Estimating Stage-Frequency Curves for Engineering Design in Small Ungauged Arctic Watersheds

Chandler S. Engel, Research Civil Engineer, US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Chandler.S.Engel@erdc.dren.mil

Anna M. Wagner, Research Environmental Engineer, US Army Cold Regions Research and Engineering Laboratory, Fairbanks, Alaska, Anna.M.Wagner@erdc.dren.mil

Jeremy J. Giovando, Research Civil Engineer, US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Jeremy.J.Giovando@usace.army.mil

David Ho, Research Civil Engineer, US Army Hydrologic and Engineering Center, Davis, California, David.Ho@usace.army.mil

Abstract

The design of hydraulic structures in the Arctic is complicated by unique runoff processes caused by shallow terrain relief which promotes snow-damming and refreeze of runoff. We discuss the challenges encountered in modeling snowmelt runoff into two coastal freshwater lagoons in Utqiaġvik, Alaska. Stage-frequency curves with quantified uncertainty were required to design two new discharge gates to allow snowmelt runoff flows through a proposed coastal revetment. Snowpack accumulation and ablation were modeled using SnowModel which was used to force a physically based hydraulic runoff model (HEC-RAS) to estimate runoff hydrographs arriving at the lagoons. We discuss the approach used to develop stage-frequency curves with uncertainty using a volume-driven Monte Carlo (MC) simulation. This approach accounts for uncertainty in snow-damming and refreeze processes which affect the arrival time of snowmelt inflow peaks to the subject lagoons. This methodology is adaptable and can be applied in other similar environments where secondary runoff processes, which are challenging to model directly, may be dominant.

Introduction

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 codes 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.

In this study we aimed to develop a means to quantify future runoff volumes and timing without directly modeling runoff delay processes. The method is centered on calibrating a snow accumulation model to seasonal runoff volumes, which are not affected by the runoff delays. The variability of runoff timing was quantified using a range of simulated runoff hydrograph shapes representing different runoff delay scenarios. A Monte Carlo framework was used to combine these approaches and derive stage-frequency curves with uncertainty for waterbodies receiving runoff through the snowmelt period.

Background

The US Army Corps of Engineers (USACE) Alaska District is planning to construct a coastal revetment in the city of Utqiaġvik, AK to mitigate coastal erosion risk. Utqiaġvik is the northernmost incorporated place in the United States, situated on coast of the Arctic Ocean well above the Arctic Circle on Alaska's North Slope. The rock revetment is designed to prevent erosion from wave action that is threatening the community. 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 discharge structures will be constructed to effectively pass snowmelt through to the ocean during the runoff period.

There are two primary watersheds in this region impacting these new discharge structures (Figure 1). One watershed, 19.8 km^2 basin, draining to the Middle Salt Lagoon, and a 12.8 km^2 basin draining into a complex of small dams and lagoons above the Tasigarook Lagoon. 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 snowmelt makes its way to the lagoons where it is partially retained. Sand berms that are constructed seasonally on the beach to prevent seawater from entering the lagoons are breached and the meltwater is released to the ocean.

