

# LATE-SUMMER PEAK IN SEDIMENT ACCUMULATION IN TWO LAKES WITH CONTRASTING WATERSHEDS, ALASKA

DAVID FORTIN<sup>1</sup>, DARRELL S. KAUFMAN<sup>1\*</sup>, MEGAN ARNOLD<sup>1</sup>, ERIK SCHIEFER<sup>2</sup> and  
NATHAN HAWLEY<sup>3</sup>

<sup>1</sup>School of Earth Sciences & Environmental Sustainability, Northern Arizona University, Flagstaff, USA

<sup>2</sup>Department of Geography, Planning and Recreation, Northern Arizona University, Flagstaff, USA

<sup>3</sup>National Oceanic and Atmospheric Administration, Great Lakes Environmental Research Laboratory,  
Ann Arbor, USA

*\*Corresponding author*

Fortin, D., Kaufman, D.S., Arnold, M., Schiefer, E. and Hawley, N. 2015. Late-summer peak in sediment accumulation in two lakes with contrasting watersheds, Alaska. *Geografiska Annaler: Series A, Physical Geography*, 97, 709–719. DOI:10.1111/geoa.12110

**ABSTRACT.** The timing of clastic sedimentation in two glacial-fed lakes with contrasting watersheds was monitored using sequencing sediment traps for two consecutive years at Allison Lake (Chugach Range, Alaska) and four months at Shainin Lake (Brooks Range, Alaska). Shainin Lake is a weakly stratified lake fed by distant glaciers, whereas Allison Lake is more strongly stratified and fed predominantly by proximal glaciers. At Shainin Lake, sediment accumulation started in late June and reached its maximum in mid-August, just before lake mixing and during a period of low river discharge. The grain size of the sediment reaching the sediment trap in Shainin Lake was homogenous throughout the summer. At Allison Lake, pulsed sedimentation of coarse particles during late summer and early fall storms were superimposed on the fine-grained sedimentation pattern similar to that observed at Shainin Lake. These storms triggered underflows that were observed in the thermal structure of the lake and deposited abundant sediment. The sequencing sediment traps reveal a lag between fluvial discharge and sediment deposition at both lakes, implying limitations to interpreting intra-annual sedimentary features in terms of inflow discharge.

**Key words:** lake sedimentation, glacier-fed lake, Alaska

## Introduction

Due to their high sedimentation rates and sensitivity to temperature and hydrological changes, glacially fed arctic and alpine lakes provide long, high-resolution records that are central to regional and global paleoenvironmental reconstructions (Ojala *et al.* 2012). Inter-decadal to inter-annual variability of clastic fluxes into these lakes,

measured from sediment density, varve thickness and sediment texture (grain-size distribution), have been variously interpreted as a combination of variable fluvial transport resulting from spring snow melt, summer rain and summer glacial melt, which are modified by internal lake processes (Hodder *et al.* 2007). The structure of rhythmic but non-varved clastic lake sediments from a glaciated watershed has also been related to summer rainstorms (Schiefer *et al.* 2011), whereas low-frequency changes in the accumulation rate of sediment in glacially fed lakes are often interpreted as changes in glacier size (proximity) and activity (Smith 1981; Leonard 1997; Bakke *et al.* 2005; Larsen *et al.* 2011).

Understanding the hydroclimatic and geomorphic controls on sediment transport and limnologic controls on deposition in glacier-fed lakes is important for improving paleoclimatic inferences from lake sediments. However, *in situ* sediment-flux measurements in glaciated watersheds are scarce, and instead, hydroclimatologic reconstructions from varved and non-varved clastic sediments are generally based on statistical correlations between sediment properties and instrumental climate data (Hughen *et al.* 2000; Bird *et al.* 2009; Cuen *et al.* 2010; Lapointe *et al.* 2012). While these correlations may provide the basis for calibration-in-time climate reconstructions, the physical mechanisms of sediment transport and delivery that govern the correlations often remain unknown. A processed-based approach is needed to test the inferred relations between sediment deposition and hydrological events within a watershed (e.g. Hodder *et al.* 2007; Cockburn and Lamoureux 2008). Sediment traps installed

Table 1. Physical characteristics of Shainin and Allison lakes and their watersheds

	Shainin Lake	Allison Lake
Lake area (km <sup>2</sup> )	4.5	1.7
Lake maximum depth (m)	25	55
Lake surface elevation (m a.s.l.)	840	410
Watershed area (km <sup>2</sup> )	143.2	13.2
Lake:watershed ratio	0.03	0.13
Total glacier area (km <sup>2</sup> ) <sup>1</sup>	1.70	2.18
Glacier:watershed ratio	0.01	0.17
Water depth above the trap (m)	23.0	33.0
Distance of the trap from inflow (km)	1.75	1.30

<sup>1</sup>Based on 2010 Landsat images.

within lakes, combined with fluvial and physical limnology monitoring, allow examination of the processes that govern sediment transport and accumulation in lakes (Hawley and Eddie 2007; Cockburn and Lamoureux 2008; Orwin *et al.* 2010), including how hydrological events are transmitted and preserved within lacustrine sediment sequences (Hodder *et al.* 2007).

Here we report results from sequencing sediment traps from two contrasting glacier-fed lakes in Alaska (Table 1). The lakes were originally selected for paleo-environmental reconstructions from lake sediments (Arnold and Kaufman 2012; Ceperley 2014). In addition to sediment coring and sub-bottom imagery, sediment traps were installed in both lakes to better understand the timing and mechanisms of sediment delivery to the floor of each lake. At Shainin Lake, the trap was installed near the depocenter of the lake, where seismic profiles and sediment cores show that accumulation rates are the highest. At Allison Lake, the distal location of the trap was chosen to better understand the timing of the sedimentation where the annual laminations (varves) are best preserved. The more proximal sites at Allison Lake are dominated by erosive turbidities that compromise the integrity of the sediment sequence. Although the two lakes were not at first selected for a comparative study, the data from the sequencing sediment traps highlight common and dissimilar mechanisms responsible for sedimentation in two contrasting glacier-fed lakes.

