Modeling Suspended Sediment Discharge in a Glaciated Arctic Catchment–Lake Peters, Northeast Brooks Range, Alaska

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Abstract

Seasonal suspended sediment transfer in glaciated catchments is responsive to meteorological, geomorphological, and glacio-fluvial conditions, and thus is a useful indicator of environmental system dynamics. Knowledge of multifaceted fluvial sediment-transfer processes is limited in the Arctic–a region sensitive to contemporary environmental change. For two glaciated sub-catchments at Lake Peters, northeast Brooks Range, Alaska, we conducted a two-year endeavor to monitor the hydrology and meteorology, and used the data to derive multiple-regression models of suspended sediment load. Statistical selection of the best models shows that incorporating meteorological or temporal explanatory variables improves performances of turbidity- and discharge-based sediment models. The resulting modeled specific suspended sediment yields to Lake Peters are: 33 (20-60) Mg km^{-2} yr^{-1} in 2015, and 79 (50-140) Mg km^{-2} yr^{-1} in 2016 (95% confidence band estimates). In contrast to previous studies in Arctic Alaska, fluvial suspended sediment transfer to Lake Peters was primarily influenced by rainfall, and secondarily influenced by temperature-driven melt processes associated with clockwise diurnal hysteresis. Despite different sub-catchment glacier coverage, specific yields were the same order of magnitude from the two primary inflows to Lake Peters, which are Carnivore Creek (128 km^2; 10% glacier coverage) and Chamberlin Creek (8 km^2; 23% glacier coverage). Seasonal to longer term sediment exhaustion and/or contrasting glacier dynamics may explain the lower than expected relative specific sediment yield from the more heavily glacierized Chamberlin Creek catchment. Absolute suspended sediment yield (Mg yr^{-1}) from Carnivore Creek to Lake Peters was 28 times greater than from Chamberlin Creek, which we attribute to catchment size and sediment supply differences. Our results are useful for predicting changes in fluvial sediment transport in glaciated Arctic catchments.

Data Availability Statement

The sediment data and data used for generating variables to input to our sediment models are openly available in the Arctic Data Center at https://arcticdata.io/catalog/view/urn:uuid:df1eace5-4dd7-4517-a985-e4113c631044 (Broadman et al., 2019). Data that support the findings of this study are also available from the corresponding author upon request.

Main Text

Introduction

Quantitative estimates of annual fluvial suspended sediment yield (hereafter, ‘sediment yield’) are sought by physical scientists as signals of environmental dynamics, by ecologists for their associations with water quality and habitat value, and by engineers for hydro-infrastructure and river system design. Measuring sediment yields presents a challenge, because sediment transfer is inherently variable in space and time

(Morehead, Syvitski, Hutton, & Peckham, 2003; Orwin, Lamoureux, Warburton, & Beylich, 2010). Research from glaciated Arctic catchments indicates that sediment transfer typically reflects catchment-scale processes (Hodgkins, Cooper, Wadham, & Tranter, 2003), including meteorological forcing (Lewis & Lamoureux, 2010; Syvitski, 2002), glacial dynamics (Bogen & Bønses, 2003; Gurnell, Hannah, & Lawler, 1996; Hodson & Ferguson, 1999; Hodson, Tranter, Dowdeswell, Gurnell, & Hagen, 1997), and other geomorphological processes (Hasholt et al., 2005). The complexity of meteorological forcing on sediment transfer in glaciated catchments is accentuated by reports of substantial variations through time over recent millennia (Saarni, Saarinen, & Lensu, 2015), and across spatial scales (Striberger et al., 2011). Sediment transfer can vary significantly on inter-annual, decadal, and century scales (Bogen & Bønses, 2003; Gurnell et al., 1996; Lewis, Lafrenière, & Lamoureux, 2012; Lewkowicz & Wolfe, 1994; Orwin & Smart, 2004a; Richards, 1984; Tape, Verbyla, & Welker, 2011), and may reflect landscape evolution over glacial-interglacial cycles (Church & Ryder, 1972; Church & Slaymaker, 1989; Leonard, 1997). Within a single open-channel season, the majority of annual catchment-scale sediment yield can be transported during one, or a few, discrete events (Bogen & Bonses, 2003; Dugan, Lamoureux, Lafrenière, & Lewis, 2009; Fenn, Gurnell, & Beecroft, 1985; Hasholt et al., 2005; Lewis et al., 2012; Schiefer et al., 2017; Østrem, 1975). Sediment availability and exhaustion can greatly affect seasonal sediment transfer (Bogen & Bønses, 2003; Forbes & Lamoureux, 2005; Hodgkins, 1999; Hodgkins et al., 2003; Hodson et al., 1998; Irvine-Fynn et al., 2005). Proglacial instrumentation and sampling programs to directly measure suspended sediment concentrations (SSCs) at daily, or preferably hourly or finer sampling intervals (Orwin et al., 2010), over periods longer than one open-channel season are rare in the Arctic (Hasholt et al., 2005). Consequently, statistical models are relied upon to estimate annual sediment transfer from discontinuous samples of SSC. In Arctic Canada, automated sampling has enabled continuous measurement of SSC fluctuations and estimation of sediment yields using spline curves (Cockburn & Lamoureux, 2008; Favaro & Lamoureux, 2014; Lewis et al., 2012); however, such intensive sampling throughout the full length of the open-channel season is not always feasible. More typically, statistical models comprise simple sediment rating curves, using either discharge (Bogen & Bonses, 2003; Dugan et al., 2009; Fenn et al., 1985; Forbes & Lamoureux, 2005; Hodgkins, 1996; Hodson et al., 1998; Horowitz, 2003; Lamb & Toniolo, 2016; Lewkowicz & Wolfe, 1994; McLaren, 1981; O'Farrell et al., 2009; Rasch, Elberling, Jakobsen, & Hasholt 2000; Østrem, 1975), or, less often, turbidity (Harrington & Harrington, 2013) as the single predictor of SSC. Despite their popularity, failure to adequately account for quasi-autocorrelation has been identified as a pitfall associated with the use of simple sediment rating curves (Hodgkins, 1999; Hodson & Ferguson, 1999). Quasi-autocorrelation arises from shortfalls in formulation of the regression model, including: an incorrect fit, failing to identify the presence of lags, changes in response between the dependent and independent variables, and omitting relevant independent variables (Fenn et al., 1985; Gao, 2008; Hodson & Ferguson, 1999). SSC may be underestimated or overestimated by simple sediment rating curves (Gao, 2008; Walling, 1977), with perturbations smoothed and margin for error reduced as the monitoring period increases (Horowitz, 2003). However, monitoring spanning more than a couple of months of one or two open-channel seasons is rare in remote arctic environments (e.g. Bogen & Bønses, 2003). Statistical methods can be applied to address quasi-autocorrelation, improving the predictive ability of sediment rating curves. For example, separating rating curves according to discrete temporal periods, or stage, have both proven popular, with varied success (Harrington & Harrington, 2013; Hodgkins, 1996; Hodson et al., 1998; Horowitz, 2003; Lewkowicz & Wolfe, 1994; McLaren, 1981; Richards, 1984; Walling, 1977; Østrem, 1975). Multiple-regression models, incorporating hydrological, temporal, and meteorological explanatory variables with optimal lag times, are often preferable over rating-curve-separation because they account for processes that can decouple SSCs from contemporaneous discharge or turbidity fluctuations, and help us understand multifaceted, dynamic processes driving glaciofluvial sedimentation (Hodgkins, 1999; Hodson & Ferguson, 1999; Irvine-Fynn et al., 2005; Richards, 1984; Willis, Richards, & Sharp, 1996). Temporal variables can be used as indicators of sediment availability, including: hysteresis effects, intra-season variability, and seasonal variations. Meteorological variables can also capture temporal variability in SSCs, including: diurnal and longer cycles of solar radiation and temperature affecting melt-related erosion and transfer; and rainfall-induced events generating hillslope erosion and delivery processes, extra-channel erosion, and sediment entrainment with rising discharge. Further, inclusion of meteorological variables in sediment modeling can provide useful information for interpreting past climates from longer sedimentary records, and assessing sensitivity to climate change through hydroclimatic system forecasting (Forbes & Lamoureux, 2005; Gordeev, 2006; Lewis & Lamoureux, 2010; Syvitski, 2002). Despite potential advantages, multiple-regression models are uncommonly used for studying suspended sediment transfer in catchments above the Arctic Circle (Hodgkins, 1999; Hodson & Ferguson, 1999; Irvine-Fynn et al., 2005; Schiefer et al., 2017). In Arctic Alaska (defined hereafter as Alaskan land above the Arctic Circle—66.33°N), even simple sediment rating curves have rarely been constructed (Arnborg et al., 1967; Lamb & Toniolo, 2016; Rainwater & Guy, 1961; Trefry, Rember, & Trocine, 2004). The objective of this paper is to use multiple-regression models to estimate seasonal sediment yields, and interpret physical processes driving these yields, at Lake Peters, northeast Brooks Range, Arctic National Wildlife Refuge, Alaska, a site selected for hydrological and paleoenvironmental research (Benson, Kaufman, McKay, Sciefer, & Fortin 2019; Broadman et al., 2019; Ellerbrook, 2018; Thurston, 2017).

