The Presence and Widespread Distribution of Dark Sediment in Greenland Ice Sheet Supraglacial Streams Implies Substantial Impact of Microbial Communities on Sediment Deposition and Albedo

Sasha Z. Leidman1, Åsa K. Rennermalm1, Rohi Muthyala1, Qizhong Guo2, and Irina Overeem3,4

1Department of Geography, Rutgers, The State University of New Jersey, Piscataway, NJ, USA, 2Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ, USA, 3INSTAAR, University of Colorado at Boulder, Boulder, CO, USA, 4Department of Geological Sciences, University of Colorado at Boulder, Boulder, CO, USA

Abstract Melting on the Greenland Ice Sheet leads to extensive supraglacial stream networks. These streams accumulate low-albedo sediments disproportionately contribute to melting. Studies analyzing supraglacial sediment distribution and hydrodynamic properties are rare. Here, we examine a 130-m supraglacial stream reach in southwest Greenland using drone imagery, bathymetry, and hydrology measurements from 2017. Sediment covered 24% of the channel and had a mass-median diameter of 0.027 mm. We applied calculations of critical Shields stress to determine the minimum water depth needed to initiate sediment movement. In order for theoretical critical water depths to match observed depths, sediment grains would need to be 2.48 mm (near the grain size for cryoconite granules) indicating that microbial growth within sediment caused extensive flocculation. Without flocculation, sediment would flush out of floodplains and supraglacial streams would have significantly higher albedos. Supraglacial stream albedo might therefore be sensitive to changing stream chemistry, temperature, and meltwater supply.

Plain Language Summary Meltwater formed on the surface of the Greenland Ice Sheet drains through abundant networks of rivers and streams on the ice surface. These streams consolidate dark-colored sediment that can increase the amount of solar energy absorbed by the ice. To investigate the extent and causes of these deposits, we collected samples of sediment from southwest Greenland along with drone imagery, high-resolution GPS measurements of the stream geometry, and measurements of the water flow over the course of a week in 2017. We analyzed the sediment to determine its size and applied our findings to fluid dynamics equations. These calculations showed that sediment in glacial streams can only be present if the sediment is being consolidated into millimeter-scale granules by bacteria growing in the sediment. Thus, the amount of solar energy absorbed by the streams on the ice sheet likely depends on the health and longevity of this bacteria and further warming in Greenland may lead to more extensive sediment deposits in glacial streams.

1. Introduction

Meltwater generated on the surface of the Greenland Ice Sheet (GrIS) causes the formation of extensive supraglacial stream networks (Chu, 2014; Pitcher & Smith, 2019; Rennermalm et al., 2013a; Smith et al., 2015). While remote sensing platforms have detected the existence of supraglacial streams on the GrIS for decades (Ryan et al., 2018; Thomsen, 1986; Yang & Smith, 2013), little research has investigated their flow characteristics and morphology. Supraglacial streams form highly interconnected systems with multiyear stability (S. L. S. Germain & Moorman, 2019; Pitcher & Smith, 2019; Smith et al., 2015). With an albedo of 0.19–0.26, supraglacial streams are significantly darker than bare ice (albedo = ~0.55) (Ryan et al., 2018). While supraglacial streams and meltwater ponds only cover 2% of the ice sheet surface in southwest Greenland, the combined effect of these low-albedo surfaces is responsible for 12% of the ice albedo variation, thereby disproportionately contributing to negative surface mass balances (Ryan et al., 2018). Modeling results show that the areal coverage of supraglacial surface water will increase with climate warming, especially
in northeast Greenland, exacerbating the melting caused by the exceptionally low albedo of supraglacial streams (Igneczki et al., 2016). Supraglacial streams also supply as much as 41%–98% of total proglacial river discharge (Smith et al., 2015) making them vital for understanding the hydrology of glacial systems and the impact of Greenland on large-scale ocean circulation (Bakker et al., 2016; Rennermalm et al., 2007) and global sea level (Broeke et al., 2016; Fettweis et al., 2013; Moon et al., 2018; Muntjewerf et al., 2020). While emerging literature examines supraglacial stream morphology and flow characteristics of supraglacial streams (S. L. S. Germain & Moorman, 2019; S. L. S. T. Germain & Moorman, 2016; Gleason et al., 2016; Marston, 1983; Smith et al., 2017; Yang et al., 2016, 2018), few studies look at sediment in these streams or even mention its prevalence. We define sediment as insoluble organic or inorganic components within a stream such as cryoconite, eolian deposits, minerals, and ash. Additionally, while several studies have tried to model supraglacial stream networks at the regional or channel scale (Jarosch & Gudmundsson, 2012; Karlstrom & Yang, 2016; Smith et al., 2015), due to the impracticality of large-scale in situ measurements, they often approximate stream geometries as highly incised rectangular or polygonal cross sections (Gleason et al., 2016; Jarosch & Gudmundsson, 2012; Smith et al., 2015) potentially leading to errors in determining supraglacial stream albedo or routing times.

In southwest Greenland, the ice sheet surface supplies ample sediment to supraglacial streams. Dirty ice with distributed impurities of sediment and dust cover as much as 80%–95% of the ice sheet surface (Ryan et al., 2018). Some of this sediment forms cryoconite, a combination of sediment and organic matter. Cryoconite material melts into the ice surface forming cryoconite holes (Macdonell & Fitzsimons, 2008). These holes vary substantially in size but had an average diameter of 103 mm and average depth of 227 mm on Austre Brøggerbreen, Svalbard (Cook et al., 2016). In southwest Greenland, cryoconite holes cover 0.6% of the ice sheet surface on average (Ryan et al., 2018). Wetted cryoconite has an albedo of 0.09 (Bøggild et al., 2010). This albedo difference equates to cryoconite absorbing 23% more solar radiation than clean supraglacial stream beds. As cryoconite holes grow and coalesce, they connect with the supraglacial hydrologic drainage network (Macdonell & Fitzsimons, 2008). As a result, cryoconite can wash out of cryoconite holes and be consolidated into supraglacial streams (Gleason et al., 2016). This process is accelerated during cloudy and rainy conditions when incoming shortwave radiation is relatively low (Takeuchi et al., 2018). While cryoconite consolidated in holes has relatively little impact on overall solar absorption because of the high zenith angle needed to be in direct view of the sun (Ryan et al., 2018), cryoconite that has washed into supraglacial streams absorb radiation from a wide range of zenith angles. Ample research has gone into analyzing the chemical and biological composition of cryoconite within cryoconite holes (Gerdel & Drouet, 1960; Gibbon, 1979; Hodson et al., 2010; Macdonell & Fitzsimons, 2008; Nagatsuka et al., 2014; Uetake et al., 2016). However, there is a lack of research on how sediment is transported within supraglacial stream channels and the fluid dynamics necessary to transport sediment along the stream beds.

