The hydrology of glacier-bed overdeepenings

Swift, Darrel A.; Tallentire, Guy D.; Farinotti, Daniel; Cook, Simon J.; Higson, William J.; Bryant, Robert G.

Published in:
Earth Surface Processes and Landforms

DOI:
10.1002/esp.5173
10.1002/esp.5173

Publication date:
2021

Citation for published version (APA):
Swift, D. A., Tallentire, G. D., Farinotti, D., Cook, S. J., Higson, W. J., & Bryant, R. G. (2021). The hydrology of glacier-bed overdeepenings: Sediment transport mechanics, drainage system morphology, and geomorphological implications. *Earth Surface Processes and Landforms*, *46*(11), 2264-2278. https://doi.org/10.1002/esp.5173, https://doi.org/10.1002/esp.5173

Received: 25 August 2020 | Revised: 25 May 2021 | Accepted: 26 May 2021
DOI: 10.1002/esp.5173

RESEARCH ARTICLE

ESPL WILEY

The hydrology of glacier-bed overdeepenings: Sediment transport mechanics, drainage system morphology, and geomorphological implications

Darrel A. Swift[1] | **Guy D. Tallentire**[1,2] | **Daniel Farinotti**[3,4] | **Simon J. Cook**[5,6] | **William J. Higson**[1] | **Robert G. Bryant**[1]

[1]Department of Geography, University of Sheffield, Sheffield, UK
[2]Geography and Environment, Loughborough University, Loughborough, UK
[3]Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH, Zurich, Switzerland
[4]Swiss Federal Institute for Forest, Snow and Landscape Research, WSL, Birmensdorf, Switzerland
[5]Geography and Environmental Science, University of Dundee, Dundee, UK
[6]UNESCO Centre for Water Law, Policy and Science, University of Dundee, Dundee, UK

Correspondence
Darrel A. Swift, Department of Geography, University of Sheffield, Winter Street. Sheffield, S10 2TN, UK.
Email: d.a.swift@sheffield.ac.uk

Funding information
University of Sheffield

Abstract

Evacuation of basal sediment by subglacial drainage is an important mediator of rates of glacial erosion and glacier flow. Glacial erosion patterns can produce closed basins (i.e., overdeepenings) in glacier beds, thereby introducing adverse bed gradients that are hypothesized to reduce drainage system efficiency and thus favour basal sediment accumulation. To establish how the presence of a terminal overdeepening might mediate seasonal drainage system evolution and glacial sediment export, we measured suspended sediment transport from Findelengletscher, Switzerland during late August and early September 2016. Analyses of these data demonstrate poor hydraulic efficiency of drainage pathways in the terminus region but high sediment availability. Specifically, the rate of increase of sediment concentration with discharge was found to be significantly lower than that anticipated if channelized flow paths were present. Sediment availability to these flow paths was also higher than would be anticipated for discrete bedrock-floored subglacial channels. Our findings indicate that subglacial drainage in the terminal region of Findelengletscher is dominated by distributed flow where entrainment capacity increases only marginally with discharge, but flow has extensive access to an abundant sediment store. This high availability maintains sediment connectivity between the glacial and proglacial realm and means daily sediment yield is unusually high relative to yields exhibited by similar Alpine glaciers. We present a conceptual model illustrating the potential influence of ice-bed morphology on subglacial drainage evolution and sediment evacuation mechanics, patterns and yields, and recommend that bed morphology should be an explicit consideration when monitoring and evaluating glaciated basin sediment export rates.

KEYWORDS
erosion, glaciology, overdeepening, sediment transport, subglacial hydrology

1 | INTRODUCTION

Rates and patterns of subglacial erosion and glacier-bed evolution likely depend very strongly on the effectiveness of processes that transport and evacuate erosion products from the glacial system (Hooke, 1991; Alley *et al.*, 2003, 2019; Cook *et al.*, 2020). Inefficient evacuation of erosion products should promote sediment storage in the form of till deposits that shield bedrock from direct erosion (Hooke, 1991; Alley *et al.*, 2003). Such deposits will also influence rates of glacier flow by permitting soft-sediment deformation to contribute to rates of basal slip (Iverson *et al*., 1995). Nonetheless, knowledge of subglacial transport processes and their effectiveness is lacking (Jaeger & Koppes, 2016; Alley *et al*., 2019), particularly for ice-marginal areas that mediate the supply of glacial products to the proglacial realm (Alley *et al*., 1997; Porter *et al*., 2019). For example, sediment export rates from glacial systems appear inherently variable across space and time (e.g., Hallet *et al*., 1996; Riihimaki *et al*., 2005; Koppes *et al*., 2015; Delaney *et al*., 2018), leading to uncertainty regarding the utility of sediment budget studies and the relation between true subglacial bedrock erosion rates and those estimated from measured sediment yields (Koppes & Montgomery, 2009; Hilger & Beylich, 2019). These uncertainties combine to limit our understanding of the response of glacial and proglacial systems to future climate change.

The wide application of proglacial stream sediment loads as proxies for subglacial bedrock erosion rates (e.g., Gurnell *et al*., 1996; Hallet *et al*., 1996) reflects the accepted dominance of fluvial transport in glacial sediment budgets. Orders of magnitude variation in such proxy erosion rates between glaciers of similar size (e.g., Hallet *et al*., 1996; Cook *et al*., 2020) indicates that seasonal melt volume and drainage efficiency (e.g., Koppes *et al*., 2015; Alley *et al*., 2019; Cook *et al*., 2020) are important sediment evacuation controls. Nonetheless, temporal analyses of sediment export records have identified numerous possible entrainment processes (e.g., Gurnell *et al*., 1992; Willis *et al*., 1996; Anderson *et al*., 1999; Riihimaki *et al*., 2005; Swift *et al*., 2005a), and our understanding of key evacuation mechanisms and their drivers remains incomplete (Jaeger & Koppes, 2016). Notably, field studies have observed contrasting seasonal evacuation dynamics. On the one hand, many glaciers exhibit sediment-export exhaustion, meaning annual loads are dominated by synoptic early season ('first-flush') melt events (e.g., Fenn, 1987; Collins, 1989, 1990; Riihimaki *et al*., 2005; Gimbert *et al*., 2016) during periods of inefficient (i.e., 'distributed') subglacial drainage. On the other hand, certain studies have indicated increasing sediment availability (e.g., Clifford *et al*., 1995; Swift *et al*., 2005a; Perolo *et al*., 2019), such that annual loads are dominated by summer-period diurnal melt cycles that supply hydraulically efficient subglacial channels.

This study addresses the hypothesis that glacier bed morphology critically influences sediment export processes, patterns, and rates because it exerts a key control on subglacial drainage system morphology (cf. Hooke, 1991; Alley *et al*., 2003; Cook & Swift, 2012). For positively sloping glacier beds, abundant surface melt produced during the summer leads to the evolution of hydrologically efficient (i.e., channelized) subglacial drainage paths (Shreve, 1972; Nienow *et al*., 1998) that theoretically have prodigious transport capacity (Alley *et al*., 1997). In contrast, less efficient (i.e., distributed) forms of drainage should persist where glacier beds are strongly inclined in the opposing direction (Röthlisberger & Lang, 1987; Hooke, 1991; Alley *et al*., 2003), meaning substantive basins ('overdeepenings') in glacier and ice sheet beds should accumulate till deposits (Hooke, 1991; Cook & Swift, 2012). Such overdeepenings are common in the ablation areas of temperate ice masses (e.g., Swift *et al*., 2018), where surface melt is believed to promote focused and effective subglacial bedrock erosion (e.g., Hooke, 1991; Herman *et al*., 2011; Egholm *et al*., 2012; Patton *et al*. 2016). Theoretical studies confirm that overdeepenings promote less efficient forms of subglacial drainage (e.g., Creyts *et al*., 2013; Werder, 2016), and a handful of field studies have provided further insights (see Cook & Swift, 2012). Notably, studies of an overdeepened section of Storglaciären, Sweden have indicated inefficient subglacial drainage comprising poorly linked water pockets above a layer of till (Hooke & Pohjola, 1994), and the persistent englacial routing of surface melt (Hooke *et al*., 1988; Fountain *et al*., 2005).

To address the hypothesis that adverse bed slopes are a first-order control on subglacial drainage morphology and the processes of sediment entrainment and evacuation, we have monitored and analysed suspended sediment transport in the proglacial stream of Findelengletscher, Switzerland (Figure 1). At the time of our study,

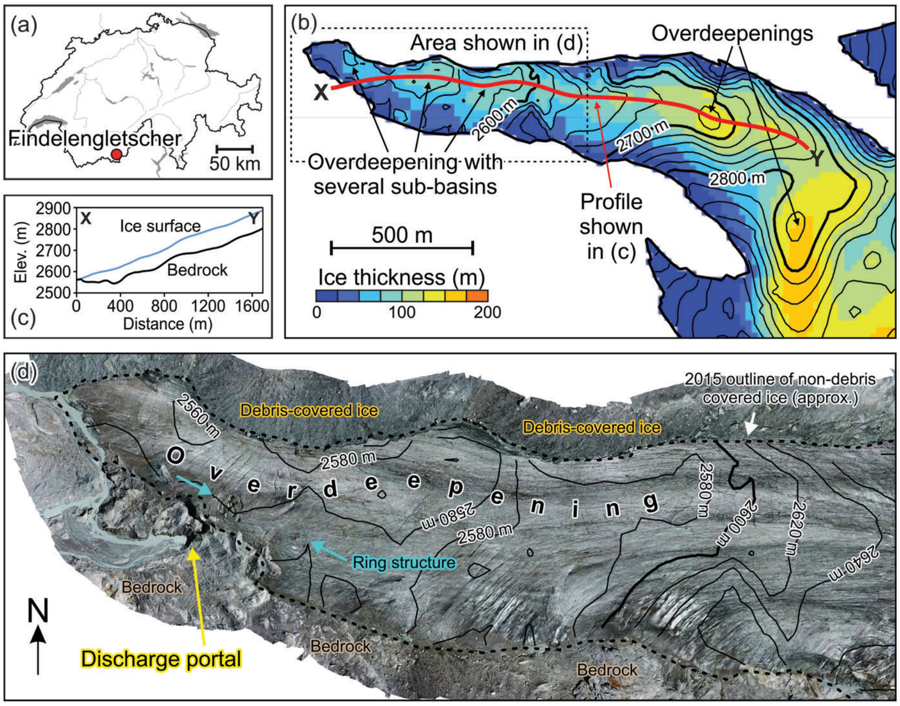


FIGURE 1 (a) Study location. (b) Ice thickness (colour scale) and bed topography (contours) of the ablation and terminus area in 2015 (Feiger *et al*., 2018) obtained by ground-penetration radar (GPR) survey. Bed and ice surface elevation in 2015 along profile X–Y (red) is shown in (c). (d) Ortho-image of the terminus in September 2016 (this study) obtained by unmanned aerial vehicle (UAV) survey. Annotations highlight features described in the text; bed topography (contours) are as shown in (b). The discharge portal in 2016 was located at 46°00'32.9"N, 7°49'42.9"E. A water intake structure where discharge measurements were obtained is located at 46°00'24.1"N, 7°48'42.7"E

field data (Figure 1) indicated that the terminus of this relatively steep Alpine glacier was situated within an overdeepened section of the glacier bed. Because temperate glacier drainage system evolution is typically driven by synoptic changes in melt volume at the melt season start (cf. Nienow *et al*., 1998; Swift *et al*., 2005b), the system at Findelengletscher at the time of the study was assumed to have reached a stable late-season configuration.

