Case study of a large summer flood on the North Slope of Alaska: bedload transport

J. P. McNamara, J. A. Oatley, D. L. Kane and L. D. Hinzman

ABSTRACT

The relative importance of snowmelt versus rain-generated floods on sediment transport in arctic streams is largely unknown because studies documenting either event-type are rare. An August 2002 precipitation event produced the largest discharge level (snowmelt or rain) over the previous ten-year period of hydrologic and geomorphologic monitoring in the Upper Kuparuk River, Alaska providing an opportunity to document the geomorphologic response to of an arctic stream to an extreme event. In this study we document the geomorphologic response and estimate the bedload transport rate using the virtual velocity method. This flood mobilized virtually the entire bed, with the exception of random boulders greater than 0.5 m. The channel cross-section and water edge survey data illustrate the considerable morphologic response generated by the flood. The magnitude of this response resulted in only a 13% tracer rock recovery rate. The total bedload transport was estimated to be 870 m^3 of bed material through the study cross sections. Channel morphology, and therefore habitat, is maintained by large and infrequent summer rain events. These events, particularly when they occur in the late summer months, when active layer depth is at its greatest, have the potential to generate orders of magnitude more bedload transport than a snowmelt runoff event. It is unclear, however, if the lack of significant bedload transport during snowmelt is due to protection by bedfast ice or if flows are insufficient.

Key words | Arctic, bedload, channel ice, floods, permafrost, sediment transport

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INTRODUCTION

Throughout the Alaskan Arctic the spring snowmelt runoff is generally the largest hydrologic event of the year. However, in the smaller headwater basins occasional summer rain events produce runoff that equals or surpasses the peak flow of the snowmelt runoff event (e.g. Kane *et al.* 2003). It is often assumed that smaller, more frequent, flows, as opposed to infrequent large flows, transport the most amount of sediment over time (e.g. Wolman & Miller 1960). However, in small Arctic streams during the snowmelt runoff period the river channel is commonly armoured by various forms of ice (bottom ice, bedfast ice and aufeis). Best *et al.* (2005) suggested that, because of bedfast ice, sediment is likely unavailable during the high-frequency (annual) snowmelt event and little geomorphologic work can be accomplished. This suggestion, however, has not been tested. The importance of large, infrequent summer rain events on channel maintenance is also largely unknown because few studies have documented the geomorphologic response of non-glaciated Arctic streams to high magnitude events.

In 1998 we initiated a monitoring program to document the impact of permafrost and channel ice on channel morphology. The maximum peak stream flow during the 10-yr period of record for the study site occurred the week of 15 August 2002. The peak flow rate was estimated to be 120 m^3/s. In addition to closing the Dalton highway, washing

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out culverts and damaging Trans-Alaskan Oil Pipeline service roads, this event put an unprecedented morphologic response within the study reach. This paper presents an analysis of the bedload transport and morphologic response that occurred during the 15 August 2002 event. This paper presents an analysis of the bedload transport rate using indirect methods and the morphologic response that occurred during the 15 August 2002 rain event.

SITE DESCRIPTION

The Kuparuk River drains 8,140 km^2 in the northeast corner of Alaska (see McNamara *et al.* 1998; Kane *et al.* 2000, 2003; Déry *et al.* 2005 for a detailed map of the location and discussion of its hydrological characteristics). The channel initiates in the Brooks Range and flows north through the foothills, across the coastal plain, and into the Arctic Ocean. The entire basin is underlain by permafrost, which ranges from 250 to 600 m in depth (Osterkamp & Payne 1981).

This study was performed in the upper reaches of the Kuparuk River, approximately 15 km downstream from channel initialization, and just upstream from where the river intersects the Dalton Highway and the Trans-Alaskan Oil Pipeline (Figure 1). At this location the stream is fourth order, based on USGS 1:63 360 maps, and drains an area of approximately 142 km^2 (McNamara *et al.* 1997, 1998, 1999). Upstream from the study location the watershed is essentially free from anthropogenic influences that could affect sedimentation processes.

