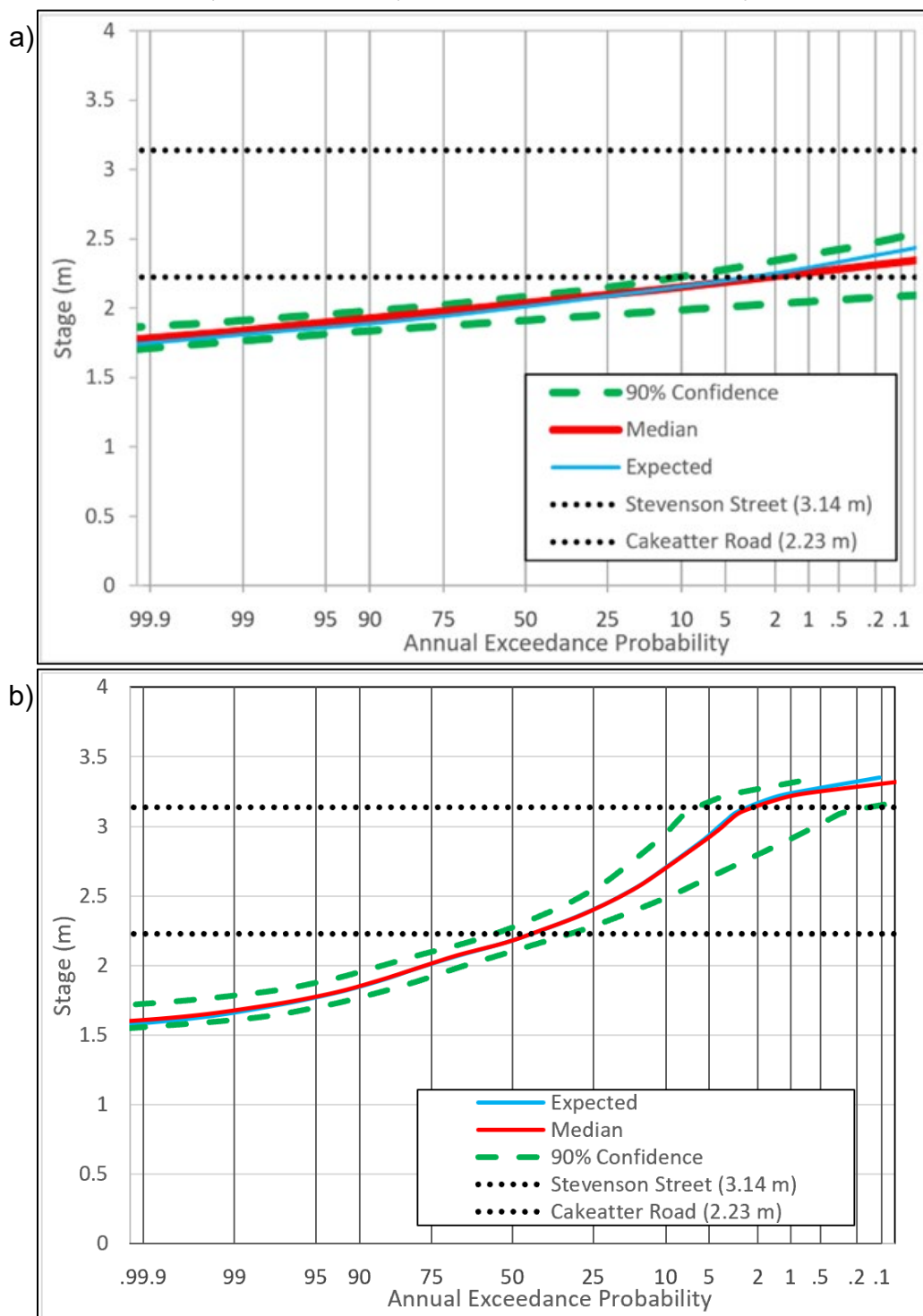
3.2.4.1 Middle Salt Lagoon

The stage-frequency curves computed from the 35-day volume curve and peak flow frequency curve are shown in Figure 30. The metric to test convergence was the 1% AEP at Middle Salt Lagoon. The 1% AEP convergences around 8,000 realizations for the stages generated from the peak flow curve, while the 1% AEP convergence near 14,000 realizations (Figure C-1 and C-2, in Appendix C) for the stages generated from the 35-day volume curve.

Both methods assume that the existing outlet structures are open and unobstructed. The 35-day volume elevations are much lower than the elevations calculated using the peak flow method because the runoff first must fill the available storage space available in the lagoons. The peak

flow estimates are much more conservative because they are based only on the stages resulting from a steady state peak flow and there is no volume conservation.