Our primary objective was to elucidate drainage system morphology within the terminal region by characterizing discharge-velocity (or discharge-entrainment) relationships using analyses of discharge and sediment transfer records (cf. Müller & Förstner, 1968; Alley *et al*., 1997; Swift *et al*., 2005a; see Study Area and Methods section). A secondary objective was to analyse temporal variability in transport to explore auxiliary entrainment processes. Similar approaches have been applied widely in fluvial research (e.g., Cudden & Hoey, 2003), and have been foundational in developing insights into the structure and behaviour of relatively inaccessible subglacial drainage systems (e.g., Sharp, 1991; Richards *et al*., 1996). Our data and findings serve to address the imbalance in observations of sediment export from glaciers with and without overdeepened beds, and we advance a general model of drainage evolution and sediment export that likely explains some of the previously observed spatial and temporal variability in glacial erosion rates and sediment yields. Nonetheless, the elucidation of small-scale subglacial processes in the absence of direct access to the glacier bed remains a considerable challenge (cf. Sharp, 1991; Stone & Clarke, 1996).

2 | STUDY AREA AND METHODS

Suspended sediment transport in the proglacial stream at Findelengletscher was monitored during August and September 2016. Monitoring was conducted as close as practicable to the discharge portal (Figures 1 and 2) to negate modification of glacial sediment export patterns by proglacial entrainment and deposition processes (e.g., Bogen, 1980; Holmlund *et al*., 1996; Stott *et al*., 2008; Leggat *et al*., 2015; Guillon *et al*., 2017; Mao *et al*., 2019; Perolo *et al*., 2019). Bedload transport was not monitored due to the impracticalities of deploying conventional bedload sampling (e.g., Cudden & Hoey, 2003). Discharge from the portal was turbid (Figure 2a,b), indicating the routing of flow along the glacier bed. An ice-penetrating radar study aimed at resolving the ice-bed topography was undertaken in 2015 (Feiger *et al*., 2018) and has revealed numerous overdeepenings (Figure 1b). This included a *c*. 500 m-long overdeepened section beneath the terminus region that may have comprised several sub-basins (Figure 1c). The presence of this 'terminal overdeepening' was confirmed by further radar surveys in 2016 and 2017 (Swift *et al*., *in prep*). Since 2017, thinning of ice in the area shown in Figure 1(d) has led to rapid terminus retreat (M. Huss, pers. comm.; GLAMOS, 2020).

Transport was monitored at 10 s intervals and stored as 1-min averages using two Partech IR15C turbidity sensors (Figure 2b). Daily manual samples were also obtained and filtered in the field using pre-weighed 0.45 μm Whatman CN filter papers to permit later conversion of turbidity values to gravimetric concentration units (by means of the calibration relationship shown in Figure 2d). Exaggerated stage variability due to the narrow channel width resulted in the turbidity sensors being exposed at periods of low flow. In addition, blocks of glacier ice up to several metres (longest axis) that were periodically flushed from the portal mouth frequently became entrapped by the sensor mountings (Figure 2a), meaning sensor deployment had to be refined mid-study (Figure 2c). The turbidity records were therefore later checked to remove erroneous values after linearly rescaling each record using minimum and maximum values recorded in the field. Values were further rejected during periods of inconsistent sensor behaviour (defined as sensor-to-sensor output diverging by > 15%) and the rescaled records (e.g., Figure 3a) were then averaged (Figure 3b). Specification of an appropriate turbidity calibration relationship (Figure 2d) included application of a correction to address suspected under-sampling of suspended material by the manual sample obtained at the highest flow stage (see Supporting Information).

To infer drainage system morphology, we analysed the relationship between discharge (Q_w) and suspended sediment concentration (ϕ_s) (cf. Müller & Förstner, 1968; Asselman, 2000). Fluvial transport

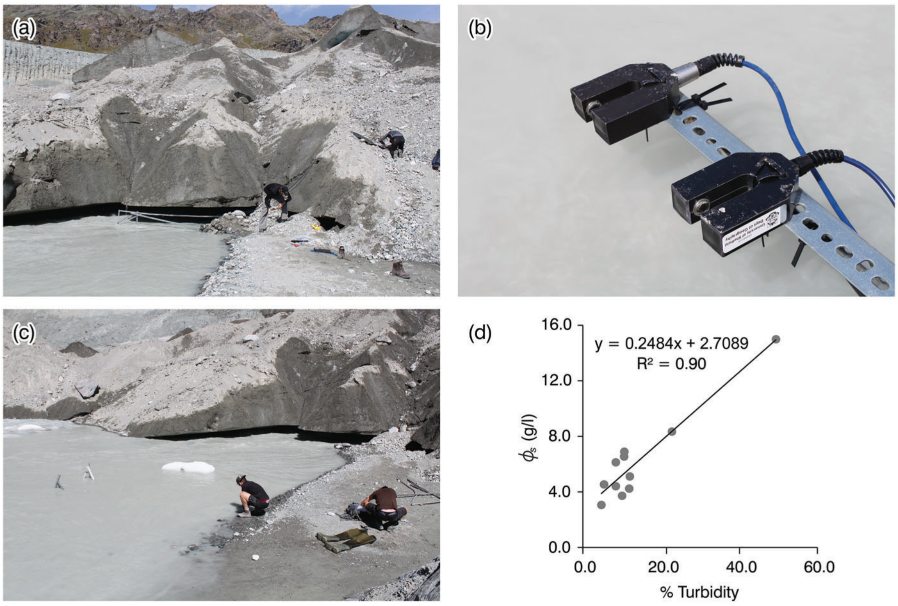


FIGURE 2 (a) The glacier portal and measurement location used until 23 August 2016. (b) The turbidity sensors as mounted in (a). (c) The portal and refined sensor arrangement, employing separate movable structures, used from 24 August 2016 (note the stationary ice-block). (d) The turbidity calibration relationship obtained from instantaneous turbidity values and corresponding gravimetric values obtained from dried, field-filtered samples. Values on the % Turbidity axis represent the mean value of both sensors after rescaling the individual turbidity records using minimum and maximum values recorded in the field (see text)

capacity is determined largely by flow velocity, which at a defined flow cross-section is a function of discharge (Müller & Förstner, 1968). The general empirical equation $\phi_s = a \cdot Q_w{}^b$ has therefore been applied widely in fluvial environments (e.g., Rickenmann, 2001; Morehead *et al.*, 2003; Swift *et al.*, 2005a). In this context, parameters *a* and *b* are empirically derived and express the availability of sediment and the rate of increase of the erosive power of the flow, respectively (Müller & Förstner, 1968; Asselman, 2000). This relationship was plotted using calibrated values from the 1-min turbidity record and corresponding values from a 15-min record of instantaneous discharge (courtesy of Grande Dixence S.A.) measured *c.* 1.63 km downstream of the portal (Figure 1). Values were further filtered to include only those where the individual sensor values agreed to within 5% of their operating range. Further, to avoid underestimation of relationship parameters, concentration values were obtained by calibrating the highest corresponding turbidity value from either sensor (in preference to the averaged value of both sensors). Finally, time values for the discharge record required adjustment to account for the travel time of water to the intake structure. Using a notable fall in stage witnessed at the portal on 23 August at 17:00 h, this travel time was estimated to be *c.* 30 min.

To address the secondary objective of understanding auxiliary sediment transfer processes, we analysed the nature of short-lived (< 1 h) sediment 'flushes' (or 'pulses', cf. Collins, 1979) that occur independently of changes in discharge and that are common in proglacial sediment transport records (e.g., Gurnell & Warburton, 1990). Such phenomena have potential to provide insight into evacuation mechanisms that may reflect drainage system morphology (e.g., Gurnell *et al.*, 1992; Swift *et al.*, 2005a), although they also have importance because they may weaken or bias observed relationships between suspended sediment transport and discharge (e.g., Fenn *et al.*, 1985). An automated procedure was used to identify flush event start-, peak- and end-points (Figure 3b), and to permit analysis of flush characteristics, including time-of-day, magnitude, and shape (the latter value being the ratio of rising-limb to falling-limb length in minutes, cf. Gurnell & Warburton, 1990). Our procedure initially identifies possible flushes by flagging increases in concentration that exceed a manually chosen value in g l^{-1} s^{-1} (the 'flush threshold value', see Results section). Further details of the procedure are provided in the Supporting Information.

3 | RESULTS

Suspended sediment concentration and discharge during the monitored period are shown in Figure 4 and paired discharge and concentration values are shown in Figure 5(a). The latter dataset comprised 278 values that covered 81% of the discharge range during the monitored period (Figure 6). The paired discharge–concentration values were fitted with an equation with the form $\phi_s = a \cdot Q_w{}^b$ (Figure 5a; see Study Area and Methods section). The paired values did not appear to be noticeably biased towards the rising or falling limbs of the discharge record (Figure 4), and the values demonstrated a reasonably homoscedastic distribution about the fitted curve (Figure 5a). Slightly increased scatter on the concentration axis at discharge values exceeding *c.* 8 m^3 s^{-1} (Figure 5a) was the result of some values coinciding with short-lived 'flushes' (Figure 5b; see later), but the number of values thus affected appears to be small. None of the concentration values were found to coincide with discharge lows

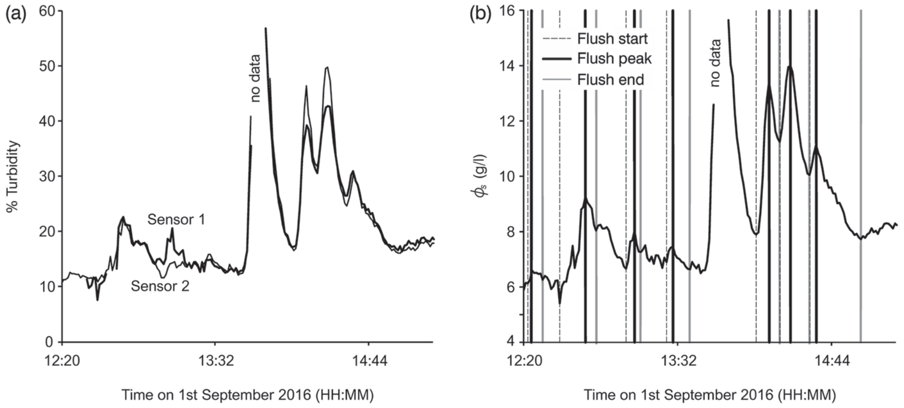


FIGURE 3 (a) Typical turbidity time series. 'No data' indicates a gap in both records resulting from turbidity exceeding the operating range of both sensors. (b) The final calibrated record (i.e., suspended sediment concentration) over the same time period as in (a). The panel also shows sediment flushes identified using a flush threshold value of 0.15 (see text for definition). The flush at c. 14:00 h is excluded from our flush analyses (see text) because the data gap means that the timing of the flush peak cannot be determined

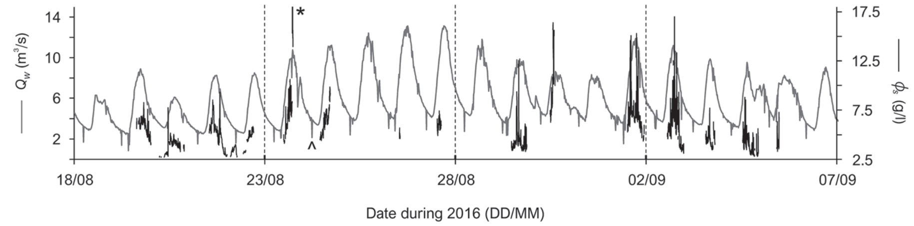


FIGURE 4 Discharge and suspended sediment time series during the monitored period. Gaps in the sediment time series are explained in the text. The asterisk (*) indicates a sediment flush at c. 17:00 h on 23 August 2016 (see text). Discharge was measured at a water intake structure downstream of the glacier (see text) and the circumflex accent (^) indicates a typical discharge anomaly caused by automated purging of sediment from that structure