The study site is characterized by a broad alluvial floodplain, with the primary vegetation being low shrubs and tussock tundra (Walker *et al.* 1989). Alternate banks tend to be steep, with occasional undercutting and sloughing occurring. There is a distinct channel thalweg and the pool-riffle spacing varies from approximately one to five channel widths within the reach. The channel length through the

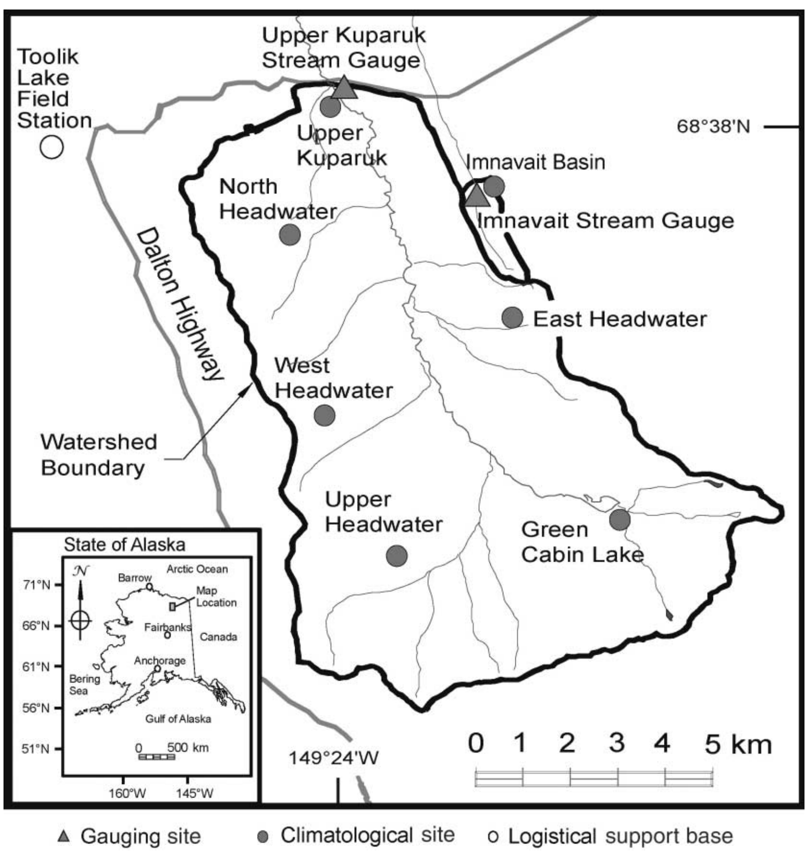

Figure 1 | Location map of study area in the Upper Kuparuk catchment; study area just upstream of gauging site.

study reach is approximately 400 m. The channel has a meandering, alternate bar, pool-riffle morphology. The reach average slope is 0.0075. The study reach features one long, straight length of channel followed by a right-hand bend (Figure 2). The bed material is primarily cobbles, with many boulders located throughout the reach. There is very little gravel in the thalweg, but significant amounts on bar tops. Wolman pebble counts performed throughout the reach yielded D50 values between 36 mm and 91 mm. At winter's end prior to ablation, this channel reach is often completely filled with aufeis (Yoshikawa *et al.* 2007).

The hydrology of the region is dominated by the cold Arctic climate. The open water season comprises only about four months of the year. Through the summer months, precipitation occurs primarily as rain, although summer snowfall accumulations are common (Olsson *et al.* 2002). The first stream flow peak each year is due to snowmelt (Figure 3), which tends to be larger than most summer peaks. However, there was a rain-generated stream flow peak greater than the snowmelt peak in four of the ten years presented in Figure 3.