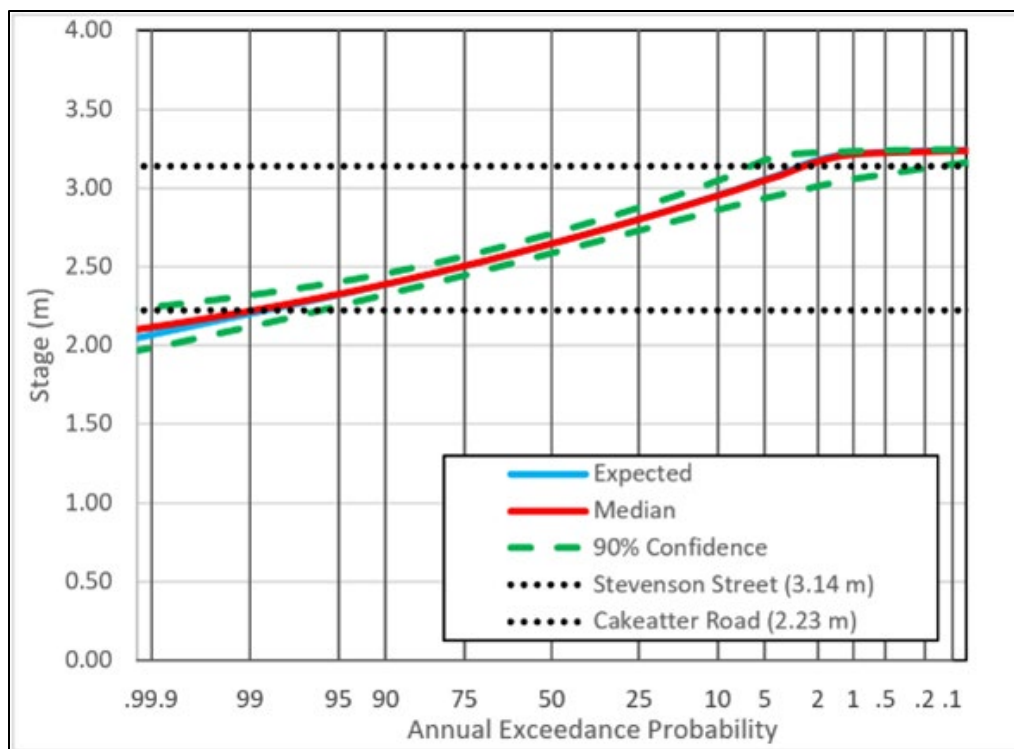
Figure 30. Stage-frequency curve for the Middle Salt Lagoon computed using the (a) 35-day volume frequency curve and (b) peak flow frequency curve.



Based on the 35-day volume stage frequency curve, the section of Cakeatter road adjacent to Middle Salt Lagoon has an approximately 3% probability of being overtopped for any given year, and the probability of Stevenson Street overtopping is much less than 0.01% provided meltwater can freely discharge through the existing outlet structure.

A final condition with the outlet closed was considered in the Middle Salt Lagoon. This scenario represents the case where the structure does not discharge flow as it receives runoff and the runoff volume would be stored in the lagoon (Figure 31). The results are consequently sensitive to the volume frequency curve, or how much inflow is expected and must be stored each year. The results suggest that there is an approximately 2% probability of Stevenson Street being overtopped for any given year if the outlet structure does not allow for the release of incoming meltwater, compared to the approximately 0.01% probability when assuming the outlet is open. This case was only considered for Middle Salt Lagoon because the storage volume of Tasigarook Lagoon is very small.

Figure 31. Stage-frequency curve for the Middle Salt Lagoon computed using the 35-day volume frequency curve assuming the outlet structure was closed.