Study Area

Lake Peters (69.32°N 145.05°W) is situated approximately 300 km north of the Arctic Circle, and 70 km from the Arctic Ocean in the Brooks Range, Alaska (Figure 1). Lake Peters catchment (171 km^2) is ringed by steep mountains, and glaciated (9%) with some of the largest valley glaciers in Arctic Alaska. Bedrock comprises low-grade metasedimentary and sedimentary rocks, primarily southward-dipping sandstone, semischist, and phyllite, with minor chert and quartzite (Reed, 1968). Terminal cirque and lateral moraines formed during the Little Ice Age (*ca.* 1200-1850 CE) are conspicuous around the margins of extant glaciers in the headwaters of Lake Peters (Evison, Calkin, & Ellis, 1996). Interpolated climate data for Lake Peters (1980 - 2009) shows mean annual precipitation of 360 mm, and mean January and July monthly temperatures of -22.0°C and 10.5°C, respectively (Stavros & Hill, 2013). Permafrost is known to occur at the bases of hillslopes and in bottoms of river valleys in the Brooks Range (Kanevskiy et al., 2011). Soils are sparse, and vegetation largely consists of arctic grasses, herbs, and riparian shrubs. Above 1300 m, channel-side vegetation is sparse. Lake Peters is the primary source of the Sadlerochit River, which discharges into the Arctic Ocean. Carnivore Creek (128 km^2 catchment; 10% glacier coverage based on aerial photos taken in 2016) and Chamberlin Creek (8 km^2catchment; 23% glacier coverage) are the primary inflows to Lake Peters (Figure 2), although several minor non-glaciated catchments also flow into Lake Peters over and through large alluvial fans (Figure 1). The Carnivore sub-catchment covers 75% of the total area of the Lake Peters catchment. The eastern side of the Carnivore valley is glacierized, channels are more deeply incised, and side-valley alluvial fans are more compact, compared to the western side. The lower reach of Carnivore Creek flows over a shallow slope with plane bed morphology, surrounded by a terraced floodplain and some periglacial surface features. Chamberlin Creek's catchment is comparatively steep, with the summit of Mount Chamberlin (2750 m asl) only 4.7 km from Lake Peters. Chamberlin Glacier (1.9 km^2) is the third largest glacier in Lake Peters catchment. In the upper catchment, Chamberlin Creek flows over and through moraines; in the mid-catchment the channel has incised into a confined bedrock-controlled valley, with steep step-pools; and downstream of the alluvial fan apex the creek flows over lower-grade step-pools (Figure 3).

Methodology

Hydrological and Meteorological Data

Four (2015) and two (2016) field stints of up to three weeks occurred during each open-channel season (05/18 – 09/17), with hydrological sampling balanced among other field priorities. Hydrological and meteorological stations were setup for continuous monitoring at 30 or 60 minute intervals (Figures 1 and 3). At the meteorological stations (854, 1425, and 1750 m asl), data loggers recorded air temperature, ground temperature (2 cm and 30 cm depth), and rainfall. The meteorological station at 854 m asl also recorded solar radiation and barometric pressure. Meteorological instrumentation is described in Broadman et al. (2019). At the hydrological stations, we used In-Situ TROLL 9500 ("TROLL") instruments to measure water-pressure and turbidity, and Hobo Onset U20 ("Hobo") instruments to measure water pressure. Additionally, time-lapse cameras photographed the hydrological stations hourly throughout the open-channel seasons. In Carnivore

Creek, and during the 2015 season in Chamberlin Creek, the TROLL and Hobo instruments were secured in thalwegs of relatively stable reaches close to Lake Peters, upstream from where the main channel anabranches (CAR and CHB_a on Figure 1). During the 2016 season in Chamberlin Creek, the instruments were secured farther upstream at the apex of the alluvial fan (CHB_b on Figure 1). Turbidity data were used after removing erroneous data due to fouling or instrument dislodgement, resulting in discontinuous time-series. Unrecorded or erroneous stage data was infilled using regressions or photographic reconstructions where available (Broadman et al., 2019; Thurston, 2017). To generate statistics, unrecorded temperature data was also infilled using regressions (Appendix I), but only the original meteorological records were used for sediment modeling. SSCs in Carnivore and Chamberlin Creeks were sampled manually at the hydrological stations using a depth-integrated handheld sampler (US DH-48). The liquid volume of each sample was recorded, prior to filtering with GN-4 Metricel membrane disc filters (0.8 μm). Filters were later dried in a laboratory oven and weighed (± 0.01 mg). For discharge, we used a Hach FH950 portable velocity meter to measure current velocities and cross-sections near the hydrological stations. In the 2016 field season the velocity meter was inoperable, so only cross-section areas were used for calculating discharge (Broadman et al., 2019). The discharge data was used to construct stage-discharge rating curves and establish continuous discharge records (Broadman et al., 2019; Thurston, 2017).