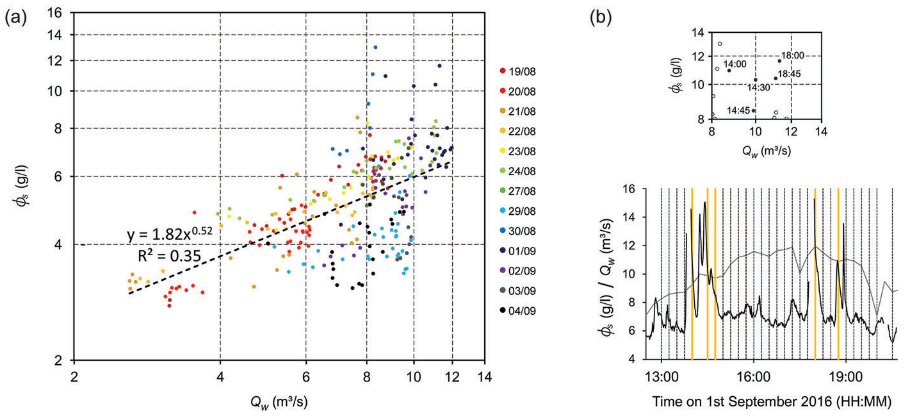
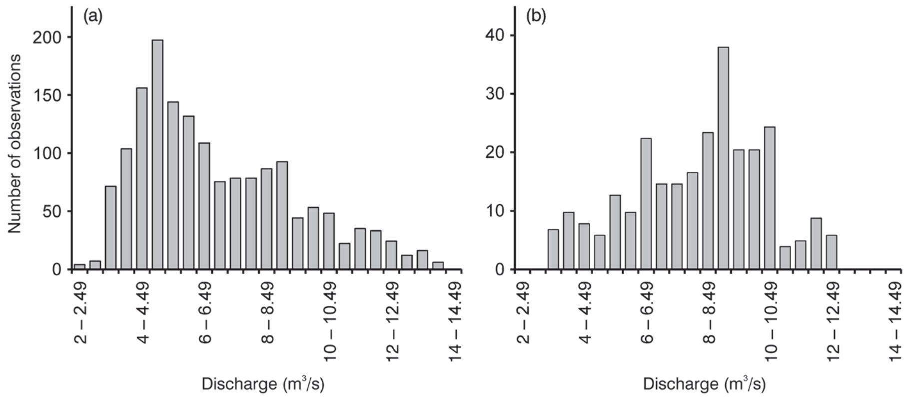


FIGURE 5 (a) Relationship of the form $\phi_s = a \cdot Q_w{}^b$ for paired values of discharge (Q_w) and suspended sediment concentration (ϕ_s) at Findelengletscher ($n = 278$; $p < 0.01$). Symbols are coloured according to the date of the corresponding diurnal discharge cycle (day/month) in 2016. (b) Part of the plot area shown in (a) that includes values on 1 September 2016 (filled circles) for which sediment concentration exceeded 8 g l^{-1}, and, below, a time series plot of discharge and concentration on the same date. Vertical lines in the time series plot indicate the timing of paired values shown in (a); yellow vertical lines correspond to the filled circles in the plot above and show that the latter occurred during substantive sediment flushes

FIGURE 6 Frequency plots of (a) all discharge values during the monitored period; and (b) discharge values coinciding with values from both sensors that do not diverge by > 5% of sensor range. Discharge values in all plots have been aggregated into 0.5 m^3 s^{-1} bins



caused by ‘purges’ of the water intake structure (Figure 4), and only 12 values (4%) were within 20 min of a sediment flush peak, as identified by the automated method (see later). The results of this analysis demonstrated a discharge–concentration relationship *b* coefficient of 0.52 (Figure 5a). Further analysis of the relationship for each of 10 individual diurnal discharge cycles, where *n* (the number of paired discharge–concentration values) exceeded 10, demonstrated a mean daily *b* value of 0.55 ± 0.23 and no discernible temporal trend in the magnitude of *b*.

Flush frequency was dependent on the chosen flush threshold value (Figure 7). A threshold value of 0.05 identified 260+ flushes and this number declined to 209 using a value of 0.15. Using the latter threshold, mean flush length was 9.1 min. Flush frequency did not appear to vary with discharge stage, and flushes were only slightly more common during periods of rising stage (Figure 7a). Nonetheless, flushes during periods of falling stage were typically > 33% larger (Figure 7b) and had steeper rising limbs (Figure 7c). Mean flush shape (i.e., rising-limb to falling-limb length ratio) was also notably different during rising versus falling stage (ratio values of 1.32 and 0.78, respectively). However, only the very largest flushes were notably asymmetrical (ratio values < 0.5). Analysis of sediment concentration values at flush start-, peak- and end-points indicated that flushes were responsible, on average, for a 14% increase in sediment load (i.e., above the load ‘underlying’ the flush peak).

4 | DISCUSSION

4.1 | Morphology of the drainage system in the terminus region

For glaciers with positively inclined beds, strong summer diurnal melt cycles motivate the development of channelized drainage that dominates subglacial water routing beneath the ablation area (cf. Röthlisberger, 1972; Nienow *et al*., 1998). Such ice-confined channels cannot adjust their dimensions to accommodate rapid diurnal changes in melt (cf. Röthlisberger, 1972; Gimbert *et al*., 2018), meaning changes in flow discharge must be accommodated dominantly by changes in flow velocity. In these circumstances, Alley *et al*. (1997) have shown that the bedload equation developed by Bagnold (1980) leads us to expect that the dependence of sediment transport on discharge will be extremely strong, up to $Q_s \propto Q_w{}^{9/2}$ (which, converting load to concentration, means $\phi_s \propto Q_w{}^{7/2}$). The relationship $\phi_s \propto Q_w{}^{1/2}$ that we observed at Findelengletscher (Figure 5a) indicates a *b* value that is confidently < 1 and is therefore inconsistent with expectations for channelized flow. It is also inconsistent with data for mountain rivers analysed by Müller and Förstner (1968), where *b* was > 2. Only lowland rivers observed by Müller and Förstner (1968) had values < 2, including the Seerhein, which is the outflow of upper Lake Constance, Switzerland/Germany, where $b = 0$.

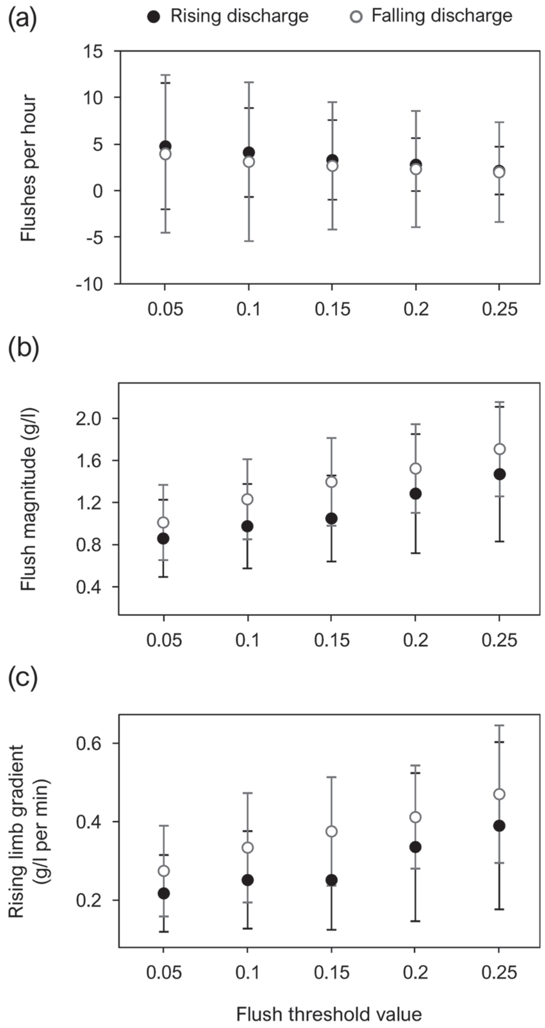


FIGURE 7 Flush characteristics and their sensitivity to the choice of flush threshold value in g l^{-1} s^{-1} (see text). Error bars indicate one standard deviation from the mean

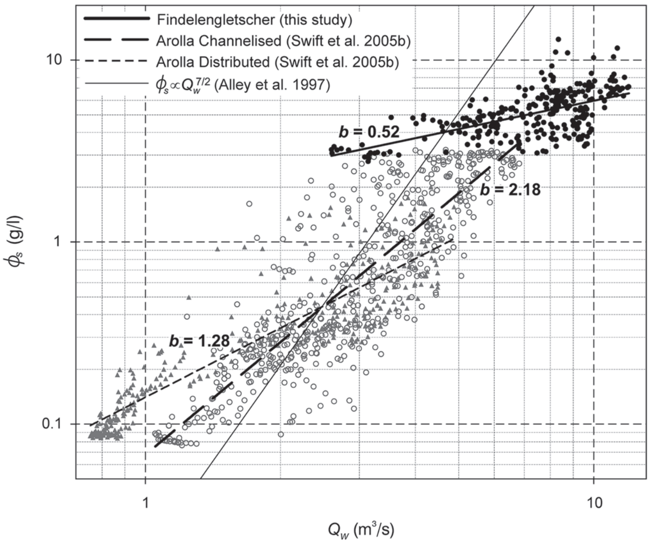


FIGURE 8 Relationships between discharge and sediment concentration at Findelengletscher (this study) and Haut Glacier d'Arolla (subperiods 4 and 6 of the 1998 melt season, from Swift *et al.*, 2005a). The relations have the form $\phi_s = a \cdot Q_w^b$ (see text) and are plotted over the range of values observed during each study and for all $p < 0.01$. The relation proposed by Alley *et al.* (1997) (see text) is plotted using an arbitrary intercept value. Findelengletscher is twice as large as Haut Glacier d'Arolla in terms of area of ice cover, meaning summer discharge minima and maxima at Findelengletscher are, in comparison, higher

The formation of hydraulically efficient channelized subglacial drainage during the summer is commonplace at temperate glaciers, and such systems are widely regarded as the dominant sediment transfer mechanism within glacial systems (e.g., Alley *et al*., 1997; Herman *et al*., 2011). However, on adverse bed slopes, theoretical work predicts that channel water pressures should tend toward ice overburden pressure, meaning channelized drainage should 'collapse', causing flow to distribute across the glacier bed (Röthlisberger & Lang, 1987; Hooke, 1991; Alley *et al*., 1998; Creyts & Clark, 2010). Both Hooke (1991) and Alley *et al*. (2003) proposed that the accompanying collapse in transport capacity should result in fluvial sediment deposition and therefore till accumulation on the adverse slope, causing the adverse slope gradient to tend toward the threshold slope for re-establishment of channelized drainage (e.g., Alley *et al*., 1998). Thus, sediment connectivity between the glacial–proglacial system will be maintained, but erosion of bedrock will be suppressed within the overdeepening and, most notably, on the adverse slope.

Distributed forms of drainage are characterized by slow transit velocities (e.g., Nienow *et al*., 1998) and a positive relationship between discharge and water pressure (e.g., Kamb, 1987), which dictate that changes in flow discharge are accommodated partly by growth in system cross-section area. Examples include the enlargement of basal cavities or other water-filled pockets that form part of a linked-cavity system (e.g., Iken & Bindschadler, 1986), increased canal incision into basal sediments (e.g., Kyrke-Smith & Fowler, 2014), or by increased depth of water in a basal 'sheet' (e.g., Creyts & Schoof, 2009). Assuming such systems were to accommodate changes in discharge by roughly equal adjustments in flow depth, width and velocity, the analysis of Alley *et al*. (1997) anticipates $Q_s \propto Q_w^2$ (which, by conversion, means $\phi_s \propto Q_w^{1.3}$). A remarkably similar relation of $\phi_s \propto Q_w^{1.2}$ (Figure 8) was observed by Swift *et al*. (2005a) during the early melt season at Haut Glacier d'Arolla, Switzerland, when subglacial flow was dominated by distributed pathways. The relation was observed to switch to $\phi_s \propto Q_w^{2.3}$ following establishment of a channelized subglacial drainage system, evidenced by rapid system flow velocities measured using dye tracing (Swift *et al*., 2005b).

The relation for Findelengletscher is shown in Figure 8 alongside example empirical relations for the two system types observed at Haut Glacier d'Arolla (Swift *et al*., 2005a). A hypothetical relation where $\phi_s \propto Q_w^{7/2}$ (Alley *et al*., 1997; see earlier) is also shown. In addition to differences in *b*, Figure 8 illustrates differences in *a* (the intercept value) that reflect relative differences in sediment availability (e.g., Müller & Förstner, 1968; Asselman, 2000). With respect to the period of distributed drainage at Haut Glacier d'Arolla, the availability difference means that sediment concentrations at Findelengletscher at equivalent discharges to those at Haut Glacier d'Arolla were almost an order of magnitude greater.