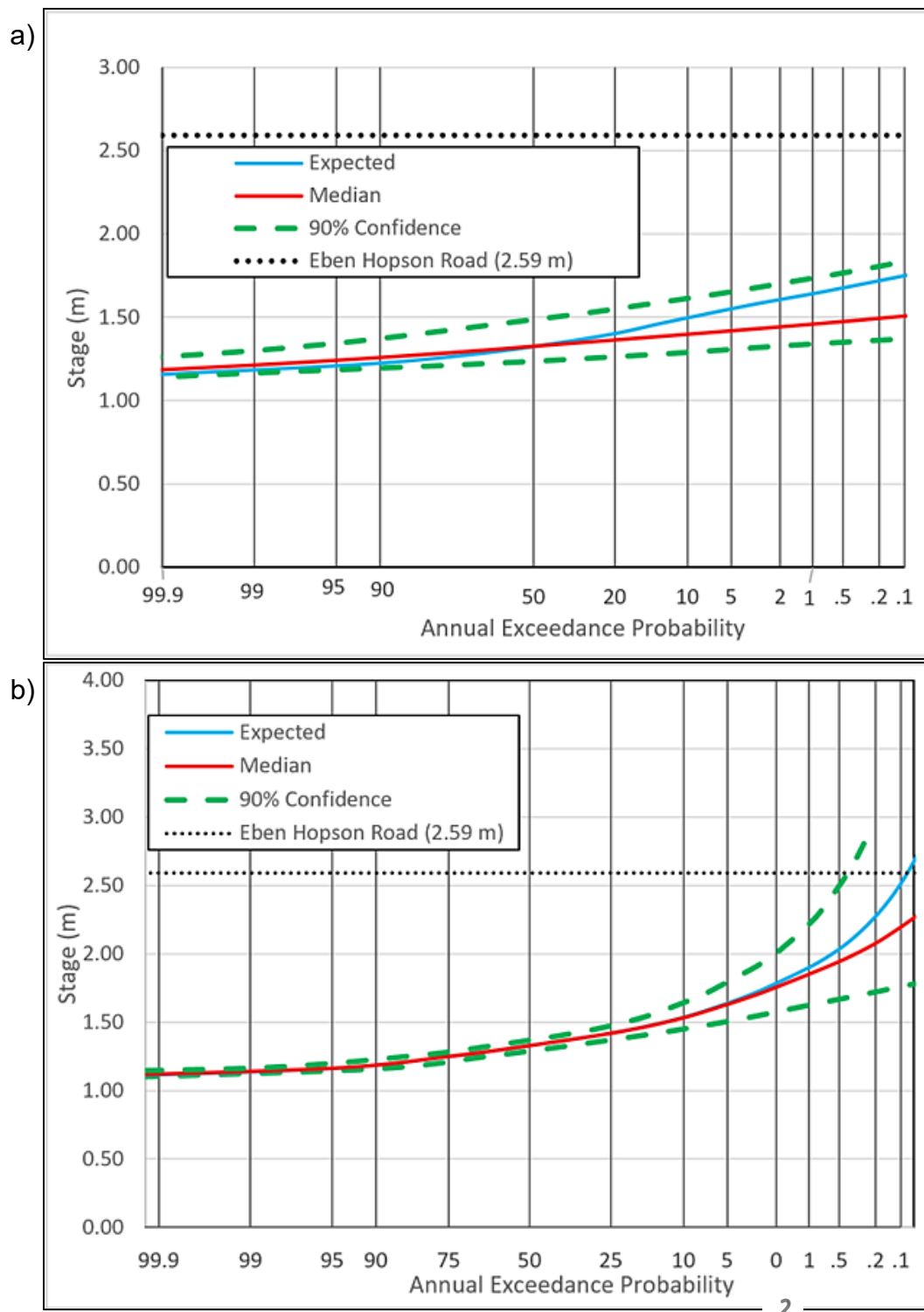
3.2.4.2 Tasigarook Lagoon

The stage-frequency curves computed from the 35-day volume curve and the peak flow frequency curve are shown in Figure 32. The metric to test convergence was the 1% AEP at Middle Salt Lagoon. The 1% AEP convergences around 7,100 realizations for the stages generated from the peak flow curve (Figure C-3, Appendix C), while the 1% AEP convergence near 31,500 realizations for the stages generated from the 35-day volume curve.

Both methods assume that the existing outlet structures are open and unobstructed. The 35-day volume elevations are much lower than the peak flow elevations because the amount of stage rise is limited by the availability of melt volume to fill the lagoons. The peak flow estimates are much more conservative because they are based only on the stages resulting from a steady state peak flow and there is no volume conservation.

Based on the 35-day volume stage frequency curve the probability of Eben Hopson Road overtopping is much less than 0.01% for any given year provided meltwater can freely discharge through the existing outlet structure.

Figure 32. Stage-frequency curve for the Tasigarook Lagoon computed using the (a) 35-day volume frequency curve and (b) peak flow frequency curve.



4 Conclusions and Recommendations

4.1 Conclusions

Snow dams, meltwater refreeze, and shallow sloping terrain add significant complexity to modeling hydrologic processes in the arctic. In this study we found that while our simulated snow accumulation and ablation reasonably agreed with available observations (SWE measurements, SCA depletion curves, and time-lapse camera photos) in Utqiagvik, it was challenging to quantify the delay in runoff onset and to simulate the timing of the runoff hydrograph accurately.

To address this challenge and meet the study objective, we developed two different methods for calculating stage-frequency curves for the Middle Salt Lagoon and the Tasigarook Lagoons. The first was a volume driven method which used the results of snow accumulation, ablation, and runoff models to create inputs to a Monte Carlo analysis of stage frequency which captured uncertainty in volume-frequency, based on the length of the record, and the timing of runoff arrival (inflow hydrograph shape). The second method was a simplified peak flow driven method which used transposed peak annual flows from a nearby USGS gage and an assumption of steady-state inflows to the lagoons to create a conservative estimate of the stage frequency curves. The second method also used a Monte Carlo analysis to capture uncertainty, but only based on the length of record of the peak annual flows.

The volume driven method incorporates the volumetric results of the snow accumulation and melt volumes, as well as the shapes of the runoff hydrographs from the hydrologic modeling. The peak flow driven method draws directly from measured flows in an adjacent basin but is a mostly statistical approach that does not include information about the volume or timing of the runoff obtained through the modeling efforts. Additionally, the computed LP3 peak curve did not fit the peak values well, suggesting the peak flow dataset may need to be further looked at for removing potential trends. The results from the volume driven method are preferred to the peak flow driven method which should be viewed as a conservative reference case.

The key findings of the study are as follows:

- The existing outlet structures at Middle Salt Lagoon and Tasigarook Lagoon both appear to have adequate hydraulic capacity to pass snowmelt runoff without overtopping even for large annual runoff volumes with low probabilities of occurring ($>0.1\%$ AEP).
- The results suggest that there is an approximately 2% probability of Stevenson Street being overtopped on any given year if discharge from the outlet structure on Middle Salt Lagoon is blocked and incoming meltwater is not released.
- The results suggest that there is an approximately 3% probability of Cakeatter Road (near the intersection with Stevenson Street) overtopped on any given year, with the outlet structure on Middle Salt Lagoon freely discharging, and an approximately 99% probability if it is blocked and incoming meltwater is not released.
- Tasigarook Lagoon is small and not capable of storing all the meltwater for most years, so the outlet must be opened during runoff to prevent overtopping of Eben Hopson Road.

4.2 Recommendations

General recommendations to take into consideration during final outlet structure design are that the stage-frequency curves from the volume driven method should be the primary ones used, with the peak flow driven results viewed as a conservative case for reference.

If significant modifications to the outlet structures and their capacities are made, the results of this analysis may be affected as the stages in the lagoons are a function of both the inflow of runoff and the outflow of stored water in the lagoons. Revisions to the analysis may be necessary if major changes to the structures are anticipated.

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Appendix A: Time-Lapse Camera Photos

Figure A-1. Time-lapse camera photos for 2015–2019 (Seyednasrollah et al. 2019; Milliman et al. 2019).

