Physical and geochemical characteristics of the Upper Sailor Bar 2008, Upper Sailor Bar 2009 and Upper Sunrise 2010/2011 gravel additions

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Chapter 1: INTRODUCTION and OBJECTIVE

1.1 Objective

Results described in this report are based on field data collected from August 2011 to June 2012 on the Lower American River. This project was sponsored by the U.S. Bureau of Reclamation and Sacramento Water Forum. Three restoration sites of varying ages were monitored during the project, and these sites are referred to as Upper Sailor Bar 2008, Upper Sailor Bar 2009 and Upper Sunrise 2010/2011; data was collected both before and after restoration of each site, and this report also has annual summaries that show some trends over the four years of gravel addition projects.

Objectives for the field work are summarized below:

- Conduct grain size analyses using pebble counts and bulk samples
- Conduct gravel mobility tests and analysis using tracer rocks and scour chains
- Measure depth and velocity of surface water
- Measure gravel permeability with salt water tracer tests
- Measure hyporheic pressure head (upwelling and downwelling) using mini-piezometers
- Measure and record temperature data using temperature loggers
- Measure hyporheic water quality field parameters (dissolved oxygen, turbidity, electrical conductivity, pH, and temperature) from mini-piezometers installed in the spawning gravel

1.2 Background

The protection and rehabilitation of salmonid spawning habitats is important for multiple reasons. Salmonid species have been shown to be critical indicators of water quality, ecosystem health and watershed management (DeVries, 2000). Additionally, compared to historical levels, there has been a significant decline in salmonid populations. Degradation of habitat is identified as a primary contributing agent and is believed to be a result of anthropogenic influences on the spawning habitat (Horner, 2004; Kondolf et al., 2008). Because degradation of spawning habitat may be a leading cause of declining populations of salmon, there has been a recent emphasis on the evaluation and restoration of spawning sites on rivers across northwest America (Schuett-Hames et al., 1996; Schuett-Hames, 1997; Kondolf et al., 2008). Dams, urbanization, artificial levees, channel modification and input from hatcheries impact the natural balance of the riparian system as well as limit the quantity and quality of spawning gravel needed by resident salmonid populations (Vyverberg et al., 1997; Phillips, 2003; Hannon and Deason, 2005).

Spawning Habitat Requirements

Salmonids use gravel beds of rivers as spawning habitat and to incubate embryos. Natural gravel bed streams are characterized by pool-riffle sequences, have abundant bedload material, and are generally coarse-grained. Female salmon spawn by excavating a pit to build a redd (nest) in the stream gravel. After spawning, the female salmon buries the eggs by moving gravel and forming an egg pocket (Wu, 2000). This morphology deflects surface water through the shallow gravel, and creates localized flow through the redd (Figure 1.1). On the American River, salmonids construct redds that are 20 to 30 cm deep in the stream gravel (Hannon, 2008; Monaghan and Milner 2009).

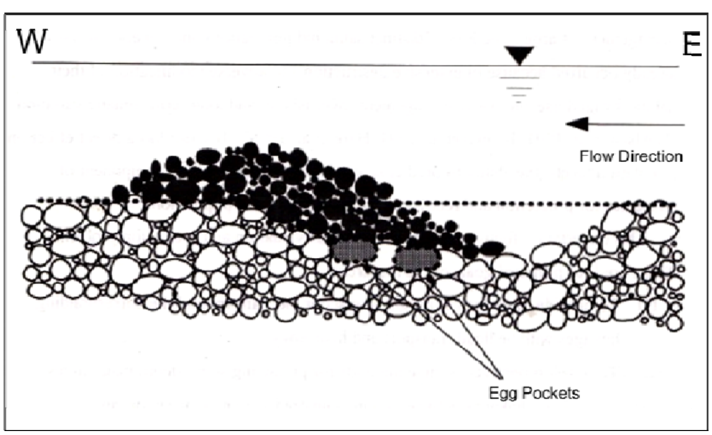


Figure 1.1: A representative salmonid redd, longitudinal cross section. Depicted are the original bed surface elevation (dashed line), locations of two egg pockets, and disturbed bed material (shaded particles) forming a tailspill. (From DeVries, 2000)

Hyporheic Zone

The shallow environment that serves as the interface between stream water on the surface and groundwater in the subsurface is called the hyporheic zone. The hyporheic zone is a transition zone where chemicals, nutrients and organic matter are exchanged. This zone is important to salmon egg survival, because hyporheic flow brings oxygenated stream water to the subsurface, and flushes metabolic waste from the intragravel environment (Coble, 1961; Vaux, 1962; Chevalier et al., 1984). The hyporheic environment is highly variable, and there are physical and chemical gradients that have measureable effect on habitat and egg survival (Turner and Phillips 2009).

From a hydraulic standpoint, the sedimentary deposits produced by gravel bed streams are heterogeneous and anisotropic (Tucker, 1981; Fetter, 2001). Flow through the gravel is assumed to be laminar, although residence time of water molecules may only be hours or days based on results from our tracer tests in the stream gravel. The flow of water across the interface is a function of the hydraulic conductivity of the sediments and the hydraulic gradient acting across the hyporheic zone (Ingebritsen and Sanford 1998).

Bed topography creates discreet points of water exchange through the hyporheic zone on a larger scale (Figure 1.2). The pools and riffles that naturally form in gravel bed streams create

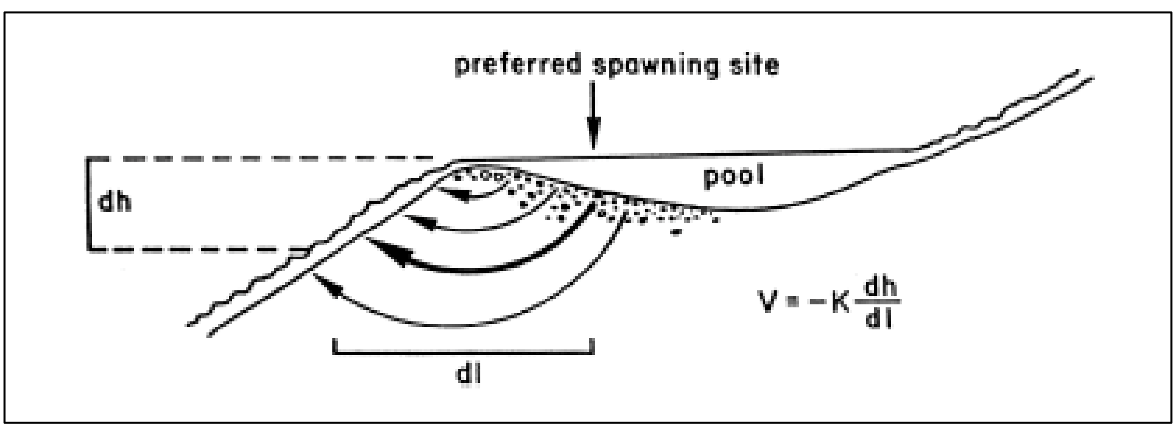


Figure 1.2: Diagram of groundwater flow through the tail of a pool through a riffle. The lower elevation of the water surface in the riffle creates a hydraulic gradient. V is Darcy velocity and K is hydraulic conductivity, vertical scale is greatly exaggerated. (From Kondolf et al., 2008)

points of high and low pressure that facilitate water movement through the streambed (Harvey and Bencala, 1993). Pools create higher backwater and higher pressure on the upstream side, and water is forced through the riffles to the low-pressure areas on the downstream side (Kondolf et al. 2008).

1.3 Study Area

Lower American River

The Lower American River lies below Nimbus Dam (Figure 1.3), and has had multiple anthropogenic influences that impact salmonid habitat. Nimbus Dam does not have fish passage, so more than 90% of the upstream habitat is lost to modern salmon and steelhead runs. Large flows have caused the river to become incised below the dams (Horner, 2004; Fairman, 2007), and managed flows have reduced the mid-range flood events that would have mobilized sediment and replenished the spawning gravel. A coarse, armored layer often caps the surface of the stream and further degrades the spawning habitat (Horner, 2004; Horner, 2009). Sediment deficiency has caused the Lower American River to lose, on average, 50,000 cubic yards of gravel per year (Fairman, 2007). Managed releases from the dams affect the temperature and volume of flow in the river, and this may not be in cycle with a naturally flow regime (Monaghan and Milner 2009).