The transport of sediment as bedload along terrestrial fluvial channels has been studied for over a century (Einstein, 1941; Gilbert, 1914; Meyer-Peter & Müller, 1948; Shields, 1936a, 1936b). Studies of supraglacial streams suggest that they have similar hydraulic properties as terrestrial systems (Gleason et al., 2016; Marston, 1983). Sediment transport concepts, however, have not yet been applied to supraglacial streams. A widely used method to analyze stream sediment movement is the analysis of shear stress (e.g., Cao et al., 2006; Garcia, 2008; Miedema, 2010; Miller et al., 1977; Shields, 1936b). Particles start moving when the applied shear stress is larger than the threshold, also called the critical shear stress. The applied Shields stress, \( \theta \), is the nondimensionalized expression of the applied shear stress (Shields, 1936b) and is defined as

\[
\theta = \frac{\tau_b}{(\rho - \rho_s)gD}
\]

where \( \tau_b \) is the shear stress applied by the fluid flow at the bed, \( \rho_s \) is the density of the sediment, \( \rho \) is the density of water, \( g \) is the acceleration due to gravity, and \( D \) is the grain diameter. The sediment transport capacity is related to the excess of the Shields stress imparted on grains over the critical Shields stress. The critical Shields stress is roughly constant across grain sizes and therefore can be used to approximate the minimum water depth required for motion of grains for streams in which hydraulic radius is roughly equal to water depth and where water surface slope is relatively constant. The critical Shields stress is largely used to determine the water flow needed for the initiation of sediment motion; however, in streams with high turbulence and low bed frictions (e.g., supraglacial streams), it can be used as an approximation of the
As a result, the incorporation of sediment transport concepts into the analysis of supraglacial streams may provide insights into how flow conditions affect the albedo of Greenland’s ablation zone and therefore improve estimations of Greenland’s contribution to sea level rise.

Here, we examine the spatial and grain size distribution of sediment in a supraglacial stream reach in 2017 in southwest Greenland. Using hydrological observations, in situ elevation measurements, and uncrewed aerial vehicle (UAV) imagery, we map the sediment distribution and bathymetry of the stream reach and determine the bed shear stress within the channel. We use the relationship between particle Reynolds number and critical Shields stress (Miller et al., 1977) to analyze the flow conditions required for particle incipient motion in supraglacial streams and predict the likely sediment cover. We discuss explanations for discrepancies between predicted and observed sediment cover and strategies for predicting sediment cover across broader spatial scales. Finally, we use our observed sediment cover along with width and depth measurements from Gleason et al. (2016) to identify the ideal geometric approximation of channel shape for modeling supraglacial stream flow.

2. Study Site

Field measurements were collected in July 2017 at a field site on the ice sheet located 2 km east of the ice edge in southwest Greenland (67.153 N, −50.000 W) (Figure 1). This area has extensive and persistent supraglacial stream networks (Smith et al., 2015) due to copious melting from relatively warm summer temperatures, low surface albedo, and thin winter snow cover (Van As et al., 2012). This region is well studied with its radiative (van den Broeke et al., 2008), meteorological (Van de Wal et al., 2005), and proglacial (Hasholt et al., 2013; Rennermalm et al., 2013b) characteristics well constrained. All measurements were collected on a single stream reach (137 m long); however, UAV surveys and reconnaissance within a roughly 4 km² area showed that sediment deposits were fairly consistent within multiple streams in the area.
3. Methods

3.1. Observations

A hydrologic gaging station was installed at the downstream end of the stream reach. The stream reach had no tributaries over 5% of flow and no major slope changes following guidelines defined by the United States Geological Survey (USGS) (Holmes, 2001). Water level was measured every 5 min between 24 and 30 July 2017 using a Solinst Levellogger pressure transducer fixed to a pole installed at the bottom of the stream reach along with a Barologger set adjacent to the stream to adjust for air pressure variability (Figure 2a). Stage data were detrended to remove the effect of bed incision. Stream velocity measurements taken 90 times within the study period with a USGS pygmy current meter indicated that peak bankfull flow velocities were around 0.85 ± 0.13 m/s, within the lower range of streams analyzed by Smith et al. (2015). Water surface slope was determined using a TopCon B20 autolevel and a leveling rod. Water temperature was determined using an Onset temperature probe (model TMCx-HD with an accuracy of ±0.25°C).

Sediment samples were collected during low flow when shallow, sediment-covered areas of the stream bed (hereafter termed floodplains) were exposed to air. While the timing of floodplain inundation depends on the geometry of the stream channel, photos taken every 5 min of the stream reach with a pole-mounted timelapse camera (TimelapseCam 8.0) indicated that floodplains were above the water line for 9–15 h per

---

Figure 2. (a) Time series of stream stage recorded at the gauging station at the downstream end of the reach plotted with the resultant bed shear stress using a stream slope of 0.00115. The yellow triangle indicates the time at which UAV imagery was collected. The blue line indicates the critical depth calculated from the observed D50 grain size and the red line indicates the critical depth observed from the bathymetric measurements. The gauging station was located in a fairly confined section of stream; therefore, water levels were higher than upstream locations on average. (b) Grain size distribution for the sediment samples collected in the floodplains with average D10 and D90 plotted in black circles (n = 18), the D50 used for determining critical water depth plotted as a blue diamond (0.027 mm), and the effective grain size determined via calculations from the observed critical water depth plotted as a red square. The gray line represents the best fit log-normal distribution through the D10, D50, and D90 values (μ = 3.13, σ = 1.17). The effective grain size represents the 99.9th percentile grain size. (c) Modified Shields diagram from Miller et al. (1977) plotted with the calculated values of the critical Shields stress (θc) and particle Reynolds number (Re*) for the grain size measured by laboratory analysis (left) and derived grain size from field measurements of flow depth (right). UAV, uncrewed aerial vehicle.
day. A total of six samples were analyzed to determine their grain size distribution (Figure 2b). Grain size was determined by adding dilute (10%) hydrogen peroxide solution to the samples until all organic matter was dissolved (minimum of 24 h) and then using a Malvern grain size analyzer (Switzer & Pile, 2015). Each sample was analyzed in triplicate.

