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Deglaciation controls on sediment yield: towards capturing spatio-temporal variability

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Abstract

Accelerated glacier and ice sheet retreat and thinning in recent decades has profound consequences for catchment sediment supply with attendant repercussions for nutrient cycling, carbon fluxes and natural resource management. This paper evaluates the impacts of deglaciation on sediment yields from glaciated, deglaciating and recently-deglaciated catchments. It summarises the key characteristics of sediment yields from glaciated catchments to be that they span five orders of magnitude, vary with latitude and are greatest in high-relief and tectonically-active regions. We review the available quantitative data on sediment yields from glaciated catchments and we comment extensively on spatio-temporal variability to understand global to local and inter- and intra-catchment controls. Significant gaps in the available sediment yield data and also in our knowledge of sediment sources, pathways and sinks are identified. We constrain a set of novel approaches by which these gaps could be addressed. In particular, we suggest that the opportunities presented by emerging datasets and analytical methods enabling landcover changes, Digital Elevation Model (DEM) change detection, analyses of connectivity and analyses of sediment plumes are exciting and these approaches should become practical tools for understanding intra- and inter-catchment sediment yields from deglaciating landscapes. We showcase preliminary studies utilising these datasets and they are used to formulate hypotheses designed to stimulate further research.

Key words: sediment; glacier; water; satellite image; landcover; DEM

Highlights:

- Explanation of importance of understanding sediment yields from deglaciating catchments
- Concise summary of the key characteristics of sediment yields from glaciated catchments
- Review of spatio-temporal trends in global data compilation
- Identification of gaps in the available data and therefore our knowledge
- Suggestions for capitalising on emerging datasets and methods to address these gaps

1. Introduction and aims

Global climate change has wide-ranging and severe implications for the behaviour of earth surface systems and landscape evolution. Proglacial areas are one of the most rapidly changing natural earth surface systems due to glacier and ice sheet mass loss and permafrost degradation, all of which have become accentuated over the last three decades (IPCC, 2019) and all of which are predicted to continue for many decades (e.g. Shannon et al., 2019). There are profound consequences of this accelerating deglaciation (Hugonnet et al., 2021), which is the progressive loss of glacier ice from a catchment, for society and for the natural environment and these impacts are mostly linked to meltwater and sediment yields. Whilst great effort has been directed towards understanding spatio-temporal variability in meltwater yields with deglaciation (e.g. Huss and Hock, 2018), in contrast sediment yields are understudied, yet they are a bulk signal of geomorphological activity and therefore of landscape stability within a catchment.

Quantifying sediment yields, especially spatio-temporal variability, is not a trivial task. Sediment yields tend to be calculated solely in hydrological terms if considering export from a catchment, either from in-stream gauging of turbidity or suspended sediment concentration, or from lake or fjord sedimentary deposits. It is possible that aeolian transport might be included in these estimates although it is rarely quantified and rather assumed that contribution is unlikely to be a significant proportion of the sediment yield total in most glacial environments. Sediment yields are not a linear manifestation of climate change, because they are mediated by other earth surface system functions that are also driven by changing climate. In mountain or alpine regions, changes in slope stability due to glacial de-buttressing (e.g. Ballantyne, 2002; Porter et al., 2010; Knight and Harrison, 2017), exposure of ground previously covered by glacial ice (e.g. Midgley et al., 2018) and release of debris previously stored beneath glaciers and ice sheets (e.g. Fujita and Sakai, 2014; Love et al., 2016) all influence catchment sediment supply (Figure 1). Furthermore, in the short to medium term, it is anticipated that proglacial lakes will continue to form and expand (e.g. Carrivick and Tweed, 2013; Carrivick and Quincey, 2014; Song et al., 2017; Haritashya et al., 2018) and shifts in meltwater runoff and thus hydrological regime will occur, with annual totals increasing until ‘peak water’ is reached, after which glacier retreat is unable to maintain rising meltwater levels (Overeem and Syvitski, 2010; Huss and Hock, 2018). Such hydrological shifts are complex and are not simply characterised by variations in water availability in catchments; they include changes to the temporal pattern of ice and snow melt, timing and duration of the melt season, and sediment availability. Hydrological shifts will also occur in the Arctic, where sediment availability in low relief tundra can be determined by ice cover and permafrost distribution (Lafrenière and Lamoureux, 2019).

Hydrological adjustments will drive changes in associated geomorphological processes (e.g. Orwin et al., 2010; Delaney et al., 2017; Lane et al., 2017). Determining potential catchment geomorphological responses to changes in glacier forcing is challenging (e.g. Micheletti and Lane, 2016; Cordier et al., 2017; Lane et al., 2017), but it is vital if we are to better understand the implications of such changes. Alterations in geomorphological activity as glaciers diminish and, in many cases, as they eventually disappear (Zekollari et al., 2019) must be understood because suspended sediment yields are key indicator of environmental change (e.g. Walling, 1995; Braun et al., 2000; Hodgkins et al., 2003; Mao and Carrillo, 2015). We can expect deglaciation to force alterations to spatio-temporal patterns of erosion, transportation and deposition of sediments with implications for areas downstream (Orwin et al., 2010; Jaeger and Koppes, 2016; Micheletti and Lane, 2016; Lane et al., 2017; Delaney et al., 2018; Figure 1). Glaciers in high mountain catchments and in the Arctic have been shown to be particularly sensitive to recent climate change and locations are experiencing rapid glacial melting (e.g. Barry, 2006; Bajracharya et al., 2014; Huss and Hock, 2018; Dussaillant et al., 2019) and changes to sediment fluxes (e.g. Bendixen et al., 2017). In the Arctic generally, modelling suggests that for every 2 °C of warming a 30 % increase in the sediment flux could result and for each 20 % increase in water discharge, a 10 % increase in sediment load could follow (Gordeev, 2006).

The term ‘glaciated’ does not imply complete glacier cover, rather that a proportion of the catchment contains glacier ice. Distinct sediment transfer processes *within* glaciated catchments have been studied (Porter et al., 2018) but there is less understanding of the nature of the links *between* catchments and their variability (e.g. Korup, 2002; Harris and Murton, 2005; Knight and Harrison, 2017). Integrated studies of sediment transfer from glaciated catchments are rare (Hilger and Beylich, 2019); exceptions include Maizels (1979); Hammer and Smith (1983); Gurnell and Clark (1987); Warburton (1990, 1992); Hinderer et al., (2013); Beylich et al., (2017). Although there is a body of more recent work that recognises some of the likely impacts of modern deglaciation (e.g.

Orwin et al., 2010; Porter et al., 2010; Bendixen et al., 2017; Delaney et al., 2017; Knight and Harrison, 2017; Lane et al., 2017; Comti et al., 2019; Hogan et al., 2019), there has been little quantitative assessment of the potential impacts on sediment yields at regional or global scales. Indeed, as Hodgkins et al. (2003, p.16) so acutely observed nearly two decades ago: "Attempts to infer long-term change in sediment yields at remote glaciated catchments are typically confounded by an absence of historic time series". Walling (2006) and Hinderer (2012) have both re-stated this problem regarding understanding global patterns of sediment yield.

Most research on sediment yield from glaciated catchments is done with the purpose of understanding local geomorphology. Nonetheless, it is crucial, timely and of wide interest to better understand sediment yields from glaciated catchments, which are often associated with high rates of sediment transfer (e.g. Gabbud and Lane, 2016) for both societies' benefit and that of the natural environment because:

- Sediment can be a significant problem for water resource operations and management. Overall, control works on alpine mountain rivers enforce a poorly connected channel system. Specifically, check dams and retention basins reduce sediment connectivity and sediment yield (Cucciaro et al., 2019; Stutenbecker et al., 2019), whilst channel lining on alluvial fans promotes sediment transfer (Marchi et al., 2019).
- The design of water storage, abstraction and supply systems involving dams, reservoirs, weirs and channels needs to be sensitive to sediment fluxes (Stutenbecker et al., 2019) and there are also practical implications for the development and maintenance of hydro-electric powers schemes in glaciated catchments (e.g. Vuille et al., 2018; Bhajantri et al., 2019).
- Sediment fluxes can affect water quality because contaminants can adhere onto the sediment particles. In addition, deglaciation can reduce streamflow in some locations which in turn can lead to concentrations of pollutants (e.g. Vuille et al., 2018).
- Changes to sediment fluxes can affect recreational activities (e.g. mountaineering, trekking, ski tourism), especially in high mountain areas where rockfalls and debris flows present hazards (e.g. Watson and King, 2018)
- Sediment fluxes control terrestrial biogeochemical cycling (Figure 1) in glaciated catchments (e.g. Anderson, 2007) and nutrient cycling (e.g. Li et al., 2020). Carbon fluxes are especially

affected by sediment; suspended sediment absorbs dissolved carbon dioxide in substantial quantities (e.g. Pierre et al., 2019; Gebhardt et al., 2005), where that carbon is sourced from melting glaciers, ice caps and ice sheets (e.g. Hood et al., 2015).

- Aquatic food webs and ecological networks in proglacial environments are fundamentally affected by suspended sediment and bedload (Figure 1) as river channel stability reflects habitat stability (e.g. Döll and Zhang, 2010; Milner et al., 2017).
- Regionally and globally, sediment yields are dominated by those from glaciated catchments (Hallet et al. 1996). They control shallow marine sedimentation (e.g. Vandekerkhove et al., 2020) and hence shallow marine biogeochemistry (carbon and nutrient mineralisation) and shallow marine ecology (e.g. Rysgaard et al., 1998; Arendt et al., 2011; Figure 1). For example, Sahade et al. (2015) linked sedimentation to benthic ecology in Antarctica, and deglaciating catchments have been shown to produce very significant iron fluxes to the oceans, perhaps enough to affect oceanic productivity and thereby potentially also climate (Raiswell et al., 2006). Suspended sediment from glaciers could be a lethal threat to Antarctic krill and thus a detriment to the entire Antarctic ecosystem (Fuentes et al., 2016).

The level of importance of sediment yields in each of these listed cases of course depends on who you are and your concerns.

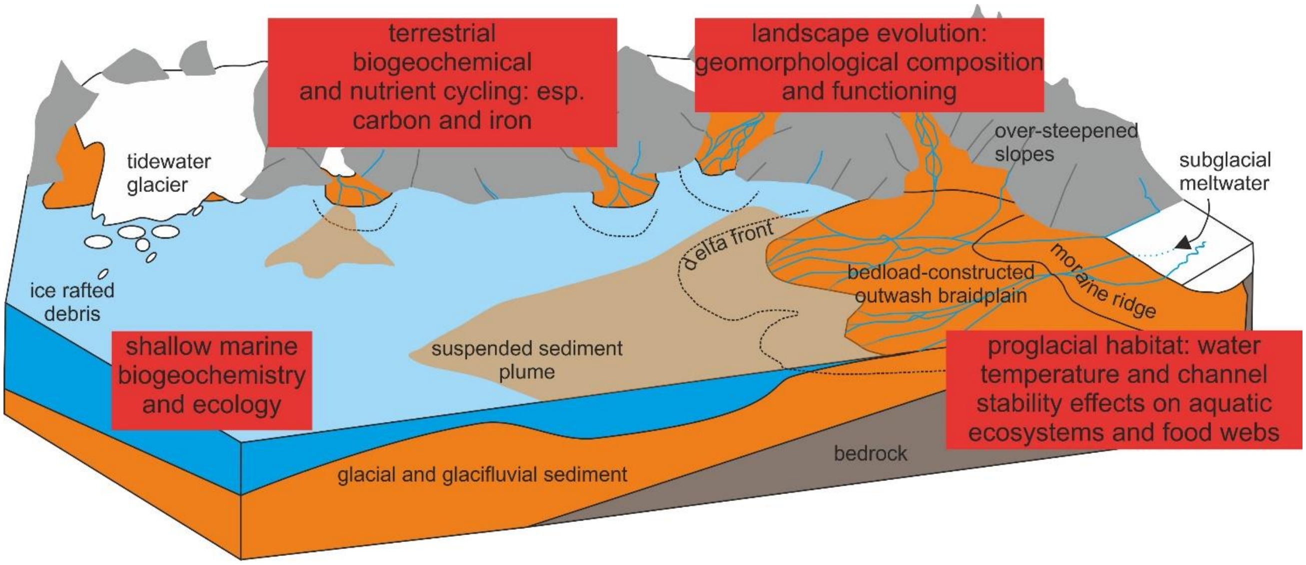

Figure 1. Illustration of the importance of sediment yields and sediment budgets of deglaciating catchments on local and regional earth surface system processes.

Overall, ongoing climate change raises three clear sets of questions about sediment fluxes from deglaciating catchments. Firstly, what information exists on sediment yields from such catchments at local, regional and global levels? How much reliable and consistent data is there? Are there enough sites to enable specific patterns to be identified? If so, what are the temporal patterns at particular sites? Secondly, are there significant temporal trends in sediment yields from these data? Are sediment fluxes (and by inference erosion rates) generally parallel to glacier mass loss or to terminus retreat rates? Are sediment yields from deglaciating catchments increasing, decreasing or is there no pattern? What are the recurrence intervals of magnitude of sediment yield for different catchments? And thirdly and finally, to what extent is it possible to quantify spatio-temporal patterns of future sediment yields? This paper notes the conceptualisation of temporal patterns of sediment yields over glacial cycles recently proposed by Antoniazza and Lane (2021) so focuses on spatio-temporal issues and spatial analysis. It addresses each of these three sets of questions to evaluate the impacts of deglaciation on sediment yields. It is motivated to do so that future sediment yields might be better estimated.