Shainin Lake is an arctic lake located on the north slope of the Brooks Range. Small distant glaciers that occupy approximately 1% of the watershed area feed the lake. The second site, Allison Lake is located in the subarctic Chugach Range. Glaciers

cover approximately 18% of the area of steep slopes of the Allison Lake watershed. At Allison Lake, the closest glacier is located 2.2 km upstream of the lake, whereas at Shainin Lake the glaciers are more than 20 km upstream. Combined with lake level, local and regional discharge, meteorological and grain-size data, we examine the timing of sediment accumulation in these lakes. Using lake temperature data acquired continuously during the trap deployment, we also explore the role of underflows on sediment fluxes near the bottom of the lakes.

## Study sites

### *Shainin Lake*

Shainin Lake (68.3° N, 151.1° W; 840 m a.s.l.) is a moraine-dammed lake located along the northern front of the central Brooks Range, Alaska (Fig. 1). The relatively shallow lake is fed by two main tributaries, Kayak Creek and Alapah River, which are confluent 6 km to the south (upvalley) of Shainin Lake. The primary inflow river cuts through a large emerged delta at the lake inlet.

The headwaters of Shainin Lake are located 25 km to the south, along the primary topographic divide of the central Brooks Range. The highest tributaries support two extant cirque glaciers, each <1 km<sup>2</sup>. Aerial imagery taken in 2007 shows that the largest glacier, West Alapah Glacier, covers about 0.9 km<sup>2</sup> of the 143.2 km<sup>2</sup> watershed. East Alapah Glacier, located approximately 1 km to the northwest, is half the size. Together the two cirque glaciers cover less than 1% of the surface area of the watershed. Despite their limited extent, the Alapah glaciers have a significant influence on the sedimentology of Shainin Lake as evidenced by the turbid water of Shainin Lake visible in aerial photographs and satellite images taken in multiple years. This turbidity results most likely from both the contemporary release of sediments in glacial runoff and from the fluvial erosion of inherited glacial sediment stored within the watershed during periods of high flow.

The climate of the central Brooks Range is polar (Fig. 2). The mean annual temperature at nearby (37 km east and 972 m a.s.l.) Anaktuvuk Pass station for the 1953–1973 period is −11.2°C and the annual average precipitation is 251 mm for the same period (National Climatic Center [NCDC], <http://www.ncdc.noaa.gov>, 1 September 2014). Precipitation mostly occurs as rain during the summer months and typically peaks in August (Fig. 2). Although the inflow and outflows to

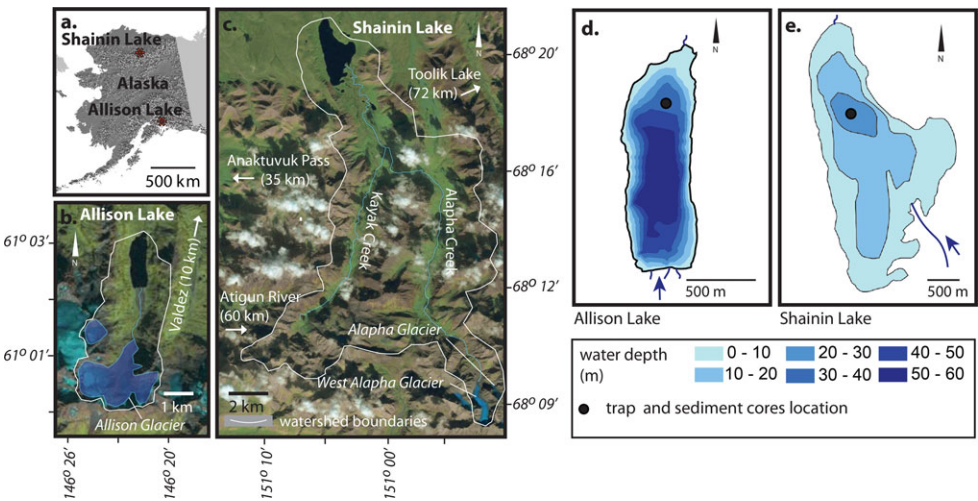


Fig. 1. (a) Location of the two watersheds. (b) Allison Lake and its catchment. (c) Shainin Lake and its catchment. (d) Allison Lake bathymetric map. (e) Shainin Lake and its catchment. Note that the figures have different scales.

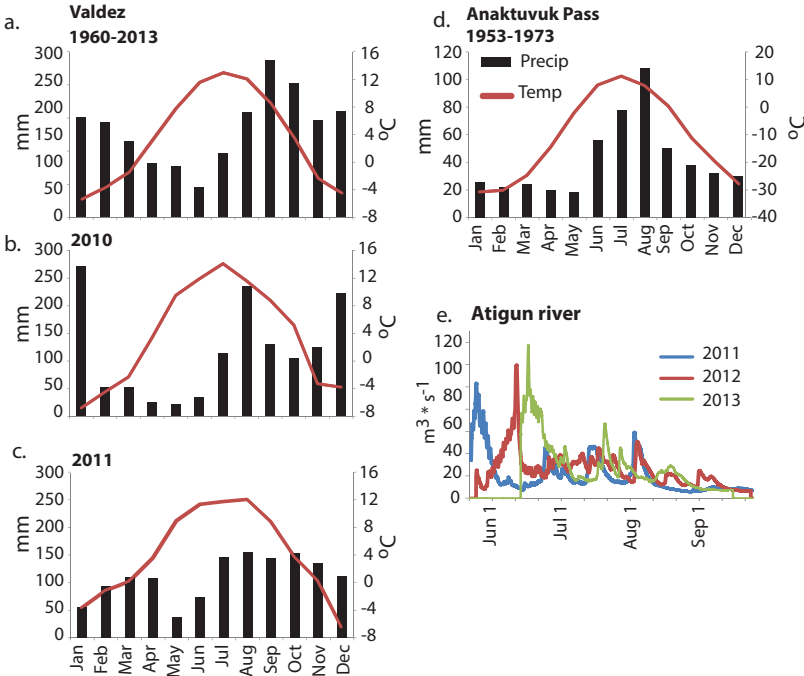


Fig. 2. Climographs for (a–c) Valdez weather station (509686) and (d) Anaktuvuk Pass (PAKP). Data from NCDC (<http://www.ncdc.noaa.gov>). (e) Atigun River discharge (USGS station 15905100, <http://waterdata.usgs.gov/nwis/rt/station?>).