Overlapping camera imagery over the stream reach was collected via a DJI Phantom 3 quadcopter UAV system with an 8-megapixel camera, at 16:00 on July 24, 2017. Orange plastic markers (0.25 × 0.38 m) with black Xs were placed around the stream reach and were clearly visible within the imagery to act as ground control points. Marker positions were recorded with a Trimble R7 global navigation satellite system (GNSS). Camera imagery was analyzed in Agisoft Photoscan Pro to produce a georeferenced digital elevation model (DEM) and orthomosaic image with 1.3 cm horizontal resolution. The orthomosaic image was used to digitize the shoreline position. While the water level fluctuated significantly throughout the day, pressure transducer measurements suggested that imagery was collected near the peak flow period (Figure 2a). Elevation was extracted from the DEM every 1 m along each shoreline and interpolated using inverse weighted distance to determine the elevation of the water surface. The orthomosaic image was classified in ArcGIS Pro using a maximum likelihood classification with 20 signature polygons into two classes: sediment-covered and sediment-free stream areas. The resulting sediment-covered areas (Figure 1b) were used in a zonal statistic to determine the average water depth for sediment deposition areas.

The bathymetry of the stream bed was determined using point GNSS measurements since photogrammetry through water can result in poor DEM accuracy (Feurer et al., 2008). The GNSS rover was attached to a 2-m pole with a wheeled bottom in order to collect points continuously every 1 s without lifting the rover unit. To increase GNSS precision, postprocessing kinematic (PPK) corrections of rover measurements were performed using a GNSS base station located on bedrock by the ice edge. The GNSS was set to collect a measurement every second as the pole was wheeled across the streambed resulting in a total of 9,484 points with an average point spacing of 0.31 m. A bathymetric surface was interpolated using empirical Bayesian kriging of the elevation points. The bathymetric surface was subtracted from the water surface raster to obtain values for bankfull water depth throughout the stream reach.

### 3.2. Critical Shields Stress

The critical Shields stress ($\theta_c$) is the threshold value of the applied Shields stress ($\theta$) imparted by the fluid flow on sediment particles that would cause the initiation of their movement for a given grain size (Shields, 1936b). This criterion was later modified to establish an explicit relationship between the applied Shields stress based on fluid flow characteristics and the critical shear stress based on properties of the sediment (Buffington & Montgomery, 1999; Cao et al., 2006; Garcia, 2008; Miller et al., 1977). For a steady uniform flow, the gravitational force of the water flow exactly counterbalances the resistant force provided by the bed in the opposing direction. Thus, the fluid-flow-induced shear stress at the bed can be related to the hydraulic radius ($R$) of the channel and the water surface slope ($s$):

$$\tau_b = \rho g R s$$  

(2)

For uniform flow, as assumed above, the water surface slope is equal to the channel bed slope. While the critical Shields stress was developed to determine the necessary conditions for sediment transport in terrestrial streams, the similar hydraulic properties between supraglacial streams and terrestrial streams (Gleason et al., 2016) suggest that it is likely justified to apply analysis of incipient motion to supraglacial streams. Sediment is expected to be nearly exclusively transported during flood stage, whereas settling is more prevalent in floodplains during the falling limb of the meltwater hydrograph (Mao et al., 2014). Since the local acceleration due to gravity is a function of latitude, the international gravity formula (Wooland, 1979) was used to determine a value of 9.82261 m/s$^2$ for $g$. Average water temperatures were 0.191°C so a water density of 999.9 kg/m$^3$ was used (Tanaka et al., 2001). Sediment density was assumed as the density of quartz (2,650 kg/m$^3$), the most abundant mineral in cryoconite (Nagatsuka et al., 2014). This value matches well with the density value (2,630 kg/m$^3$) calculated from the mineral composition of cryoconite (Nagatsuka et al., 2014) combined with a 5% organic material composition measured by Bøggild et al. (2010). For calculations of applied Shields stress, water depth was used instead of the hydraulic radius of the stream channel.
This simplification is true for channels in which the width is significantly larger than depth (Petersen-Øverleir, 2008). For our stream channel, the width to depth ratio generally increases upstream with average values of 19.5 ± 12.5 resulting in an average difference between depth and hydraulic radius of only 2.3%. These assumptions allow for Equation 1 to be simplified as

\[ \theta = \frac{0.60596 Hs}{D} \]  

for our particular stream where \( H \) is the water depth.

The critical Shields stress (\( \theta_c \)) can be determined using the dimensionless particle Reynolds number (\( Re_* \)) (Miller et al., 1977). \( Re_* \) is defined by

\[ Re_* = \left( \frac{(\rho_s - \rho)}{\rho} \right) \frac{gD}{\nu} \]  

where \( \nu \) is the kinematic viscosity of water (1.7804 \( \times \) 10\(^{-6} \) m\(^2\)/s for water at 0.191°C) (Kestin et al., 1978).

Miller et al. (1977) determined the relationship between \( \theta_c \) and \( Re_* \) using data collected through flume experiments. The relationships below were obtained by digitizing the modified Shields curve in Figure 2 of Miller et al. (1977) and fitting two exponential regression equations. Based on those regressions, \( \theta_c \) can be calculated as a function of \( Re_* \):

\[ \theta_c = \begin{cases} 
0.07380 Re_*^{0.36418} & \text{if } 0.1 < Re_* < 10 (12.51 \mu m < D < 269 \mu m) (R^2 = 0.991) \\
0.02386 Re_*^{0.09639} & \text{if } 10 < Re_* < 1000 (269 \mu m < D < 5805 \mu m) (R^2 = 0.921) 
\end{cases} \]  

At the incipient motion of sediment particles, the applied Shields stress (\( \theta \)) is equal to the critical Shields stress (\( \theta_c \)). By setting \( \theta \) from Equation 1 equal to \( \theta_c \) from Equation 4 and inserting the known values of \( \rho_s, \rho, g, \) and \( \nu \), we get a relationship between water depth, slope, and grain size for our particular stream system at the time of initial motion of sediment particles:

\[ H = \begin{cases} 
0.0005908D^{0.4537} & \text{if } 12.51 \mu m < D < 269 \mu m \\
0.1613D^{1.145} & \text{if } 269 \mu m < D < 5805 \mu m 
\end{cases} \]  

Equation 5 is used to determine the minimum water depth for the initiation of sediment transport for a given grain size and stream slope, hereafter referred to as the critical water depth.

### 3.3. Estimating Channel Geometry

Large-scale hydrologic models aimed at analyzing ablation zone albedo and the routing times of meltwater through supraglacial drainage require the use of idealized cross-section geometries for their calculations. We use calculated critical water depths to determine the best approximation for supraglacial stream geometries that could be easily incorporated into large-scale hydrologic models for subcritical flow (Froude number < 1). Three different cross-section geometries were analyzed: half-ellipse (U-shaped) cross sections with the \( a \) axis as the width and the \( b \) axis as the maximum depth, isosceles triangle cross sections, and sinusoidal cross sections where the width is the period of the sine curve and the depth is twice the amplitude.

