Measuring Gravel Bar Mobility in Large Rivers with Tracer Gravel

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Final Report No. ST-2022-8101-01

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14. ABSTRACT

The Bureau of Reclamation deployed 600 tracer clasts labeled with Passive Integrated Transponder (PIT) tags on gravel bars in the Methow River in the vicinity of the Sugar Levee near Twisp, WA in October 2018. The purpose of the experiment was to test a hypothesis that the Sugar Levee is disrupting sediment transport dynamics through the study reach and causing ‘excess’ deposition on a gravel bar downstream of the levee, resulting in bank erosion and property loss on the opposite bank. Searches for the tracers in 2020 and 2021 recovered and surveyed the locations of 448 (75%) and 356 (59%) of the rocks installed. Many rocks remain on the bar where they were installed, but a few have traveled more than a mile. Rocks installed on two bars adjacent to the levee are much more mobile than tracers installed further upstream. This is likely due to an increase in channel slope caused by incision adjacent to the levee.

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Acronyms and Abbreviations

D_{50}	50th percentile of a grain size distribution, or median grain size
D_{70}	70th percentile of a grain size distribution
GPS	Global Positioning System
ID	Identifier
PIT tag	Passive Integrated Transponder tag
Reclamation	Bureau of Reclamation
RFID	Radio Frequency Identification
USGS	U.S. Geological Survey
WY	Water Year

Measurements

cfs	cubic feet per second
ft	feet
kg	kilogram
m	meter
mm	millimeter
s	second

Contents

Executive Summary

The Bureau of Reclamation deployed 600 tracer clasts labeled with Passive Integrated Transponder (PIT) tags on gravel bars in the Methow River in the vicinity of the Sugar Levee near Twisp, WA. PIT tags equip each rock with a unique identifier that can be detected and read from a few feet away via Radio Frequency Identification (RFID) technology. The purpose of the experiment was to test a hypothesis that the Sugar Levee is disrupting sediment transport dynamics through the study reach and causing ‘excess’ deposition on a gravel bar downstream of the levee, resulting in bank erosion and property loss on the opposite bank.

The tracer rocks were installed on 4 gravel bars upstream of the levee and on 1 bar across the river from the levee in October 2018. Searches for the tracers in 2020 and 2021 recovered and surveyed the locations of 448 (75%) and 356 (59%) of the 600 rocks installed. Of the rocks installed on the furthest upstream bars (assigned the names Bar 0, Bar 1, Bar 2), 80% remain on the bar where they were installed. In contrast, 45% of the tracers installed on the bar immediately upstream of the levee (Bar 3) and 87% of the tracers installed on the bar across the river from the levee (Bar 4) have been eroded and transported downstream. Some tracers have traveled more than a mile.

We found a weak negative correlation between tracer size and tracer mobility, but it does not appear to explain the differences in tracer mobility. Instead, an increase in bed slope at the upstream end of Bar 3 continuing to the downstream end of the levee appears to be responsible for the enhanced sediment mobility adjacent to the levee. It seems likely that confinement by the levee has caused the river to incise adjacent to the levee, resulting in the increased steepness.

No tracers from Bars 0, 1, or 2 were found downstream in 2021. Tracers eroded from those bars have disappeared. They may be trapped in areas that were too deep or swift to search by wading or they may have been transported even further downstream.

All but three of the tracers found downstream of Bar 4 were installed on Bar 4. This over-representation of tracers from Bar 4 found downstream is also unexplained. This may be partially an artifact of the relatively low recovery rates but that seems unlikely to be the full explanation. Resolving this mystery requires finding more of the missing tracers and new techniques, such as a boat mounted RFID detector system, are needed to improve recovery rates.

Introduction

There is some evidence in the sediment transport literature that there is a relationship between the typical travel distance of gravel clasts in rivers and the spacing of gravel bars [*Hassan and Bradley*, 2017; *Pyrce and Ashmore*, 2003a; 2003b; 2005]. This makes intuitive sense although it is not easy to separate cause from effect: The gravel bars may act as traps that modulate sediment travel distance or the gravel bars are where they are because some other factor (another aspect of river morphology, the length of a typical flood, etc.) favors a particular travel distance and results in the construction of gravel bars.

The Sugar Levee occupies the right bank of the Methow River near Twisp, WA (Figure 1). The levee prevents the river from migrating to the south. Our hypothesis is that the levee is disrupting the typical bar-to-bar sediment transport dynamics, resulting in ‘excess’ deposition on a point bar downstream of the levee that is causing erosion on the opposite bank. To test this hypothesis, we conducted a gravel tracer experiment using 600 rocks labeled with Passive Integrated Transponder (PIT) tags. The PIT tags equip each tracer clast with a unique identifier that can be detected from up to about 1 m using a portable radio frequency identification (RFID) system. PIT tagged gravel tracking is a well-established method for observing sediment transport in rivers [*Bradley and Tucker*, 2012; *Olinde and Johnson*, 2015; *Phillips and Jerolmack*, 2014; *Phillips et al.*, 2013].

Study Area

The Methow River in north-central Washington is a tributary of the Columbia River that flows mostly south from headwaters on the east side of the North Cascade Mountains (Figure 1). The study area is centered on the Sugar Levee about 1 mile north of the town of Twisp, WA on the east side of State Route 20. The drainage area at the site is about 1074 mi^2. Mean annual precipitation is 35.6 inches [*USGS*, 2022]. The elevation at the upstream end of the study reach is about 1605 ft dropping to 1580 ft and the downstream end of the study reach. The average slope over the reach is 0.003. High flows capable of mobilizing sediment during the study period have been driven by snowmelt in the late spring, peaking in mid-May to early June.

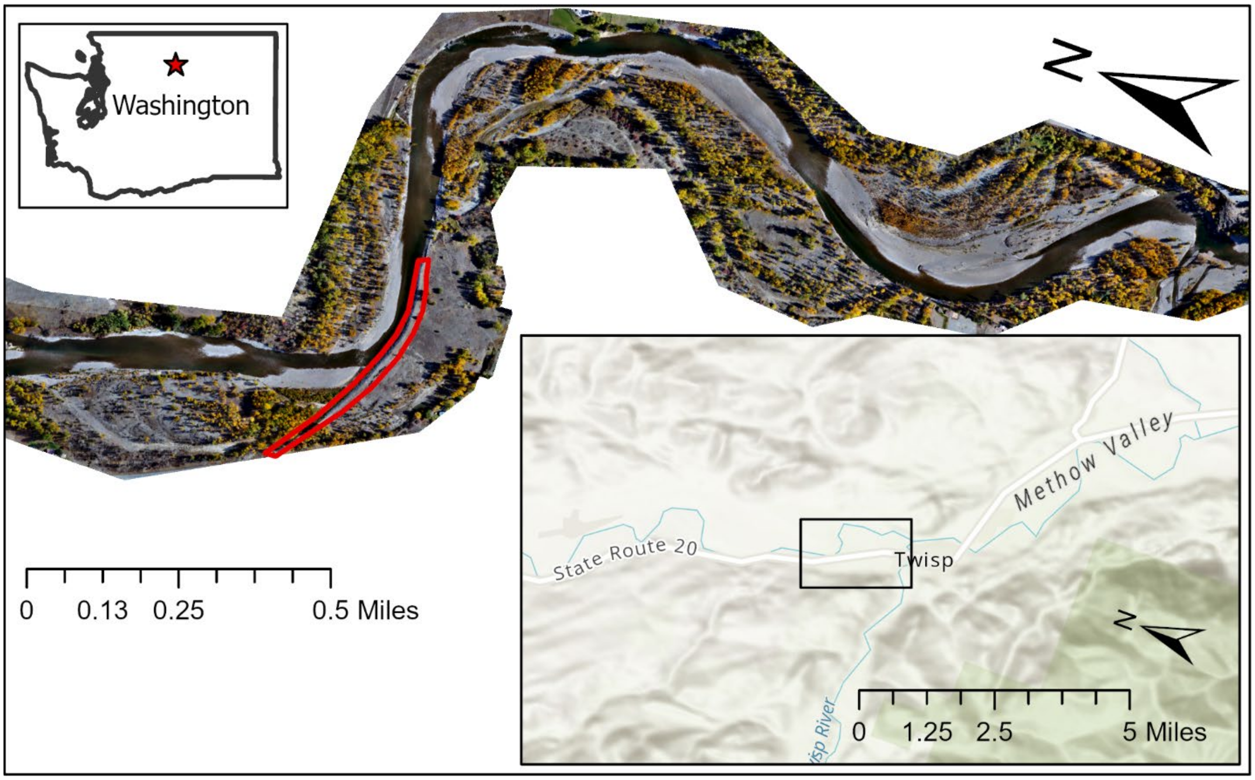


Figure 1. The Methow River study area in north-central Washington. Flow is left to right in the aerial image and the Sugar Levee is outlined in red.