The American watershed (Figure 1.3) is 4,890 square kilometers in area with headwaters at the crest of the Sierra Nevada, at an elevation of approximately 3000 meters. The terminus of the river is at the confluence with the Sacramento River, at an elevation close to sea level (Fairman, 2007). The drainage basin can be separated into two parts, Upper and Lower. The upper segment, above Folsom and Natoma Lakes, consists of multiple forks with steeper gradient and higher energy flows through steep canyon walls. The lower segment lies below dams and has a gradient of approximately 0.06 (Horner, 2004), with lower energy flows across alluvium plain material (Redd, 2010).

Below Nimbus Dam, the American River cuts into steep cliffs formed by Miocene to Pliocene aged sandstone and siltstone of the Fair Oaks and Mehrten Formations (Schlemon, 1967). The river bed and south bank are composed of terraced Pleistocene-aged alluvial gravels that formed during Riverbank time (Schlemon, 1967).

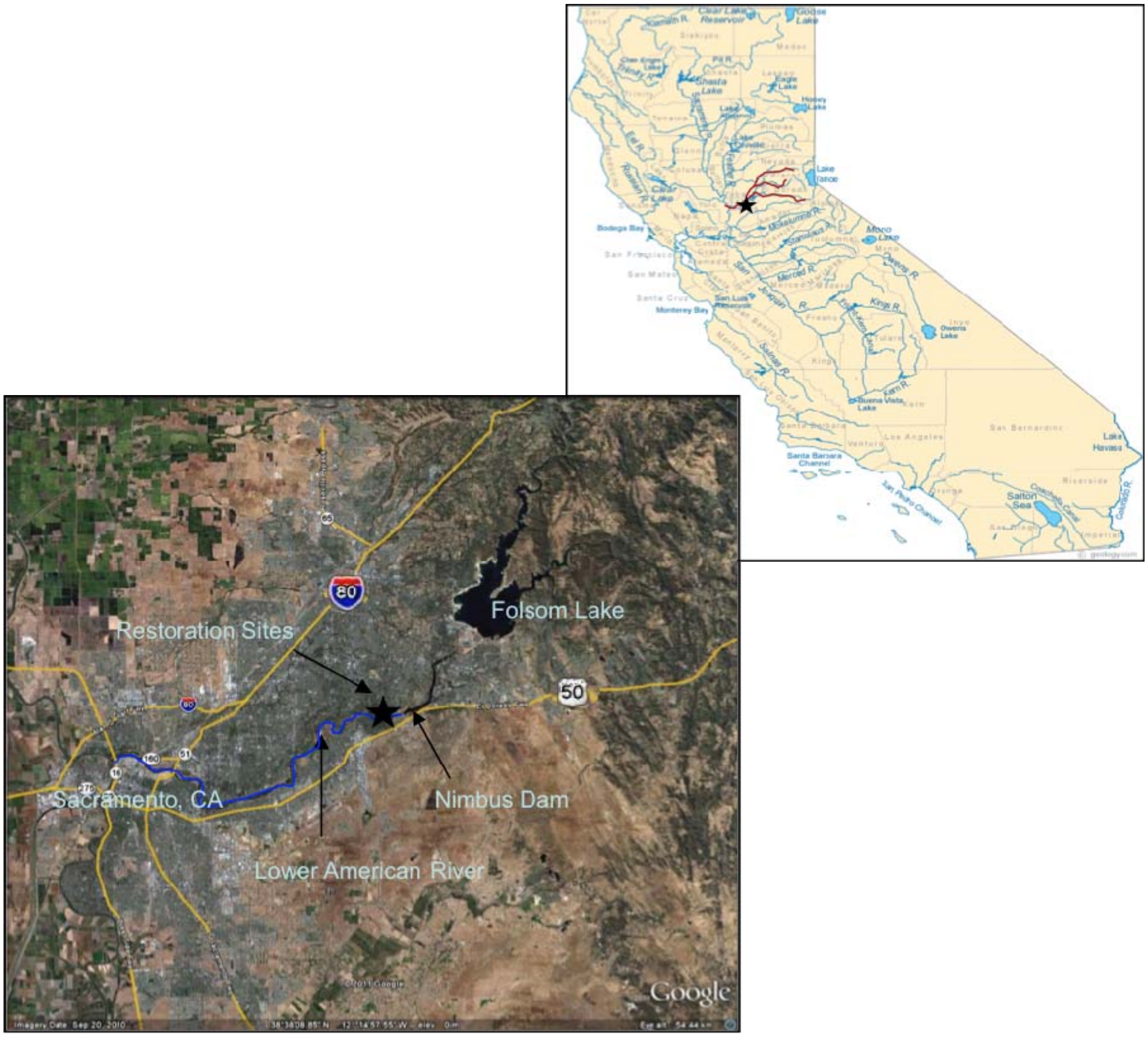


Figure 1.3: Location map of the American River restoration site in Sacramento, California.

The Mediterranean climate of the Sacramento region is characterized by warm, dry summers and cool, wet winters. Precipitation ranges from cm/year in the lower segments of the watershed to 200 cm/yr in the higher elevations of the American River Basin (NOAA, 2011). According to the USGS (2009), regional stream flow is highly seasonal, and prior to construction of Folsom and Nimbus dams yearly peak flows ranged from 10,000 to 180,000 cfs. After dam construction, yearly peak flows range from 1,000 cfs to 135,000 cfs. The dam is operated for flood control, water supply for irrigation, and recreation.

Daily peak flows were highly variable during the time period summarized in this study (September 2008 to June 2012) (Figure 1.4). Discharge during the fall Chinook salmon run ranged from a low of 800 cfs to in 2008 to a high of 3000 cfs in 2010. Managers generally try to avoid flow fluctuations during the spawning season to prevent dewatering of redds. In 2011 there was concern that spring flows as low as 1000 cfs might dewater steelhead redds. Annual peak flows were also highly variable, with a maximum of 30,000 cfs during winter storms in 2010 and 2011. These higher flows have the ability to mobilize gravel, and there was concern that restoration sites might be washed out by higher flows. Some gravel did mobilize during the high flow events, but the restoration sites were largely intact when the high flows receded. On an annual basis, higher releases in March, April, May and June are for agricultural exports, and some high releases during the summer months are related to delta water quality. Other winter and spring releases are for flood control and to maintain flood storage capacity in the reservoir. These competing needs for water all put demand on the system. Folsom Dam is an under-sized system, with more demand for water and more demand for flood protection than is available in the 970,000 acre-foot capacity lake.

