# Monitoring the Effectiveness of Gravel Augmentations for Salmonid Habitat Improvement Downstream from Dams

Completion Report
Project 0295
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## Abstract

Tracer particles implanted with passive integrated transducer (PIT) tags and topographic surveys were used to monitor the transport characteristics of gravel augmentations downstream from a dam on Grass Valley Creek, a wadable stream in northern California, over a 6-year period. Tracers were first deployed in a gravel stockpile placed in the stream by a local conservation organization in the fall of 2007. Additional tracers were added in the fall of each year through 2011, usually with more placed gravel. Radio frequency tracer relocation and topographic surveys in the stream channel were performed each summer from 2008 through 2012. Downstream transport of the augmented gravel was found to be limited to a reach less than 10 channel widths in length, with the limit of transport defined by a sharp deposition front. Bank erosion and channel widening were associated with bar deposition upstream from the deposition front, whereas virtually no geomorphic change or augmented gravel was detected beyond the front. Relocations of individual tracer particles showed that annual and total particle transport distances were bimodal, in that most individual stones either remained stationary or moved to the deposition front. Relatively few tracers moved intermediate distances. Geomorphic adjustments observed upstream from the deposition front suggest that local deposition of augmented gravel can trigger bank erosion that encourages further local deposition, and therefore decreases the rate at which the augmented gravel propagates downstream. Thus, increasing gravel augmentation rates beyond the transport capacity of the channel may actually increase the time required for the effects of the augmentations to improve downstream habitats.

## Introduction

Gravel augmentation programs intended to improve salmonid habitat are currently underway in a number of stream where the natural delivery of gravel from upstream is impeded by BOR dams, including those on Clear Creek, and the Trinity, Sacramento, American, and Stanislaus Rivers in California. Despite the widespread use of gravel augmentation in river management, many aspects of the practice are poorly understood. Depending on how it is implemented, a gravel augmentation might resemble episodic inputs of discrete sediment slugs, such as could result from large hillslope failures or the delivery of debris flows from tributaries, or it may more closely resemble the delivery of an unimpaired bedload sediment supply from upstream river reaches. The dynamics of the first of these two conditions would presumably be most closely approximated by a single large augmentation, whereas the second condition might be simulated by persistently introducing relatively small quantities gravel over a long period of time.

A number of recent geomorphic studies conducted in laboratory flumes (Lisle et al. 1997; Cui et al. 2003a; Sklar et al. 2009) or by numerical simulation of gravel transport (Lisle et al. 2001; Cui et al. 2003b; Cui and Parker 2005; Greimann et al. 2006) strongly suggest that the evolution a gravel slug, a single large input of gravel at a given location, is dominated by dispersion. The region of maximum aggradation due to the slug tends to remain near the input location and its magnitude diminishes over time. Such a sediment input would alter geomorphic and habitat conditions locally, but its effect on conditions downstream would become negligible at a relatively short distance determined by the magnitude of the input.

At the other end of the spectrum, the concepts of a graded stream (Schumm 1977) informs us that a change in the sediment supply sustained over geologic time will ultimately alter channel morphology, substrate composition, and habitat conditions over arbitrarily long distances. Any tendency for a sediment supply input at a given location to disperse is overwhelmed by the accumulation of those sediments in downstream reaches over time. In the limit, the distance over which a persistent gravel source determines downstream substrate characteristics is limited only by its dilution by other downstream sources only.

With these two end members in mind, it can be concluded that the effectiveness of gravel augmentation for improving downstream habitats within a specified time frame under a given hydrologic regime depends on both the rate that gravel is added to the stream and the duration of sustained additions. At present, however, the geomorphic literature provides little guidance on how to optimize these parameters. It is by no means clear whether the addition of, say, 100 units of gravel in one year is equivalent to the addition of 10 units per year for 10 years, or exactly what the benefits of one approach over the other may be. It could be argued that large gravel additions are needed to quickly alter habitat conditions over as long a stretch of river as possible. It could also be argued that adding very large quantities of gravel over a short time span could cause excessive aggradation and reduce the topographic relief of the river bed and habitat diversity near the augmentation point without materially improving downstream habitats.

The research project summarized here investigates issues such as these by tracking the downstream propagation of augmented gravel downstream from a Bureau of Reclamation dam with Passive Integrated Transponder (PIT) tags. All bed material sediment from the upper basin is trapped behind that dam. In 2006, the Trinity County Resource Conservation District (TCRCD) acquired funding from California Department of Fish and Game to embark on a multi-year gravel augmentation effort intended to mitigate for the loss of the natural gravel supply. These ongoing augmentation activities presented an excellent opportunity to document the behavior of augmented gravel in a relatively small, wadable stream.

## Study Area

Grass Valley Creek (GVC) drains a 32.6 square mile basin in the southeastern corner of the Klamath Mountain region in northern California (Figure 1). The study area is located about 9.7 miles upstream from GVC's confluence with the Trinity River and about 1/3 of a mile downstream from Buckhorn Dam, a sediment control structure constructed in 1990. At this location, GVC is a $4^{th}$-order bedrock-controlled system with a bankfull width of 20-30 ft and a segment-scale slope of about 0.0065. The 1.5-year peak flow event is estimated to be about 142 $ft^3/s$. Except where altered by recent gravel augmentations, the native channel substrate in the area is characterized by bedrock hydraulic controls, bedrock-floored pools, and riffles and runs with substrates dominated by rounded to sub-angular granitic cobbles (Dickenson 2008). Sand and very fine gravel derived from the weathered granite is present in small surface patches and in the interstitial spaces between larger clasts. An example of surface particles typically found in a riffle or run is shown in Figure 2 and a corresponding size distribution is given in Figure 3.

Current substrate conditions reflect recent evacuation of abundant sandy sediment. The majority of the GVC watershed is underlain by the Shasta Bally Batholith (Snoke and Barnes 2006), a deeply-weathered granitic intrusion that erodes to yield abundant sand and very fine gravel when stabilizing vegetation is removed. Following intense logging activity in the watershed in the 1950s and 1960s, GVC was identified as a major source of sandy sediments that were negatively impacting salmonid habitat in the Trinity River, motivating the US Bureau of Reclamation to construct Buckhorn Dam in the early 1990s. Bed material sampling conducted in the first several years following dam construction showed that the channel substrate was composed primarily of sand overlaying shallow bedrock (PWA 2000). Thus, Buckhorn Dam and other watershed rehabilitation actions implemented in the 1990s appear to have greatly reduced the yield of sand from the watershed (Trso 2004; Gaeuman 2010).

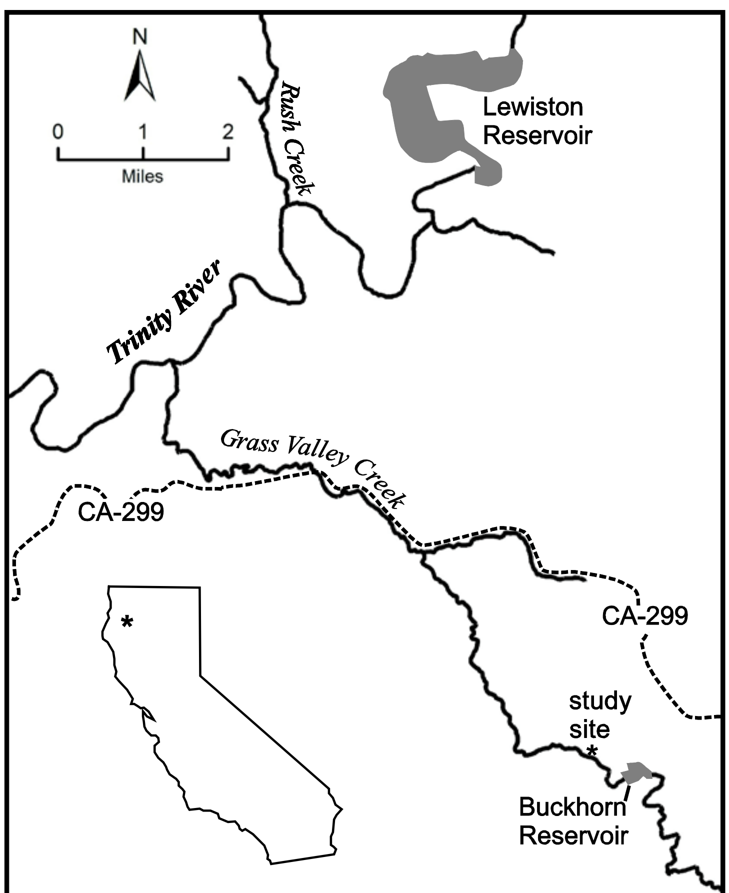

Figure 1: Map showing the location of the study area.

Figure 2: Photograph looking upstream from near station 185 showing native alluvium typical of riffles and runs in the study reach.

## Buckhorn Dam

A brief summary of Buckhorn Dam's main design features is needed to clarify the relationship between dam operations and downstream hydrology. Buckhorn Dam is designed to function essentially as a run-of-the-river facility. Flood inflows to the reservoir are immediate transmitted downstream by the overtopping of a large spillway that can accommodate discharges of up to 14,400 $ft^3/s$. The only outlet capable of controlled releases from Buckhorn Reservoir is relatively small, with a maximum release capacity of 243 $ft^3/s$. However, the controlled flow through the outlet works has rarely deviated from 6 $ft^3/s$ for the past decade. That minimal release defines the baseflow discharge in the creek through the dry summer and early fall months when the water surface in the reservoir is below the spillway elevation. Although this base release can draw down the reservoir water surface below the spillway crest by the end of summer, reservoir storage capacity is relatively small, so the pool refills rapidly after the onset of winter rains and winter peak flows generally pass over the spillway.

## TCRCD Gravel Augmentations

Aside from its purpose of trapping sandy sediments produced in the upper GVC watershed, construction of Buckhorn Dam had the unintended consequence of also eliminating the supply of gravel delivered to GVC downstream from the dam. Such a disruption in the gravel supply can result in a reduction in the availability of the gravelly substrates that salmonids use for spawning (Kondolf 2000). The Trinity County Resource Conservation District (TCRCD) therefore began augmenting the gravel supply to GVC in the fall of 2006 when approximately 20 to 30 $yd^3$ of gravel was placed in the channel 0.34 miles downstream from the base of the dam's spillway.

