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Key Points:

- Decreasing glacier coverage increases interannual variability in watershed runoff
- Glacier loss alters riverine organic carbon and nutrient concentrations and yields, with response varying depending on the constituent
- Glacier loss consistently increases the stochasticity in the export of organic carbon and nutrients at the watershed scale

Supporting Information:

Supporting Information may be found in the online version of this article.

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Glacier Retreat Amplifies Interannual Variability in Watershed Runoff, Organic Carbon and Nutrient Yields

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Abstract Glacier retreat is projected to drive major shifts in the hydrology of many high-elevation and high-latitude watersheds. In particular, future decreases in glacier runoff are hypothesized to reduce the stability of hydro-biogeochemical export. We test this hypothesis using a decade of discharge, dissolved organic carbon, total dissolved nitrogen and soluble reactive phosphorus data from four Alaskan watersheds spanning a gradient in glacier cover. We demonstrate that glacier decline leads to lower and more variable runoff across years, with 2.6–4.3 times greater interannual variability in lightly-glacierized compared to glacier-dominated watersheds. Biogeochemical export also became more stochastic with retreat, with up to a five-fold increase in interannual variability. However, the responses of riverine concentrations and yields to changes in glacier cover varied widely between constituents. Such shifts in the magnitude and stochasticity of hydro-biogeochemical yields have important implications for the ecological stability of downstream ecosystems.

Plain Language Summary We present the first decadal-scale analysis of riverine carbon and nutrient export from glacierized watersheds, providing insights into how biogeochemical yields will shift as glaciers retreat, and new terrestrial ecosystems emerge. Using organic carbon, nutrient (N and P) and discharge data from four watersheds in southeast Alaska spanning a gradient from glacier- to forest-dominated, we demonstrate that glacier retreat not only alters the quantity of freshwater, organic carbon and nutrients exported downstream but also increases the year-to-year variability of these yields. In doing so, we test a long-standing hypothesis, highlighting that glacier retreat amplifies stochasticity in freshwater and biogeochemical yields. These findings have important consequences for understanding the stability of downstream freshwater and marine ecosystems already experiencing a suite of physical and biogeochemical stresses.

1. Introduction

The loss of mountain glaciers in response to anthropogenic climate change is initiating a global ecosystem shift, with the potential to produce ~265,000 km² of new terrestrial ecosystems by 2100 (Bosson et al., 2023; Rounce et al., 2023). Loss of glacier ice and the emergence of these post-glacial ecosystems is driving fundamental shifts in the flow regime and physical and biogeochemical properties of rivers (e.g., Fountain & Tangborn, 1985; Holt et al., 2021; Hood & Scott, 2008; Kohler et al., 2024; Milner et al., 2007), which will propagate to downstream freshwater and marine ecosystems, influencing element cycling and the net carbon balance. Globally, many glacierized regions have already passed “peak water,” resulting in steady declines in annual watershed runoff that are projected to continue throughout the 21st century (Carnahan et al., 2019; Huss & Hock, 2018). Consequently, watershed flow regimes will continue to shift from glacier-dominated toward seasonal snowmelt- and rainfall-driven (Bliss et al., 2014). This transition will alter the timing and decrease the magnitude of runoff, whilst increasing variability in seasonal water yields due to the loss of hydrological subsidies from melting ice reservoirs (Bliss et al., 2014; Curran et al., 2025; Fleming & Clarke, 2005). Thus, changes in glacier volume will have wide-ranging impacts to the quality, availability and predictability of freshwater, with important implications for people who rely on these resources for ecosystem services (Milner et al., 2017).

Runoff from melting glaciers is also a key driver of watershed carbon and nutrient budgets (Hawkings et al., 2025; Hood & Scott, 2008). Thus, downstream ecosystems, whose biogeochemistry, productivity, and ecology are influenced by seasonal meltwater, and carbon and nutrient inputs, will be impacted by diminished ice cover (Hawkings et al., 2025; Milner et al., 2017). Similar to runoff, the seasonal release of meltwater from glaciers is hypothesized to dampen interannual variability in riverine carbon and nutrient export (Milner et al., 2017).

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However, we currently lack a quantitative understanding of how glacier retreat and subsequent watershed revegetation influence the trajectory and predictability of ecologically important biogeochemical fluxes. Despite a strong conceptual foundation for this hypothesis, our ability to test it has been limited by a dearth of multi-year, paired carbon, nutrient and discharge records for glacierized watersheds.