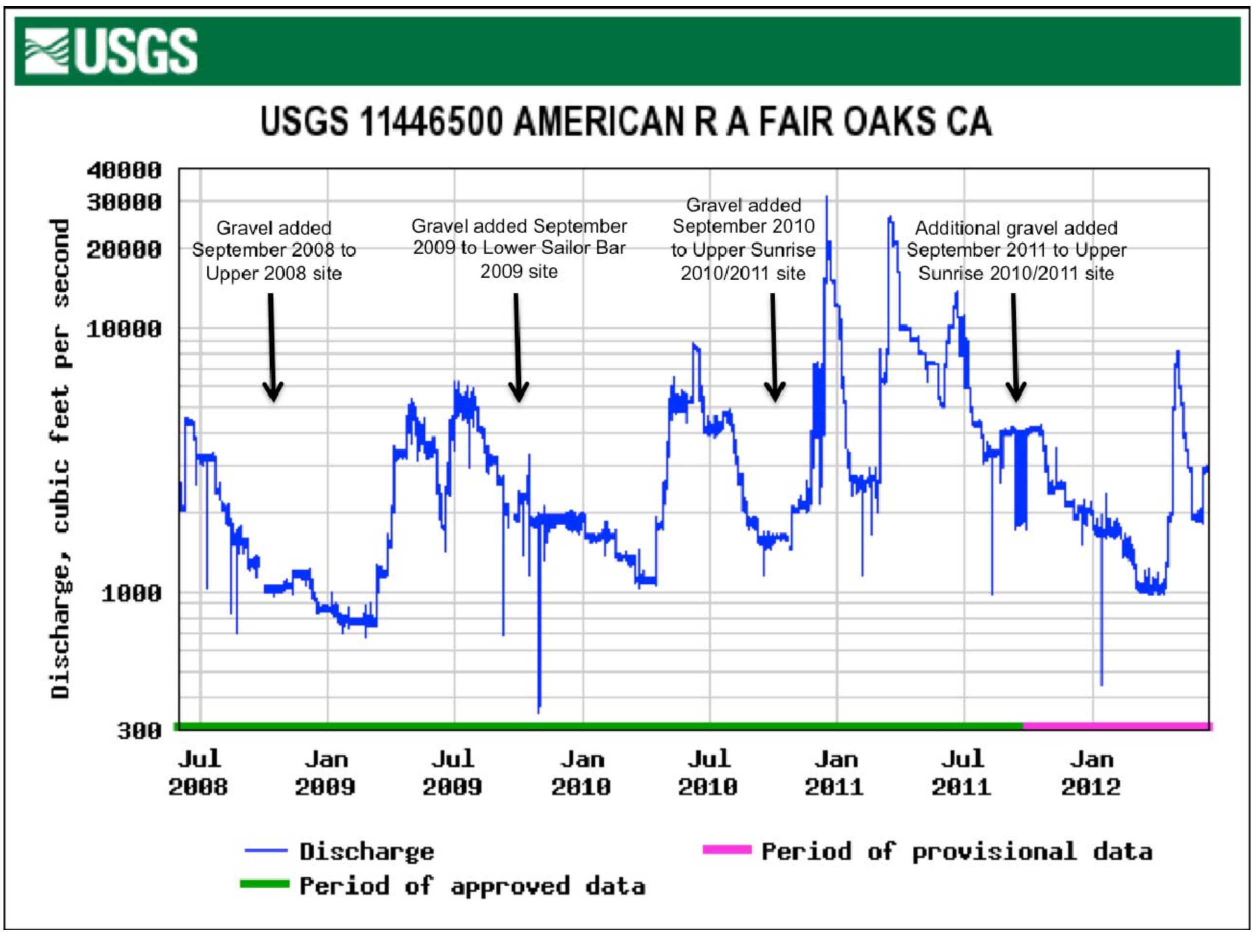


Figure 1.4: Hydrograph showing the dam releases from July 2008 to June 2012. Daily discharge of 800 cfs to 30,000 cfs on the American River, Sacramento, California. (From the USGS, 2012) Arrows indicate when specific sites were augmented by the adding gravel.

1.4 Methods

Restoration work is sponsored by the U.S. Bureau of Reclamation Sacramento office, as part of the Central Valley Project Improvement Act (CVPIA section b.13) mandate to evaluate and improve gravel conditions below federal dams. The project includes collaborators from California State University Sacramento (CSUS), the California Department of Fish and Game (DFG), The Sacramento Water Forum, US Fish and Wildlife Service, and Kramer Fish Sciences. Rehabilitation under these remediation projects has centered on gravel manipulation and gravel addition.

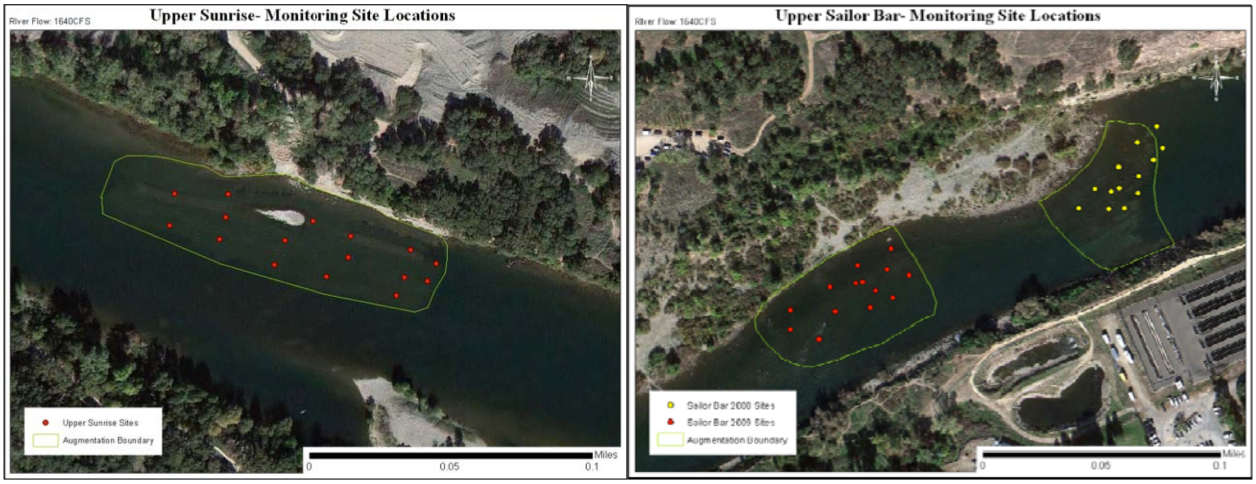
Restoration work began in the mid-1990's with assessment of physical conditions in the river. This included evaluation of the physical conditions of spawning gravels and measurements of stream flow, water depth, grain size, substrate permeability, dissolved oxygen content and temperature. Most spawning occurs along a six-mile stretch just below Nimbus Dam where the river has a gradient of approximately 0.06 and surface gravel had low permeability. These sites had poor quality spawning habitat due to inappropriate gravel size associated with either an excess of fine sediment and clay layers causing low permeability , or an excess of coarse sediment and the presence of coarse lag deposits that cause surficial armoring (Vyverberg, 1997; Horner, 2004).

Figure 1.5: Tractors adding clean unseasoned gravel from dredging piles on the north bank to the Upper Sunrise study area.

Based on the results of early studies, Phase 2 actions were aimed at artificially improving spawning habitats at different sites. This allowed for later comparison of treatment effectiveness.

Phase 2 gravel augmentations consist of adding thousands of cubic yards of presorted gravel (Figure 1.5) to each site. There are three restoration sites below Nimbus Dam on the American River (Figure 1.6). The first site, Upper Sailor Bar 2008 (Figure 1.7ii), was augmented in 2008 and has been monitored yearly for the past four years. In 2009, the Upper Sailor Bar 2009 (Figure 7ii) was augmented and has been monitored for the past three years. Lastly, in 2010 and again in 2011 gravel was added to the Upper Sunrise 2010/2011 site (Figure 1.7i) and has been monitored for the past two years.

Figure 1.6: Three restoration sites on the American River below Nimbus Dam in Sacramento, California.



(i) **(ii)**

Figure 1.7: Detailed maps of restoration sites. Upper Sailor Bar 2008 was augmented in 2008 (ii) and has been monitored yearly since restoration. Upper Sailor Bar 2009 was augmented in 2009 (ii) and has been monitored yearly since restoration. Upper Sunrise 2010/2011 was augmented in 2010 and again in 2011 (i) and has been monitored yearly since both restorations. Colored dots are sampling sites.

Phase 3 includes post-treatment monitoring and evaluation, and provides an understanding of the hydrologic and geomorphic changes resulting from the restoration work of Phase 2. The objective of this report is to analyze the effectiveness of the treatment of each site. CSUS has focused on physical and hydrologic measurements at the three gravel addition sites, and has used these measurements to characterize salmonid spawning habitat.

Study at all sites has used a BACI study design ("Before, After, Control, Impact") to show differences between restored and unrestored gravel areas. This approach was used to evaluate changes to the physical environment, determine the components and mechanisms that have changed, and identify the effect that each modifications has had in a particular environment.

Chapter 2: GRAIN SIZE

2.1 Background

Gravel size is a major factor in a productive salmonid spawning habitat (Nawa et al., 1990; DeVries, 2000; Horner, 2004; Kondolf et al., 2008). Salmon spawn successfully when hyporheic habitat in the gravel is suitable for redd construction, incubation and emergence (Kondolf et al., 2008). The presence of dams can affect gravel deposits because changes in sediment supply and gravel compaction may render gravels immobile (Fairman, 2007).

According to Kondolf et al. (2008), redd construction requires specific gravel size and relative mobility so spawning females are able to excavate a depression in the streambed. Eggs must have exchange of hyporheic water; therefore, high permeability is imperative for natural hydrodynamic processes and allows oxygenated surface water to interact with the hyporheic zone (Figure 1.1 and 1.2). Grain size is an important variable in this exchange. Finer sediment is detrimental emergence of fry, and fine sediments can effectively smother incubating eggs. Alevins must be able to wriggle between pore-spaces of the gravel, so high percentage of fines can hinder these processes, rendering the gravel unsuitable as salmonid spawning habitat.

