ANCHOR-ICE RAFTING OF COARSE SEDIMENT: OBSERVATIONS FROM THE LARAMIE RIVER, WYOMING, USA

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ABSTRACT
Comparisons of ice rafted and bedload sediment samples collected in the Laramie River, Wyoming show that ice rafting is more efficient than bedload transport at transporting coarse sediment downstream. The average size of ice rafted sediment was 4.69 mm; bedload sediment samples collected during peak discharge averaged 0.92 mm in diameter. Although average ice rafted sediment is coarser than average bedload, there is overlap in the sediment sizes transported by these two processes. Ice rafting transports sediment from fine sand to boulders downstream. Anchor ice formation and ice rafting occur in the spring and fall when discharge is low, so the period of coarsest sediment transport does not coincide with peak discharge.

INTRODUCTION
Anchor ice, a derivative form of frazil (Tsang, 1982), is ice that forms on the bottom of rivers, lakes, and oceans. Formation of anchor ice in rivers causes many engineering problems, including blocked water intakes (Michel, 1971; Daly, 1991; Foulds and Wigle, 1977), decreased discharge (Arden and Wigle, 1972), and increased stage (Tsang, 1982; Yamazaki et al., 1998) that can cause local flooding. Environmental conditions leading to frazil and anchor ice formation have been studied in detail, with the goal of minimizing the adverse effects of these types of ice formation (Michel, 1971; Tsang, 1982; Daly, 1994). Anchor ice commonly forms in a supercooled, turbulent water column on cold, clear, windy nights. Although anchor ice can form on any size bed material, it preferentially forms on gravel and cobble substrates in riffles. Individual masses of anchor ice may rise off the bed at any time during the night, but most anchor ice is released from the bed in the morning when the sun warms the water (Michel, 1971; Arden and Wigle, 1972; Tsang, 1982).

When anchor ice releases from the bed it carries entrained sediment to the river surface. This entrained sediment (Figure 1) is transported downstream (ice rafted) as the released anchor ice drifts on the current. When the ice melts, the sediment sinks back to the bed. Thus, the diurnal formation and release of anchor ice results in ice-induced sediment transport (ice rafting) in rivers. There are many anecdotal observations of

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fluvial ice rafting (Barnes, 1928; Benson and Osterkamp, 1974; Michel, 1971; Arden and Wigle, 1972; Tsang, 1982), but beyond noting that anchor ice transports coarse sediment (sand to cobbles), there is little information on the anchor-ice rafting phenomena. In this paper, we compare the size of ice-rafted sediment to bedload sediment transported during maximum spring runoff.

Figure 1: Anchor ice with entrained sediment.

STUDY AREA
All observations for this study were made on the Laramie River, upstream of the city of Laramie, Wyoming. The Laramie River is a meandering, riffle-and-pool stream (type C5 of Rosgen, 1996) that flows through a large, semi-arid intermountain basin straddling the Wyoming/Colorado border (Figure 2). The drainage basin area upstream of the study area is 2000 km². The elevation at the study area is 2200 m. Pools, which make up 85% of the river, have coarse sand beds and slopes of $10^{-4}$. Riffle beds are composed of gravel and cobbles, and have slopes of $10^{-3}$.

Figure 2: Location map. The boundaries of the Laramie River drainage are shown by the dark stippling. All observations were made near the city of Laramie (black dot).
Although there are no large dams or reservoirs on the Laramie River, the river is heavily impacted by man. There are 67 irrigation diversions upstream of the study area (Thorburn, 1993). Most of these diversions are simple headgates built into the river banks, but there are a number of low-head dams up to 2 m high. Water diversion begins in the spring before the peak runoff associated with snowmelt, so spring and summer flows are reduced. These diversions are turned off after the growing season, so they have little impact on fall, winter, and early spring discharge. Thorburn (1993), using a synthesized mean annual hydrograph based on 30 years of data, estimates that peak spring flows are reduced by 60% from diversions. Using the 30-year measured hydrograph, Thorburn estimated the average maximum annual discharge is 14 m$^3$ s$^{-1}$ at present. The maximum annual discharge occurs around June 1. Between October and March, the river is 5 to 10 m wide, 20 to 50 cm deep, and has current speeds of 15 to 60 cm s$^{-1}$. Discharge during this period is less than 1.2 m$^3$ s$^{-1}$.