A flood frequency analysis of rain and snowmelt generated peak flows is presented in Figure 4. Details of the analysis are presented in Kane *et al.* (2008). Flow rates for exceedence probabilities greater than approximately 20%

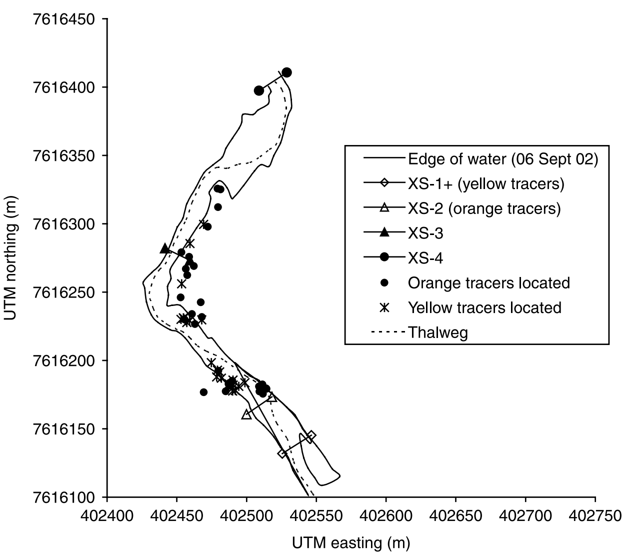

Figure 2 | A planform map of the study reach, showing the four cross sections. Also shown are the post-flood recovered tracer locations. The flow direction is south to north (bottom to top).

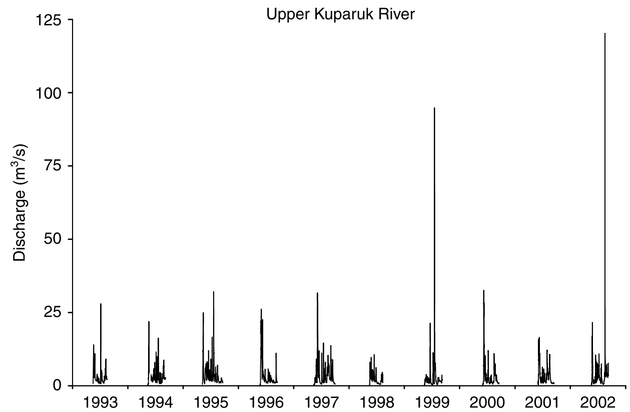

Figure 3 | Annual hydrographs for the Upper Kuparuk River. The first event each year is from snowmelt, all others are from rain.

tend to be similar for snowmelt and rain-generated floods. However, for low probability (high magnitude) events rain-generated flows are higher. The storm described in this paper has a Log-Pearson III exceedence probability of 3.5%, or a return period of 29 years (Figure 4). Whereas the peak flow for this storm was 120 m^3/s, the snowmelt-generated peak flow for the same exceedence probability is 42 m^3/s.

FIELD METHODS

The remote location of the study site, combined with the infrequent nature of bed load transport in the Upper Kuparuk River, made it impractical to monitor bed load transport continuously. We therefore used indirect methods including passive and active tracer rock techniques, scour chains, cross-sectional surveys and Wolman pebble counts.

Two groups of passive tracers in the form of brightly painted rocks with epoxy coating were placed in the study reach. The first group of 201 orange-painted tracers was installed in June 2000. This group ranged in *b*-axis size from 30 mm to 270 mm, with a median size of 60 mm, and was placed on the bed surface at cross section 2 (Figure 2). The initial location was at the top of a long, steep riffle. A second group of passive tracers was added in June 2001. This group of 182 yellow-painted tracers was located at cross section 1, near the lower end of a deep pool. These tracers ranged in size from 30 mm to 230 mm, with a median size of 85 mm.

A group of 19 radio-transmitter tracers were added to the orange tracers at cross section 2 in July 2001 following

