

Repeated high flows drive morphological change in rivers in recently deglaciated catchments

Lawrence J. B. Eagle¹  | Jonathan L. Carrivick¹ | Alexander M. Milner^{2,3} | Lee E. Brown¹ | Megan J. Klaar¹

¹School of Geography & water@leeds, University of Leeds, Leeds, LS2 9JT, UK

²School of Geography, Earth and Environmental Sciences, University of Birmingham, B15 2TT, Birmingham, UK

³Institute of Arctic Biology, University of Alaska, Fairbanks, AK, 99775, USA

Correspondence

Lawrence Eagle, School of Geography & water@leeds, University of Leeds. Leeds, LS2 9JT, UK.

Email: lawrenceeaglejb@gmail.com.

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Abstract

Climate change is decreasing glacier cover and increasing the frequency and magnitude of precipitation-driven high flows and floods in many regions of the world. Precipitation may become the dominant water source for river systems in recently deglaciated catchments, with major rainfall events driving significant changes in river channel morphology. Few studies, however, have examined river channel response to repeated precipitation-driven high flows. In this study, we measured the geomorphological condition of four low-order rivers in recently deglaciated catchments (70–210 years ice free) before and after a series of repeated precipitation-driven high flows during summer 2014. High flows drove substantial initial morphological change, with up to 75% change in baseflow channel planform position and active channel form change from pre- to post-high flow. Post-high flow years were associated with increased instream wood and geomorphological complexity at all but the youngest river. Channel changes were part of an active relaxation stage at all rivers, where channels continued to migrate, and complexity varied through time. Overall, these measurements permit us to propose a conceptual model of the role of geomorphologically effective high flows in the context of paraglacial adjustment theory. Specifically, we suggest that older rivers in recently deglaciated catchments can undergo a short-term (<10 years) increase in the rate of geomorphological development as a result of the recruitment of instream wood and channel migration during and following repeated precipitation-driven high flows. Enhancing our knowledge of these geomorphological and paraglacial processes in response to high flows is important for the effective management of riverine water and ecosystem resources in rapidly changing environments.

KEYWORDS

ecosystem disturbance, floods, fluvial sediment transport, geomorphological development, instream wood, paraglacial adjustment, repeated high flow

1 | INTRODUCTION

Arctic, sub-arctic and high mountain regions are presently experiencing more extreme and rapid responses to climate change than other

parts of the world (Pepin et al., 2015; Box et al., 2019). In addition to increasing atmospheric temperature (Hansen et al., 2006), these regions are expected to encounter increases in the occurrence of extreme rainfall (Bintanja & Andry, 2017; Curtis, 2019), leading to increased frequency and magnitude of precipitation-driven floods (Berghuijs et al., 2017). The increasing frequency and magnitude of precipitation-driven floods and high flows are important because

The data used in this study is available from the corresponding author upon reasonable request.

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these events can substantially alter river hydraulic and geomorphological conditions (Schindler & Smol, 2006).

Extreme floods, whose peak discharges are characterised by recurrence intervals >50–100 years (Woodward et al., 2015), can drive major geomorphological change in rivers (Hauer & Habersack, 2009; Magilligan et al., 2015; Fryirs, 2017). Extreme floods have been shown to mobilise substantial volumes of sediment and drive changes to river planform (Thompson & Croke, 2013; Pasternack & Wyrick, 2017; Borga et al., 2019). Specific geomorphological responses depend upon the flood hydrograph and the catchment geology, topography including valley confinement, landcover and connectivity (Milan, 2012; Brogan et al., 2017; Lane et al., 2017; Righini et al., 2017; Tunncliffe et al., 2017; Scorpio et al., 2018; Wohl et al., 2019).

In addition to mobilising sediment through bed and bank erosion, floods facilitate widespread erosion, transport and local accumulations of instream wood (Comiti et al., 2016; Steeb et al., 2017). Instream wood drives localised changes to velocity profiles, accelerating flow locally, increasing turbulence and enhancing erosion and deposition, driving downstream sediment fining and the development of low-velocity geomorphological unit types (Naiman et al., 1999; Klaar et al., 2011), as well as altering river-wide fluvial processes (Montgomery et al., 1995; Abbe & Montgomery, 1996; Wenzel et al., 2014). As a roughness element, the form of a wood structure (Daniels & Rhoads, 2003; Wondzell & Bisson, 2003) influences the extent of hydraulic change and sediment erosion/deposition (Gippel et al., 1996; Abbe & Montgomery, 2003; Hughes et al., 2007). Where increases in instream wood abundance and complexity occur, it can be expected to play an important role in the development of instream (baseflow and active channel) geomorphic complexity (Wohl et al., 2015; Wohl et al., 2016; Grabowski et al., 2019).

A post-flood geomorphological relaxation or response stage can be recognised immediately after extreme floods (Milan, 2012). Flood-mobilised sediment alongside newly accumulated or exposed roughness elements, such as instream wood and boulders (Brummer et al., 2006), drive ongoing geomorphological change through increased local erosion and deposition (Lester & Wright, 2009). The stability or persistence of geomorphological features post-high flow (Dean & Schmidt, 2013) defines the duration of this period.

The capacity of a given flood or high flow to drive geomorphological change is related to the overall energy available to effect change (Wolman & Miller, 1960; Costa & O'Connor, 1995). Geomorphological change is associated with increased total energy available, rather than simply peak flow magnitude, flood frequency or total duration. This framework has since been supported in observational work (Chappell et al., 2003), although not in all cases (Amponsah, 2017). Yet much of the literature continues to focus on single event, extreme, high-magnitude floods (e.g. Haschenburger & Wilcock, 2003; Carrivick & Rushmer, 2006; Carrivick & Rushmer, 2009; Hauer & Habersack, 2009; Dean & Schmidt, 2013; Fryirs et al., 2015).

Sequences of large floods have been shown to drive substantial morphological change in observational and modelling studies (Warburton, 1994; Dunning et al., 2013; Guan et al., 2016). However, the aggregated effects of smaller high flows (including smaller floods), or those occurring in quick succession, have received less attention. Repeated high flows are defined here as a high-frequency series of recurrent discharge peaks which individually may not be considered

to represent significant flood disturbances (flow and flood pulses; Bertoldi et al., 2010) occurring over weeks to months. Understanding the effects of these smaller 'flow pulses' (< 1 to 1 year return intervals) and 'flood pulses' (on average 1 in 2 year return intervals; terms defined by Bertoldi et al., 2010) are necessary because they can mobilise sediment (e.g. Kavan et al., 2017), drive localised morphological change (Pickup & Warner, 1976; Chappell et al., 2003; Zonta et al., 2005; Brown et al., 2015; Surian et al., 2015; Stocker-Waldhuber et al., 2017) and, with water temperature (e.g. Carrivick et al., 2012), can govern water quality. Previous research has demonstrated repeated high flows drive significant geomorphological change in large, braided, gravel bed rivers (Bertoldi et al., 2010; Mao & Surian, 2010). The geomorphological response of low-order (first to third order) rivers to repeated large floods and to repeated high flows (Lenzi et al., 2006; Rickenmann et al., 2012; Rainato et al., 2018) has been explored yet still requires further advancement (Comiti & Mao, 2012).

Rivers in Arctic, sub-arctic and mountainous environments are intrinsically linked to paraglacial adjustment, as water sources shift following complete catchment deglaciation (e.g. Carrivick et al., 2013). Projected increases in precipitation have been identified as a significant contributor to future river flows following glacier decline (Immerzeel et al., 2013; Milner et al., 2017). Initially unstable and active morphological conditions are observed as numerous geomorphological and hydrological processes alter the landscape (Church & Ryder, 1972; Ballantyne, 2002). Young catchments (those that have been recently deglaciated), with abundant unconsolidated glacial sediment (McCull, 2012; Carrivick & Heckmann, 2017), demonstrate high terrestrial landform erosion rates and sediment availability (Klaar et al., 2015). Whilst a temporal trend for decreasing sediment supply is observed as vegetation and soil organic matter develop (Egli et al., 2006; Malone et al., 2018) with systems becoming less sensitive to change (Harvey, 2001). Physical disturbances such as rock slope failures, debris flows and fluvial incision can continue to locally mobilise sediment despite the trend for stabilisation (Curry et al., 2006; Ballantyne & Stone, 2013; Legg et al., 2014).