Temporal changes in *a* were observed by Swift *et al*. (2005a) at Haut Glacier d'Arolla both prior to and after the switch from distributed to channelized drainage. Decreases in *a* during the period of distributed drainage were argued to result from depletion of basal sediment sources accumulated since the end of the preceding melt season, with increases in *a* argued to reflect enhanced disturbance of basal sources and distributed pathways during 'spring' basal-slip events (cf. Mair *et al*., 2002). Changes in *a* during the period of channelized drainage were positive and correlated with diurnal discharge-cycle amplitude. This implied that sediment availability was later linked to the strength (and therefore spatial influence) of a diurnally reversing hydraulic gradient that operated between channels and adjacent areas of distributed drainage (Swift *et al*., 2005a, 2005b). This feature of subglacial hydrology arises from diurnal overpressurization of channels by surface melt, and is referred to as the 'variable pressure axis', or VPA (Hubbard *et al*., 1995; Nienow *et al*., 2005; Davison *et al*., 2019). A similar pattern of increasing sediment availability at Haut Glacier d'Arolla was also observed by Perolo *et al.* (2019). Because *b* is inconsistent with channelized drainage, we conclude that high sediment availability at Findelengletscher (expressed by the high value of *a*) reflects access of a distributed system to copious sources of sediment at the glacier bed.

Empirical studies have further shown that sediment transport in mountain and glacier streams is typically characterized by strong clockwise hysteresis and a significant bedload component (e.g., Liestøl, 1967; Gurnell, 1987). Clockwise hysteresis is associated with flow in discrete channels because near- or in-channel sediment sources are typically supply-limited and exhausted rapidly as discharge rises (e.g., Bogen, 1980; Riihimaki *et al*., 2005; Gimbert *et al*., 2018). Diurnal hysteresis is particularly pronounced in subglacial streams because rising flows will expand to access areas of bed where glacial bedrock erosion has replenished sediment flushed by the previous high flow (Liestøl, 1967). In addition, strong velocity and turbulence hysteresis in confined subglacial channels should dictate rapid entrainment of in-channel sediment deposited by preceding high flows (e.g., Richards, 1982; Bombar, 2016; Khuntia *et al*., 2019). Discrete channels also have high competence and therefore bedload transport may represent one-third to two-thirds of the total sediment load (e.g., Østrem, 1975; Gurnell, 1987; Hallet *et al*., 1996; Riihimaki *et al*., 2005). Our analyses of transport time series at Findelengletscher indicates the absence of clockwise hysteresis in suspended sediment transport (Figure 9), and, though we did not quantify bedload transport, qualitative observations indicated bedload transport rates were uncharacteristically low.

The discharge of ice blocks from the portal (e.g., Figure 2c) was frequent and this too may be indicative of drainage system morphology (cf. Collins, 1979). Blocks were occasionally observed to be ejected after collapse events from inside the portal that were audible to witnesses, though such events were never visible because of the low nature of the portal roof (Figure 2). Nonetheless, block emergence was not always preceded by an audible event, meaning events may have originated some distance inside the portal. These events were presumed to result from the collapse of ice from the roofs of englacial or subglacial drainage paths, meaning such paths were likely to have been unusually broad.

4.2 | Significance of sediment flushes for sediment load and drainage morphology

Short-lived flushes of sediment unrelated to discharge variability are common in sediment transport records from glacial drainage systems (e.g., Willis *et al*., 1996). The increase in sediment load associated with each flush (see Results section) indicates that the proportion of total load evacuated by flush activity during the monitored period was likely only *c.* 7%. A not dissimilar estimate of 9% was reported by Gurnell and Warburton (1990). Nonetheless, identification of flush origin could provide independent support for our interpretation of subglacial drainage system morphology (above). Previously proposed subglacial mechanisms of flush generation include temporary flow diversion events (caused, for example, by blocking of channels by collapsed ice; e.g., Collins, 1990), collapse of unstable soft-sediment channel margins (e.g., Collins, 1979), increases in flow through areas of distributed drainage (for example, during rainfall; e.g., Raymond *et al*., 1995), the rapid formation or reorganization of drainage flow paths (Collins, 1989, 1990; Anderson *et al*. 1999; Riihimaki *et al*., 2005), and 'disturbance' of the basal zone (for example, by glacier advance or rapid basal-slip events; e.g., Gurnell *et al*., 1988; Gurnell, 1995; Willis *et al*., 1996; Swift *et al*., 2005a).

Most studies have attributed flushes to subglacial (rather than proglacial) sources, but attribution is almost always speculative because of the inaccessible nature of glacier beds. A notable analysis of 571 flushes over a 22-day period at Glacier de Tsidjiore Nouve, Switzerland by Gurnell and Warburton (1990) could attribute only a

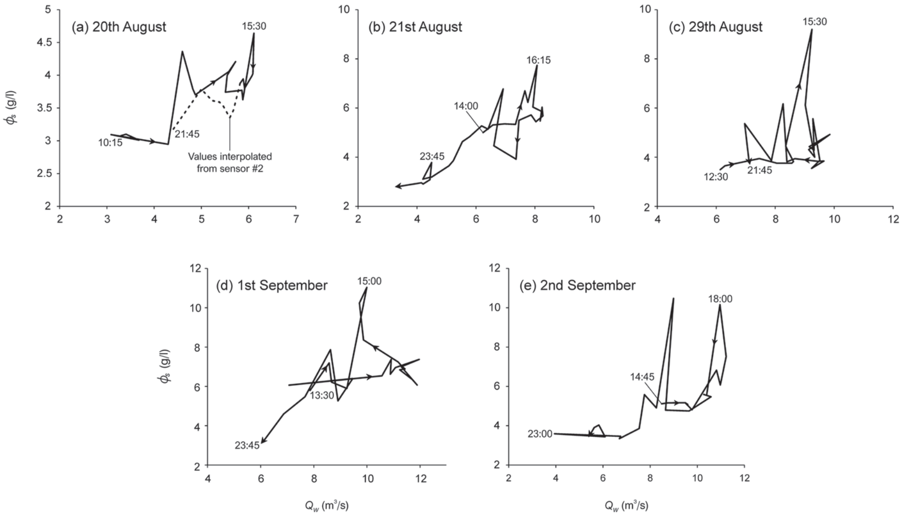


FIGURE 9 Discharge–concentration plots for days during 2016 at Findelengletscher (calibrated values, sensor 1 only) showing absence of clear clockwise hysteresis. Arrows show direction of time. Peak discharge on each day occurred at c. 18:00 h

few flushes to ‘glacial’ (rather than proglacial) sources. Flushes observed by Collins (1979) at Gornergletscher, Switzerland were very likely subglacial, nonetheless, because they were associated with the evacuation of cobble-sized pieces of ice from the drainage portal. Collins (1979) thus suggested these flushes occurred due to channel migration, which fractured the basal ice. Flushes observed to occur in association with changes in ice motion can also be confidently identified as subglacial in origin. At Variegated Glacier, Alaska, sediment flushes occurred during periods of enhanced basal slip associated with surging (Humphrey *et al*., 1986; Kamb & Engelhardt, 1987; Humphrey & Raymond, 1994); at Midtdalsbreen, Norway, flushes that were independent of discharge occurred shortly after peaks in glacier motion (Willis *et al*., 1996); and observations at two Alaskan glaciers by Raymond *et al*. (1995) demonstrated that flushes occurred simultaneously with ice motion events during periods of rainfall.

The numerous sediment transport studies undertaken at Haut Glacier d’Arolla between 1982 and 1998 (e.g., Gurnell *et al*., 1992; Clifford *et al*., 1995; Swift *et al*., 2005a) are unusual in that proglacial stream monitoring for these studies has typically been undertaken very close to the terminus (within *c*. 100 m), meaning there is high confidence that flushes are subglacial in origin. Curiously, these studies reveal longer-term periods of enhanced flushing in the early melt season (so-called ‘spring’ or ‘first-flush’ events; cf. Fenn, 1987), but reveal only sparse evidence of the short-lived flush events observed so commonly by this study and at Gornergletscher by, for example, Collins (1979). For example, short-lived flushes identified by Swift *et al*. (2005a) from large positive residuals in the discharge–sediment concentration relationships mainly occurred (a) during a period of frequent rainfall (subperiod 7 in 1998), and (b) following rapid basal ‘slip’ events associated with a longer (several day) ‘spring’ motion event (subperiod 2) during the period of distributed subglacial drainage.

The small number of flushes at Glacier d’Tsidjiore Nouve considered by Gurnell and Warburton (1990) to be of glacial origin were strongly asymmetric in form, having notably steeper rising limbs than falling limbs. Such asymmetry would appear consistent with the hysteresis effect that would likely arise if a sediment source were accessed by a discrete channel (Bogen, 1980). Likewise, only a few of the flushes observed at Findelengletscher were strongly asymmetric (i.e., shape value < 0.5), and, of these, one (Figure 10) was witnessed by observers at the portal. The event was notable for having occurred during a steep rise in stage that followed an unexpected discharge decline, and for being accompanied by the evacuation of numerous ice blocks. The event was therefore interpreted to be the result of temporary obstruction of part of the drainage system by ice collapse. *Post hoc* analysis of the time series data to identify similar ‘discharge-disruption’ flush events found only 13 possible events, which represented only *c*. 6% of all flushes identified using a threshold value of 0.15.

Most flushes observed at Findelengletscher were instead near-symmetric (see Results section) with the range of shape values being consistent with those of flushes at Glacier de Tsidjiore Nouve that Gurnell and Warburton (1990) attributed to proglacial sources. Gurnell and Warburton (1990) were able to reproduce such flushes in the field by manual addition of fine sediment to the stream. Importantly, manual addition of sediment in this way means entrainment would not have been characterized by hysteresis that would be expected when channelized flows interact with a sediment source (see earlier). This leads us to similarly conclude that most flushes at Findelengletscher – though clearly subglacial in origin – were inconsistent with channelized drainage. The equal number of flushes observed on rising and falling discharge limbs at Findelengletscher is also consistent with flush numbers observed by Gurnell and Warburton (1990). However, falling limb flushes at Findelengletscher were larger than observed by Gurnell and Warburton (1990), meaning flush magnitude patterns did not exhibit diurnal hysteresis characteristic of exhaustion of sources accessed by channelized flow (Liestøl, 1967). This leads us to conclude that contrasting mechanisms may be responsible for flushes occurring on rising-discharge versus falling-discharge flow.