The percentage of the stream cross section covered in sediment was determined for each cross section based on the percentage of the wetted perimeter below the critical water depth (\( H \), Equation 6). Values for average supraglacial river channel width, depth, and slope (14.79 m, 1.38 m, and 0.00145, respectively, \( n = 9 \)) were obtained from Gleason et al. (2016) to better represent the hydraulic properties of supraglacial streams in southwest Greenland instead of the single stream measured in this study. The theoretical percentage sediment cover values were then compared to the total sediment cover for the stream reach determined through the supervised classification of the UAV imagery.
4. Results

UAV imagery showed that sediment was mainly concentrated in the shallower depth stream edges (Figure 1a). Sediment covered 24.4% of the stream reach (Figure 1b). Bankfull water depths averaged 0.246 m throughout the stream reach but were as high as 0.885 m in the deepest areas (Figure 1c). The bankfull water depth of sediment-covered areas was 0.146 ± 0.091 m (mean ± 1 standard deviation), 53% of the sediment-free areas (depth = 0.279 ± 0.157 m). Water level fluctuated significantly each day (Figure 2a) with the average high water level 0.44 ± 0.16 m higher than the morning low water level resulting in floodplains being exposed to the air each night. On average, high flow occurred at 15:41 local time and low flow occurred at 4:52 local time. Observations indicated that sediment did not freeze overnight or was completely melted before it was inundated the next day.

Grain size analysis for the treated sediment samples showed an average D50 (mass-median diameter) of 0.027 ± 0.0057 mm (mean ± standard deviation of 18 D50 measurements) (Figure 2). Water surface slope at peak flow was 0.00115 m m⁻¹. Substituting these values into Equation 6a, the expected critical water depth would be extremely shallow, only 4.31 mm. This calculated critical water depth is only 3.0% of the observed critical water depth (0.146 m). The area with water depths less than 4.31 mm is negligible (1.2%) and within the margin of error of the water depth measurements. In contrast, the effective grain size calculated from Equation 6b using the observed critical depth of 0.146 m was 2.48 ± 1.36 mm, which is 91 times larger than the lab-measured D50. While quantitative measurements were not taken, this size is very similar to the size of cryoconite granules observed in the field. The effective grain size would need to be 11.9 mm in order to have 100% sediment cover in the stream. The sediment transport capacity at bankfull stage of the stream, calculated from Luque and van Beek’s (1976) bedload formula (Equation 6 of Sklar & Dietrich, 2008), is 0.305 kg/s assuming the observed average depth, effective grain size, and the average bankfull width of the channel (0.246 m, 2.48 mm, and 8.66 m, respectively). This value is notably lower than the sediment transport capacity of 1.15 kg/s assuming that the sediment being transported is 0.027 mm in size.

Assuming that the effective grain size of this stream is representative of supraglacial stream sediment across Greenland, the initiation of motion of sediment should be proportional to the water surface slope (Equation 6) (Figure 3b). Thus, the critical depth, or depth in which sediment movement initiates is equal to

\[ H = \frac{0.00016813}{s} \]  

assuming the granule size of 2.48 mm (Figure 2) and that the stream is not starved of sediment. Using the average slope from Gleason et al. (2016) (0.00145), the expected critical depth at which sediment mobilized would be 0.116 m (Figure 3b). This critical depth was applied to elliptical, triangular, and sinusoidal cross...
sections with the average width and depth of Greenlandic supraglacial rivers from Gleason et al. (2016) (14.79 m and 1.38 m, respectively) to determine the proportion of the wetted perimeter with a water depth less than the expected critical depth (Figure 3a). An elliptically shaped channel would result in the average cross section covered with 0.05 m of sediment or 0.3% of the width (Figure 3a). A triangular cross section would have 1.24 m covered in sediment or 8.4% of the width. A sinusoidal stream cross-section geometry would result in an average sediment cover of 18.1%, much closer to the 24.4% determined from field observations. This suggests that sinusoidal channel geometries are more representative of supraglacial streams than U-shaped or triangular channels under subcritical flow.

5. Discussion

Here, we show that sediment is prevalent within supraglacial stream channels and accumulates in shallow floodplain regions. This sediment deposition potentially decreases the albedo of the stream system and further contributes to increased melting, lowering the surface mass balance of the ice sheet. The grain size of sediment determined from laboratory analysis showed a D50 of 0.027 mm, matching closely with the coarse silt (0.020–0.063 mm) sized grain size distribution found by Bøggild et al. (2010). However, the critical Shields stress shows that this size is likely too small to explain the observed sediment depositional pattern (Figure 1c). Instead, a grain size of 2.48 mm is required to explain the observed distribution. This value is much closer to the expected diameter of cryoconite granules (Hodson et al., 2010; Takeuchi et al., 2001; Uetake et al., 2016) suggesting that sediment in supraglacial streams is transported as clumped granule units instead of dispersed fine grain sediments. This result is corroborated by visual observations of granular sediments saltating along the stream bed and depositing in floodplains. Thus, we surmise that organic matter and cyanobacteria within the cryoconite granules are causing the effective grain size to increase by 91-fold.

Our results suggest that deposition of sediment within supraglacial stream channels depends on the formation of cryoconite granules that are more difficult to transport by the stream than small mineral grains. The impact of flocculation on the sediment transport in terrestrial freshwater systems has been extensively studied (Fox et al., 2004; Guo & He, 2011). The cohesiveness of granules allows them to maintain their shape even in relatively fast flowing water (Uetake et al., 2016); however, these granules break down when transported to laboratory facilities, even before being exposed to hydrogen peroxide. Cryoconite granules consist of 80%–99% inorganic mineral components (Bøggild et al., 2010; Gerdel & Drouet, 1960; Takeuchi et al., 2001; Uetake et al., 2016) and are predominantly composed of quartz and plagioclase grains along with a handful of other minerals such as hornblende, K-spar, and clay minerals (Nagatsuka et al., 2014). Despite the small amount of organic material in cryoconite, it is likely sufficient to conglomerate small mineral grains into larger granules. The organic component of cryoconite is composed of humic material (Takeuchi et al., 2001) and microorganisms including filamentous cyanobacteria, heterotrophic bacteria, viruses, fungi, green algae, diatoms, rotifers, tardigrades, and nematodes (Macdonell & Fitzsimons, 2008). Humic material and microorganisms cause cryoconite to bind into granules (Takeuchi et al., 2001). Phormidesmis priestleyi is the dominant cyanobacteria species in cryoconite granules and the concentration of Oscillatoriacean cyanobacteria is significantly correlated with granule size (Uetake et al., 2016) indicating that while they do not contain dark intercellular pigments, their filamentous structure facilitates grain conglomeration. Additionally, cyanobacteria can produce glue-like extracellular polymeric substances (Hodson et al., 2010). Humic material makes up 11% of the total carbon concentration in the cryoconite and is mainly composed of humic acid from bacteria decomposition (Takeuchi et al., 2001). This humic material has high concentrations of molecules with conjugated bonds such as benzene rings and polyethylene chains which cause the dark coloration in cryoconite (Takeuchi et al., 2001). The presence of green algae (e.g., Ancylonema nordenskioeldii) also help reduce the cryoconite albedo (Uetake et al., 2016). While the cryoconite hole depth (Gibbon, 1979) and microbial community structure (Takeuchi, 2001) can vary with altitude and location, the most prevalent photosynthetic microorganism is A. nordenskioeldii making up 44%–83% of the total biomass (Uetake et al., 2016).