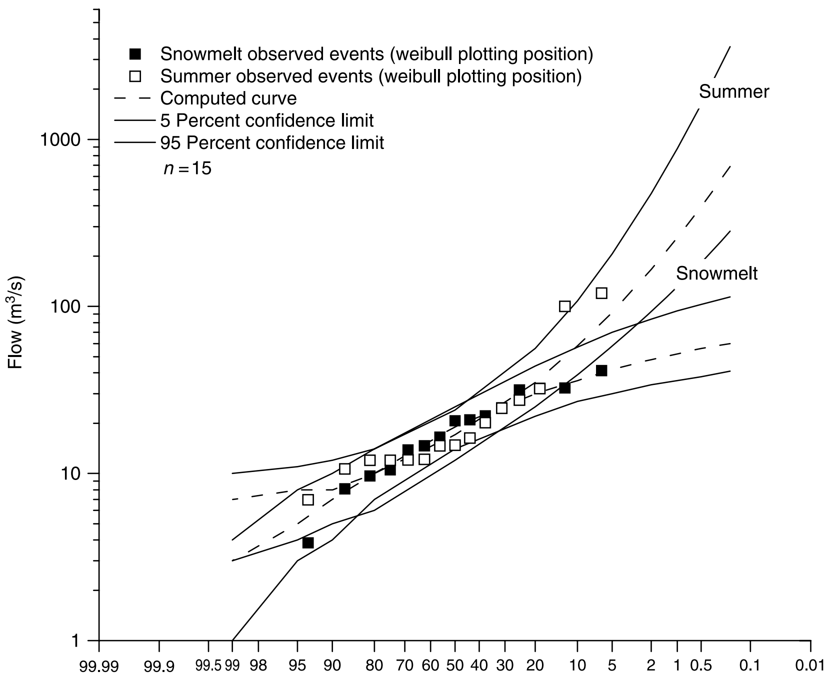

Figure 4 | Flood frequency analyses for the Upper Kuparuk River for high flows (both rain and snowmelt) and low flows (modified from Kane *et al.* 2008).

the methods of McNamara & Borden (2004). These tracers ranged in size from 50 mm to 150 mm, with a median size of 59 mm. To implant the radios required that a 15 mm diameter hole be bored 55 mm into the rocks. The radio transmitters were then bonded into the holes. The transmitters were programmed to emit a specific signal when stationary, and a different signal when in motion, in order to provide data of incipient motion, travel time and step frequency. A Telonics radio receiver and signal processor were used to monitor the radio-transmitter signals and a Campbell Scientific CR10X data logger was used to record all signals. The transmitters had a useful battery life of approximately 12 months and were intended to last from July 2001 through July 2002. This lifespan was achieved by using a quiescent standby period through the winter months from 1 October 2001 through 1 May 2002.

Channel cross-section surveys were conducted twice each year from September 1998 through June 2002 soon after the snowmelt runoff recession began and at the end of the open water season in late August or early September. In addition to cross-section surveys, detailed topographic surveys were performed in July 2002 and again in September 2002. The majority of the survey data were obtained using a total station electronic theodolite. Some survey data were also obtained using a Trimble survey-grade GPS unit.

Seventeen scour chains were located throughout the study reach. Scour chains are chains that are anchored deep in the bed material and are used to monitor scour and deposition. After an event, buried chains can be located with a metal detector and the material covering the chain can provide information about the size of material that was moved during the event. If scour has occurred during an event there will be more links exposed than there were prior to the event. Scour chains were surveyed after major rain events, after snowmelt, and every fall.

Wolman pebble counts were performed at eight different locations within the study reach to determine the surface material grain size distribution. Subsurface grain size surveys were determined on a bar top in cross section 1, both before and after the 15 August 2002 event. In determining the subsurface grain size distribution an area of 1 m by 1 m was selected. A surface pebble count was then performed. The bed material was then removed to a depth of approximately 2 × D84 (approximately 17 cm in this case). A volume of approximately 40 L of material was then removed from the area and sorted by size class. The size classes were then weighed and counted down to the 4 mm size class.

ANALYSIS METHODS

The objective of this analysis is to use information obtained from tracer rock movement during the 15 August 2002 event to estimate the total bed load transport during the event. The bed load transport rate can be estimated as a function of the virtual velocity of tracer particles. The virtual velocity, v_b, is defined as the total distance traveled by individual tracer particles divided by the time interval over which movement occurred.

The approach used in this analysis was presented by Haschenburger & Church (1998) and Wilcock (1997). The relationship used to calculate the mass rate of bed load transport, G_b, is given by

$$G_b = v_b d_s w_s (1 - p)\rho_s, \tag{1}$$

where

v_b = virtual velocity of bed load material (m/h)
d_s = the active depth of the streambed (m)
w_s = the active width of the streambed (m)
p = porosity of channel sediment
ρ_s = sediment density (kg/m^3)
G_b = mass transport rate of bed material (kg/h).