Methods

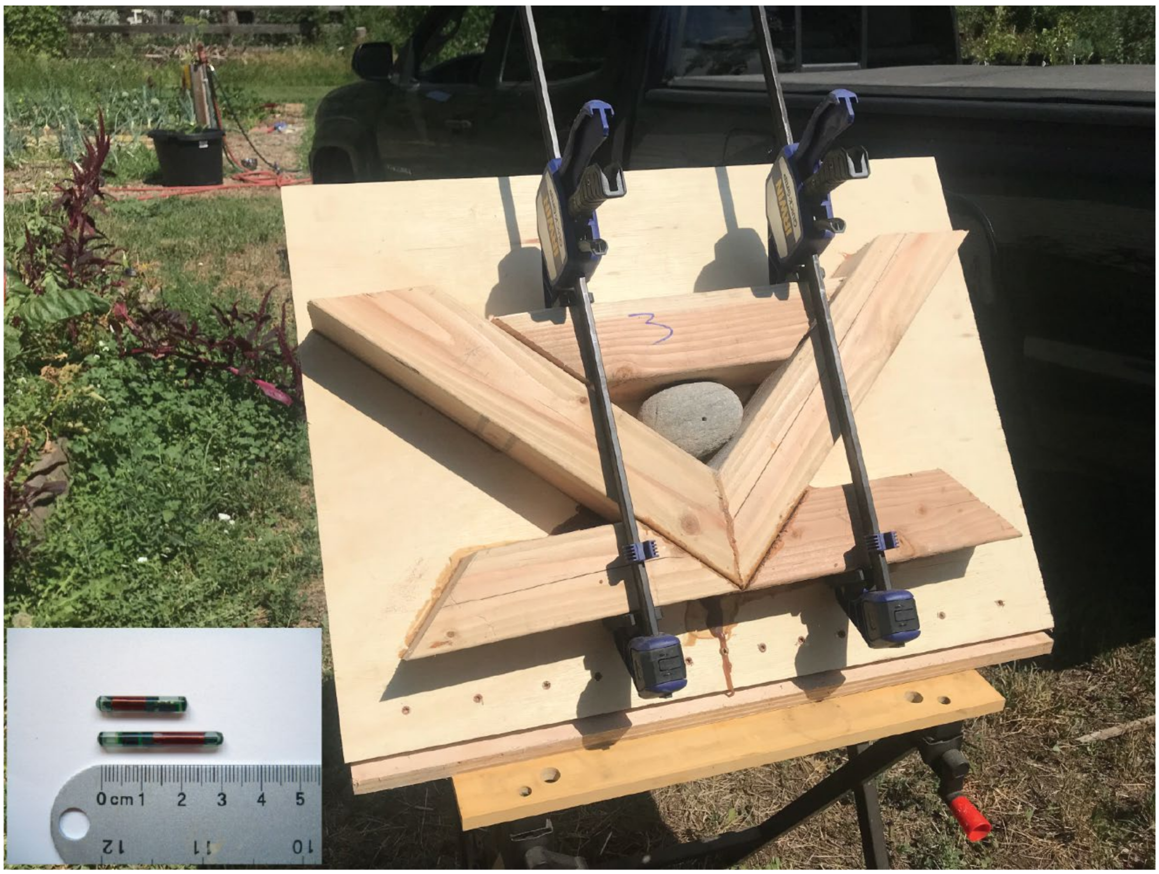
Tracer Preparation

I prepared tracer clasts using coarse gravel and cobbles obtained from a landscape supply yard near Golden, CO. The material was mostly granitic, with some schist and gneiss. This is similar to the composition of the native material in the study area. The size of clasts selected for tracer preparation was guided by the average of five grain size distributions derived from Wolman pebble counts conducted on the Methow River [*Wolman*, 1954]. Rocks were secured in a custom-built drilling rig based on a design developed by [*Slaven et al.*, 2014], shown in Figure 2, and drilled using a hammer drill and a 5/32” carbide hammer drill bit.

After drilling a group of rocks (20-30 at a time), I inserted a 32 mm PIT into the hole in the rock and sealed the hole with waterproof marine epoxy putty. Then I weighed the rocks, measured the a, b, and c-axes with calipers, scanned the RFID (the unique identifier stored on the PIT tag), and recorded the data. Then I calculated the grain size distribution of all the tracers prepared so far and compared it to the average of the measured grain size distributions. The comparison provided guidance for selecting the size of the next batch of rocks. If the tracer size distribution

was too coarse, I selected smaller rocks for the next batch. If it was too fine, I selected larger rocks. I prepared six hundred rocks, totaling more than 767 kg. The median grain size (D_{50}) of the tracers was about 84 mm. The grain size distribution of the tracers and the natural material is shown in Figure 3. The rocks were sorted into about 20 five-gallon buckets, loaded into a pickup, and driven to the study site.

Figure 2. The contraption used to secure rocks for drilling. The inset shows 23 mm and 32 mm PIT tags. Only 32 mm tags were used in this study.



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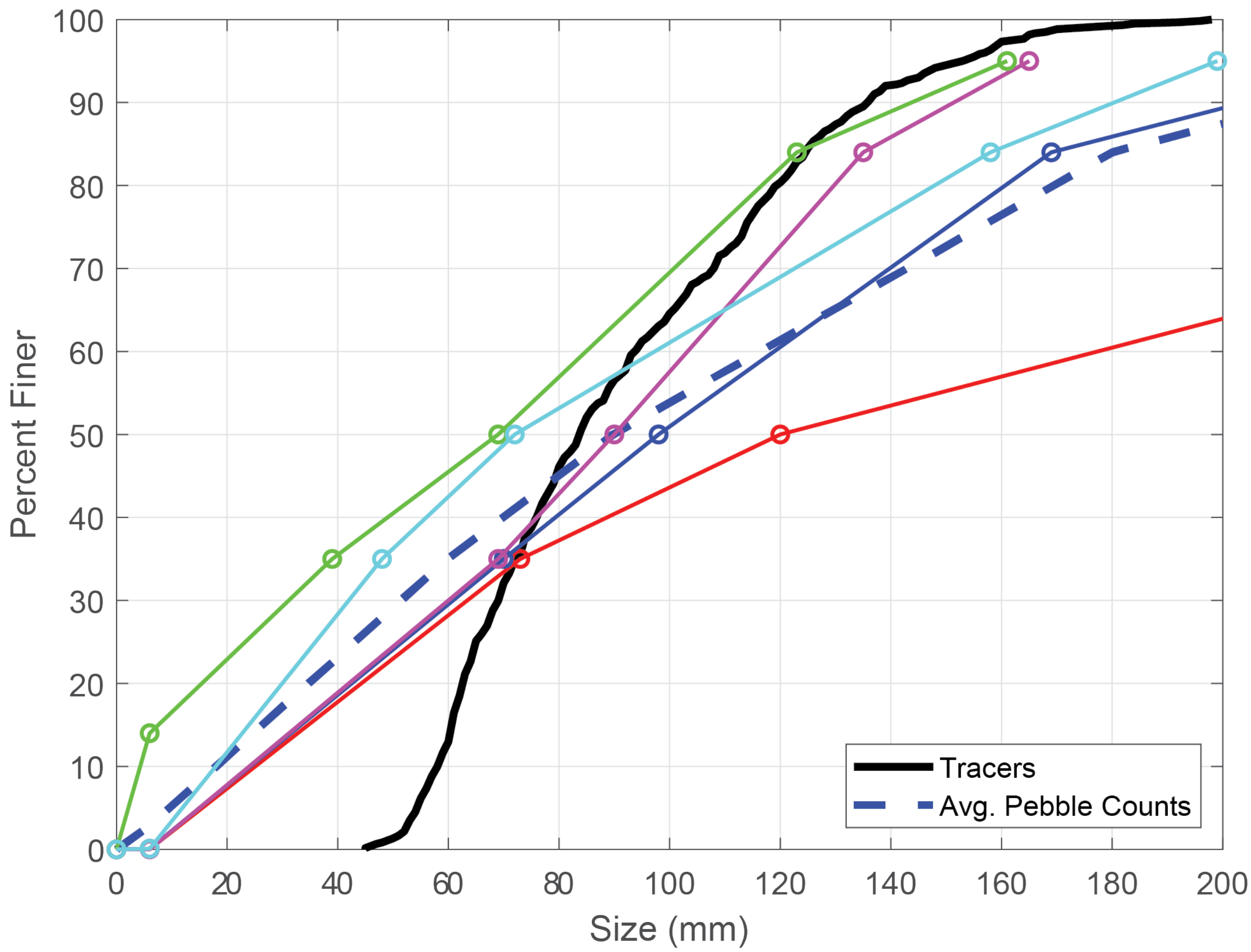

Figure 3. The distribution of tracer grain size and the distributions of the size of the natural material derived from pebble counts. The dashed blue line is the average of the five distributions plotted as colored lines with open circles.

Tracer Installation

Reclamation staff installed tracers on five gravel bars in the vicinity of the Sugar Levee during Oct. 2-4, 2018. The bar furthest upstream, assigned the label Bar 0, is a large left bank bar about 2000 ft upstream of the Sugar Levee. Bar 1 is a smaller low bar on the right bank. Bar 2 is a low mid-channel bar. Bar 3 is a very large right bank bar that terminates against the upstream end of the Sugar Levee. Bar 4 is across from the levee on the left bank. On each bar, we installed groups of 3 tracers spaced 10 feet apart along lines running perpendicular to the direction of flow. In an attempt to place the tracer in a natural position, a rock of similar size was removed and replaced with a tracer. The lines were spaced 20 feet apart in the flow parallel direction on all bars except Bar 3, where the lines were 25 feet apart. Generally speaking, each tracer group include a qualitatively determined small, medium, and large tracer. After placing the tracers, the RFIDs were recorded, and center of the cluster was surveyed with a high precision GPS (Global Positioning System). Towards the end of the tracer installation, a few clusters of 4 tracers were

installed on Bar 0. When the battery that powered the RFID scanner failed, the remaining 35 tracers were scattered around a single point at the downstream end of Bar 0. The RFIDs of those tracers were determined later and associated with the survey point.