Conversely, if gravel is too large, female salmon will be unable to construct redds (Figure 2.1). Grains that have a median size greater than 10% of the female spawner's body length are usually too large to be moved during redd construction, and therefore limit habitat suitability (Kondolf, 2000; Horner, 2004; Kris Vyverberg, personal communication). During high flow events, larger grains are left behind as lag deposits while finer material is winnowed away. This results in coarser and coarser bed material, and an armored bed forms (Bunte and Apt, 2001). This reduces intergravel flow and is an additional hindrance for female salmon when constructing redds.

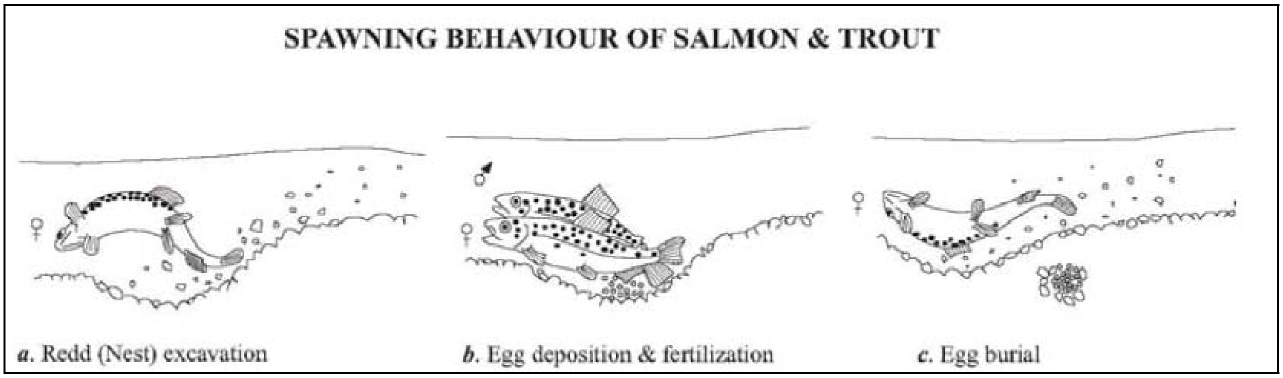


Figure 2.1: Spawning behavior of salmonids. (from Soulsby et al., 2001)

2.2 Methods

Background

Wolman (1954) and Leopold (1970) created a method to characterize streambed surface gravel sizes, where gravel size is measured as the intermediate axis of the particle, and placed into Wolman size categories. This method allows quick site assessment, and can be used to identify heavily armored or impacted areas of the stream.

Bulk samples provide another method of characterizing grain size. Bulk samples are collected with a shovel, and include smaller material that may be missed with pebble counts. With this method, a larger sample is collected at one discreet point; samples are weighed and sieved, and gravel size is plotted in weight percent size categories. Details of each method are given below.

Pebble Counts

Grain size was determined by the Wolman (1954) pebble count method and was taken along straight-line segments. Each pebble count consisted of one hundred rocks in a line segment, with the collection path recorded by GPS. Pebble counts were executed by taking a step forward and picking up the rock that was directly below the big toe portion of the field worker's foot. This ensured a random selection of sample grains; the first grain touched was the grain measured. Pebble sizes were determined with a template (Figure 2.2) that contained size classes from 5/16 inch to seven inches.

Figure 2.2: Pebble size template measuring intermediate axis diameter of grains. The largest size that the grain will not fit through is the determined lower end of the grain size range.

Bulk Samples

Bulk samples were collected before and after restoration at each site. Each bulk sample site was chosen by randomly tossing a marker to locate the center of the bulk sample area. Finding the largest surface grain in the sample area and multiplying the weight of that grain by 100 determined bulk sample size. This gives a 99% confidence interval that the sample size is sufficient to accurately characterize the grain sizes present. Surface and subsurface samples were collected separately to identify river bed armoring. The depth of the surface sample was defined as the diameter of the largest surface grain (Ettema, 1984). Bulk samples were collected with a shovel. A plywood shield was installed (Figure 2.3i) immediately upstream of the sample area to reduce current velocity and prevent the finest materials from escaping downstream. Five gallon buckets were used to transport the sample material to shore, where buckets of gravel were drained and then weighed (Bunte and Abt, 2001). Seven rocker sieves from 5/16 inch to 7 inches in size were used to separate the grains (Figure 2.3ii). Sieve openings were 5/16, 5/8, 7/8, 1.25, 1.75, 2.5, and 3.5 inches in size. Grains larger than 3.5 inches were manually measured with a template. Grains were split into size classes using the rocker sieves, and grains from each size class were then weighed on a digital scale. The sample with grains less than 8 mm was weighed and collected in steel cans and sealed for further detailed analysis (sieving) in the lab. The weight of each grain size was compared with the total weight of the sample to determine the percent weight distribution.

Grain size data are used by engineers and project designers on restoration projects. Natural streambeds can contain particles that vary five orders of magnitude in size (Kondolf et al., 2008), so grain size data are often plotted on a log scale as cumulative frequency percent. For example, a D_{90}(y) value will show 90% of the sample is finer and 10% of the sample is courser than a given size (x); additionally, the D_{50} value from the graph is considered the median particle diameter. Kondolf (2000) also employed a bulk sample method that separated results from substrate gravels and subsurface gravels. The ratio of the d_{50} values between surface and subsurface samples allowed him to calculate an armoring index.

i **ii**

Figure 2.3: Plywood shield to prevent fines from escaping downstream (i). Five gallon buckets containing different size classes after grains were sieved (ii).

2.3 Results

Pebble Counts

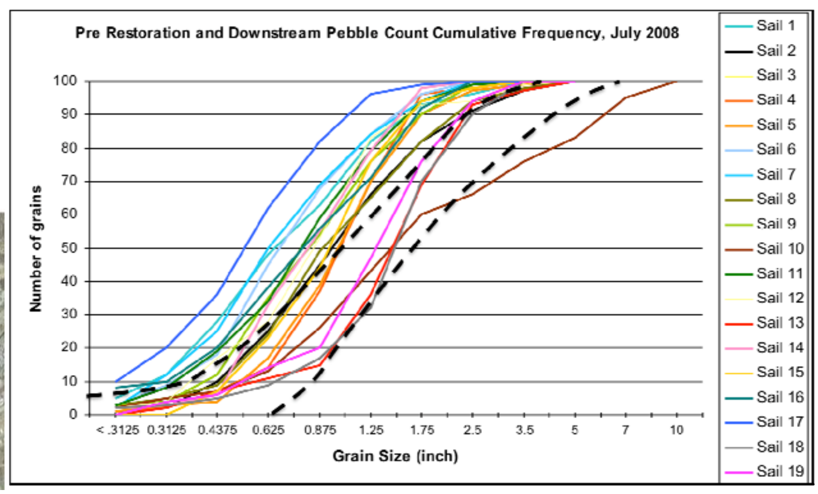
Upper Sailor Bar 2008 Site

19 pebble counts were conducted at the 2008 restoration site and surrounding area before the Upper Sailor Bar 2008 restoration project started (Figure 2.4i). The larger area was included to look for trends below Nimbus Dam. Figure 2.4ii shows the cumulative frequency graph for the 19

pebble counts conducted from the western tip of Sailor Bar downstream to the Sunrise Bridge. These pre-restoration pebble counts showed a range in grain sizes from fine-grained sand to 10 inch diameter boulders. Median grain size diameters (D_{50}) ranged from 7/16 to 1 ¼ inch and samples were poorly sorted. 9 Pebble counts were conducted in June 2009 after the gravel addition was completed. Figure 2.5i shows a map of the transects and pebble count locations, and Figure 2.5ii shows the cumulative frequency graph for the 9 pebble counts conducted after restoration. D_{50} values range from 5/8 to 7/8 and the samples are better sorted.