Shainin Lake are not gauged, the level of Shainin Lake closely resembles the discharge of the Atigun River (USGS station 15905100), located 69 km east of Shainin Lake. Like Alapha Creek, the

Atigun River drains a major valley on the north side of the central Brooks Range. The discharge of the Atigun River is characterized by a sharp spring peak that typically occurs around mid June

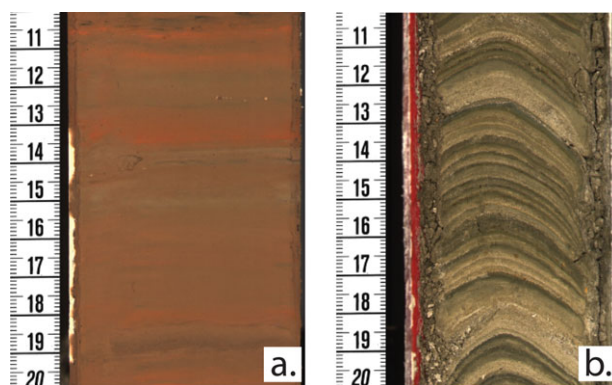


Fig. 3. Linescan images of sediments from (a) Shainin Lake and (b) Allison Lake. Scale is centimeters.

(Fig. 2). This spring freshet event is followed by smaller, rain-driven discharge events throughout the summer until early September. After September the temperature drops below freezing and precipitation occurs as snow.

Shainin Lake is dimictic, with weak summer stratification. At nearby Toolik Lake, ice cover typically spans from late November until early June (Environmental Data Center Team, [http://toolik.alaska.edu/edc/abiotic\\_monitoring/data\\_query.php](http://toolik.alaska.edu/edc/abiotic_monitoring/data_query.php), 23 Jul., 2015). The sediments of Shainin Lake are predominately laminated on scales of centimeters to millimeters (Fig. 3). These laminations are neither rhythmic nor annually deposited (Ceperley 2014).

#### *Allison Lake*

Allison Lake (61.05° N, 146.35 °W; 410 m a.s.l.) is situated in a deep glacier-carved trough about 9 km south of Valdez, Alaska (Fig. 1). Allison Glacier (informal name) is located 2.2 km upvalley from the lake and feeds a broad outwash plain, which borders Allison Lake on the south.

Valdez experiences a maritime climate. From 1960 to 2013 the mean annual temperature at Valdez, elevation 10 m a.s.l., was 3.9°C, mean annual precipitation was 175 cm, and mean annual snowfall was 724 cm (Fig. 2) (NCDC, <http://www.ncdc.noaa.gov>, 1 September 2014). Precipitation peaks in September, with an average monthly total of 24.5 cm. The hydrograph of the Allison Lake outlet is strongly bimodal, with peak flows during the spring snowmelt and late summer rainfall events (K. Pendergast, R&M Consultants, Inc., unpub.). Allison Lake is dimictic, with stronger summer stratification than Lake Shainin. In 2010, a sensor recording lake surface temperature

indicated that the lake was ice covered from mid November to mid June. The sediment accumulating in Allison Lake is rhythmically laminated (Fig. 2), and profiles of short-lived radionuclides indicate that the layers are formed annually (Arnold and Kaufman 2012). The varves are typically composed of one or multiple coarse-grained sub-laminations terminated by a clay cap, a structure typical of glacier varves (Ashley 1995).

#### **Methods**

The sediment fluxes arriving near the bottom of the lakes were measured using programmable sequencing sediment traps. We used the sequencing sediment traps described by Muzzi and Eadie (2002), which feature a motorized carousel of 23, 60 mL polyethylene sample bottles (Fig. 4) positioned at the base of a 1.6 m high collection tube with a 20-cm-diameter opening (8:1 aspect ratio above the collection funnel). The traps are a total of 2.1 m high and were anchored so that the top of the trap was 2.5 m above the bottom of the lakes. Temperature loggers installed on the mooring line recorded water temperature at 2 h intervals at the top of the trap, midway through the water column, and 2 m below the surface. One trap was positioned at the deepest point of Shainin Lake, and one each at the distal and proximal ends of Allison Lake (Fig. 1).

At Shainin Lake, the sediment trap was deployed from the ice surface in late April 2013. Sediment collection started on 5 May and continued with a new bottle rotation every five day until 19 Aug., when the trap was retrieved. A logger inside the trap registered the timing of the rotations. A water-level logger was installed 2 m below the lake surface on the same line. Water-level changes were reconstructed by adjusting for barometric

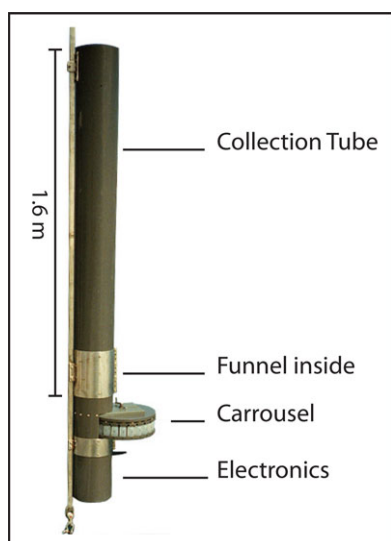


Fig. 4. Sediment trap designed by Muzzi and Eadie (2002) and used in the study.

pressure recorded at Toolik Field Station at 2 h time increments. In addition, daily discharge measurements of the Atigun River (USGS station 15905100), located 69 km east of Shainin Lake, were used for comparison with water-level data.