The aim of this study is to quantify the extent to which repeated high flows (eight flow and flood pulses with recurrence intervals of up to 5 years) drive morphological change from the analysis of four rivers in recently deglaciated catchments at different stages of paraglacial adjustment in Glacier Bay, Alaska (Malone et al., 2018). On the basis of previous work, three hypotheses were tested in this study:

- H1** *Repeated high flows will change baseflow river channel position and active channel form due to significant bank erosion, sediment transport (Pasternack & Wyrick, 2017) and accumulation of instream wood (Ruiz-Villanueva et al., 2016);*
- H2** *Post-high flow response of baseflow channel position and active channel form will be greatest at older sites, due to greater change in relative sediment supply and instream wood recruitment and;*
- H3** *Repeated high flows will facilitate the ongoing development of river geomorphological complexity due to fluvial sediment transport which represents an important element of ongoing paraglacial adjustment in rivers in recently deglaciated catchments.*

2 | METHODS

2.1 | Study site

Glacier Bay National Park and Preserve in south-east Alaska (58°10'–59°15' N; 135°15'–138°10' W) is dominated by a tidal fjord, 150 km long and 20 km wide (Figure 1). The park covers an area of 11,030 km² with a maritime climate and a mean annual precipitation of 1,400 mm. At least three Holocene glacier advances and retreats have occurred in Glacier Bay (Lawson et al., 2004; Wiles et al., 2011), the largest being the formation of a Neoglacial ice sheet during the Little Ice Age which covered the majority of the region at its maximum (~1700). Retreat of the ice sheets began at the end of the Little Ice Age, and its rate was identified as one of the most rapid in modern global conditions (Chapin et al., 1994). Glacier retreat has resulted in the development of proglacial landscapes and river systems undergoing rapid adjustment to meltwater and sediment supply regimes as part of paraglacial adjustment.

Landscape development has a number of key recognised stages in Glacier Bay (Chapin et al., 1994), beginning with the development of a crust of blue-green algae, lichens, liverworts, forbs, mountain avens (*Dryas drummondii*) and sparse willows (*Salix* spp.). Mountain avens are an effective fixer of nitrogen and as a result dominate early-stage successional landscapes, alongside individuals of willow. By ~50 years ice free, Sitka alder (*Alnus crispa*) and willow are the dominant plant species, mountain avens is typically lost and cottonwood (*Populus trichocarpa*) begins to occur. After ~100 years, generally Sitka spruce (*Picea sitchensis*) dominates with an increasing contribution of Western hemlock (*Tsuga heterophylla*) through time. Forest canopies have tree densities varying from 250 to 370 trees per ha (Fastie, 1995), with tree height reaching ~40 m (Chapin et al., 1994).

As catchment glacial cover declines, the depletion and stabilisation of formerly deposited glacial sediment results in decreasing suspended sediment loads and increased channel stability in river systems (Sidle & Milner, 1989). The initial development of vegetation including trees in the riparian corridor acts to stabilise banks as their roots bind soils and ground cover decreases erosion, which in turn

further increases river channel stability. As riparian wood is accumulated into the river channel it provides a roughness element, causing significant local and reach scale alterations to hydrogeomorphic conditions (Klaar et al., 2011; Wenzel et al., 2014). Instream wood facilitates the continued development of instream geomorphic and hydraulic habitat (Milner and Gloyne-Phillips, 2005; Klaar et al., 2011). A peak in habitat complexity is observed in rivers at an intermediate age (~150 years), as instream wood begins to accumulate but channels still support high velocity habitat types (Klaar et al., 2009). Fluvial systems in the National Park have been aged based upon the time since glacier ice recession from the stream mouth using historic records and imagery (Milner et al., 2000). This allows for a space-for-time substitution approach to be applied in studies of their physical and ecological succession (Milner et al., 2008; Klaar et al., 2009; Klaar et al., 2015).

Four recently deglaciated ungauged catchments with long-term geomorphological records were selected for study: Wolf Point Creek, Ice Valley Stream, Berg Bay South Stream and Rush Point Creek (Table 1, Figure 2). These four catchments (~20–30 km²) span a 140-year age range (from 70 to 210 years; Table 1). Consequently, these catchments can be considered to represent diverse stages of paraglacial adjustment with varied catchment sediment stability and riverine development. Other than their stage of paraglacial adjustment and vegetative succession, these catchments share broad morphological similarities. These similarities allow for comparison of their morphological response to disturbances, including repeated high flows to be made. The study sites at each of these rivers are alluvial and support predominantly pool-riffle sequences (Montgomery & Buffington, 1997).

During the summer of 2014, recurrent intense precipitation events occurred from June to September, which resulted in the wettest summer period in a 30 year record (Milner et al., 2018), causing repeated flooding and high flows across the region of south-east Alaska and within Glacier Bay. Additional information regarding weather patterns and regional river flows are reported in Supplementary Information 1 (Supplementary Figures S1, S2 and Table 1). Through the summer, eight notable high flow events occurred, characterised by peak discharges exceeding twice the median daily

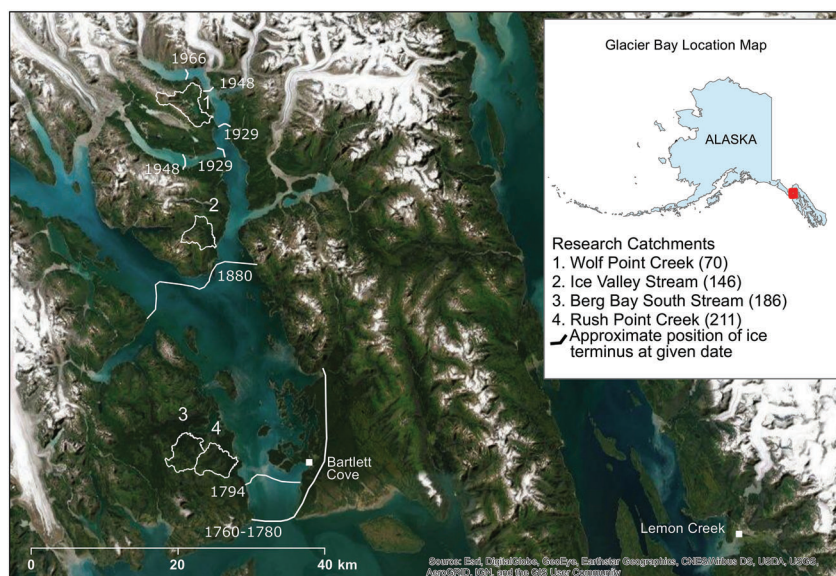


FIGURE 1 Map of Glacier Bay, Alaska, including location of study catchments (outlined in white; age recorded in parentheses, described time since ice recession from river mouths) and rainfall and river gauge locations (Bartlett Cove and Lemon Creek, respectively)

TABLE 1 Physical characteristics of study rivers. Adapted from Hill *et al.* (2009), Klaar *et al.* (2009) and Klaar *et al.* (2015). River age equals years since ice recession from mouth. Average discharge calculated from gauged flow in 2007. Reach gradient calculated over intensively studied representative reach. Estimated critical bed shear stress calculated using D_{50} (Berenbrock & Tranmer, 2008).