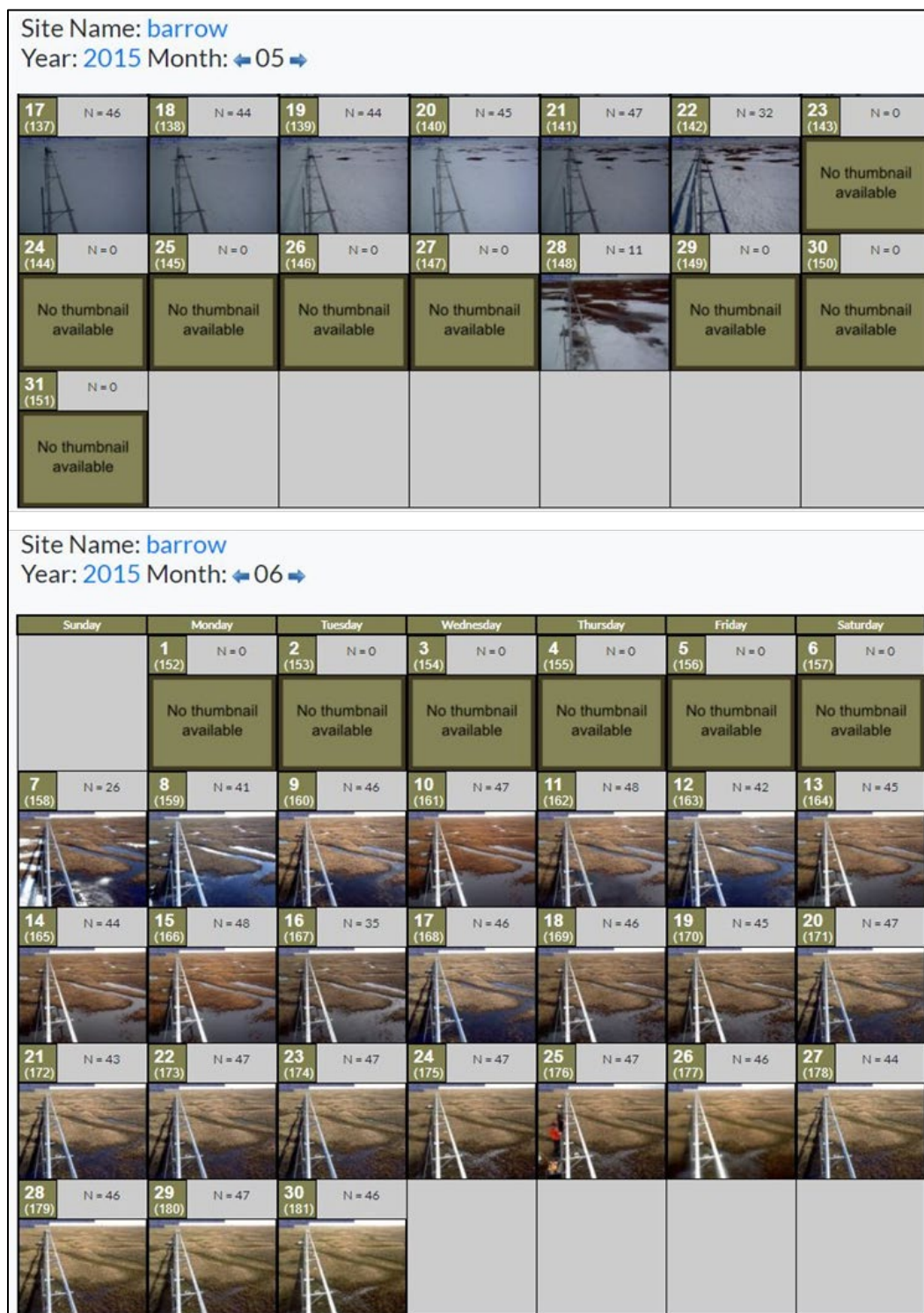


Figure A-1. Time-lapse camera photos for 2015–2019 (Seyednasrollah et al. 2019; Milliman et al. 2019).