Here we examine how watershed glacier cover modulates the magnitude and interannual variability in runoff, carbon and nutrient yields. We employ a decade (2015–2024) of discharge, carbon (dissolved organic carbon; DOC) and nutrient (nitrogen and phosphorus; N and P, respectively) data from four glacierized watersheds in the Coast Mountains of Alaska that span a wide range of glacier cover (2%–55%; Table S1 in Supporting Information S1). We paired continuous discharge with discrete DOC and nutrient data to form concentration-discharge relationships, which were used to model daily concentrations and watershed DOC and nutrient yields for the main glacier melt season (May 1st–September 30th; Figures S1 and S2 in Supporting Information S1). We evaluate how interannual variability in runoff, DOC and nutrient yields, quantified as coefficient of variance (CV), is related to watershed glacier cover. This enabled us to test the long-standing hypothesis that glacier retreat leads to greater interannual stochasticity in watershed runoff, organic carbon and nutrient export.

2. Methods

2.1. Sample Collection, Nutrient Analysis and Discharge Monitoring

Mendenhall (55%), Herbert (42%), Cowee (12%) and Montana (2% watershed glacier cover) rivers are well-studied and representative in size and elevation range of hundreds of coastal watersheds along the Gulf of Alaska (Table S1 in Supporting Information S1; Fellman et al., 2025; Giesbrecht et al., 2022). These watersheds are situated close to Juneau (Figure S3 in Supporting Information S1), in the northern portion of the coastal temperate rainforest (mean annual precipitation and temperature 1,580 mm and 5.6°C). The watersheds cover a mean elevation range of 480–994 m, and share similar vegetation and geology. The glaciated portions of these watersheds are underlain by Cretaceous-Tertiary aged tonalite. Downstream of the glaciers, bedrock is Permian-Cretaceous metamorphic with sedimentary and volcanic protoliths (schists, gneiss, quartzite, marble, metaturbidite, and metabasalt). In Herbert and Mendenhall, these rocks are largely metavolcanic, whereas in Cowee they are more sedimentary in origin. Montana Creek includes contributions of both metavolcanic and sedimentary rocks. Lower river reaches are dominated by Quaternary glaciomarine deposits and alluvial sediments (Behnke et al., 2023; Hood et al., 2020; Wilson et al., 2015). High elevation reaches of the watersheds have glacier ice, snow cover, and alpine tundra with poorly developed soils, while lower elevations are forested, with wetlands forming on moderate slopes.

Streamwater samples were collected using standard methods and components of this data set have been published previously (e.g., Fellman et al., 2023, 2025; Harley et al., 2023). Streamwater sampling for soluble reactive phosphorus (SRP) was conducted from 2015 to 2024, while sampling for DOC and total dissolved nitrogen (TDN) ran from 2018 to 2024. Sampling captured the periods of maximum glacier melt (i.e., May 1st–September 30th annually) and covered the majority of variation in discharge for these periods (Fellman et al., 2014), although the number of samples collected varied between analytes, years and watersheds (Table S1 and Figure S2 in Supporting Information S1). For each sampling event, grab samples were collected from a well-mixed region of the river and filtered to 0.7 μm (2015–2022, precombusted GF/F, 450°C, 4 hr) or 0.45 μm (2023–2024, AquaPrep capsule filter). For DOC and TDN, filtrate was collected in acid-washed and precombusted glass vials, acidified to pH 2 (12 M HCl) and stored in the dark at 5°C (<1 week). For SRP, filtrate was stored frozen (–20°C) in acid-washed HDPE plastic bottles.

Concentrations of DOC and TDN were quantified using high-temperature combustion (Shimadzu TOC/TN_{L-CSH} analyzer) and standard methods (Stubbins & Dittmar, 2012). Reported values are the mean of three to five replicate injections with a coefficient of variance of <2%. The standard deviation between repeat measurements of in-house standards was $\leq 8\%$ and $\leq 11\%$ for DOC and TDN, respectively. Concentrations of SRP were measured via colorimetry using the ascorbic acid method and a 5 cm quartz cuvette to detect low concentrations (Murphy & Riley, 1962). Re-analysis of the samples yielded an analytical precision of 0.2 $\mu\text{g P L}^{-1}$.