METHODS

Daily trips were made to the study reach during periods of potential anchor ice formation (November/December and February/March) from November 1999 to March 2002. These are transitional periods when there are significant amounts of open water along the river and the nights are cold enough to produce anchor ice. No anchor ice forms when there is a solid surface ice cover, between early December and mid-February. All the ice rafted sediment samples used in the statistical analyses are from released, floating anchor ice masses that were collected on mornings following anchor ice formation events. These samples were collected from two different locations: in the city of Laramie and 18 km upstream at Mears Ranch (Figure 2). River morphology (slope, width, depth, meander length), bed material, and flow characteristics are similar at the two locations. At the 95% confidence interval there is no difference between the mean grain sizes of the ice-rafted sediment samples from the two locations, nor from the two sets of bedload samples. Based on this, we assume the ice rafted sediment samples from the two locations come from one population. We also assume that the bedload samples come from one population.

Anchor ice samples were collected by wading into the river and holding a dip net at one location in the flow. When the net filled, we drained the excess water and transferred the ice to a 20 l bucket. The bucket was returned to the lab and the ice melted. Sediment was separated from melt water, and the sample was oven-dried and stored for later sieve analysis. Anchor-ice rafted sediment samples were collected in November 1993, and between November 1999 and March 2002. In addition to the random dip net samples, we made observations of the coarsest sediment that was found in floating and attached anchor ice masses. Specifically searching for the coarsest sediment gave us an indication of the largest bed material that anchor ice is capable of carrying.

Bedload samples were collected using the method outlined by Ryan and Troendle (1997). A BL-84 hand-held bedload sampler was used to collect composite bedload samples. The BL-84 is a 7.6 cm square metal nozzle with a 0.250 mm mesh bag attached. Twenty equally spaced verticals were used for each bedload sample, the verticals were spaced 45 to 75 cm apart along the sampling cross section. The sampler was placed on the bed for 1 minute at each vertical in a cross section. Bedload sampling cross sections were located towards the tails of pools, where flow was relatively uniform.
All bedload samples were collected between May 22 and 30, 2001. This was the period of maximum discharge in 2001. The coarsest material moved as bedload should have moved at this time. Discharge, measured concurrently with bedload, ranged from 1 to 10 m$^3$ s$^{-1}$.

Ice-rafterd and bedload sediment samples were analyzed by sieving. Sample particles between 19 and 0.0625 mm were sieved at 1/2 phi intervals (phi = –log$_2$ (grain size in mm)). Particles with intermediate axes >19 mm did not fit through the coarsest sieve, so their size was determined by hand. We weighed each of the coarse particles, and used the weights to determine ‘nominal diameters’ (diameter of a sphere having the same volume, Krumbein and Pettijohn, 1938). After sieving, the method of moments was used to determine the geometric mean grain size for each sample (Krumbein and Pettijohn, 1938). We use the geometric mean as a measure of central tendency because it is associated with the most abundant grains in an asymmetrical grain size distribution. The mean grain sizes from the individual samples are used to estimate the mean grain size for ice-raftered sediment and bedload sediment populations in the Laramie River. A modified form of the two-tailed t-test was used to test the null hypothesis that the mean grain sizes of ice-raftered sediment and bedload sediment are the same ($H_0$: $\mu_{\text{ice rafted}} = \mu_{\text{bedload}}$). An alpha of 0.05 was used. The modified form of the t-test was necessary because of inhomogeneity of the variances of the ice-raftered and bedload samples. In addition to mean values, we present probability plots of individual samples to give an indication of the distribution of sediment sizes found in individual samples.

RESULTS

Based on our observations from 1999 through 2002, there are, on average, 14 anchor ice formation events in the fall and 17 in the spring. The amount of anchor ice that forms during any given event varied from a few small patches to 25 % of the river bottom. The amount of anchor ice that forms is a function of the amount of open water and the ambient atmospheric conditions. In all cases, anchor ice formed on the Laramie River at night, and was released on the following mornings. Released anchor ice melted during the day. On the Laramie River, anchor ice formation, release, and the associated ice rafting are diurnal events. Anchor ice formation was most prominent in riffles with gravel beds. When an event was small, the only anchor ice would be 10-cm-diameter masses in the riffles. During large events, the bottoms of entire riffles would be covered with sediment laden anchor ice 20 to 30 cm thick, and small masses of anchor ice would be found throughout the sand bed of the pools.

The t-test results in the rejection of the null hypothesis, i.e. the mean grain sizes of ice-rafterd and bedload sediment are not the same ($t_{0.025} = 8.3$, $P < 0.001$, 31.7 degrees of freedom) (Figure 3). Based on rejection of the null hypothesis, we conclude that the mean grain size of ice-raftered sediment is greater than the mean bedload grain size. The mean grain size of ice-raftered sediment is 3.77 mm larger than sediment transported as bedload (range: 2.65 mm to 4.69 mm at a confidence interval of 95 %).