Site	River age (2014)	River length (km)	Average Discharge (m^3/s)	Reach Gradient (%)	Catchment size (km^2)	Max Elevation (m)	Mean Elevation (m)	Max Catchment Slope ($^\circ$)	Mean Catchment Slope ($^\circ$)	River order	Dominant substrate
Wolf Point Creek	70	2.2	2.3	1.1	29.8	817	317	52	11	2	Large Cobble
Ice Valley Stream	146	8.3	3.0	1.0	19.2	732	310	50	16	2	Cobble
Berg Bay South Stream	186	7.2	5.0	0.8	27.3	490	208	41	10	3	Gravel
Rush Point Creek	211	6.6	7.5	0.9	26.3	551	234	51	13	2	Gravel

TABLE 1 Continued

Site	Estimated critical bed shear stress (N/m^2)	Dominant riparian vegetation	Dominant catchment vegetation	Instream wood abundance (pieces per 100 m)	Instream wood key member diameter (m)	Instream wood piece length (m)	Instream wood structure dimensions (m)	Lake influenced
Wolf Point Creek	53.8–112	Alder <i>Alnus crispa</i>	Cottonwood <i>P. trichocarpa</i>	1.3	0.12	6.0	5.3×1.1	Yes
Ice Valley Stream	53.8–112	Cottonwood <i>Populus trichocarpa</i>	Sitka spruce <i>P. sitchensis</i>	1.3	0.18	9.5	10.6×2.7	No
Berg Bay South Stream	12.2–25.9	Sitka spruce <i>Picea sitchensis</i>	Sitka spruce <i>P. sitchensis</i>	1.4	0.29	14.0	13.8×3.2	No
Rush Point Creek	25.9–53.8	Sitka spruce <i>P. sitchensis</i>	Sitka spruce <i>P. sitchensis</i>	1.8	0.40	16.5	15.7×3.6	No

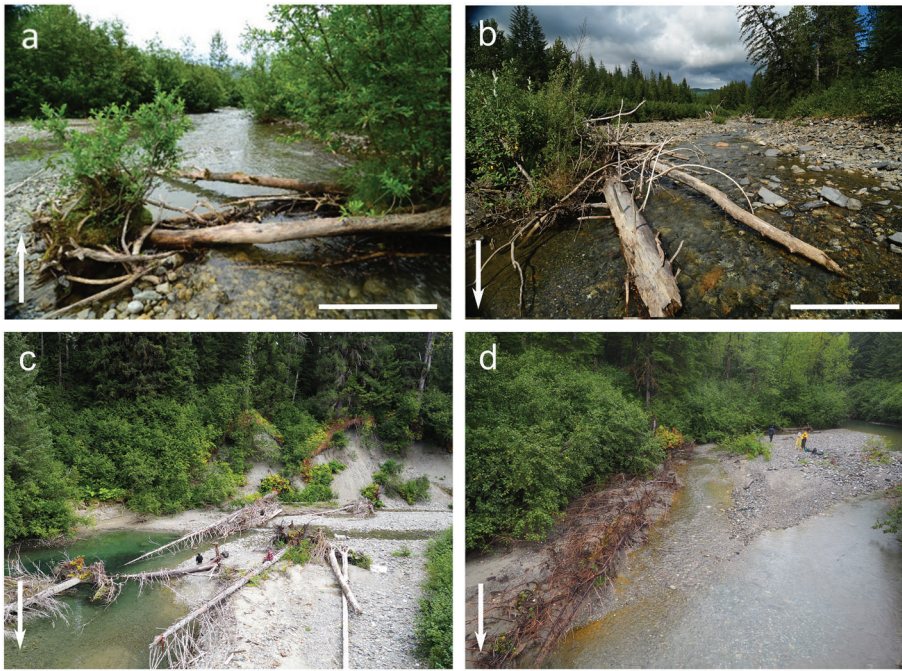


FIGURE 2 Channels at four study rivers: (a) Wolf Point Creek, (b) Ice Valley Stream, (c) Berg Bay South Stream and (d) Rush Point Creek. Direction of flow indicated by arrow. White lines provide 1 m scale in foreground of a and b, people provide scale in c and d

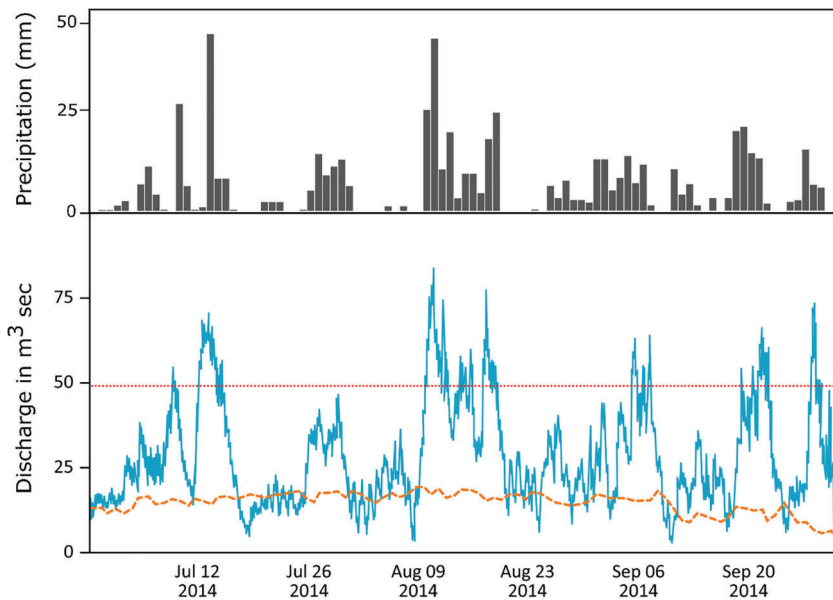


FIGURE 3 (a) Daily summer 2014 precipitation totals (mm) in Bartlett Cove, Glacier Bay and (b) Hydrograph for local stream Lemon Creek in 2014. Median daily discharge in orange over 33 years (1952–1973 and 2002–2016). Typical bankfull discharge for Lemon Creek (red; Curran *et al.*, 2016)

discharge. These included a series of three floods over nine days (10 August 2014 to 18 August 2014; Figure 3), and a flood with discharge eight times the daily median (Milner *et al.*, 2018). The regional extent of weather patterns observed during the summer of 2014 (Bond *et al.*, 2015), alongside the available precipitation and discharge data for local rivers, provides evidence for the occurrence of repeated high flows (flood and flow pulses) in the study rivers throughout the summer of 2014.

The absence of detailed river discharge data for our study rivers prevents the precise description of the form of each flow and flood pulse at each site and consequently precludes quantitative analyses of the relationship between river channel response and geomorphological effectiveness of floods. However, the data sets included in this study allow for valuable information to be gathered regarding the morphological response of rivers to a group of flow events.

2.2 | Geomorphological mapping of baseflow channels and analyses

Ground-based surveys of river planform were undertaken in two pre-high flow (2007, 2010, as reported in Klaar *et al.*, 2009, 2011) and three post-high flow (2015, 2016, 2017) years. River channel position was mapped over a minimum of 1.3 km, in all years except 2015 where surveys were completed over ~600 m, starting at the tidal limit of the river. Surveys were always undertaken during baseflow conditions to allow for comparisons of outputs between years. Mapping was completed to ~1 m accuracy using research-grade Global Positioning System (GPS) devices, Thales Promark 3 (Magellan, California) and Trimble GeoXT (Trimble Navigation Limited, Westminster, Colorado), and associated Mobile Mapper and Pathfinder software, respectively, to produce georeferenced shapefiles. Mapping of river channel geomorphology and hydrology were undertaken using a

Channel Geomorphic Unit (CGU) approach, first established in Glacier Bay National Park by Klaar et al. (2009). CGUs were mapped along the same survey stretches as planform surveys. During CGU surveys the thalweg length of each CGU was recorded moving downstream using a hierarchical visual approach based upon bed form, levels of turbulence and position within the channel (Hawkins et al., 1993, Klaar et al., 2009). To ensure consistency in the allocation of CGUs to CGU types across years, training was given to new surveyors by previous survey personnel. Surveys were completed at baseflow each year. GPS maps were checked for GPS accuracy errors and then lengths of all CGUs were extracted in ArcMap 10.4.1 (ESRI, 2011).