The aims of this paper are therefore to; (i) deliver a concise summary of the key characteristics of sediment yields from glaciated catchments, (ii) review the available information on sediment yields from such catchments and evaluate the spatio-temporal trends in this data, (iii) use that review to identify significant gaps in the available data and therefore our knowledge, and (iv) present some novel approaches by which these gaps could begin to be addressed. This paper is therefore structured into three sections; (i) controls (chapters 1-4), (ii) sediment yield estimates (chapters 5-7), and (iii) analyses related to sediment transfer (chapters 8-13).

2. Key characteristics of sediment yields from glaciated catchments with time

The geological record of shallow marine, fjord and lake sediments best represents sedimentation rates and crucially those are usually at a point where a core sample is abstracted; an aggregate effect of the entire upstream catchment. Rarely are calculations made for specific sediment yield. Where those calculations include a normalisation for catchment area and rock density, sediment yields have apparently increased during the early Holocene during deglaciation from the Last Glacial Maximum (LGM) and declined during the mid Holocene, as summarised in the conceptual model recently proposed from a literature review by Antoniazza and Lane (2021). In a late-Pleistocene/Holocene context it is often unknown how eustatic and isostatic sea-level changes have affected catchment area, nor how changes in amount and magnitude of precipitation affect sedimentation records.

Sediment yields from deglaciating catchments might have increased in the last few thousand years (Fig. 2). However, whether that increase could perhaps be explained by deglaciation since the Little Ice Age is a matter of debate. For example, Bogen (2008) reported a five-fold increase in sedimentation rate between 1695 and 1995 for Lake Storglomvatn in Norway, whereas as Desloges (1994) reported that glacier terminus retreat from Little Ice Age positions in western Canada had exposed accommodation space in the landscape for sediment to become trapped and yields halved. Decadal-scale measurements have attributed very high sediment yields to rapid deglaciation (e.g. Koppes and Hallet, 2006; Meigs et al., 2006). The few long-term records of specific sediment yield therefore offer an insight of what can be expected on a global scale and over millennial timescales with deglaciation, but on centennial timescales local factors such as geology and topography will determine sediment availability and sediment pathways and hence sediment yield trajectories. Annual sediment yields are highly variable and reflect stochastic variability and weather such as high-magnitude precipitation events rather than deglaciation.

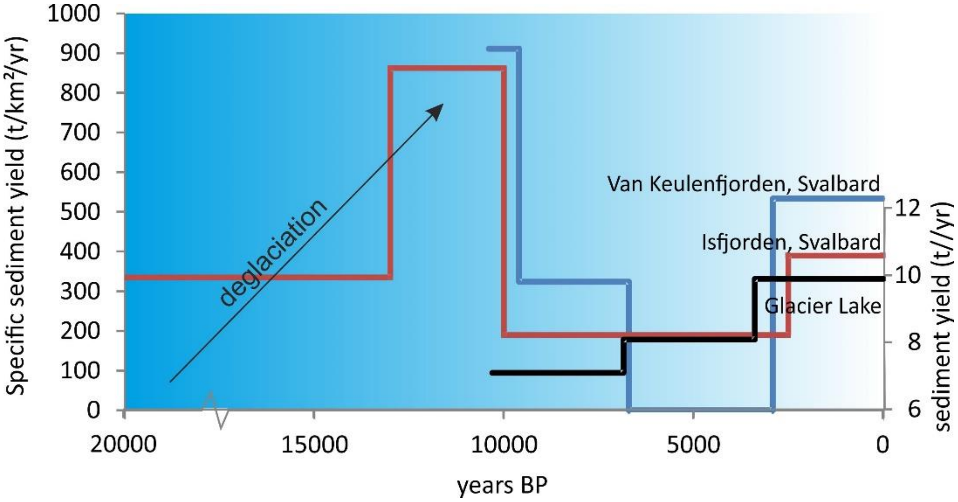

Figure 2. Holocene record of sediment yield where that has been determined for discrete time periods. Data for van Keulenfjorden from Elverhøi et al. (1998), Isfjorden from Elverhøi et al. (1995) and fromGlacier Lake from Evans (1997).

Following accelerated glacier retreat in recent decades compared to the centennial rate since the Little Ice Age (e.g. Davies and Glasser, 2012; Stokes et al., 2018; IPCC, 2019; Carrivick et al., 2019) sediment yields from mountain catchments have increased (e.g., Costa et al., 2018; Micheletti et al., 2015). But from where in catchments is that sediment derived and how will those contributions change in the future? Subglacial bedrock erosion is the dominant source of sediment from glaciers and is chiefly controlled by the capacity of subglacial meltwater to deliver sediment to glacier margins (e.g. Collins, 1989; Overeem et al., 2017). Bedrock erosion will probably decrease in the next decades to centuries as a response to reduced glacier sliding (e.g. Dehecq et al., 2019). In contrast, increases in sediment transport may occur over seasonal and decadal timescales as glacier meltwater production increases (e.g. Delaney et al., 2018). The legacy of glaciation is also important; disappearance of some glaciers will be relatively swift (Zekollari et al., 2019), but the recent and/or former presence of glacier ice will continue to mediate catchment processes (Orwin et al., 2010; Jaeger and Koppes, 2016). A review of fluvial sediment fluxes by Holmes et al. (2002) found no clear trends over decades of data from the largest eight rivers in the Arctic. Given the confounding signals in at-a-point records and the complexity and interacting nature of these catchment processes, it is crucial to understand sediment sources, pathways and sinks, which means recourse to spatially-distributed analyses.

3. Deciphering spatial controls on sediment yield

Catchment processes and especially sediment sources, pathways and sinks have traditionally been understood best via sediment budget studies. Sediment budget studies quantify storages (volumes) and pathways (location and magnitude of fluxes) of sediment *within* a catchment (e.g. Warburton, 1990, 1992; Jordan and Slaymaker, 1991; Reid and Dunne, 1996; Slaymaker et al., 2003; Bonneau et al., 2017). Characteristics of sediment transfer within glaciated catchments that make them distinct from other environments are primarily those that are temperature dependent. They are thus highly susceptible to climate change. These characteristics include:

- Phase changes of water resulting in sediment mobilisation, seasonal transfer of sediment, mass movements, direct transport processes related to frozen water such as slush flows and avalanches, and ground ice dynamics and associated sediment mass transfer (Tweed et al., 2007;

Hilger and Beylich, 2019). These processes influence the temporal and spatial patterns of erosion, transportation and deposition of sediments.

- Processes of weathering, fluvial and aeolian activity and slope process regimes in glaciated catchments are modified by changes in temperature (Hewitt, 2002; Lane et al., 2017). Freeze-thaw processes weaken material for erosion and the areal extent of permafrost that now experiences ground temperature oscillations above and below 0°C is increasing (e.g. Mollaret et al., 2019).
- The presence of water in glaciated and deglaciating environments is as important as the severity of cold in determining sediment transfer rates through the generation of excess moisture during melting, diurnally, seasonally and over longer timescales (e.g. Matsuoka and Sakai, 1999; Hasholt et al., 2005; Slaymaker, 2008; Orwin et al., 2010).

Sediment fluxes in most deglaciating catchments can be conceptualised as comprising longitudinal fluxes from glaciers, and lateral fluxes from hillslopes (Caine and Swanson, 1989; Buoncristiani and Campy, 2001; Caine, 2004; Carrivick et al., 2013; Carrivick and Heckman, 2007). Glaciers produce prodigious amounts of sediment (Hallet et al., 1996), the calibre of which ranges in size from huge boulders to fine sands, silts and clays (e.g. Hallet et al., 1996; Benn and Evans, 2010). However, proglacial parts of catchments remobilise vast amounts of sediment, and correspondingly specific sediment yield is far greater for distal or ‘glacier-fed’ rivers than proximal ‘glacier outlets’ (Fig. 3). This suggests that, in glaciated regions, sediment yield will increase with catchment area, as reported by Church et al. (1989) from 63 river gauging records in western Canada. This recognition of the importance of proglacial areas - hillslopes, braidplains, river channel banks and beds - in their contribution to overall specific sediment yield is especially important given the expansion of proglacial areas since the Little Ice Age (Carrivick and Heckmann, 2017; Carrivick et al., 2018, 2019).

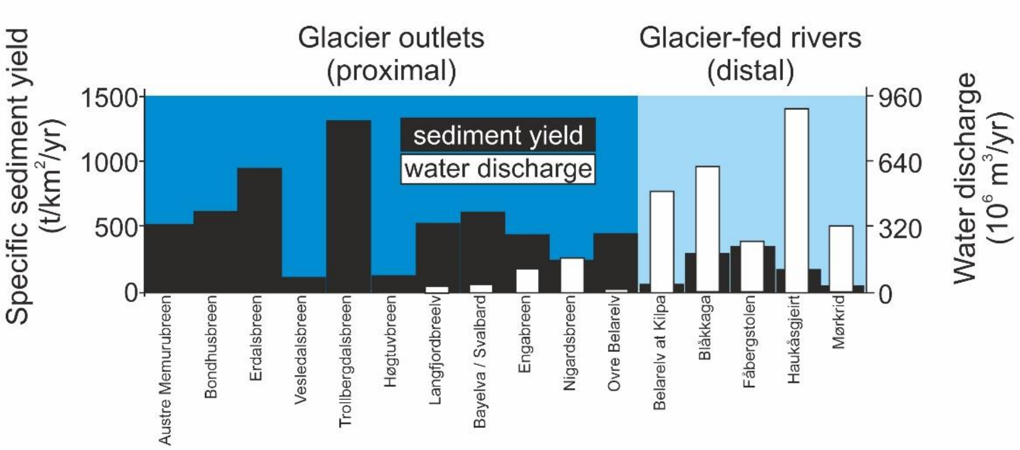

Figure 3. Water discharge and specific sediment yield from in-stream monitoring gauges located proximal and distal to glacier termini in glaciated catchments of Norway. This figure is an adaptation of Bogen's (2008) figure 2 and is of mean sediment yield over typically 2 to 8 years duration. Some of these glaciers were (probably) advancing during the study period if comparison is made with the records and comments of Chinn et al. (2005).

Regional controls such as tectonic uplift, lithology, and glacier properties such as sliding velocity and thermal regime have all been shown to influence sediment yields from glaciated catchments (e.g. Hallet et al., 1996; Koppes and Montgomery, 2009; Jaeger and Koppes, 2016). Therefore on a regional scale, contributions to total specific sediment yield by glacial ice, hillslopes and valley floor sediments (braidplains and river channel banks and beds) and therefore variability in sediment yield *between* glaciated catchments, is controlled by a range of interacting variables including as topographic relief, lithology, hydrology, precipitation, air and ground temperature, which together determine sediment entrainment and transportation processes (e.g. Evans, 1998; Owen et al., 2003; Orwin et al., 2010; Jaeger and Koppes, 2016).

In more detail, and in what can be considered as the glacial realm of a catchment sediment system (Fig. 4), glaciers and ice sheets transport sediment within, beneath or on ice and by meltwater flowing through englacial, subglacial or supraglacial conduits, respectively. Supraglacial debris from valley sides feeds into moraines, which are often reworked with meltwater to produce kames, and constitute both temporary stores and sources of sediment within glaciated catchments (e.g. Knight et al., 2007; Fig. 4). Ablation-fed meltwater releases englacial and subglacial sediment into the proglacial environment, where it may be transported out of the catchment by fluvioglacial processes or remain in storage until it is transported by subaerial processes. The subglacial zone can exert a significant influence on sediment supply, depending on the amounts of debris entrained by glaciers and ice sheets (e.g. Knight et al. 2002; Delaney et al., 2017), the presence or absence of a deforming bed (e.g. Hunter et al., 1996; Alley et al., 1997) and the sediment transport capacity of the subglacial hydraulic system (e.g. Love et al., 2016).

Glaciers and ice sheet outlet glaciers often produce over-steepened topographic relief due to glacier erosion. When the ice retreats and the areas formerly occupied by ice become part of the proglacial zone, the buttressing effects of the ice are no longer present. Paraglacial slope readjustment during deglaciation results both from these unstable hillslopes and from the voluminous readily erodible sediment (e.g. Porter et al., 2010; Knight and Harrison, 2017; Mancini and Lane, 2020). The manifestation of this paraglacial time period and of these paraglacial processes is a widespread and intense reworking of sediments throughout the whole sediment cascade (e.g. Orwin and Smart, 2004; Barnard et al., 2006; Knight and Harrison, 2017). In terms of *geomorphological composition*, the hillslope realm of a catchment sediment system (Fig. 4) is therefore dominated by mass movements including falls, slides, slumps and flows that produce a wide range of erosional scars and sedimentary deposits such as free faces or cliffs, gullies, scree, debris cones and debris fans, and alluvial fans (Fig. 4) as slope adjustments occur and as surface and sub-surface drainage pathways evolve rapidly. Landforms in deglaciating catchments tend to be transient, manifestations of dis-equilibrium both on short-term (Carrivick and Heckmann, 2017) and much longer time scales (Hoffman, 2015). There can be great inter- and intra-variability in geomorphological functioning, i.e. sediment fluxes even in adjacent catchments with similar glacier morphology, geology and climate (Carrivick and Rushmer, 2009).