In addition to released anchor ice transporting, on average, coarser sediment than bedload, it also transports the largest individual sediment grains. The largest particle found in the 32 anchor ice samples measured 128 × 86 × 26 mm and weighed 450 g. Sediment particles larger than the coarsest sieve size (19 mm) were common in anchor ice samples. Although the 450 g particle was the coarsest sediment we retrieved in any
of our random samples, we saw many clasts much larger than that in floating and attached anchor ice masses during our daily trips to the river. The largest sediment particle we recovered from an anchor ice mass measured $280 \times 160 \times 30$ mm and weighed 1700 g. This is approaching the size of the largest bed material in the river, so it is clear that anchor ice can ice raft the largest sediment clasts found on the riverbed. In comparison, the largest clast from the 13 bedload samples measured $33 \times 16 \times 15$ mm and weighed 12 g.

Figure 3: Geometric mean grain sizes of anchor ice and bedload-transported sediment samples from the Laramie River. Circles mark the mean grain size of individual samples, bar marks position of the mean value, taken to be the population size.

Cumulative probability plots (Figure 4) show that released anchor ice does not just transport coarse material. Individual ice-rafted samples contain between 4 % and 70 % sand. The bedload samples contain between 45 % and 80 % sand.

The results from this analysis show that, although there is overlap in the size of sediment transported by ice rafting and bedload (Figure 4), the ice rafted material is, on average, 3.77 mm larger in diameter than the bedload (Figure 3). Anchor ice is capable of transporting all sediment sizes found on the river bed (Figure 4).

**DISCUSSION**

It is possible that our sampling methods result in a bias in the mean grain size of ice rafted and bedload sediment samples. This bias may occur because the anchor ice sampling technique preferentially excludes fine sediment or because the bedload sampler preferentially excludes the coarse material. The anchor ice samples consistently have more fine material (< 0.25 mm) than the bedload samples (Figure 4), so it seems unlikely that fine material is preferentially excluded. (The reason that there is little sediment < 0.25 mm in the bedload samples is because the mesh size on the BL-84 sampler is 0.25 mm, so smaller material, which is considered to be suspended load, washes out.) The other possibility is that the bedload sampler preferentially excludes the coarse material. This is a real problem when the size of bedload material approaches the size of the throat of the sampler (7.6 cm). The largest bedload clast is
much smaller than this, so it is probable that all sizes of sediment moving as bedload were captured by the sampler.

Figure 4: Cumulative probability plots for ice rafted and bedload sediment samples. Each line is the probability plot for one sample. Note that the x-axis scale is a base-2 log scale, with the coarsest sizes plotted on the left.

Another potential source of bias enters the analysis through the bedload sampling technique. Bedload samples were collected near the tails of pools, where the bed sediment is predominately sand, rather than in riffles, where the bed is composed of gravel and cobbles. Thus, there was no gravel in the sampling location. However, we visually checked the riffles downstream of our sampling sites after sampling, and rarely saw gravel moving in the riffles. Sand, either as sheet flows or ripples, was often seen transiting the riffles at peak flows. Based on these visual observations, we conclude that very little gravel was in motion anywhere on the river bed.

It is reasonable to compare the ice-rafted sediment samples to the bedload samples collected in the pools, because the ice-rafted sediment transits the pools. It is a paradox of ice rafting that coarse sediment is transported at the top of the water column rather than at the bed. Ice supplies the buoyancy to ‘suspend’ coarse sediment at the top of the water column, where it can move through low-velocity, low-shear-stress reaches. When the ice begins to melt, the entrained sediment settles to the bottom. Ice rafting can result in long transport trajectories for coarse sediment in riffle and pool systems like the Laramie River.

A final potential error source for the comparisons in this study also involve under-estimating the size of sediment transported as bedload. Because of low peak flows in 2001, the peak discharge during our bedload sampling was only 71 % of the 30-year average reported by Thorburn (1993). It is probable that larger sediment moves downstream as bedload during years with higher spring floods. However, the mean bedload grain size would have to increase by a factor of 5 to match the mean ice-rafted grain size (Figure 3). There is an even greater disparity between the coarsest materials moved as bedload and by ice rafting, so we are confident in our analysis that ice rafting is responsible for moving the coarsest sediment downstream.
When released anchor ice masses are observed floating down a river, it is the large entrained sediment clasts that catch the eye. This study shows that released anchor ice transports the coarsest sedimentary material downstream through the study reach on the Laramie River. This ice rafting occurs when flow is at a minimum. Coarse sediment transport during minimum flow is counterintuitive, and the effects of ice rafting on the overall sediment dynamics in rivers is unknown. There is a growing recognition that ice formation in rivers may have important effects on fluvial sediment dynamics (Ettema, in press). In rivers where seasonal ice covers form, the effects of anchor ice formation and ice rafting should be considered in any study of the fluvial sediment dynamics.

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