This method represents an estimate of the average bed load transport rate as the first three terms of the equation can each vary temporally and spatially during a given flood event. Haschenburger & Church (1998) relate this transport rate to the stream power at the peak discharge value for the event, with the stream power calculated by

$$\Omega = \gamma Q_p S, \tag{2}$$

where

Ω = stream power per unit length of channel (W/m)
γ = specific weight of water (N/m^3)
Q_p = peak discharge (m^3/s)
S = channel slope.

The virtual velocity of the bed load material can be calculated directly from knowledge of the tracer materials' initial and final positions, and knowledge of the time period between the initial and final movements. Typically this time period is taken as the total time that the minimum competent flow was exceeded during the event, as incipient motion data are rarely available in natural channel studies. In this study, a dimensionless critical shear stress, or Shields parameter, approach was used to determine the critical shear stress for incipient motion according to

$$\tau_c^* = \tau_c / g(\rho_s - \rho) d_{50}, \tag{3}$$

where

τ_c^* = dimensionless critical shear stress, or Shield's parameter
τ_c = γRS = shear stress at incipient motion (N/m^2)
γ = specific weight (N/m^3)
R = hydraulic radius (m)
S = energy slope (m/m)
ρ_s = sediment density (kg/m^3)
ρ = fluid density (kg/m^3)
d_{50} = median particle diameter (m).

Once τ_c was determined the channel cross-section geometry was analyzed to determine the hydraulic radius, R, cross-section area, A, and discharge, Q, required to generate the critical shear stress value. For this calculation the water surface slope, and therefore the energy slope, was assumed to approximate the reach average bed slope. The discharge at that flow depth was then calculated using Manning's equation:

$$Q = \frac{1}{n} R^{2/3} S^{1/2} A, \tag{4}$$

where

Q = discharge (m^3/s)
n = Manning's roughness coefficient
A = cross-section area (m^2).

Manning's roughness was determined by visual inspection and comparison to standard tables. Estimates of discharge using Manning's equation are subject to considerable error. However, previous estimates of discharge using Manning's equation at this site agreed favorably with established flow rating curves (Kane *et al.* 2003).

The discharge value from Equation (4) was considered to be the critical discharge for incipient motion. The hourly flow history for the study site was then investigated to determine how often the critical discharge value was exceeded, and how often this occurred during the snowmelt runoff period.

The active depth of the channel is the depth to which bed material is being mobilized. This is also a difficult parameter to determine, as there is generally no way to measure this directly during an event. Scour indicators provide the local maximum estimates, while burial depths of individual tracers provide local minimum estimates (Haschenburger & Church 1998). The active width is the width of the channel that contributes mobilized material. In marginally competent floods this can be less than the width of the channel. For a flood of the magnitude of the 15 August 2002 Kuparuk River event the active width can reasonably be considered to be the average channel width. No direct measurements of bed porosity, p, were made for the Upper Kuparuk River and there is little data of this nature available in the literature. Leopold *et al.* (1964) presents an average value of 0.25 for gravel bed-rivers. This value was used in this analysis.

RESULTS AND DISCUSSION

Morphologic response

The snowmelt events between 1998 and 2002 produced no appreciable changes in scour chain position, channel cross-section surveys or tracer position (data not shown). The 2002 rain event, however, generated a great deal of topographic change in the bed, with several areas aggraded by more than a meter, others that were degraded as much, and lateral bank erosion as high as 10 m. The primary geomorphologic changes involved the modification of existing bars, creation of new bars, severe bank erosion, and adjustment of the thalweg and water edge for similar discharges.

Cross section 1 (Figure 5(a)) underwent considerable changes during the event. The left bank was eroded by 4 m horizontally, the thalweg was scoured vertically by 0.28 m and shifted towards the newly eroded left bank, and an existing bar on river right was aggraded by as much as 0.75 m.