In terms of the *geomorphological functioning* of these exceptionally dynamic proglacial systems, glacier retreat and thinning generally increases connectivity between hillslopes and valley floors (Cavalli et al., 2013). However, disconnections can occur as moraine ridges interrupt sediment pathways, as diffusive drainage develops on alluvial fans (Mancini and Lane, 2020) and as overdeepenings such as cirques and troughs become exposed (Cavalli et al., 2013). Increased connection between hillslope gullies, stream channels and recently exposed formerly subglacial sediments is also to be expected (Lane et al., 2017) and increased connection produces greater sediment yields (Schlunegger et al., 2009). Connectivity changes and the predominance of debris flows on alpine hillsides, for example (Cavalli et al., 2013; Schopper et al., 2019), explain how an increasing availability of sediment, due to deglaciation, can become mobilised, transported, and exported from a catchment from glacial, hillslope and valley floor sources. It is likely that ongoing and future climate warming and consequent glacier recession and permafrost thawing will both release additional hillslope sediment into catchment proglacial systems as well as that mobilised by glacial meltwater across a valley floor (Carrivick et al., 2018; 2019).

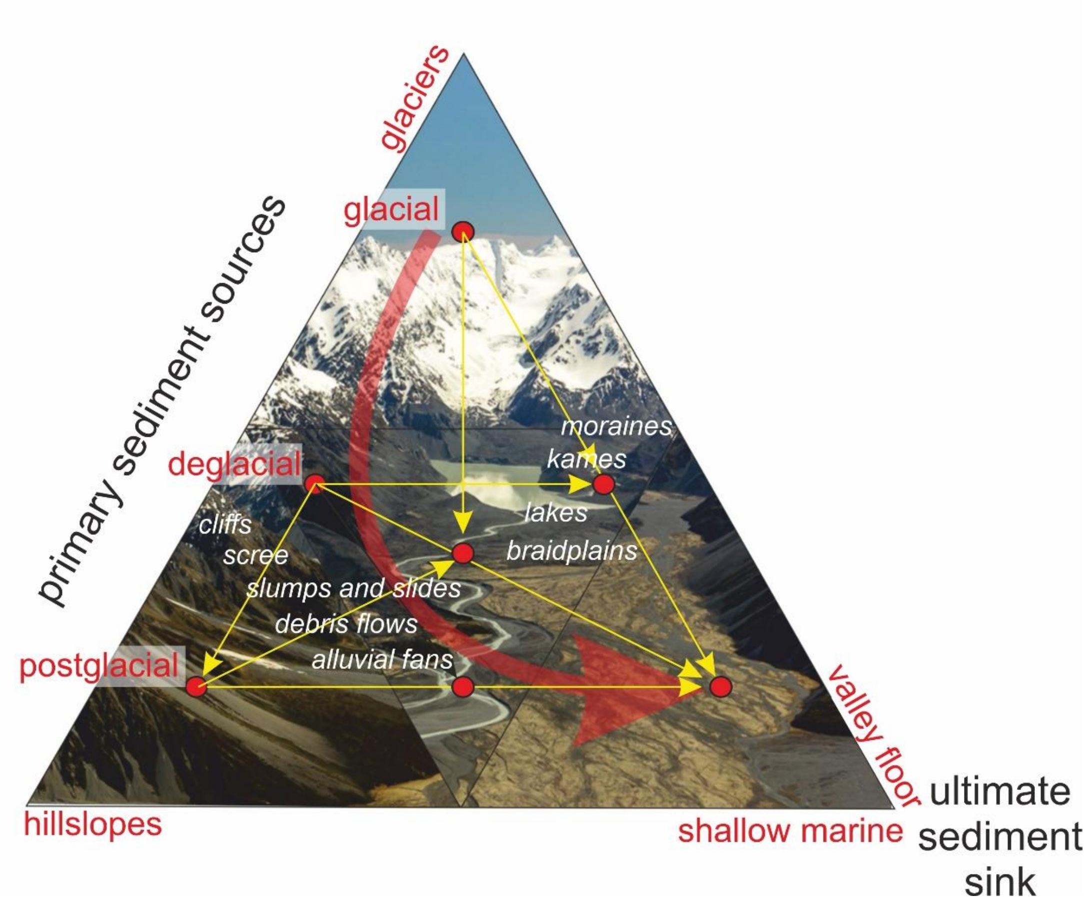

Figure 4. Visualisation of major sediment sources, pathways and sinks within glaciated catchments. Major sediment realms are represented by triangles; a glacial, hillslope and valley floor realm, between which sits a lakes and braidplains realm. Sources and storages of sediment are in red text. Major landforms, which can be viewed as intermediary and transient sediment storages within each realm, are in white text. Black arrows denote major fluxes or pathways of sediment, and the large red arrow indicates the general trajectory of changes in contributions to total sediment yield with deglaciation, i.e. away from glacier-dominated towards hillslope-dominated.

On valley floors, river channel erosion, storage and consequent valley floor aggradation *within* deglaciating catchments (Fig. 4) varies with changing hydrological regimes (e.g. Hodson et al., 1998; Cockburn and Lamoureux, 2008). Within proglacial fluvial systems, suspended sediment is generally supply-controlled and bedload usually hydraulically-controlled (Comiti et al., 2019; Mao et al., 2019); therefore, it is accepted that suspended sediment fluxes are more responsive to climate-driven changes (Hodgkins et al., 2003). Partitioning between bedload and suspended load is due to clast size and fluvial abrasion, whereas the overall down-valley fining of sediment and thus reduction in sediment flux is attributable to weathering (Sklar et al., 2020). There are significant variations in sediment fluxes on diurnal and seasonal timescales because of the variations in the processes on which sediment transport depends (e.g. Bogen, 1980; Hodgkins et al., 2003; Middleton et al., 2019). Specifically, Bakker et al. (2019) have shown from high-resolution elevation changes that net erosion or deposition - and hence sediment flux - depends on sediment supply, but in a non-liner relationship due to frequent infilling and excavation of minor topographic depressions with repeated flow discharges capable of bedload transport.

4. Episodic events

Sediment from glaciated catchments is often transported in high-magnitude, episodic events such as glacier lake outburst floods 'GLOFs', heavy rainfall, debris flows, rapid and intense snow and ice melt (Marren, 2005). For example, mass movements were invoked to explain extremely high suspended sediment concentrations in Arctic Canada after snowmelt and warm air temperatures by Lewis et al. (2000). Lenzi et al., (2003) reported that 27 % of the sediment transported within a 16-year period from an alpine catchment was during a single flash flood. In the high Arctic, fjord sediments might be dominated by those produced during outburst floods (Willems et al., 2011). Data from the Watson River at Kangerlussuaq in west Greenland has shown that whilst a lot of sediment is retained on sandar, or gravel outwash braid plains, nevertheless sediment and solute fluxes are high and dominated by outburst flood events (Hasholt et al., 2013; Mikkelsen et al., 2013; Yde et al., 2014). However, estimation of the contribution of such episodic debris pulses to long-term sediment fluxes is problematic because of limited data on their recurrence and the lack of knowledge of the extent of upstream sediment input (e.g. Korup et al., 2004; Heckmann et al, 2016).

The formation, growth and drainage of increasing numbers of proglacial lakes is predicted to accompany climate change (e.g. Evans and Clague, 1994; Richardson and Reynolds, 2000; Chikita and Yamada, 2005; Carrivick and Tweed, 2016; Song et al., 2017). The evolution of proglacial lakes has enormous implications for sediment fluxes. Proglacial lakes can disconnect the downstream movement of glacially derived sediment (Carrivick and Tweed, 2013; Bogen et al., 2015; Lane et al., 2017) and act as sediment sinks in deglaciating catchments. Such sediment sinks may effectively offset the effects of increased connectivity of hillslopes and tributary streams with the proglacial zone.

In mountainous terrain, some regulation of catchment sediment flux is also controlled by landsliding which can generate and retain large volumes of sediment (e.g. Korup, 2005; Cossart et al., 2013; Clapuyt et al., 2019). Research in the Himalayas, Tien Shan and New Zealand has demonstrated that dams formed by landslide and moraine material have marked impacts on sediment fluxes following failure (e.g. Cenderelli and Wohl, 2003; Korup et al., 2006; Fan et al., 2020).

The recent rock slides into Elliot Creek, western Canada, and in the Chamoli region of Uttarakhand state, India have both highlighted the immense and widespread disturbance to fluvial and sediment systems that can be caused instantaneously and with virtually no prior warning. Both events have ongoing studies by international multi-disciplinary scientific teams, but the crude dimensions of the events are clear. The Elliot Creek landslide of December 2020 caused a c. 100m high tsunami wave in a proglacial lake. That wave overtopped the moraine dam of the lake and eroded alpine valley floor sediments up to > 20m depth (Fig. 5) and subsequently also shallow fjord sediments. The February 2021 landslide in the Chamoli region of India included detachment of part of a small hanging glacier and the landslide transformed into a debris flow. That flow had a hyperconcentrated rheology by the time it reached hydropower installations and settlements many tens of kilometres down valley, tragically killing tens of people and wreaking destruction on livelihoods and infrastructure. The sediment plume from the hyperconcentrated flow was detectable > 500 km down valley as it mixed with ambient river water which, given the winter season, was relatively clear. In both cases the voluminous quantities and widespread availability of sediment along the river valleys heightened the downstream impact of the events.

Episodic events are disturbance events, and so temporary storage of sediment between events and system response are therefore important elements of sediment flux studies. Rates of erosion, and hence sediment supply, vary markedly; research suggests that catchments in unstable tectonic settings have denudation rates that are an order of magnitude higher than those in more stable tectonic settings (e.g. Ahnert, 1970; Hallet et al., 1996; Koppes and Montgomery, 2009). Typifying the sediment budgets of even small catchments is difficult given this spatio-temporal variability and such difficulties increase when attempting to extrapolate results temporally from year to year and spatially to other areas in similar environments.

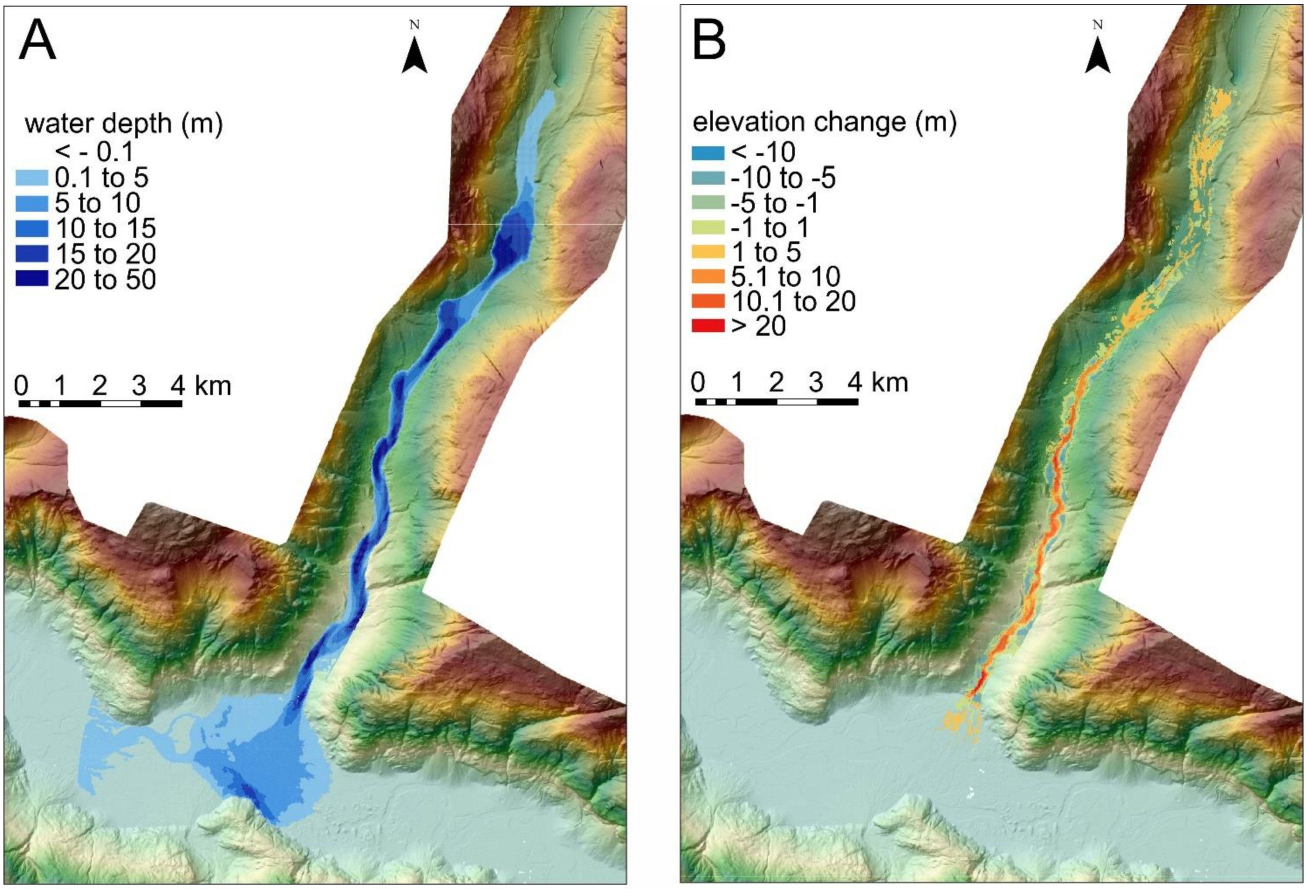

Figure 5. Numerical model simulation of Elliot Creek outburst flood caused by a landslide into a glacial lake generating a tsunami wave ~ 100 m high. The simulation suggests water depths up to 50 m (A) and changes in topography of up to 20 m (B), both after just 12 minutes.