Subsequent spatial analysis of mapped data was completed in ArcMap 10.4.1 and summary metrics, outlined below, were calculated in Microsoft Excel 2013, R Studio version 1.1.456 and R version 3.5.1 (R-Core-Team, 2017). A braiding index was calculated (Equation 1), where the score equals the sum of all wetted channels counted in n cross sections of riverbed divided by n (Egozi & Ashmore, 2008).

$$\text{Braiding index} = \frac{\sum \text{number of wetted channels per cross section}}{n} \quad (1)$$

In this study, it was not possible to distinguish the main baseflow river channel from mapped secondary channels. Given the presence of braided sections in each river, it was not possible to calculate a main active channel sinuosity score, as proposed by Egozi & Ashmore (2008). Therefore, sinuosity here quantifies the meandering nature of the baseflow river channel. Baseflow river channel sinuosity was calculated using Equation 2, where sinuosity equals the total wetted length of the stream channel divided by the average number of wetted channels, divided by the downstream valley length.

$$\text{Sinuosity} = \frac{\text{total wetted channel length (m)} \div \text{average number of wetted channels}}{\text{downstream valley length (m)}} \quad (2)$$

A percentage metric of baseflow wetted channel positional persistence (persistence) was also calculated (Equation 3). The metric is based on the persistence of occupied raster cells between two surveys either both before, one before and one after or both after the floods. GPS line maps were converted to raster layers, and the raster calculator tool was used to create a new raster layer containing all cells occupied in both surveys (Supplementary Figure S3). The number of cells occupied in this new raster layer was divided by the total number of unique cells occupied across both surveys (i.e. sum of both raster layers cell counts minus number of shared cells). This was multiplied by 100 to create a percentage score, in which, a score of 100 means that the wetted stream channel was identical in both surveys (i.e. no grid cells representing a wetted channel were lost or formed). A score of 0 means no part of a wetted stream channel was shared between the two surveys (no grid cells representing a wetted channel were shared). Comparisons were allocated to one of three relative high flow periods (Table 2). No survey was available for Berg Bay South Stream in 2010 or Rush Point Creek in 2016, due to access limitations to these remote wilderness sites. As such, no pre-high flow comparison was made for Berg Bay South Stream.

TABLE 2 Year comparison allocations to relative high flow periods in persistence analyses.

Relative high flow period	Year comparisons
Pre-high flow	2007–2010
High flow	2007–2015, 2007–2016, 2007–2017 2010–2015, 2010–2016, 2010–2017
Post-high flow	2015–2016, 2015–2017 2016–2017

$$\text{Persistence} = \left(\frac{\text{number of raster cells occupied in both layers}}{\sum \text{number of unique raster cells occupied in each layer} - \text{number of raster cells occupied in both layers}} \right) \times 100 \quad (3)$$

The relationship between relative high flow period, the sites and persistence of the river channel was tested using a Wald chi squared test for difference based upon a GLM which incorporated relative high flow period and site into a model with the form: Persistence = $\alpha + \beta_1 \times$ relative high flow period (categorical – pre-high flow, high flow and post-high flow periods) + $\beta_2 \times$ site (Fox & Weisberg, 2011).

The locations of instream wood were recorded during mapping surveys. Instream wood was defined as pieces with trunk diameters >10 cm and lengths >1 m. This was then used to calculate instream wood abundance per 100 m channel length in each survey (Equation 4), by

$$\text{Instream wood abundance per 100m} = \left(\frac{\text{total number of instream wood pieces}}{\text{total wetted channel length}} \right) \times 100 \quad (4)$$

Channel geomorphological complexity was calculated using Shannon's Diversity Index (SHDI) calculated from raster layers using Equation 5 (McGarigal et al., 2012). SHDI increases from 0 to 1 as geomorphological unit type richness increases and/or as the proportional contribution of geomorphological unit types becomes more equitable.

$$\text{SHDI} = - \sum_{i=1}^m (P_i \times \ln P_i) \quad (5)$$

Principal component analysis (PCA) was used to explore relationships in summary planform metrics, proportional contribution of channel geomorphological unit types and geomorphological complexity (SHDI) between rivers through the study period including the 2014 high flows. Where covariates with strong pairwise correlations ($r_s > \pm 0.7$) were identified metrics were removed from the dataset depending upon their perceived relevance in response to high flows (R-Core-Team, 2017).

2.3 | Sediment and active channel cross sections surveys and analyses

A modified Wolman walk (Wolman, 1954) moving in a zigzag walk upstream was used to collect sediment b axis length data (nearest mm) from a minimum of 300 ($n = 300$ to $\sim 2,700$) sediment

particles at each river in 2008 and 2017 only. A minimum of 30 measurements were taken from sediment in at least 5 CGUs of each type found at each river. No sediment data collection was possible at Wolf Point Creek in 2008. These data were used to calculate D_{50} for each site and CGU type.

The Kolmogorov Smirnov test was used to test if the distribution of sediment b axis lengths were significantly different between years within and between rivers, p values were adjusted for multiple testing using a Bonferonni adjustment (R-Core-Team, 2017).

Cross sections established in the 1980s by Sidle & Milner (1989) in a reach representative of the wider river network were re-surveyed in a number of years pre- and post-high flow (years varied with sites, see Figure 4). A cross section was established at the upstream (cross section 1) and downstream (cross section 2) end of each representative reach. Elevation was measured at 0.5 m intervals across the river using a dumpy level (Topcon, Tokyo, Japan) mounted on an adjustable tripod. Streambed area (m^2) over a comparable area of river cross section was calculated for each cross section in each year available. From this, the change in total sediment area (%) and the persistence of cross section position (%) was calculated for pairs of years.

3 | RESULTS

During the pre-high flow period (2007–2010), persistence of the position of the baseflow wetted river channel was high (mean = $58.4 \pm 7.2\%$, Table 3) across all sites. The highest pre-high flow persistence score was recorded at the oldest site (Rush Point Creek – 65.8%), whilst the lowest score was recorded at the intermediate age (146 years) site (Ice Valley Stream – 51.5%). During the high flow event period, persistence declined at all sites (mean = $42.7 \pm 12.2\%$), with the lowest mean persistence scores observed at Berg Bay South Stream – $27.8 \pm 3.5\%$. Post-high flow persistence of the baseflow wetted channel remained lower than that recorded in the pre-high flow period (mean = $46.0 \pm 13.8\%$). However, Wolf Point Creek had the highest persistence score recorded during any period, with 72.6% of the wetted river channel remaining in the same position between surveys. Berg Bay South Stream post-high flow had the lowest average post-high flow persistence score (mean = $35.2 \pm 3.6\%$). Relative high flow period (pre-high flow, high flow and post-high flow) was found to be a significant predictor of persistence (Wald = 7.15, $p = 0.027$, Table 3). Site was found to be a significant predictor of persistence (Wald = 26.35, $p < 0.001$).