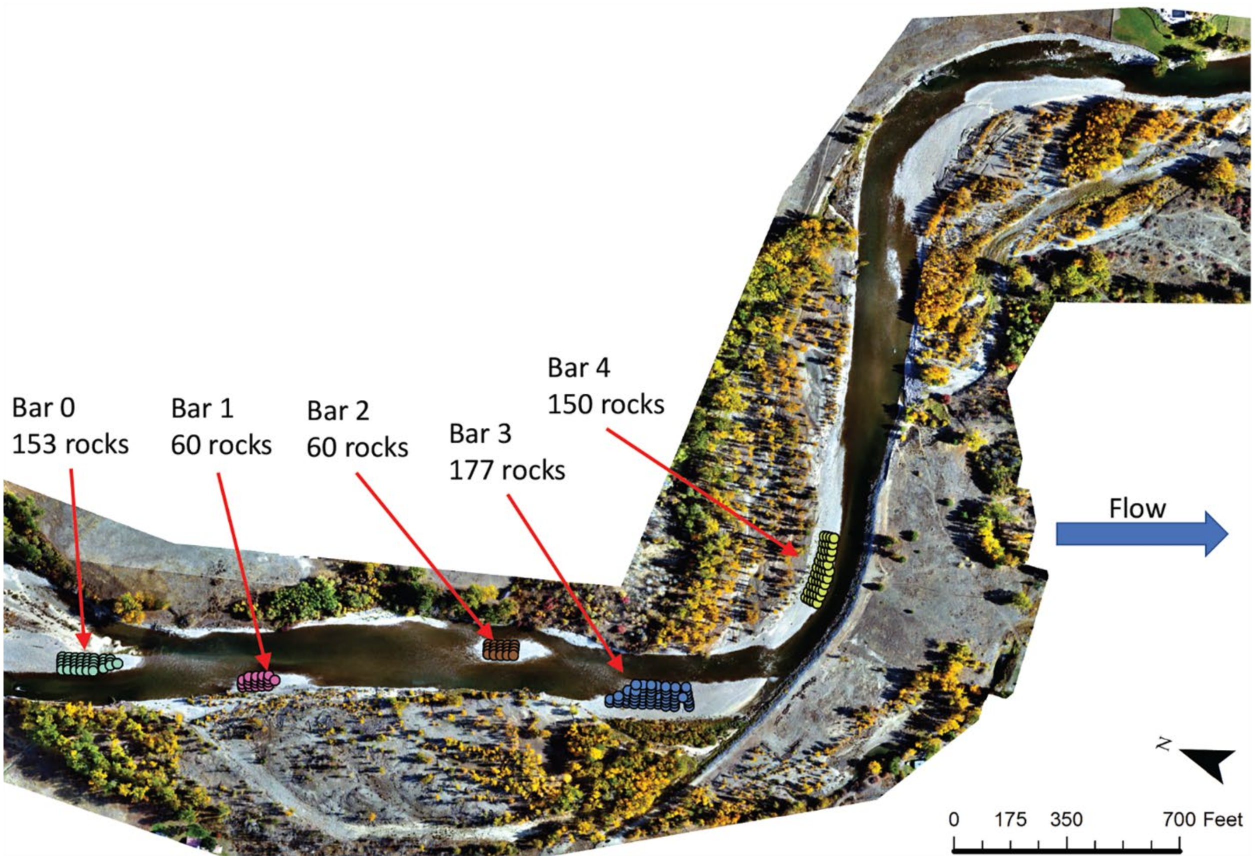

Figure 4. The locations of 600 tracers installed in October 2018. Each colored circle represents 3 tracers.

Tracer Recovery

Tracer recovery consists of walking gravel bars and wading the channel with a backpack mounted RFID reader system. The system energizes a coil of wire in an antenna to generate a magnetic field which induces a current any PIT tags within about 1 m of the antenna. The current induced in the PIT tag charges a capacitor and the PIT tag transmits a unique tag identifier to the reader when the capacitor discharges. When a tag is detected, the reader sounds an audible alarm, records the detection in an internal database, and transmits the tag detection information over a Bluetooth serial connection. We used a tablet computer running the Android operating system to display the detection information. When a tag was detected, the location of the tracer was surveyed with a GPS system and the tag ID recorded with the survey point in the GPS software. The tag ID and survey point number was also recorded in a notebook along with any relevant notes, such as the detection time. Errors recording tracer IDs either in the notebook or in the GPS software were resolved by comparing those data to the internal reader database after the

recovery. In areas that were densely populated with tracers, mainly the installation areas, multiple detections in a short amount of time led to some un-surveyed detections. These were resolved by comparing detection times with nearby tracers that were surveyed.

The study area is large, so the search for tracers must prioritize the areas where tracers are most likely to be found. The highest priority search areas were the installation gravel bars. Many tracers do not move far or do not move at all, so a large fraction of the tracer population remains on the installation bar. It was also expected that tracers at the upstream end of the study reach (between Bars 0 and 3) would tend to move from one bar to the next, so this technique was expected to also recover tracers from upstream bars. The submerged transverse bars that connect Bar 0 to Bar 1 and Bar 2 to Bar 3 (visible as lighter colored, shallower areas in Figure 4) were also high priority. Shallow areas at the bar margins, downstream of Bar 1, and upstream of Bar 2 were also prioritized. The lower surfaces of the point bar downstream of Bar 4 (not labeled in Figure 4, but referred to as Bar 5 later in the report) and the shallow submerged area upstream of Bar 5 were also prioritized. The 2020 recovery ended at the downstream end of Bar 5. The 2021 recovery was extended to a left bank bar about 0.5 miles downstream of Bar 5. Areas of the channel that were too deep or too swift to wade were not searched. This includes much of the channel adjacent to Bar 3, the channel between Bar 4 and the Sugar Levee, and most of the channel adjacent to and downstream from Bar 5.

Results

Floods

High flows capable of mobilizing sediment have occurred only during snowmelt in the late spring over the duration of the study. The hydrograph from the USGS gage at Winthrop, WA (USGS 12448500) for water years (WY) 2019-2021 is shown in Figure 5. The Winthrop gage is upstream of the study area and is more representative of the flow at the site than the gage at Twisp, which is downstream of the confluence with the Twisp River, a significant tributary. Flows during WY 2019-2021 have peaked in mid-May to early June between about 7,000 and 10,000 cfs. The highest flow was in 2020, peaking at 9760 cfs on June 2, slightly less than the expected 2-year peak flow (9860 cfs). The 2021 flood peaked at 7,900 cfs on May 18, just below the expected 1.5-year peak flow (8140 cfs)[*Byrne and Bountry*, 2021]. The lowest peak flow during the study period, 7220 cfs, occurred on May 17, 2019. It was thought that this flow was too low to mobilize the tracers, so no recovery was performed in 2019. Based on the results of the 2021 tracer recovery after a slightly larger flood, this was probably a mistake. In retrospect, it seems likely that at least some tracers were mobilized in the 2019 flood.

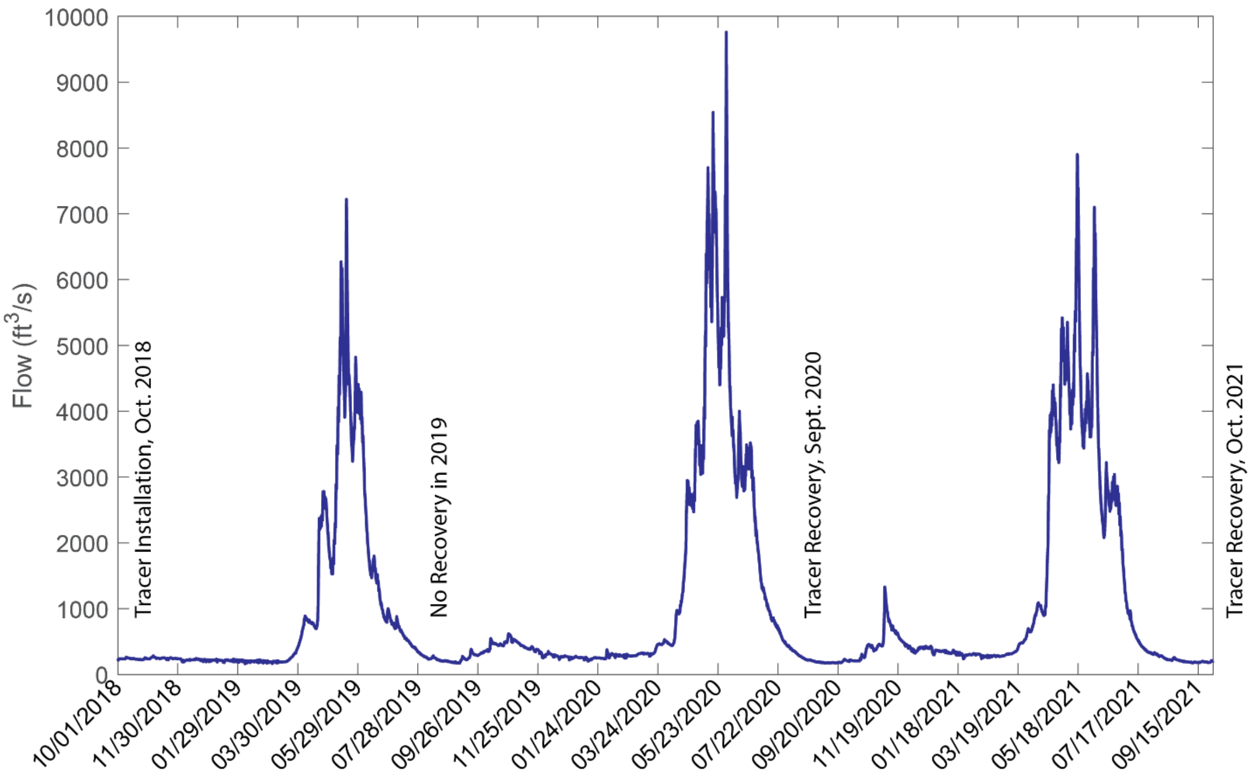

Figure 5. The Methow River hydrograph at Winthrop, WA (USGS 12448500) for water years 2019 to 2021.