Flocculation of cryoconite likely increased the effective grain size to 2.48 mm in our measured stream system. This is larger than the mean size of granules observed on Himalayan glaciers (mean = 0.5 mm,
range 0.1–3.0 mm) (Takeuchi et al., 2001) yet smaller than the average granule size measured in Svalbard (6.78 mm) (Hodson et al., 2010). This flocculation process occurs slowly, usually over the course of several years (Hodson et al., 2010) and up to 11 years in Antarctic cryoconites (Fountain et al., 2004), indicating that Greenlandic cryoconite might have more time to develop into larger granules than Himalayan cryoconite potentially as a result of fewer orographically driven cloudy days. As a result of microbial growth within granules, the total carbon and nitrogen contents increase with increased granule diameter (Uetake et al., 2016). This suggests that as cloud cover decreases in southwest Greenland due to climate change (Hahn et al., 2020; Hofer et al., 2017), the longevity of cryoconite holes will increase. In turn, the effective grain size of sediment within supraglacial streams will increase and the albedo of fluvial networks will decrease assuming that supraglacial streams will not dramatically change their geometry. Increased cryoconite longevity may also increase in the amount of carbon and nitrogen delivered to the subglacial environment. Our work suggests that sediment deposition within supraglacial stream channels is dependent on processes forming cryoconite granules. Increased concentrations of phosphorus, nitrogen, and organic carbon, as well as increased temperatures, increase bacteria growth in cryoconite granules (Säwström et al., 2007). Changes in phosphorus and nitrogen loading to the ablation zone therefore might alter granule growth rates and influence sediment cover. Increases in black carbon and dust supplied to the ablation zone from intercontinental sources therefore not only might increase melting due to decreases in albedo (Goelles & Bøggild, 2017) but also may supply nutrients to increase cryoconite growth rates and cause further deposition of sediment in supraglacial streams. Additionally, changes in cryoconite hole water temperature from increased sensible heat flux and lengthening of the melt season (Fettweis et al., 2013) might increase flocculation rates further leading to increased deposition and albedo reductions. It is not clear, however, how the increase in microbial growth rates due to increases in temperature and nutrient supply might be counterbalanced by increased frequency of “flushing” events from anomalously warm, cloudy periods that transport nutrients and organic carbon from cryoconite holes to the hydrologic system (Foreman et al., 2007). While freezing of granules during periods when floodplains were exposed was not a significant factor in this stream reach in July due to the fact that air temperatures generally rose well above freezing before floodplains were resubmerged, this might need to be factored into the critical Shields stress when applying these concepts in colder regions.

The formation of granules is mainly the result of cyanobacterial growth indicating that the albedo of the ablation zone might be sensitive to chemical and physical processes that dictate microbial health. Small changes in cryoconite granule size can result in significant increases in sediment cover. For our particular stream system, the amount of area covered at each depth interval is roughly equivalent, indicating that increases in effective grain size would likely significantly increase sediment areal coverage. Considering that cryoconite albedo is 38%–53% that of clean stream beds (Ryan et al., 2018), these changes would likely cause significant changes in ablation zone albedo. While it is hard to predict how flocculation will be affected by the expected increases in melt rates in Greenland (Fettweis et al., 2013), these factors should be considered when modeling Greenland’s surface mass balance.

As we have shown, the application of hydraulic processes and sediment transport can lead to a more process-based understanding of supraglacial stream albedo in Greenland. This framework could potentially lead to much more predictability in the spatial distribution of albedo within the ablation zone by predicting channel sediment cover. The relationship between water surface slope and the critical water depth for sediment movement (Equation 5 and Figure 3b) can be applied to water surface slopes extracted from satellite data sets such as the ArcticDEM (Samapriya, 2017) or Ice, Cloud and land Elevation Satellite 2 (ICESAT2; Markus et al., 2017). The ArcticDEM is a 2-m-gridded elevation data set derived from photogrammetric analysis of WorldView satellite imagery and ICESAT2 is a six-beam laser altimetry data set. Both could be used to deduce how the water depth of sediment cover might change with latitude and elevation. Additionally, incorporating sinusoidal cross-section geometries into supraglacial routing models may improve estimates of the delay between meltwater production and moulin inputs although channel geometries are still likely better represented as U-shaped for supercritical flow (Gleason et al., 2016). Our work could be further extended by applying hydraulic modeling that can incorporate variable bed roughness values and stream cross-section geometries in order to determine sediment cover in more complex stream geometries such as sinuous channels and channels with variable water surface slopes. Hydraulic modeling that incorporates thermal incision rates similar to Jarosch and Gudmundsson (2012) could determine if increases in
flow or flow variability could flush out sediments or if changes in bed geometry would accommodate larger flows while maintaining widespread floodplains. In order to relate these findings to albedo and ablation, consideration needs to be made for the ability of sediment to insulate the ice surface above a critical sediment thickness. For high-latitude sediment, like that observed in this study, the thickness of a sediment deposit that results in greater insulation than radiative melting is likely around 30–40 mm (Reznichenko et al., 2010). Insulation of ice was observed in the field for some of the largest floodplains in small patches. While areas of the floodplain with homogeneous sediment coverage were generally flat, more heterogeneous areas exhibited more “cryoconite pitting” (Gleason et al., 2016) which may factor into the form roughness of the bed reducing mobilization. Taking into account these considerations, the application of the critical Shields stresses to cryoconite granule movement can help better constrain the amount and timing of water flowing into the subglacial environment and therefore improve estimates of Greenland’s contribution to sea level rise.