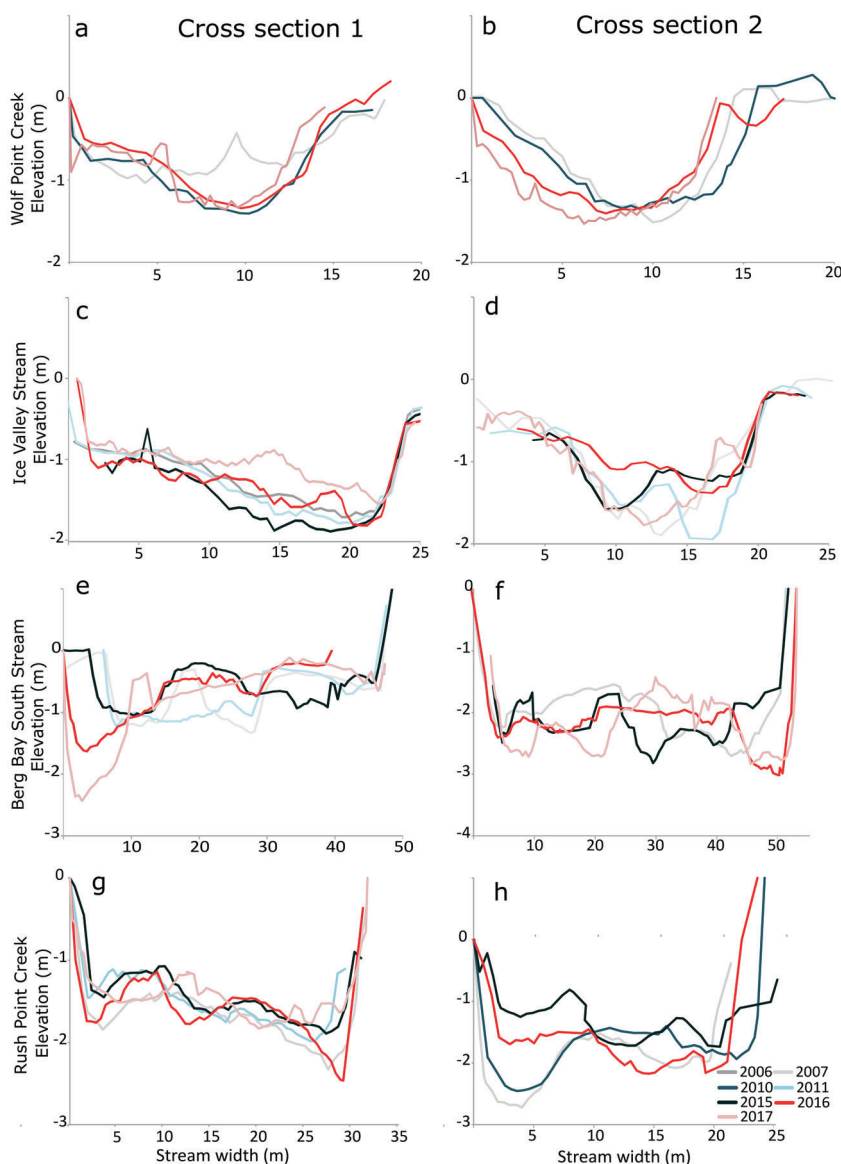


FIGURE 4 Riverbed profiles at two cross section at each site in pre- and post-high flow years. See legend for individual years: (a, b) Wolf Point Creek, (c, d) Ice Valley Stream, (e, f) Berg Bay South Stream and (g, h) Rush Point Creek

TABLE 3 Persistence scores for each relative high flow period at each site. Where multiple comparisons are made within a relative high flow period mean (± 1 standard deviation) is reported.

Site	Pre-high flow	High flow	Post-high flow
Wolf Point Creek	58.0	46.0 (± 6.5)	72.6
Ice Valley Stream	51.5	40.1 (± 8.5)	46.6 (± 11.0)
Berg Bay South Stream	NA	27.8 (± 3.5)	35.2 (± 3.6)
Rush Point Creek	65.8	54.7 (± 13.4)	50.0

Response of active channel cross sections varied through time both between and within individual sites (Figure 4, Table 4). At Wolf Point Creek, both cross sections demonstrated high persistence of position ($\geq 75\%$) during pre- (2007–2010) and high flow (2010–2016) comparisons. Both cross sections demonstrated degradation pre-high flow with up to a 19% loss of streambed area. The pair of cross sections saw contrasting responses during the high flow period with continued degradation of cross section 2 (16% of area) and aggregation at cross section 1 (12% of area). Limited change in stream bed area was observed post-high flow at either cross section ($\leq 3\%$), but at cross section 2, persistence fell to 56% with substantial erosion along the right hand bank.

At Ice Valley Stream, both cross sections showed high persistence of position ($>70\%$) pre-high flow, but some erosion of sediment (up to 16%) was observed. Cross section 1 experienced continued erosion during the high flow period (12%) but revealed a substantial change to active channel form with a decline in persistence of position to 48%. During the post-high flow comparisons, the cross section remained highly mobile with significant deposition of new sediment occurring from 2015 to 2016 and 2016 to 2017 (29% and 31% change in areas, respectively). Cross section 2 demonstrated initial deposition of sediment over the high flow period followed by an 18% decline in area from 2016 to 2017. Despite these changes persistence of position remained high $>70\%$ throughout the duration of the study.

At the Berg Bay South Stream pre-high flow percentage change in active streambed area was extremely low ($<1\%$). During the high flow period aggradation occurred at cross section 1 (4% change in area) and erosion at cross section 2 (5% change in area). Despite these low percentage changes, the area of sediment deposited and scoured were the second and third highest during the high flow period across all sites. During post-high flow years, erosion occurred at both cross sections with the largest and fourth largest (out of 13) total change in bed sediment observed for any site despite relatively low percentage changes ($<8\%$) and high persistence of position ($>75\%$).

The oldest site, Rush Point Creek, demonstrated a varied active channel response between the two cross sections. Cross section 1 was broadly stable following the aggregation of a large amount of sediment in the pre-high flow period (17% change) with the lowest topographical response ($<3\%$ change in sediment area) of any cross section. In contrast cross section 2 demonstrated substantial changes to form throughout the duration of the study. Substantial deposition occurred during the high flows (28% change in area) the largest area of sediment ($\sim 9.2 \text{ m}^2$) moved at any site during any relative high flow period. Persistence was low as a result of this deposition (54%) and remained low during the post-high flow period (67%). See Figure 5 for images of typical responses observed across the study rivers.

Pre-high flow trends in sediment b axis cumulative length frequency curves persisted following repeated high flows (Figure 6), with older sites (Berg Bay South Stream $D_{50} = 31 \text{ mm}$, Rush Point Creek $D_{50} = 37 \text{ mm}$) having finer sediments than younger sites (Ice Valley Stream $D_{50} = 76 \text{ mm}$, Wolf Point Creek $D_{50} = 84 \text{ mm}$; Figure 6). Significant sediment fining was identified in segment scale cumulative length frequency curves at Rush Point Creek (Table 5). In contrast, at Berg Bay South Stream, a loss of fine sediments was identified following flooding, resulting in statistically significant changes in cumulative length frequency curves (Table 5) between initial and post-high flow surveys. Trends in sediment size observed at the segment scale were mirrored in CGU specific cumulative length frequency curves (Supplementary Table S2 and Supplementary Figure S5).

Pre-high flow proportion of CGU types was consistent between years across the chronosequence (Figure 7). Post-high flow the extent of CGU compositional change varied across rivers. Wolf Point Creek demonstrated limited change in overall CGU composition following high flows, although an increase in the proportional contribution of rapids was identified, alongside a 50% loss of pre-high flow pool and backwater CGUs. A major shift in dominant CGU types from riffles to runs was observed at the intermediate aged river (Ice Valley Stream), occurring with increases in slow flowing CGU types (particularly pools) post-high flow. The oldest two rivers (Berg Bay South Stream and Rush Point Creek) saw an overall increase in the contribution of slow flow units during post-high flow years.

Instream wood abundance increased at all rivers from pre- to post-high flow (Table 6, Figure 5), except Wolf Point Creek where it declined from 0.9 to 0.3 pieces per 100 m. The largest increases from before to after the high flows occurred at Ice Valley Stream and Berg Bay South where wood abundance increased by 1.2 pieces per 100 m. An increase of 0.8 pieces per 100 m was observed at Rush Point Creek. During the post-high flow period wood abundance fluctuated at these three rivers. Braiding demonstrated no response to the high flows at Wolf Point Creek but increased slightly at all older rivers reaching the highest value at each river during 2015 the first post-high flow year. Sinuosity demonstrated declines from before to after the repeated high flows at all rivers except Rush Point Creek where no change occurred, although a small decline was recorded from 2015 to 2017.