Sediment Models

SSCs measured in Carnivore and Chamberlin Creeks were modeled using a combination of hydrologic, meteorological, and temporal variables. The modeling periods are the 2015 and 2016 open-channel seasons, which encompass the vast majority of annual sediment transfer to Lake Peters. To develop multiple-regression models of SSC for Carnivore and Chamberlin Creeks, a similar approach to Hodgkins (1999) and Schiefer et al. (2017) was used. We assessed 60 potential predictors: a range of hydrological, meteorological, and temporal explanatory variables, all linearly interpolated to match times of SSC sampling (Table 1). The frequency of SSC sampling was sufficiently discrete that when we tested for serial autocorrelation, a negative result was returned, thus no adjustment was necessary. Correlations among predictor variables were calculated in R software (Thurston, 2017). Correlated variables ($p < 0.05$), which could introduce spurious relations if input as covariates, were grouped to ensure that they would not be selected in the same model. A for-loop was constructed to cycle through the correlated groups, applying the 'glmulti' function for exhaustive candidate testing (Calcagno & Mazancourt, 2010) for each sub-catchment separately (Thurston, 2017). Akaike's (1977) information criterion (AIC) was used to assess the relative goodness of fit for each candidate model, while avoiding overfitting (Burnham & Anderson, 2002), and statistics for the best models with similarly low AICs were compared.

Sediment Yield Methods

NTU- and Q-based ($\log_e$ transformed) modeled SSCs (converted from mg L^{-1} to mg m^{-3}) were multiplied by discharge separately to give sediment yield (mg s^{-1}) and converted to integrate mass over longer periods (Mg yr^{-1}). Confidence and prediction intervals for modeled SSCs were calculated in R, then converted to lower and upper yields using the same method. NTU- and Q-based half-hourly or hourly sediment yields (depending on the interval of model parameters) were bridged by taking the period of available NTU-based yields and subsequently filling gaps where NTU-based yield values were not available with Q-based yield values, to give continuous records of sediment yield for both Carnivore and Chamberlin Creeks for the majority of the 2015 and 2016 open-channel seasons. For early- and late-season, when modeled SSCs could not be predicted with either NTU- or Q-based models due to lack of data, average sediment yield below the corresponding estimated low-flow discharge estimated from photographs and field notes was used (< 10 m^3s^{-1} and < 5 m^3s^{-1} in Carnivore Creek; < 0.25 m^3 s^{-1} in Chamberlin Creek). Subsequently, sediment yields for the entire open-channel seasons in both creeks could be estimated. We used May 18 to September 17 as the open-channel period, based on data availability and field photographs. During mid-May when flows were ice affected, field observations and photographs indicate that our dataset may exclude up to one week of low-flow water and sediment discharge. We are confident that no significant late-season events were missed based on photographic evidence and regressions of Q from our study with the nearby Hula Hula River discharge (U.S.

Geological Survey gauge 15980000), with the latter explaining about half the late season Q variability.

Results

Carnivore and Chamberlin Creek Hydrology

Carnivore Creek discharged approximately 95% of the total measured water volume to Lake Peters in 2015 and 2016, with Chamberlin Creek accounting for the remaining 5%. No distinct spring freshet (independent of rainfall) was observed in either season, although in 2016 ice had partially melted and delivered the first flush of water and sediment, then refrozen, prior to the period of record commencing. Both creeks showed a diurnal trend peaking at 01:00, with the trend more distinct in Carnivore Creek. In 2015, Q exhibited five distinct peaks from low flow (>20 $m^3 s^{-1}$ in Carnivore Creek; >1 m^3 s^{-1} in Chamberlin Creek); whereas, in 2016, Q was elevated for an extended period between mid-June and mid-July in both creeks, with distinct peaks above this elevated flow throughout the season (Figure 4). Total water discharge in 2016 was greater than in 2015 by 28% for Carnivore Creek, but not significantly different for Chamberlin Creek. The largest flood peak in both creeks occurred on 07/07/16. Maximum 2016 Q in Carnivore Creek during this flood (98 m^3 s^{-1}) was more than double the maximum 2015 Q (48 $m^3 s^{-1}$) (Table 2). Maximum 2016 Q during this flood in Chamberlin Creek is estimated to be 21 $m^3 s^{-1}$—seven times larger than the maximum Q of 3 m^3 s^{-1} in 2015 (Figure 4), noting the wider error margin because of photographic estimation (Table 2). Photographic evidence supports quantitative conclusions that the flood of 07/07/16 was more peaked in Chamberlin Creek than in Carnivore Creek. Turbidity maxima over 2500 NTU were recorded in Carnivore Creek in both 2015 and 2016 (Table 2; Figure 4). The maximum manually sampled SSC (1400 mg L^{-1}) corresponds with the maximum 2015 NTU, but SSC was not sampled during the 2016 flood. Neither NTU nor SSC data are available for Chamberlin Creek during the 2016 flood. Available NTU and manually sampled SSC records for Chamberlin Creek peaked on 6/22/15, reaching 1200 NTU and 650 mg L^{-1}, respectively, corresponding with a period of elevated Q (Table 2; Figure 4). Two high, spurious SSCs, which do not correspond with high NTU or Q, were sampled in Chamberlin Creek on 7/24/15.