Recovery Rates

The Sept. 2020 tracer recovery found 75% of the tracers. At least 90% of the tracers installed on the upstream bars (Bars 0, 1, and 2) were recovered. Recovery rates were lower on the bars adjacent to the Sugar Levee: 68% of the tracers on Bar 3 were recovered and only 48% of the tracers installed on Bar 4. Only 59% of tracers were recovered in the Oct. 2021 survey. More than 71% of the tracers from Bars 0, 1, and 2 were recovered. 58% of the Bar 3 tracers were recovered and only 25% of the Bar 4 tracers. Figure 6 summarizes the tracer recovery rates.

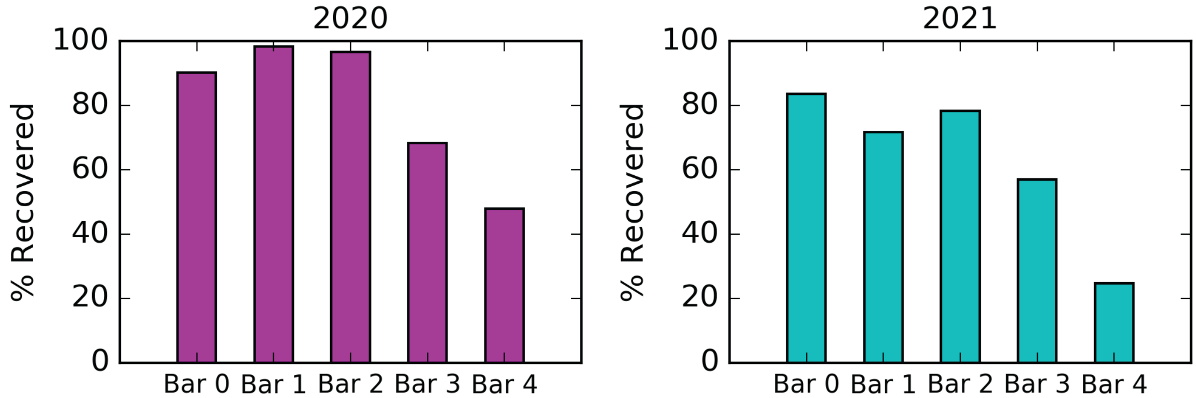

Figure 6. Tracer recovery rates by installation bar. In 2020 (left panel), 448/600 tracers were recovered, about 75%. In 2021 (right panel), 356/600 tracers were recovered, about 59%.

Tracer Positions

2020 Recovery

The 2019 and 2020 floods transported tracers to at least the downstream end of Bar 5, which is where the 2020 survey ended. Figure 7 shows the location of tracers surveyed in the 2020 recovery. Most tracers had not moved beyond the bar where they were installed, but a few traveled more than 2000 ft downstream. The distribution of tracer displacement is shown in Figure 8. One tracer eroded from Bar 0 was deposited at the water's edge at the upstream end of Bar 4. A few tracers from Bar 1 were transported into the shallow water immediately downstream of the bar. One tracer from Bar 2 was deposited midway down Bar 4 and another in the shallow water upstream of Bar 5. A few tracers eroded from Bar 3 were deposited on Bar 4 and in the shallow water an upstream of Bar 5. No tracers from upstream were found on Bars 1, 2, or 3 and no tracers were found on the submerged, transverse bars that connect Bars 0 and 1 and Bars 2 and 3. 81% of the tracers installed on Bar 4 (122/150) were eroded, leaving only 28 original tracers on Bar 4. Of the 122 tracers eroded, 44 were found downstream on Bar 5 and in the shallow water upstream of Bar 5. The results of the tracer recovery survey are summarized in Table 1.

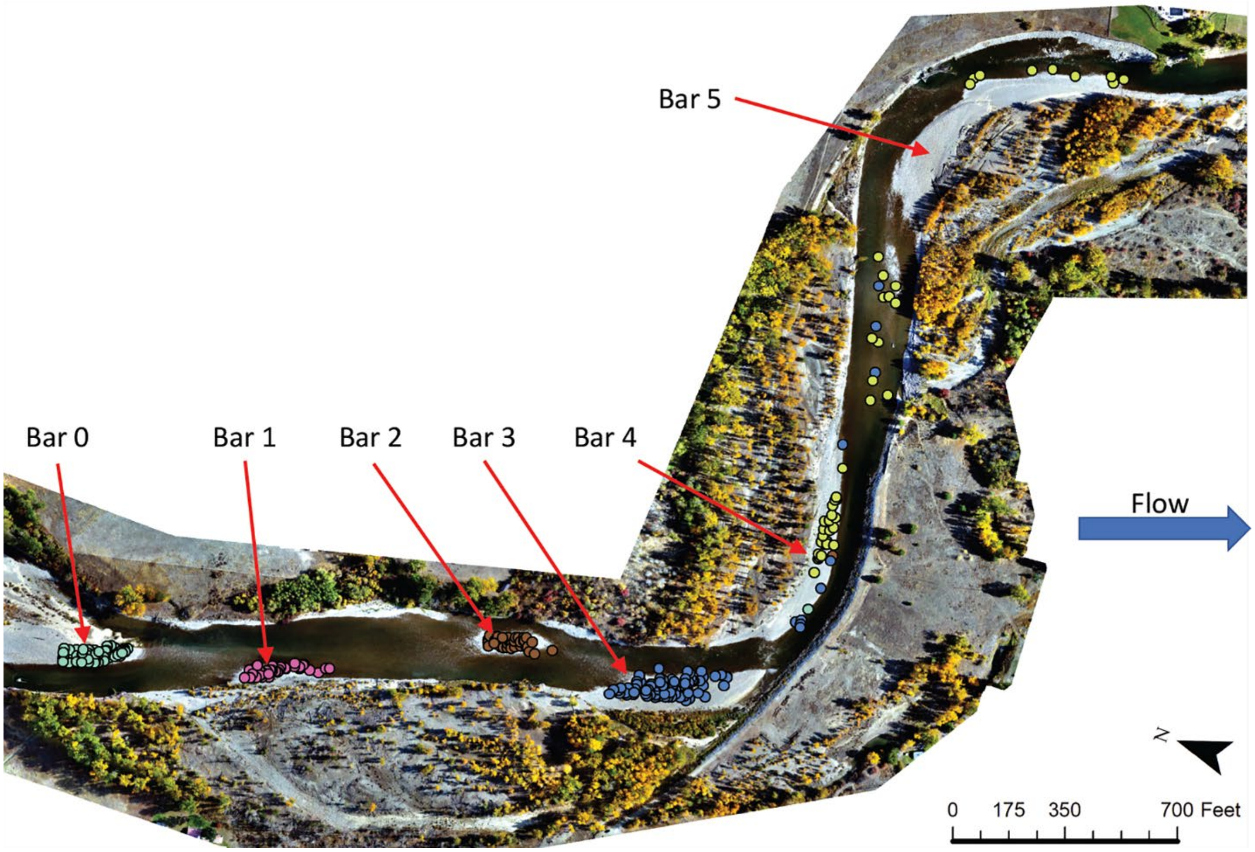

Figure 7. The locations of the tracers recovered in Sept. 2020. Tracers are colored according to installation bar. In contrast to Figure 4, each circle represents one tracer. Tracers installed on Bar 0 are represented by cyan dots. Bar 1 tracers are colored pink. Bar 2 tracers are shown in brown. Bar 3 tracers are blue, and Bar 4 tracers are yellow.