A number of these summary metrics and geomorphological unit types demonstrated covariance, resulting in backwaters, glides, riffles and sinuosity being removed from the data set prior to PCA. PCA explained 44% of variation in the data set in one axis and an additional 23% of variation in the second axis (Figure 8). Principal component (PC) 1 was associated predominantly with geomorphological complexity (SHDI), proportional contribution of pools and instream wood abundance driving differentiation between sites along the first axis in

TABLE 4 Cross section sediment areas, and percentage change in total area and persistence of form between years.

	Cross section 1										Cross section 2						
	2007	2010	2015	2016	2017	2007	2010	2015	2016	2017	2007	2010	2015	2016	2017		
Wolf Point Creek																	
Area (m ²)	17.48	14.19	NA	15.83	16.11	14.98	13.60	NA	11.42	11.76	14.98	13.60	NA	11.42	11.76		
Area change (%)	-18.8	2010-2016	2015-2016	2016-2017		2007-2010		2010-2016		2016-2017	2007-2010		2010-2016	2015-2016	2016-2017		
Persistence (%)	75.1	11.6	NA	1.7		-9.2		NA	NA		81.8		-16.3	NA	3.0		
		86.4	NA	85.1		81.8		82.6	NA		81.8		82.6	NA	55.7		
Ice Valley Stream																	
Area (m ²)	17.96	15.11	13.25	17.13	22.50	14.24	13.28	15.04	16.87	13.78	14.24	13.28	15.04	16.87	13.78		
Area change (%)	-15.9	2008-2011	2015-2016	2016-2017		2007-2011		2011-2015		2016-2017	2007-2011		2011-2015	2015-2016	2016-2017		
Persistence (%)	75.2	-12.3	29.3	31.3		-6.8		13.2	12.2	-18.3	-6.8		13.2	12.2	-18.3		
		48.2	41.7	66.0		73.0		75.7	81.6	72.8	73.0		75.7	81.6	72.8		
Berg Bay South																	
Area (m ²)	90.40	90.64	94.69	90.01	88.07	102.05	NA	96.44	90.17	88.38	102.05	NA	96.44	90.17	88.38		
Area change (%)	0.3	2007-2010	2010-2015	2016-2017		2007-2010		2015-2016		2016-2017	2007-2010		2007-2015	2015-2016	2016-2017		
Persistence (%)	90.6	4.5	-4.9	-2.2		NA		-2.2			NA		-5.5	-6.5	-2.0		
		82.6	84.1	87.5		NA		87.5			NA		83.5	77.8	85.6		
Rush Point Creek																	
Area (m ²)	39.81	46.57	47.96	42.28	46.57	34.97	32.39	41.62	38.41	NA	34.97	32.39	41.62	38.41	NA		
Area change (%)	17.0	2007-2011	2015-2016	2016-2017		2007-2010		2010-2015		2016-2017	2007-2010		2010-2015	2015-2016	2016-2017		
Persistence (%)	81.6	3.0	-11.8	10.1		-7.4		28.5	-7.7	NA	-7.4		28.5	-7.7	NA		
		90.7	86.4	79.2		73.7		54.0	67.2	NA	73.7		54.0	67.2	NA		

FIGURE 5 River channel response images from study rivers – (a), (b) and (c) depict the same reach where the thalweg migrates, instream wood is deposited and riverbank erosion and instream wood recruitment occurs; (d) and (e) depict same reach where lateral migration of the baseflow channel occurs alongside river bank erosion and (f) is an example of instream wood recruitment and associated channel development

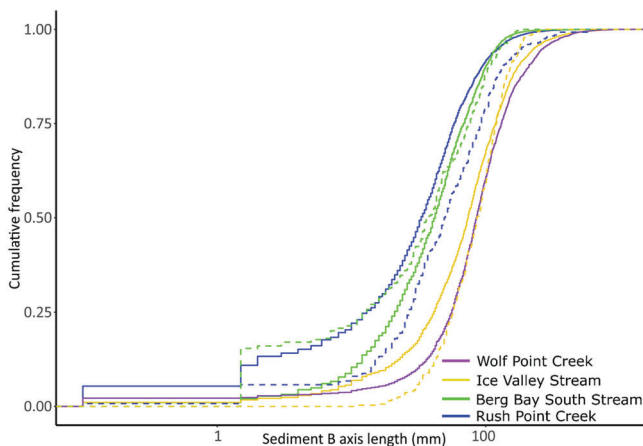


FIGURE 6 Full river segment sediment b-axis length cumulative frequency curves (solid lines post-high flow (2017), dashed lines pre-high flow (2008))

the PCA biplot. PC2 was predominantly associated positively with proportional contribution of runs and negatively with contribution of rapids. Pre-high flow years were spread across the negative and near zero PC1 values of the PCA plot. Post-high flow years at older sites

(Berg Bay South Stream and Rush Point Creek) were associated with positive PC1 values on the biplot influenced by high geomorphological complexity, contribution of pools and abundance of instream wood. In contrast, the youngest river Wolf Point Creek remained associated with negative PC1 and positive/near zero PC2 the plot, associated with a high proportional contribution of runs.

4 | DISCUSSION

Our study extends our current understanding of small river response to repeated high flows. In particular, three significant findings demonstrate the importance of repeated high flows as a driver of geomorphological change in rivers in recently deglaciated catchments, including accelerated paraglacial adjustment: (1) The high flows altered baseflow channel position and active channel form at all four rivers, highlighting the capacity of repeated high flows to influence morphology in low-order rivers. (2) Varied post-high flow responses were observed across sites with older rivers, which had higher instream wood availability and morphological complexity, demonstrating the highest levels of post-high flow change. (3) A conceptual model can be proposed which highlights the role of high flows in

TABLE 5 Kolmogorov Smirnov test p values (Bonferroni adjusted) for comparison of sediment size between years and across rivers.

	Ice Valley Stream 2008	Berg Bay South Stream 2008	Rush Point Creek 2008
Ice Valley Stream 2017	0.391	<0.001	<0.001
Berg Bay South Stream 2017	<0.001	<0.001	<0.001
Rush Point Creek 2017	<0.001	0.063	<0.001

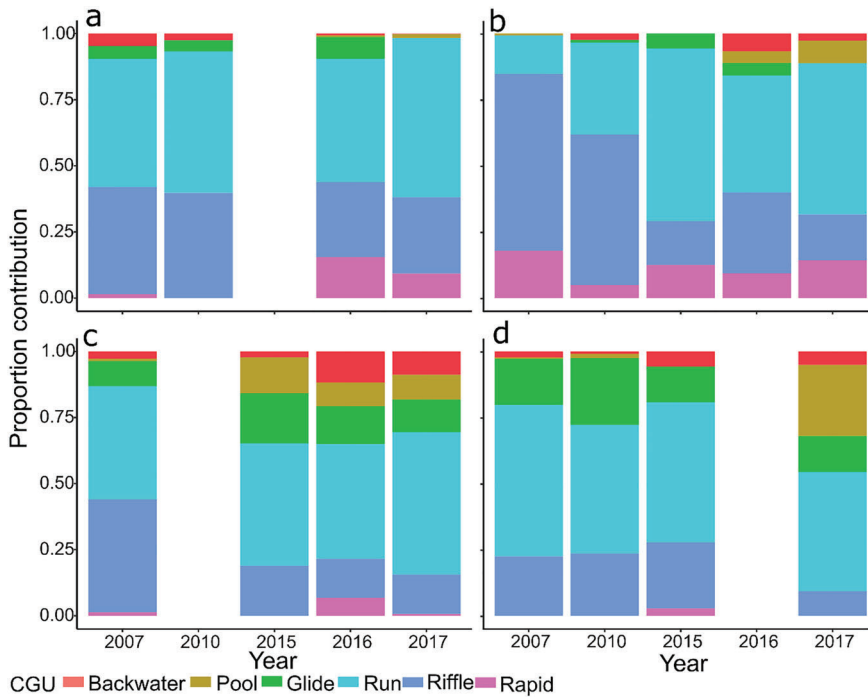


FIGURE 7 Cumulative proportion bar charts for (a) Wolf Point Creek, (b) Ice Valley Stream, (c) Berg Bay South Stream and (d) Rush Point Creek segments in all years