5. Evaluation of existing datasets of specific sediment yield from glaciated catchments

Shallow marine sediments can provide millennial scale sediment yields (Fig. 1). Lake sediments tend to be more conducive to gaining centennial sediment yields (e.g. Hicks et al., 1990; Desloges, 1994; Bogen, 1996; Hasholt et al., 2000). Focusing on sediment yields in recent decades, as a response to recent climate change, substantial amounts of sediment exported from deglaciating catchments are most usually achieved by fluvial transport (Gurnell and Clark 1987; Hallet et al., 1996). Therefore, recent sediment yields tend to be derived from *in situ* direct measurements made with gauges within proglacial streams and rivers. Direct measurements are usually limited to quantification of turbidity as a proxy for suspended sediment and they are expressed as export rates because (i) there are often insurmountable practical and technological difficulties in attempting to obtain direct suspended sediment samples (i.e. via bottling and filtering) and (ii) reliable measurements of bedload transport are exceptionally difficult to obtain due to the necessity of repeated visits to mitigate highly variable flows and the instability of gravel-bedded river channels, respectively.

Mindful of these problems with direct monitoring and motivated by our questions posed in the introduction to this paper, we herein created our own database of sediment yields from glaciated catchments. We sought out published literature and regional or national reports to identify sediment yield data (Supplementary file) and we were guided by a range of research experts to whom we are grateful for assistance.

Generally, available data is of three main types: i) published studies of catchment-based monitoring and/or modelling of sediment yields generally over short time periods, but with some sparse examples of longer time series data (e.g. Love et al., 2016); ii) syntheses or reviews of sediment yield data on a regional scale (e.g. Hinderer et al., 2013) and iii) records of suspended sediment yields based on catchment monitoring by appropriate organisations (e.g. USGS). We emphasise that our study is based on records that we were able to identify and access and for which the necessary data are available to quantitatively consider our questions.

In-stream (direct) monitoring of sediment fluxes tends to be conducted through national programs or as part of research projects. Whilst both types of data collection have advantages, neither of these proved to be ideal for our purpose. National campaigns can be funded sufficiently well to support a large number of gauges over a wide area, but raw data is often impossible to obtain, yet is necessary to understand the reports; for example what rock density was used to derive a mass of sediment and was this spatially variable across a catchment? Research projects cannot usually fund more than a few years in-stream data collection, and so are usually spatially sparse and temporally short-lived and often intermittent, e.g. for the ablation season only, thereby precluding consistent time-series data from the same catchment. Research projects also tend to publish data syntheses, either graphically or as bulk 'headline quantities', which suffer from the same limitations as national campaigns in not being transparent in all calculations. Perhaps worst of all, both national campaign reports and research projects are frustratingly inconsistent in what metric they report. We have noted reports of sediment yield (t/yr), mass flux (t/yr), specific sediment yield (t/yr/km^2), annual sediment flux (m^3/yr), effective erosion rate (mm/yr) and denudation rate (mm/yr). The suitability of terminology and units in all of these metrics can be debated, but at the very least we contend that they should not be used inter-changeably and that they need standardising. Regarding the latter point, specific sediment yield is the only metric that is normalised for both rock density and catchment area and hence is our preferred metric to permit spatio-temporal comparisons.

For countries with significant numbers and areas of glaciated catchments, fluvial sediment flux monitoring programmes exist to the best of our knowledge at a national level in Argentina (http://bdhi.hidricosargentina.gob.ar/), Alaska (via the USGS at: https://cida.usgs.gov/sediment/), and Chile (http://www.dga.cl/Paginas/estaciones.aspx). Iceland monitors suspended sediment via the Icelandic Meteorological Office and Norway monitor suspended sediment via the Norwegian Energy and Water Directorate (NVE), but these data are not immediately available from websites. In all these countries, the fluvial sediment flux monitoring spans many morpho-climatic zones, not just glaciated catchments. Where glaciated catchments are included, records often (i) relate to water stage only as the catchment is being monitored for flood risk; and (ii) are derived many kilometres downstream from the glacier. This latter issue means that the glacial contribution to catchment runoff is often very small; for example, only one of 28 sites that we identified in Austria is located in glaciated headwaters, and only three that we identified in Alaska are glacially-influenced at all. Additionally, some national monitoring programs have only been recently established or have only recently been made coherent (e.g. Austria: Lalk et al., 2015, 2019). Others have been discontinued: the impressive fluvial sediment monitoring program across New Zealand encompassing > 200 gauges

(NIWA, 2020) was unfortunately stopped in the mid-1990s (Hicks, pers comm). In Iceland, suspended sediment sampling has formed part of river monitoring for at least 60 years, with the mainstay of the sampling effort concentrated in rivers with hydroelectric power potential or those in which jökulhlaups occur (Harðardóttir and Snorasson, 2003). The dearth of quantification of sediment yields from Antarctica were partly addressed by Kavan et al. (2017) who reported relatively high yields for nearly-deglaciated catchments.

A prevalent problem with reporting of sediment yields concerns conversion between (i) volume estimates from lake sedimentary architecture (including varves), fjord sediment thickness (whether derived by seismic or radar survey) or from DEMs (Digital Elevation Models) of difference to derive effective erosion rate in mm a^{-1} and (ii) mass estimates from in-stream gauging of turbidity or suspended sediment concentration and water discharge to derive specific sediment yield in t km^{-2} a^{-1}. Only one of these (volume or mass) will be measured in the field because it depends on the method used, but the other figure is often reported alongside. This suggests that a conversion has been performed, using an estimate of mean sediment or rock density, which is often vaguely reported at best. Suspended sediment loads in glacial rivers are often used to calculate erosion rates from glaciated catchments (e.g. Bogen, 1996), but such rates must be minima given that within-catchment storage is seldom accounted for. Numerous studies omit to point out that such calculations assume 100% efflux of material from the catchment with no sediment storage; that is, an ‘effective delivery ratio’ = 1.

Nonetheless, there are several good compilations of data published in research literature. Hallet et al. (1996) collated and discussed sediment yields derived from published literature, focused on ~60 sites chiefly in Norway and Alaska. This was, at the time, an advance on earlier work by Hicks et al., (1990) and Gurnell and Clark (1987) and included data from larger and more active valley glacier catchments. Hallet et al. (1996) did not include South American catchments, and the Himalaya and the Alps were both poorly represented as were Canada, Greenland, Iceland and New Zealand. Their data was further limited in that only ~ 10 catchments had records > 10 years in duration, but nonetheless Hallet et al., (1996) concluded that i) sediment yields from extensively glaciated catchments form a distinct population when compared to non-glaciated catchments and ii) sediment yields tend to increase with basin size, and with tectonic uplift rates, the latter of which might be viewed as driving both energy within a system for mass movements, but also as aiding sediment supply.

Unfortunately, newer published data for the same sites identified in Hallet et al., (1996) were almost impossible to trace. We did secure new data for three sites in Alaska (Muir inlet, Upper Taan fjord and Tyndall Glacier), two in Svalbard (Kongsvegen, Finsterwalderbreen) and three in Norway (Nigardsbreen, Engabreen, Tunsbergdalsbreen). Hinderer et al., (2013) present a comprehensive analysis of sediment yields from the European Alps in which some of the data cross-correlate with that presented in Hallet et al., (1996).

Due to the problems of repeating or updating the datasets reported by Hallet et al. (1996), we looked for datasets from other sites. We were able to identify > 100 different additional sites that now have specific sediment yield data published and these are depicted in Figure 5. The citations for the specific sediment yields reported in Figure 6 are listed in our (Supplementary file), which also includes complementary, but not direct comparable, published data such as erosion rates, denudation rates and mass fluxes. Forty five of the specific sediment yield records depicted in Figure 6 are derived from records > 10 years in duration, which is important to reduce short-term stochastic variability (Ballantyne and Harris, 1994; Walling, 1995) and so it is perhaps interesting that we found no relationship between survey duration and specific sediment yield within this data, either globally or when split by sub-region (Fig. 7A). We interpret this lack of a relationship to be due to local factors such as lithology, because at individual sites sediment yield estimates derived from decadal records are lower than estimates derived from annual records; sites with sediment yield estimated over multiple time periods include Laguna San Rafael, Gornergletsher/Gornera, Iceberg Lake, Haast.

In the following sections of this paper, we report the key findings from our critical review and analysis of sediment yield datasets from contemporary glaciated catchments. The outcomes of this review subsequently guide data analysis for locations where reliable and consistent time series data of > 10 years duration is available. That data analysis identifies significant gaps in our understanding and leads to the second part of this study, which proposes a series of hypotheses together with innovative applications of emerging datasets and analytical methods that might be used to (i) test those hypotheses and thereby (ii) further understanding of sediment yields from presently deglaciating catchments, most importantly in order to help estimate future changes.

6. Key findings from direct measurements of sediment yields

Our compilation of contemporary mean specific sediment yields from deglaciating catchments from records 10 years or greater in duration indicates a global range that spans 5 orders of magnitude (Fig. 6). There is a global pattern of lower specific sediment yields from glaciated catchments at higher latitudes, as reported by Fernandez et al. (2017) and Starke et al. (2020) for example, and of higher specific sediment yields from high-relief and especially from tectonically active catchments, as reported by Hallet et al. (1996) (Fig. 6). Only New Zealand catchments apparently yield >10,000 t $km^{-2}a^{-1}$. Compared to the compilation by Hallet et al. (1996), Figure 6 (and the additional records in our Supplementary file) illustrates many more sites and greater coverage, notably for South America and the Himalaya and reports in the units of specific sediment yield, i.e. normalised for catchment area and catchment rock density. We find a (statistically insignificant) relationship of declining specific sediment yield with longer survey durations for most world sub-regions (Fig. 7A).

Catchment areas upstream of the gauges from which these specific sediment yields are calculated vary considerably around the World, from up to 100 km^2 in Scandinavia, Svalbard and the Antarctic Peninsula, to 1000 km^2 in some examples in the European Alps, to 10,000 km^2 for some examples from New Zealand and up to 100,000 km^2 in examples from the Himalaya. This spatial scale issue is important for realising relaxation times and controls on erosion rates (Church and Slaymaker, 1989). It means non-linear relationships such as that Slaymaker (2018) identified in British Columbia, Canada, where the relationship of sediment yield with catchment area is negatively correlated in large basins (>30,000 km^2) and positively correlated in smaller (< 30,000 km^2) basins. In contrast, across the European Alps, Hinderer et al., (2013) found a weakly negative relationship between specific sediment yield and catchment area. In this study, we found no relationship, either globally or by major world sub-region (Fig. 7B) and outcome that agrees with the findings of Gurnell et al. (1996) for glaciated catchments.

Very few studies reporting specific sediment yields include consideration of the glacier size and since most of the world's glaciers are < 1 km^2 there is probably a bias in these sediment yield compilation towards larger glaciers. The percentage of the catchment that is covered by glacial ice is also rarely reported and unfortunately that means recourse to evaluating responses of sediment yields to changes in glacier cover by substituting space for time (i.e. comparing sediment yields from climatically and geologically similar catchments, but with different percentage glacier cover). Such comparisons could be achieved with considerable use of (retrospective) spatial analysis if the location of the gauges is known and historical satellite imagery can be obtained. A notable study for the explicit consideration of glacial cover is that by Hinderer et al. (2013) who showed that despite wide scatter in the relationship, sediment yields of glaciated basins with > 50% glacier coverage are nearly one order of magnitude higher than non-glaciated basins or basins with < 10% glacier coverage. In one of very few studies directly on ice sheet margins, a study of a 12,600 km^2 catchment in west Greenland with near total (95 %) glacier cover by Hasholt et al. (2018) quantified the mean specific sediment yield over an 11 year period to be 13,900 t/yr/km^2. They attributed this very high yield to subglacial meltwater in the temperate fringes of the Greenland ice sheet, but they also noted the significant role of the proglacial area in supplying sediment during floods.