Lake Peters Meteorology

Air temperature averaged 4°C and ground temperature averaged 6°C at the meteorological stations throughout the open-channel seasons (Table 2). Mean temperature at the 854 m asl station was 6°C, decreasing to 2-3°C at 1750 m asl. Hourly air temperatures ranged from -13°C (T. 1425 m asl, 09/15/16 0400; and T. 1750 m asl, 09/15/16 0100) to 23°C (T. 854 m asl, 07/15/16 1100). Ground temperatures ranged from -2°C (GT. 1750 m asl, 09/01/16 0200) to 23°C (GT. 1425 m asl, 07/06/15 1900). The warmest air and ground temperatures were observed from May through July, with cooling in August and September (Figure 4). Temperature showed diurnal cycles, and other intra-season variability, at all three elevations. Non-diurnal intra-season variability was smoothed and delayed in the ground temperature records, which rarely dropped below 0°C. A complete hourly rainfall record for both years was only obtained at the low-elevation station. Precipitation at 854 m asl totaled 142 mm in 2015 and 231 mm in 2016, with 24-37% more precipitation measured at higher elevations. The largest total seasonal precipitation recorded was 304 mm at 1750 m asl in 2016. In 2015 maximum P_1 was 5.2 mm (1750 m asl; 06/30 2100), and in 2016 maximum P_1 was 7.6 mm (1425 m asl; 06/22 1100) (Table 2). The most intense P_{24} of 34 mm (1750 m asl) occurred during the July 2016 flood.

Sediment Model Results

To develop a useful predictive tool, 2015 and 2016 data was used in one unified model of SSC. To avoid overfitting and spurious relations, our best models do not fit predictors that are significantly correlated. Correlated groups can be generalized as follows: a) $\log_e$transformed Q variables and NTU; b) P variables; c) T, GT, and SR variables; and d) $\cos_{hr}$ and $\sin_{hr}$; with Q_E and H standalone, although groups specific to each primary predictor were used for modeling. Carnivore Creek NTU is significantly correlated with $P_{12,24}$ and $T_{12,24}$ at all elevations, as well as with $T_{2,6}$ and $GT_{12,24}$ at 854 m asl, and P_6 and GT_2 at 1425 m asl. Chamberlin Creek NTU is uncorrelated with most P variables and significantly correlated with most T and

GT variables. Carnivore Creek Q is significantly correlated with $P_{12,24}$ at all elevations, with P_6 at 1425 and 1750 m asl, and with all T and GT variables. Chamberlin Creek Q is also significantly correlated with most P variables and all T and GT variables. In some cases, the temporal variables were also correlated with the primary predictors, or with the meteorological or other temporal variables. Compared with simple sediment rating curves, the additional predictor variables (uncorrelated with NTU or Q) improve variability explained (R^2) by 15% and 9% in Carnivore Creek, and 9% and 27% in Chamberlin Creek for NTU- and Q-based models, respectively. Best-fit combinations varied between creeks, and with the base predictor–NTU or Q (Table 3). Q was the only retained discharge variable (i.e. ΣQ and ΔQ were not incorporated in any of the best-fit models). Temperature and precipitation variables were excluded from most of the models because of significant correlations with the primary predictors. Exceptions include ground temperature ($GT_2$1750 m asl) in the Carnivore Creek NTU-based model, and precipitation (P_{12} 1750 m asl) in the Chamberlin Creek NTU-based model. Sin_{hr} is a significant tertiary predictor in the Chamberlin Creek NTU-based model, indicative of higher SSCs at 1800 than at 0600. In the Q-based model for Carnivore Creek, $cos_{hr}$was selected, indicative of higher SSCs at midnight than at noon. We found H to be a significant additional predictor in the Chamberlin Creek Q-based model. SSCs output by the NTU-based models reached maximums of 2275 and 2409 mg L^{-1} in Carnivore Creek, and 261 and 203 mg L^{-1} in Chamberlin Creek, in 2015 and 2016, respectively (Figure 4).

Sediment Yield Results

NTU-based multiple-regression models explain more variability in SSCs than Q-based models (Table 3), making them our first choice for predicting annual sediment yields. However, the turbidity sensor failed at times, and there are no substitutes for NTU measurements, such that NTU-based models could not be used alone. Q-based models could be applied with fewer gaps, but data were still lacking for the shoulder periods of each season. Photographic and field observation evidence of Q during ungauged shoulder periods led us to use average SSCs at low flows to fill early- and late-season gaps. Bridging the three methods in preferential order allowed sediment yields to be estimated (Table 4). Given that there is minimal sediment transfer at low flow, using our approximation for shoulder periods makes little difference to the estimated sediment yields; 5.4% and 13% (2015) and 0.17% and 1.7% (2016) of the total open-channel season sediment yield in Carnivore and Chamberlin Creeks, respectively, was approximated from average SSCs at low flow. Furthermore, our sediment yield results are supported by estimates based on sediment accumulation rates measured in Lake Peters (Thurston, 2017). Total seasonal suspended sediment discharge into Lake Peters from Carnivore Creek is one or two orders of magnitude higher than suspended sediment discharge from Chamberlin Creek, with the former contributing 96% of the total yield from these two major tributaries (Table 4). When normalized by catchment area and averaged across 2015 and 2016, the specific sediment yields were 58 and 33 Mg $km^{-2}yr^{-1}$ from Carnivore and Chamberlin Creeks, respectively. Sediment yield for Carnivore and Chamberlin Creeks is 59% and 37% greater, respectively, in 2016 than 2015. Most of the suspended sediment loads in both creeks are transported within a few days during discrete events (Figure 5). In Carnivore Creek, over 49% and 50% of the sediment yield is modeled to have been discharged in 48 consecutive hours for 2015 (August 3-5) and 2016 (July 7-9), respectively. In Chamberlin Creek, 12% and 57% of the sediment yield is modeled to have been discharged in 48 consecutive hours for 2015 (August 3-5) and 2016 (July 7-9), respectively.

Discussion

Best-fit Sediment Models

Our best-fit models are statistically significant predictors of SSC in tributaries to Lake Peters, although there is considerable unexplained variability (Table 3). Mass wasting independent of discharge (Gao, 2008; Hammer & Smith, 1983; Hasholt et al., 2005; Walker & Hudson, 2003), and sediment pulses associated with glacier motion (Hasholt et al., 2005; Willis et al., 1996), may cause transient flushes of sediment not accounted for by our models. Compared with Carnivore Creek, the consistency and accuracy of SSC modeling is lessor in Chamberlin Creek, which has a smaller sub-catchment size. This is relatable to the inherent flashiness of smaller catchments (Horowitz, 2003), making complex sediment transfer processes difficult to quantify, even with continuous and high-resolution model predictors. NTU-based models outperformed Q-based models as a predictor of SSC, which is not surprising given SSC can vary by two orders of magnitude for any one discharge (Morehead et al., 2003), whereas turbidity is a more direct surrogate for SSC. In contrast to our models (Table 3), earlier multiple-regression sediment models developed for arctic rivers have not incorporated NTU, but have favored alternative discharge variables (ΣQ, ΔQ, Q_E, and/or Q^2), with positive and/or negative coefficients depending on the catchment, season, or sub-season (Hodgkins, 1999; Hodson and Ferguson, 1999; Irvine-Fynn et al., 2005; Schiefer et al., 2017). Further, these earlier models have been geographically limited to catchments in Svalbard. In all cases at Lake Peters, inclusion of additional meteorological or temporal predictor variables (uncorrelated with NTU or Q) improved performance of models predicting SSCs (Table 3), and supported our understanding of sediment transfer processes over two years of open-channel flow. The best-fit model predictors could not be used standalone to interpret physical processes, because exclusion of correlated predictors to avoid overfitting masked some meteorology–hydrology interactions, and numerous predictor combinations provided statistically significant model outputs. Therefore, further analysis of the hydrometeorological data, as well as qualitative geomorphologic evaluations, informed our understanding of sediment transfer processes at Lake Peters.