6. Conclusions

Supraglacial streams can contain large amounts of cryoconite sediment that covers up to a quarter of the channel bed. Deposition of cryoconite can be better understood using the critical Shields stress for the initiation of sediment transport. By applying this criterion, we find that the effective grain size of sediment within supraglacial streams is substantially larger than the average grain size of individual mineral particles. This is likely the result of cryobacteria and organic matter causing grains to form millimeter-scale granules that are able to hold their shape through sediment transport. As a result, stream sediment cover is significantly greater than it would be without flocculation. Flocculation-induced increases in supraglacial sediment cover likely cause the albedo of supraglacial streams to decrease by around 16%. Therefore, while cyanobacteria has a fairly low albedo, its ability to substantially increase sediment cover in supraglacial streams likely has a much larger effect on increasing melt rates. Flocculation may be influenced by the growth conditions of cryoconite and the microbial ecology of surrounding cryoconite holes: therefore, increases in sensible heat flux and nutrients supplied to the ice sheet might further increase sediment cover and cause melt rates to exacerbate. This relationship suggests that changes in climate and microbial health might have large implications for the amount sediment cover in the ablation zone and therefore needs to be considered when determining Greenland’s surface mass balance and contribution to sea level rise.

Data Availability Statement

All data used in this manuscript are available via the Arctic Data Center (https://doi.org/10.18739/A2WH2DG0D) or by contacting the corresponding author.

References

Bakker, P., Schmittner, A., Lenaerts, J. T. M., Abe-Ouchi, A., Bl D., Broeke, M. R., et al. (2016). Fate of the Atlantic meridional overturning circulation: Strong decline under continued warming and Greenland melting. Geophysical Research Letters, 43, 12252–12260. https://doi.org/10.1002/2016GL070457

Beggild, C. E., Brandt, R. E., Brown, K. J., & Warren, S. G. (2010). The ablation zone in northeast Greenland: Ice types, albedos and impurities. Journal of Glaciology, 56(195), 101–113. https://doi.org/10.3189/002214310791190776

Broeke, M. R. V. D., Enderlin, E. M., Howat, I. M., Munneke, P. K., Noël, B. F. Y., Jan van de Berg, W., et al. (2016). On the recent contribution of the Greenland ice sheet to sea level change. The Cryosphere, 10(5), 1933–1946. https://doi.org/10.5194/tc-10-1933-2016

Buffington, J. M., & Montgomery, D. R. (1999). Effect of sediment supply on surface textures of gravel-bed rivers. Water Resources Research, 35(11), 3523–3530.

Cao, Z., Pender, G., & Meng, J. (2006). Explicit formulation of the Shields diagram for incipient motion of sediment. Journal of Hydraulic Engineering, 132(10), 1097–1099. https://doi.org/10.1061/(ASCE)0733-9429(2006)132

Chu, V. W. (2014). Greenland ice sheet hydrology: A review. Progress in Physical Geography, 38(1), 19–54. https://doi.org/10.1177/0309133313507075

Cook, J. M., Hodson, A. J., & Irvine-Fynn, T. D. L. (2016). Supraglacial weathering crust dynamics inferred from cryoconite hole hydrology. Hydrological Processes, 30(3), 433–446. https://doi.org/10.1002/hyp.10602

Einstein, H. A. (1941). Formulas for the transportation of bed load. Transactions of ASCE, 561–597.

Fettweis, X., Franco, B., Tedesco, M., Van Anh, J. H., Lenaerts, J. T., Van Den Broeke, M. R., & Gallée, H. (2013). Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. The Cryosphere, 7(2), 469–489. https://doi.org/10.5194/tc-7-469-2013

Feurer, D., Bailly, J.-S., Puech, C., Le Coarer, Y., & Vaux, A. A. (2008). Very-high-resolution mapping of river-immersed topography by remote sensing. Progress in Physical Geography, 32(4), 403–419. https://doi.org/10.1177/0309133808096030
Foreman, C. M., Sattler, B., Mikucki, J. A., Porazinska, D. L., & Priscu, J. C. (2007). Metabolic activity and diversity of cryoconites in the Taylor Valley, Antarctica. Journal of Geophysical Research, 112, G04S32. https://doi.org/10.1029/2006JG000358

Fountain, A. G., Tranter, M., Nylén, T. H., Lewis, K. J., & Mueller, D. R. (2004). Evolution of cryoconite holes and their contribution to meltwater runoff from glaciers in the McMurdo Dry Valleys, Antarctica. Journal of Glaciology, 50(168), 35–45.

Fox, J. M., Hill, P. S., Milligan, T. G., & Baldarin, A. (2004). Flocculation and sedimentation on the Po river delta. Marine Geology, 203, 95–107. https://doi.org/10.1016/S0025-3227(03)00332-3

Garcia, M. H. (Ed.). (2008). Sedimentation Engineering: Processes, Measurements, Modeling, and Practice, ASCE Manuals Rep. Eng. Pract. (Vol. 110). Reston, VA: American Society of Civil Engineers. https://ascelibrary.org/doi/10.1061/9780784408148

Gerdel, R. W., & Drouet, F. (1960). The cryoconite of Thule area, Greenland. Transactions of the American Microscopical Society, 79(3), 256–272.

Germain, S. L. S. T., & Moorman, B. J. (2016). The development of a pulsating supraglacial stream. Annales of Glaciology, 57(72), 31–38. https://doi.org/10.1017/aog.2016.16

Germain, S. L. S., & Moorman, B. J. (2019). Long-term observations of supraglacial streams on an Arctic glacier. Journal of Glaciology, 1–12.

Gibbon, P. W. F. (1979). Cryoconite holes on Sermilikasv, west Greenland. Journal of Glaciology, 28(86), 177–181.

Gilbert, G. K. (1914). The transportation of debris by running water, 86, Washington, D.C: United States Government Printing Office. https://books.google.com/books?hl=en&lr=&id=i3HVAAAAMAAJ&ots=3aWeM6rlBm&sig=VDAxjKncUbBsfOkAw+IWF2G2C-9sA&v=onepage&q=Surface%20water%20data%20collection.%20Geophysical%20Research%20Letters&f=false

Gleason, C. J., Smith, I. C., Chu, V. W., Legleiter, C. J., Pitcher, L. H., Overstreet, B. T., et al. (2016). Characterizing supraglacial meltwater channel hydraulic characteristics on the Greenland Ice Sheet from in situ observations. Earth Surface Processes and Landforms, 41(14), 2111–2122. https://doi.org/10.1002/esp.3977

Goelles, T., & Begdill, C. E. (2017). Albedo reduction of ice caused by dust and black carbon accumulation: A model applied to the K-transect, west Greenland. Journal of Glaciology, 63(242), 1063–1076. https://doi.org/10.1017/jog.2017.74