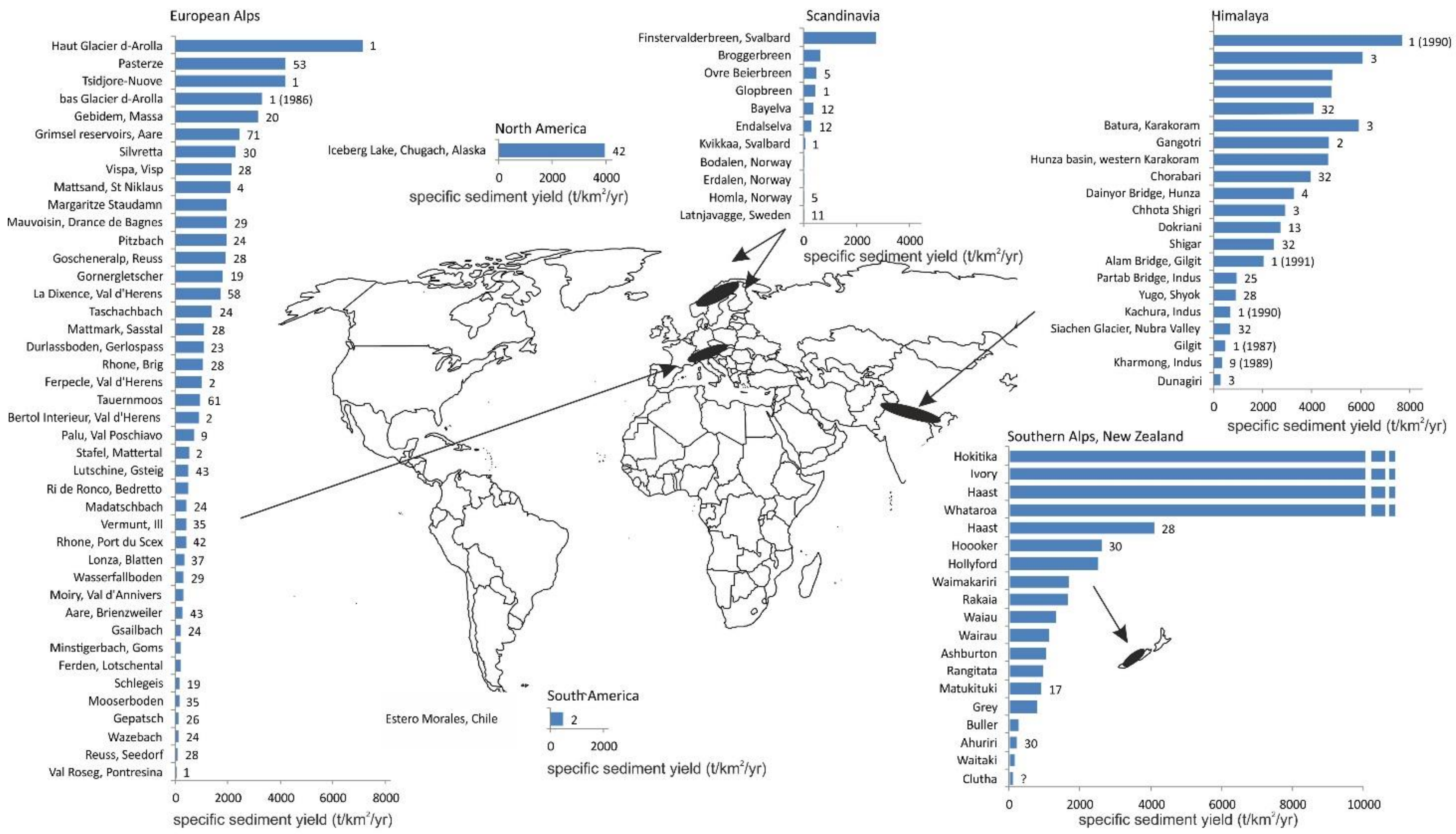
European Alps
Haut Glacier d-Arolla 1
Pasterze 53
Tsidjore-Nuove 1
bas Glacier d-Arolla 1 (1986)
Gebidem, Massa 20
Grimsel reservoirs, Aare 71
Silvretta 30
Vispa, Visp 28
Mattsand, St Niklaus 4
Margaritze Staudamn
Mauvoisin, Drance de Bagnes 29
Pitzbach 24
Goscheneralp, Reuss 28
Gornergletscher 19
La Dixence, Val d'Herens 58
Taschachbach 24
Mattmark, Sasstal 28
Durlassboden, Gerlospass 23
Rhone, Brig 28
Ferpecle, Val d'Herens 2
Tauernmoos 61
Bertol Interieur, Val d'Herens 2
Palu, Val Poschiavo 9
Stafel, Mattertal 2
Lutschine, Gsteig 43
Ri de Ronco, Bedretto
Madatschbach 24
Vermunt, Ill 35
Rhone, Port du Scex 42
Lonza, Blatten 37
Wasserfallboden 29
Moiry, Val d'Annivers
Aare, Brienzweiler 43
Gsailbach 24
Minstigerbach, Goms
Ferden, Lotschental
Schlegeis 19
Mooserboden 35
Gepatsch 26
Wazebach 24
Reuss, Seedorf 28
Val Roseg, Pontresina 1
0
2000
4000
6000
8000
specific sediment yield (t/km²/yr)
North America
Iceberg Lake, Chugach, Alaska 42
0
2000
4000
specific sediment yield (t/km²/yr)
Scandinavia
Finstervalderbreen, Svalbard
Broggerbreen
Ovre Beierbreen 5
Glopbreen 1
Bayelva 12
Endalselva 12
Kvikkaa, Svalbard 1
Bodalen, Norway
Erdalen, Norway
Homla, Norway 5
Latnjavagge, Sweden 11
0
2000
4000
specific sediment yield (t/km²/yr)
Himalaya
1 (1990)
3
32
Batura, Karakoram 3
Gangotri 2
Hunza basin, western Karakoram
Chorabari 32
Dainyor Bridge, Hunza 4
Chhota Shigri 3
Dokriani 13
Shigar 32
Alam Bridge, Gilgit 1 (1991)
Partab Bridge, Indus 25
Yugo, Shyok 28
Kachura, Indus 1 (1990)
Siachen Glacier, Nubra Valley 32
Gilgit 1 (1987)
Kharmong, Indus 9 (1989)
Dunagiri 3
0
2000
4000
6000
8000
specific sediment yield (t/km²/yr)
Southern Alps, New Zealand
Hokitika
Ivory
Haast
Whataroa
Haast 28
Hoooker 30
Hollyford
Waimakariri
Rakaia
Waiau
Wairau
Ashburton
Rangitata
Matukituki 17
Grey
Buller
Ahuriri 30
Waitaki
Clutha ?
0
2000
4000
6000
8000
10000
specific sediment yield (t/km²/yr)
South America
Estero Morales, Chile 2
0
2000
specific sediment yield (t/km²/yr)

Figure 6. Specific sediment yield from glaciated catchments additional to (or extended time series of) those reported by Hallet et al. (1996). Numbers at end of bars are duration in years over which the mean specific sediment yield has been determined. Note apparent paucity of monitoring from North and South America, but otherwise rather more extensive coverage than available to Hallet et al. (1996). References for each of these specific sediment yield records is given in a Supplementary file. It is important to note we only consider the mean value of records 10 years duration or greater, and that several Norwegian and New Zealand glaciers advanced in response to positive mass balances between the 1960s and 2000 (Chinn et al., 2005).

For sites with specific sediment yields calculated as a mean over more than ten years, catchment landcover data, most notably glacier cover, will likely have changed yet this data is necessary in order to compare successive time intervals of sediment yields with respect to changing catchment conditions. In their empirical analysis of landcover effects on sediment yield across the European Alps, Hinderer et al. (2013) noted considerable scatter, but i) weakly positive correlations of sediment yield with catchment relief, discharge and glacial cover, ii) a weak negative correlation of sediment yield with forest cover and iii) no clear correlation of sediment yield with lithology. Given these empirical relationships of sediment yield with basin characteristics identified by Hinderer et al. (2013), it can be realised that spatial analysis offers potential to unravel the spatio-temporal complexities of sediment yields.

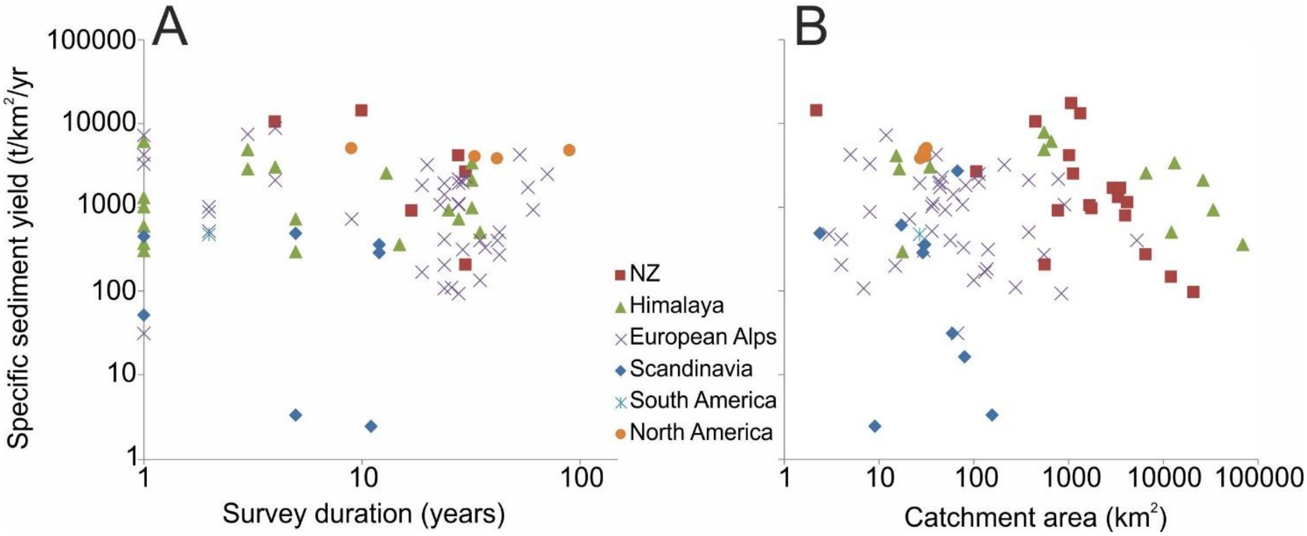

Figure 7. Compilation of specific sediment yield data globally in glaciated regions and relationship with survey duration (A) and catchment area (B).

7. Modelling of spatio-temporally distributed sediment yield

Modelling of sediment yield has been hampered by the very poor correlation between water discharge and suspended sediment transport (Morehead et al., 2003). Several types of models can be fitted through estimates of sediment yield at a single site but must factor extreme events as well as long-term trends (e.g. Heideman et al., 2018). There have been several qualitative appreciations of the spatial distribution of sediment yield from glaciated catchments, for example in Canada (Church et al., 1989) and the Upper Indus in Pakistan (Faran Ali et al., 2008).

One approach to modelling spatially-distributed sediment yield has been via DEM analysis, specifically via filling gullies (sediment sources) and removing fans (sediment sinks) and then applying a flow routing algorithm to identify sediment pathways (e.g. Tunnicliffe and Church, 2011). Others have developed spatially-distributed models to examine the response of discrete landforms to landcover changes; such as ice cover and permafrost effects on arctic-type river morphology and channel dynamics (e.g. Lauzon et al., 2019) but do not consider sediment yield explicitly. Altmann et al. (2020a) have shown that DEM analysis (and vegetation cover data) can be used to derive, via statistical parameter optimisation, sediment contributing area as a predictor to sediment yield.

Empirical models can be used to relate specific sediment yield to catchment characteristics such as lithology, topography and land use (Morehead et al., 2003). These models are best suited for application on a regional scale and are in widespread use outside of glaciated landscapes (e.g. De Vente et al., 2013; Pandey et al., 2016). In glaciated environments, these empirical models have been applied spatially across the western Himalaya (Jain et al., 2003). They can be sophisticated enough to include transient climate (e.g. Kettner and Syvitski, 2008) and thus to output a time-varying sediment flux. One example of this type of spatial modelling (for a single time period) is that using > 200 river station gauges and an empirical model now hosted at NIWA in New Zealand. The model relates specific sediment yield to mean annual rainfall (gridded from spot data) and to an ‘erosion terrain’ classification and was calibrated from the river-gauging data. The erosion terrains were defined based on slope, rock type, soils, dominant erosion processes, and expert knowledge (Fig. 8).

The latest models have greater process representation to include spatial heterogeneity of land surface erodibility and with gridded rainfall and air temperature datasets they permit estimation of ice and snow melt as well as erosive rainfall (e.g. Costa et al., 2018; Battista et al., 2019).