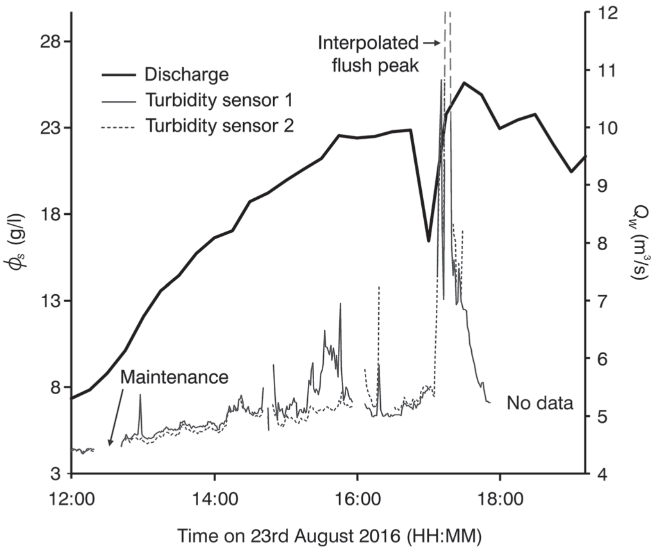


FIGURE 10 Sediment concentration and discharge on the afternoon of 23 August 2016, showing a notable flush event (lighter grey lines, showing extent of agreement between the two sensors) preceded by an unusual decline in discharge (thick black line). Concentration at the flush peak is unknown and the inferred peak (annotated) has been interpolated from the rate of change of concentration measured prior to and after the peak. Minimum and maximum stage during the event were witnessed at the glacier terminus at approximately 17:00 and 17:30 h, in agreement with the discharge record. Peak sediment concentration occurred at c. 17:15 h during the rapid rise in discharge prior to the subsequent ‘flood’ peak and was associated with the discharge of ice blocks and slush

This discussion further indicates the possibility that distributed and channelized systems exhibit distinctive flush forms and frequencies, with channelized drainage (e.g., as at Haut Glacier d’Arolla) exhibiting low flush frequency and chiefly asymmetric flush-form. If channel-bank collapse accounts for the majority of such flushes within channelized systems, the paucity of such events at Haut Glacier d’Arolla is perhaps unsurprising given that substantial sediment cliffs adjacent to channels are likely rare in the subglacial environment. Further, we argue that such collapse would most likely occur during undercutting by rising flows, and that the collapsed material would be less likely to be mobilized during falling flows. Flushes at Findelenglestcher do not conform to this pattern because the larger flushes occur on the falling discharge limb. Further, bank collapse is highly unlikely within distributed systems, where flow depths are very small. We conclude that flush origin at Findelengletscher is most likely a ‘basal-disturbance’ process in the presence of high sediment availability.

4.3 | Synthesis and mechanistic model

We draw together our key results and discussion to propose a conceptual mechanistic model of drainage and sediment evacuation processes at Findelengletscher (Figure 11).

Our key findings are inconsistent with channelized subglacial drainage. First, the discharge-suspended sediment concentration relationship indicated high sediment availability and unusually weak dependence of flow velocity on discharge; second, the symmetric form of flushes appeared to be inconsistent with a sediment source being accessed by a discrete flow (cf. Gurnell & Warburton, 1990); and third, clear hysteresis was absent from flush magnitude patterns and the discharge–sediment concentration plots (Figures 7 and 9). From this we infer that terminal region subglacial drainage at Findelengletscher was predominantly via distributed pathways (Figure 11), where variation in discharge was accommodated largely by adjustment in system cross-sectional area. Because the observed dependence of sediment concentration on discharge (i.e., $\phi_s \propto Q_w^{1/2}$) was weaker than that observed for distributed drainage at Haut Glacier d'Arolla (i.e., $\phi_s \propto Q_w$), it is possible that system enlargement included exploitation of englacial flow paths (Figure 11D). Nonetheless, high sediment concentrations imply persistent subglacial flow, meaning adjustments in cross-sectional area change may have been achieved by, for example, canal incision into basal sediments, or increased ice-bed separation (i.e., water ponding).

Occasional large asymmetric flushes that were accompanied by discharge variability and ice block evacuation were consistent with those at Gornergletscher attributed by Collins (1979) to flow path blockages caused by tunnel-roof collapse. At Findelengletscher, these ice blocks were frequently too large to have been evacuated through a distributed system, therefore it would seem that the collapse events occurred in broad, low-roofed channels that connect the distributed system with the portal (Figure 11F). Such events might also have occurred within englacial conduits, which may also have been unusually broad if they were 'graded' to the overdeepening 'lip' (cf. Fountain & Walder, 1998). However, because most flushes were near-symmetric, flush form further supports the existence of distributed subglacial drainage. We propose that flushes on the rising discharge limb that were lower in magnitude reflected pressurized expansion of distributed flow across the soft-sediment bed (cf. Swift *et al.*, 2005a). We further advance that the larger and slightly more asymmetric flushes that characterized flushing on the falling limb (see Results section) indicate a different mobilization mechanism; for example, basal disturbance resulting from the re-coupling of areas of the glacier sole with the soft-sediment bed as discharge (and hence the 'thickness' of the subglacial water layer and ice-bed separation) declines. Finally, the qualitative observation of limited bedload transport relative to suspended load is consistent with low-competency flow paths emerging from an overdeepened glacier bed (e.g., Pearce *et al.*, 2003).

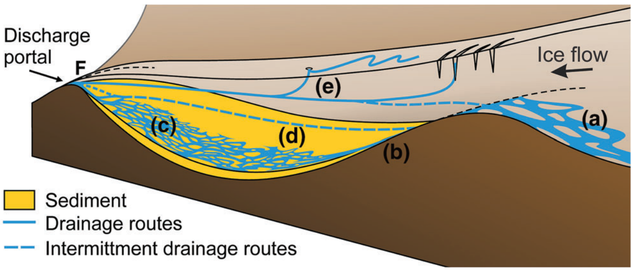


FIGURE 11 Inferred drainage paths and their configuration in the ablation area of a temperate valley glacier with a terminal overdeepening. The diagram emphasizes the switch from channelized to distributed subglacial drainage, which is associated with the presence of adverse slopes (A and C). Not all features are necessarily present at Findelengletscher. A: distributed drainage on the adverse slopes of overdeepenings; B: channelized drainage on normal slopes connecting overdeepenings; C: distributed drainage and deposited sediment occupying the terminal overdeepening; D and E: possible subglacial-to-englacial drainage connections that may fully or partly span the overdeepened area (direct routes are indicated, but the routes may be tortuous; for example, as a result of exploiting englacial debris septa or fractures); F: channelized englacial and subglacial paths feeding the portal

4.4 | Significance of bed morphology for drainage mechanics and sediment yields

Ongoing warming of global climate is likely to increase sediment yields from glaciated basins in coming decades because glacier retreat provides a melt 'dividend' (e.g., Kaser *et al.*, 2010; Huss & Hock, 2018) that is likely to enhance rates of sediment evacuation (Koppes & Montgomery, 2009; Lane & Nienow, 2019; Delaney & Adhikari, 2020) and possibly, therefore, rates of subglacial bedrock erosion too (e.g., Alley *et al.*, 2019). Nonetheless, observed variabilities in glacier sediment yields (see Introduction section) indicate that crucial driving factors remain poorly understood (e.g., Jaeger & Koppes, 2016). Notably, subglacial environments have been argued to lack potential for sediment storage sufficient to influence yields over decadal timescales (Riihimaki *et al.*, 2005), and many studies have emphasized the supply-limited nature of subglacial streams on account of strong hysteresis in discharge–sediment transport relationships (e.g., Riihimaki *et al.*, 2005; Koppes *et al.*, 2015; Gimbert *et al.*, 2016). However, closed-basin bedrock topography beneath mountain glaciers is abundant (e.g., Frey *et al.*, 2010; Linsbauer *et al.*, 2016; Colonia *et al.*, 2017) and could greatly influence subglacial drainage efficiency and sediment storage potential.

Delaney *et al.* (2018) observed that discharge availability failed to capture recent decadal evolution of catchment sediment export at both Gornergletscher and Aletschgletscher and further observed that yield-based erosion rate estimates for both catchments were only 30–50% of typical rates for glaciers of the Swiss Alps ($\sim$1 mm a^{-1}). Comparison of likely daily August 2016 export rates at Findelengletscher indicated by our dataset with similar estimates from 1993 presented by Barrett and Collins (1997) indicates the same decadal variability. Using equipment installed in the water intake structure (Figure 1), Barrett and Collins (1997) reported mean 'late August' suspended sediment fluxes of 529 t d^{-1}. In contrast, our observed discharge–sediment concentration relation for Findelengletscher in 2016 (Figure 5) indicates mean daily late-August suspended sediment loads of *c.* 2.5 kt d^{-1}. Assuming the observed discharge–sediment concentration relation can be applied at Findelengletscher throughout 2016, the total annual suspended sediment load from the glacier in that year would have been *c.* 189 kt.

The latter value would correspond to an effective erosion rate (cf. Hallet *et al*., 1996) of *c*. 5 mm a^{-1} if assuming a bedrock density of 2.7 g cm^{-3} (Nishiyama *et al*., 2019) and glacier area of 13 km^2 (Feiger *et al*., 2018). Such a value greatly exceeds regional rock uplift rates and local rates indicated by sediment yields (e.g., Stutenbecker *et al*., 2018; Delaney *et al*., 2018). Decadal variability might therefore be explained by retreat causing terminal zone processes to be conditioned, periodically, by areas of overdeepening.

Several detailed studies of sediment export from Gornergletscher motivate further insightful discussion that implicates overdeepening-related conditioning of sediment export rates and processes. Like Findelengletscher, Gornergletscher is significantly longer than Haut Glacier d'Arolla, and the bed appears to contain several overdeepenings (e.g., Iken *et al*., 1996; Delaney *et al*., 2019). Collins (1979) observed frequent flush activity at Gornergletscher that – based on our inferences at Findelengletscher – might indicate the absence of channelized drainage in the terminal region. Ice-block discharge events were observed to accompany flushes at Gornergletscher (Collins, 1979), which at Findelengletscher we attribute to roof-collapse of broad channels that connect the distributed system with the portal. In addition, many studies at Gornergletscher (e.g., Collins, 1989) have demonstrated remarkably different seasonal patterns of sediment evacuation to that observed at Haut Glacier d'Arolla. Though both glaciers exhibit so-called 'first-flush' events (e.g., Fenn *et al*., 1985), which typically last several days, sediment export from Gornergletscher thereafter declines. At Haut Glacier d'Arolla, in contrast, an initial exhaustion effect attributable to the inception of discrete channels is later reversed by the establishment of variable pressure axes surrounding such channels (Swift *et al*., 2005a). Thus, we hypothesize that suppression by bed topography of the seasonal development of a channelized system like that observed at Haut Glacier d'Arolla is a possible explanation for apparent seasonal sediment exhaustion at Gornergletscher.

Proglacial processes are clearly an additional factor that modulates catchment export rates (e.g., Lane *et al*., 2017), and studies such as Delaney *et al*. (2018), Collins (1979) and Barrett and Collins (1997) were undertaken using measurements obtained from intake structures below extensive proglacial areas. Nonetheless, our discussion of observations at Findelengletscher indicates that decadal and seasonal patterns of sediment export from glacier systems are likely mediated very strongly by bed morphology and its influence on glacial sediment storage and subglacial drainage efficiency. These implications are summarized in Figure 12 for ice masses in steady state (Figure 12, panel i) and at stages of retreat (Figure 12, panel ii).