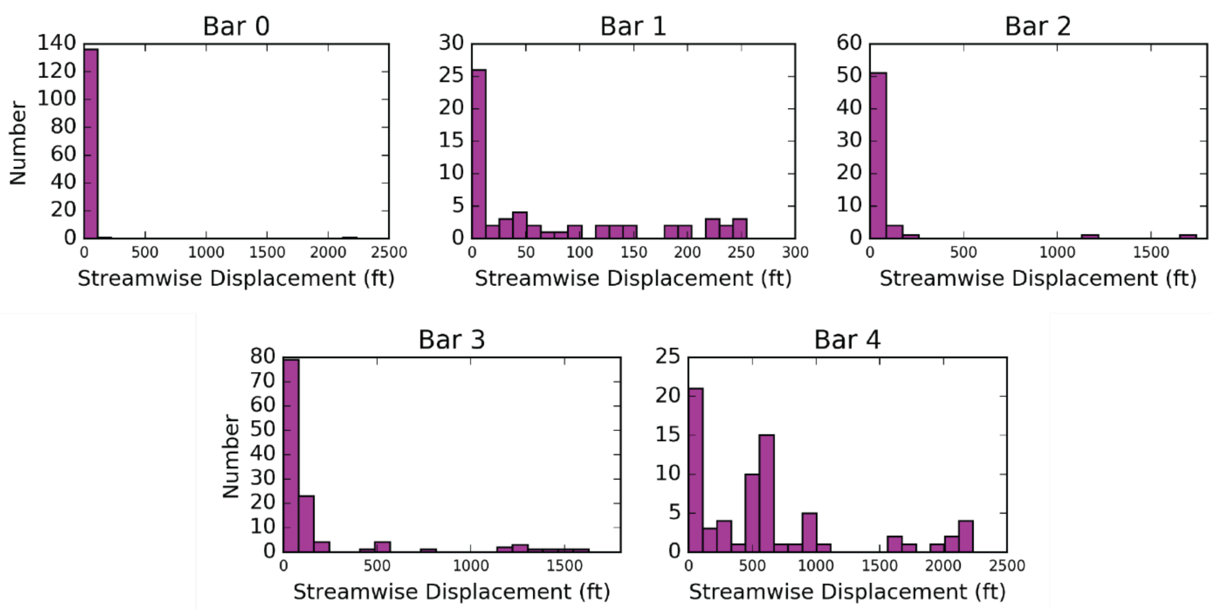

Figure 8. The distribution of tracer displacement by source bar by 2020.

2021 Recovery

We extended the Oct. 2021 tracer search about 0.5 miles further downstream from the end of the 2020 survey to the very large left bank bar labeled Bar 7 in Figure 9. Six tracers from Bar 4 were found there, four of which were not recovered in 2020. Therefore, it is possible that they had been transported to Bar 7 prior to the 2020 flood.

More tracers were eroded in 2021 from the three upstream bars than in the previous floods but not a single tracer from Bars 0, 1, or 2 was found downstream. Tracers from these bars found downstream in 2020 were not recovered in 2021, as shown by the reduced x-axis scale relative to Figure 8 in the cumulative displacement plots in Figure 10. Eight additional tracers were eroded from Bar 3 for a total 79 eroded over the course of the study. Three Bar 3 tracers were recovered on Bar 5. One was found in the same location as the Bar 4 tracer (yellow circle) mid-way down the bar in Figure 9. The other two are at the very downstream end of from Bar 5. No other Bar 3 tracers were recovered. Eight additional tracers also eroded from Bar 5 for a total of 130 eroded. Only 17 Bar 4 tracers were recovered: a group of 6 in the shallow water upstream of Bar 5, one in the middle of Bar 5, 5 at the downstream end, and 6 on Bar 7. No tracers were found on Bar 6.

Table 1. The number of tracers eroded from and remaining on the bar where they were installed. The eroded numbers are cumulative in 2021

Year	Bar 0	Bar 1	Bar 2	Bar 3	Bar 4
2018	Installed: 153	Installed: 60	Installed: 60	Installed: 177	Installed: 150
2020	Eroded: 16 Remaining: 137	Eroded: 1 Remaining: 59	Eroded: 4 Remaining: 56	Eroded: 71 Remaining: 106	Eroded: 122 Remaining: 28
2021	Eroded: 25 Remaining: 128	Eroded: 17 Remaining: 43	Eroded: 13 Remaining: 47	Eroded: 79 Remaining: 98	Eroded: 130 Remaining: 20

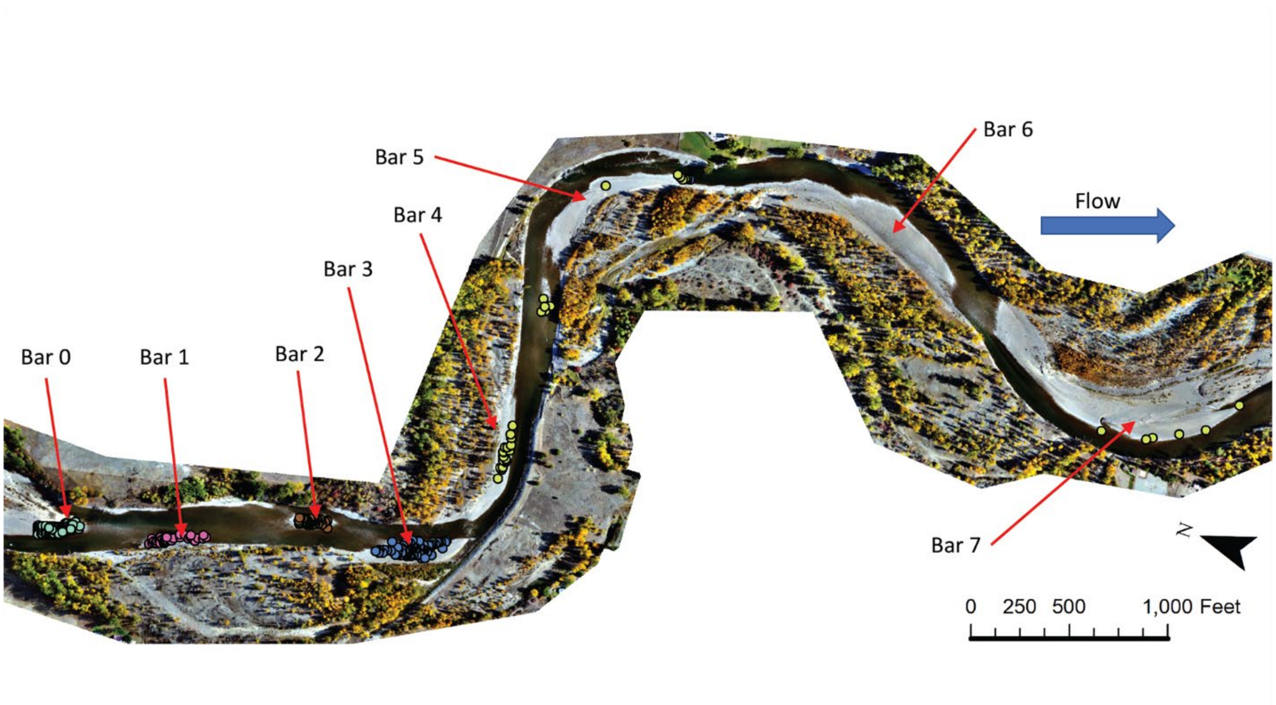

Figure 9. The locations of the tracers recovered in Oct. 2021. Tracers are colored according to installation bar. Each circle represents one tracer.

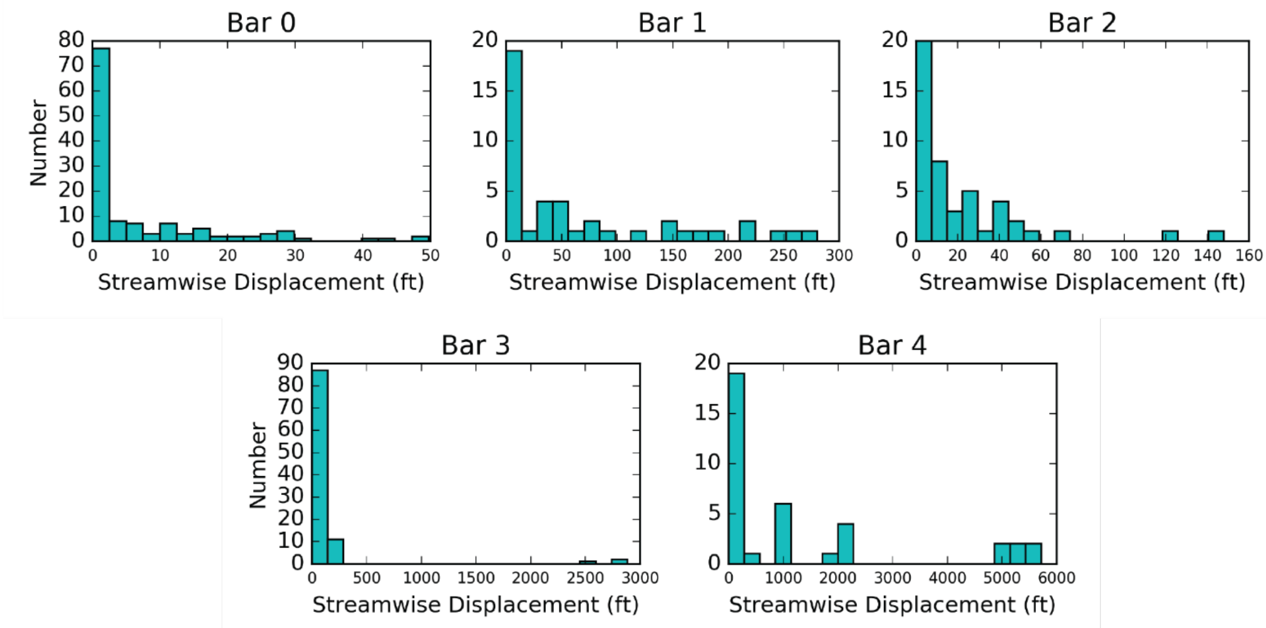

Figure 10. The distribution of cumulative tracer displacement by source bar by 2021.