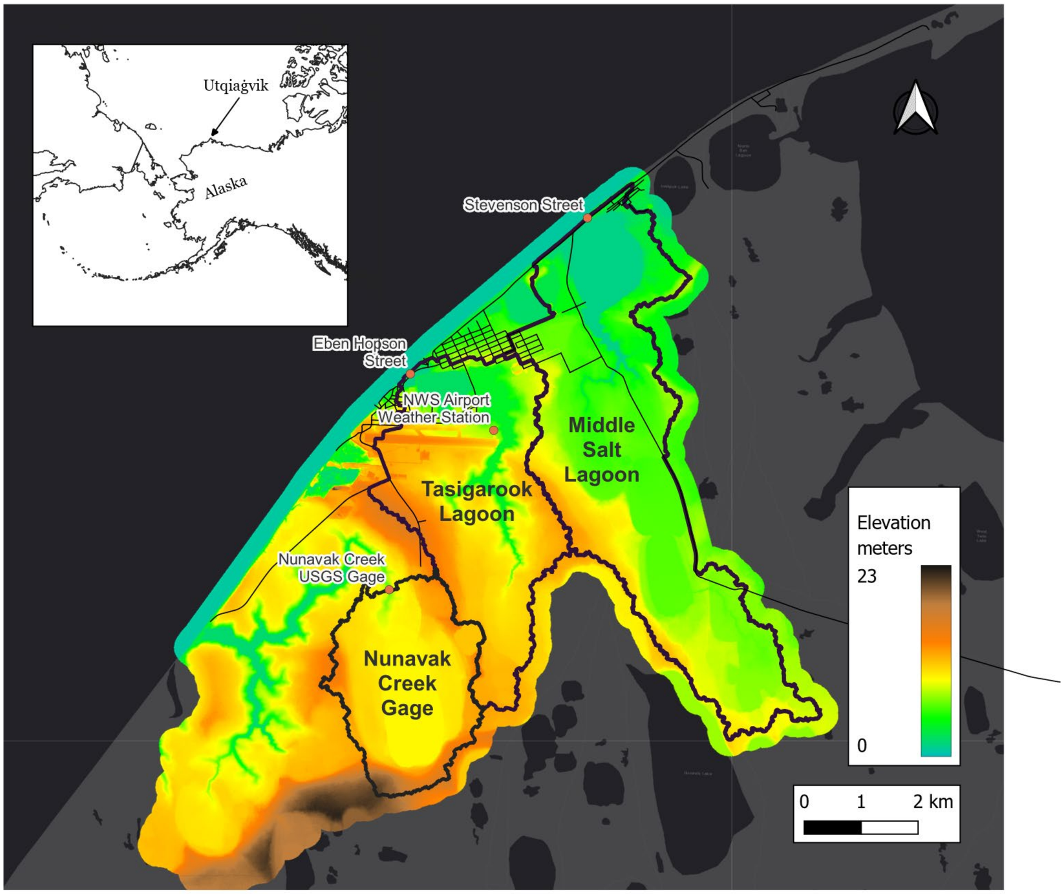

Figure 1. Utqiaġvik location map where watersheds are outlined in black.

Methods

SnowModel (Liston and Elder, 2006) was used to simulate snow depth and water-equivalent evolution, snow distribution by wind, surface energy exchanges and snowmelt. Metrological inputs to the model include air temperature, relative humidity, wind speed and direction, and precipitation data. SnowModel was selected because the approved model for USACE projects, the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), currently cannot explicitly model wind driven snow redistribution or ice lenses in the snowpack which are important processes in the study area.

The USACE-HEC's River Analysis System (HEC-RAS) 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 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). 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 2-dimensional Diffusive Wave

Approximation to the Shallow Water Equations to simulate runoff in a mesh model domain. HEC-RAS allows users to define a spatially variable precipitation boundary condition which is applied to the mesh. We used this feature to define the snowmelt or LWASS timeseries as the model's hydrologic boundary condition.

Results

The snow accumulation, ablation and runoff models were applied to the basins draining to the Tasigarook and Middle Salt Lagoons. Hydrographs and the runoff volume during a 35-day window starting at runoff onset at the lagoons were compiled for 40 years (1982-2021). Basic volume statistics are summarized in Table 1. We fit the annual series of volumes using a Log-Pearson Type III (LP3) distribution using the HEC Statistical Software Package (SSP) using Bulletin 17B methodology.

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 35-day volume for each year then scaled to a range of runoff volumes spanning the volume-frequency curve (Figure 2).

Table 2. Simulated basin runoff volumes in millions of cubic meters (MCM).

	Middle Salt (MCM)	Tasigarook (MCM)
Minimum	1.36	0.76
Maximum	3.05	1.91
Mean	2.13	1.26
Standard Deviation	0.49	0.32

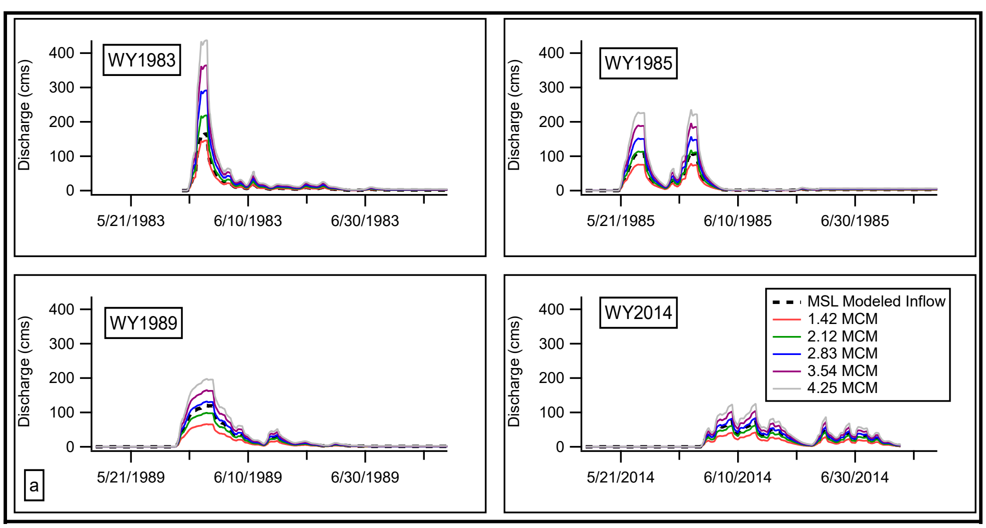

Figure 2. Scaled snowmelt runoff curve shapes for the Middle Salt Lagoon watershed.

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 3). 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.

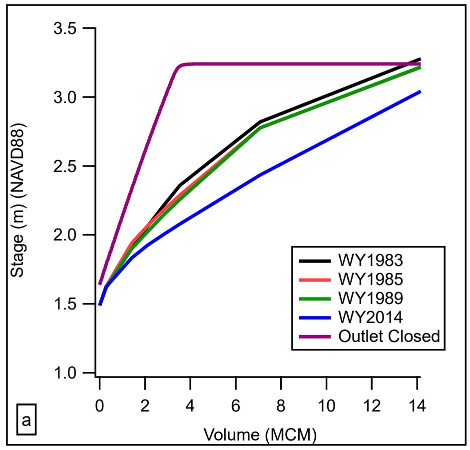

Figure 3. Stage-volume curves for Middle Salt Lagoon for different inflow hydrograph shapes (Figure 2).