Discharge data from 2015 to 2024 was acquired for May 1st through September 30th a period accounting for ~76%–84% of annual discharge in the study watersheds. Discharge measurements for the Mendenhall River were obtained from the U.S. Geological Survey (USGS; site #15052500). Herbert River discharge for 2015–2017 was

modeled based on historic (1966–1971) USGS data of Herbert River (site #15054200) discharge and its previously established relationship to Mendenhall River discharge (robust across the seasonal range, $R^2 = 0.92$; Hood et al., 2020). Starting in 2018, Herbert River stage height was measured at 15-min intervals using a Campbell Scientific SR50A sensor. Similarly, for the whole study period, Cowee Creek's stage was measured at 15-min intervals using a stilling well equipped with a pressure transducer (In Situ Level Troll 500). Montana Creek's discharge data was obtained from the USGS (site #10552800) for 2015–2018. For 2019–2024, the National Weather Service maintained the site for stage measurements (site #MCAA2). Where USGS data were not available, or modeled discharge was not used (Herbert post-2017), manual flow measurements were made across the hydrograph to derive stage-discharge relationships and convert continuous stage measurements to discharge. Flow measurements were collected using a SonTek FlowTracker or FlowTracker 2 at wadable levels and a Teledyne RD Instruments River Ray Acoustic Doppler Current Profiler at higher flows. Discharge and associated metadata are available in Hood et al., 2024 for the period 2019–2023.

2.2. Runoff and Nutrient Yields

The USGS Load Estimator (LOADEST; Runkel et al., 2004) was used to calculate seasonal DOC, TDN and SRP fluxes via LoadRunner (version 1.2). LoadRunner automates runs of LOADEST, which uses timeseries of paired discharge and constituent concentrations to construct calibration regressions that are then applied to daily discharge records to obtain element fluxes. Glacier-dominated and forest-dominated watersheds have fundamentally different hydrographs and transport processes that impact riverine organic carbon and nutrient concentrations (e.g., Hood & Scott, 2008). To account for these differences, each watershed and analyte was modeled independently. LOADEST has a series of embedded models, those with variables for long-term change during the calibration period were excluded from selection (i.e., selection restricted to models 1, 2, 4, and 6) and the model chosen for each watershed-analyte combination had the lowest Akaike Information Criterion score, following best practice for when no a priori reason for model preference exists. The Adjusted Maximum Likelihood Estimator (AMLE) was used to fit the calibration equation, as is typical (e.g., Lung et al., 2018; McClelland et al., 2016; Zolkos et al., 2020) and thus reported model data are AMLE values.

SRP fluxes were modeled from 2015 to 2024, whereas, given the absence of measured data prior to 2018, the DOC and TDN modeled period was 2018 to 2024. Small discharge data gaps of ≤ 14 days were automatically interpolated in LoadRunner before analysis. The concentration data used to form the models was uncensored (i.e., above detection). Values $< 0.1 \text{ mg C L}^{-1}$, 0.01 mg N L^{-1} and $0.02 \text{ } \mu\text{g P L}^{-1}$ for DOC, TDN and SRP respectively, and/or beyond 3σ from the mean were dropped from the data set prior to forming the regression models. All measured concentration and discharge data reported here are those used to form the LOADEST models. LOADEST output presents standard error, standard error of prediction of calculated loads, R^2 of AMLE estimates and residuals data, in order to verify model fit and that residual error is normally distributed. Comparison of standard error of prediction with mean daily AMLE loads demonstrated that all constituents were modeled well using LOADEST (CV: 3.9%–18.8%), with the highest uncertainty associated with SRP loads (mean CV 15.6%; the mean CV for DOC and TDN was 8.6% and 5.4%, respectively; Table S2 in Supporting Information S1).