At Allison Lake, sediment traps were deployed during two consecutive years (2009–2011). One trap was anchored near the delta slope of the main inflow and a second trap in a distal location, at water depths of 42 m and 32 m, respectively. Both traps were deployed in early August 2009 and were programmed to expose collection bottles over 10–30 days intervals (Supplementary Information Table S1). However, due to malfunction of its motor, the proximal trap stopped capturing sediment in May 2010 and continued to malfunction following redeployment. The malfunction also occurred during the 2009 deployment, and therefore we do not use any data from the proximal trap. The distal trap captured samples continuously throughout both deployment years and was retrieved in July 2011. Daily discharge from the outflow of Allison Lake is used in the analysis (K. Pendergast, R&M Consultants, Inc., unpub.). The instrumental meteorological data come from the nearby station WSO located in Valdez (NCDC, <http://www.ncdc.noaa.gov>).

The trapped sediment was rinsed from the collection bottles, centrifuged prior to decanting, then air-dried and weighed. The organic-matter

content of the sediment recovered in surface sediment from both lakes is negligible (<5% based on loss on ignition at 550°C) and no adjustment was made in the flux calculations. The first sample of Shainin Lake (1–5 May) was discarded because it contained excess sediment that was inadvertently collected during failed attempts to anchor the trap.

Grain-size analysis was performed on the second year of Allison Lake samples and on all samples from Shainin Lake. The air-dried samples were treated with 30%  $\text{H}_2\text{O}_2$  to remove any organic matter and were subsequently deflocculated using Na-hexametaphosphate. Grain size was measured by laser diffraction using a LS-230 Beckman-Coulter analyzer, with 30 s of ultrasonic dispersion before each run. Very low sediment fluxes under ice cover precluded textural analyses of the winter samples. All of the time-series data collected in this study are presented in the Supplementary Information (Table S2).

## Results

### *Shainin Lake*

The extent to which 2013 was representative of the climatology at Shainin Lake is uncertain because over half of the instrumental weather data at Anaktuvuk Pass station are missing for 2013. The shape of the hydrograph of the Atigun River for that year (Fig. 2) is similar to the hydrographs of the two other years recorded at that station. Notably, in 2013, peak flow occurred late, on 17 Jun., compared with 25 May and 11 Jun. in 2010 and 2011, respectively. A total of  $9.2 \text{ mg cm}^{-2}$  of sediment was collected in the trap during the 105 days of exposure (average =  $0.09 \text{ mg cm}^{-2} \text{ d}^{-1}$ ). Although this value almost certainly includes the peak in sedimentation rate, it is nonetheless a minimum value for the annual sediment flux at the center of Shainin Lake. The sediment collected by our sampler in Shainin Lake is markedly fine grained (following pretreatment by deflocculent), with little change during the study period (Fig. 5) other than a slight decrease in the median and  $D_{90}$  as the season advanced. The median is consistently finer than  $10 \mu\text{m}$ , with  $D_{90}$  between 19 and  $25 \mu\text{m}$ .

**2013 snowmelt period.** Water level in Shainin Lake began rising on 1 Jun. following a few days of above-freezing temperature (Fig. 5). A few days later, diurnal temperature oscillations at the lake surface indicate that the lake became ice free. After a brief decline in water level during the first week of June related to subzero temperatures and a pause



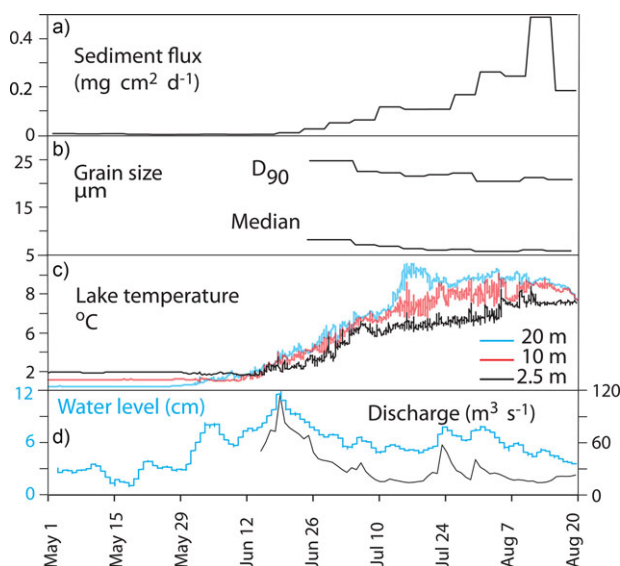


Fig. 5. Shainin Lake (a) sediment flux; (b) grain size, including median and coarse fraction ( $D_{90}$ ); (c) lake water temperature; depths are distance from the lake floor; and (d) discharge, showing Atigun River (USGS station 15905100) and water level at Shainin Lake above 20 Apr., 2013 level.

in snow melt, the lake level rose constantly from 8 to 17 Jun. On 17 Jun., Shainin Lake reached its maximum water level while the Atigun River registered its annual peak flow. Despite the highest inflow discharge, the period between 5 May and 19 Jun. accounts for only slightly more than 1% of the total sediment flux collected by the trap during the period of deployment. The first significant accumulation of sediment in the trap occurred one week after peak flow.

*2013 summer precipitation and glacial melt.* Apart from small precipitation-driven events, Shainin Lake water level and the Atigun River discharge stabilized after the initial spring freshet (Fig. 5). In contrast, the amount of trapped sediment increased during that same period to reach a maximum accumulation rate of  $0.5 \text{ mg cm}^{-2} \text{ d}^{-1}$  during the second week of August. The lake remained weakly stratified throughout the summer until mixing occurred on 19 Aug., the day we retrieved the trap. Interestingly, the temperature of the lake at 2.5 m above the bottom increased during the summer, following a pattern similar to the mid-depth and near-surface temperature. This whole-lake warming might have resulted from the passage of diffuse flows throughout the water column, or from weak mixing, but our data are not sufficient to confirm either possibility.