Meteorological Controls on Sediment Transfer

Precipitation was excluded from three of four best-fit models due to significant correlations with Q and NTU, suggesting that precipitation has a strong influence on discharge and turbidity. P_{12}at 1750 m asl was a significant predictor in the Chamberlin Creek NTU-based model (Table 3). P_{12} possibly represents a coarse fraction of suspended sediment eroded and entrained during precipitation-induced high discharges. This would be consistent with nephelometric turbidimeter signals being more sensitive to fine particles (clay and silt) due to their greater light scattering efficiency and particle surface area, thus potentially under-representing the coarse (sand) fraction (Orwin et al., 2010).

We estimated that substantial seasonal sediment delivery in both study creeks was transported over 48 hours (Figure 5). The hydrological response to rainfall during these events may have been enhanced by their timing in mid-July to early-August, when channel-ice and snow were less likely to impede erosion (e.g. Crawford & Stanley, 2014; Irvine-Fynn et al., 2005), and glacier conduits are likely open to flush sediment into the proglacial fluvial system. Additionally, the placement of hydrological stations near stream outlets may have represented the rainfall signal more completely than if they were placed farther upstream (e.g. Irvine-Fynn et al., 2005; Orwin & Smart, 2004b; Willis et al., 1996). The short duration over which the majority of sediment is transferred to Lake Peters is comparable with other rivers that drain the northern Brooks Range, including: the Kuparuk River near Prudhoe Bay where 90% of the annual suspended sediment load was transferred over three days in 2001 (Rember & Trefry, 2004); the Sagavanirktok River, with 88% over 12 days in 2001 (Rember & Trefry, 2004); and the Colville River, with 62% over 13 days in 1961 (Walker & Hudson, 2003), although these studies emphasize melt processes rather than rainfall.

Similar to precipitation variables, temperature variables were excluded from three of four best-fit models due to significant correlations with other predictors. We note that such correlations have not been reported by authors of similar models (Irvine-Fynn et al., 2005; Schiefer et al., 2017). Albeit model limitations, field observations and diurnal signals suggest that temperature-driven melt processes influence sediment transfer in both Carnivore and Chamberlin Creeks. The inclusion of GT_2 (1750 m asl) in our Carnivore NTU-based model suggests that melt-processes mobilize a sediment supply less discernible to the turbidity sensor. We note that this model (Table 3) is the first to incorporate ground temperature as a supplementary predictor of SSC, although ground conditions have previously been related to sediment transfer in the Arctic (Favaro & Lamoureux, 2014; Irvine-Fynn et al., 2005; Syvitski, 2002). Supplementing this NTU-based model with ground temperature (using GT_2 at 1750 m asl, R2 = 0.68) explains slightly more variability in SSCs than air temperature (using T_2 at 1750 m asl, $R^2 = 0.63$), which may relate to ground temperatures better reflecting thaw-related sediment mobilization and/or improved model relations with high-frequency filtering in the ground temperature record (Figure 4).

Although both rainfall and temperature affect discharge and sediment transfer, they do not fully explain the disparities between the 2015 versus 2016 hydrographs (Figure 4). In 2016, Q was elevated for an extended period between mid-June and mid-July in both creeks, but neither precipitation nor temperature were notably higher in 2016. End-of-winter snow water equivalence has been positively related to discharge and sediment transfer in the Arctic (Bogen & Bønses, 2003; Cockburn & Lamoureux, 2008; Forbes & Lamoureux, 2005; Lewkowicz & Wolfe, 1994); however, simple DEM differencing of repeat photogrammetric surfaces calibrated for catchment snow measurement at Lake Peters (Broadman et al., 2019; Nolan, Larsen, & Sturm, 2015) suggested a greater overall snowpack in 2015, thus snow water equivalence does not explain the elevated 2016 Q. Limitations associated with developing continuous discharge time-series from stage could contribute to the seasonal hydrograph differences, although such limitations do not appear great enough to affect average Q, nor the magnitude of sediment yield results (Thurston, 2017). An earlier study on Chamberlin Creek reports an average discharge of 0.65 m^3 $s^{-1}$for 44 days in late summer (between 07/01/1958 and 08/13/1958) (Rainwater & Guy, 1961), which is similar to the mean daily discharges of 0.62 and 0.77 m^3 s^{-1} (2015 and 2016, respectively) for the same days of the year in this study.

We interpret temperature-driven melt processes as secondary to rainfall in controlling sediment yield, because most of the sediment load is transported to Lake Peters during rainfall-induced flood events. Although the same intensity and volume of rainfall does not necessarily equate to the same magnitude of sediment load, rainfall is clearly associated with events that transport the majority of the annual sediment yield to Lake Peters. Rainfall and sediment transfer are strongly correlated from the onset of the open-channel seasons, with no distinct shift between temperature-driven spring snowmelt and late summer rainfall-induced sediment transfer during the period of record in 2015 and 2016, as has been observed in Arctic Canada (Dugan et al., 2009; Lewis et al., 2012; McLaren, 1981). In Arctic Alaska, literature reporting sediment yields (Table 5) has not established the metrological processes driving water and sediment discharge, although hydrograph research provides inference. At Lake Peters, the dual snowmelt and rainfall early in the open-channel-season, and more significant rainfall in July and August, is inconsistent with a regional hydrograph developed for the coastal plain of the Arctic National Wildlife Refuge, which showed most of the total water discharge during the spring freshet (Lyons & Trawicki, 1994) and later work that applies this as an assumption (e.g. Rember & Trefry, 2004). Following observation of an extreme flood event in the Upper Kuparuk River, Kane et al. (2003) suggest that most floods of record in Arctic Alaska are rainfall-generated, especially in smaller catchments; however, our research suggests that seasonal floods are also rainfall-generated. At Lake Peters, significantly greater, and primarily rainfall-driven, discharge volume in 2016 explains the higher annual sediment yield that year than in 2015. In Svalbard and Arctic Canada, metrological processes driving sediment discharge have been researched, in addition to hydrographs. Dominantly rainfall-induced sediment transfer (Bogen & Bønses, 2003; Lamoureux, 2000; Lewis et al., 2012), similar to Lake Peters, and temperature-dominated melt regimes of sediment transfer (Braun, Hardy, Bradley, & Retelle, 2001; Favaro & Lamoureux, 2014; Hardy, 1996; Irvine-Fynn et al., 2005; Moore, Hughen, Miller, & Overpeck, 2001; Smith, Bradley, & Abbott, 2004), have both been reported. Comparison with arctic forecasting studies suggests that relatively small, mountainous arctic catchments (e.g. Lake Peters; and Lewis & Lamoureux, 2010) are more responsive to rainfall than larger, coastal arctic catchments (e.g. Syvitski, 2002).