Cross section 2 (Figure 5(b)) was the initial location of the orange tracers. This section is located in a riffle. Typically

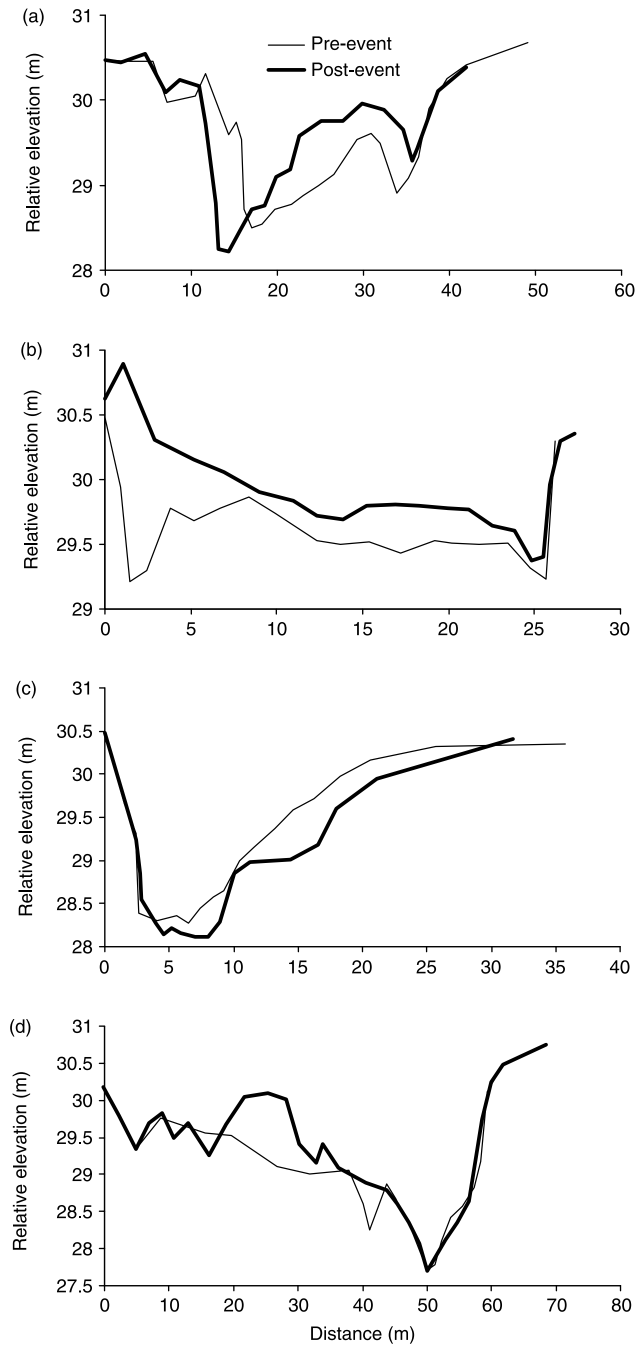

Figure 5 | Pre-event and post-event cross-secion surveys for (a) cross section 1, (b) cross section 2, (c) cross section 3 and (d) cross section 4.

riffles represent depositional regions and, as Figure 5(b) shows, that was the case during this event. There was deposition across the entire width of the cross section, with a large bar forming on river left that extended to the top of the left bank. This bar represents over 1.5 m of aggradation.

Cross section 3 (Figure 5(c)) was just below a sharp right bend in the channel. The left bank was stable through the event. There was some deposition in the thalweg, but most of the deposition occurred on the left bank where there was up to 0.58 m of deposition. Three scour chains on the left side of this cross section were buried deep enough that they could not be located with a metal detector (~0.5 m). It is possible that, near the hydrograph peak, there was erosion in this cross section that filled in during the falling limb, thus burying the scour chains deeper than the net aggradation.

Cross section 4 (Figure 5(d)) was at the end of the study reach. The left bank and thalweg were relatively stable. However, a scour chain located in the cross section was buried under cobbles and boulders up to 30 cm in diameter (median axis), indicating that the bed was mobile. A large bar formed on the left side of the cross section above the active channel.

Bed material grain size

Prior to the August flood the channel thalweg was primarily composed of large cobble material with some small cobble and large gravel present. This situation created a very open matrix with a great deal of void space. After the flood event, the difference in the bed material composition was visually obvious. There was a large amount of small and medium-sized gravel filling all of the void spaces that had been present. This would indicate that the winnowing process that removes much of the finer material from the channel occurs fairly rapidly.