#### *Allison Lake*

The meteorological data from Valdez indicate that precipitation amount was nearly normal in 2009 and slightly below normal in 2010. Temperature during the study period was typical of the longer-term climate (Fig. 2). In 2009–2010, a total of  $79.1 \text{ mg cm}^{-2}$  of sediment was collected in the trap during the 361 days of exposure at the distal end of Allison Lake (average =  $0.22 \text{ mg cm}^{-2} \text{ d}^{-1}$ ). In 2010–2011, over a period of 351 days, a total of  $90.7 \text{ mg cm}^{-2}$  accumulated in the sediment trap ( $0.26 \text{ mg cm}^{-2} \text{ d}^{-1}$ ). The annual sediment flux to the site averaged  $87.3 \text{ mg cm}^{-2} \text{ yr}^{-1}$ . During the two years of observation at Allison Lake, late-summer storms were the dominant triggers to sediment delivery to the trap. These storms generated strong turbidity flows characterized by short-lived episodes of higher temperatures near the bottom of the lake than at mid-depth. The median grain size of sediment (following treatment with deflocculent) sampled during these three events ranges between 9 and  $16 \text{ μm}$ , with  $D_{90}$  between 22 and  $59 \text{ μm}$  (Fig. 6). The coarseness of the sediment delivered during these events distinguishes them from the fine-grained ambient sediment deposited during the rest of the late summer and early fall.

*2009 summer precipitation and glacial melt.* The distal sediment trap was first installed into Allison

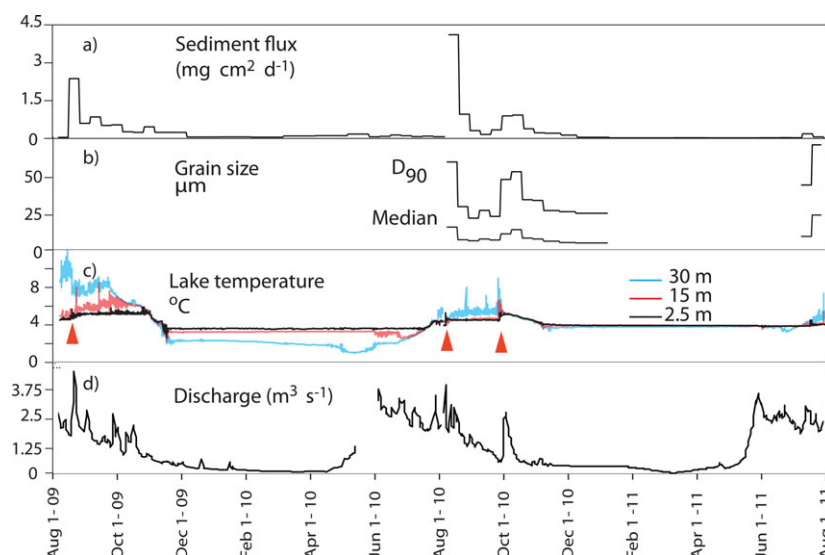


Fig. 6. Allison Lake (a) sediment flux; (b) grain size, including median and coarse fraction ( $D_{90}$ ); (c) lake water temperature; depths are distance from the lake floor, black triangles mark short-lived warm-water events ascribed to underflow currents and red triangles mark mid-depth temperature anomalies ascribed to interflow currents; and (d) outflow discharge of Allison Lake.

Lake on 5 Aug., 2009. On 16 Aug., a major precipitation event coinciding with late-summer high temperatures and hence a rain-on-ice and rain-on-bare ground (snow-free) resulted in the highest discharge for that sampling year (Fig. 6). On that same day, the water temperature at 2.5 m above the lake bottom increased almost  $1^{\circ}\text{C}$ , suggesting the passage of a turbid underflow, displacing the colder water upward. A few days later, on 20 Aug., and again on 10 Sep., temperature perturbations were clearly noticeable at mid-depth, suggesting the passage of strong interflows. During the four-month period from mid-August until mid-October, 80% of the annual sediment flux reached the trap. Notably, 29% of the annual sediment deposition occurred between 4 and 23 Aug., a period during which annual maximum discharge was reached and rain fell on the exposed glacier ice and on exposed glacial deposits. This likely mobilized a large amount of sediment and caused turbid lake inflows, presumably recorded as the passage of an underflow and interflows during that period. Maximum daily air temperature remained above freezing until the beginning of November and discharge of the outflow stream remained above  $1.7 \text{ m}^3 \text{ s}^{-1}$  until mid October.

**2010 winter and spring.** Following the decline in discharge and air temperature after mid-October,

sediment flux was negligible for three months. In April, snowmelt and outflow discharge increased as temperatures rose above freezing. During that period, only a small amount of sediment reached the trap. Despite a sharp rise in snow-melt-driven discharge culminating on 1 Jun., sediment flux to the trap remained low until the end of the sampling period on 20 Jul.

**2010 summer precipitation and glacial melt.** The trap was recovered then re-installed in Allison Lake on 4 Aug., 2010, following a strong rainstorm that precluded an earlier re-deployment. On the day of the trap deployment, discharge attained its peak for that sampling year, reaching over  $3.7 \text{ m}^3 \text{ s}^{-1}$  (Fig. 6). On that same day, the near-bottom temperature of the lake reached  $4.8^{\circ}\text{C}$  while a temperature of  $4.2^{\circ}\text{C}$  was recorded at 15 m, pointing toward the passage of a dense underflow for a few hours. During the first 10 days of the sampling interval, at the tail of the high-discharge event, 46% of the annual sediment flux had reached the sediment trap. A second rain-on-ice event, from 26 Sep. to 4 Oct., 2010, increased discharge sharply and resulted in another underflow on 26 Sep., once again characterized by an inversion of temperature near the bottom of the water column. That late-fall storm was associated with 20% of the annual sediment flux of trapped sediment. Together,

the period from 5 Aug. to 2 Nov. accounted for 94% of the total sediment flux for that sampling year.

*2011 winter and spring.* Unlike the previous sampling year when winter and spring accounted for nearly 20% of the annual sediment flux, the 2011 winter and following spring freshet, which culminated on 28 May, 2011, generated no significant sediment flux in the sediment trap. The last sample bottle closed on 19 Jul., prior to retrieving the trap.