Temporal Variability in Suspended Sediment

Variables representing variations in sediment availability were considered, including: $\cos_{hr}$ and $\sin_{hr}$to capture diurnal variability; ΔQ to represent other hysteresis effects; Q_E to represent sediment supply variability within a season; and H and ΣQ as indicators of seasonal trends (Table 1). Selection of $\cos_{hr}$ and $-\sin_{hr}$ in the best-fit models for Carnivore and Chamberlin Creeks, respectively, are indicative of clockwise diurnal variability in the Q-SSC and NTU-SSC relations. Some Arctic sediment transfer studies have found no evidence of hysteresis control beyond covariation with discharge (Hodgkins, 1996; Hodgkins, 1999; Irvine-Fynn et al., 2005), while others have found prominent hysteresis effects over various time periods (Arnborg et al., 1967; Hodson et al., 1999; Lewkowicz & Wolfe, 1994; McDonald and Lamoureux, 2009; Richards, 1984; Schiefer et al., 2017; Østrem, 1975). Both $\cos_{hr}$ and $-\sin_{hr}$ are likely related to the glacier meltwater cycle, during which sediment is entrained on rising daily discharge, resulting in higher SSCs on the rising limb, compared to when sediment is deposited farther downstream as meltwater discharge wanes (Lewkowicz & Wolfe, 1994; McDonald and Lamoureux, 2009; Richards, 1984). The diurnal SSC peak is later in Carnivore Creek than in Chamberlin Creek, which we attribute to the greater sediment transfer distance and lower slope of Carnivore Creek.

Suspended sediment exhaustion over the course of the open-channel season is suggested by the negative H coefficient in the Q-based model for Chamberlin Creek, but is not suggested for Carnivore Creek (Table 3), probably due to discrepancies in catchment characteristics. Chamberlin sub-catchment is small and steep, compared with the gently sloping lower valley of Carnivore Creek (Figure 2), with less potential for transient intra-annual sediment storage and remobilization. Differences among the glaciers' thermal regimes (Bogen & Bønses, 2003; Hodson & Ferguson, 1999), or the pace of Quaternary-scale paraglacial denudation (Church & Ryder, 1972; Church & Slaymaker, 1989), could also explain seasonal exhaustion in the sub-catchment of Chamberlin Creek, but not in Carnivore Creek.

Glaciofluvial Processes and Sediment Yield

Glacier coverage is a well-known control of sediment yield (Hallet et al., 1996; Meade et al., 1990), and heavily glaciated catchments in Alaska have been found to produce an order of magnitude more sediment than other Alaskan catchments (Hallet et al., 1996). Against this trend, we found that specific sediment yields (SSYs) for Chamberlin Creek (23% glacier coverage) were similar to Carnivore Creek (10% glacier coverage) in 2015, and less in 2016 (Table 5). Our results are comparable with Gurnell et al. (1996), who also found an inverse relation between SSY and glacier coverage for Alaskan catchments. If the rates of glacier recession and glacier thermal regimes are consistent between sub-catchments, this signifies the importance of non-glacial processes. Non-glacial sediment sources (i.e. proglacial extra-channel and hillslope sources) eroded during rainfall events are likely significant, as reported for Matanuska Glacier in southern Alaska (O'Farrell et al., 2009). At Lake Peters, more exceptional sediment delivery from Carnivore Creek during high discharge events dominates the yield to Lake Peters, despite lower glacier coverage than Chamberlin Creek (Table 4; Figure 4). Conversely, at low flow, Chamberlin Creek's steeper slopes result in persistently turbid water on the alluvial fan (63 NTU average for $Q < 0.325$ m^3s^{-1}), compared with relatively clear water in Carnivore Creek (30 NTU average for $Q < 15$ m^3s^{-1}), although low flow delivery is a meager proportion of the sediment yield.

Glacier processes may enhance sediment delivery in Carnivore Creek under the current hydrological regime. Ellerbrook (2018) report that old water (glacier melt and subsurface flow) contributed a higher proportion of the hydrograph than rainfall in the Carnivore sub-catchment, whereas rainfall dominated over old water in the Chamberlin sub-catchment. If the glaciers have surface-bed connections, it is possible that more intense rainfall over the Carnivore glaciers contributes to erosive glacier processes, compared with Chamberlin sub-catchment, which is a more isolated massif. Subglacial conduits may have melted by the time the most peaked rainfall events occur (mid-July to early-August), supporting subglacial erosion and enhancing hydrological response (e.g. Bogen & Bønses, 2003; Gurnell et al., 1996; Hodson & Ferguson, 1999; Hodson et al., 1997). The nearby polythermal McCall Glacier (~50 km west of Lake Peters) was found to have a zone of basal sliding, and moulins—likely transferring surface meltwater to the glacier's base, but a complex subglacial drainage network was probably not active (Pattyn et al., 2009). Although the contemporary subglacial network at Lake Peters has not been studied, Benson et al. (2019) relates millennial-scale changes in sediment accumulation and other sediment properties in Lake Peters to large-scale glacial fluctuations and other hydro-climatic Holocene trends, and note that increased accumulation rates during the last century may reflect contemporary glacier retreat.

Conclusion

At Lake Peters, multiple-regression models provided insight into complex, catchment-scale, physical processes. Under the current regime, seasonal rainfall generated floods are the dominant driver of fluvial sediment transfer to Lake Peters, and high total water discharge lends to Carnivore Creek contributing the majority of the total sediment yield. Secondary melt processes are associated with clockwise diurnal hysteresis, and data revealed seasonal sediment exhaustion in Chamberlin Creek. A glaciological study would be required to more definitively associate glacier dynamics with the hydrological results. Albeit different years of monitoring, the SSYs we estimated for the Lake Peters catchment are comparable with the Chandler, Itkillik, and upper Sagavanirktok Rivers, Arctic Alaska.