This augmentation location defines the upstream boundary of the present study reach. With a $D_{50}$ of 37 mm and a $D_{90}$ of 55 mm, the augmentation gravel was significantly finer than and better sorted than the native substrate (Figure 3).

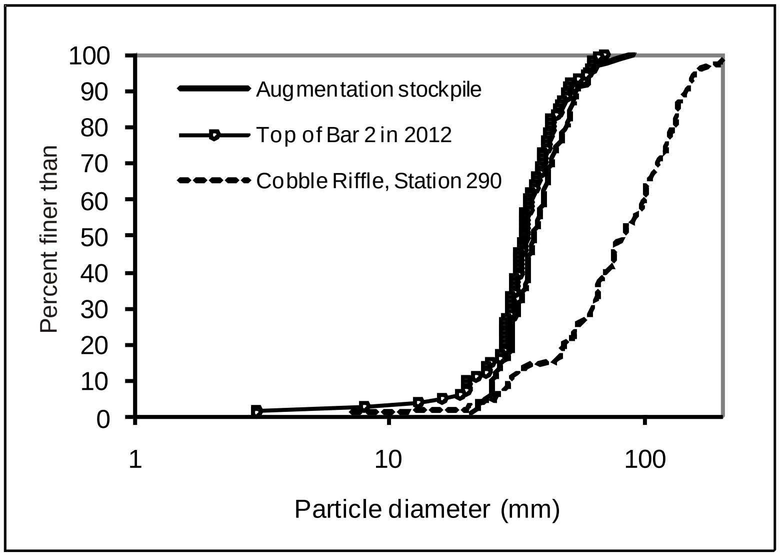


Figure 3: Examples of the particle size distributions of bulk augmentation gravel, deposited augmentation gravel, and native substrate.

The gravel placed by TCRCD was salvaged from stockpiles intended to supply gravel augmentation in the outflow channel immediately downstream from the Dam's outlet works and upstream from where spillway flows re-enters the stream. Reclamation staff had placed small quantities of gravel in that channel in the late 1990s, but further placement was abandoned when flows from the outlet works alone proved insufficient to mobilize it. Although the source of the gravel is not well documented, it was brought to the Buckhorn Dam site from Lewiston, CA, and was likely derived from the Trinity River. In addition being smaller and better sorted, the augmentation gravel differs from the native substrate in that it is comprised of a variety of lithologies, none of which resemble the local Shasta Bally granite, and in being rounded rather than sub-angular.

Placement consisted of piling the gravel on the left margin of the channel during the fall baseflow period. The pile encroached well into the wetted channel, but care was taken to leave a gap in the gravel approximately 5 ft wide to allow for fish passage. Gravel was piled as high as possible, that is, at the angle of repose, so that any erosion along the toe of the pile would cause gravel to slide down the face of the pile into the water. It was expected that winter storms would generate flows capable of entraining and redistributing the placed gravel.

TCRCD continued gravel augmentation in the fall of 2007 when another gravel recruitment pile containing an estimated 60 $yd^3$ of gravel was placed at the same location. About half of that pile was removed during the winter of WY2008, and TCRCD reconstituted the pile to near its original dimensions in the fall of 2008. The winter of WY2009 was considerably wetter than the previous year, so that by the spring of 2009 the majority of the pile had been removed. TCRCD returned in the fall of 2009 to push the remainder of the pile, approximately 15 $yd^3$ into the wetted channel. This relatively small quantity of gravel was entrained and distributed downstream the following winter. At this point, the supply of suitable augmentation gravel left near Buckhorn Dam by Reclamation was exhausted and no additional gravel was placed in 2010.

In 2011, TCRCD engaged the operator of a local gravel quarry to supply more gravel with a size distribution similar to the material already placed. However, the gravel delivered to the GVC augmentation site was substantially coarser than the material placed in previous years. The material delivered included cobbles up to 6 inches in intermediate diameter and very little material less than 1 inch in diameter. TCRCD required the contractor to re-sieve the sediment to remove oversize particles and mix in some 1-inch minus gravel. An estimated 30 $yd^3$ of the resulting mixture was then placed in the creek. However, the material was still visibly coarser than the previous placements. In addition, the method of placement was altered. Instead of making a tall, steep pile, TCRCD constructed a relatively low windrow along the left bank that extended at least 40 ft upstream from the original augmentation area. The winter flows of WY2012 entrained little if any of the material in the placed windrow. This lack of entrainment was first assessed visually, but would later be confirmed by the presence of tracer particles that had been seeded in the windrow. Both the size gradation of the material and the placement configuration were considered unsuitable entrainment and transport, so most of the windrow was removed in the fall of 2012. A portion of the removed material was replaced with 11 $yd^3$ of smaller gravel that was placed in a steep pile in the original augmentation area.

**Stream Flow in the Study Area**

The gravel augmentation work that is the subject of this investigation began in the fall of 2006, and monitoring efforts began in the fall of the following year and continued through WY2012. Thus the hydrologic record relevant to this investigation spans water years 2007-2012.

For water years 2009 through 2012, discharge at the project site is quantified by summing the reservoir release discharge through the outlet works and the discharge flowing over the dam's spillway. The outlet release is obtained by consulting a log book kept by the dam operators from Reclamation's Northern California Area Office (NCAO). As previously mentions, the outlet release is nearly always maintained at 6 $ft^3/s$. The discharge over the spillway can be estimated with a pressure transducer in Buckhorn Reservoir that records the reservoir stage in combination with a discharge rating curve for the spillway crest. The reservoir stage data can be accessed under the identifier GVO (Grass Valley Out) at http://cdec.water.ca.gov/reservoir.html. The rating curve for the spillway was obtained from NCAO.

The GVO stage recorder was inoperable for most of water years 2007 and 2008. Discharge for those years is estimated by correlation with USGS gage 11525630, Grass Valley Creek near Lewiston (GVNL), which started operating in WY2005. Regression analysis yielded 2 relationships: one for a subset of the data in which daily mean flows at GVNL were between 30 and 100 $ft^3/s$ and another for GVNL flows greater than 100 $ft^3/s$. The $r^2$ values determined for these relationships were 0.53 and 0.66, respectively.

Wet-season daily peak hydrographs at the base of Buckhorn Dam are compared to the estimated 2-year peak flow and the estimated threshold of entrainment in Figures 4. The 2-yr peak flow displayed on the graphs was estimated through a correlation with a pair of downstream USGS gages. The annual peak flow series from GVNL was combined with that of the nearby discontinued USGS gaging station 11525600, Grass Valley Creek near Fawn Lodge (GVNF), and the full 37-year time series was fit to a Log-Pearson III probability distribution. The 2-year flood determined for the two USGS gages was then transferred to the GVO gage using the regression relationship for GVNL discharges greater than 100 $ft^3/s$ noted above.

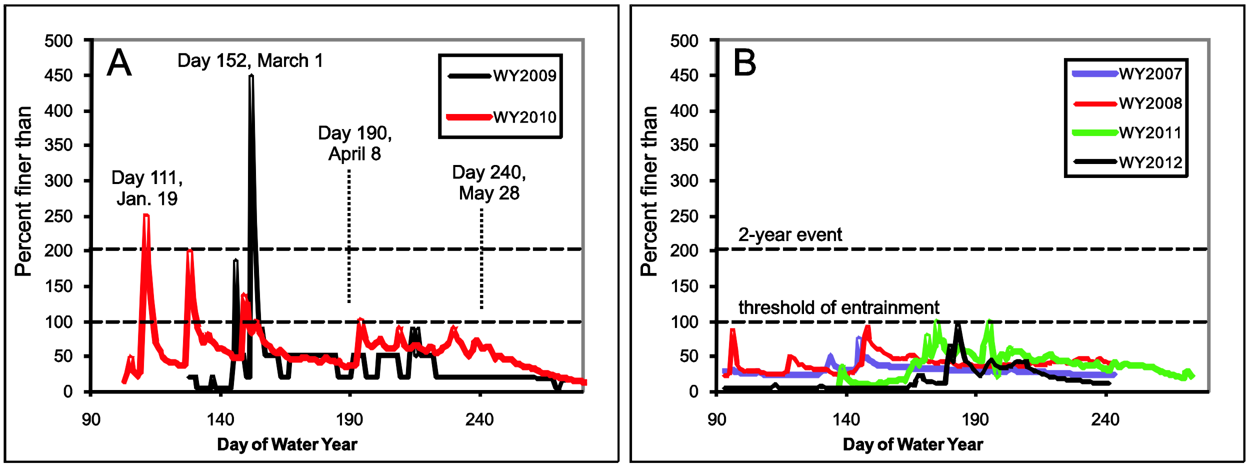


Figure 4: Wet season peak streamflow at the study site, WY2007-WY2012. Panel A shows years with larger than average peaks, and panel B shows years with relatively small peaks.

The threshold of entrainment shown on the graphs was determined with an experiment performed during an April 2011 flow release from the Buckhorn Dam outlet works that peaked at 100 $ft^3/s$. The purpose of the release was to provide baseline design information for an upgrade to the Dam's toe drains that Reclamation was planning at the time. However, the release also provided an opportunity to test sediment entrainment at a known discharge. About 50 gravel particles ranging in size from 25 mm to about 60 mm were painted bright orange and placed on the bed surface in numerous locations throughout the study reach. Some particle movement was observed, but few of the seeded stones moved more than the equivalent of a few particle diameters. In general, particle movements were limited to settling into a more stable position in their immediate vicinity. It was therefore concluded that shear stresses generated by a discharge of 100 $ft^3/s$ are close to, but slightly less than, the threshold of entrainment at most bed location within the study reach.

Two of the 6 water years considered in this report, 2009 and 2010, included flows in excess of the 2-year flood (Figure 4a). Flows in 2009 were dominated by a large peak that briefly attained a magnitude more than twice that of the 2-yr event, whereas the 2010 hydrograph includes a pair of more modest peaks with longer durations. Flows in the remaining 4 water years, however, either did not exceed the minimum discharge needed to mobilize the bed in the study reach.