## Discussion

### Trap efficiency

The extent to which the sediment caught in the traps precisely records sedimentation on the lake bottom is uncertain. The collection efficiency of sediment traps depends on their design, the physical conditions in the water, and the characteristics of the particles, mainly the settling velocity. Theoretically, the design of the traps used in this study, with the 8:1 aspect ratio above the collection tube, allows a fairly constant relative efficiency for currents velocities  $<12 \text{ cm s}^{-1}$ ; whereas, under-trapping is expected when currents are higher, with efficiencies of 75–95% between 12 and  $30 \text{ cm s}^{-1}$  (Baker *et al.* 1988; Buesseler *et al.* 2007). All sediment traps tend to have a bias toward more rapidly settling particles versus those that settle more slowly, and the higher the relative advective flow velocity, the less likely the trapped sediment will accurately represent the *in situ* flux in terms of the total mass and grain size (Buesseler *et al.* 2007). These biases, which have not been specifically studied in small lakes with high deposition rates, limit the interpretation of the sediment fluxes measured by the traps, and the ability to extrapolate across the lake floor.

Sediment trap efficiency can be evaluated by comparing the sediment accumulation rate in the traps with the rate estimated from sediment cores taken nearby the traps themselves. At Allison Lake, during two years of deployment, the annual sediment flux in the trap averaged  $87.1 \text{ mg cm}^{-2} \text{ yr}^{-1}$ . This translates to about  $1 \text{ mm yr}^{-1}$  based on a dry bulk density of  $1.18 \text{ g cm}^{-3}$ , which we measured in a surface core from this location. This compares with measured varve thicknesses that average  $4.4 \pm 2.3 \text{ mm}$  ( $\pm 1\sigma$ ) over the past 80 years. The amount of sediment captured in the trap therefore seems to under-represent the actual fluxes at the lake floor by a factor of at least 50% and likely higher. Without surface cores taken at the time of the retrieval of the sediment traps, this difference

cannot be calculated more accurately. The short period of trap deployment at Shainin Lake (105 days) and the absence of chronological control on the surface sediments preclude an accurate assessment of sedimentation rate based on surface cores at this site.

### Shainin Lake

The area of glacial cover in the catchment of Shainin Lake is only 1% of the basin area, and summer glacier melt is unlikely to have a significant impact on the hydrograph of Alapah River where it flows into Shainin Lake. The Alapah River channel pattern is meandering rather than a typical braided outwash plain, such as the one that feeds Allison Lake. However, the glaciers in Shainin Lake catchment supply sediment by direct glacial processes such as bed erosion, sub-glacial and intra-glacial sediment evacuation. Glacial sediments stored within the watershed most likely constitute another source of sediments available for fluvial transport during periods of high flow. Other studies in glacier-fed watersheds of Alaska have shown that the spring freshet contributes significantly to fluvial sediment transport (Riihimäki 2005; M. Loso, pers. com.), and we hence expect that the high-discharge spring freshet should have transported sediment to Shainin Lake. However, the 2013 spring peak flow resulted in insignificant sediment deposition during the first three weeks of June, but instead sediment deposition peaked while discharge of the Atigun River reached the lowest flow of the study period (Fig. 5). Over the study period, an inverse relation between discharge and sediment deposition was observed, somewhat similar to the pattern reported by Smith *et al.* (1982) at Hector Lake, a deep glacier-fed lake where sedimentation peaks in late summer when river discharge is moderate.

Relying solely on sediment trap data, we cannot determine if the absence of sediment deposition during the spring freshet is related to a delay between sediment delivery and sediment deposition or to a sediment-poor peak flow during snow melt. Assuming that sediment transport at Shainin Lake is positively related to river discharge throughout the spring and the summer, sediment aggregation could explain the observed pattern of late summer sediment deposition. Given the cohesiveness of fine glacial sediments, the physical, chemical and biological aggregation of particles (flocculation) is expected to occur in both lakes. Laboratory experiments have shown that physical aggregation of clay particles, or more specifically the formation



of larger particles due to the physical collision of smaller ones, increases their fall velocity (Samadi-Boroujeni *et al.* 2005; Fathi-Moghadam *et al.* 2011) and becomes more prevalent as sediment concentration increases. This physical aggregation, which occurs toward the end of the season when the particle concentration reaches a threshold level, was previously suggested as the primary mechanism for flocculation in glacier-fed lakes (O'Brien and Pietraszek-Mattner 1998; Hodder 2009). Alternatively, Shainin Lake watershed might be a sediment-limited system, or the inflow channels might be protected by snow cover during peak runoff. In either case, the spring freshet would not mobilize significant quantities of sediment, and the observed timing of sediment delivery to Shainin Lake would reflect the timing of glacial melt rather than the intensity of fluvial discharge.

It is also possible that the fine sediment intermittently stuck to the funnel walls of the trap and fell into the collection bottles after a sufficient amount had accumulated to induce slumping. Although such a mechanism may have introduced some short-term delay in the delivery of the sediments to the trap bottle, we do not believe that it is the primary control on the timing of sediment accumulation in the trap bottles.

#### *Allison Lake*

The timing of deposition observed at Allison Lake shares an important similarity with that observed at Shainin Lake; during the two years of monitoring, the spring freshet, which corresponds to annual peak flow or near annual peak flow conditions, resulted in very low or insignificant sediment accumulation. At Allison Lake, sedimentation was also mostly observed during the late summer, but contrary to Shainin Lake, these late-summer pulses appear to be driven by short-lived, high-discharge events that trigger sediment-rich underflows. The late-summer rainstorms responsible for these sediment-rich underflows occurred when the glacier hydrologic system was well developed and ample sediment sources were potentially available within the glacier and at its margins (Röthlisberger and Lang 1987; Riihimäki *et al.* 2005). Our estimate of underflow occurrences at Allison Lake is conservative; with loggers positioned 2.5 m above the lake bottom, bottom-hugging turbidity flows might not have been recorded. Additionally, the distal position of the trap at Allison Lake may have caused an additional underestimation of the occurrence of underflows.

The accumulation of fine-grained sediments during periods of low discharge at Allison Lake exhibit the same pattern observed at Shainin Lake, with an increase in sedimentation toward the end of the ice-free season. This shows that the formation of the clay cap, which constitutes a fundamental unit of a varve couplet, occurs before the onset of lake ice.