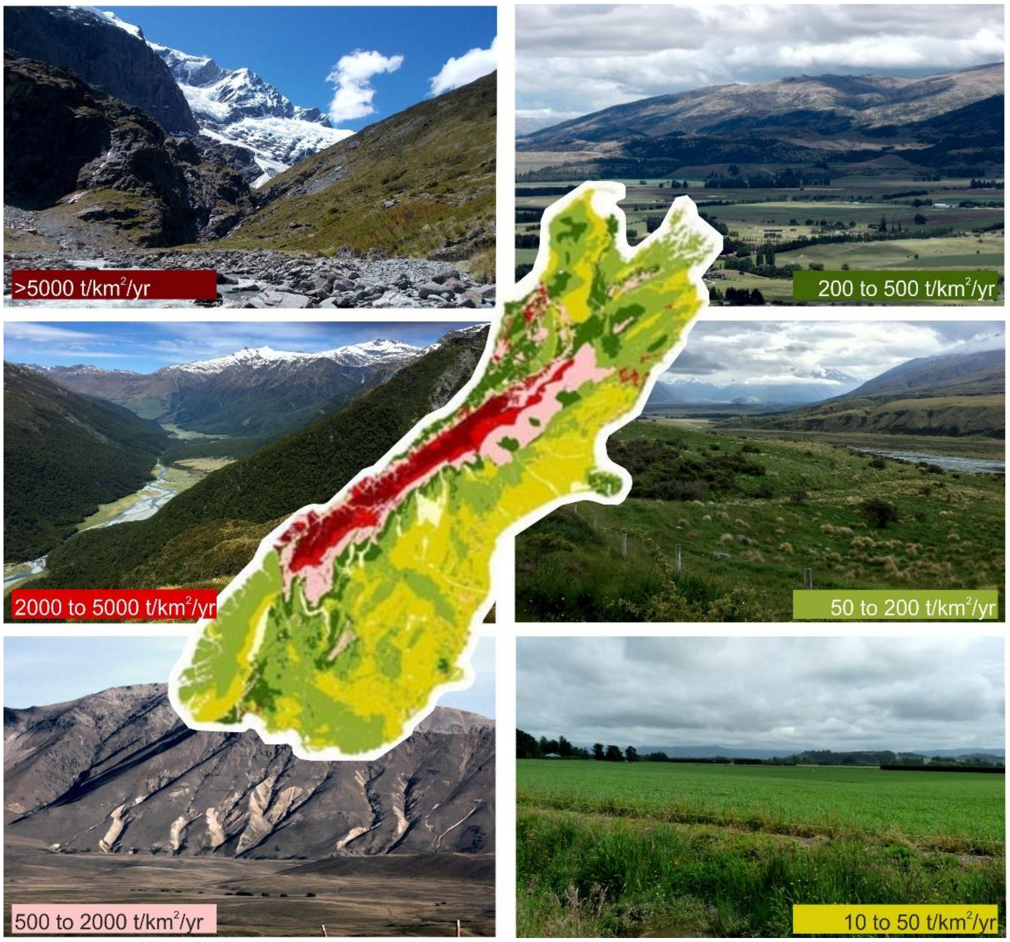

Figure 8: Example of spatially-distributed sediment yield modelling from New Zealand, as based on > 200 river monitoring sites that were operational up until the mid-1990s. Images are representative terrain of each category (colour-coded) on the map.

8. Capitalising on emerging datasets and methods

A key principal of the geosciences is to understand the past in order to assist projections of future environmental conditions and historical satellite imagery is a major tool in understanding the last few decades of changes. There are emerging and exciting opportunities offered by cloud computing, which can unlock the spatio-temporal coverage of these archives and thus address the (almost inherent) spatio-temporal variability in specific sediment yield. For example, the Landsat series of satellite sensors provide images back to the early 1980s and are already available within Google Earth Engine. Spatial changes can be partially explained by climate, and recently the ERA5 gridded climate parameters have been extended back to the 1950s, meaning powerful analyses such as spatial correlations between landcover changes and climate changes should now be possible.

Historical elevation models are emerging all the time, as archival imagery is re-processed using modern methods, such as for the 1980s across Greenland (Korsgaard et al., 2016) and as recent high-resolution images are automatically processed to generate high quality digital elevation models, such as ArcticDEM (Porter et al., 2018) and REMA, for Antarctica (Howat et al., 2019). Crucially, these DEMs are available as time-stamped 'strip files', enabling changes to be detected in unprecedented spatio-temporal detail. This part of the paper first discusses these two opportunities: landcover changes and DEM change detection. It then relates two allied sets of analyses that are emerging and offering practical prospects for understanding sediment yields in deglaciating landscapes, namely analyses of connectivity and analyses of sediment plumes, where these sub-sections are arranged in logical order from source to sink. Throughout, preliminary studies are showcased and used to formulate hypotheses to guide further investigations.

9. Landcover change detection

High-resolution images that are multi-spectral can be used to discern major changes in landcover. In glaciated regions of the Arctic, for example, landcover changes reported for the last decades include diminishing glacier ice (Bamber et al., 2018; Box et al., 2018), increasing number and area of glacier-fed lakes (Shugar et al., 2020), drying permafrost causing rapid land surface hydrology changes (Teufel and Sushama, 2019), expanding vegetation, so-called 'greening' (Myers-Smith et al., 2020), river braid plain aggradation, possibly widening, as glaciers erode sediment (Overeem et al., 2017) and as permafrost degrades, and freshwater and coastal delta progradation (Bendixen et al., 2017; Piliouras and Rowland, 2020) (Fig. 9). Similar patterns of landcover change and impacts on meltwater and sediment mobility can be observed on the Antarctic Peninsula (Fig. 10).

These landcover changes (Figs. 9, 10) in glaciated regions are important because they determine water and sediment sources and routing. They also control water source contributions and hence water quality, especially water temperature and turbidity. In almost all mountainous parts of the world, landcover changes in glaciated regions have direct consequences for human habitation, health and livelihoods. In the Arctic, drinking water quality is a problem for the health of indigenous Arctic populations (Harper et al., 2020). Water quality also affects human livelihoods and economic development in the Arctic; for example the life-cycle of salmon depends on water temperature and turbidity, and in Greenland salmon fishing provides 90% of exports and 13% of its Gross Domestic Product (GDP) (Arnason, 2007). In Alaska and in Arctic Canada salmon fishing provides tens of thousands of jobs and hundreds of millions of USD to GDP (Gislason et al., 2017). Economic development across the Arctic depends on rivers as transport networks but must also manage water quality issues; e.g. hydropower turbines are susceptible to damage from suspended sediment and reservoirs are prone to a loss of capacity due to sedimentation. Similar problems for hydropower installations on glacial rivers persist across all inhabited temperate mountain ranges. In the Antarctic, water quality determines the composition and health of marine ecosystems (e.g. Dunbar et al., 1998).

More widely, understanding past landcover changes and land surface hydrology and sediment sources and pathways will help understanding of; (i) carbon storage/release associated with lakes and rivers (c.f. Dean et al., 2020), (ii) land surface albedo and thus regional heat balances and ocean circulation (c.f. Bowling et al., 2003). Hypothesis: ***sediment yield is correlated with landcover instability and with climate change***

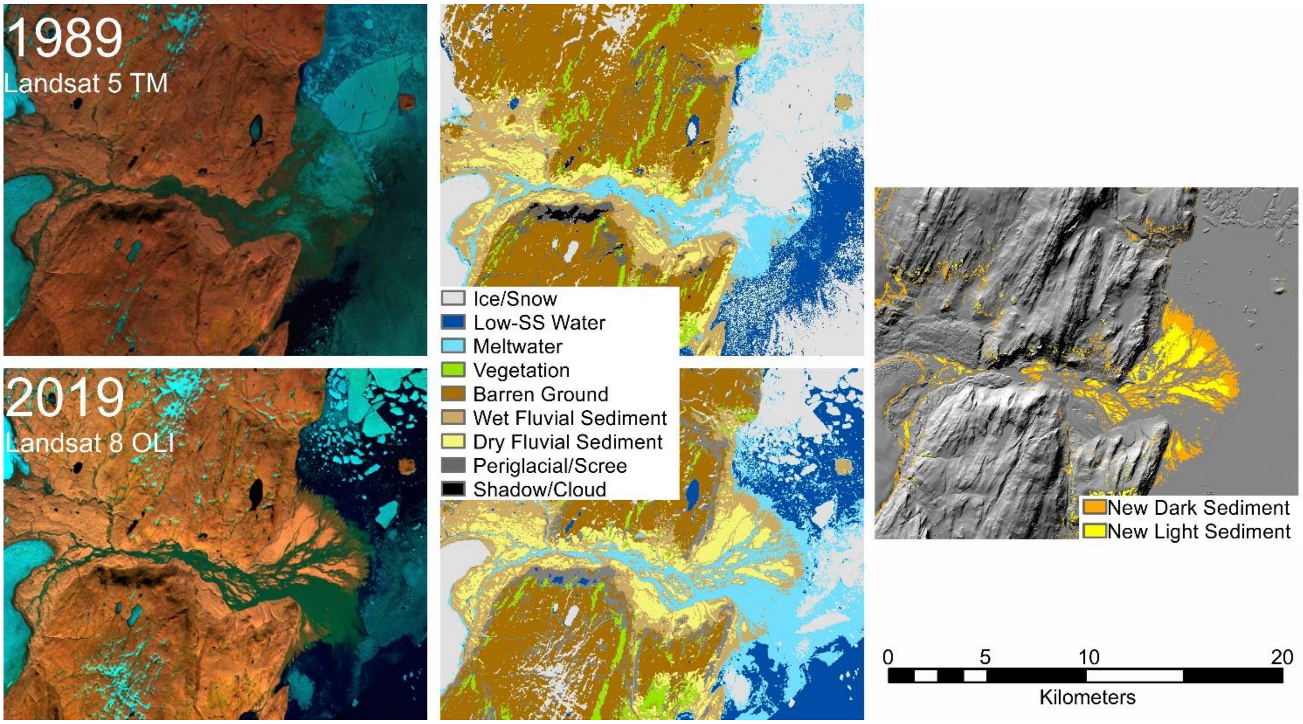

Figure 9. Binary change detection (presence/absence) of two sediment classes of landcover in Sondre Mellemland, NE Greenland, evidencing delta progradation and fluvial sediment aggradation between 1989 and 2019. Performed in Google Earth Engine by Michael Grimes.

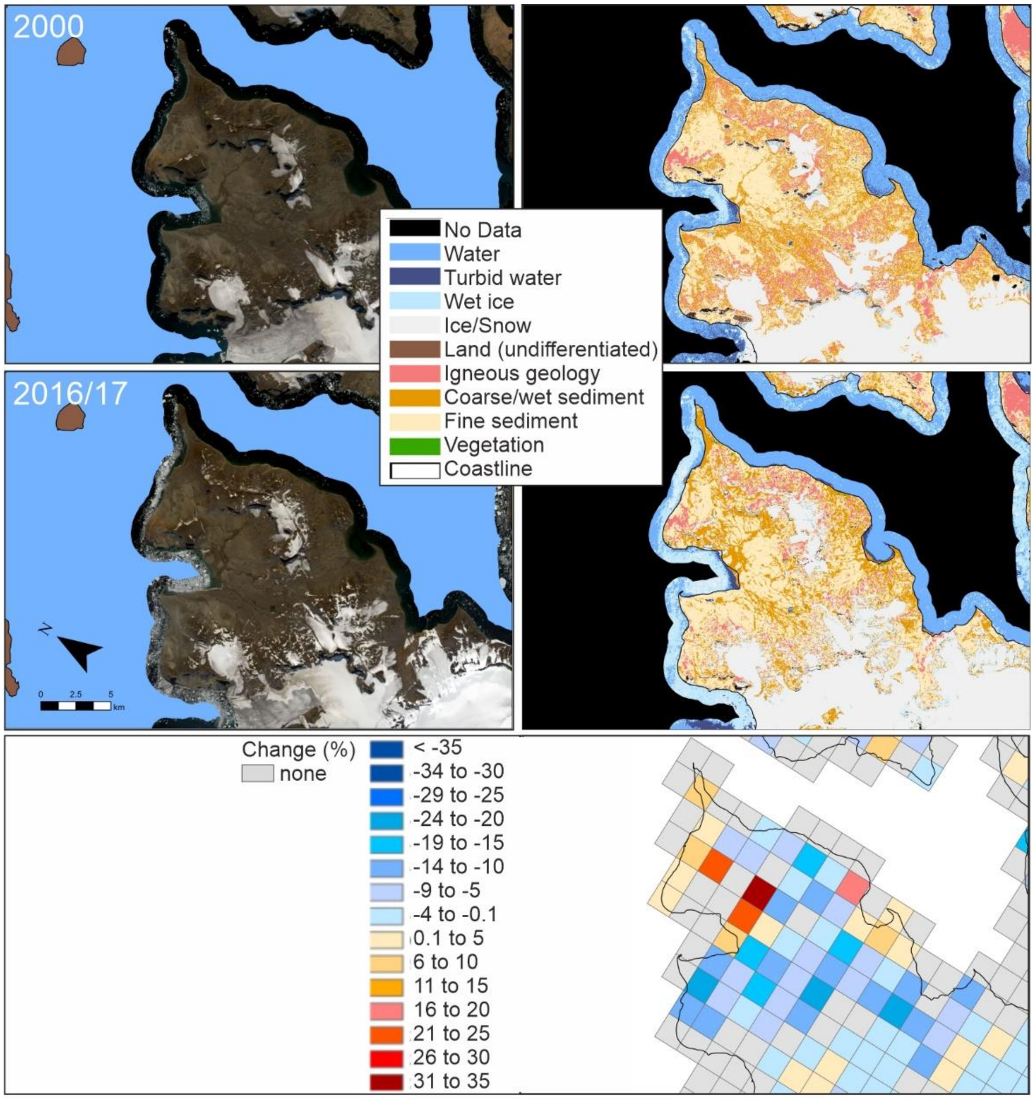

Figure 10. Change detection of coverage of 'coarse wet sediment' landcover class on the Ulu Peninsula of James Ross Island, Antarctic Peninsula, between 2000 and 2010. Performed in Google Earth Engine by Chris Stringer.