TABLE 6 Summary statistics of reach scale mapping

Site	Year	Wood abundance (pieces per 100 m)	Sinuosity	Braiding	Shannon's diversity
Wolf Point Creek	2007	0.9	1.4	1.2	1.10
	2010	NA	1.5	1.2	0.94
	2016	0.8	1.3	1.2	1.29
	2017	0.3	1.4	1.1	0.99
Ice Valley Stream	2007	1.3	1.8	1.2	0.87
	2010	NA	1.7	1.2	0.99
	2015	2.5	1.4	1.4	1.22
	2016	1.5	1.9	1.1	1.41
	2017	NA	1.4	1.2	1.23
Berg Bay South Stream	2007	1.2	1.3	1.4	1.15
	2015	2.4	1.2	1.5	1.37
	2016	4.1	1.2	1.4	1.60
	2017	2.4	1.3	1.3	1.40
Rush Point Creek	2007	1.6	1.5	1.1	1.09
	2010	NA	1.4	1.0	1.16
	2015	2.4	1.4	1.2	1.33
	2017	2.0	1.3	1.2	1.36

driving the ongoing development of river channel morphological complexity during paraglacial adjustment.

4.1 | River responses to repeat high flows

We demonstrate that repeated high flows are capable of causing substantial channel change in low-order rivers. The decreased wetted channel persistence and high levels of cross section change in relation to the high flows provides support for H1 that repeated high flows would drive a decrease in baseflow channel positional persistence and alter active channel form. Major changes to the form of the active

channel and shifts in the position of the baseflow channel have been reported for extreme floods (Milan, 2012; Dean & Schmidt, 2013). The observed positional change suggests the summer high flows (in 2014) exceeded the extrinsic geomorphological threshold of this study's river channels, with changes in base flow channel summary metrics at all sites (Downs & Gregory, 1993; Fryirs, 2017). A similar response has previously been reported for a series of repeated high flows (six flow and flood pulses) in a large gravel-bed river in which entire sections of the river channel network were reworked (Bertoldi et al., 2010; Surian et al., 2015). Our study extends these findings and indicates that flow and flood pulses are also capable of causing extensive in channel change in low-order rivers. An important future step in

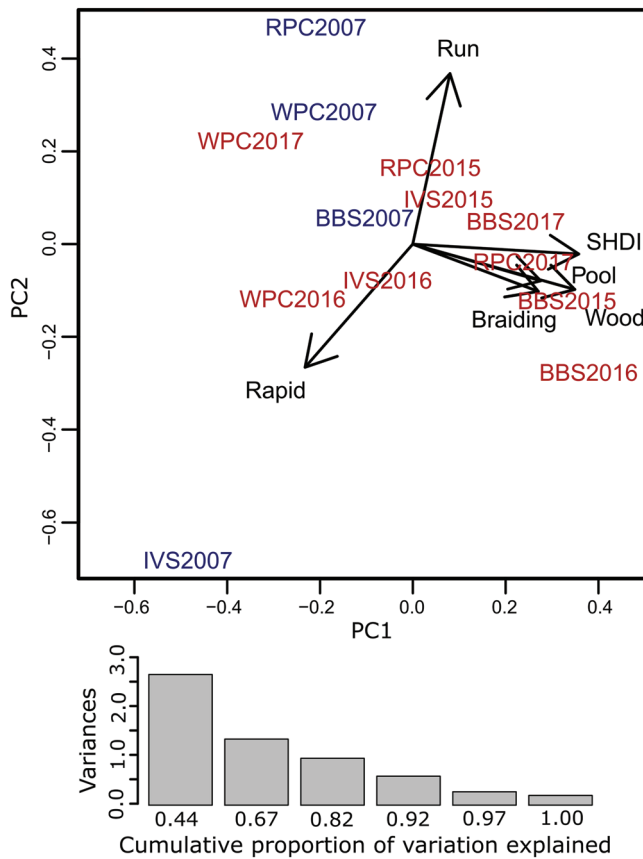


FIGURE 8 Principal components biplot with axis variances and proportion of variation explained. Pre-high flow years (blue) and post-high flow years (red)

understanding the role of high flows in river channel change is the quantitative analyses of the relationship between river channel response and geomorphological effectiveness of floods represents an important future step. To date this topic has received limited attention, with research mainly addressing extreme floods (Leyland et al., 2017). This is in part a result of the unpredictable nature of such high flows which makes field data collection challenging.

Of the four rivers, the lowest response in channel morphology to the repeated summer high flows occurred at the youngest river (Wolf Point Creek – 70 years since deglaciation). Active channel change was dominated by incision evidenced in the limited lateral migration and minor channel profile adjustment. This small response is consistent with that reported to similar floods in forested headwater rivers (Phillips, 2002). Geomorphological complexity reduced as a response to the repeated high flows with the loss of pool and backwater habitats and an increasing proportional contribution of rapids. In part the reduced morphological response at Wolf Point Creek, compared to the older rivers in this study, may result from the dominance of larger bed material and the presence of an upstream lake which can buffer flood flows and capture sediment (Jones et al., 2014b), although there can be substantial variability in this role (Leach & Laudon, 2019). In addition, the loss of instream wood from pre- to post-high flow recorded at Wolf Point Creek may have further limited the channel's response.

The three older rivers in the study demonstrated a number of consistent changes from before to after the 2014 high flows. Despite extensive baseflow channel positional and active channel form change

(of up to 75%), geomorphological complexity demonstrated resistance to the high flows with increases in the diversity of CGU types and the proportional contribution of low velocity CGU units (glide, pool and backwater). This increasing contribution of low velocity CGUs is likely to be associated with the accumulation of instream wood during the high flow period (Montgomery et al., 2003), driving the formation of low velocity CGUs (Abbe & Montgomery, 1996).

Instream wood accumulation was potentially the result of bank erosion and positional change observed at each site within the riparian forests. This process has been shown to be the dominant driver of wood recruitment in small catchments (Martin & Benda, 2001). Recruitment of instream wood is likely to facilitate further local baseflow channel positional change (Gomi et al., 2001; Jones et al., 2014a), with differences in wood characteristics determining the extent of channel response to the high flows. Larger individual wood pieces (30 cm to ~40 cm diameter and 10 m to ~20 m length) found at older study rivers (Klaar et al., 2011) are more effective roughness elements than smaller pieces (dominant at Wolf Point Creek), possibly enabling more extensive lateral and vertical channel change (Abbe & Montgomery, 1996; Montgomery et al., 2003; Mao et al., 2008).

4.2 | Post-high flow morphological response

Extensive morphological change following the summer high flows has been observed in the three older rivers in this study, during which the channels remained extremely active supporting H2 that the post-high flow response of active river channel form and baseflow positional persistence will be greatest at older sites. Such mobile channels have been reported in response to extreme floods in rivers of varying sizes where substantial volumes of sediment are mobilised during floods (Milan, 2012; Dean & Schmidt, 2013; Tunncliffe et al., 2017). To date, negligible evidence exists for similar responses following repeated high flows as observed in our study. Our findings indicate that high flows during the study period had the capacity to drive substantial baseflow and active river channel change, and therefore should be considered to represent important geomorphological events in low-order rivers.