Seasonal biogeochemical yields were calculated by summing modeled daily loads for the analysis period for each calendar year and normalizing them to watershed area (Table S1 in Supporting Information S1). Similarly, runoff (mm) represents discharge scaled up to either total daily flow or total flow for the measurement period and then normalized to watershed area. Interannual variability, measured as CV, was calculated from total seasonal yields (Table S1 in Supporting Information S1). Incomplete discharge data (i.e., flow gap > 14 days) for Montana in May 2017 and August/September 2022 meant that seasonal yields were not calculated for these years (Table S1 in Supporting Information S1). Nonetheless, measured concentration and discharge data from 2017 and 2022 were used to form the models and thus daily discharge and modeled concentration data were reported where available (i.e., Table S1 in Supporting Information S1 and Figures 1 and 2). One-way analysis of variance tests followed by post-hoc Tukey were used to assess differences in seasonal runoff, daily concentrations, and seasonal DOC and nutrient yields between watersheds.

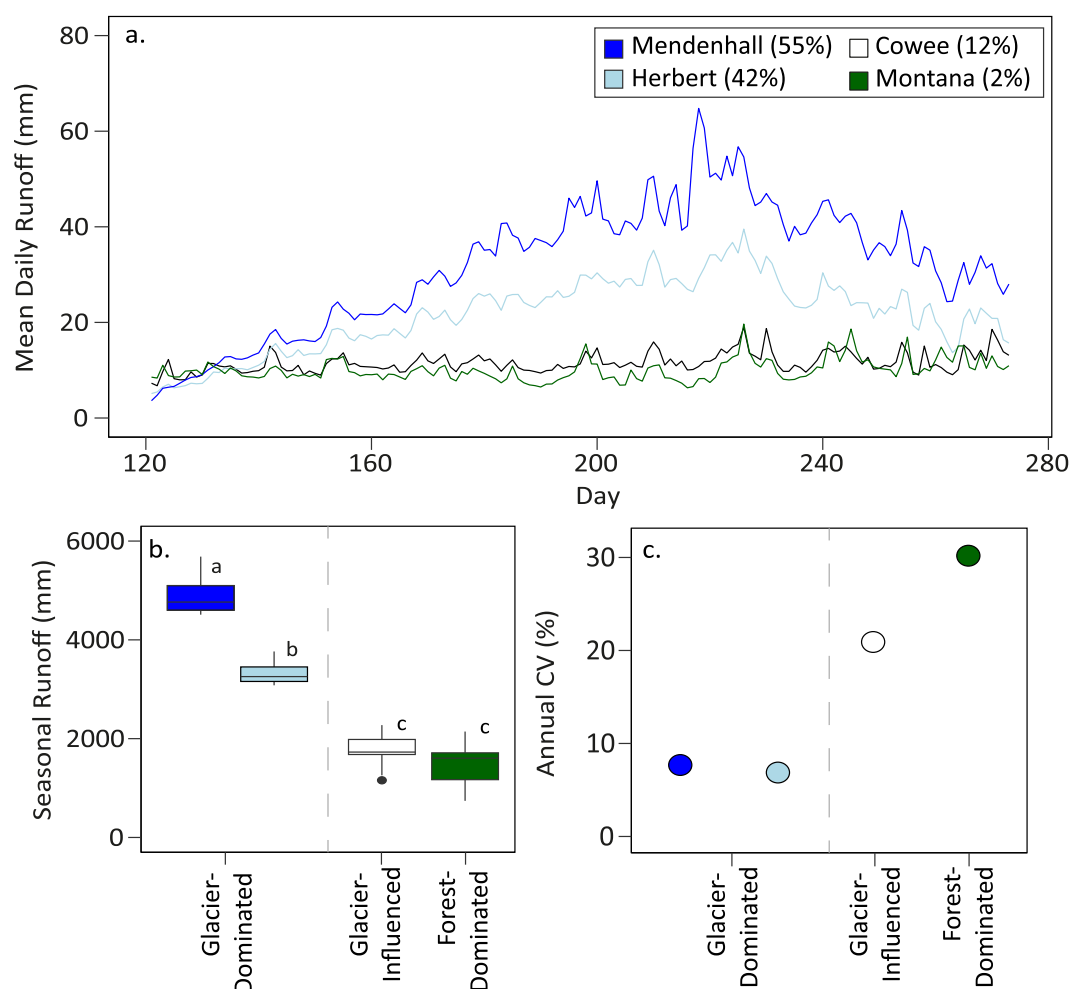


Figure 1. (a.) Daily runoff for each watershed, averaged over 10 years. (b.) Boxplots of seasonal runoff for 2015–2024. (c.) Interannual variability in runoff, measured as coefficient of variance (CV), where higher values indicate greater variability in freshwater export between years. Runoff (mm) is expressed as the volume of water discharged per unit of watershed area in a given time period. Each panel is colored and separated by watershed, with a vertical dashed line separating the glacier-dominated watersheds. Letters in panel b. indicate statistical significance (p -value < 0.05) between watersheds, where shared letters indicate no significant difference. Values in parentheses in the legend are % watershed glacier cover.