Tracer Mobility vs. Tracer Size

The mobile tracer population is somewhat smaller in size than the immobile tracers, but the difference is mainly for tracers larger than the median grain size (D_{50}). Figure 11 compares the size distribution of immobile tracers (those that remain on the bar where they were installed) and mobile tracers (recovered downstream or missing) to the original tracer size distribution. For both populations, there is little difference from the original tracer size distribution for tracers smaller than the original D_{50}. For tracers larger than the D_{50}, immobile tracers tend to be slightly larger than the installed tracers, while highly mobile tracers tend to be slightly smaller than the installed tracers. This indicates a weak negative correlation between tracer size and mobility. The most notable difference is reduced mobility for tracers larger than about 120 mm, best seen in the histograms on the bottom row of Figure 11.

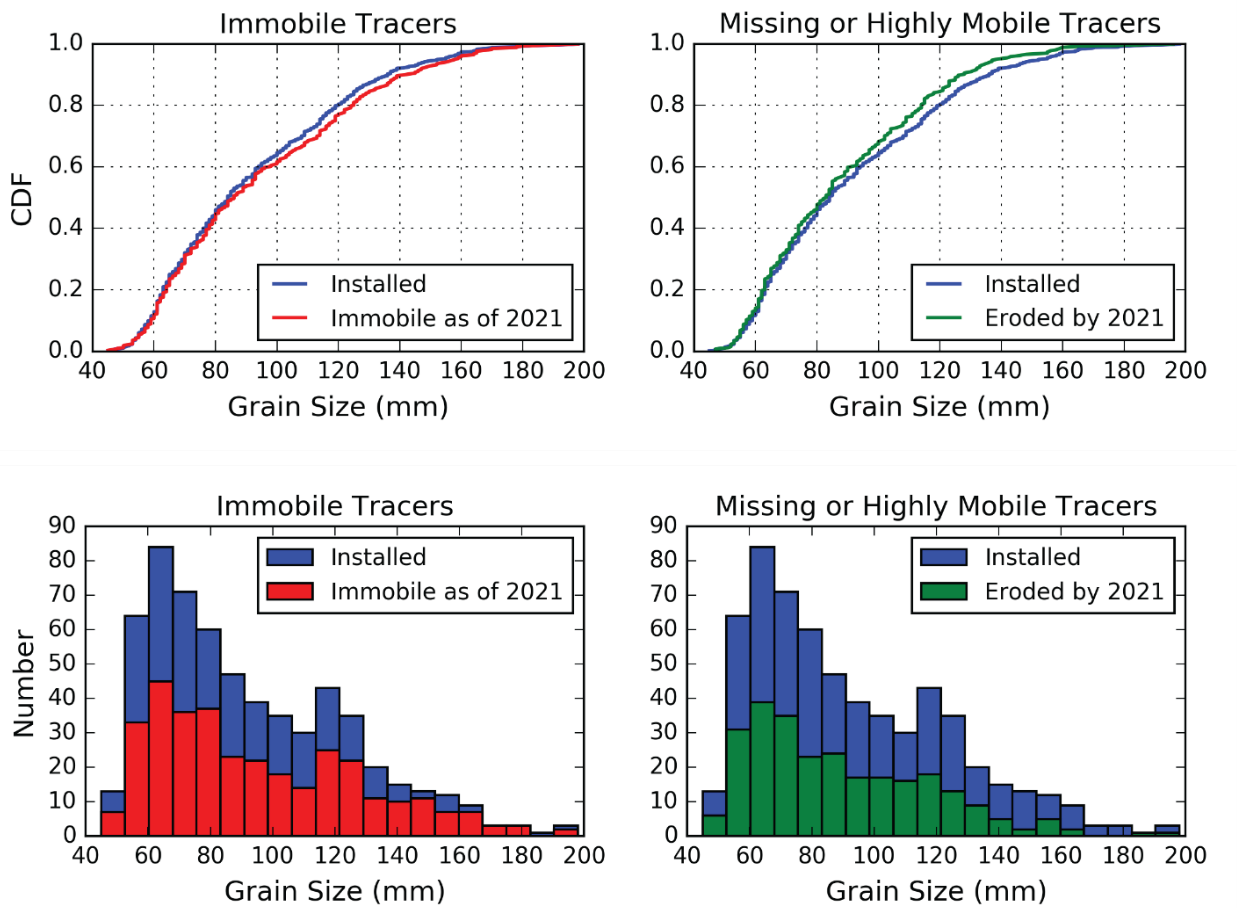

Figure 11. The size distribution of tracers that have not been eroded from the installation bar (left) and the distribution of tracers that have been eroded from the installation bar (either recovered downstream or missing). The top row shows the empirical cumulative distribution functions (ECDF). The bottom row shows the histograms.

Discussion

Recovery Rates

The tracer recovery rates in this study (Figure 6) are lower than those in a previous tracer study I conducted in a smaller river [*Bradley*, 2017; *Bradley and Tucker*, 2012]. I tracked nearly 900 rocks over ten years in Halfmoon Creek near Leadville, CO and had recovery rates above 90% in all years but one. Halfmoon Creek is wadeable everywhere at low flow and even after 10 years, tracers were distributed over less than 0.6 miles. The Methow River tracers have spread out over about 1.5 miles in just 3 years and there are large areas that are too deep and/or swift to wade, even at low flow. Unrecovered tracers may have washed out of the study reach all together or perhaps the missing tracers are hiding in the un-wadeable areas. This is discussed in more detail below. In either case, new techniques, such as a boat-based detection system, are needed to improve tracer recovery rates in larger rivers.

Tracer Transport

Bar 4 has lost a higher fraction of tracers than any other bar (Table 1) and eroded tracers have not been replaced by tracers from upstream. This is consistent with the hypothesis that the Sugar Levee is disrupting the expected sediment transport dynamics by constraining deposition on Bar 4. However, Bar 3 has also lost a large percentage of tracers (45%) and has accumulated no tracers from upstream. This suggests that the levee may also be affecting Bar 3.

I computed a channel profile along the line shown in Figure 12 from the topographic surface, shown in Figure 13. The slope of the different segments was computed by fitting a line to the channel profile between slope breaks. The channel steepens and narrows downstream of Bar 2 and is incised in the vicinity of Bar 4 to the downstream end of the levee. The steepness of this part of the river may account for the enhanced tracer erosion from Bar 3 and 4. It appears that confinement by the levee has caused the river to incise, narrow and steepen. There is a subtle break in slope visible in Figure 13 at the location of the riffle between the downstream end of Bar 3 and the upstream end of Bar 4. Downstream of the riffle, there is a very steep section about 100 ft long before the slope moderates. This riffle is very coarse, and it may act to partially arrest the upstream migration of a knick zone initiated by incision caused by the levee.

Hydraulic modeling confirms that sediment transport may be enhanced along Bars 3 and 4. *Byrne and Bountry* [2021] developed a hydraulic model of the Methow River in the vicinity of the Sugar Levee. Figure 14 shows the model water surface profile and velocity profile from Bar 0 to the upstream end of Bar 5 at a modeled flow of 9860 cfs. In response to the bed steepening at the upstream end of Bar 3 (about station 1900 ft), the water surface profile steepens slightly, and the water accelerates. It decelerates when it encounters a backwater that begins at about station 2300 ft and extends to just upstream of station 2600. This backwater spans the riffle crest and is presumably caused by the levee. Despite the backwater, a narrow corridor of high

velocity water exists along the inner bank, adjacent to Bar 4. The profile line misses this corridor, but it can be seen in the 2-dimensional velocity model results in Figure 15. Downstream of the backwater, the water speeds up until it encounters the shallow depositional area upstream of Bar 5.