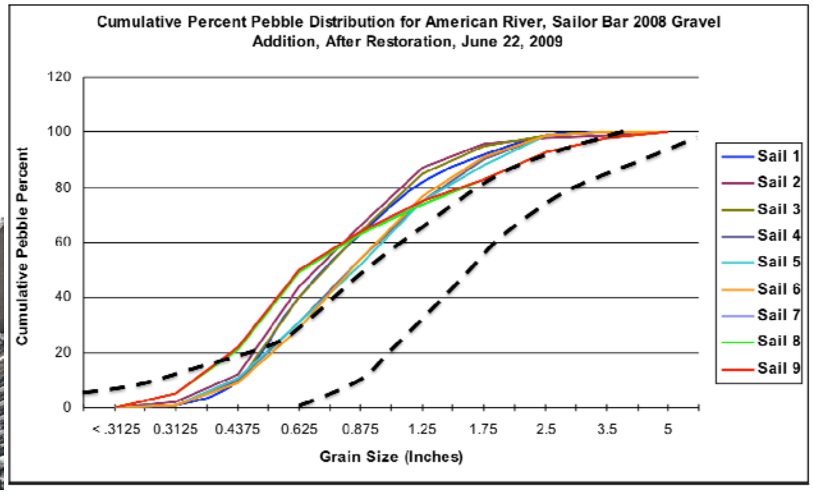
Grain size trends were also examined through time at the 2008 site. Figure 2.6 shows a comparison between average cumulative percent pebble distribution before restoration, directly after restoration and three years after restoration when this report was written. Pre restoration pebble counts were larger, on average, then suitable salmon spawning habitat grain size range. Post restoration pebble counts were within a suitable spawning habitat grain size range. Pebble counts as of 2012 indicate that there is a higher percentage of fines accumulating at the site, although D_{50} values are staying consistently around 1.25 inches and are still in a suitable spawning size range.

(i)



(ii)

Figure 2.4: Map of 1.2 mile section of Lower American River just below Nimbus Dam (i) showing the downstream pebble count locations with red dots. Pebble counts were conducted from the 2008 pre restoration site downstream to the Sunrise Bridge. Cumulative frequency graph (ii) for pebble counts conducted at Sailor Bar 2008 pre gravel addition site. Transects are listed upstream to downstream. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values ranged from 7/16 inch to 1 ¼ inches and samples were poorly sorted.



(i) (ii)

Figure 2.5: Map of Upper Sailor Bar 2008 (i) showing post-restoration pebble count transects conducted in June 2009. High flows prevented additional measurements. Cumulative frequency graph (ii) for pebble counts conducted at Sailor Bar 2008 post gravel addition site. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values range from 5/8 inch to 7/8 inch and samples are moderately to well sorted.

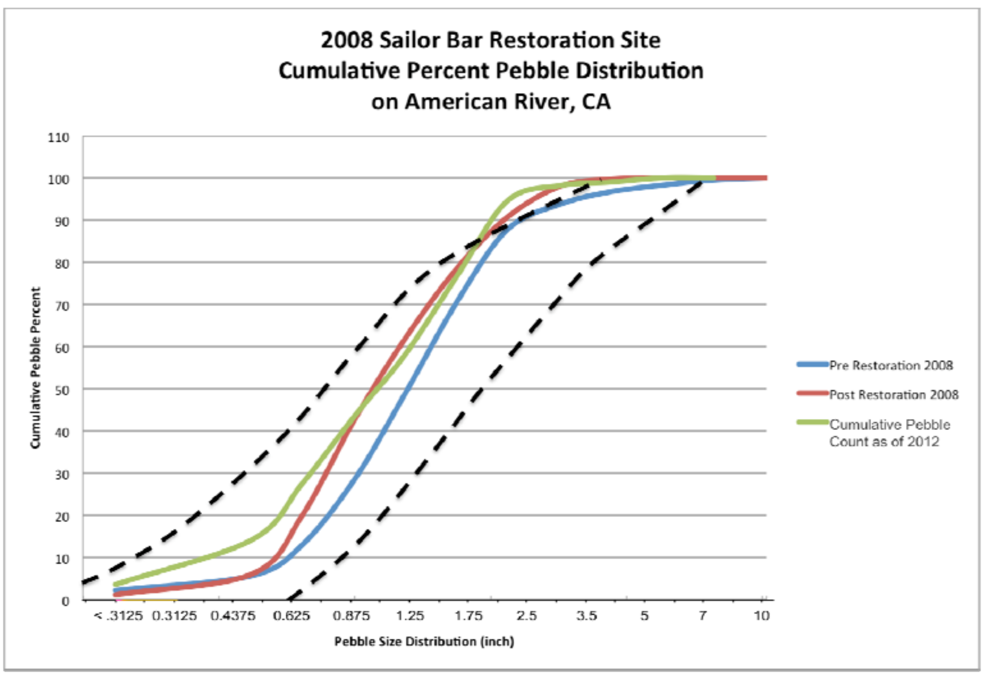


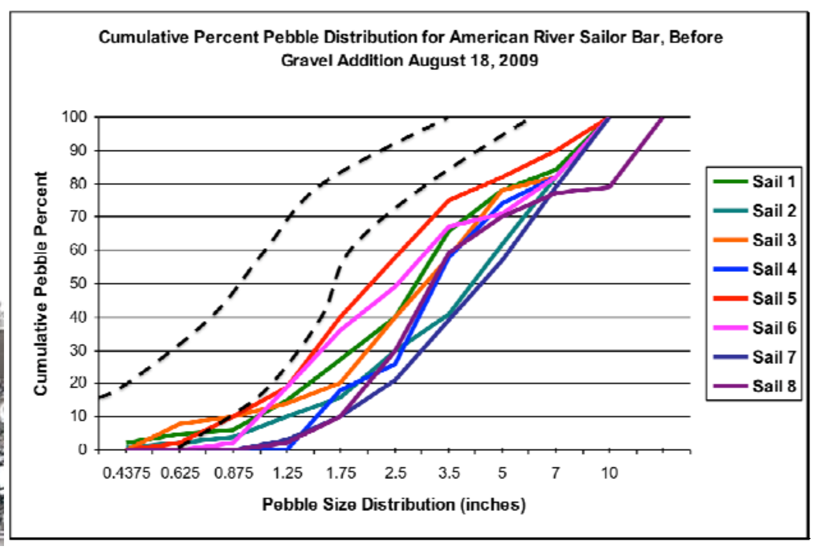
Figure 2.6: Average cumulative percent pebble counts for the 2008 Upper Sailor Bar site. Black dashed lines indicate suitable spawning habitat. Pre restoration (blue) d_{50} grain sizes were larger, post restoration (red) pebble counts were smaller, and pebble counts conducted in 2012 (green) indicate that sediment has mobilized over a 4 year period, resulting in both finer and coarser components at the site than were present immediately after restoration. Most material is still in a suitable spawning range.

Upper Sailor Bar 2009 Site

8 Pebble counts were conducted at the restoration site before the Upper Sailor Bar 2009

restoration project started (Figure 2.7i). Figure 2.7ii shows the cumulative frequency graph for the 8 pebble counts conducted. The pre-restoration pebble counts showed a range in grain sizes from fine-grained sand to 10inch diameter boulders. D_{50} ranged from 2 inches to 4.25 inches and are poorly to moderately sorted.

8 Pebble counts were conducted in May 2010 after the gravel addition was completed, Figure 2.8i shows a map of the transects of the pebble count locations. Figure 2.8ii shows the cumulative frequency graph for the 8 pebble counts conducted after restoration. D_{50} values range from 7/8 inch to 1.5 inches, sediment is better sorted, and within suitable salmon spawning habitat size requirements. Figure 2.9 shows a comparison between average cumulative percent pebble distribution before restoration, directly after restoration and three years after restoration when this report was written. Pre restoration pebble counts were larger, on average, then suitable salmon spawning habitat grain size range. Post restoration pebble counts were within a suitable spawning habitat grain size range with mean D_{50} values of approximately1.25 inches. Pebble counts conducted at this site in 2012 indicate that grains are getting larger with time as fine material is winnowed away. Grain sizes at this site are moving closer to pre restoration sizes.



(i) (ii)

Figure 2.7: Map (i) showing pre restoration pebble count transects conducted in August 2009 for Upper Sailor Bar 2009. Cumulative frequency graph (ii) for pebble counts conducted at Upper Sailor Bar 2009 pre gravel addition site. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values range from 2 inches to 4.25 inches and are poorly to moderately sorted.