At neither lake does the pattern of lake-sediment deposition documented in this study agree with the timing of sediment transport observed in rivers of other glacierized watersheds. For example, during three years of observation of the outflow of Bench Glacier (1999–2002), located 30 km east of Allison Glacier, the spring freshet was associated with a sharp increase in stream sediment concentration (Riihimäki *et al.* 2005). Furthermore, sediment transported by the glacial stream was approximately proportional to discharge throughout the melt season, although an annual clockwise pattern of hysteresis was observed, with lower concentrations progressing from the spring to late summer despite similar discharge levels. Other studies of glacial-fed rivers have concluded that, where sediment is available, the quantity transported by outflow streams corresponds directly to meltwater discharge with hysteresis patterns related to changing sediment availability thorough the melt season (Hammer and Smith 1983; Fenn 1987; Gregory 1987; Fountain 1996). In the absence of fluvial sediment transport data, the timing of sediment deposition at both lakes may result from a sediment-limited system during spring snow melt.

#### **Conclusions**

This study demonstrates that monitoring a few physical processes in a lake and its catchment can provide key insights into the controls on sedimentation. At Shainin Lake, it demonstrates an important lag between fluvial sediment transport to the lake and deposition of fine-grained sediments ( $<10\ \mu\text{m}$ ) in the trap. At Allison Lake, where sediment deposition was monitored during two consecutive years, the bulk of the annual sedimentation in the distal part of the lake occurred during late fall storms that induced turbidity currents. The remaining part of the annual flux, composed of fine-grained sediments, did not settle under lake ice but rather during the late summer and early fall. To better understand the causes responsible for the absence of sediment deposition during spring freshet, fluvial sediment monitoring and sediment trap experiments should be combined.

Our results also indicate that a varve sequence such as the one at Allison Lake can be difficult to interpret in terms of annual climate. Over the two years of monitoring, sediment accumulation seems to reflect the occurrence of late summer and early fall storminess rather than summer temperature, discharge or annual precipitation. The potentially erosive nature of turbidity currents in some parts of the lake bottom also point toward caution when interpreting a sediment record such as the one from Allison Lake (Lambert and Giovanoli 1988; Schiefer *et al.* 2006).

## Acknowledgements

Jason Briner, Elizabeth Ceperley, William D'Andrea, Anne Krawiec, Barney Peterson, Heidi Roop, Caleb Schiff and David Vaillencourt assisted in the field, and Katherine Whitacre and Megan Saalfeld assisted in the laboratory. CH2MHill Polar Services and Toolik Field Station provided logistical support. Access to Shainin Lake was by permission of the Arctic Slope Regional Corporation. We are grateful to them for allowing access to their land. Copper Valley Electric Association commissioned the discharge data from Allison Lake. The Flagstaff office of the US Geological Survey allowed access to their grain-size analyzer. This study was funded by NSF awards ARC-1107662 (Shainin Lake), and EAR-0823522 and ARC-0909332 (Allison Lake). DF was supported by a postdoctoral scholar award through Northern Arizona University. Datasets were provided by the Toolik Field Station Environmental Data Center with support from NSF grants 455541 and 1048361. This is GLERL contribution # 1769.

David Fortin, Darrell Kaufman, Megan Arnold, School of Earth Sciences & Environmental Sustainability, Northern Arizona University, 625 S Knoles Drive, bldg. 12, Flagstaff, AZ 86011

E-mail: david.fortin@nau.edu, darrell.kaufman@nau.edu, arnold.megan.s@gmail.com

Nathan Hawley, NOAA / GLERL, 4840 S. State Rd., Ann Arbor, MI 48108-9719

E-mail: nathan.hawley@noaa.gov

Erik Schiefer, Geography, Planning and Recreation, Northern Arizona University, 19 W McConnell Drive, PO Box 15016, Flagstaff, AZ 86011-5016

E-mail: erik.schiefer@nau.edu

## References

Arnold, M.S. and Kaufman, D.S., 2012. Hydro-climate and sediment variations at Allison Lake, south-central

Alaska. In: *42nd International Arctic Workshop, Program and Abstracts 2012*. Institute of Arctic and Alpine Research (INSTAAR), University of Colorado at Boulder. 6–8.

Ashley, G.M., 1995. Glaciolacustrine environments. In: Menzies, J. (ed.), *Glacial Environments: Modern Glacial Environment: Processes, Dynamics, and Sediments*, vol. 1. Butterworth-Heinemann, Oxford. 417–444.

Baker, E.T., Milburn, H.B. and Tennant, D.A., 1988. Field assessment of sediment trap efficiency under varying flow conditions. *Journal of Marine Research*, 46, 573–592.

Bakke, J., Lie, Ø., Nesje, A., Dahl, S.O. and Paasche, Ø., 2005. Utilizing physical sediment variability in glacier-fed lakes for continuous glacier reconstructions during the Holocene, northern Folgefonna, western Norway. *The Holocene*, 15, 161–176.

Bird, B.W., Abbott, M.B., Finney, B.P. and Kutchko, B., 2009. A 2000 year varve-based climate record from the central Brooks Range, Alaska. *Journal of Paleolimnology*, 41, 25–41.

Buesseler, K.O., Antia, A.N., Chen, M., Fowler, S.W., Gardner, W.D., Gustafsson, O., Harada, K., Michaels, A.F., van der Loeff, M.R., Sarin, M., Steinberg, D.K. and Trull, T., 2007. An assessment of the use of sediment traps for estimating upper ocean particle fluxes. *Journal of Marine Research*, 65, 345–416.

Ceperley, E.G., 2014. *Reconstructing late Pleistocene and Holocene glacier fluctuations using cosmogenic <sup>10</sup>Be exposure dating and lacustrine sediment*, Brooks Range, Arctic Alaska, Master thesis, University at Buffalo, State University of New York. 115 p.

Cockburn, J.M.H. and Lamoureux, S.F., 2008. Inflow and lake controls on short-term mass accumulation and sedimentary particle size in a High Arctic lake: implication for interpreting varved lacustrine sedimentary records. *Journal of Paleolimnology*, 40(3), 923–942. doi:10.1007/s10933-008-9207-5

Cuven, S., Francus, P. and Lamoureux, S.F., 2010. Estimation of grain size variability with micro X-ray fluorescence in laminated lacustrine sediments, Cape Bounty, Canadian High Arctic. *Journal of Paleolimnology*, 44(3), 803–817.