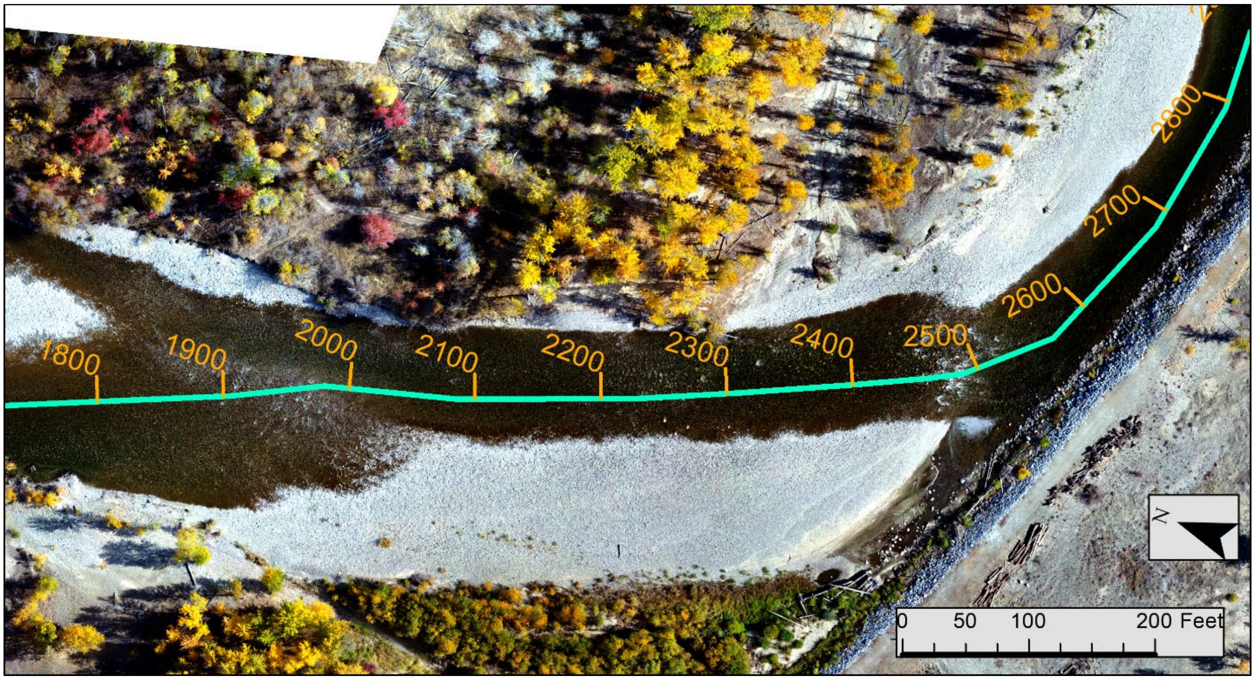

Figure 12. The line used to compute topographic and hydraulic profiles. Stationing labels along the line are in feet.

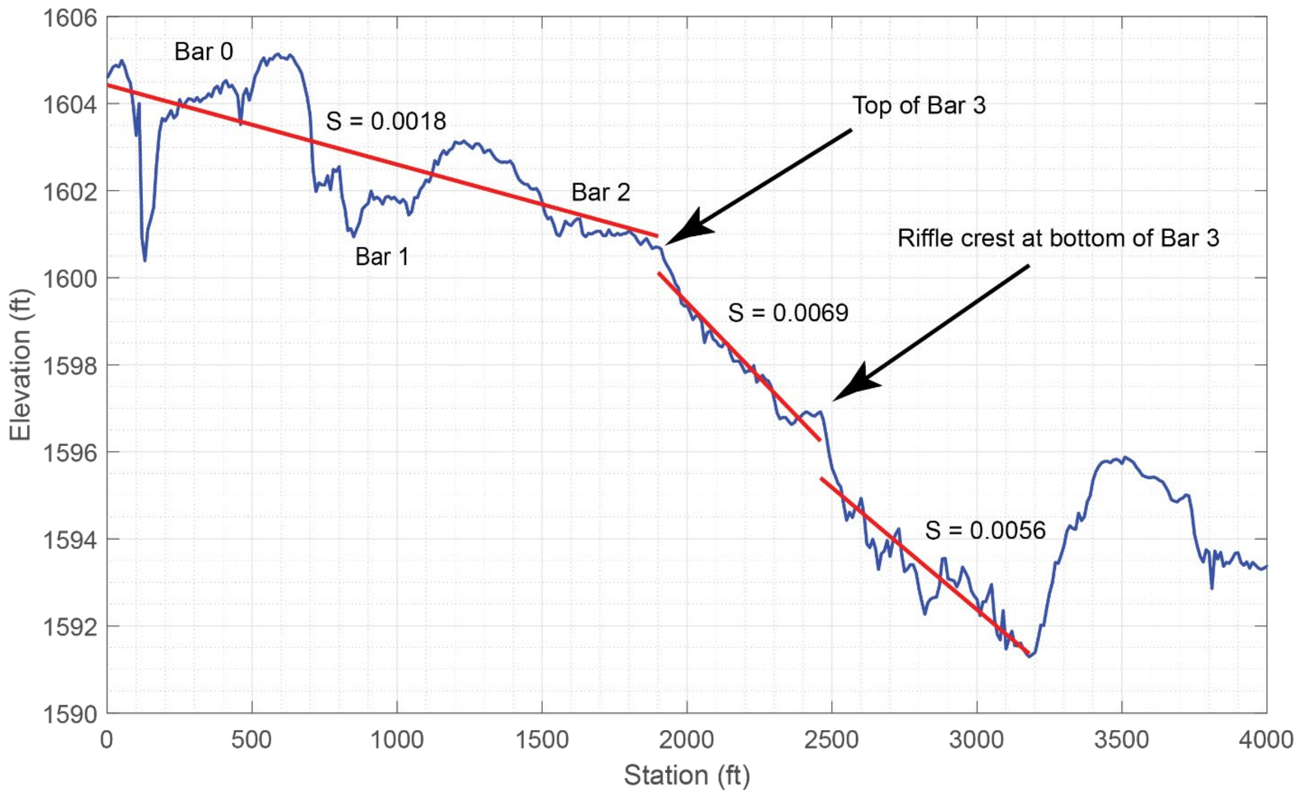

Figure 13. The channel profile through the upstream part of the study reach. Slope estimates (S) are derived from linear fits to bed elevations through each segment. The channel profile is based on a 2020 topobathymetric survey.

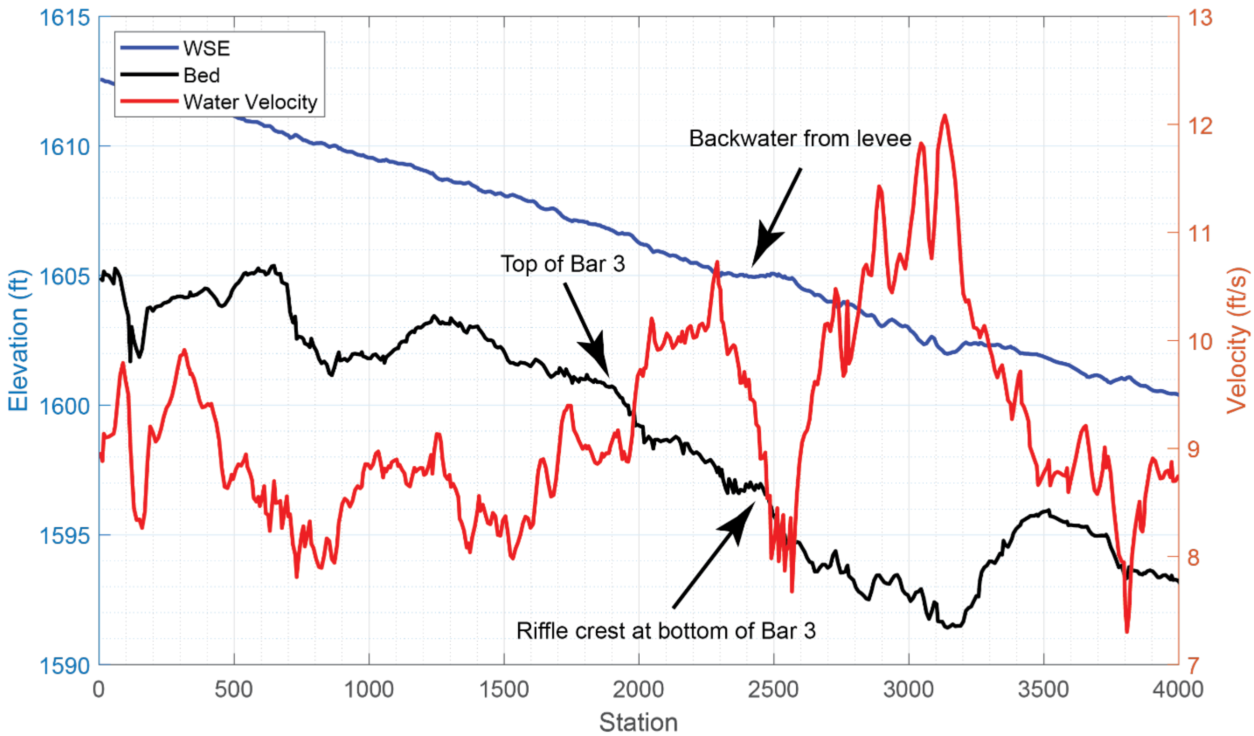

Figure 14. Water surface and water velocity profiles through the study reach derived from a hydraulic model of the river at 9860 cfs. The bed profile differs slightly from Figure 13 because it was derived from the model mesh rather than the topobathymetric surface.