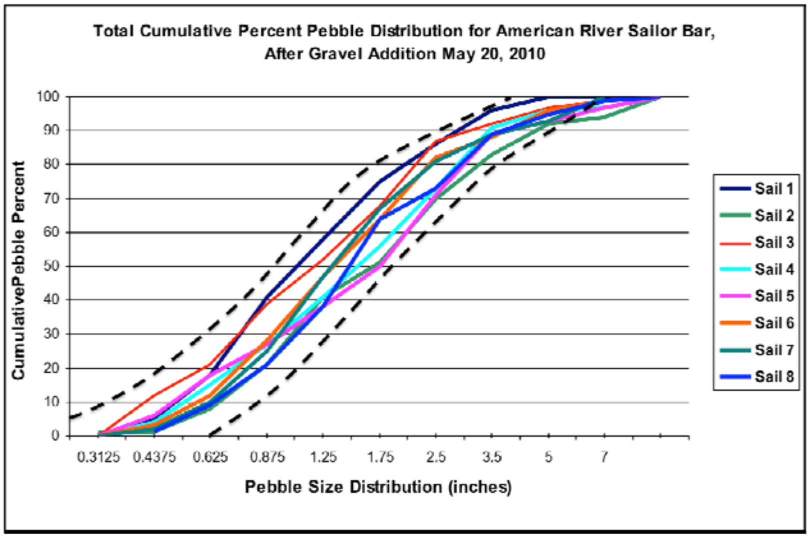


Figure 2.8: Cumulative frequency graph for pebble counts conducted at Upper Sailor Bar 2008 post gravel addition site. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values range from 7/8 inch to 1.5 inches, are better sorted and within suitable salmon spawning habitat requirements.

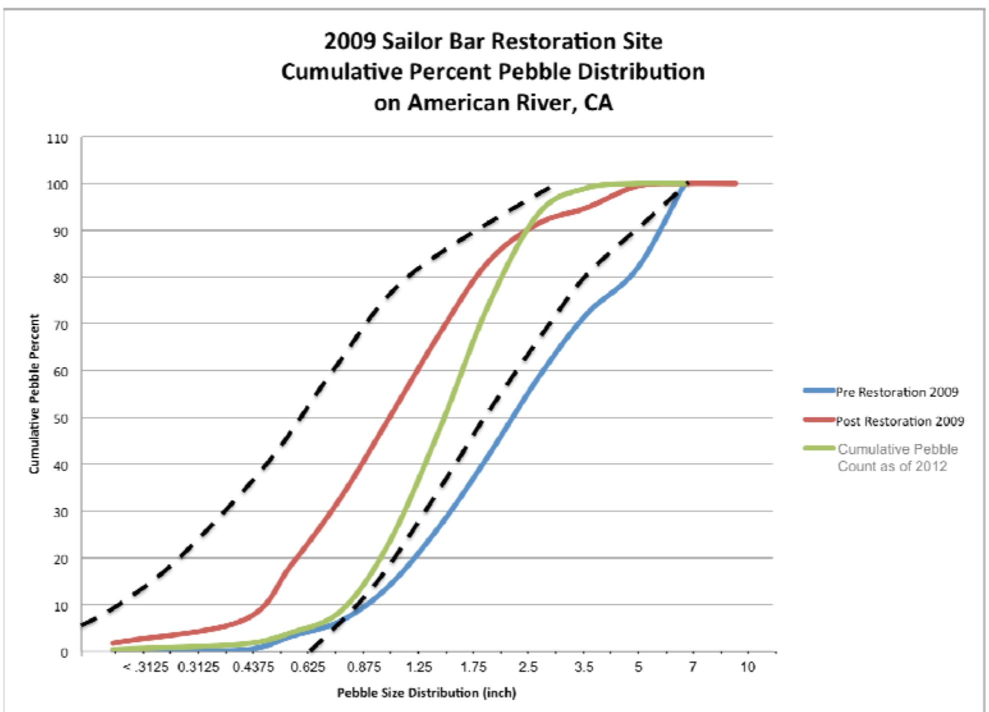
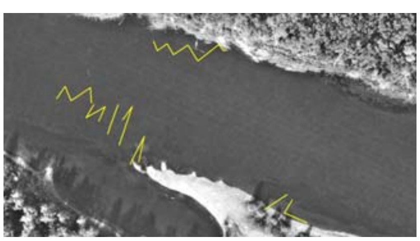


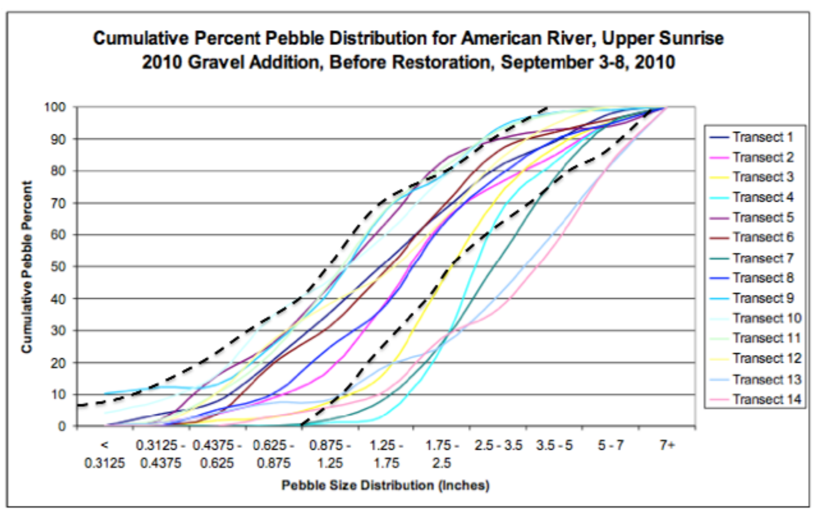
Figure 2.9: Average cumulative percent pebble counts for Upper Sailor Bar 2009. Black dashed line indicates the gravel size range for suitable spawning habitat. Pre restoration (blue) pebble counts were larger, on average, then suitable salmon spawning habitat grain size range. Post restoration (red) pebble counts were within a suitable spawning habitat grain size range. Pebble counts as of 2012 (green) indicate that grains are getting larger and although are still in a suitable spawning grain size range, are moving closer to pre restoration sizes.

Upper Sunrise 2010/2011 Site

14 Pebble counts were conducted at the restoration site before the Upper Sunrise 2010/2011 restoration project started (Figure 2.10i). Figure 2.10ii shows the cumulative frequency graph for the 14 pebble counts conducted. The pre-restoration pebble counts showed a range in grain sizes from fine-grained sand to 7 inch diameter boulders. D_{50} ranged from 7/8 to 5 inches for the fourteen samples and samples were poorly sorted.

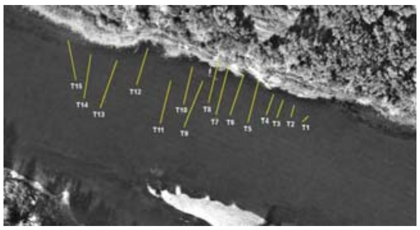
15 Pebble counts were conducted in October 2010 after the gravel addition was completed, Figure 2.11i shows a map of the transects of the pebble count locations. Figure 2.11ii shows the cumulative frequency graph for the 9 pebble counts conducted after restoration. D_{50} values range from 7/8 inch to 1.5 and are better sorted and within the suitable salmon habitat size requirements. Figure 2.12 shows a comparison between average cumulative percent pebble distribution before restoration and directly after restoration. Pre restoration pebble counts show that the substrate was larger, on average, and close to being unsuitable for salmon spawning habitat. Post restoration pebble counts were within a suitable spawning habitat grain size range, with D_{50} values from approximately 0.9 to 1.25 inches.

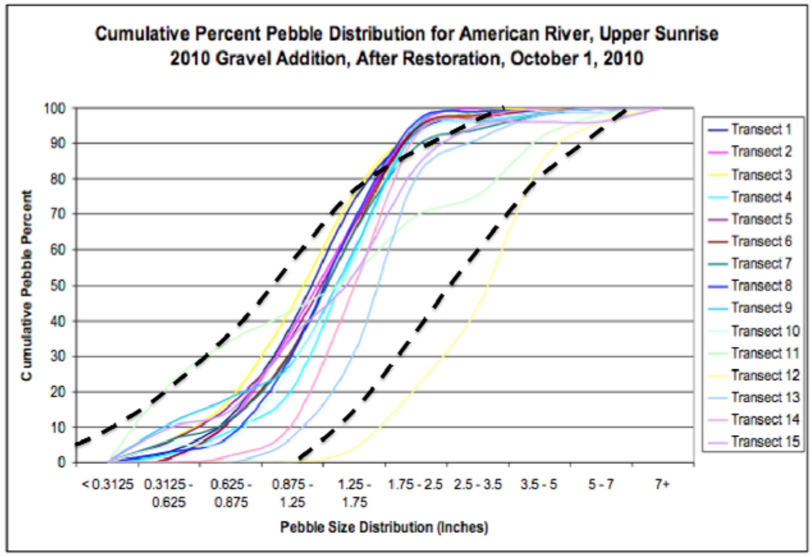




(i) (ii)

Figure 2.10: Map of Upper Sunrise 2010/2011 (i) showing pre restoration pebble count transects conducted in September 2010. (ii) Cumulative frequency graph for pebble counts conducted at Upper Sunrise 2010/2011 site before gravel addition. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values range from 7/8 inch to 5 inches and samples are poorly sorted.