As shown in Figure 12 (panels i–iii), all glaciers are expected to exhibit spring peaks in sediment export (i.e., so-called 'first-flush' events) because rapidly expanding distributed systems access sediment that has accumulated since the end of the previous melt season (e.g., Collins, 1989; Swift *et al*., 2005a). However, the spring peak may be larger for glacial systems with suppressed subglacial drainage efficiency (Figure 12, panel ii) because of greater year-to-year storage potential for subglacial sediment. Thereafter, ice-bed morphology dictates one of two seasonal sediment export patterns: (1) increasing export arising from highly efficient channelized drainage with abundant access to basal sediment sources (Figure 12, panel i) because of the development of strong variable pressure axes focused on major

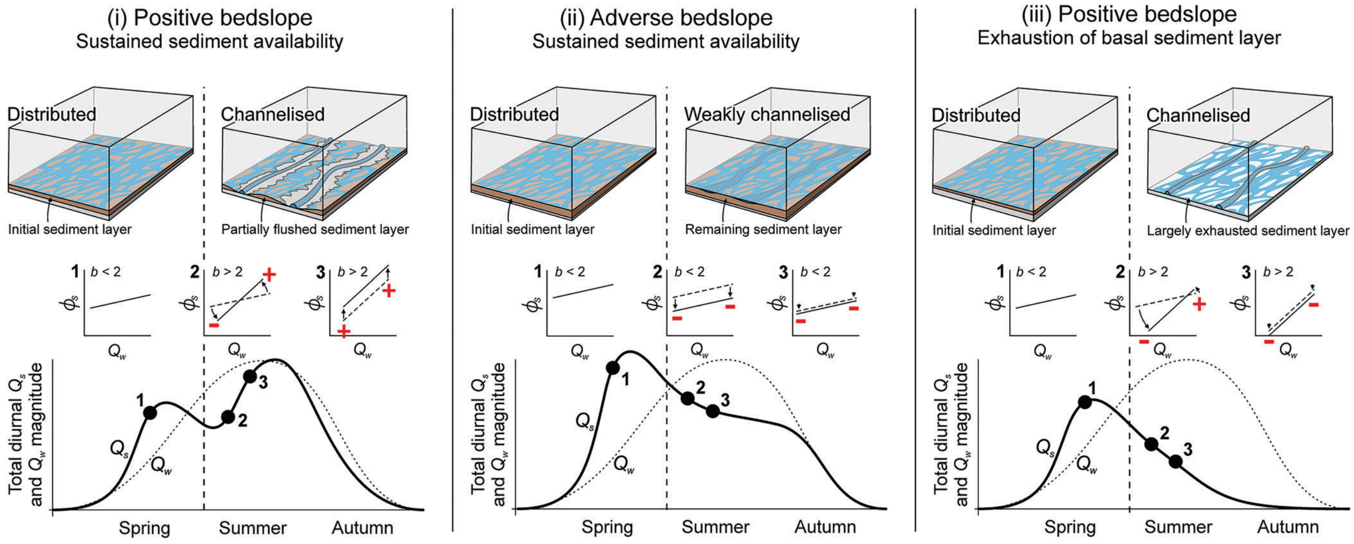


FIGURE 12 Generalized conceptual model of seasonal and decadal subglacial drainage evolution and suspended sediment export patterns from the terminal zone of a temperate ice mass. Panels (i)–(iii) show implications of areas of positive and adverse bed slope for spring–summer drainage morphology, evolution of discharge–sediment concentration relationships, and seasonal evolution of sediment export rate. The three-dimensional 'models' illustrate drainage system morphological characteristics and sediment layer thickness; ice and water flow in each model is from upper-right to lower-left. In the schematic bivariate and time series plots below, ϕ_s is sediment concentration, Q_w is discharge, and Q_s is load, with each bivariate plot representing a specific time-point (time point 1 to time point 3) on the time series plot below. Panel (i) shows development of efficient channelized drainage by time point 2, which leads to an initial fall in load following the 'spring' peak because flow in discrete channels initially has limited access to subglacial sediment sources (Alley et al., 1997). Rates subsequently increase to reach a higher peak shortly after time point 3 as the increasing peakedness of summer diurnal supraglacial runoff cycles establishes a strong diurnally reversing hydraulic gradient (Swift et al., 2005a, 2005b). Panel (ii) shows how suppression of efficient drainage by an adverse bed slope, resulting in an inefficient system of cavities or canals, means the seasonal pattern is dominated by exhaustion of winter accumulated sediment sources. Panel (iii) shows the implications of complete early-season exhaustion of the winter-accumulated subglacial sediment store prior- or simultaneous-to the formation of efficient channels

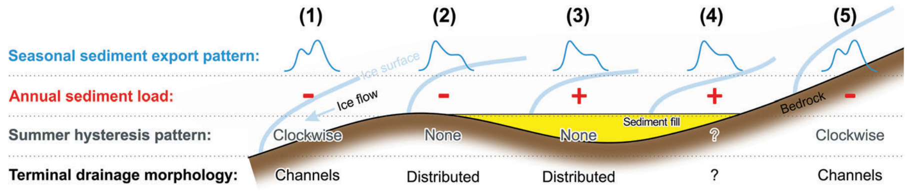


FIGURE 13 Glacier retreat in the presence of overdeepened bedrock topography (shown as five stages, 1–5) means sediment export patterns to the proglacial zone will be conditioned by the proximity of subglacial basins (i.e., overdeepenings) to the glacier terminus zone and their sediment fill level. Downstream discharge–concentration relationships will be conditioned by drainage style in the terminal area and – depending on basin-fill level and basin proximity to the glacier terminus – sediment export to the proglacial area may be enhanced by the recycling of basin sediment or inhibited by basin filling. Here, retreat is shown to occur into a full basin, but temporary proglacial lake formation could instead occur if the rate of glacial sediment export during retreat is sufficiently low. Annual load symbols indicate deviation from the long-term sediment export mean

channels (see earlier); or (2) declining export (apparent exhaustion) due to the absence of channels and their associated VPAs (Figure 12, panel ii), or perhaps even complete exhaustion of the basal sediment layer in the presence of channels (Figure 12, panel iii). In overdeepened situations, complete exhaustion might occur because flow enlarges alternative englacial flow paths, diverting flow from the bed, or because of sediment evacuation by subglacial canals. The latter could result in decreased transport capacity both by increasing subglacial system cross-section area and by increasing the magnitude of the adverse slope gradient.

Figure 13 considers the implications for decadal export patterns and yields, which will clearly depend on adverse slope characteristics (Hooke, 1991; Alley *et al*., 2003), but also overdeepening location within the glacier system. We propose that overdeepenings will have the greatest influence on catchment yields and downstream sediment signals during retreat of the margin over the basin (Figure 13, stages 3 and 4), because of the abundance of melt will combine with highest subglacial sediment availability. Comparatively, stabilization of the terminus beyond an overdeepening (stages 1 or 2) may reduce yields, especially if the adverse slope is steep, meaning the overdeepening acts as a subglacial sediment sink. The existence of such a sediment store may not be apparent to proglacial sediment monitoring efforts because transport will be conditioned by flow in near-terminus channels. Many details of the model are, however, uncertain because of limited theoretical and field observations. For example, field observations have indicated a tendency for drainage to 'avoid' overdeepenings via establishment of englacial or lateral flow paths (e.g., Fountain, 1994; Spedding & Evans, 2002; Fountain *et al*., 2005), meaning stores may be protected from evacuation during retreat. Further studies of drainage routing during retreat are therefore needed.

5 | CONCLUSION

Inferential studies of the processes of sediment evacuation from glaciers have been biased towards glacier systems that have non-overdeepened beds, studies where the ice-bed topography has not been explicitly considered, or studies where the monitoring location for sediment was downstream of large proglacial zones. For this study, monitoring was conducted near to the portal of a glacier with an overdeepened terminal area to address the hypothesis that glacier bed morphology was a key control on sediment evacuation rates and processes because of its perceived implications for subglacial drainage system efficiency and morphology. Our analyses of the acquired data provide the following conclusions:

- Sediment concentration (ϕ_s) varied proportionally with discharge (Q_w) such that exponent b in the relation $\phi_s = a \cdot Q_w{}^b$ was < 1. This finding is inconsistent with observations of sediment transport in typical mountain streams and also inconsistent with theoretical expectations of transport within subglacial channels, which indicate b > 2 (e.g., Alley *et al*., 1997).
- The finding $\phi_s \propto Q_w{}^{0.5}$ indicates highly distributed subglacial drainage in the terminal region of Findelengletscher. For comparison, $b = 1.3$ was observed during the period of distributed drainage at Haut Glacier dArolla (Swift *et al*., 2005a) and is the value anticipated for drainage systems in which variation in discharge is accommodated by equal adjustment in flow width, depth, and velocity (cf. Alley *et al*., 1997).
- The finding of b < 1 indicates that discharge was associated with minimal adjustment in flow velocity and was accommodated largely by adjustment in system cross-sectional area. Such adjustment may therefore have included exploitation of englacial pathways, rapid incision into a soft-sediment bed, or floatation of the ice (i.e., ponding of water at the glacier bed), but such details remain unknown.
- The intercept (a value) of the discharge–sediment concentration relationship at Findelengletscher indicates remarkable sediment availability. This availability is responsible for a late-summer glacial suspended sediment export rate that is estimated to be *c*. 2.5 kt d^{-1}. Such high availability is likely maintained by storage within the terminal overdeepening and the highly distributed nature of water flow.
- Sediment flushes (or 'pulses') that were unrelated to discharge were frequent, and the form and temporal characteristics of most flushes were inconsistent with channelized flow. Only a few large pulses were associated with changes in discharge that implicate flow blocking by collapse of broad ice-roofed channels.
- Our analyses of flush form indicated that flushes were generated by disturbance of the basal environment and reflective of subtly different disturbance mechanisms on rising versus falling discharge limbs. We speculate that flushes on rising limbs were generated by canal incision into soft-sediment and on falling limbs by re-coupling of ice with the soft-sediment bed.

Rates of sediment export from glacier systems are known to be inherently variable and the drivers and mechanisms known to be poorly understood. Our data from Findelengletscher and subsequent discussion leads us to advance that glacier bed morphology plays likely a very important role in determining sediment export processes, patterns, and rates. Specifically, the following findings are implied:

- The preponderance of closed basins in glacier beds indicates that overdeepenings may be a significant mediating factor in glacial sediment export from glaciated catchments, with potentially far-reaching implications for downstream sediment dynamics, glacier erosion rate estimation, glacier bed evolution, and glacier flow.
- Overdeepenings can provide sediment stores that significantly elevate export rates from glacial systems depending on their location within the glacial system (Figure 12). Export rates inferred from the discharge–concentration relation during August and September 2016 at Findelengletscher imply an annual erosion rate > 5 mm a^{-1}, which is far greater than expected for the region and is likely a result of the terminus region being located directly over the overdeepening.
- Bed morphology in general is likely a strong control on seasonal evolution of subglacial drainage efficiency and seasonal, annual, and decadal scale sediment evacuation rates, patterns, and mechanics (Figure 12). Because of the abundance of overdeepenings beneath subglacial topography and the tendency for stabilization of glacier termini on adverse slopes (e.g., Oerlemans *et al*., 2011; Jamieson *et al*., 2014) we suggest that near terminus bed-morphology should always be considered when examining and interpreting glacier and catchment sediment export rates.
- Despite its inefficiency, distributed drainage at Findelengletscher appeared able to maintain sediment connectivity (cf. Bracken *et al*., 2015; Lane *et al*., 2017) between the glacial and proglacial sediment systems. Bedload export, however, was likely reduced, with coarse material likely being retained as a lag deposit within the overdeepening (cf. Swift *et al*., 2006, 2018).
- Glacial-origin flushes of sediment that are unrelated to discharge do not appear to contribute substantially to sediment yield, being likely responsible for $< 10\%$ of load from glaciated catchments. Nonetheless, flush characteristics may be a useful indicator of subglacial drainage system morphology and opportunities to further study flush form and origin should be explored.
- Though accumulation of sediment on adverse slopes is expected to suppress erosion of bedrock within an overdeepening (cf. Hooke, 1991; Alley *et al*., 2003) the maintenance of sediment connectivity through overdeepenings means bed erosion processes upstream may continue unabated.

Finally, we emphasize the inferential nature of our study and conclusions in terms of the details of subglacial drainage system morphology, the specific generation mechanisms of subglacial origin flush events, and the implications for decadal variability in glaciated catchment yields. Further research is therefore required to understand the details of water routing through overdeepenings, and the implications for sediment storage and entrainment processes on seasonal to decadal scales, to fully understand the mediating effect on annual to decadal sediment export rates and their response to glacier retreat.

ACKNOWLEDGEMENTS

The authors are grateful to Grande Dixence S.A. for providing access to the discharge data. Alan Smalley and Joe Hufton provided laboratory assistance. G.D.T., D.A.S. and S.J.C. gratefully acknowledge the University of Sheffield 'Global Learning Opportunities in the Social Sciences (GLOSS)' Research Associate Scheme, which funded G.D.T.'s participation in this work, and supported other field research costs.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The sediment data used in this study are available in the Supporting Information of this article. The discharge data also used in this study are available from Grande Dixence S.A. Restrictions apply to the availability of these data, and these data are available from the authors with the permission of Grande Dixence S.A.

ORCID

Darrel A. Swift https://orcid.org/0000-0001-5320-5104
Guy D. Tallentire https://orcid.org/0000-0002-0389-6581
Daniel Farinotti https://orcid.org/0000-0003-3417-4570
Simon J. Cook https://orcid.org/0000-0003-1532-6532
Robert G. Bryant https://orcid.org/0000-0001-7943-4781

REFERENCES

Alley, R., Cuffey, K. & Zoet, L. (2019) Glacial erosion: Status and outlook. *Annals of Glaciology*, 60(80), 1–13. https://doi.org/10.1017/aog.2019.38

Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E. & Larson, G.J. (1997) How glaciers entrain and transport basal sediment: Physical constraints. *Quaternary Science Reviews*, 19, 1017–1038.