## Methods

The methods used to explore the behavior of the augmented gravel and its effects on the morphology and substrate in downstream reaches of GVC can be considered to belong to one of three categories. These are 1) substrate characterization and mapping, 2) topographic surveys, and 3) radio-tagged tracer particles.

### *Substrate Characterization and Mapping*

Initial monitoring of these gravel augmentations began in 2007 when Trinity River Restoration Program (TRRP) provided minimal funding to prepare, deploy, and relocate tracer stones in 2007 and 2008. This early work, which was conducted by New Albion Geotechnical, relied on geomorphic mapping and measurements with a tape to document the downstream propagation of the from the augmentation gravel and quantify tracer displacement distances. Because the augmented gravel is visually distinguishable from the native bed material on the basis of size, shape, and lithology, deposits of the augmented material are readily identifiable. This qualitative approach was supplemented by pebble counts to quantify the grain size differences observed between the native bed material, the deposited augmentation gravel, the augmentation source material prior to placement in the stream. Characteristic substrate conditions in areas of native bed and in areas with newly deposited augmented gravel were also documented photographically. The results of this early monitoring are summarized in the contractor's report to TRRP (Dickenson 2008).

Despite the simple methods employed by New Albion Geotechnical, their work successfully summarizes the behavior of the augmented gravel in 2007 and 2008 because total transport distances were short. However, those methods were clearly inadequate for measuring the larger transport distances and the topographic changes that occurred after WY2008. The later studies supported by S&T funds therefore made use of more advanced surveying equipment.

### *Topographic Surveys*

Changes in bed elevation, cross sectional geometry, and channel planform are quantified with repeat topographic surveys of cross section, longitudinal bed and water surface profiles, and shore line positions. Annual surveys began in the fall of 2009. The survey data extends more than 500 ft downstream from the gravel augmentation location, which is well downstream of the region where any evidence of gravel deposition or channel change could be detected. A total of 10 cross sections were surveyed one or more times between 2009 and 2012 (Figure 5, Table 1).

Five of the 10 cross sections were established specifically for this study, and 5 were re-occupations of cross sections established by Pacific Watershed Associates (PWA), a contractor hired by Trinity County in the early 1990s to assess the effectiveness of the sediment control actions in the GVC watershed (PWA 2000). The PWA surveys, which were first conducted in 1992 and repeated in 1993 and 1995, provide a useful baseline from which to assess changes over longer time scales. All survey data were collected with a Trimble M3 Total Station and are referenced to a common local coordinate system and datum.

| XS Name | PWA Name | Years Surveyed | Pin Coords. N, E, Z (feet) |
|---|---|---|---|
| XS10 | PWA-8 | 1995, 2007, 2009, 2010, 2011, 2012 | Left: 5000.66, 5003.39, 998.95<br>Right: 5083.49, 5004.38, 999.13 |
| XS65 | -- | 2009, 2010, 2011, 2012 | Left: 5009.70, 4980.31, 992.57<br>Right: 5068.11, 4936.62, 992.51 |
| XS75 | -- | 2012 | Left: 4998.24, 4947.56, 992.39<br>Right: same as XS65 |
| XS110 | PWA-9 | 1995, 2010, 2011, 2012 | Left: 4969.51, 4942.50, 998.72<br>Right: 5043.08, 4905.97, 997.19 |
| XS112 | -- | 2012 | Left: same as XS75<br>Right: same as XS130 |
| XS130 | -- | 2009, 2010, 2011, 2012 | Left: 4985.6, 4903.7, (tree)<br>Right: 5028.08, 4899.34, 992.17 |
| XS185 | PWA-10 | 1995, 2009, 2010, 2011, 2012 | Left: 4038.58, 4893.08, 1000.32<br>Right: 4989.30, 4836.60, 999.19 |
| XS290 | PWA-11 | 1995, 2010, 2012 | Left: 4890.54, 4788.33, 990.33<br>Right: 4934.41, 4763.80, 999.25 |
| XS470 | PWA-12 | 1995, 2010 | Left: 4940.6, 4617.6 (tree)<br>Right: 4977.53, 4671.49, 997.21 |
| XS508 | -- | 2010 | Left: 4963, 4590, (tree)<br>Right: 4998.41, 4634.21, 994.13 |

Table 1: Summary of cross sections and end monuments included in this study, including 1995 PWA survey data. Left monuments for XS130, XS470, and XS508 are trees rather than rebar pins. Left monuments for XS290 and XS470 replace older monuments set by PWA.

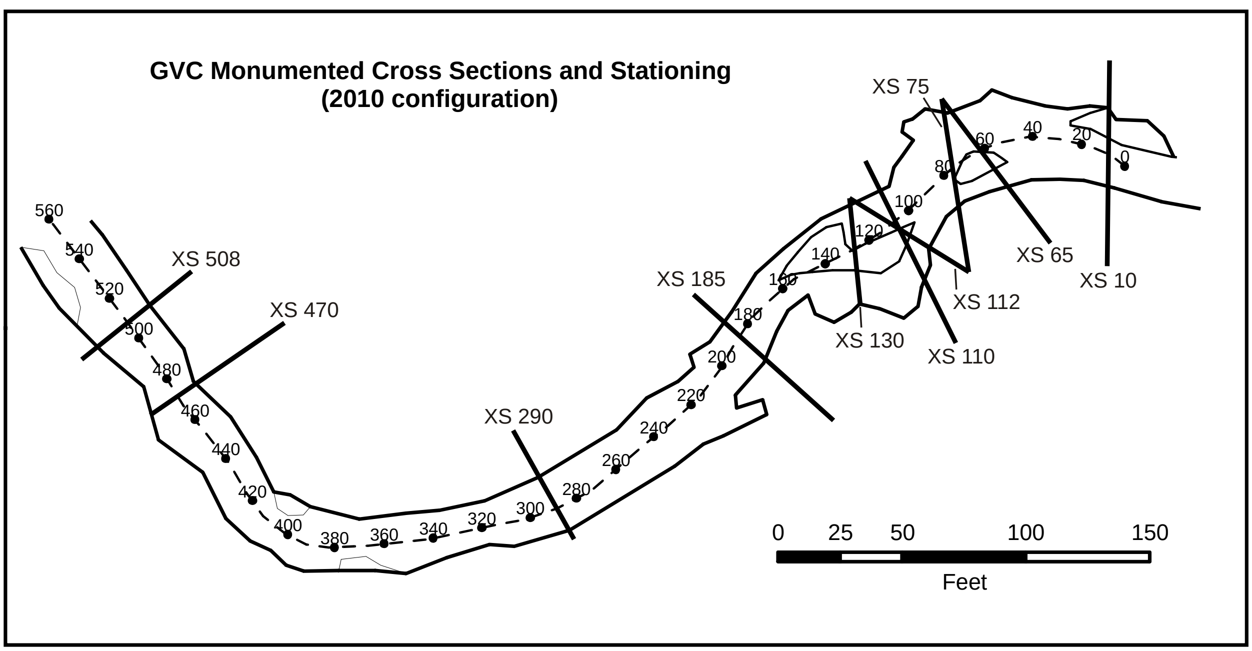


Figure 5: General map of the study area showing cross section locations and the downstream stationing along the channel centerline.

*Radio-tagged Tracer Particles*

The downstream propagation of the gravel was tracked using with Passive Integrated Transponder (PIT) tags that were inserted into individual tracer stones. The tags selected for this study, which are 32 mm long and 3.65 mm thick, were inserted in coarse gravel clasts by drilling a hole in the stone, inserting the tags, and sealing the hole with epoxy. The tags transmit a radio signal (134.2 kHz) that carries a unique number that allows the identification of individual tags. This capability is referred to as radio frequency identification (RFID). Despite their ability to transmit radio signals, the tags have no internal power source. Instead, power is supplied by the detection equipment, which produces an alternating magnetic field that induces a current in a coil embedded in the tags. Because they do not rely on internal batteries, PIT tags can be made smaller than active radio transmitters and they can remain operational in the field indefinitely. Because radio signal penetrate non-magnetic media, the 32-mm tags used in this study are detectable when buried up to 3 ft deep in the substrate. PIT tags have been used previously for tracking sediment particles in both stream and beach applications, where they have been shown to be useful and cost-effective (Nichols 2004; Lamarre et al. 2005; Bradley and Tucker 2012).

Tracers stones prepared for this study were obtained from alluvial deposits along the Willamette River near Corvallis, Oregon, and are derived primarily from sedimentary rocks of the Oregon Coast Range. They were selected to be similar in size to the augmentation gravel, but large enough to be implanted with the 32-mm PIT tags. Their intermediate axis dimension is about 60 mm, which is roughly equivalent to the $D_{90}$ of the augmentation gravel distribution (Figure 3). However, the mass of the tracer stones was minimized by selecting stones whose major axes are only slightly larger than their intermediate axes. Two batches of PIT-tagged tracers were prepared for this study. The first batch consisted of 200 stones that where prepared in 2007 and a second batch of 400 stones was prepared in late 2009.

A total of 482 of the tracers were deployed in the study reach over a 5-year period. The number of tracer placed each year and the placement methods varied for a number of reasons are best explained as the results of the experiment unfold. In summary, 153 tracers were introduced into the study reach in November 2007, 47 in September 2008, 226 in December 2009, 36 in November 2010, and 20 in November 2011. Details regarding these placements will be discussed in the results section.

The tracers were relocated in the late summer or early fall of each year from 2008 through 2012 using a HDX backpack reader and a pole antenna purchased from Oregon RFID, Inc. The pole antenna consists of a circular loop about 2 ft in diameter mounted on a 6-ft handle. PIT-tagged stones are detected by an investigator who wades the stream while sweeping the loop across the stream bed. The equipment used in this study was found to reliably detect particles located at least 2 ft beyond the perimeter of the antenna loop. Thus, the detection area surrounding the loop includes a region of the bed at least 6 ft in diameter. When a tag is detected, the HDX backpack reader carried on the searcher’s back transmits the detected ID to a data logger or laptop computer via a Bluetooth connection. A second investigator is required to manage the data stream to the laptop.