In contrast to the substantial post-high flow responses of the three oldest rivers in this study, Wolf Point Creek demonstrated comparatively little change in the period following the high flows. There are a number of potential reasons for this limited response. The presence of an upstream lake may act to smooth the peaks of individual flow events (although it is unlikely to alter the total energy available for change) and capture sediment mobilised by the high flows reducing any increase to sediment supply (Arp et al., 2007). The loss of instream wood observed from pre- to post-high flow may further reduce the potential to maintain geomorphological complexity (Yarnell et al., 2006). Coarser bed sediment compared with other rivers may have acted as an armour layer preventing further bed degradation following change during the high flows (Wilcock & Southard, 1989). Whilst reported channel incision and reach scale straightening during the high flows period may have acted to increase average flow velocities conveying mobilised sediment downstream of the survey section and preventing the accumulation of any new instream wood (Wilcock, 1993). Given the other similarities of catchment and channel form between Wolf Point Creek and the older rivers it is likely in

combination the above factors governed the limited morphological response.

4.3 | Floods, sediment supply and paraglacial adjustment

Substantial wetted channel migration observed in both cross section and planform analyses, as well as turnover of sediment in cross sections, demonstrate that repeated precipitation-driven high flows have the potential to drive major morphological change mobilising sediment in recently deglaciated catchments. These catchments have previously been shown to become increasingly stable through time as riparian vegetation establishes, soils develop and bank cohesion increases (Sidle & Milner, 1989; Klaar et al., 2009; Klaar et al., 2015; Malone et al., 2018), consistent with well-established principles of landscape development (Gurnell et al., 2000). As banks are stabilised and sediments stored within alluvial channels, smaller flow events become limited in their capacity to mobilise sediments. Through this process the relative importance of larger flow pulses and floods increases as they become the dominant driver of sediment transport (Gurnell et al., 2000). Our findings offer some support for H3 that repeated high flow driven fluvial sediment transport represent an important element of ongoing paraglacial adjustment (Miller, 1990; Darby et al., 2007; Guerra et al., 2017). The morphological response of the four study rivers following the high flows mirrored the temporal development of geomorphological complexity already reported for Glacier Bay National Park rivers (Klaar et al., 2009). Here, we conceptualise the role of geomorphologically effective high flows in the paraglacial adjustment model (Figure 9), based upon findings from this study within the necessary context of the wider paraglacial adjustment literature.

The sediment supply/capacity ratio can dictate the capacity for geomorphological complexity in rivers (Yarnell et al., 2006), with peaks observed at intermediate levels of sediment supply and where roughness elements are abundant. Patterns observed as geomorphological complexity develops in our study rivers in recently deglaciated catchments (Klaar et al., 2009; Klaar et al., 2015). Sediment supply in these rivers is closely coupled to their stage of paraglacial adjustment,

declining through time as catchment geomorphology stabilises and sediments are sorted within paraglacial river channels (Carrivick & Heckmann, 2017; Lane et al., 2017). However, temporal variability in sediment supply, sediment transport and landscape connectivity has recently been reported demonstrating the complexity of these relationships (Micheletti & Lane, 2016; Lane et al., 2017; Comiti et al., 2019).

High flows and floods, including repeated flow and flood pulses as observed here, have the capacity to increase the relative sediment supply through bank and bar erosion (Kociuba & Janicki, 2014; Miller et al., 2014; Fox et al., 2016; Leyland et al., 2017). Additionally, instream roughness elements (wood) can interact with high flows further increasing sediment erosion (Abbe & Montgomery, 1996; Lester & Wright, 2009; Parker et al., 2017). Together, these high flow induced changes should act to elevate the potential for a river to support geomorphological complexity (Yarnell et al., 2006; Klaar et al., 2009), as observed following the high flows in the study rivers. Although not directly evidenced in this study, increased post-high flow sediment supply is supported by extensive baseflow channel migration and active channel change observed across rivers, and by significant sediment fining response observed at Rush Point Creek. A pattern linked to increased sediment supply in experimental and observational studies (Hassan and Church, 2000, Recking, 2012). Indeed, sediment supply has recently been shown to govern channel geometry in a dataset of over 300 rivers spanning North America (Pfeiffer et al., 2017).

Due to the unstable nature of freshly recruited sediments and the presence of newly recruited roughness elements flow pulses following main high flow events may be more geomorphologically effective than similar events pre-high flow. Increases in the potential for geomorphological complexity would be more significant still where stream power is insufficient to wash out instream wood allowing rapid local accumulation (Wohl & Goode, 2008; Wohl et al., 2016), as would be the case during smaller flood and flow pulses, enhancing the river channel's capacity for geomorphological complexity (Yarnell et al., 2006). These two factors combined appear to enable the rapid development of river geomorphological complexity under suitable conditions during and following high flows. This role of high flows in paraglacial adjustment theory may become increasingly significant and prevalent globally as glaciers continue to retreat

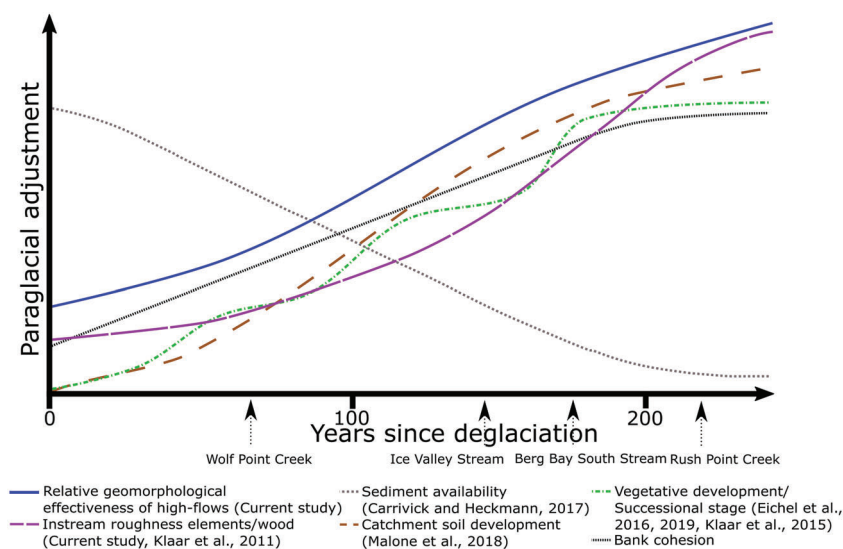


FIGURE 9 Model of paraglacial adjustment processes including relative geomorphological effectiveness of high flows

(Marzeion et al., 2014; Milner et al., 2017), and as rainfall becomes a dominant water source and falls more intensely under climate change (Trenberth, 2011; Berg et al., 2013).

5 | CONCLUSION

This study has quantified and explored the capacity of repeated precipitation-driven high flows to drive geomorphological change within rivers in recently deglaciated catchments. Repeated high flows caused significant change in baseflow channel planform persistence, adjusted active channel form, recruited large amounts of instream wood at three rivers and removed instream wood from the youngest river, with years following the high flows generally being associated with increased geomorphological complexity. Post-high flow geomorphological responses of river channels were more extensive in older rivers where instream wood was recruited and continued turnover of sediment was observed in cross sections. Inclusion of the relative importance of geomorphologically effective high flows into the paraglacial adjustment model identifies an important short-term (<10 years) driver of continued river development. Short-term geomorphological activity due to high flow pulses is likely to become increasingly pronounced both as glacial contributions to river flows decline in the future and as precipitation inputs become greater. Knowledge of such geomorphological activity will be important for understanding sediment supply, water quality and rapidly evolving riverine habitats, as well as for water and ecosystem resource management.

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ORCID

Lawrence J. B. Eagle  <https://orcid.org/0000-0003-0252-8450>

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SUPPORTING INFORMATION

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

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