3. Results and Discussion

Declining watershed glacier cover altered river flow regime by shifting the timing, magnitude, and predictability of runoff across years. In the glacier-dominated watersheds (Mendenhall and Herbert, 55% and 42% glacier cover, respectively), runoff increased from May through August, driven by snow and ice melt, and peaked during mid-to-late August (~day 227) before declining with cooling temperatures (Figure 1a). These watersheds had substantially higher mean daily (32 and 22 mm d^{-1} , Mendenhall and Herbert, respectively) and seasonal ($4,882 \pm 375$ and $3,319 \pm 228$ mm y^{-1}) runoff compared to lightly-glacierized Cowee (12% glacier cover, 12 mm d^{-1} and $1,773 \pm 371$ mm y^{-1}) and Montana (2% glacier cover, 10 mm d^{-1} and $1,489 \pm 449$ mm y^{-1}) watersheds, which lack large glaciers in their headwaters (Table S1 in Supporting Information S1). Cowee and Montana watersheds did not have the unimodal distribution in flow typical of glacier-dominated watersheds (Figure 1a and Figure S1 in Supporting Information S1; Jansson et al., 2003). Instead, their flow regimes were driven primarily by the timing and magnitude of precipitation events and melt from seasonal snowcovers (Milner et al., 2009). As a result, seasonal runoff in these watersheds was more stochastic, with interannual variability in total seasonal runoff 2.6–4.3 times higher than in the glacier-dominated watersheds (Figure 1c). As climate change continues to lead to more extreme weather (e.g., intense storms, periods of drought, and shifts in proportions of precipitation falling as rain and snow; Lader et al., 2022), the impact of glacier decline on watershed