The search proceeds by logging the tag IDs detected in a relatively small search area (about 200 $ft^2$), then surveying the area’s centroid coordinates with a Trimble M3 Total Station before proceeding to the next search area. Where a particular tag ID is detected in only one search area, it is assigned the centroid coordinates of the area. However, adjacent search areas overlap, so the same tag ID is often detected in 2 or 3 areas. In those cases, the tag is assigned the average of the coordinates of all the areas in which it was detected. Where multiple tags are assigned the same coordinates, the tag positions are randomly shifted by 1 ft or less so that relocation positions can be visually distinguished during subsequent GIS analysis. The resolution of these detection procedures are such that a minimum detectable change in tracer position of 6 ft is assumed.

## Results

### *Topographic and Substrate Changes*

<u>WY2007</u>

Prior to any significant alteration due to the gravel augmentations, the channel at and immediately downstream from the gravel augmentation location consisted of a short riffle-like length of channel that flowed into a shallow pool. Channel geometry in the area was relatively simple. The riffle-like area lacked the bar development characteristic of a true riffle. It was, instead, a simple plane-bed area resembling a low-water road crossing. This plane-bed section was where TCRCD placed gravel recruitments piles throughout the study period, beginning in the fall of 2006. WY2007 was drier than normal and the site experience no winter floods capable of transporting gravel downstream. Visual inspection the following summer showed that movement of the unstable gravel recruitment pile was limited to formation of a small gravel lobe that extended a maximum of 20 ft downstream from the pile location (Figure 6).

<u>WY2008</u>

TCRCD reconstituted and enlarged the gravel recruitment pile in the fall of 2007. The resulting pile was at least 6 ft high and 20 ft wide at its base (Figure 8, Figure 9). Once again, WY2008 proved to be relatively dry with no winter floods capable of entraining the stream bed (Figure 4b). However, flows were capable of spreading the unstable gravel pile downstream, and a new bar formed in the center of the pool between 30 and 70 ft downstream from the recruitment pile. No augmented gravel was observed downstream from the leading edge of the new bar, will be referred to as Bar 1 in the remainder of this report. Based on the baseflow depth observed in the center of the pool area prior to gravel augmentation (~ 2+ ft) and the height the bar above the baseflow water surface (0.7 ft), the fresh gravel deposits in the pool exceeded 3 ft in thickness. These developments were captured in a 2008 sketch map prepared by New Albion Geotechnical (Figure 10).

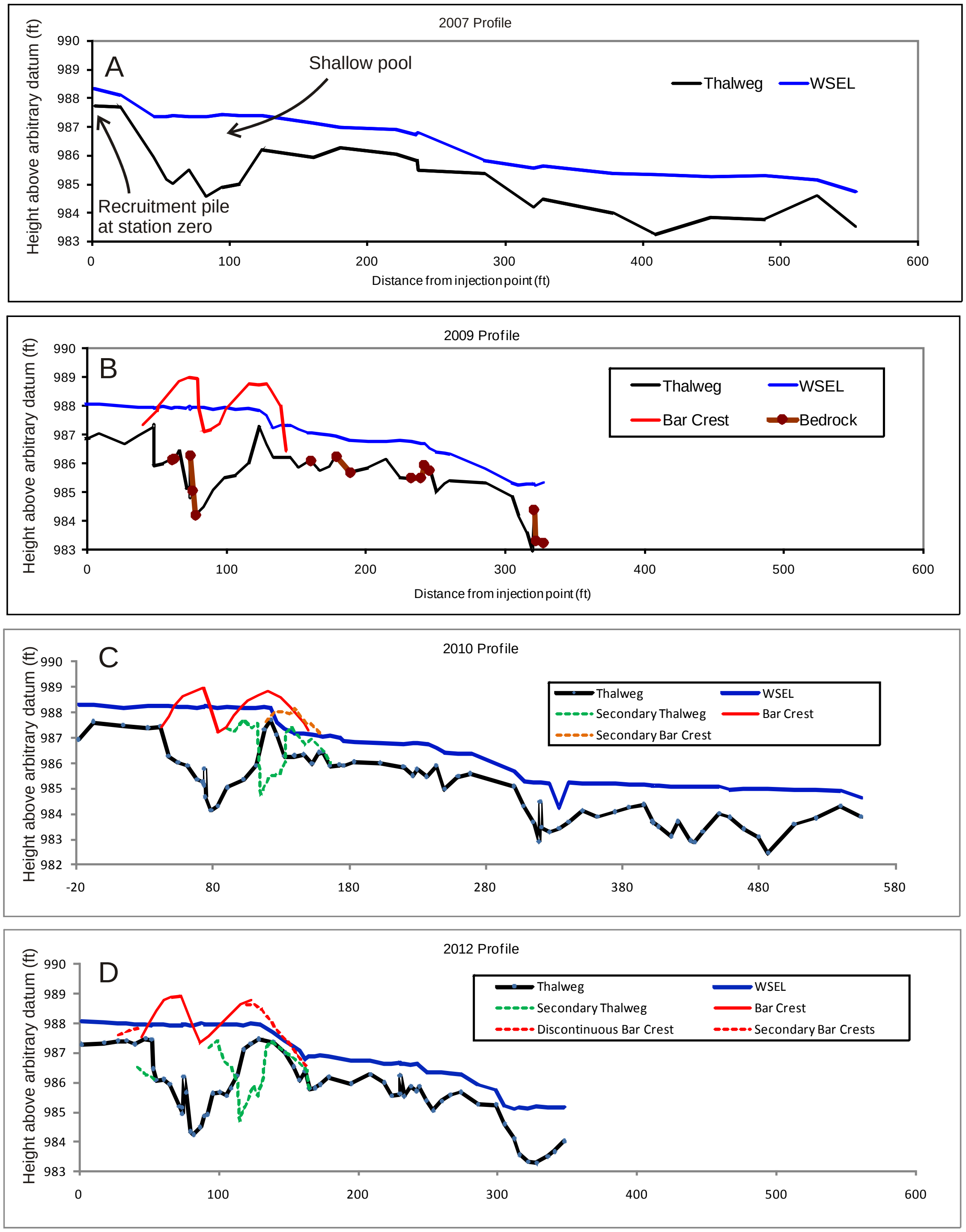


Figure 6: Longitudinal thalweg profiles through the study area. Profiles are projected onto the channel centerline for comparison. 2007 profile adapted from Dickenson (2008).

Figure 7: An upstream view of the pool immediately downstream from the gravel recruitment pile in the summer of 2007. A lobe of transported gravel and the remains of the recruitment pile are visible to the left and beyond the man, respectively.

Figure 8: The gravel recruitment pile in the fall of 2008. View is looking downstream.

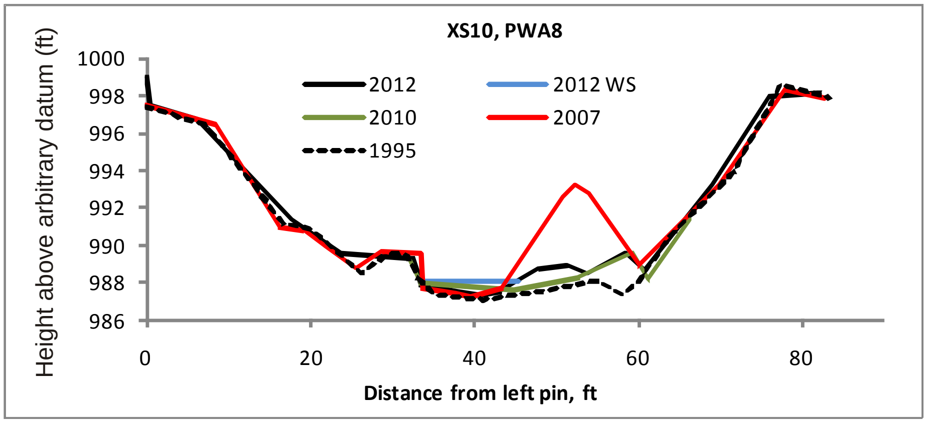


Figure 9: Cross section 10, showing the gravel recruitment pile in the fall of 2008. The section shows little changes since 1995 other than placement and erosion of the pile.

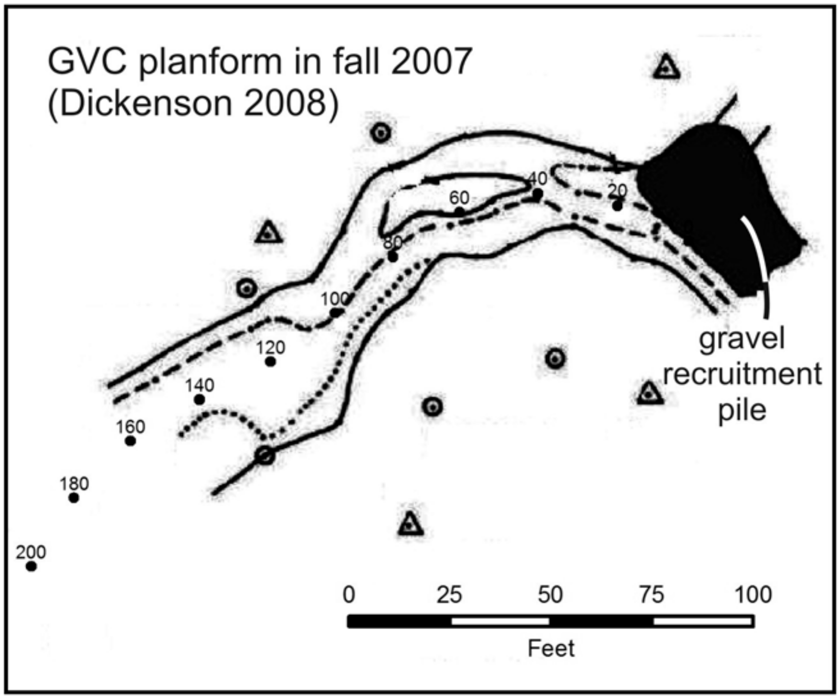


Figure 10: Map showing the configuration of the study site immediately downstream from the recruitment pile at the beginning of WY2008.