The median grain size dropped from 48.8 mm to 39.4 mm for surface material, and from 13.2 mm to 5.8 mm for subsurface materials (Figure 6). This survey is the most direct comparison of the pre-flood to post-flood bed material conditions. However, it should be noted that, prior to the flood, the bar tops contained far more fine material than the thalweg, and the differences in the thalweg composition are even more pronounced.

Tracer movement

During the event of 15 August all 402 tracers moved from their initial positions. Only 54 of the original 402 tracers were recovered after the flood (Figure 2). The 13.4% recovery rate is low, even for visual tracers. Reports in the literature are frequently near 50%, with many as high as 90% and 100% for small events (Ferguson & Wathen 1998; Hassan & Church 2001). This can likely be attributed to the magnitude of the event and the size of the channel. The bulk of the tracer rock studies in the literature have been performed in smaller channels with much smaller competent discharge levels.

The battery life of the radio-transmitter tracers was intended to last through July 2002. By August, only five transmitters were emitting any signal and none were transmitting motion signals, due to a lack of battery power. Four of these tracers were located and recovered. A fifth was located but not recovered, as it was buried by more than a meter of material under a bar that was formed during the event. Of the four recovered, one was buried 30 cm deep, one was 15 cm deep, and two were imbricated in the surface layer. A yellow tracer was also recovered from a depth of approximately 30 cm while searching for a radio-transmitter tracer.

The mean travel distance for all recovered particles was 72.8 m. Figure 7 suggests that there was not a correlation

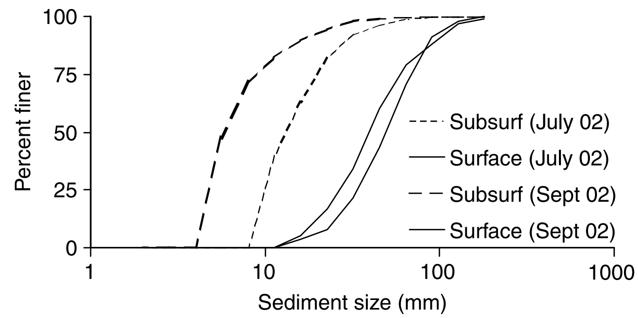

Figure 6 | The results of the grain size distribution surveys performed on the bar top in cross section 1 before, and after, the August 2002 flood.

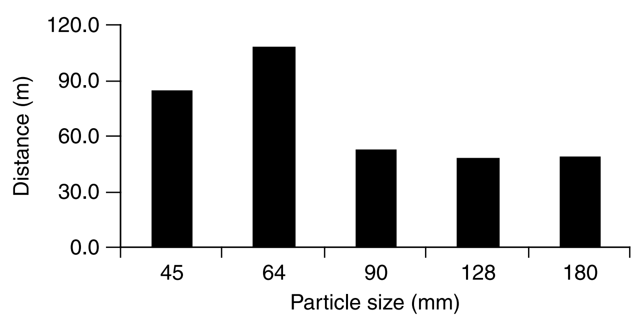

Figure 7 | Tracer material average distance traveled by half-phi size class, independent of initial placement.

between particle size and distance traveled. This suggests that there was equal mobility among all size classes, which is often reported to be the case in coarse particle channels when the entire bed is mobilized. The local morphology of the initial tracer placement appears to be a significant factor in the travel distance. The average travel distance for the tracers initially located at the top of the riffle in cross section 2 was 60.9 m. Those placed initially in the pool at cross section 1 traveled an average of 48% further, at 90.1 m.

Minimum competent discharge and bed load transport rate

Using a critical Shield's parameter of 0.06 and a median particle size of 70 mm in Equation (3) the critical shear stress for incipient motion is 69 N/m^2. Critical discharges calculated using Equation (4) are 15, 19, 15 and 17 m^3/s for cross-sections 1, 2, 3 and 4, respectively. The flow of 15 m^3/s was exceeded by 6 snowmelt events and 5 rain events between 1993 and 2002 (Figure 4). During the 15 August 2002 rain event, the competent flow was exceeded for approximately 53 h. This results in an average virtual transport velocity of 1.37 m/h.