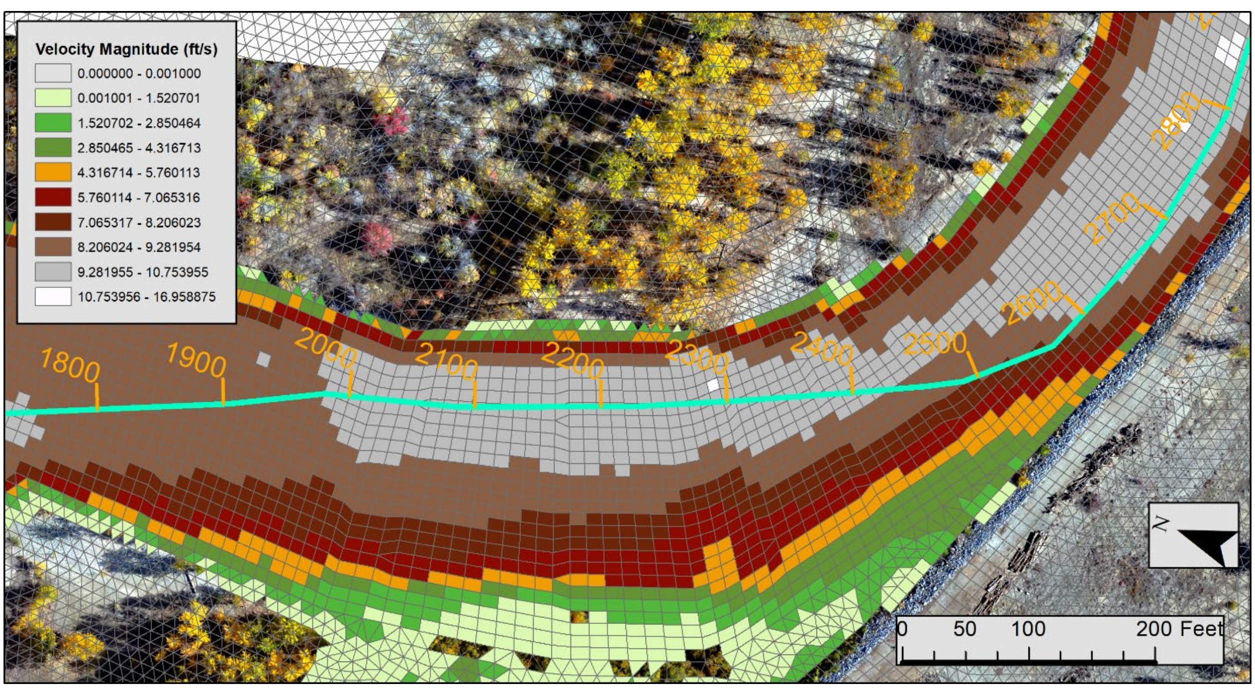

Figure 15. Modeled water velocity at 9860 cfs. A high velocity corridor along the left bank is not captured by the hydraulic profile in Figure 14.

Tracers upstream of Bar 3 are less mobile than tracers from Bars 3 and 4 and no bar-to-bar transport was observed through this part of the study area. Only about 20% of the tracers from Bars 0, 1, and 2 have been eroded, but none of those 55 eroded tracers have been found on other gravel bars. Figure 16 show the percentage of tracers remaining on each gravel bar and the recovery rate for that bar. For Bars 0, 1, and 2, once a tracer is eroded from the bar, it is gone. The same is nearly true for tracers from Bar 3: Only 3 tracers eroded from Bar 3 have been found downstream. All of the other tracers found downstream originated at Bar 4. Twenty four of the 130 tracers eroded from Bar 4 have been found downstream, yet only 3 of the 134 tracers eroded from the other bars have been found.

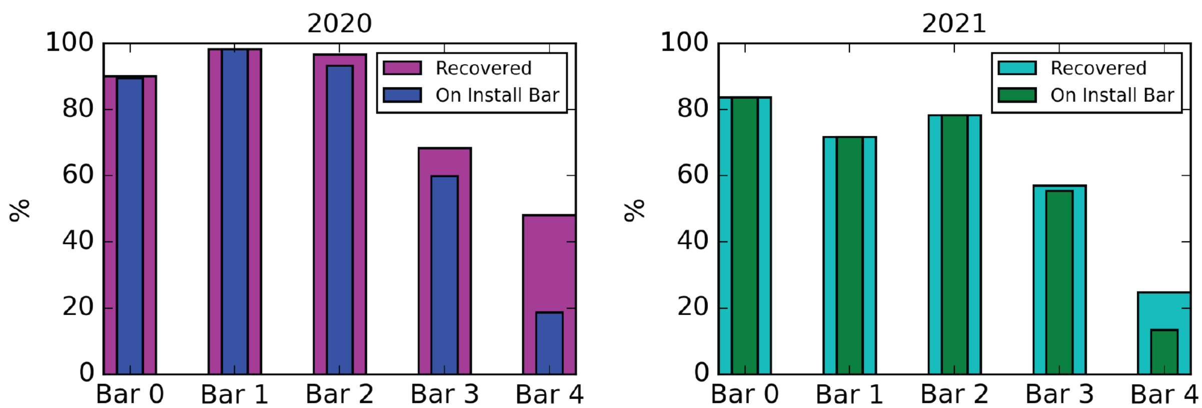

Figure 16. The percentage of tracers that remain on the bar where they were installed compared to the tracer recovery rate.

Where are the missing tracers and why are 89% (24 out of 27) of the mobile tracers (those found downstream of the bar they were installed on) from Bar 4? If deposition of tracers were a purely random event, approximately 50% of the recovered mobile tracers would be expected to have originated on Bar 4. Therefore, tracers from Bars 0 through 3 appear to be moving differently from the Bar 4 tracers. They may be trapped somewhere, such as in the deep water adjacent to the levee (moving more slowly), or they may have washed out of the study reach all together (moving faster). Figure 11 showed a weak negative correlation between tracer size and transport for the whole tracer population, so perhaps the mobile tracers from upstream are smaller than those from bars 3 and 4.

Figure 17 shows the tracer grain size distribution broken down by the installation gravel bar for all installed tracers (left panel) and tracers that were not recovered or were recovered downstream (right panel). Tracers installed on Bar 4 were very similar to Bar 2 and 3 tracers for sizes smaller than about the D_{70}. In the coarsest fraction, Bar 4 tracers are finer than Bar 2 or 3 tracers. Of the mobile tracers (right panel), those from Bars 3 and 4 are coarser than those mobilized from the upstream bars. In the coarsest fraction, tracers mobilized from Bar 3 are coarser than those from Bar 4. It is possible that the finer grain size of tracers mobilized from Bars 0, 1, and 2 plays a role in the under-representation of these tracers downstream, but it is not conclusive because of Bar 3 tracers are similarly under-represented. The over-representation of Bar 4 tracers found downstream remains a mystery.

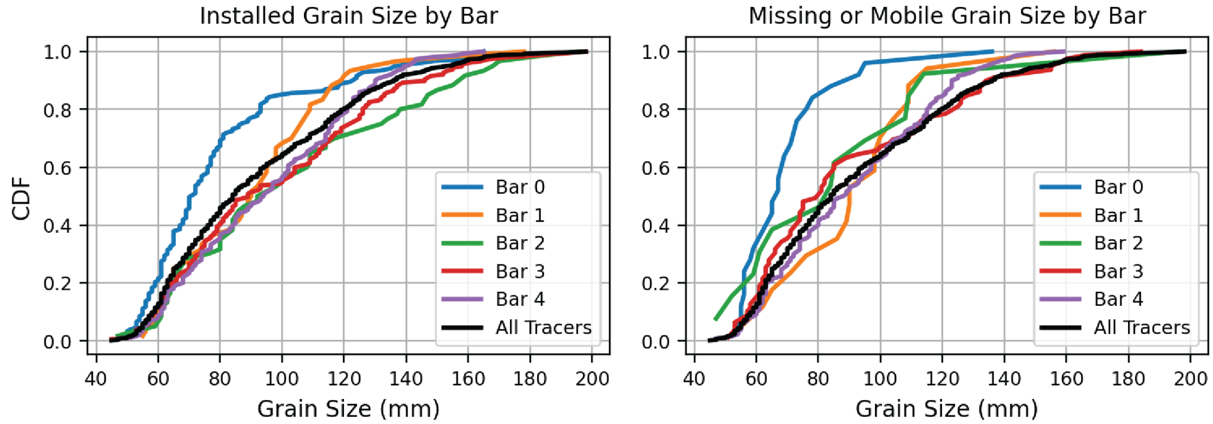

Figure 17. The grain size distribution of the tracers installed on each gravel bar (left) and the distribution of tracers that are either missing or highly mobile (right).

Conclusions

Enhanced tracer erosion from Bar 4 relative to the upstream bars supports the hypothesis that the Sugar Levee is disrupting sediment transport dynamics. However, the mechanism appears to be different from the original hypothesis. Rather than constraining accommodation space for deposition on Bar 4, it appears that the levee has caused channel incision in the vicinity of the levee. The incision kicked off upstream propagation of a knick zone that has increased the steepness of the river from the upstream end of Bar 3 to the downstream end of the levee. The increased steepness seems to account for the enhanced erosion of tracers from Bar 3. This is consistent with observations that the bed coarsens significantly about midway down Bar 3 and is very coarse and deep adjacent to the levee.

The enhanced tracer erosion from Bars 3 and 4 is not consistent with the apparent stability of these bars. Eroded sediment must be balanced by deposition from upstream if the bars are to remain stable. However, except for a few tracers from upstream found on Bar 4 in 2020, bar-to-bar transport between the installation bars was mostly absent. Nearly all tracers that were eroded from Bars 0, 1, 2, and 3 are missing. It is possible that they are trapped in areas that were too deep or swift to search (such as in the channel next to the levee) or that they have been transported out of the study area.

Tracers from Bar 4 are over-represented in tracers found downstream of their installation bar. This may be partially an artifact of the relatively low recovery rates but that seems unlikely to be the full explanation. Twenty four of 130 tracers eroded from Bar 4 have been found downstream. Only 3 of the 134 tracers eroded from the upstream bars have been found. This remains a mystery. Resolving the mystery requires finding more of the missing tracers and new techniques, such as a boat mounted RFID detector system, are needed to improve recovery rates.

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