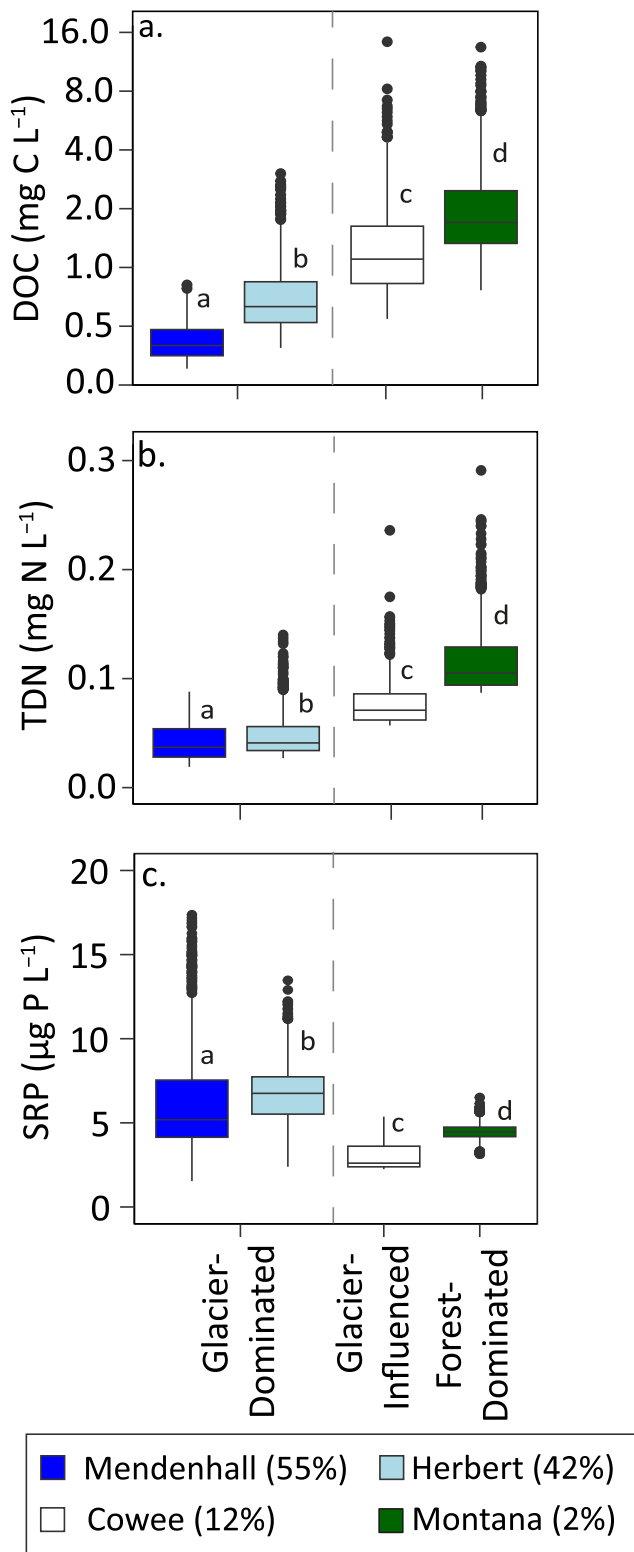


Figure 2.

stochasticity could be further amplified. Interestingly, total seasonal runoff between Cowee (glacier-influenced) and Montana was statistically indistinguishable, yet Montana (forest-dominated watershed) had more variable (+9% CV) seasonal runoff. This trend toward increased hydrologic stochasticity with declining watershed glacier cover highlights the role of glacier melt in buffering river discharge (Huss & Hock, 2018) against interannual fluctuations in precipitation and snowmelt, even at relatively low levels of glacier cover.

Changes in watershed glacier coverage also significantly influenced riverine DOC and nutrient concentrations. Lower concentrations of DOC and TDN were found in glacier-dominated compared to glacier-influenced and forest-dominated watersheds (Table S1 in Supporting Information S1 and Figures 2a and 2b). This is consistent with a larger area of lightly glacierized watersheds being vegetated versus ice covered, and a larger proportion of runoff derived from these organic matter rich reaches (Holt et al., 2021; Hood & Scott, 2008; Milner et al., 2007; Pain et al., 2025; Spinola et al., 2024). Unlike DOC and TDN, riverine concentrations of SRP increased significantly with watershed glacier cover (Figure 2c), consistent with studies demonstrating that glaciers transfer bedrock-derived nutrients (e.g., P, iron and silica) efficiently downstream, given they are extremely erosive and effective agents of mechanical weathering (Hawkings et al., 2016; Hood & Berner, 2009; Martin et al., 2020; Milner et al., 2017). Although these trends in riverine DOC, TDN, and SRP concentrations with deglaciation have been observed previously (e.g., Boix Canadell et al., 2019; Fellman et al., 2025; Holt et al., 2021; Hood & Scott, 2008; Kohler et al., 2024), our data set provides long-term evidence that they persist despite interannual variability in climate, runoff, and watershed conditions (e.g., source variability, and abiotic and biotic processing), reflecting the evolution of catchment nutrient sources governed by glacier decline.

Long-term trends in biogeochemical yields with shifting watershed glacier cover were substantially different than those for riverine concentrations, highlighting the profound impact glaciers have on transport processes and biogeochemical source pools at the watershed scale. Riverine yields of DOC were significantly higher in the forest-dominated than the glacier-dominated watersheds (Figure 3a), indicating that despite deglaciation reducing runoff, the expansion and development of soils and vegetation outweigh this loss, leading to greater riverine DOC concentrations and export. In contrast, yields of TDN did not vary significantly and thus had no relationship to watershed glacier cover (Figure 3b). This suggests that the expansion of organic and inorganic N pools (e.g., soils, vegetation, and nitrogen-fixation by colonizer plants) with deglaciation (Milner et al., 2017) elicits a rise in riverine TDN concentrations relatively similar in magnitude to the associated decrease in runoff. Watershed yields of SRP showed the most pronounced response to glacier retreat, decreasing by an average of 76% (Figure 3c). This is consistent with decreases in water yields and

Figure 2. Modeled daily concentrations across the measurement period (i.e., May 1st–September 30th), for the duration of the study (i.e., 2015–2024). Each panel is colored and separated by watershed, with a vertical dashed line separating the glacier-dominated watersheds. Concentrations that are statistically different (p -value < 0.05) between watersheds are marked with different letters. (a.) DOC—dissolved organic carbon, (b.) TDN—total dissolved nitrogen, and (c.) SRP—soluble reactive phosphorus.