(i) (ii)

Figure 2.11: Map of Sailor Bar 2008 (i) showing post restoration pebble count transects conducted in October 2010. Cumulative frequency graph (ii) for pebble counts conducted at Sailor Bar 2008 post gravel addition site. Black dashed line indicates the gravel size range for suitable spawning habitat. D_{50} values range from 7/8 inch to 1.5 inches, are samples are better sorted and within suitable spawning size range.

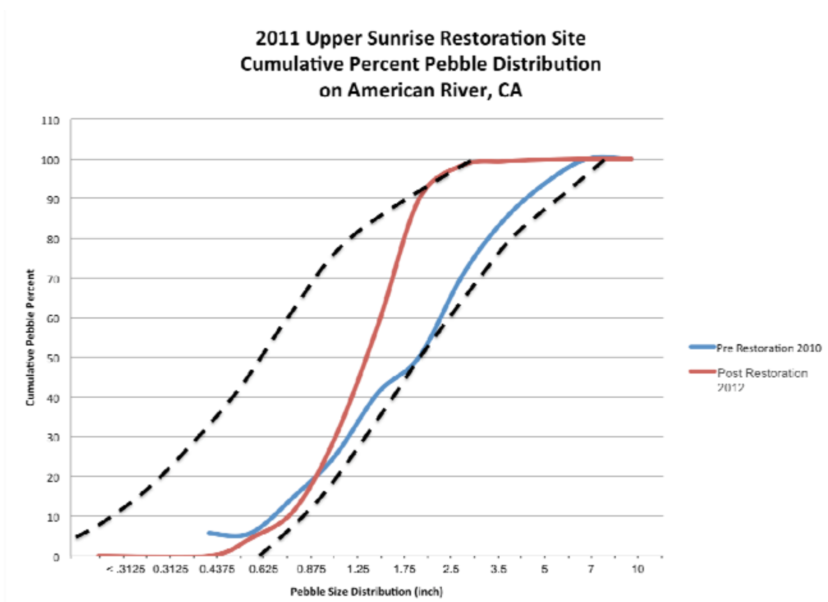


Figure 2.12: Average cumulative percent pebble counts for Upper Sunrise 2010/2011. Black dashed line indicates the gravel size range for suitable spawning habitat. Pre-restoration pebble counts (blue line) show larger grain size, on average, and are close to being unsuitable for salmon spawning habitat. Post restoration pebble counts (red line) are within spawning habitat size range.

Bulk Samples

Upper Sunrise 2010/2011Site

Bulk samples allow comparison of surface versus subsurface grain size, and are better-suited for measuring fine sediment within the stream system. Pebble counts (discussed previously) only analyze the surface sediment, and are not appropriate for measuring fine material. Two bulk samples were collected and analyzed prior to restoration at the 2010/2011 site. Figure 2.13i and 2.13ii show cumulative percent distributions for the two bulk samples. Each graph has two lines, with the dark blue line representing the surface material and the light blue line representing subsurface grain size. Both bulk samples have surface material that is larger than the suitable habitat range. Additionally, both bulk samples have excess fine material, and this is equally detrimental to salmonid fry. D_{50} values for the surface samples are 1.75 and 3.5 inches from the two bulk samples. D_{50} values for the subsurface are 1.0 inches and 1.25 inches, and up to 20% of the subsurface sample consists of sandy material. The comparison of surface to subsurface D_{50} values gives an armoring index. For these two bulk samples, the armoring index is 1.8 and 2.8.

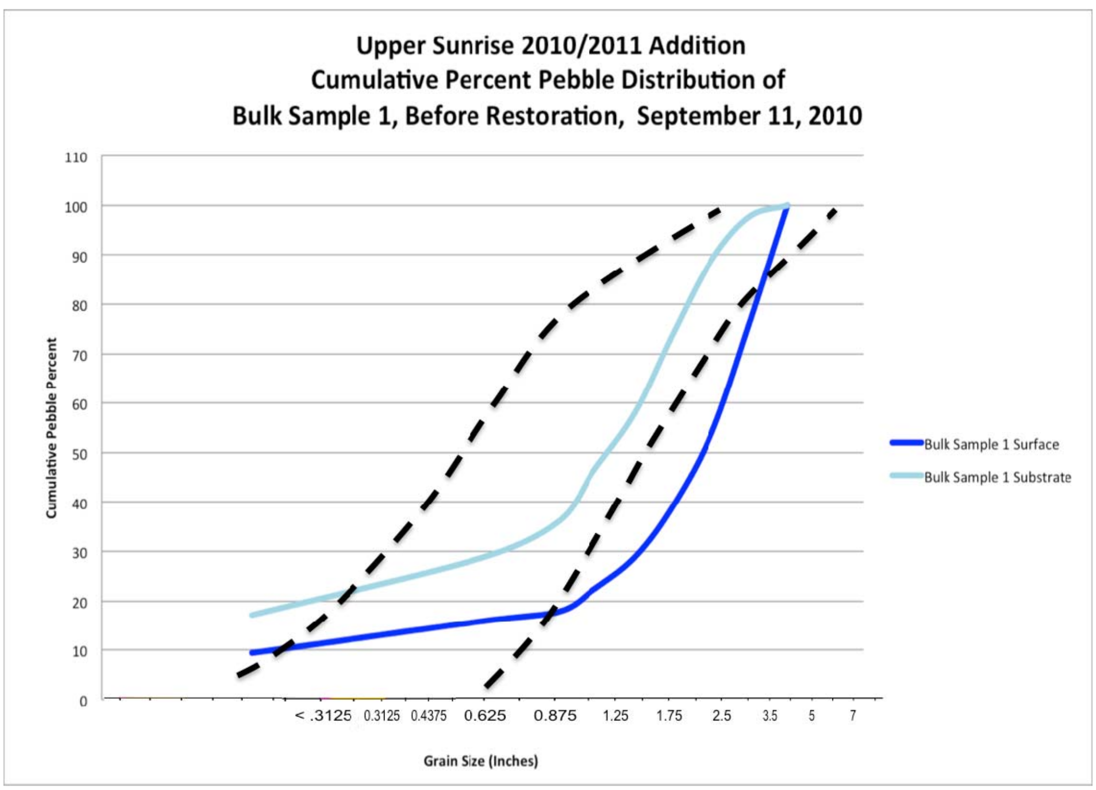


Figure 2.13i: Average cumulative percent bulk samples for Upper Sunrise 2010/2011 pre restored conditions. Black dashed line indicates the gravel size range for suitable spawning habitat. Pre restoration conditions consisted of an excess of fines and excess of larger grains rendering the salmon-spawning habitat unsuitable.