Guo, L., & He, Q. (2011). Freshwater flocculation of suspended sediments in the Yangtze River, China. Ocean Dynamics, 61, 371–386. https://doi.org/10.1007/s10236-011-0391-x

Hall, L. C., Stoltevmo, T., Hofer, S., Parfitt, R., & Ummenhofer, C. C. (2020). Importance of orography for Greenland cloud and melt response to atmospheric blocking. Journal of Climate, 33(10), 4187–4206. https://doi.org/10.1175/JCLI-D-19-0527.1

Hashbolt, B., Bech Mikkelsen, A., Holtegaard Nielsen, M., & Andreas Dahl Larsen, M. (2013). Observations of runoff and sediment and dissolved loads from the Greenland Ice Sheet at Kangergussuaq, west Greenland, 2007 to 2010. Zeitschrift für Geomorphologie, Supplemental Issues, 57(2), 3–27. https://doi.org/10.1121/2005-3/5-00121

Hodson, A., Cameron, K., Begdill, C., Irvine-fynn, T., Langford, H., Pearce, D., & Banwart, S. (2010). The structure, biological activity and biochemistry of cryoconite aggregates across an Arctic valley glacier: Longyearbreen, Svalbard. Journal of Glaciology, 56(196), 349–362.

Hofer, S., Tedstone, A. J., Fettweis, X., & Bamber, J. L. (2017). Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet. Science Advances, 3(6) e1705084.

Holmes, R. R. (2001). Surface Water Cata collection. Introduction to Field Methods for Hydrologic and Environmental Studies (Vol. 1, pp. 1–77). Reston, VA: US Department of the Interior, US Geological Survey. https://books.google.com/books?hl=en&lr=&id=Ro5RAQAIAIAJ&oi=fnd&pg=PA1&ots=Pa1fFZd&sig=VDAxjKncUbBsfOkAw+IWF2G2C-9sA&v=onepage&q=Surface%20water%20data%20collection.%20Field%20methods%20for%20hydrologic%20and%20environmental%20studies%20false

Igneczi, A., Sole, A. J., Livingstone, S. J., Leeson, A. A., Fettweis, X., Selmes, N., et al. (2016). Northeast sector of the Greenland Ice Sheet to undergo the greatest inland expansion of supraglacial lakes during the 21st century. Geophysical Research Letters, 43, 9729–9738. https://doi.org/10.1002/2013GL058740

Jarosch, A. H., & Gudmundsson, M. T. (2012). A numerical model for meltwater channel evolution in glaciers. The Cryosphere, 6, 493–503. https://doi.org/10.5194/tc-6-493-2012

Kalstrom, L., & Yang, K. (2016). Fluvial supraglacial landscape evolution on the Greenland Ice Sheet. Geophysical Research Letters, 43, 2683–2692. https://doi.org/10.1002/2016GL067697.1

Kestin, J., Sokolov, M., & Wakeham, W. A. (1978). Viscosity of liquid water in the range 8C to 150C. Journal of Physical and Chemical Reference Data, 7(941).

Luque, R. F., & van Beek, R. (1976). Erosion and transport of bed-load sediment. Journal of Hydraulic Research, 14(2), 127–144. https://doi.org/10.1080/00221687609496677

Macdonell, S., & Fitzsimons, S. (2008). The formation and hydrological significance of cryoconite holes. Progress in Physical Geography: Earth and Environment, 32(6), 595–610. https://doi.org/10.1177/0309133308101382

Mao, L., Agnese, A. D., Huincache, C., Penna, D., Engel, M., Niedrist, G., & Comiti, F. (2014). Bedload hysteresis in a glacier-fed mountain river. Earth Surface Processes and Landforms, 39(7), 964–976. https://doi.org/10.1002/esp.3563

Markus, T., Neumann, T., Martino, A., Abdalati, W., Brunt, K., Coshko, B., et al. (2017). Remote sensing of environment the ice, cloud, and land elevation satellite-2 (ICESat-2): Science requirements, concept, and implementation. Remote Sensing of Environment, 190, 260–273. https://doi.org/10.1016/j.rse.2016.12.029

Marston, R. A. (1983). Supraglacial stream dynamics on the Juneau Icefield, Alaska. Annals of the Association of American Geographers, 73(4), 597–608.

Meyer-Peter, E., & Müller, R. (1948). Formulas for bed-load transport. Paper presented at WODCON.

Miller, M., McCave, I., & Komar, P. (1977). Threshold of sediment motion under unidirectional currents. Sedimentology, 24, 507–527.

Moon, T., Ahlstrøm, A., Goelzer, H., Lipscomb, W., & Nowicki, S. (2018). Rising oceans guaranteed: Arctic land ice loss and sea level rise. Current Climate Change Reports, 4, 211–222. https://doi.org/10.1007/s40641-018-0107-0

Muntjewerf, L., Petrinii, M., Viczaino, M., Ernani, C., Sellevold, R., Scherrenberg, M. D. W., et al. (2020). Greenland ice sheet contribution to 21st century sea level rise as simulated by the coupled CESM2.1-CISM2.1. Geophysical Research Letters, 47, e2019GL086836. https://doi.org/10.1029/2019GL086836

Nagatsuka, N., Takeuchi, N., Uetake, J., & Shimada, R. (2014). Mineralogical composition of cryoconite on glaciers in northwest Greenland. Bulletin of Glaciological Research, 12, 107–114.

Petersen-Overleir, A. (2008). Fitting depth–discharge relationships in rivers with floodplains. Hydrology Research, 39(5–6), 369–384. https://doi.org/10.2166/nh.2008.303
Pitcher, L. H., & Smith, L. C. (2019). Supraglacial streams and rivers. *Annual Review of Earth and Planetary Sciences*, 47, 421–452.

Rennermalm, A. K., Moustafa, S. E., Moduszewski, J. R., Chu, V. W., Forster, R. R., Hagedorn, B., et al. (2013a). Understanding Greenland ice sheet hydrology using an integrated multi-scale approach. *Environmental Research Letters*, 8(1), 14. https://doi.org/10.1088/1748-9326/8/1/015017

Rennermalm, A. K., Smith, L. C., Chu, V. W., Box, J. E., Forster, R. R., Van Den Broeke, M. R., et al. (2013b). Evidence of meltwater retention within the Greenland ice sheet. *The Cryosphere*, 7(5), 1433–1445. https://doi.org/10.5194/tc-7-1433-2013

Rennermalm, A. K., Wood, E. F., Weaver, A. J., Eby, M., & Dey, S. J. (2007). Relative sensitivity of the Atlantic meridional overturning circulation to river discharge into Hudson Bay and the Arctic Ocean. *Journal of Geophysical Research*, 112, G04S48. https://doi.org/10.1029/2006JG000330

Reznichenko, N., Davies, T., Shulmeister, J., & McSaveney, M. (2010). Effects of debris on ice-surface melting rates: An experimental study. *Journal of Glaciology*, 56(197), 384–394.