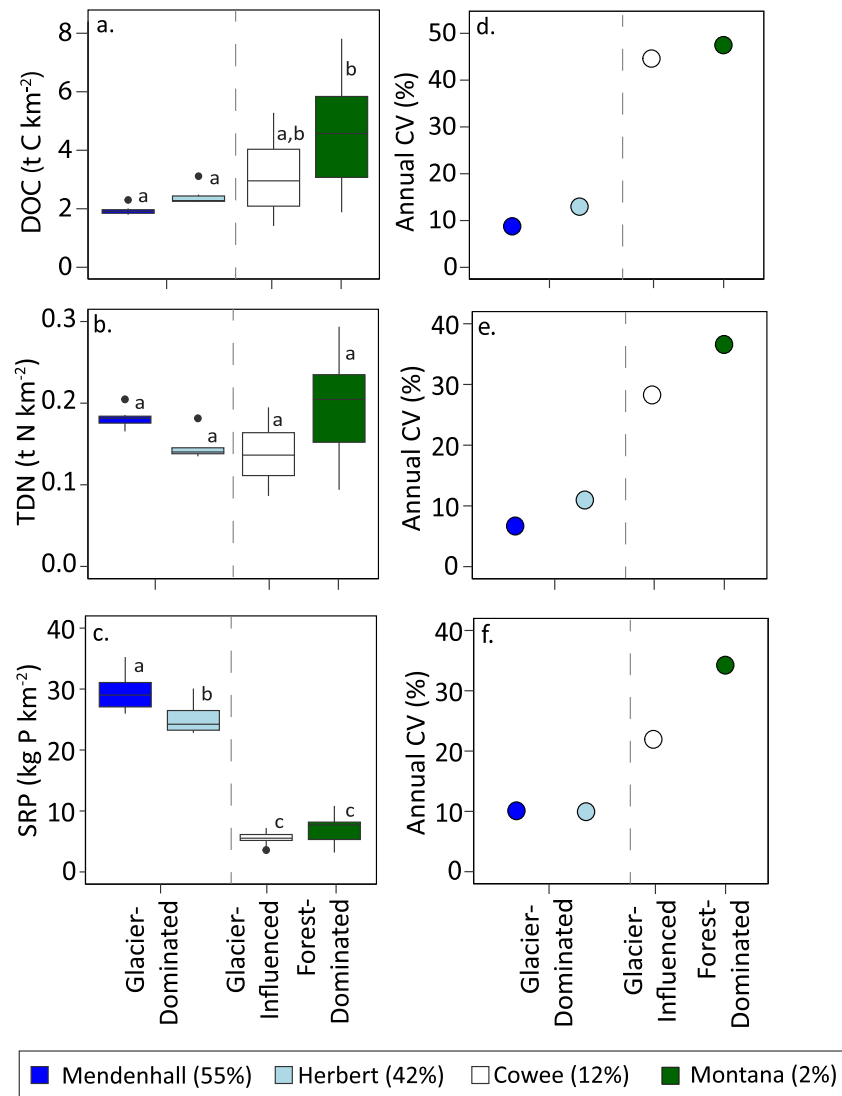


Figure 3. (a, b, and c) Cumulative yields for 2015–2024. (d, e, and f) Interannual variability in yields, quantified as the coefficient of variation (CV). Each panel is colored and separated by watershed, with a vertical dashed line separating the glacier-dominated watersheds. Yields that are statistically different (p -value < 0.05) between watersheds are marked with different letters. DOC—dissolved organic carbon, TDN—total dissolved nitrogen, and SRP—soluble reactive phosphorus. A metric ton (t) is equivalent to a megagram (Mg, i.e., 10^6 g).

liberation of bedrock-derived nutrients (Hood & Scott, 2008; Martin et al., 2020), as well as increases in instream biotic retention of SRP as river ecosystems mature (Kohler et al., 2024). Trends in riverine P may also in part reflect shifts in watershed geochemistry (e.g., presence of iron oxides and redox conditions) and organic matter composition with glacier decline (Jindo et al., 2023; Zhou et al., 2013), although these interactions and their implications for P export are poorly constrained for glacierized ecosystems. Despite these shifts in DOC and nutrient export with lower glacier coverage, in some years the lightly-glacierized watersheds exported quantities of DOC and TDN comparable to, or even lower than, the yields for glacier-dominated watersheds. This underscores that while terrestrial DOC and N pools increase with deglaciation and associated terrestrial ecosystem succession (Milner et al., 2007), annual variability in watershed-scale hydrologic and biogeochemical (e.g., biotic retention and abiotic/biotic processing) processes ultimately modulate riverine DOC and nutrient export.