WY2009

In the fall of 2008, TCRCD again reconstituted the gravel recruitment pile. In contrast to the previous 2 water years, however, WY2009 included 2 floods with peak flow that significantly exceeded the threshold of gravel entrainment (Figure 4a). By the spring of 2009, gravel from the recruitment pile was transported downstream as much as 145 ft downstream where a second bar (referred to as Bar 2) formed in the center of the channel (Figure 11). As had been the case with Bar 1 the previous year, Bar 2 ended in an abrupt deposition front with no evidence that any of the augmented gravel moved beyond the bar's leading edge. The summer of 2009 marked the beginning of monitoring activities supported by the S&T Program, and consequently the first year in which topographic changes were captured by Total Station surveys. Figure 12a shows the cross sectional geometry at Bar 1 beginning in 2009 and an example of the geometry of Bar 2 is shown in Figures 12b and 12c. Although Bars 1 and 2 both represent 3 or more feet of deposition, the adjacent thalweg was relatively deep and in several places was scoured to bedrock (Figure 12b). Deposition of the bars also appears to have triggered nearby bank erosion (Figure 13), especially along the left bank adjacent to Bar 2 where a high sandy bank retreated nearly 5 ft between 2008 and 2009 (Figure 14).

Figure 11: Upstream view from the leading edge of Bar 2 in the spring of 2009. Bar 1 is sunlit in the background and the remains of the recruitment pile is visible in the shadowed area farther upstream.

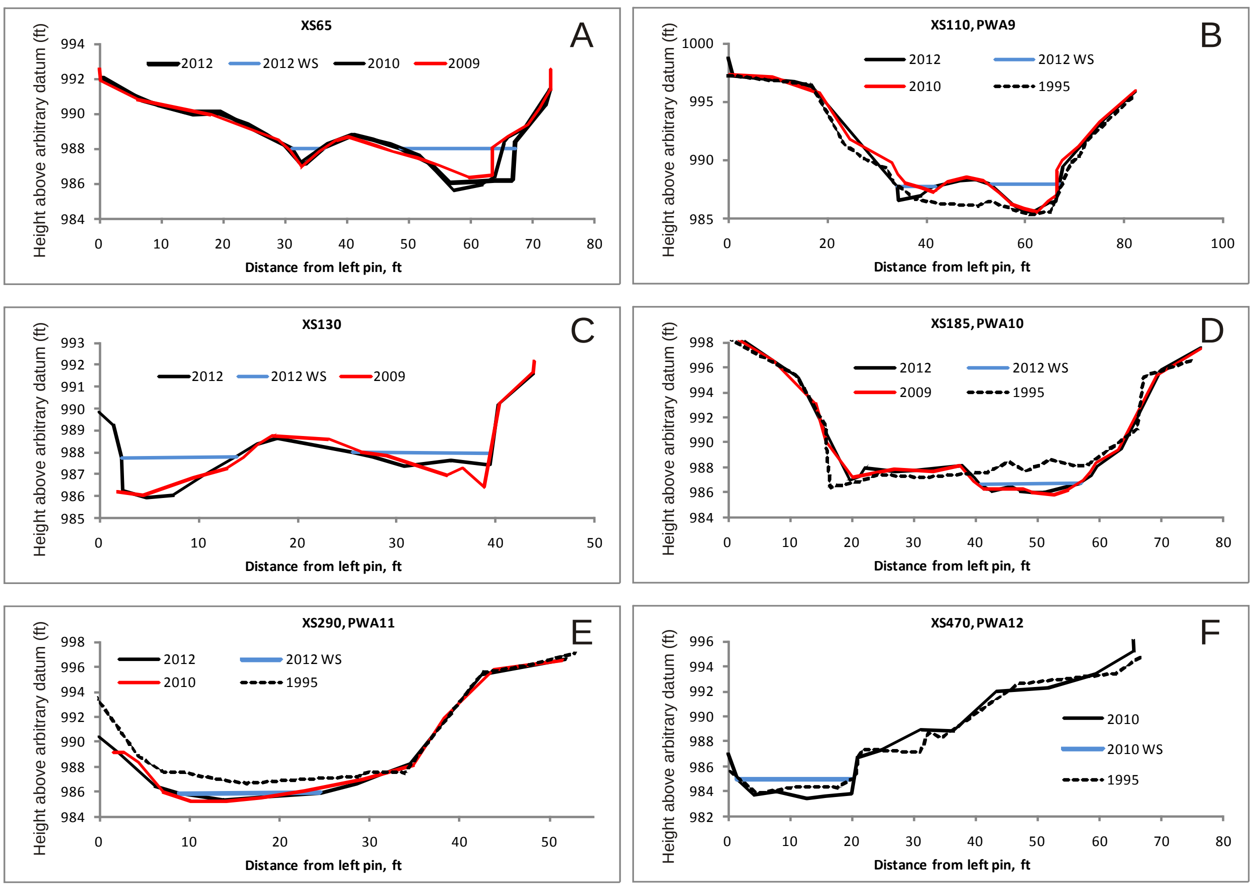


Figure 12: Cross sections showing the channel geometry at different points in time and changes noted in the text.

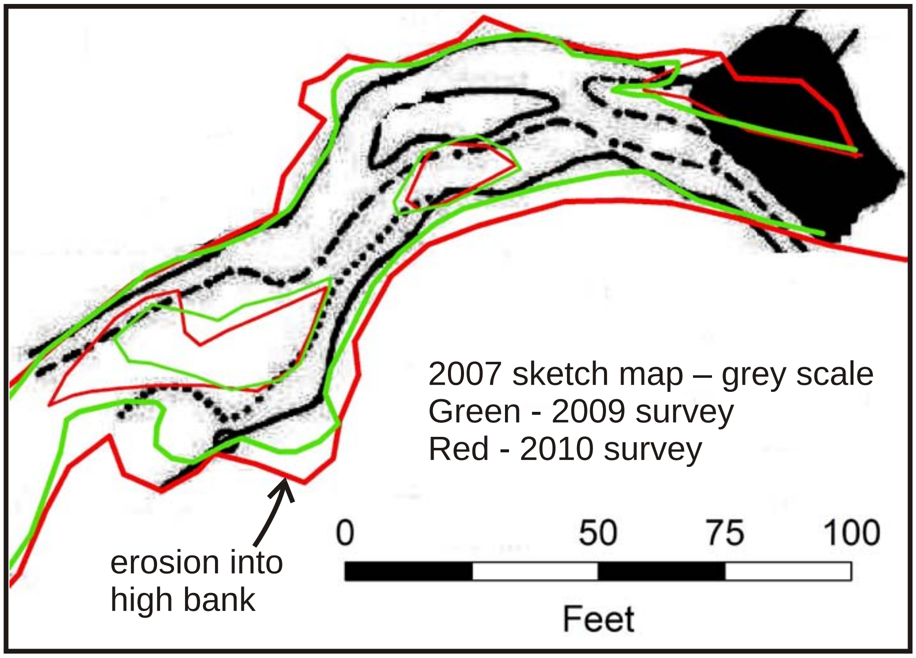


Figure 13: Planform maps showing approximate edge of wetted channel at baseflow (6 ft3/s) in 2007, 2009, and 2010.

Figure 14: Erosion into the high left bank at the location indicated on Figure 13. Photo taken in December 2009.

WY2010

WY2010 was also a relatively wet year with 2 and perhaps 3 flow events large enough to mobilize gravel in at the study site (Figure 4a). However, relatively little change in channel geometry was observed, as evidenced by cross sections (Figures 12a and 12c) as well as a comparison between longitudinal profiles surveyed in 2009 and 2010 (Figures 13b and 13c). Significant changes between the 2009 and 2010 surveys include continued bank erosion near both bars and a downstream advance of Bar 2's leading edge by about 20 ft (Figure 15). The lack of noticeable channel change is presumably related to the fact that the quantity of new gravel placed by TCRCD was much smaller than in the previous 2 years.

Figure 15: Upstream view from the leading edge of Bar 2 in the spring of 2010. Bar 1 is sunlit in the middle distance and a sunlit portion of the recruitment pile is visible in far background.

WY2011-WY2012

The flood hydrology in water years 2011 and 2012 was similar to the first few years of this study, in that none of the winter storms generated flows large enough to cause significant bed mobilization (Figure 4b). This lack of flood flows is curious, since precipitation totals were normal or above normal in both years. This is particularly true of WY2011, which was a wet year in the larger Trinity River watershed. The low flood magnitudes are presumably related to the fact that much of the precipitation came in the form of snow that melted slowly in the spring. Consequently, the flow record for WY2011 shows a long period of moderately elevated flows extending into the late spring, but no large peaks (Figure 4b). As a result of lack of floods, together with the fact that TCRCD placed no new gravel in WY2011 and placed of larger material that was not entrained in WY2012, topographic changes in the study reach were subtle. Detectable topographic changes include a slight flattening of the downstream face of Bar 2 (Figures 13d), erosion of the left bank adjacent to Bar 2 (Figure 12b), and the appearance of a small accumulation of augmentation gravel along the left bank 190 ft downstream from the augmentation location (Figure 12d and Figure 16). That accumulation, which has a maximum thickness of about 0.3 ft, is barely discernable on Figure 12d as a slight elevation of the 2012 cross section trace above the 2010 trace near station 45. The most striking change to the site over those 2 years was the establishment of dense herbaceous vegetation on both bar surfaces, and especially on Bar 1 (Figure 17).

Figure 16: Upstream view from about station 200 in 2012. The leading edge of Bar 2 is visible in the middle distance. A small accumulation of augmentation gravel is visible in the foreground near the left bank (right in the photo). The maximum and average thicknesses of the deposit are about 0.3 and 0.15 ft, respectively, and its area is approximately 200 $ft^2$.

Figure 17: Upstream view from Bar 2 in 2012 showing a dense cover of herbaceous vegetation on Bar 1 (the total station is on Bar 1).