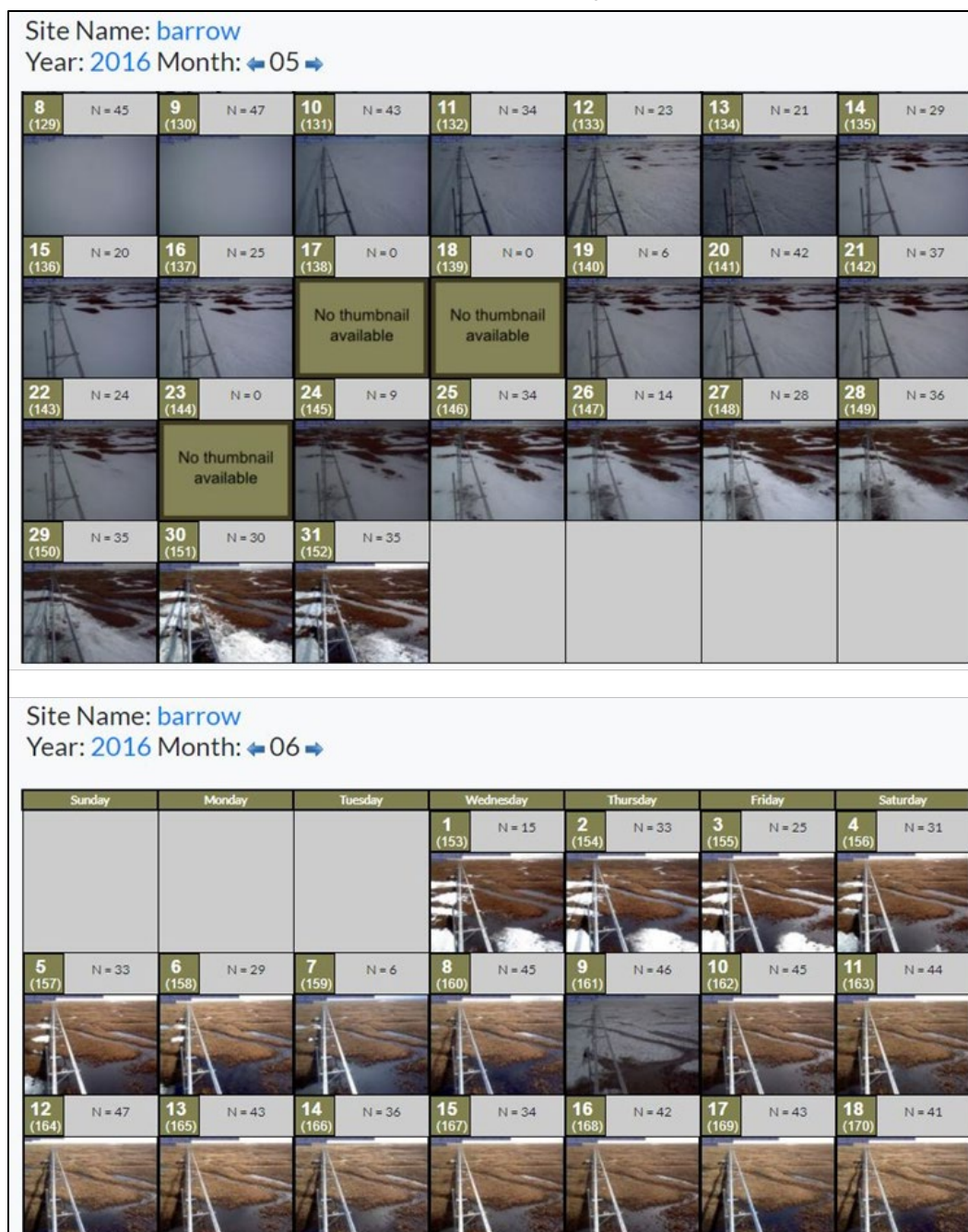


Figure A-1. Time-lapse camera photos for 2015–2019 (Seyednasrollah et al. 2019; Milliman et al. 2019).

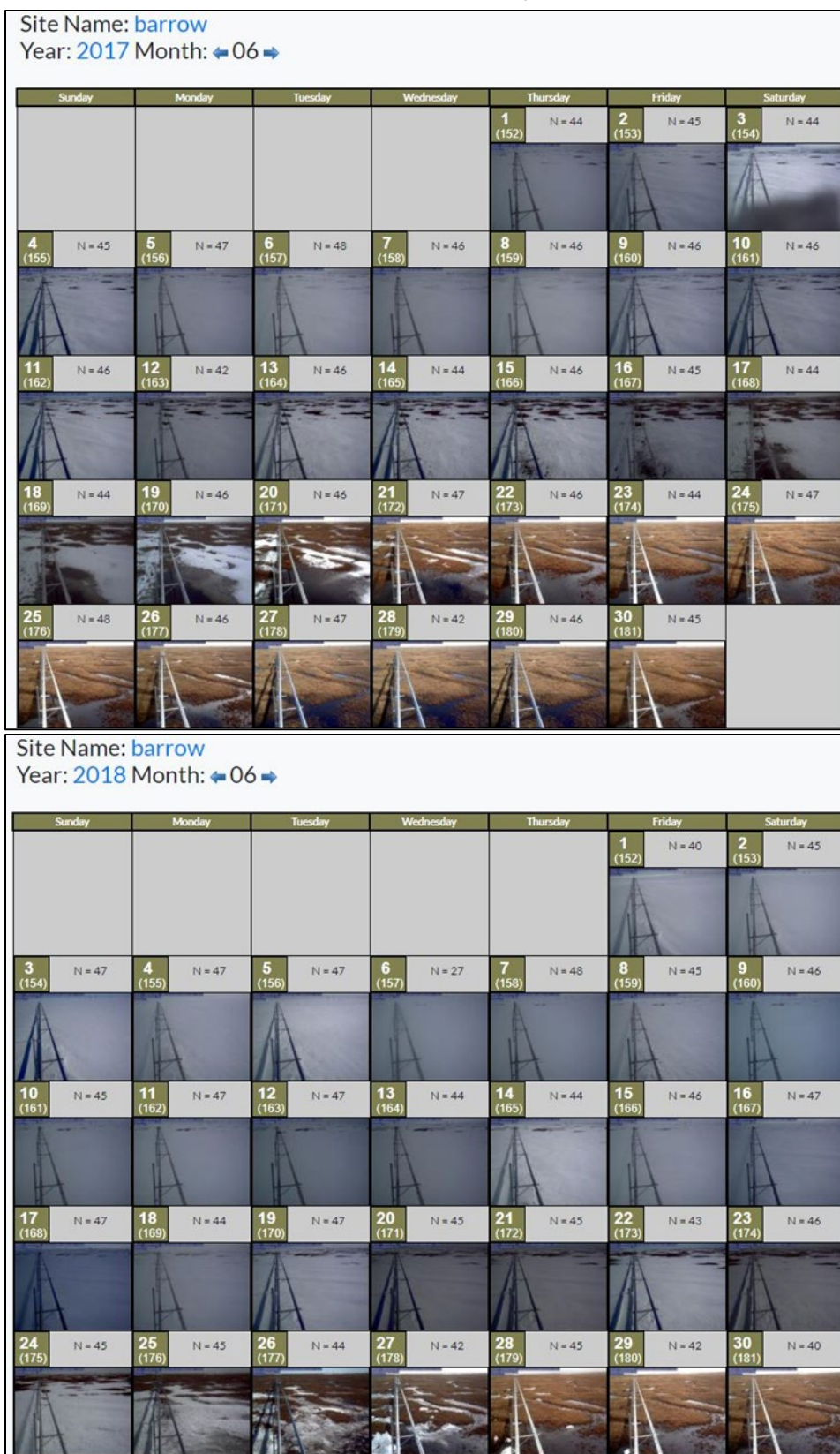
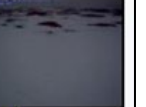
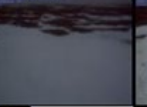
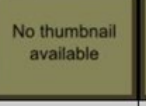
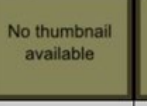
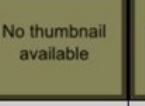
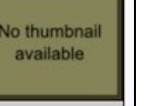
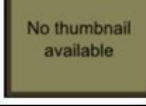


Figure A-1. Time-lapse camera photos for 2015–2019 (Seyednasrollah et al. 2019; Milliman et al. 2019).