A combination of escalating arctic melt processes (McGrath, Sass, O'Neel, Arendt, & Kienholz, 2017; Nolan, Arendt, Rabus, & Hinzman, 2005) associated with warming air temperatures, mixed snow and rain precipitation regimes (McAfee, Walsh, & Rupp, 2014), and significant rainfall (Bintanja & Andry, 2017), are likely to increase freshwater discharge (Holland, Finnis, & Serreze, 2006; Lammers, Shiklomanov, Vörösmarty, Fekete, & Peterson 2001; O'Neel, Hood, Arendt, & Sass, 2014) and sediment yields (Gordeev, 2006; Lewis & Lamoureux, 2010; Moore et al., 2001; Syvitski, 2002) over the coming decades, with few exceptions (Lamoureux 2000). Our results indicate that Lake Peters catchment will likely follow this trend. Negative feedback mechanisms, such as shrub expansion stabilizing soils (Tape et al., 2011), and exhaustion of proglacial sediment sources in some catchments (Church & Slaymaker, 1989), might buffer the increases of sediment, but such feedback mechanisms are uncertain without further arctic hydrology and geomorphology systems research.

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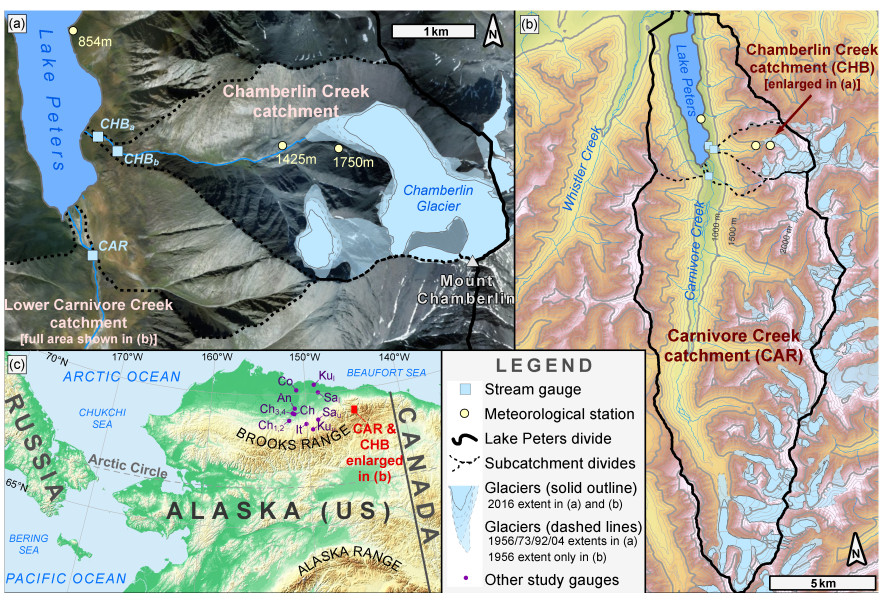