The resurvey of 2 PWA cross sections 290 and 470 feet downstream from the augmentation location show that the GVC has incised slightly since the 1990s (Figures 12e and 12f). This result is consistent with observations of the bed surface texture and lithology indicating that the TCRCD gravel augmentations have had no effect whatsoever on the channel downstream from XS185. Three more cross sections were established and surveyed only once during this study. Located 75, 112, and 508 feet downstream from the augmentation location, these data may be of value for potential future monitoring (Figure 18).

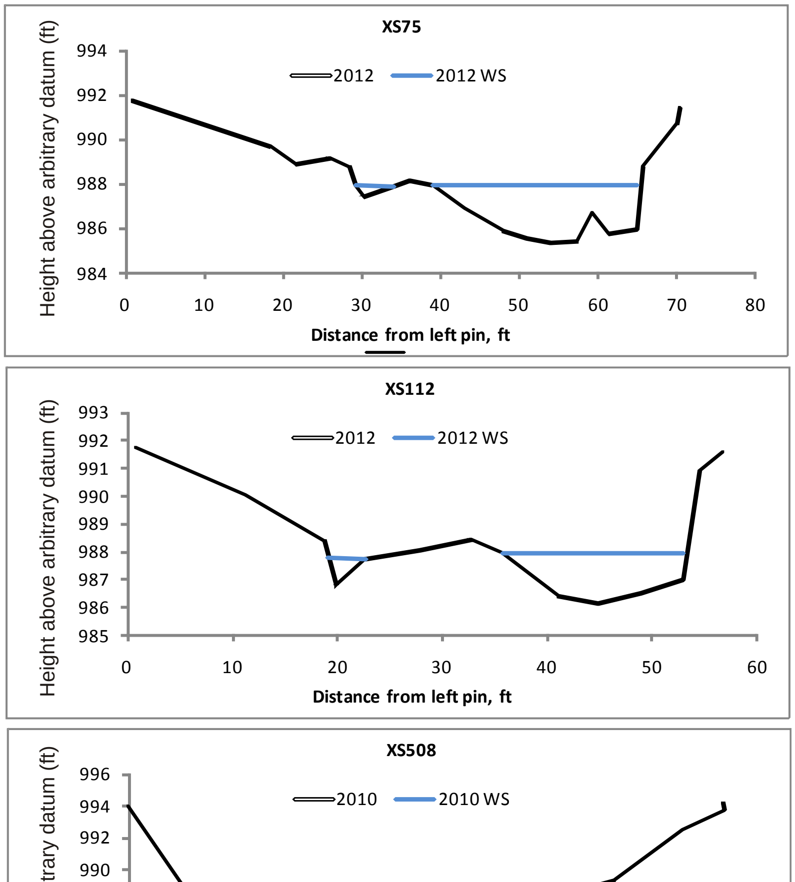


Figure 18: Cross sections that were surveyed only once for this study.

### *Tracer Placement and Relocation*

This section summarizes tracer transport characteristics by year. More complete tracer placement and relocation dates and distances traveled is given in Appendix A.

#### WY2008

All 200 of the pit-tagged tracers available in the fall of 2007 were placed in and adjacent to the TCRCD gravel recruitment pile in November 2007. Approximately half the tracers were buried in the face of the pile nearest the channel center and the other half were distributed on the streambed and covered with a layer of augmentation gravel 1-2 particles thick. This batch of tracers had been painted bright yellow, and it was considered prudent to camouflage the tracers to discourage tampering even though the field site is rather remote with limited access.

The tracers placed in the fall of 2007 were relocated the following summer. Although material entrained off the recruitment pile moved a short distance downstream into the pool, about half of the tracers that had been placed directly on the stream bed had not moved from their initial positions. Rather than leaving them on the bed through the summer and fall, we removed 47 of the tracer stones from the stream. As a result the effective number of tracers launched in WY2007 was reduced to 153. These 153 tracers are referred to as Y1 tracers, that is, the first set of yellow tracers placed.

An RFID search in the summer of 2008 successfully identified 91 (59%) of the Y1 tracers in Bar 1 or the other fresh deposits immediately downstream from the gravel recruitment pile (Table 2). A thorough search of the stream bed for several hundred feet farther downstream turned up no tracers or other evidence that any of the augmented gravel had advanced beyond the leading edge of Bar 1. The maximum transport distance of any relocated tracer was 62 ft, which places that tracer near the center of Bar 1. The mean and median transport distances of the 107 located particles was 39 and 41 ft, respectively, or about midway between the leading edge of Bar 1 and the gravel recruitment pile.

At least 3 factors may have contributed to the failure to locate 41% of the tracers. All but a few of the tracer particles were buried within the deposits. Because the maximum thickness of the deposits exceeds the reliable read range of 30-mm PIT tags, some of the tracers may have been buried too deeply for detection. In addition, all 153 of the Y1 tracers were presumably concentrated in a relatively small area (about 800 $ft^2$), such that many of the tracers were likely very near other tracers. Tests with clusters of PIT-tagged particles have confirmed that the radio signals from nearby tags can interfere with one another, so that only the strongest signal is detected. Thus, the signals from a portion of the undetected tags are likely obscured by the signals from other nearby tags. Finally, it is possible that a few of the tags may have been damaged.

| | WY2008 | WY2009 | WY2010 | WY2011 | WY2012 |
|---|---|---|---|---|---|
| Number Placed | 153 | 47 | 226 | 36 | 20 |
| Y1 Number Located | **91** | 97 | 71 | 70 | 41 |
| Y1 median dx (ft) | **41** | 15 | 0 | 0 | 0 |
| Y1 mean dx (ft) | **39** | 30 | 1 | 3 | 2 |
| Y2 Number Located | | **40** | 29 | 23 | 16 |
| Y2 median dx (ft) | | **69** | 0 | 0 | 0 |
| Y2 mean dx (ft) | | **78** | 3 | 0.3 | 0.3 |
| G1 Number Located | | | **163** | 148 | 132 |
| G1 median dx (ft) | | | **0** | 0 | 0 |
| G1 mean dx (ft) | | | **26** | 4 | 3 |
| G2 Number Located | | | | **30** | 33 |
| G2 median dx (ft) | | | | **0** | 0 |
| G2 mean dx (ft) | | | | **2** | 5 |
| G3 Number Located | | | | | **15** |
| G3 median dx (ft) | | | | | **5** |
| G3 mean dx (ft) | | | | | **19** |
| Total Number Placed | 153 | 200 | 426 | 461* | 482* |
| Percent Located | 59 | 69 | 62 | 60 | 49 |

Table 2: Summary statistics of tag placement and relocation counts, and yearly transport distances (dx). First-year relocation counts and transport are in bold font. The * indicates placement totals that include the removal of a broken Y1 tracer from the stream.

WY2009

The 47 tracer that were removed from the stream in the summer of 2008 were returned to the stream in the fall of that year by incorporating them into face of the new gravel recruitment pile TCRCD had placed in the channel. These are referred to as Y2 tracers. Forty of the 47 Y2 tracers (85%) were located the following summer (2009). The maximum transport distance was found to be 142 ft, which was nearly the exact distance to the leading edge of Bar 2 at the time. The mean and median transport distances of 78 and 69 ft correspond to a position near the crest of Bar 1. The minimum transport distance of the 40 located tracers was 40 ft.

It can be seen that the first-year median and mean transport distances tracers were roughly equal for both the Y1 and Y2 tracers. This symmetry in the distribution of transport distances was found to break down after the first year, as is evident from the transport characteristics of the Y1 tracers that were relocated in the summer of 2009. Eighty of the Y1 tracers that were located in 2008 were relocated in 2009, and an additional 17 were detected for the first time since their initial placement. The mean travel distance recorded by all 97 tracers from their last known locations was 30 ft but the median travel distance was just 15 ft. This divergence between the mean and median transport distance signals the fact that, once deposited, a majority of the tracers remain stationary in subsequent years. Only a relatively small number of tracers that are deposited at or near the bed surface or in locations subject where re-entrainment is likely continue to move downstream.

Consequently, the median distance traversed by the Y2 tracers in WY2009 was less than a fifth of the median transport of the Y2 tracers, even though the displacements assigned to 17 of the 97 Y1 tracers occurred over 2 winter flood seasons. Moreover, the median total distance the Y1 tracers had move since their initial placement was 47 ft, or approximately 68% percent the median distance traversed by the Y2 tracers. The fact that Y2 tracers had, in most cases, moved downstream beyond the Y1 tracers after just one winter in the stream suggests a transport pattern in which material entrained from the recruitment pile is preferentially transported to an active deposition front while previously deposited sediments remain largely undisturbed.

WY2010

As the supply of yellow tracers had been exhausted the previous year, a new batch of 300 tracers was prepared to the same specifications as before, except that this second batch of tracers was painted green. A total of 266 of these green tracers were placed in the stream in December 2009 and are designated the G1 tracers. The G1 tracers were placed according to a strategy intended to better resolve the influence of starting position on tracer displacement. Instead of placing all tracers in a recruitment pile at the upstream end of the study site, tracers were distributed between the augmentation location and the downstream end of Bar 2 in a grid-like fashion. Most of the tracers were arrange in clusters placed on cross section transects or other ad hoc transects, with 2 to 5 clusters per transect (Figure 19a). Clusters consisted of 2 to 4 individual tracers, with half of the stones in each cluster buried approximately 0.5 ft deep in the substrate and the other half embedded firmly in the bed surface. Ten singly-placed tracers were buried in a line perpendicular to the channel centerline at station -8, and 8 other single tracers were distributed on the bed surface in thalweg locations downstream.

Of the 226 tracers G1 placed, 163 (72%) were relocated the following summer. The mean distance traversed by the located G1 tracers in WY2010 was 26 ft and the median was zero. The 10 tracers placed singly at station -8 most closely approximated the initial conditions of the Y1 and Y2 tracers in that their longitudinal position was near the center of where the earlier gravel recruitment piles. Eight of those 10 tracers were relocated in 2010 and were found to have traveled 68 ft on average, with a median travel distance was 49 ft. Two of those tracers had moved 140 ft to a location near the leading edge of Bar 2. In that same year, a total of 100 Y1 and Y2 tracers were located with an average displacement of 2 ft and a zero median.