Despite differences in the trajectories of watershed DOC, TDN, and SRP yields with glacier retreat, this study provides unambiguous evidence to support the hypothesis that decreasing glacier cover will fundamentally shift

watersheds toward a more stochastic export regime for ecologically important elements (Milner et al., 2017). The CV values of seasonal DOC and nutrient yields ranged from 7% to 13% in glacier-dominated watersheds, compared to 22%–47% in the lightly glacierized ones (Table S1 in Supporting Information S1, Figures 3d–3f). Yields of DOC had the greatest increase in interannual variability, with a mean 4.2-fold rise in CV between glacier-dominated and lightly-glacierized watersheds. Nonetheless, substantial increases in mean interannual variability were also observed for TDN (3.6-fold) and SRP (2.8-fold; Table S1 in Supporting Information S1). The loss of hydrologic buffering from glacier ice (Fleming & Clarke, 2005) is clearly a strong driver of the increased stochasticity in watershed nutrient export. This was particularly apparent with SRP yields, for which CV values closely tracked those of runoff across the gradient in glacier cover. However, for seasonal DOC and TDN yields the increase in variability outpaced that of runoff (Table S1 in Supporting Information S1, Figures 1 and 3). This suggests watershed-scale controls on riverine DOC and TDN concentrations, such as source characteristics and hydrological connectivity to biogeochemically controlled pools, play an increasingly important and dynamic role in determining seasonal yields of DOC and TDN as catchment glacier coverage decreases. Taken together, the coherent response of interannual variability in riverine yields of DOC, TDN, and SRP to a reduction in watershed glacier cover indicates that glacier retreat is also likely to induce substantial shifts in the export regime of other ecologically relevant elements such as iron and silica (Hawkings et al., 2025; Li et al., 2019; Pryer et al., 2020) to downstream ecosystems.

Mountain glaciers are found on all of Earth's continents, and their continued retreat is leading to watershed hydrologic homogenization, with glacier melt replaced by precipitation and snowmelt as the primary source of streamflow (Bliss et al., 2014; Carnahan et al., 2019; Huss & Hock, 2018). Our findings, based on four rivers in southeast Alaska, demonstrate that declining watershed glacier coverage is likely to drive significant changes to the magnitude and stability of riverine runoff and biogeochemical yields, with potential implications for composition, reactivity and riverine stoichiometry (Fellman et al., 2025). Despite global variability in the pace and trajectory of hydrologic and ecosystem responses to ice loss (Bliss et al., 2014; Bosson et al., 2023; Carnahan et al., 2019; Huss & Hock, 2018), we expect the trend toward increased stochasticity to be broadly applicable to other watersheds experiencing glacier decline. In particular, regions with high-precipitation, maritime climates and rapid glacier decline, such as Patagonia, Norway and New Zealand (Rounce et al., 2023) are likely to experience similar hydro-biogeochemical shifts to those documented here. Importantly, we identified a substantial and consistent increase in stochasticity associated with the export of both bio- and geogenically-derived elements. Such perturbations to the hydro-biogeochemical function of glacier rivers raise critical questions regarding impacts to downstream biogeochemical cycling. Given the role of carbon and nutrient availability in the ecological energetics of glacier-fed streams (Kohler et al., 2024) and the well-documented subsidies that glacier-derived DOC and nutrients provide to downstream ecosystems (e.g., Arimitsu et al., 2018; Fellman et al., 2015; Hawkings et al., 2025), shifts to the consistency and properties of biogeochemical yields are likely to impact food web dynamics and associated ecosystem services of receiving stream networks and coastal zones in poorly constrained ways.

Global Research Statement

This work took place in Lingít Aaní on the lands of the Aak'w Kwáan.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Modeled and measured constituent data, as well as discharge has been made publicly available via the Open Science Framework (OSF; Holt, 2025).

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