Site Name: [barrow](#)
 Year: 2019 Month: [◀ 06 ▶](#)

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
						1 (152) N = 41 
2 (153) N = 39 	3 (154) N = 38 	4 (155) N = 40 	5 (156) N = 41 	6 (157) N = 43 	7 (158) N = 36 	8 (159) N = 41 
9 (160) N = 39 	10 (161) N = 37 	11 (162) N = 44 	12 (163) N = 43 	13 (164) N = 40 	14 (165) N = 36 	15 (166) N = 30 
16 (167) N = 36 	17 (168) N = 39 	18 (169) N = 32 	19 (170) N = 37 	20 (171) N = 43 	21 (172) N = 42 	22 (173) N = 44 
23 (174) N = 44 	24 (175) N = 46 	25 (176) N = 34 	26 (177) N = 0 	27 (178) N = 0 	28 (179) N = 0 	29 (180) N = 0 
30 (181) N = 0 			No thumbnail available	No thumbnail available	No thumbnail available	No thumbnail available

Appendix B: Modeled Runoff Volumes

Table B-1. Annual maximum 35-day runoff volumes for Middle Salt Lagoon and Tasigarook Lagoon watersheds.

Year	Middle Salt (MCM)*	Tasigarook (MCM)	Year	Middle Salt (MCM)	Tasigarook (MCM)
1982	2.0	1.2	2002	1.5	0.9
1983	1.6	0.9	2003	1.9	1.2
1984	2.6	1.5	2004	3.0	1.8
1985	2.1	1.2	2005	1.9	1.1
1986	2.4	1.5	2006	2.7	1.7
1987	1.7	1.0	2007	2.1	1.2
1988	1.4	0.8	2008	2.3	1.3
1989	2.6	1.5	2009	2.6	1.5
1990	1.5	0.9	2010	2.8	1.6
1991	1.6	1.0	2011	2.5	1.5
1992	1.6	0.9	2012	2.6	1.5
1993	1.9	1.1	2013	1.9	1.1
1994	3.1	1.9	2014	2.6	1.7
1995	2.8	1.7	2015	2.6	1.6
1996	1.7	0.9	2016	1.4	0.8
1997	2.1	1.3	2017	1.7	1.0
1998	2.2	1.3	2018	2.6	1.6
1999	2.0	1.1	2019	2.5	1.5
2000	2.4	1.4	2020	1.9	1.1
2001	1.7	1.0	2021	1.4	0.8

*Million cubic meters.

Appendix C: Stage Frequency Convergence

Figure C-1. Middle Salt Lagoon (a) and Tasigarook (b) example iterations (200 iterations shown) from the Monte Carlo simulation.