WY2011

The large number of tracers introduced into the stream over the first 3 years of the study and the relatively short transport distances observed had resulted in a spatial density of tracers believed to be high enough to contribute to radio interference and difficulties with tracer detection. Thus, the numbers of tracers introduced in the final 2 years of the study was reduced. In the fall of 2011, 36 tracers, designated as the G2 population, were distributed among 4 transects (Figure 19b). Twelve tracers were placed on the bed surface in pairs on XS10 at the upstream end of the study reach, 12 were placed across the channel on XS110 near the head of Bar 2, and 10 were placed on XS185 a short distance downstream from the leading edge of Bar 2, and 2 were placed at station 212 well downstream from any augmentation gravel. Few of these tracers moved during the 2011 flood season, which lacked flows capable of entraining substantial portions of the bed. Of the tracers placed on XS10, 10 were located and only 1 had moved a detectable distance (6 ft). One of 9 located tracers that had been placed on XS110 moved 10 ft and the rest remained stationary. Only 2 of 9 located tracers that had been placed on XS185 showed detectable movements of 14 and 24 ft. Finally, neither of the tracers placed at station 212 moved. Likewise, almost no movement of tracer populations placed in prior years was detected.

A relatively large number of tracer stones were wholly or partly visible at the bed surface when the RFID tracer relocation work was performed in the summer of 2011. Most, but not all, of the exposed tracers were G1 stones that had been embedded in the bed surface or buried at a shallow depth in the fall of 2009. Of 66 tracers that were visible at the surface, 49 could be identified by identification numbers that had been written on the stones with a marker and had remained legible. Of those 49 identified tracers, only 43 were detected by the RFID equipments. The failure to detect 6 of 49 stones represents a possible tag failure rate of about 12% over a period of between 1 and 3 years. Although the range of possible reasons for tag failure is unknown, the fate of one of the Y1 tracers was clear. In its 4 years in the river that tracer had travelled 198 ft downstream from the recruitment pile where it started, 40 ft farther than any other tracer, where it was visually located on the bed surface. After confirming that its RFID tag was non-operational, the tracer was removed from the stream and inspected. The stone had developed a crack running through the area where the stone had been drilled. Although the stone was still intact when it was found, slight tension was sufficient to pull it apart and reveal that the crack ran through the hardened epoxy used to seat the tag in the drill hole and through the tag itself.

WY2012

A total of 40 tracers were placed in the stream in the fall of 2011. Ten were placed on XS10, and the remaining 30 were buried in 3 lines on and adjacent to the windrow of coarse gravel that TCRCD had placed along the stream bank that year. However, upon returning to the study area the following spring it was evident that very little of the windrow had been mobilized. It was decided at that time that the overly coarse windrow would be removed from the stream if possible, so the tracers that could be located in the windrow were removed. Twenty tracers were therefore located at their placement locations and removed, such that no more than 20 tracers remained in the stream (Figure 19c). These tracers are designated as the G3 population. The 10 tracers in the windrow that were not removed were typically those placed nearest the stream center. Slight erosion along the steep face of the windrow likely caused some of those particles to ravel into the channel where they were not easily visible (RFID equipment was not available when the tracers were removed). Others may have remained buried in the windrow and may have been removed along with the windrow.

Again, very little movement of tracers placed in prior years was detected in WY2011, and this lack of movement held true for the 10 G3 tracers that had been placed in the windrow and possibly remained in the stream. Of those, 8 were found in the fall of 2012, and 7 of them had not moved more than a few feet. However one of those tracers moved 32 feet downstream. Also, in sharp contrast to the tracers placed in previous years, the G3 tracers placed on XS10 were surprisingly mobile. Seven of those tracers were located in 20, and 6 of them moved between 26 and 49 ft, such that the average and median displacement of those 7 stones was 35 and 42 ft, respectively. Some of the G2 tracers placed on XS10 the previous year also showed anomalously large transport distances in WY2011. Of the 12 G2 tracers originally placed on that transect, 9 were located in the fall of 2012. Six of those had not moved, but the remaining 3 were found between 36 and 41 ft downstream. However, 2 of the 3 were not located in 2011, so how the total transport distance is divided between the 2 years is unknown.

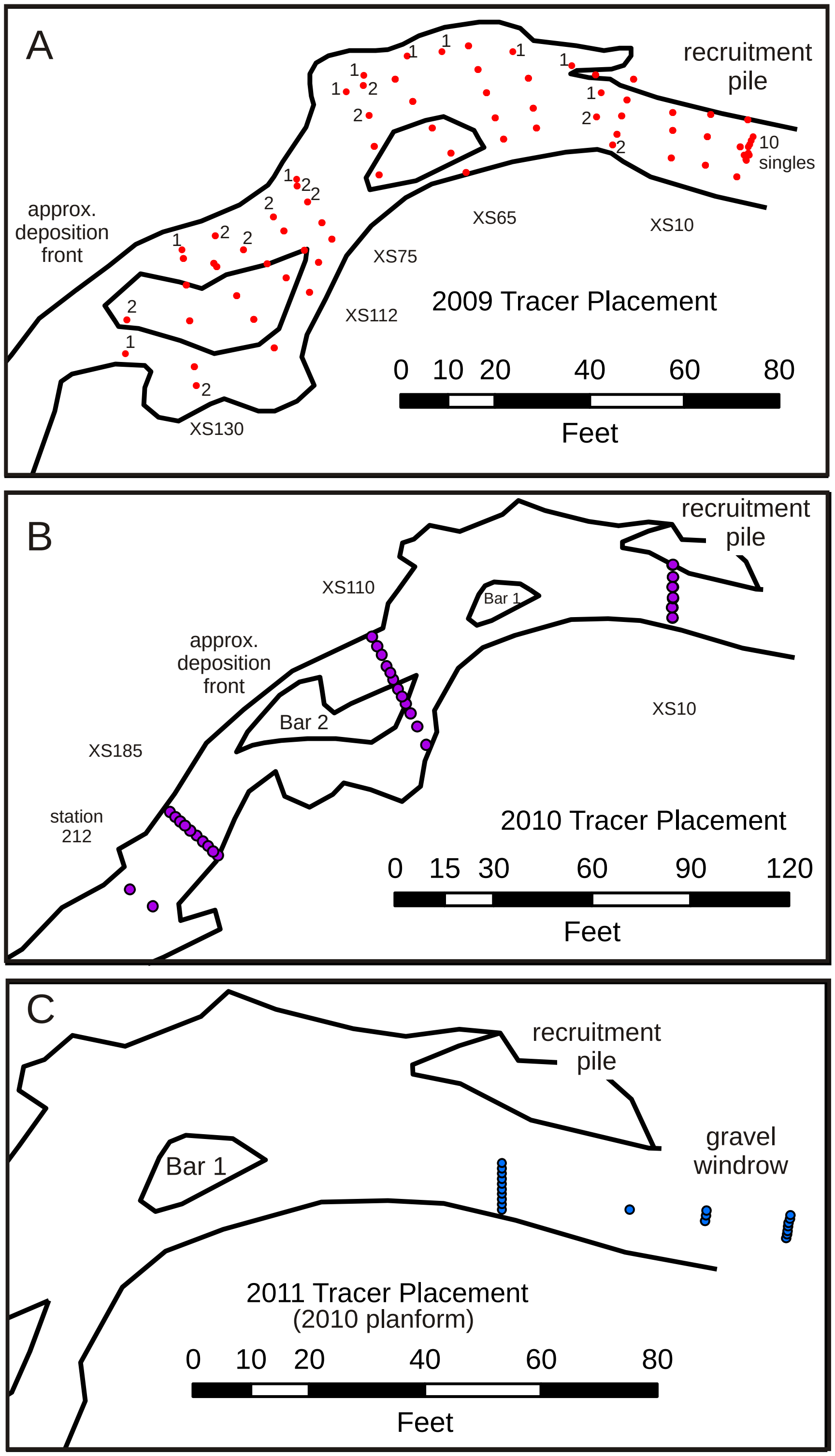


Figure 19: Tracer placement locations in WY2009-2011. Red symbols in panel A represent clusters of 4 tracers unless a different number of tracers is indicated.

## Discussion

Among the most obvious result of the tracer relocation performed in this study is that the tracers are far more mobile the first year they are in the stream than in subsequent years. In addition to the statistics listed in Table 2, that result is succinctly summarized in Table 3.

| Tracer Group | Num. Tracer with dx > 6 ft | Num. Tracers with Max dx in Year 1 | Percent of Max dx Occurring in year 1 |
|---|---|---|---|
| Y1 | 87 | 61 | 70 |
| Y2 | 40 | 40 | 100 |
| G1 | 79 | 72 | 91 |
| G2 | 5 | 3 | 60 |
| G3 | 7 | 7 | 100 |

Table 3: Numbers and percentages of single year displacements (dx) that occurred the first year tracers were in the stream.

For the Y1 and Y2 tracers, the tendency for greatest mobility in the first year can be explained in terms of the instability of the gravel recruitment piles and the initial deposition of the two bars that formed a short distance downstream. Clearly, raveling of the recruitment piles into the flow causes particles to be momentarily entrained. Although this does not imply that the particles will remain in transport for a large distance, it does encourage at least some downstream displacement. Obvious new bars were deposited in WY2008 and WY2009 when the Y1 and Y2 tracers were introduced. Many of the tracers were buried in the subsurface of those bars where they will no longer be available for transport until changing conditions trigger erosion of those bars.

In the case of the G1 tracers, decreases in mobility after the first year are linked to several phenomena. Most obviously, the second and third winters after the G1 tracers were introduced into the stream lacked floods capable of mobilizing large areas of the bed. However, it is also likely that transport of the G1 tracers in WY2010 resulted in many of them to coming to rest in relatively stable locations, or perhaps being buried in depositional areas. Finally, it is interesting to note that the leading edge of Bar 2 appears to represent an approximate downstream limit for gravel and tracer transport. Thus, the closer any particle gets to that location, the more limited is the potential for future transport.