10. Detecting distributed elevation changes

Elevation changes can be used to infer erosion and deposition, especially in response to deglaciation of catchments. To be confident in the cause of these elevation changes, the time between successive surveys must be short enough to bracket the land-forming event and thus to mitigate aggregate effects of multiple events through time. Additionally, a 'level of detection' should be carefully calculated and applied, above which elevation changes can be considered to be real, rather than artefacts of DEM uncertainty or error (Kasprak et al., 2019). The availability of airborne laser scanning and terrestrial laser scanning signalled a step-change in our ability to detect land forming events in space and time (e.g. Carrivick et al., 2013; Fig. 11), but those technologies have arguably been superseded by the ease of use of Structure from Motion Multi View Stereo (SfM) methods and workflows (e.g. Carrivick et al., 2016; Smith et al., 2016). In both these laser scanning and structure-from-motion workflows, the initial data product is a 3D point cloud. However, those point clouds are under-utilised in the literature, rather being converted to regular grids for a more familiar format, which is formally-supported in both commercial and open source software and easily permits volumes of portions of the grid to be computed - and hence rates of change to be calculated - for every pixel/grid cell (Fig. 11).

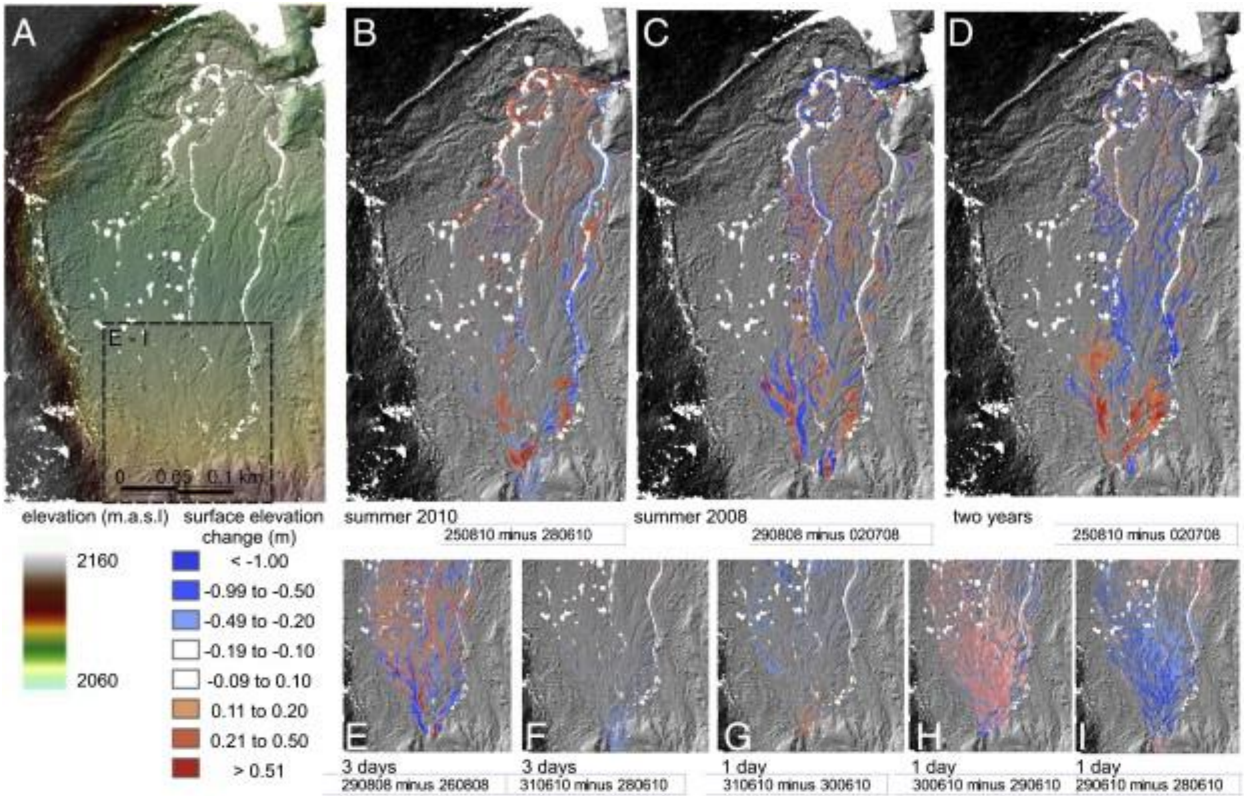

Figure 11. Alpine river proglacial outwash plain (sandur) elevation changes across seasonal, monthly and daily time-scales, measured with airborne and terrestrial laser scanning, from Carrivick et al. (2013).

Where coherent elevation changes above the level of detection occur in space; e.g. many adjacent pixels/cells having the same type of change, and multiple surveys are conducted, then sediment sources, pathways and sinks can be identified and spatially analysed (e.g. Kociuba, 2017). In fluvial processes, these elevation changes mostly reflect bedload transport (e.g. Cazzador et al., 2021), for suspended sediments will largely be deposited in low-energy settings such as lakes and would have to be present as unusually thick deposits to be detected by repeated surveys, and are rapidly re-worked and removed by subsequent events such as intense rainfall.

In an analysis of multiple DEMs covering decadal time scales, Altman et al., (2020) identified that whilst slope–channel coupling was persistent across their study site and through time, there was a decrease in the efficiency of sediment transport from slopes to channels. They interpreted these developments to be due to the driving forces of deglaciation; namely increasing air temperature and decreasing short-term precipitation patterns, and to consequential increasing runoff. Shorter time scale studies have sought to explain sediment sources, pathways and sinks in deglaciating catchments in relation to geomorphological work (e.g. Müller et al., 2014), to topographic metrics (e.g. Cavalli et al., 2017) and to changing connectivity with glacier recession (Lane et al., 2017; Mancini and Lane, 2020), for example.

Connectivity analysis has become a key method for moving from qualitative to (semi-)quantitative evaluations of sediment movement. Heckmann et al., (2018) have reviewed the concepts and indices and identified opportunities and challenges. The application of connectivity methods to understanding processes within deglaciating catchments has been demonstrated recently, for example by Llena et al., (2019) and Cavalli et al., (2019a, b). Changes in connectivity in space and time (Cossart et al., 2018) should become a key tool for explaining or even predicting changes in sediment yield.

High-resolution DEMs of difference, so called DoDs, have also been used to derive sediment delivery ratios as proxies of functional connectivity (Heckmann and Vericat, 2018; Dusik et al., 2019). Specifically, as Heckmann and Vericat (2018) report, accumulating the values of a DoD along downslope flowpaths, the net balance, i.e. sediment yield (SY), for the contributing area of each cell can be computed. The same analysis applied only to cells of the DoD with negative values yields a minimum estimate of erosion (E) within the contributing area. The division of SY by E yields a maximum estimate of the sediment delivery ratio (SDR), that is the proportion of material eroded within the contributing area of each cell that has been exported from that area. This ability to determine sediment yield (and SDRs) at high spatio-temporal resolution should mitigate many of the problems highlighted in part 1 of this paper with traditional ‘at-a-point’ gauging for processes-understanding. Hypothesis: ***sediment yield is correlated with a negative catchment mass balance***; i.e. with negative volume changes.

11. Detecting hydrological network and connectivity changes

Understanding connectivity between hillslopes and river channels enables linkages between river reaches, the influence of sediment sources on channel morphology and the mechanisms and liability to propagation of morphological change to be considered (Hooke, 2003). The more connected a surface is, the greater the volume and the more efficient transmission of material can exist across it. Therefore, the hypothesis that ***sediment yield is positively correlated with high connectivity***, can be proposed. Indices of connectivity enable (semi-)quantitative evaluations of material transfer across a surface, such as for water, sediment and solutes. Recent reviews by Heckmann et al. (2018) and by Cavalli et al. (2019) detail existing indices of sediment connectivity and make suggestions of how they can be best used to constrain structural-functional correlations. They also caution that a full understanding of connectivity probably requires employment of these indices alongside field-based particle tracking and sediment provenance analyses, as well as with numerical model simulations. Nonetheless, a major advantage of connectivity analysis is that it can be conducted across spatial scales (Bracken et al., 2015), making it an ideal tool for addressing the spatio-temporal gaps in field data for considering inter- and intra-catchment responses to deglaciation. Harries et al. (2021) have recently explored the impact of climate on sediment connectivity and sediment export in three adjacent deglaciating catchments in the Andes and highlighted the preconditioning of the catchment responses to climate forcings by bedrock lithology.

In mountain headwater catchments, connectivity is complex; steep hillslopes promote transmission of material onto valley floors, but glacial overdeepenings and moraine ridges can act as efficient interruptions to pathways, for example (Cavalli et al., 2013). Furthermore, as proglacial areas expand, it can be suggested from DEM analyses that connectivity evolves, especially of the channels (Goldin et al., 2016) and also that the position, number and total length of streams increases (Fig. 12). Conversely, it would be reasonable to assume that with ice margin recession and declining glacier volumes fluvial incision by glacial rivers will progressively straighten channels and simplify a proglacial fluvial network. Such (rapid) evolution of the position and number of streams and of the connectivity over successive decades has great implications for water resource management, for natural hazard assessments and for the nature and quality of both terrestrial and aquatic organism habitats. With regard to the habitats of aquatic organisms, the percentage glacier cover, which is a proxy for channel stability and water temperature (e.g. Brown et al., 2010, 2015), can be determined per grid cell and it can be shown that these values will dramatically alter in the coming decades (Fig. 13).

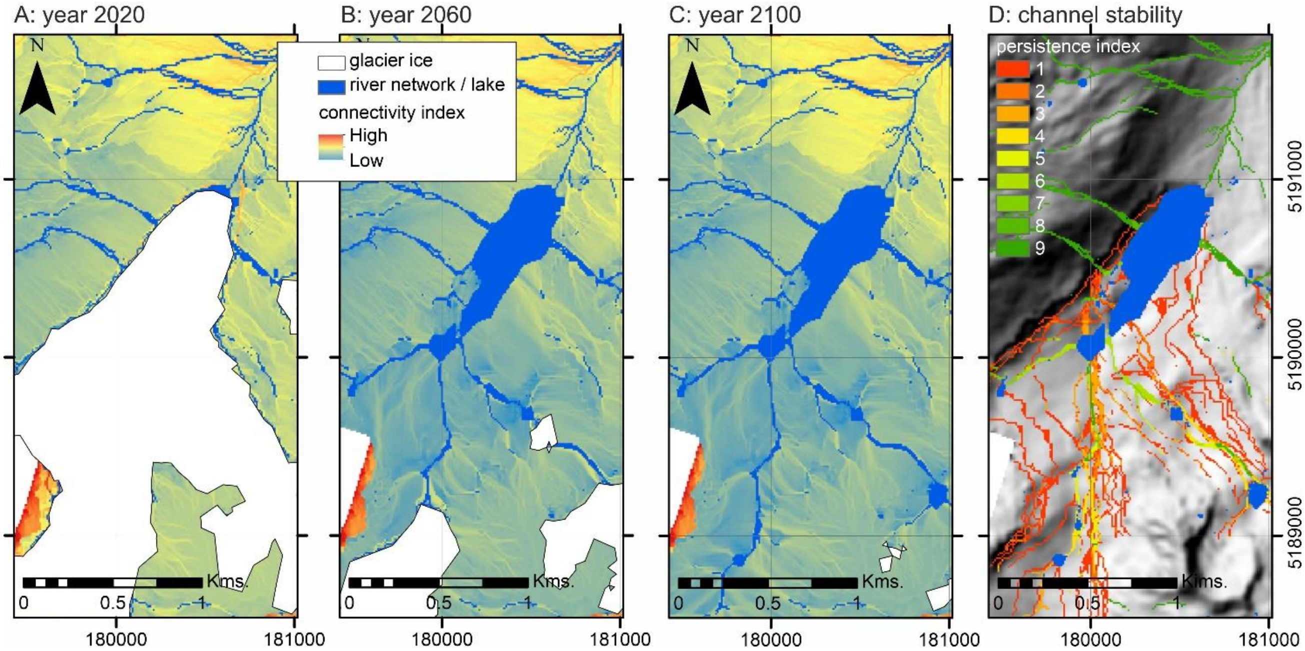

Figure 12. Example of determination of spatially-distributed connectivity using SedInConnect (Crema and Cavalli, 2018) for the expanding proglacial area of a shrinking glacier on the north side of the mountain peak Similaun on the Austria - Italy border. Future ice extents for year 2020 (A), year 2060 (B) and year 2100 (C) are from Matthias Huss (pers. comm.) but reflect the modelling of Zekollari et al. (2019). Panel D incorporates analyses of stream pathways from a contributing area analysis for every decade between 2020 and 2100 and simply counts the number of decades each grid cell is 'wet'. Grid coordinates are in UTM zone 33N.