Ryan, J. C., Hubbard, A., Stibal, M., Irvine-Fynn, T. D., Cook, J., Smith, L. C., et al. (2018). Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities. *Nature Communications*, 9(1), 1–10. https://doi.org/10.1038/s41467-018-03353-2

Samaprity, R. (2017). ArcticDEM batch pipeline Zenodo. http://doi.org/10.5281/zenodo.842056

Siwström, C., Laybourn-parry, J., Granelli, W., & Anesio, A. M. (2007). Heterotrophic bacterial and viral dynamics in arctic freshwaters: Results from a weld study and nutrient-temperature manipulation experiments. *Polar Biology*, 30, 1407–1415. https://doi.org/10.1007/s00300-007-0301-3

Shields, A. (1936a). *Use of dimensional analysis and turbulence research for sediment transport*, 26. Berlin, Germany: Preussen Research Laboratory for Water and Marine Constructions.

Shields, A. (1936b). Applications of similarity principles and turbulence research to bed-load movement (Vol. 167). Berlin: Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau. https://authors.library.caltech.edu/259921/Shields.pdf

Sklar, L. S., & Dietrich, W. E. (2008). Implications of the saltation–abrasion bedrock incision model for steady-state river longitudinal profile relief and concavity. *Earth Surface Processes and Landforms*, 33(7), 1129–1151. https://doi.org/10.1002/esp1689

Smith, L. C., Chu, V. W., Yang, K., Gleason, C. J., Pitcher, L. H., Rennermalm, A. K., et al. (2015). Efficient meltwater drainage through supraglacial streams and rivers on the southwest Greenland ice sheet. *Proceedings of the National Academy of Sciences of the United States of America*, 112(4), 1001–1006. https://doi.org/10.1073/pnas.1413024112

Smith, L. C., Yang, K., Pitcher, L. H., Overstreet, B. T., Chu, V. W., Rennermalm, K., et al. (2017). Direct measurements of meltwater runoff on the Greenland ice sheet surface. *Proceedings of the National Academy of Sciences*, 114, E10622–E10631. https://doi.org/10.1073/pnas.1707743114

Switzer, A. D., & Pile, J. (2015). Grain size analysis. In I. Shennan, A. J. Long, & B. P. Horton (Eds.), *Handbook of sea-level research* (1st ed., pp. 331–346). John Wiley & Sons, Ltd.

Takeuchi, N. (2001). The altitudinal distribution of snow algae on an Alaska glacier (Gulkana Glacier in the Alaska Range). *Hydrological Processes*, 15, 3447–3459. https://doi.org/10.1002/hyp.1040

Takeuchi, N., Kohshima, S., Seko, K., & Takeuchi, N. (2001). Structure, formation, and darkening process of albedo-reducing material (cryoconite) on a Himalayan glacier: A granular algal mat growing on the glacier. *Arctic, Antarctic, and Alpine Research*, 33(2), 115–122. https://doi.org/10.1080/15230430.2001.12003413

Takeuchi, N., Sakaki, R., Uetake, J., Nagatsuka, N., Shimada, R., Niwano, M., & Aoki, T. (2018). Temporal variations of cryoconite holes and cryoconite coverage on the ablation ice surface of Qaanaaq Glacier in northwest Greenland. *Annals of Glaciology*, 59, 21–30. https://doi.org/10.1017/aog.2018.19

Tanaka, M., Girard, G., Davis, R., Peuto, A., & Bignell, N. (2001). Recommended table for the density of water between 0 °C and 40 °C based on recent experimental reports. *Metrology*, 38, 301–309.

Thomensen, H. (1986). Photogrammetric and satellite mapping of the margins of the inland ice, west Greenland. *Annals of Glaciology*, 8, 164–167.

Uetake, J., Tanaka, S., Segawa, T., Takeuchi, N., Nagatsuka, N., Motoyama, H., & Aoki, T. (2016). Microbial community variation in cryoconite granules on Qaanaaq Glacier, NW Greenland. *FEMS Microbiology Ecology*, 92(1), 1–10. https://doi.org/10.1093/femsec/fiw127

Van As, D., Hubbard, A. L., Hasholt, B., Mikkelsen, A. B., Van Den Broeke, M. R., & Fausto, R. S. (2012). Large surface meltwater discharge from the Kangerlussuaq sector of the Greenland ice sheet during the record-warm year 2010 explained by detailed energy balance observations. *The Cryosphere*, 6(4), 199–209. https://doi.org/10.5194/tc-6-199-2012

Van de Wal, R. W. S., Greuell, W., Van den Broeke, M. R., Reijmer, C. J., & Oerlemans, J. (2005). Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, west Greenland. *Annals of Glaciology*, 42(August), 311–316. https://doi.org/10.3189/172756405781812529

van den Broeke, M., Smeets, P., Ettema, J., & Munné, P. K. (2008). Surface radiation balance in the ablation zone of the west Greenland ice sheet. *Journal of Geophysical Research*, 113, D13105. https://doi.org/10.1029/2007JD009283

van Rijn, L. C. (2007). Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. *Journal of Hydraulic Engineering*, 133(6), 649–667. https://doi.org/10.1061/(ASCE)0733-9429(2007)133:6(649)

Woodland, G. P. (1979). The new gravity system—Changes in international gravity base values and anomaly values. *Geophysics*, 44(8), 1352–1366.

Yang, K., & Smith, L. C. (2013). Supraglacial streams on the Greenland ice sheet delineated from combined spectral-shape information in high-resolution satellite imagery. *IEEE Geoscience and Remote Sensing Letters*, 10(4), 801–805. https://doi.org/10.1109/LGRS.2012.2224316

Yang, K., Smith, L. C., Chu, V. W., Pitcher, L. H., Gleason, C. J., Rennermalm, A. K., & Li, M. (2016). Fluvial morphology of supraglacial river networks on the southwest Greenland Ice Sheet. *Glaciological Research and Remote Sensing*, 3(4), 485–492. https://doi.org/10.1002/2015GL068160

Yang, K., Smith, L. C., Karlstrom, L., Cooper, M. G., Tedesco, M., & van As, D. V. (2018). A new surface meltwater routing model for use on the Greenland Ice Sheet surface. *The Cryosphere*, 12(12), 3791–3811.