The bootstrapped LP3 fit was obtained for each realization of the MC simulation by randomly perturbing the input annual series of runoff volumes for each watershed. This produced a unique volume-frequency curve each time, capturing the uncertainty in the volume annual series due to the length of the series. Most of the variation was in the high and low probability events (Figure 4). The distribution of stages created using the stage-volume curves as a transfer function are shown in Figure 5.

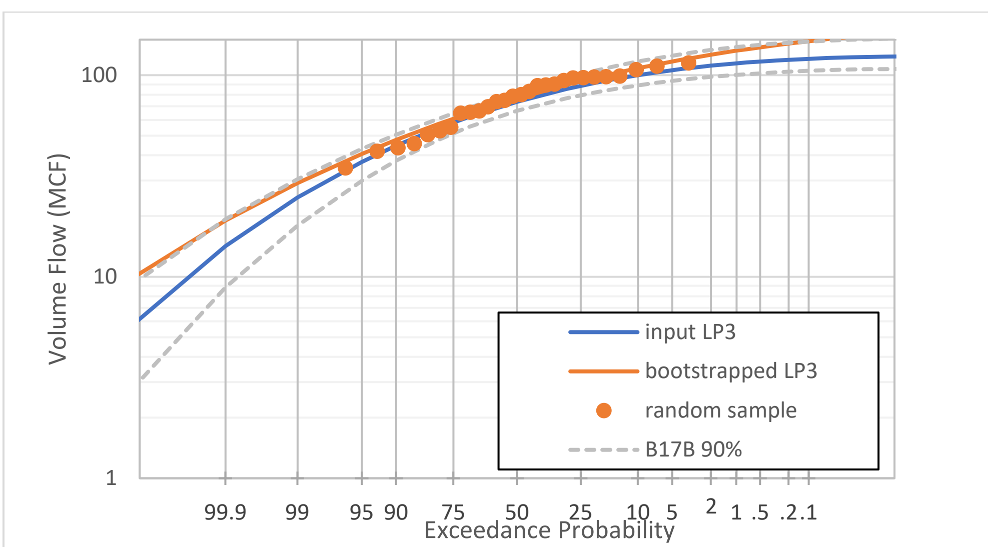

Figure 4. Example bootstrapped LP3 fit for the Middle Salt Lagoon volume-frequency curve.

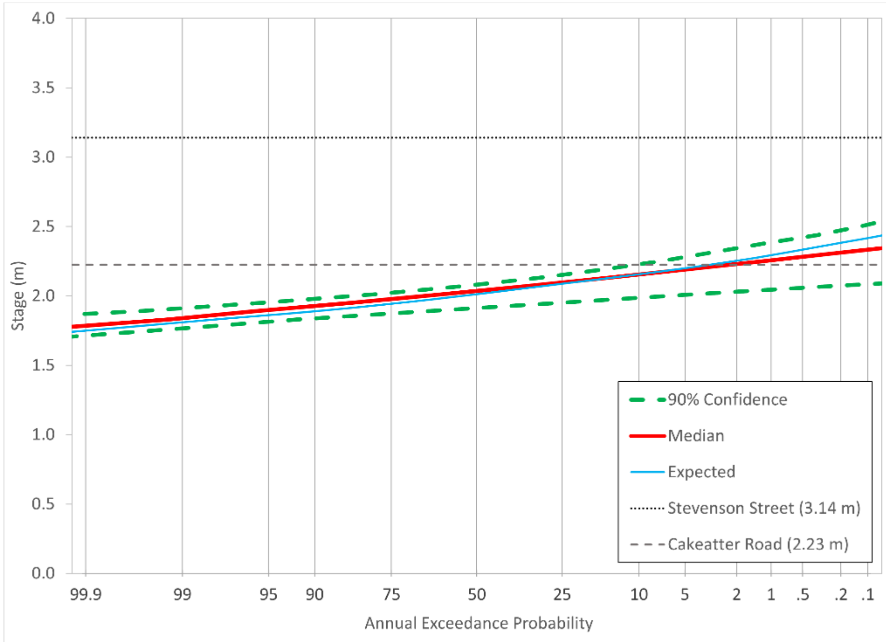

Figure 5. Example stage-frequency curve for the Middle Salt Lagoon including uncertainty.

Discussion and Conclusion

Snow dams, meltwater refreeze, and shallow terrain add significant complexity to modeling hydrologic processes in the arctic. While we have identified likely causes for runoff delay, a complete process-based modeling framework suitable for engineering applications that captures these phenomena at a basin scale has not been developed to date. Simply ignoring the unique processes in this region by applying commonly used runoff modeling methods yields results that do not capture the uncertainty the runoff delays introduce and is an unattractive approach. We present a method of estimating stage-frequency of lagoons receiving meltwater which includes consideration of uncertainty in the total volume of runoff and the variability in runoff delay.