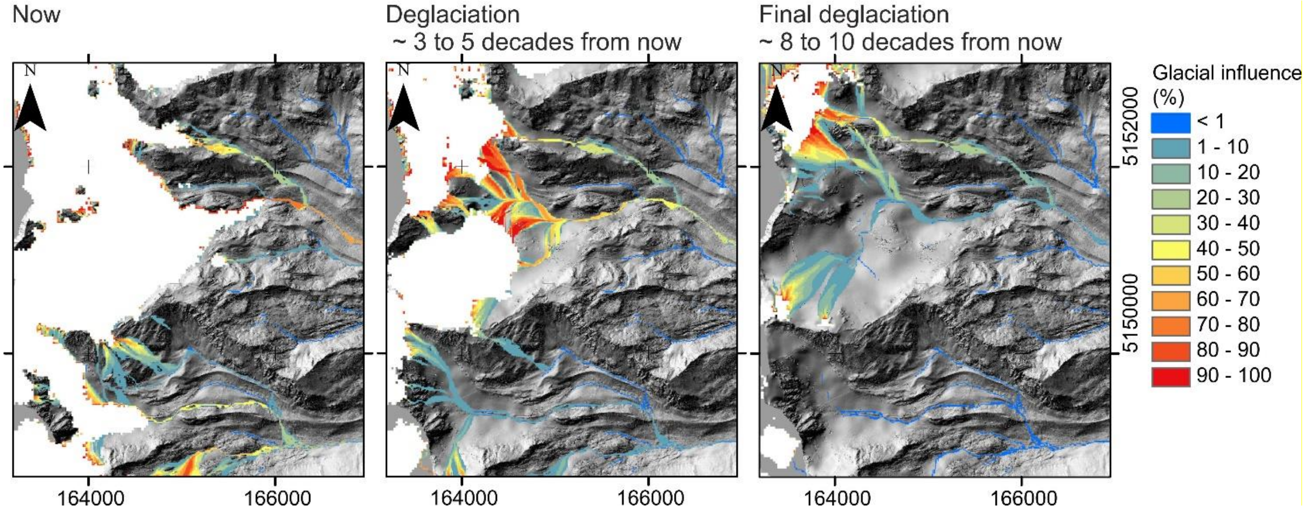

Figure 13. Example of hydrological analysis of changing glacier cover effects on stream pathways and glacier meltwater influence the eastern side of Monte Cevedale and Monte Vioz in the Trento region of northern Italy. This contributing area analysis not only demarcates the position of streams but is elaborated to determine the percentage glacier cover upstream of each stream grid cell; i.e. the glacial influence for every stream cell. Future ice extents are from Matthias Huss (pers. comm.) but reflect the modelling of Zekollari et al. (2019). Grid coordinates are in UTM zone 33N.

12. Plumes

Meltwater emerging from beneath a glacier or from a proglacial area into a fjord deposits bedload as a delta, often a Gilbert-type delta, but also rises as a buoyant forced plume due to density contrasts with the ambient saline water. The configuration of a plume is usually controlled by tides or else by high winds speeds (Dowdeswell and Cromack, 1991). Fine sediment beneath a meltwater plume can be flocculated and floc sizes and fraction of mass bound within flocs can have a pronounced increase with depth rather than down fjord, which can cause under-estimation of sediment fluxes if relying on surface water observations (Curran et al., 2004).

Sedimentation rates from plumes tend to be dominated by infrequent high magnitude short-lived flood events and can be several tens of metres per year in total and the volume can be several millions of m^3 per year (Cowan and Powell, 1991). Proglacial rivers entering fjords via deltas and fans can exhibit quite different sediment transport processes to those direct from glaciers; the former can deposit one quarter of the sediment initially, but they exhibit redeposition and resuspension due to sediment transport within hyperpycnal flows, whereas suspended sediment direct from a glacier terminus is transported far farther into a fjord, but tidal pumping and water mixing lead to the removal of three quarters of it (Zajączkowski, 2008). Plumes and associated ice-contact fans tend to be stable in position over years (Schild et al., 2016) through decades to century scales (Dowdeswell et al., 2015) and are highly sensitive in aggradation/incisions phases with glacier advance/retreat, respectively. It is therefore possible to suggest a hypothesis that ***sediment yield is positively correlated with plume size***, specifically suspended sediment volume.

Plumes can be sampled *in situ* for suspended sediment concentration, depth and horizontal extent, using a submersible deep water sampler, for example (Fig. 14) However, this field work is expensive in time and money and only produces spot samples, which nonetheless are essential for calibrating measurements gained from remote sensing.

Plumes can be studied remotely using several types of optical (and infra-red wavelength; e.g. Schild et al., 2017) band imagery but the preference in glacier-related studies in recent years has been to employ Moderate Resolution Imaging Spectroradiometer (MODIS) band 1 reflectance imagery. These analyses tend to be simpler for plumes emanating from proglacial rivers (from glaciers with land-terminating margins) in deltas; i.e. with wide and straight fjord-head geometries, whereas at marine-terminating margins, fluctuations in terminus position, calving, ice melange and sea-ice cover can create problems (Tedstone and Arnold, 2012; Schild et al., 2016). Furthermore, they are limited by the 250 m pixel size and by the necessity for sunlit conditions.

Figure 14. Plume sampling in the Zackenberg River plume (A), NE Greenland, using a conductivity, temperature and pressure probe-logger (B) and suspended sediment via a submersible deep water sampler (C). Note contrast between turbid water in foreground of A versus clearer blue water in distance.

In a study of three proglacial rivers in west Greenland, six plumes apparently increased in extent and in suspended sediment concentration between 2000 and 2012, though not significantly (Hudson et al., 2014). Plumes have usefully been linked in timing and size to ice sheet hydrology (Chu et al., 2009; McGrath et al., 2010; Schild et al., 2016) and whilst these studies have noticed sediment exhaustion effects and englacial temporary storage effects, any contributions from ice-marginal or proglacial realms were not considered. Harnessing the impressive capability of Google Earth Engine and development of sediment concentration retrieval algorithms specifically for Landsat7 Enhanced Thematic Mapper and to Earth Observation-1 Advanced Land Imager images by Overeem et al. (2017) has given insight to the disproportionate contribution of Greenland to global sediment discharge to oceans. Specifically, from their remote sending analysis of plumes, Overeem et al. (2017) reported that 8% of global sediment discharge is delivered by just 1% of the total water runoff. Of the 160 Greenland rivers they studied, those that originated from deeply incised, fast-moving glaciers formed distinct sediment-export hotspots; these 15% of Greenland’s rivers transport 80% of the total sediment load of the ice sheet.

Notwithstanding the aforementioned constraints of using this sort of remotely-sensed imagery, there are opportunities to estimate sediment fluxes from other rapidly deglaciating parts of the world, such as Iceland (Hodgkins et al., 2016), or Patagonia (Fig. 15), for example.

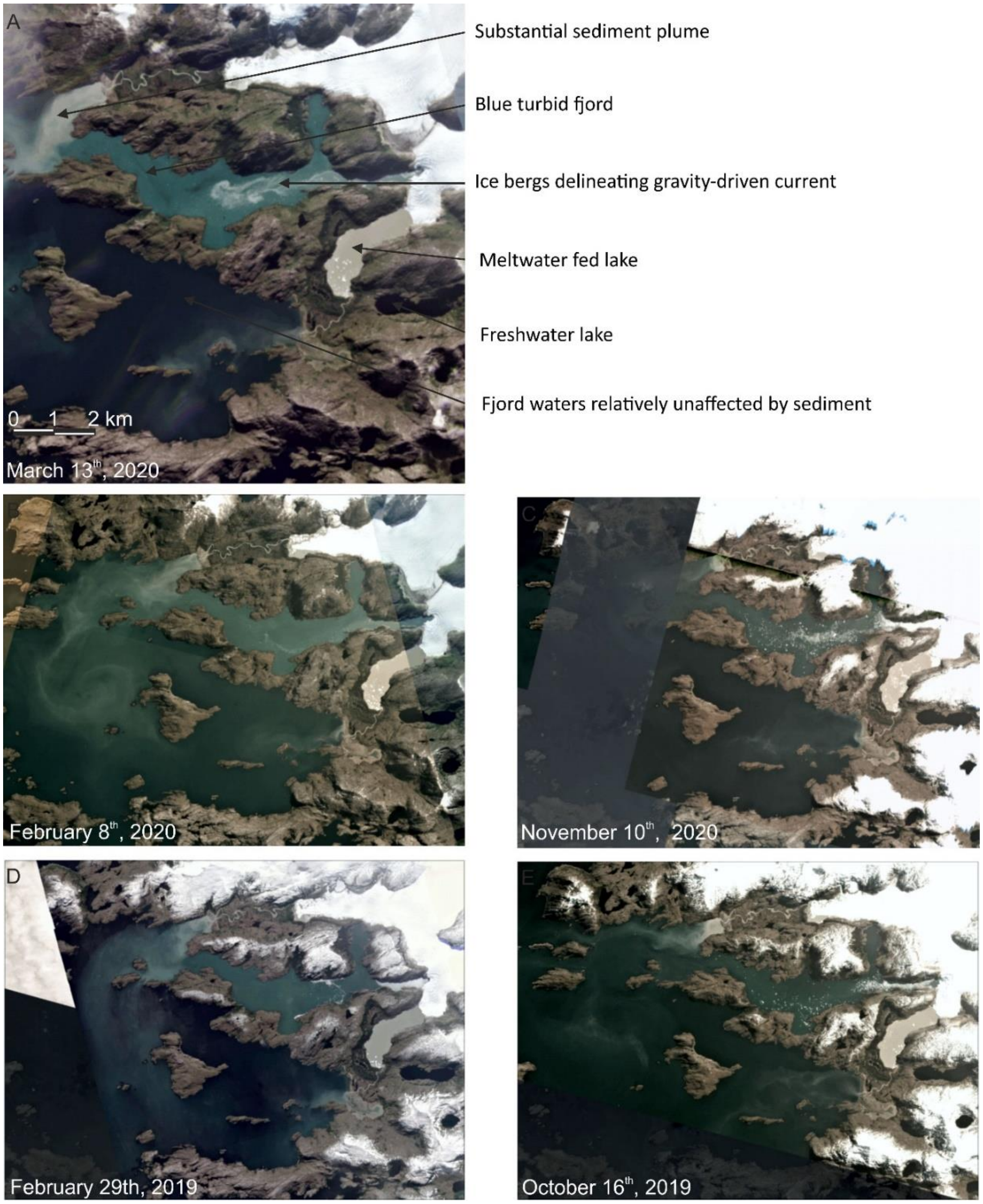

Figure 15. Example from 55° 13' S, 69° 54' W (western Isla Hoste, Bahía Cook, Chile) of suspended sediment being discharged into a shallow marine setting via a substantial plume fed from a proglacial river, suspended sediment from a calving glacier, ice bergs from a calving glacier, and an ice-marginal lake. For comparison the dark waters of a freshwater lake and of a fjord are also indicated in panel A. Panels B to E indicate the spatio-temporal variability in this sediment delivery as waters change colour, plumes wax and wane and ice berg numbers and sizes alter, for example.

13. Conclusions

Deglaciation is causing intense and widespread redistribution of sediment and that affects landscape stability and water quality and hence human health and livelihoods. It is therefore crucial, timely and of wide interest to better understand sediment yields from glaciated catchments. The major reasons for understanding deglaciating sediment yields are because: (i) sediment can be a significant problem for water resource operations and management, (ii) design of water storage, abstraction and supply systems involving dams, reservoirs, weirs and channels needs to be sensitive to sediment fluxes and there are also practical implications for the development and maintenance of hydro-electric powers schemes in glaciated catchment, (iii) sediment fluxes can affect water quality and in some cases contaminants and deglaciation can reduce streamflow leading to concentrations of pollutants.

The key characteristics of sediment yields from glaciated catchments have been shown to be that: (i) globally and between rivers they span five orders of magnitude, (ii) there is a strong pattern with latitude, likely reflecting glacier dynamics, and (iii) the very highest sediment yields are associated with high catchment relief and tectonically-active regions. However, these patterns only become evident where mean rates from longer-term records (> 10 years) are used because there is extremely high spatio-temporal variability in catchment processes.

Our examination of these spatio-temporal records has identified gaps in our knowledge of sediment yields from deglciating catchments, namely (i) a relative lack of consistent published data on sediment yields, (iii) very few studies reporting specific sediment yields include consideration of the percentage of the catchment that is covered by glacial ice, (iii) both national campaign reports and research projects are inconsistent in the metric used to report sediment yields.

This paper has created a conceptual diagram to consider sediment sources, pathways and sinks changing with progression from glacial to deglacial to postglacial times (Fig. 4). In realisation of the need to better quantify inter- and intra-catchment sediment movements, not least in an efficient and repeatable manner, it has showcased preliminary studies capitalising on emerging datasets and methods to demonstrate their utility for addressing the problem of measuring and understanding the spatio-temporal complexity in sediment yields from deglaciating catchments. In doing so, we have identified four testable hypotheses by which knowledge and understanding of sediment fluxes in deglaciating catchments can be increased: (i) sediment yield is correlated with landcover instability and with climate change; (ii) sediment yield is correlated with a negative catchment mass balance; (iii) sediment yield is positively correlated with high connectivity and (iv) sediment yield is positively correlated with plume size, specifically suspended sediment volume. These hypotheses should stimulate further research to the benefit of society.

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