The active depth was estimated to be 0.5 m. This is assumed to be the average active depth across the channel width. This value is based on the surveyed erosion and deposition within the cross sections, depth of the recovered radio-transmitter tracers, and the fact that several scour chains in the reach were no longer detectable using a metal detector that has a sensitivity to a depth of approximately 0.5 m. Locally there were many areas that underwent substantially more than 0.5 m of scour or deposition. However, taken over the entire study reach, an average value of 0.5 m is a conservative estimate. The active channel width was assumed to be the average channel width, which is approximately 24 m based on several surveyed cross sections in the vicinity of the tracer rocks.

Using these values in Equation (1), the event transported approximately 1732 metric tons of material through the study cross sections, or 33 metric tons/h. Assuming a material density of 2,650 kg/m^3 and a porosity of 0.25, this is equivalent to 870 m^3 of bed material. We acknowledge that this rough estimate is subject to errors in estimating parameters, including active depth, active width, critical Shield's parameter and others, and that those errors are compounded by using local measurements to estimate reach average parameters. However, we have attempted to use values that result in a conservative estimate of transported material.

Comparison of rain and snowmelt events

To address the question of dominant discharge it is necessary to compare snowmelt and rain events of equivalent discharge. Unfortunately, we do not have equivalent events. The 15 August 2002 rain event was several factors greater than any snowmelt event; a snowmelt event of this magnitude has not occurred during the period of record and would be extremely rare (Figure 4). During the period when we monitored channel morphology 3 of 4 snowmelt events produced competent flow (greater than 15 m^3/s). We did not observe significant channel change during the competent snowmelt events. Some scour chain locations underwent minor deposition or erosion of fine material, but there were no detectable changes to channel morphology. There are no rain-generated storms comparable to the competent snowmelt flows. We do not know if the dominance of summer rain events over snowmelt events for causing channel change is because permafrost and channel ice protects the channel, as proposed by Best *et al.* (2005), or if snowmelt events simply do not have sufficient flow to be effective. Regardless, the 15 August 2002 rain event produced significant channel change.

The suggestion by Best *et al.* (2005) that frozen sediments and bedfast channel ice protects the channel from bed load transport during snowmelt requires that both conditions persist through the competent snowmelt flow period. Our field observations suggest in some years this bedfast ice persists, while in other years bedfast ice lifts from the bed and "rafts" sediment downstream. The role of frozen sediments is unknown. However, recent studies have shown that substream thaw depth in gravel bed streams near the Kuparuk River increases much more rapidly than in adjacent soils (Brosten *et al.* 2007; Zarnetske *et al.* 2007, 2008). In early June 2004, approximately two weeks after snowmelt, the depth of thaw under a tributary stream of Toolik Lake was 100 cm (Brosten *et al.* 2007). Given that the active depth of the 15 August 2002 rain event was estimated to be only 50 cm, it is possible that sufficient bed material is available for transport soon after bedfast ice is gone.

CONCLUSIONS

The question concerning the dominant discharge (the discharge that produces the most amount of geomorphologic work over time) remains open because we do not have data on competent rain and snowmelt events of equivalent magnitude. We can say that large summer rain events that far exceed the theoretical competent flow cause considerable channel change and that snowmelt events up to 1.5 times the theoretical competent flow do not. It is necessary to observe bed load transport and channel change associated with summer storm of approximately 15–25 m^3/s. We do not know if rain events of comparable magnitude to the competent snowmelt events would move more material than the snowmelt events, nor do we know if snowmelt events equivalent to the 2002 event would move comparable material or even if such an event is possible. Regardless, we have shown that the maximum flood event of record that occurred on 15 August 2002 produced considerable channel change and bed load transport.

It is clear that the channel morphology, and therefore habitat, is maintained by large and infrequent summer rain events. These events, particularly when they occur in the late summer months, when active layer depth is at its greatest, have the potential to generate orders of magnitude more bed load transport than a snowmelt runoff event. It is unclear, however, if the lack of significant bed load transport during snowmelt is due to protection by bedfast ice or if flows are insufficient.

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