Alley, R.B., Lawson, D.E., Evenson, E.B., Strasser, J.C. & Larson, G. (1998) Glaciohydraulic supercooling: A freeze-on mechanism to create stratified, debris-rich basal ice: II. *Theory*. *Journal of Glaciology*, 44, 563–569.

Alley, R.B., Lawson, D.E., Larson, G.J., Evenson, E.B. & Baker, G.S. (2003) Stabilizing feedbacks in glacier-bed erosion. *Nature*, 424(6950), 758–760. https://doi.org/10.1038/nature01839

Anderson, S., Fernald, K., Anderson, R. & Humphrey, N. (1999) Physical and chemical characterization of a spring flood event, Bench Glacier, Alaska, U.S.A.: Evidence for water storage. *Journal of Glaciology*, 45(150), 177–189. https://doi.org/10.3189/S0022143000001684

Asselman, N.E.M. (2000) Fitting and interpretation of sediment rating curves. *Journal of Hydrology*, 234, 228–248.

Bagnold, R.A. (1980) An empirical correlation of bedload transport rates in flumes and natural rivers. *Royal Society of London Proceedings*, A372, 453–473.

Barrett, A. & Collins, D. (1997) Interaction between water pressure in the basal drainage system and discharge from an Alpine glacier before and during a rainfall-induced subglacial hydrological event. *Annals of Glaciology*, 24, 288–292.

Bogen, J. (1980) The hysteresis effect of sediment transport systems. *Norsk Geogrrafisk Tidsskrift*, 34, 45–54.

Bombar, G. (2016) Hysteresis and shear velocity in unsteady flows. *Journal of Applied Fluid Mechanics*, 9, 839–853.

Bracken, L., Turnbull, L., Wainwright, J. & Bogaart, P. (2015) Sediment connectivity: A framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, 402, 177–188.

Clifford, N.J., Richards, K.S., Brown, R.A. & Lane, S.N. (1995) Scales of variation of suspended sediment concentration and turbidity in a glacial meltwater stream. *Geografiska Annaler*, 77(A), 45–65.

Collins, D.N. (1979) Sediment concentration in meltwaters as an indicator of erosion processes beneath an alpine glacier. *Journal of Glaciology*, 23, 247–257.

Collins, D.N. (1989) Seasonal development of subglacial drainage and suspended sediment delivery to melt waters beneath an Alpine glacier. *Annals of Glaciology*, 13, 45–50.

Collins, D.N. (1990) Seasonal and annual variations of suspended sediment transport in meltwaters draining from an Alpine glacier. *IAHS Publication*, 193, 439–446.

Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C. & Cochachin, A. (2017) Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the Peruvian Andes: Approach, first results, and perspectives for adaptation to climate change. *Water*, 9, 336.

Cook, S.J. & Swift, D.A. (2012) Subglacial basins: Their origin and importance in glacial systems and landscapes. *Earth-Science Reviews*, 115, 332–372.

Cook, S.J., Swift, D.A., Kirkbride, M.P., Knight, P.G. & Waller, R.I. (2020) The empirical basis for modelling glacial erosion rates. *Nature Communications*, 11, 759. https://doi.org/10.1038/s41467-020-14583-8

Creyts, T.T. & Clark, G.K.C. (2010) Hydraulics of subglacial supercooling: Theory and simulations for clear water flows. *Journal of Geophysical Research*, 115, F03021. https://doi.org/10.1029/2009JF001417

Creyts, T.T., Clarke, G.K.C. & Church, M. (2013) Evolution of subglacial overdeepenings in response to sediment redistribution and glaciohydraulic supercooling. *Journal of Geophysical Research: Earth Surface*, 1182, 423–446.

Creyts, T.T. & Schoof, C.G. (2009) Drainage through subglacial water sheets. *Journal of Geophysical Research*, 114, F04008. https://doi.org/10.1029/2008JF001215

Cudden, J.R. & Hoey, T.B. (2003) The causes of bedload pulses in a gravel channel: The implications of bedload grain-size distributions. *Earth Surface Processes and Landforms*, 28, 1411–1428.

Davison, B.J., Sole, A.J., Livingstone, S.J., Cowton, T.R. & Nienow, P.W. (2019) The influence of hydrology on the dynamics of land-terminating sectors of the Greenland Ice Sheet. *Frontiers in Earth Science*, 7, 10. https://doi.org/10.3389/feart.2019.00010

Delaney, I. & Adhikari, S. (2020) Increased subglacial sediment discharge in a warming climate: Consideration of ice dynamics, glacial erosion, and fluvial sediment transport. *Geophysical Research Letters*, 47, e2019GL085672. https://doi.org/10.1029/2019GL085672

Delaney, I., Bauder, A., Werder, M.A. & Farinotti, D. (2018) Regional and annual variability in subglacial sediment transport by water for two glaciers in the Swiss Alps. *Frontiers in Earth Science*, 6, 175. https://doi.org/10.3389/feart.2018.00175

Delaney, I., Werder, M.A. & Farinotti, D. (2019) A physically based model for fluvial transport of subglacial sediment. *Journal of Geophysical Research: Earth Surface*, 124, 2197–2223.

Egholm, D.L., Pedersen, V.K., Knudsen, M.F. & Larsen, N.K. (2012) Coupling the flow of ice, water, and sediment in a glacial landscape evolution model. *Geomorphology*, 141-142, 47–66.

Feiger, N., Huss, M., Leinss, S., Sold, L. & Farinotti, D. (2018) The bedrock topography of Gries- and Findelengletscher. *Geographica Helvetica*, 73, 1–9. https://doi.org/10.5194/gh-73-1-2018

Fenn, C.R. (1987) Sediment transfer processes in alpine glacier basins. In: Gurnell, A.M. & Clark, M.J. (Eds.) *Glacio–fluvial sediment transfer: An Alpine perspective*. Chichester: Wiley, pp. 59–85.

Fenn, C.R., Gurnell, A.M. & Beecroft, I.R. (1985) An evaluation of the use of suspended sediment rating curves for the prediction of suspended sediment concentration in a proglacial stream. *Geografiska Annaler*, 67A, 71–82.

Fountain, A.G. (1994) Borehole water level variations and implications for the subglacial hydraulics of South Cascade Glacier, Washington State, USA. *Journal of Glaciology*, 40, 293–304.

Fountain, A.G., Jacobel, R.W., Schlichting, R. & Jansson, P. (2005) Fractures as the main pathways of water flow in temperate glaciers. *Nature*, 433, 618–621.

Fountain, A.G. & Walder, J.S. (1998) Water flow through temperate glaciers. *Reviews of Geophysics*, 36, 299–328.

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. & Paul, F. (2010) A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards and Earth System Sciences*, 10, 339–352.

Gimbert, F., Tsai, V.C., Amundson, J.M., Bartholomaus, T.C. & Walter, J.I. (2016) Subseasonal changes observed in subglacial channel pressure, size, and sediment transport. *Geophysical Research Letters*, 43, 3786–3794.

GLAMOS (2020). The Swiss Glaciers 2017/18 and 2018/19. In: Bauder, A., Huss, M. & Linsbauer, A. (Eds.), *Glaciological Report No. 139/140 of the Cryospheric Commission (EKK) of the Swiss Academy of Sciences (SCNAT) published by VAW / ETH Zürich*. https://doi.org/10.18752/glrep_139-140

Guillon, H., Mugnier, J.L. & Buoncristiani, J.F. (2017) Proglacial sediment dynamics from daily to seasonal scales in a glaciated Alpine catchment Bossons glacier, Mont-Blanc massif, France. *Earth Surface Processes and Landforms*, 43, 1478–1495. https://doi.org/10.1002/esp.4333

Gurnell, A., Hannah, D. & Lawler, D. (1996) Suspended sediment yield from glacier basins. In: Walling, D.E. & Webb, B.W. (Eds.), *Erosion and Sediment Yield: Global and Regional Perspectives*, Vol. 236. International Association of Hydrological Sciences Publication, pp. 97–104. http://hydrologie.org/redbooks/a236/iahs_236_0097.pdf

Gurnell, A.M. (1987) Suspended sediment. In: Gurnell, A.M. & Clarke, M.J. (Eds.) *Glacio-fluvial sediment transfer: An Alpine perspective*. New York: Wiley, pp. 305–354.

Gurnell, A.M. (1995) Sediment yield from Alpine glacier basins. In: Foster, I.D.L., Gurnell, A.M. & Webb, B.W. (Eds.) *Sediment and Water Quality in River Catchments*. Chichester: Wiley, pp. 407–435.

Gurnell, A.M., Clark, M.J. & Hill, C.T. (1992) Analysis and interpretation of patterns within and between hydroclimatological time series in an Alpine glacier basin. *Earth Surface Processes and Landforms*, 17, 821–839.

Gurnell, A.M. & Warburton, J. (1990) The significance of suspended sediment pulses for estimating suspended sediment load and identifying suspended sediment sources in Alpine glacier basins. In: *Hydrology in Mountainous Regions. I – Hydrological Measurements; the Water Cycle*, Vol. 193. Wallingford: IAHS Publication, pp. 463–470.

Gurnell, A.M., Warburton, J. & Clark, M.J. (1988) A comparison of sediment transport and yield characteristics of two adjacent glacier basins, Val d'Hérens, Switzerland. In: *Sediment Budgets*, Vol. 174. Wallingford: IAHS Publication, pp. 431–441.

Hallet, B., Hunter, L. & Bogen, J. (1996) Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. *Global and Planetary Change*, 12, 213–235.

Herman, F., Beaud, F., Champagnac, J.-D., Lemieux, J.-M. & Sternai, P. (2011) Glacial hydrology and erosion patterns: A mechanism for carving glacial valleys. *Earth and Planetary Science Letters*, 310, 498–508.

Hilger, L. & Beylich, A.A. (2019) Sediment budgets in high-mountain areas: Review and challenges. In: Heckmann, T. & Morche, D. (Eds.) *Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes*. Berlin: Springer.

Holmlund, P., Burman, H. & Rost, T. (1996) Sediment-mass exchange between turbid meltwater streams and proglacial deposits of storglaciären, northern Sweden. *Annals of Glaciology*, 22, 63–67. https://doi.org/10.3189/1996AoG22-1-63-67

Hooke, R.L.B., Miller, S.B. & Kohler, J. (1988) Character of the englacial and subglacial drainage system in the upper part of the ablation area of Storglaciären, Sweden. *Journal of Glaciology*, 34(117), 228–231. https://doi.org/10.1017/S0022143000032275

Hooke, R.L. (1991) Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geological Society of America Bulletin*, 103, 1104–1108.

Hooke, R.L. & Pohjola, V.A. (1994) Hydrology of a segment of a glacier situated in an overdeepening. *Journal of Glaciology*, 40, 140–148.

Hubbard, B., Sharp, M., Willis, I., Nielsen, M. & Smart, C. (1995) Borehole water-level variations and the structure of the subglacial hydrological system of Haut Glacier d'Arolla, Valais, Switzerland.

Journal of Glaciology, 41(139), 572–583. https://doi.org/10.3189/S0022143000034894

Humphrey, N., Raymond, C. & Harrison, W. (1986) Discharges of turbid water during minisurges of Variegated Glacier, Alaska, USA. *Journal of Glaciology*, 32(111), 195–207. https://doi.org/10.1017/S0022143000015513

Humphrey, N.F. & Raymond, C.F. (1994) Hydrology, erosion and sediment production in a surging glacier – Variegated Glacier, Alaska, 1982–83. *Journal of Glaciology*, 40, 539–552.

Huss, M. & Hock, R. (2018) Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8, 135–140. https://doi.org/10.1038/s41558-017-0049-x

Iken, A. & Bindschadler, R.A. (1986) Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism. *Journal of Glaciology*, 32, 101–119.