This limit to downstream transport is apparent in the near total lack of augmented gravel on the stream bed just a few 10s of feet beyond the bar front, a corresponding lack of topographic change, and the failure to detect any RFID tracers farther downstream. It can also be seen by considering the transport distances of G1 tracers as a function of initial placement position. The G1 tracers are well-suited to exploring this relationship because their initial positions were distributed throughout the reach. Of the 226 G1 tracers placed, 185 (82%) were located at least once. With the exception of 1 stone, the transport distances of those tracers lie within an envelope defined by the distance from the initial placement location to the leading edge of Bar 2 (Figure 20). The figure also depicts a somewhat bi-modal distribution of transport distances in that most of the particles either moved a relatively large proportion of the distance to the deposition front or they remained close to their initial positions. Intermediate transport distances to locations midway to the deposition front are relatively rare. In other words, particles that become entrained tend to move close to the front.

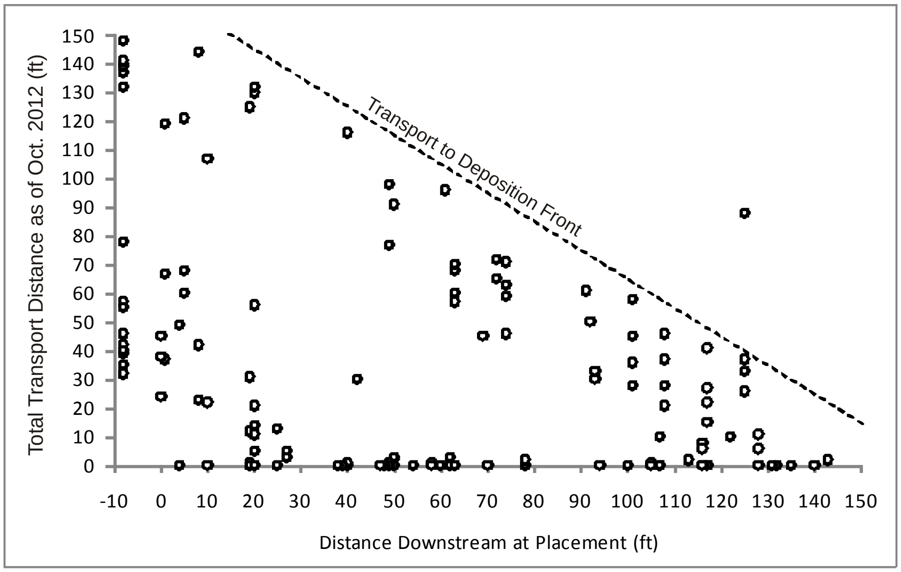


Figure 20: Total tracer displacement distance as a function of original position for G1 tracers placed in the fall of 2009.

The presence of a sharp deposition front at the leading edge of Bar 2 may reflect a reduced potential for gravel entrainment and transport beyond the bar front due to the coarse surface texture of the native stream bed. It is well known that the shear stresses necessary to entrain bed material of a given size depends on the size of that material relative to the surrounding particles, rather than on absolute size alone. This dependence on relative size is incorporated into fractional bedload transport equations through formulation of a hiding-exposure function of one kind or another (Einstein 1950; Parker 1990; Wilcock and Crowe 2003, Gaeuman et al. 2009). Thus, the RFID tracers, as well as gravel from the recruitment piles, are transported at one rate over the relatively smooth portion of the bed that has already been blanketed with added gravel, and at a much slower rate over the much coarser and rougher native bed. The conjecture that the coarse bed downstream from Bar 2 effectively traps any gravel that move beyond the deposition front was tested by placing 12 tracers on the bed surface downstream from Bar 2 in 2010 and 2011. As anticipated, 9 of those tracers remained immobile, and the maximum movement displayed by any of the 12 was 25 ft over 2 years.

Among the major uncertainties regarding a possible limit to downstream transport at the deposition front involves the whereabouts of the detected RFID tracers. As indicated in Table 2, RFID detection failed to locate 31% or more of the tracers present each year, with the failure rate reaching 51% by the final year of the study. One could argue that the missing tracers had been transported downstream beyond the search domain. However, several lines of evidence indicate that this is almost certainly not the case.

First, the RFID search was carried downstream more than 600 ft, well beyond any evidence of non-native gravel deposition. The downstream search domain spanned 2 runs with coarse bed composed of boulder, cobble, and bedrock sills, as well as 3 pools that would likely trap any incoming gravel delivered by the small to moderate floods that occurred during the study period. The failure to detect tracer stones during these downstream searches supports the conclusion drawn from substrate observations and topographic monitoring that none of the augmented gravel propagated more than 40 ft beyond the leading edge of Bar 2 over the full duration of the study.

It can also be observed that in many cases, tracers that went undetected in one or more years of the study were successfully located in other years. Using the G1 tracer group as an example, 80 of those tracers were both detected and not detected at least once in the final 3 years of the study, whereas only 41 of the G1 tracers went undetected over all 3 years. Moreover, in 35 of those 80 cases, the tracer was detected in a year subsequent to the year it was missing. This demonstrates conclusively that failure to locate a tracer does not imply that the tracer has left the study area.

Several implications for practical gravel management in regulated rivers can be drawn from these results. For one, the GVC results show that, under some circumstances, the downstream propagation of gravel that is persistently added to a stream at a single location can take the form of a migrating deposition front. Such a front defines the downstream limit of gravel propagation, such that a long period of time may be required for any benefits of gravel augmentation to reach downstream locations. The propagation of the deposition front through the GVC study reach was coupled with a striking transformation in the geometry and substrate of the reach immediately downstream from an augmentation location. A section of the GVC channel extending about 170 ft downstream from the augmentation location was transformed from a plane bed run and bedrock-controlled pool with a predominantly cobble substrate to wide, quasi-braided reach with large alluvial bars and multiple baseflow channels. This transformation occurred sequentially from upstream to downstream, with the more upstream bar forming in WY2008 and more downstream bar forming the following year. The hint of a third depositional area about 30 ft downstream from Bar 2 became evident by the end of the study. That area consisted of a 200-$ft^2$ patch of non-native gravel with a maximum estimated volume of about 1 cubic yard, but the gravel augmentation has had virtually no effect on the channel downstream from that location. The sequence of geomorphic evolution suggests that, where gravel additions trigger local geomorphic adjustments, those adjustments must be largely completed before changes due to the augmentation will be observed farther downstream.

It is plausible that the transformation observed at the GVC site is a consequence of a mismatch between the augmentation rate and the transport capacity of the flow. Coarse sediment deposition immediately downstream from the gravel recruitment piles in GVC resulted in bank erosion, as well as bar formation. Bar growth and bank erosion are coupled processes, in that the growth of bars in the channel accelerates bank erosion and widening of the bankfull channel due to bank erosion provides more accommodation space for bar growth. Banks immediately downstream from the GVC augmentation location are predominantly composed of sands and very fine gravel derived from the decomposed granite underlying the hillslopes. Because this material is more easily entrained than the coarse gravel introduced from the recruitment piles, it is preferentially removed. An exchange in the composition of the bedload takes place in which the gravel is deposited and the sandy bank material is entrained in its place. Such an exchange may be among the key factor contributing to local channel transformation. If so, reducing the extent of the exchange may effectively reduce the degree of transformation and lead to a more rapid downstream propagation of the augmented gravel.

In light of these observations, it is worth considering whether there may be threshold rate of gravel augmentation (ie, annual augmentation quantity) above which the rate of downstream gravel propagation decreases. Mechanistically, such a threshold would correspond to an augmentation quantity that exceeds the transport capacity of the stream and so accumulates and forces bank erosion a short distance downstream. Decreasing the gravel augmentation rate in such a situation may actually increase the rate at which effects of the augmentations propagate downstream.

The capacity of a stream to transport a given quantity of augmented sediment also clearly depends on the particle size of the augmented material. Reducing the size of the augmentation gravel would likely increase downstream transport capacity and decrease the tendency for local channel transformation. However, gravel augmentations usually target a particular size range of bed material believed to be deficient in the stream, so an arbitrary reduction in the augmentation particle size would probably not be justified in most cases. It may nonetheless be worth considering whether the inclusion of relatively small size fractions in the augmentation size distribution would be beneficial. For example, including a significant fraction of, say, 16 mm gravel in augmentation material composed primarily of 45-mm gravel would reduce the overall $D_{50}$ of the augmentation mix and thereby increase the mobility of the entire mixture (Parker and Klingeman 1982; Parker 2002).

## Conclusions

Gravel augmentation over a 6-year period on Grass Valley Creek caused channel widening and the deposition of 2 gravel bars in a reach of the stream extending 165 ft (6-8 channel widths) downstream from the augmentation location. This short section of channel upstream underwent a rapid geomorphic transformation from a simple plane-bed run and bedrock-controlled pool with a predominantly cobble substrate to wide, quasi-braided reach with large alluvial bars and multiple baseflow channels. Topographic evidence, as well as pebble counts and visual substrate mapping, show that very little of the augmented gravel was transported beyond a deposition front at the leading edge of the more downstream bar. By 2012, the last year of the study, the only evidence of gravel transport downstream from the deposition front was a small aggregation of perhaps 1 cubic yard of gravel and a single PIT-tagged tracer stone located 185 ft and 198 ft downstream from the augmentation location, respectively.

Tracking of nearly 500 PIT-tagged tracer stones corroborate topographic evidence showing that bedload transport dynamics in the reach were dominated by the downstream propagation of an active deposition front. Tracer transport distances were almost always largest the first year the tracers were in the stream. After the first year, tracers were often buried or otherwise deposited in stable locations, such that subsequent entrainment became less likely. Tracers that did become entrained were likely to move to a position near the deposition front. Consequently, annual tracer displacement distances are bimodally distributed, with most tracers either remaining in place or moving a significant fraction of the way to the deposition front. Relatively few tracers moved intermediate distances.

It is hypothesized that channel transformations like the one observed in GVC can be triggered by gravel augmentation input rates that exceed the transport capacity of the channel. It is further hypothesized that such a transformation will be associated with the formation of a distinct deposition front and a sharp decrease in the downstream propagation of the augmented gravel. Thus, increasing gravel augmentation rates beyond a critical threshold may actually increase the time required for the effects of gravel augmentation to propagate downstream and possibly even reduce the distance over which those effects will ultimately be felt.

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