Fathi-Moghadam, M., Arman, A., Emamgholizadeh, S. and Alikhani, A., 2011. Settling properties of cohesive sediments in lakes and reservoirs. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, July–August, 204–209.

Fenn, C.R., 1987. Sediment transfer processes in Alpine glacier basins. In: Gurnell, A.M. and Clarke, M.J. (eds), *Glacio-Fluvial Sediment Transfer: An Alpine Perspective*. John Wiley, Hoboken, NJ. 59–85.

Fountain, A.G., 1996. Effect of snow and firn hydrology on the physical and chemical characteristics of glacial runoff. *Hydrological Processes*, 10, 509–521.

Gregory, K.J., 1987. The hydrogeomorphology of alpine proglacial areas. In: Gurnell, A.M. and Clarke, M.J. (eds), *Glacio-Fluvial Sediment Transfer: An Alpine Perspective*. John Wiley, Hoboken, NJ. 87–107.

Hammer, K.M. and Smith, N.D., 1983. Sediment production and transport in a proglacial stream: Hilda Glacier, Alberta, Canada. *Boreas*, 12, 91–106.

- Hawley, N. and Eddie, B.J., 2007. Observations of sediment transport in Lake Erie during the winter of 2004–2005. *Journal of Great Lakes Research*, 33, 816–827.
- Hodder, K.R., 2009. Flocculation: a key process in the sediment flux of a large, glacier fed lake. *Earth Surface Processes and Landforms*, 34, 1151–1163. 10.1002/esp.1807
- Hodder, K.R., Gilbert, R. and Desloges, J.R., 2007. Glaciolacustrine varved sediments as alpine hydroclimatic proxy. *Journal of Paleolimnology*, 38, 365–394.
- Hughen, K.A., Overpeck, J.T. and Anderson, R.F., 2000. Recent warming in a 500-year paleotemperature record from varved sediments, Upper Soper Lake, Baffin Island, Canada. *The Holocene*, 10, 9–19.
- Lambert, A. and Giovanoli, F., 1988. Records of river born turbidity currents and indicator of slope failure in the Rhône delta of Lake Geneva. *Limnology and Oceanography*, 33, 458–468.
- Lapointe, F., Francus, P., Lamoureux, S., Saïd, M. and Cuvén, S., 2012. 1,750 years of large rainfall events inferred from particle size at East Lake, Cape Bounty, Melville Island, Canada. *Journal of Paleolimnology*, 48, 159–173.
- Larsen, D.J., Miller, G.H., Geirsdottir, A. and Thordarson, T., 2011. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvitarvatn, Iceland. *Quaternary Science Reviews*, 30, 2715–2731.
- Leonard, E.M., 1997. The relationship between glacial activity and sediment production: evidence from a 4450-year varve record of Neoglacial sedimentation in Hector Lake, Alberta, Canada. *Journal of Paleolimnology*, 17, 319–330.
- Muzzi, R.W. and Eadie, B.J., 2002. The design and performance of a sequencing sediment trap for lake research. *Marine Technology Society Journal*, 36, 2–28.
- O'Brien, N.R. and Pietraszek-Mattner, S., 1998. Origin of the fabric of laminated fine-grained glaciolacustrine deposits. *Journal of Sedimentary Research*, 68, 832–840.
- Ojala, A.E.K., Francus, P., Zolitschka, B., Besonen, M. and Lamoureux, S.F., 2012. Characteristics of sedimentary varve chronologies – a review. *Quaternary Science Review*, 43, 45–60.
- Orwin, J.F., Lamoureux, S.F., Warburton, J. and Beylich, A., 2010. A framework for characterizing fluvial sediment fluxes from source to sink in cold environments. *Geografiska. Annaler: Series A, Physical Geography* 92(2): 155–176.
- Riihimäki, C.A., MacGregor, K.R., Anderson, R.S., Anderson, S.P. and Loso, M.G., 2005. Sediment evacuation and glacial erosion rates at a small alpine glacier. *Journal of Geophysical Research*, 110, F03003.
- Röthlisberger, H. and Lang, H., 1987. Glacial hydrology. In: Gurnell, A.M. and Clarke, M.J. (eds), *Glacio-Fluvial Sediment Transfer: An Alpine Perspective*. John Wiley, Hoboken, NJ. 207–284.
- Samadi-Boroujeni, H., Fathi-Moghaddam, M., Shafae, M. and Samani, H., 2005. Modelling of sedimentation and self-weight consolidation of cohesive sediments. In: Kusuda, T., Yamanishi, H., Spearmant, J. and Gailani, J.Z. (eds), *Sediment and Ecohydraulics*, 1st edition. Elsevier, Oxford. 502.
- Schiefer, E., Gilbert, R. and Hassan, M.A., 2011. A lake sediment-based proxy of floods in the Rocky Mountain Front Ranges, Canada. *Journal of Paleolimnology*, 45, 137–145. doi:10.1007/s10933-010-9485-6
- Schiefer, E., Menounos, B. and Slaymaker, O., 2006. Extreme sediment delivery events recorded in the contemporary record of a montane lake, southern Coast Mountains, British Columbia. *Canadian Journal of Earth Sciences*, 43, 1777–1790.
- Smith, N.D., 1981. The effect of changing sediment supply on sedimentation in a glacier-fed lake. *Arctic and Alpine Research*, 13, 195–209.
- Smith, N.D., Venol, M.A. and Kennedy, S.K., 1982. Comparison of sedimentation regimes in four glacier-fed lakes of western Alberta. In: Davidson-Arnott, R., Nickling, W. and Fahey, B.D. (eds), *Research in Glacial, Glacio-fluvial, and Glacio-lacustrine Systems*. Geo Books, Norwich. 203–238.

Manuscript received 2 Oct., 2014; revised and accepted 17 May, 2015

## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Table S1. Collection bottle interval calendar.

Table S2. Excel workbook comprising four sheets with time-series data shown in Figs. 5 and 6.