Iken, A., Fabri, K. & Funk, M. (1996) Water storage and subglacial drainage conditions inferred from borehole measurements on Gornergletscher, Valais, Switzerland. *Journal of Glaciology*, 42, 233–248. https://doi.org/10.3189/S0022143000004093

Iverson, N.R., Hanson, B., Hooke, R.L.B. & Jansson, P. (1995) Flow mechanism of glaciers on soft beds. *Science*, 267(5194), 80–81. https://doi.org/10.1126/science.267.5194.80

Jaeger, J.M. & Koppes, M.N. (2016) The role of the cryosphere in source-to-sink systems. *Earth-Science Reviews*, *Source-to-Sink Systems: Sediment & Solute Transfer on the Earth Surface*, 153, 43–76. https://doi.org/10.1016/j.earscirev.2015.09.011

Jamieson, S.S.R., Vieli, A., Ó Cofaigh, C., Stokes, C.R., Livingstone, S. J. & Hillenbrand, C.-D. (2014) Understanding controls on rapid ice-stream retreat during the last deglaciation of Marguerite Bay, Antarctica, using a numerical model. *Journal of Geophysical Research Earth Surface*, 119, 247–263. https://doi.org/10.1002/2013JF002934

Kamb, B. (1987) Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research*, 92, 9083–9100.

Kamb, B. & Engelhardt, H. (1987) Waves of accelerated motion in a glacier approaching surge: the mini-surges of Variegated Glacier, Alaska, USA. *Journal of Glaciology*, 33, 27–46.

Kaser, G., Großhauser, M. & Marzeion, B. (2010) Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Science*, 107, 20223–20227.

Khuntia, J.R., Devi, K. & Khatua, K.K. (2019) Turbulence characteristics in a rough open channel under unsteady flow conditions. *ISH Journal of Hydraulic Engineering*, https://doi.org/10.1080/09715010.2019.1658549

Koppes, M., Hallet, B., Rignot, E., Mouginot, J., Wellner, J.S. & Boldt, K. (2015) Observed latitudinal variations in erosion as a function of glacier dynamics. *Nature*, 526, 100–103. https://doi.org/10.1038/nature15385

Koppes, M.N. & Montgomery, D.R. (2009) The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nature Geoscience*, 2, 644–647.

Kyrke-Smith, T.M. & Fowler, A.C. (2014) Subglacial swamps. *Proceedings of the Royal Society A*, 470, 20140340. https://doi.org/10.1098/rspa.2014.0340

Lane, S.N., Bakker, M., Gabbud, C., Micheletti, N. & Saugy, J.-N. (2017) Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology*, 277, 210–227.

Lane, S.N. & Nienow, P.W. (2019) Decadal-scale climate forcing of Alpine glacial hydrological systems. *Water Resources Research*, 55, 2478–2492.

Leggat, M.S., Owens, P.N., Stott, T.A., Forrester, B.J., Déry, S.J. & Menounos, B. (2015) Hydro-meteorological drivers and sources of suspended sediment flux in the pro-glacial zone of the retreating Castle Creek glacier, Cariboo Mountains, British Columbia, Canada. *Earth Surface Processes and Landforms*, 40, 1542–1559.

Liestøl, O. (1967) *Storbreen glacier in Jotunheimen, Norway*, Vol. 141. Tromsø: Norsk Polarinstitutt Skrifter.

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. & Allen, S. (2016) Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya—Karakoram region. *Annals of Glaciology*, 57, 119–130.

Mair, D., Nienow, P., Sharp, M.J., Wohlleben, T. & Willis, I. (2002) Influence of subglacial drainage system evolution on glacier surface motion: Haut Glacier d'Arolla, Switzerland. *Journal of Geophysical Research*, 107(B8). https://doi.org/10.1029/2001JB000514

Mao, L., Comiti, F., Carrillo, F. & Penna, D. (2019) Sediment transport in proglacial rivers. In: Heckmann, T. & Morche, D. (Eds.) *Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes*. Berlin: Springer.

Morehead, M.D., Syvitski, J.P., Hutton, E.W.H. & Peckham, S.D. (2003) Modeling the temporal variability in the flux of sediment from ungauged river basins. *Global and Planetary Change*, 39, 95–110.

Müller, G. & Förstner, U. (1968) General Relationship between Suspended Sediment Concentration and Water Discharge in the Alpenrhein and some other Rivers. *Nature*, 217, 244–245. https://doi.org/10.1038/217244a0

Nienow, P., Sharp, M. & Willis, I. (1998) Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms*, 23(9), 825–843. https://doi.org/10.1002/(SICI)1096-9837(199809)23:9<825::AID-ESP893>3.0.CO;2-2

Nienow, P.W., Hubbard, A.L., Hubbard, B.P., Chandler, D.M., Mair, D.W.F., Sharp, M.J. & Willis, I.C. (2005) Hydrological controls on diurnal ice flow variability in valley glaciers. *Journal of Geophysical Research-Earth Surface*, 110(F4), F04002. https://doi.org/10.1029/2003JF000112

Nishiyama, R., Ariga, A., Ariga, T., Lechman, A., Mair, D., Pistillo, C., *et al.* (2019) Bedrock sculpting under an active alpine glacier revealed from cosmic-ray muon radiography. *Scientific Reports*, 9, 6970.

Oerlemans, J., Jania, J. & Kolondra, L. (2011) Application of a minimal glacier model to Hansbreen, Svalbard. *The Cryosphere*, 5, 1–11.

Østrem, G. (1975) Sediment transport in glacial meltwater streams. In: Jopling, A.V. & McDonald, B.C. (Eds.) *Glaciofluvial and Glaciolacustrine Sedimentation*, Vol. 23. Tulsa, OK: Society of Economic Paleontologists and Mineralogists Special Publication SEPM Society for Sedimentary Geology, pp. 101–122.

Patton, H., Swift, D.A., Clark, C.D., Livingstone, S.J. & Cook, S.J. (2016) Distribution and characteristics of overdeepenings beneath the Greenland and Antarctic ice sheets: Implications for overdeepening origin and evolution. *Quaternary Science Reviews*, 148, 128–145. https://doi.org/10.1016/j.quascirev.2016.07.012

Pearce, J.P., Pazzaglia, F.J., Evenson, E.B., Germanoski, D., Alley, R., Lawson, D. & Denner, J. (2003) Bedload component of glacially discharged sediment: Insights from the Matanuska Glacier, Alaska. *Geology*, 31, 7–10.

Perolo, P., Bakker, M., Gabbud, C., Moradi, G., Rennie, C. & Lane, S.N. (2019) Subglacial sediment production and snout marginal ice uplift during the late ablation season of a temperate valley glacier. *Earth Surface Processes and Landforms*, 44, 1117–1136.

Porter, P.R., Smart, M.J. & Irvine-Fynn, T.D.L. (2019) Glacial sediment stores and their reworking. In: Heckmann, T. & Morche, D. (Eds.) *Geomorphology of Proglacial Systems: Landform and Sediment Dynamics in Recently Deglaciated Alpine Landscapes*. Berlin: Springer 10.1007/978-3-319-94184-4_10.

Raymond, C.F., Benedict, R.J., Harrison, W.D., Echelmeyer, K.A. & Sturn, M. (1995) Hydrological discharges and motion of Fels and Black Rapids Glaciers, Alaska, USA: implications for the structure of their drainage systems. *Journal of Glaciology*, 41, 290–304.

Richards, K. (1982) *Rivers: Form and Process in Alluvial Channels*. London: Methuen.

Richards, K., Sharp, M., Arnold, N., Gurnell, A., Clark, M., Tranter, M., Nienow, P., Brown, G., Willis, I. & Lawson, W. (1996) An integrated approach to modelling hydrology and water quality in glacierized catchments. *Hydrological Processes*, 10, 479–508. https://doi.org/10.1002/(SICI)1099-1085(199604)10:4<479::AID-HYP406>3.0.CO;2-D

Rickenmann, D. (2001) Comparison of bed load transport in torrents and gravel bed streams. *Water Resources Research*, 37, 3295–3305.

Riihimaki, C.A., MacGregor, K.R., Anderson, R.S., Anderson, S.P. & Loso, M. G. (2005) Sediment evacuation and glacial erosion rates at a small alpine glacier. *Journal of Geophysical Research*, 110, F03003. https://doi.org/10.1029/2004JF000189

Röthlisberger, H. (1972) Water pressure in intra- and subglacial channels. *Journal of Glaciology*, 2, 177–203.

Röthlisberger, H. & Lang, H. (1987) Glacial hydrology. In: Gurnell, A.M. & Clark, M.J. (Eds.) *Glacio-fluvial Sediment Transfer: An Alpine Perspective*. Chichester: Wiley, pp. 207–284.

Sharp, M.J. (1991). Hydrological inferences from meltwater quality data: the unfulfilled potential. In: *Proceedings of the British Hydrological Society Third National Hydrological Symposium*, 16–18 September 1991, 5.1–5.8.

Shreve, R. (1972) Movement of water in glaciers. *Journal of Glaciology*, 11(62), 205–214. https://doi.org/10.3189/S002214300002219X

Spedding, N. & Evans, D.J.A. (2002) Sediments and landforms at Kvíárjökull, southeast Iceland: A reappraisal of the glaciated valley land system. *Sedimentary Geology*, 149, 21–42.

Stone, D.B. & Clarke, G.K.C. (1996) In situ measurements of basal water quality and pressure as an indicator of the character of subglacial drainage systems. *Hydrological Processes*, 10, 615–628.

Stott, T., Nuttall, A.M., Eden, N., Smith, K. & Maxwell, D. (2008) Suspended sediment dynamics in the Morteratsch pro-glacial zone, Bernina Alps, Switzerland. *Geografiska Annaler A*, 90, 299–313.

Stutenbecker, L., Delunel, R., Schlunegger, F., Silva, T.A., Segvic, B., Girardclos, S., *et al.* (2018) Reduced sediment supply in a fast eroding landscape? A multi-proxy sediment budget of the upper Rhône basin, Central Alps. *Sedimentary Geology*, 375, 105–119.

Swift, D.A., Cook, S.J., Graham, D.J., Midgley, N.G., Fallick, A., Storrar, R., *et al.* (2018) Terminal zone glacial sediment transfer at a temperate overdeepened glacier system. *Quaternary Science Reviews*, 180, 111–131.

Swift, D.A., Evans, D.J.A. & Fallick, A.E. (2006) Transverse englacial debris-rich ice bands at Kvíárjökull, southeast Iceland. *Quaternary Science Reviews*, 25, 1708–1718.

Swift, D.A., Higson, W., Farinotti, D. & Bryant, R.G. (in prep.) Geomorphological evidence of the drainage system structure of Findelengletscher, Switzerland, during recent retreat. *Quaternary Science Reviews*.

Swift, D.A., Nienow, P.W. & Hoey, T.B. (2005a) Basal sediment evacuation by subglacial meltwater: Suspended sediment transport from Haut Glacier d'Arolla, Switzerland. *Earth Surface Processes and Landforms*, 307, 867–883.

Swift, D.A., Nienow, P.W., Hoey, T.B. & Mair, D.W.F. (2005b) Seasonal evolution of runoff from Haut Glacier d'Arolla, Switzerland and implications for glacial geomorphic processes. *Journal of Hydrology*, 309, 133–148.

Werder, M.A. (2016) The hydrology of subglacial overdeepenings: A new supercooling threshold formula. *Geophysical Research Letters*, 43, 2045–2052. https://doi.org/10.1002/2015GL067542

Willis, I.C., Richards, K.S. & Sharp, M.J. (1996) Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway. *Hydrological Processes*, 10, 629–648.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Swift, D.A., Tallentire, G.D., Farinotti, D., Cook, S.J., Higson, W.J. & Bryant, R.G. (2021) The hydrology of glacier-bed overdeepenings: Sediment transport mechanics, drainage system morphology, and geomorphological implications. *Earth Surface Processes and Landforms*, 1–15. Available from: https://doi.org/10.1002/esp.5173