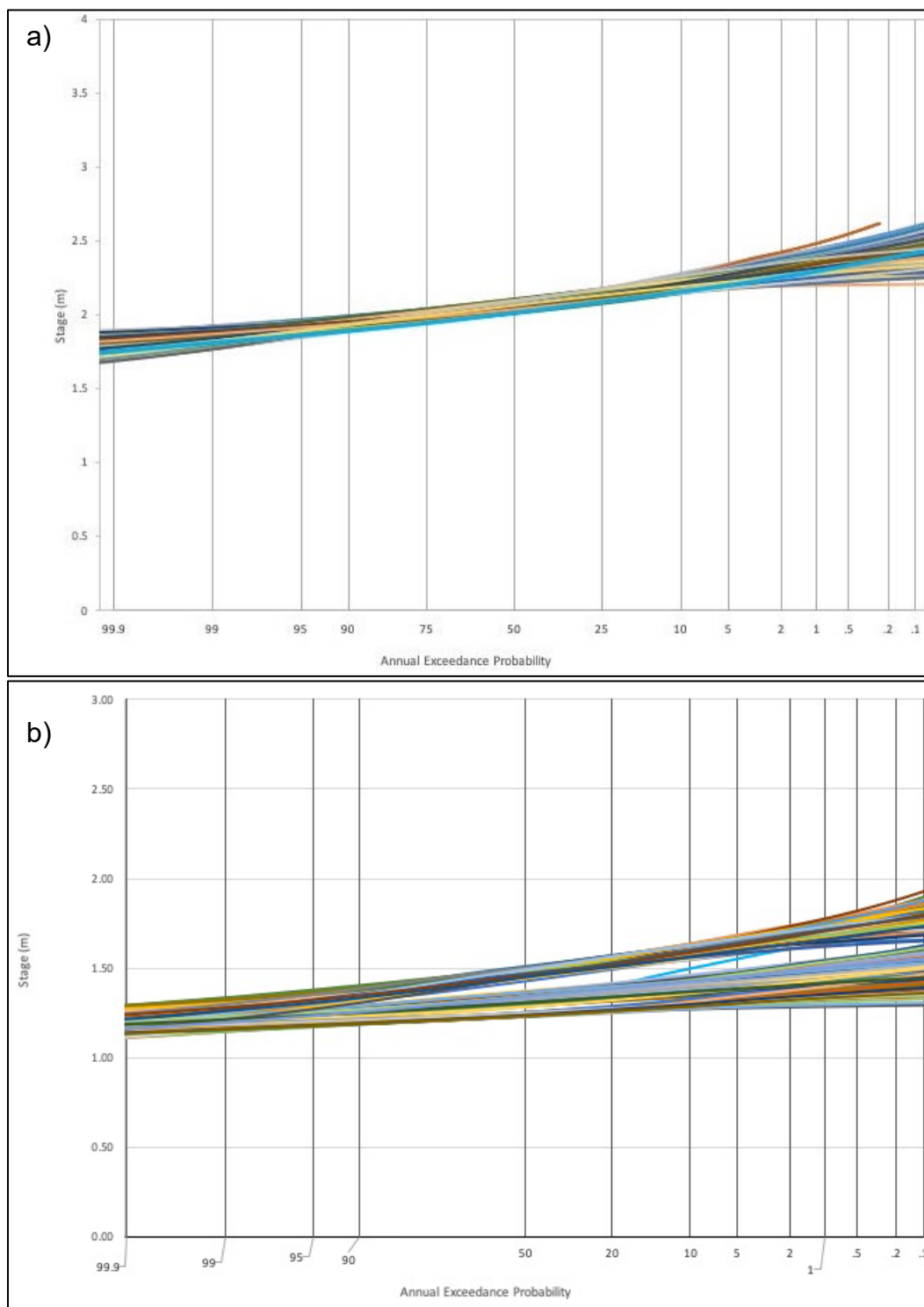


Figure C-2. Middle Salt Lagoon convergence test on 1% annual exceedance policy (AEP) 90% confidence interval of the expected estimate spans $\pm 2\%$ when error line falls below 2%. The 1% AEP stage computed from the (a) peak flow frequency curve and (b) 35-day volume.

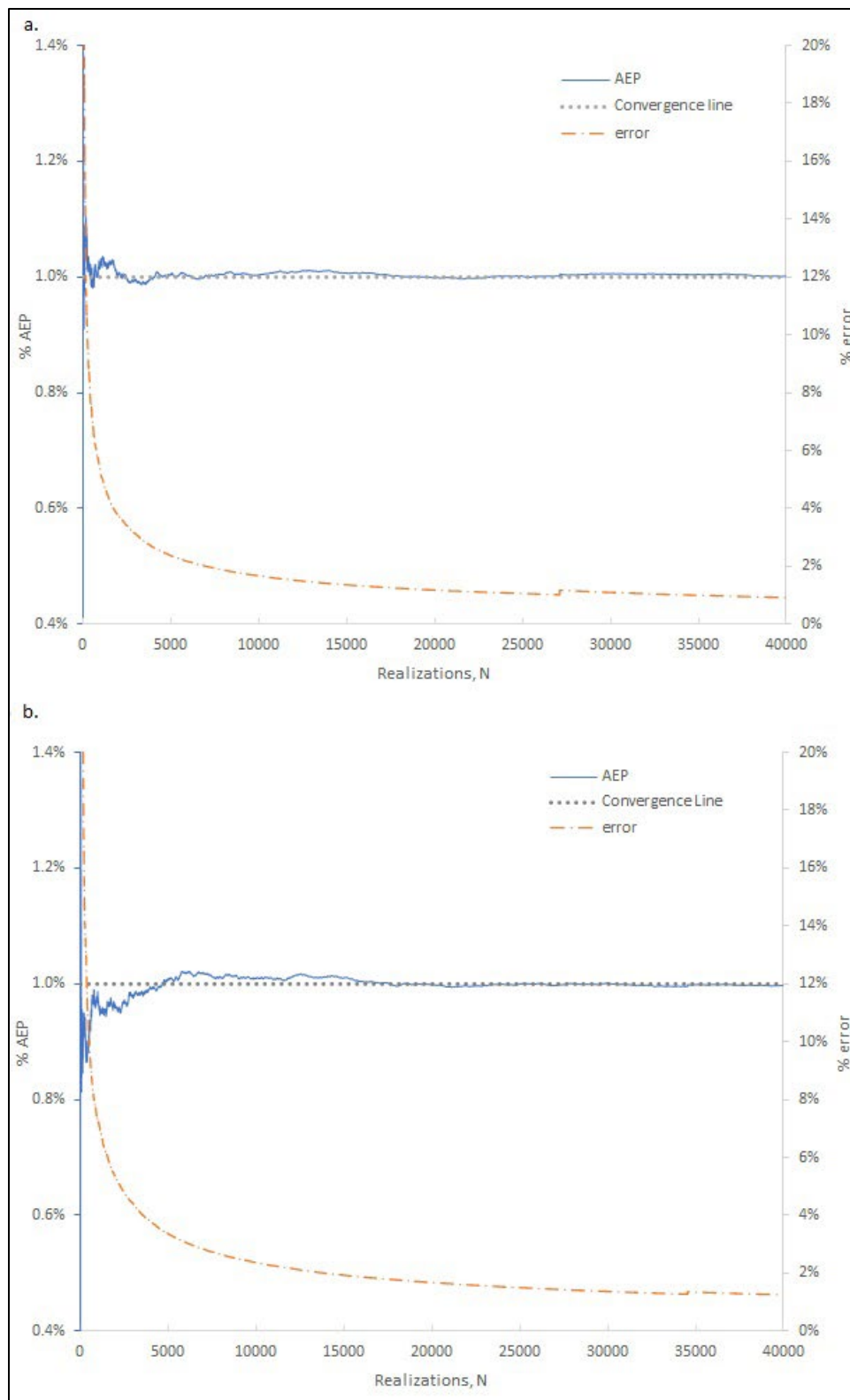
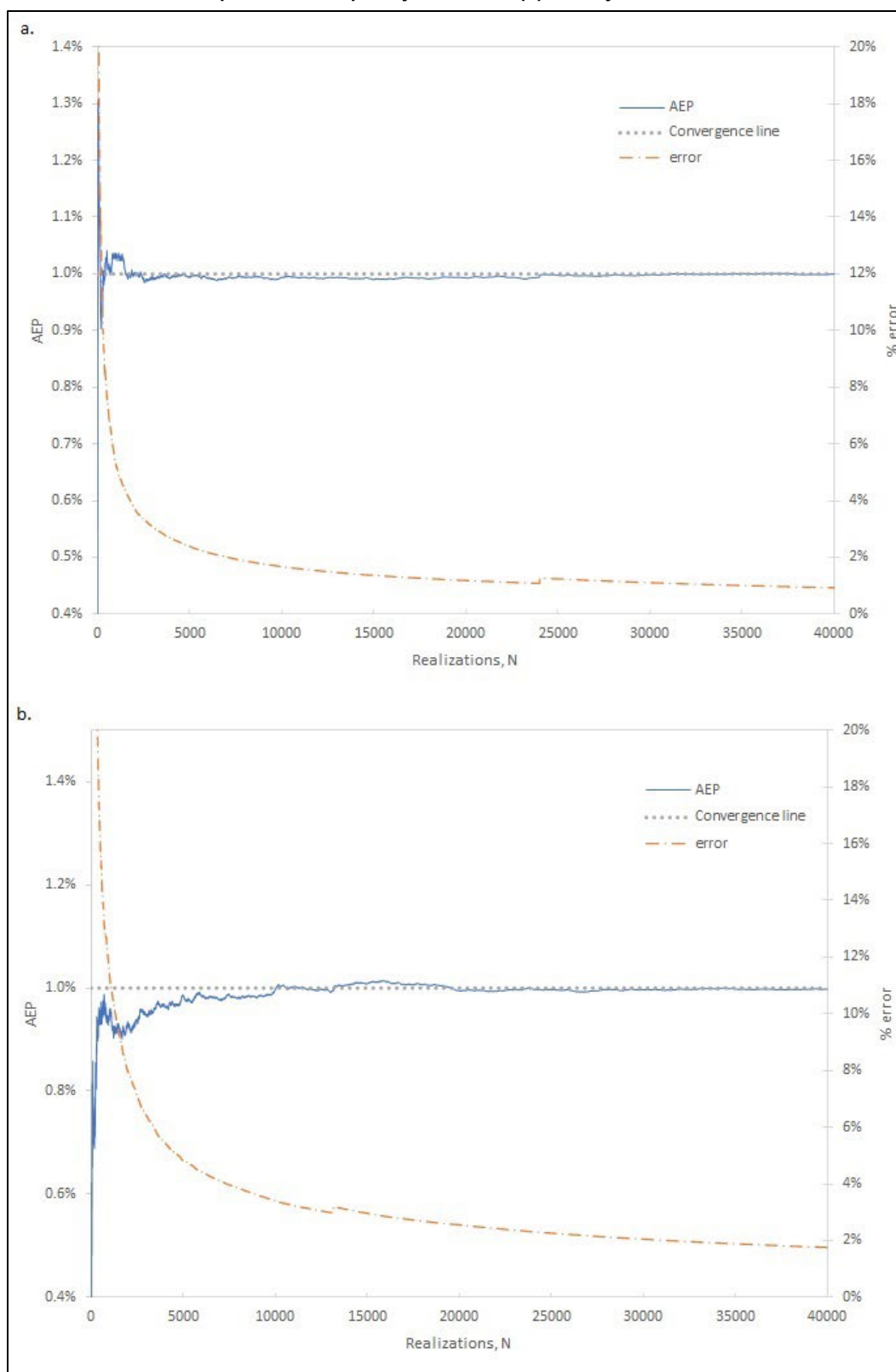