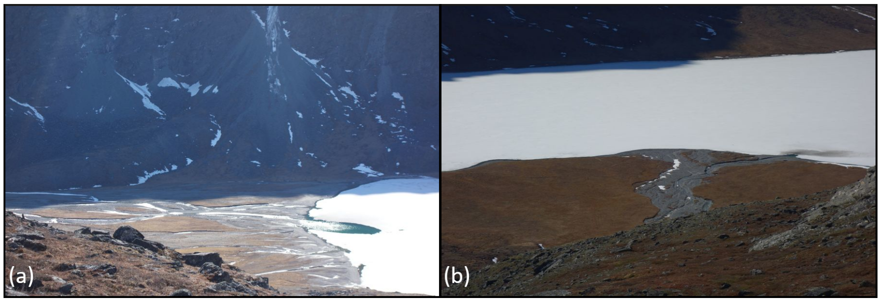
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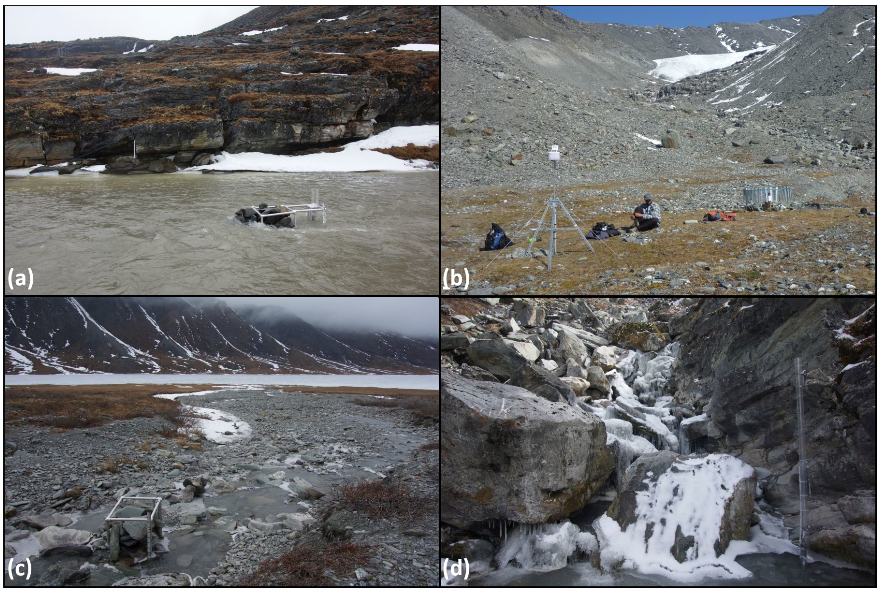
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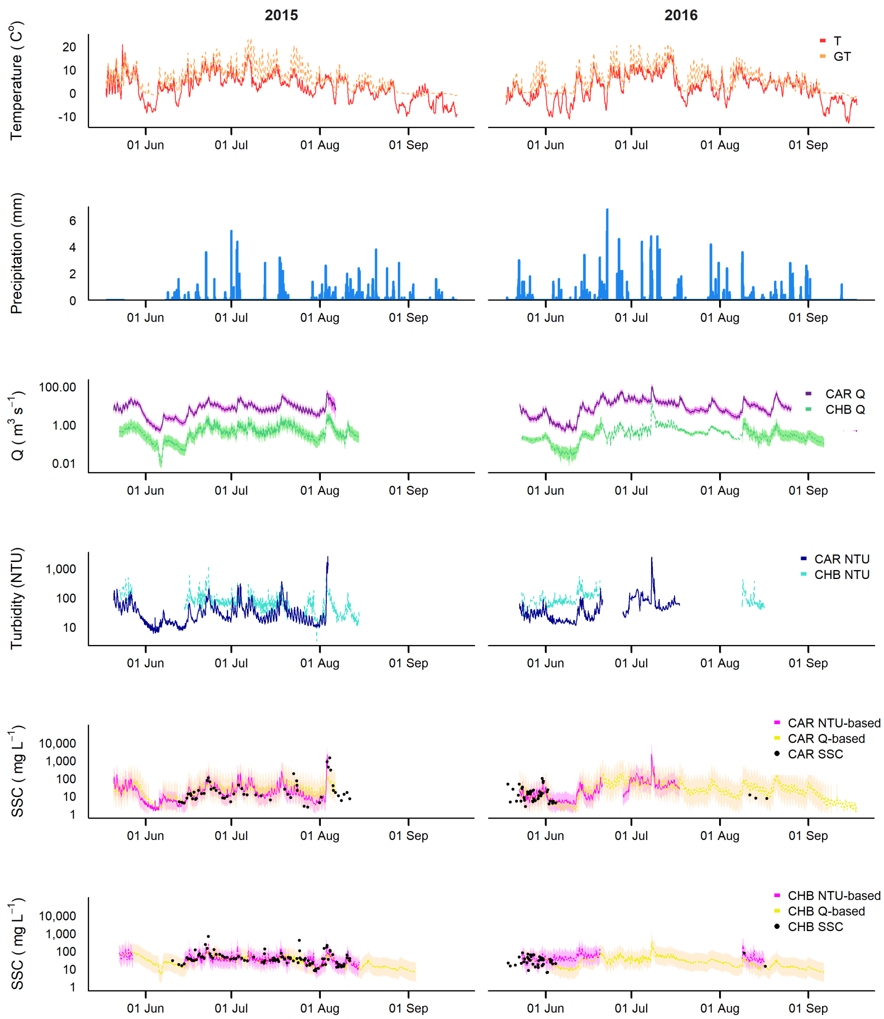
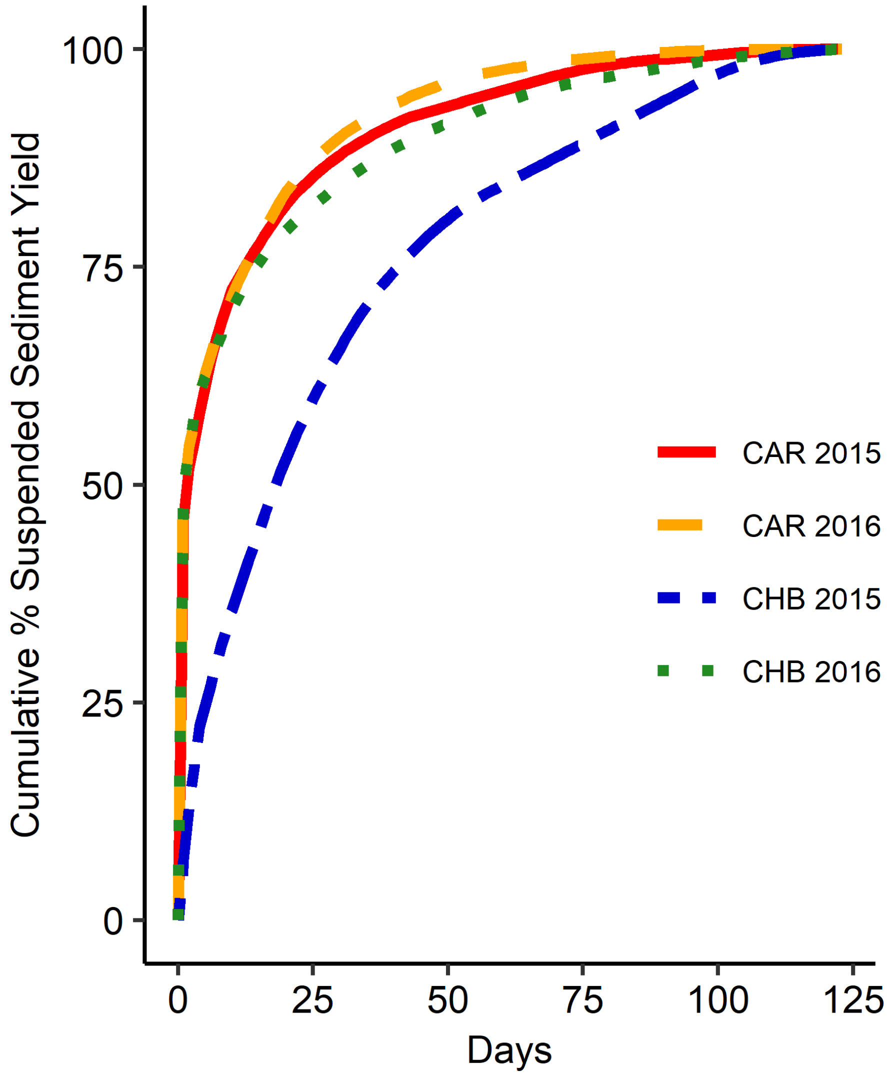
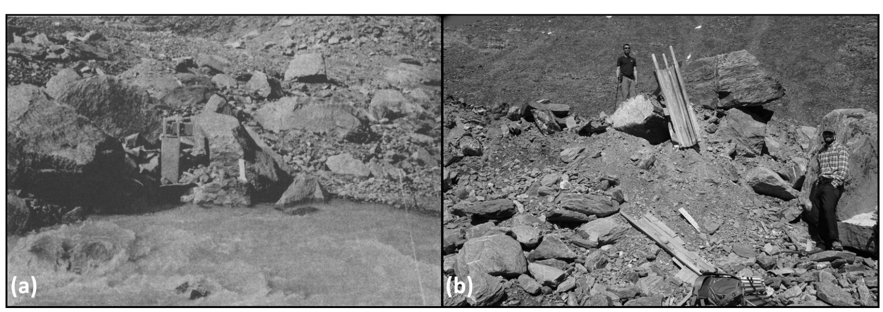

2015
2016
Temperature (C°)
T
GT
Precipitation (mm)
Q (m³ s⁻¹)
CAR Q
CHB Q
Turbidity (NTU)
CAR NTU
CHB NTU
SSC (mg L⁻¹)
CAR NTU-based
CAR Q-based
CAR SSC
CHB NTU-based
CHB Q-based
CHB SSC
01 Jun
01 Jul
01 Aug
01 Sep


Cumulative % Suspended Sediment Yield
100
75
50
25
0
0
25
50
75
100
125
Days
CAR 2015
CAR 2016
CHB 2015
CHB 2016


(a)
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