Figure C-3. Tasigarook convergence test on 1% AEP 90% confidence interval of the expected estimate spans $\pm 2\%$ when error line falls below 2%. The 1% AEP stage computed from the (a) peak flow frequency curve and (b) 35-day volume.



Abbreviations

AEP	Annual exceedance probability
CALM	Circumpolar Active Layer Monitoring
CEPOA	Corps of Engineers, Pacific Ocean, Alaska District
CMP	Corrugated metal pipe
DEM	Digital elevation model
DSW	Diffusion wave approximation of the shallow water equations
ERA5	European Centre for Medium-Range Weather Forecasts Reanalysis v5
fSCA	Fractional snow-covered area
HEC	Hydrologic Engineering Center
HEC-FDA	Hydrologic Engineering Center–Flood damage assessment
HEC-HMS	Hydrologic Engineering Center–Hydrologic Modeling System
HEC-RAS	HEC’s River Analysis System
HEC-SSP	Hydrologic Engineering Center–Statistical software program
IACWD	Interagency Advisory Committee on Water Data
LP3	Log-Pearson Type III
LWASS	Liquid water at soil surface
MCM	Million cubic meters
MGB	Multiple Grubb-Beck
ML	Multilayer

MODIS	Moderate Resolution Imaging Spectroradiometer
NALCMS	North American Land Change Monitoring System
NDSI	Normalized difference snow index
NLCD	National Land Cover Database
QSI	Quantum Spatial Inc.
SCA	Snow-covered area
SWE	Snow water equivalent
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
WBAN	Weather Bureau Army-Navy
WY	Water year

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14. ABSTRACT For the village of Utqiagvik, located at the North Slope of Alaska, a stone-armored revetment along the coastline is proposed to reduce coastal erosion. The inner drainage capacity of the revetment must be sufficient to handle seasonal runoff from snowmelt. For this effort, we investigated the snowmelt runoff and the hydraulic impact at the watershed outlet using numerical snow and hydraulic modeling of the study area. We validated the snow model results by comparing simulated snow water equivalent (SWE) values to field measurements. Additionally, the snow model was validated using satellite-based Moderate Resolution Imaging Spectroradiometer (MODIS) snow-covered area (SCA) products and time-lapse camera imagery during snowmelt. Our results indicate that the simulated SWE and snowmelt dates agree closely with measured values. The timing of modeled runoff onset was less accurate due to natural processes that delay snowmelt runoff such as snow dams and refreeze. The effect of the uncertainty from both runoff timing and volume was addressed with a Monte Carlo simulation of stage-frequency curves for the lagoons that receive snowmelt runoff. These stage-frequency curves can be used directly in the design of outlet, drainage or discharge structures for the proposed revetment.					
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