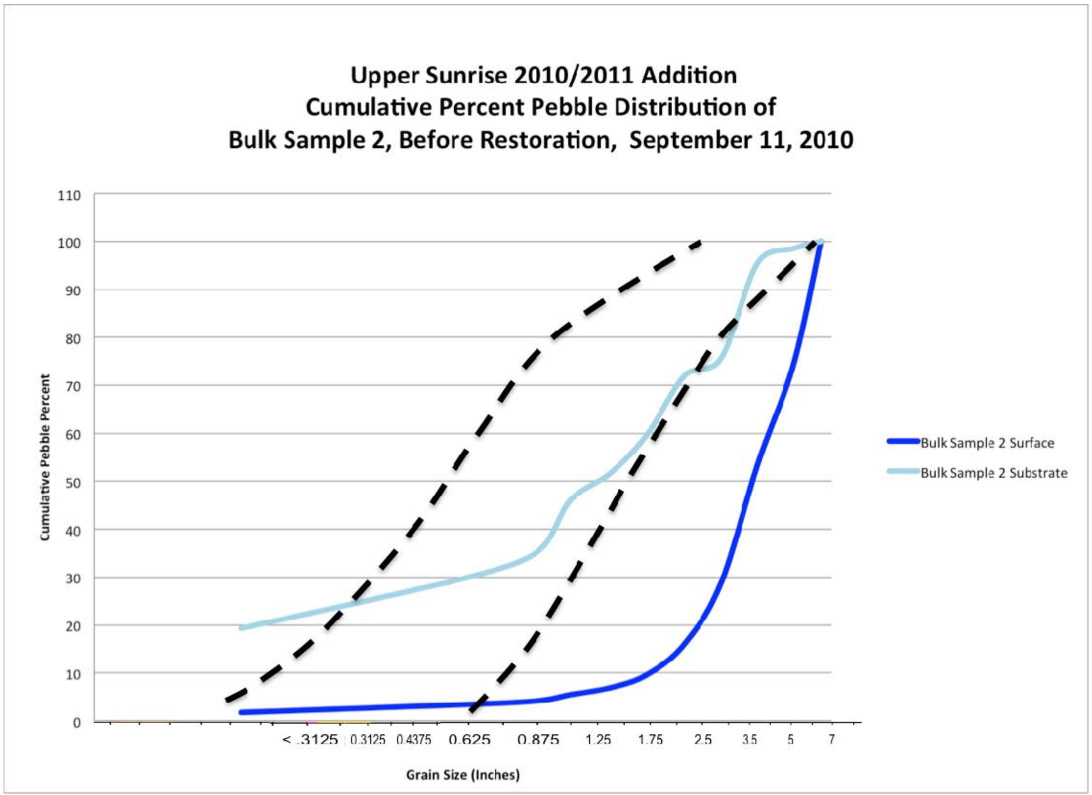
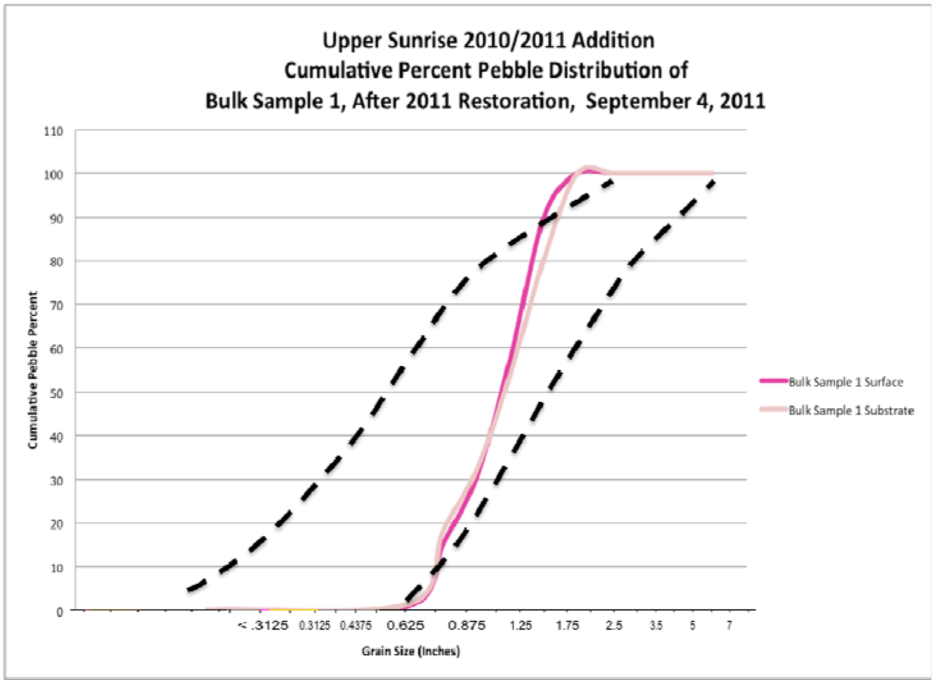


Figure 2.13ii: Average cumulative percent bulk samples for Upper Sunrise 2010/2011 pre-restored conditions. Black dashed line indicates the gravel size range for suitable spawning habitat. Pre restoration conditions consisted of an excess of fines and an excess of coarse material.

Two additional bulk samples were collected after restoration was completed in September 2011. Figures 2.14i and 2.14ii show cumulative percent distributions for each post-restoration bulk sample. The D_{50} values from these samples are 7/8 and 1.25 inches, respectively. Surface and subsurface samples are similar to each other (armoring index is close to 1), and the samples are very well sorted. Although the D_{50} values fall within the suitable spawning habitat range, the new gravel may be better sorted than is optimal. The slope of the cumulative frequency curve indicates the sorting of the sample. Coarser and finer tails are missing on the post-restoration size distribution curves, and the gravel is on the verge of having fine material that is too coarse, and coarse material that is too fine (Figure 2.14i, 2.14ii).



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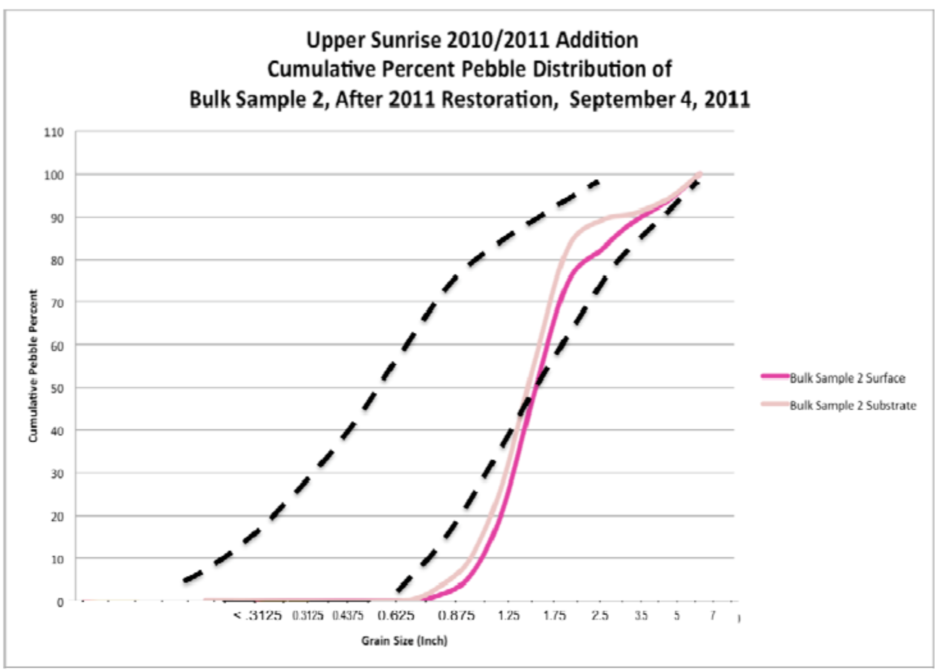

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Figure 2.14: Bulk samples collected at the Upper Sunrise 2010/2011 site after restoration. Black dashed line indicates the gravel size range for suitable spawning habitat. Post-restoration conditions are within the suitable habitat window.

2.4 Discussion

Pebble counts show that gravel size was highly variable prior to restoration. All three sites contained gravel that was coarser than the ideal spawning habitat range (Figures 2.4ii, 2.7ii, 2.10ii). Gravel was also poorly sorted before restoration.

After gravel addition, pebble counts are less variable (show better sorting), and most grains are within suitable spawning habitat size range (Figures 2.5ii, 2.8ii, 2.11ii). D_{50} ranged from 5/8” to 1/1/2” immediately after restoration at the three sites, but the mean D_{50} value has changed with time, and is now 1.25” at all sites (Table 2.1). This summary and size ranges applies only to data generated from pebble counts.

Table 2.1: Mean grain size range for each site comparing pre-restoration, post restoration, and current gravel size conditions. Data are from pebble counts.

Site	D_{50} range (inches)		
	Pre	Post	Currently
Upper Sailor Bar 2008	5/8 - 11/4	5/8 - 7/8	11/4
Lower Sailor Bar 2009	2 - 41/4	7/8 - 11/2	11/4
Upper Sunrise 2010/2011	7/8/05	7/8 - 11/2	11/4

Bulk Samples give different information about the stream bed material, and were effective at showing differences between surface and subsurface gravel sizes. Bulk samples collected before restoration at the Upper Sunrise 2010/2011 site show excess coarse material at the surface and excess fine material in the subsurface (Figure 2.13). Coarse material hinders female salmonids when they construct redds, and the fine material restricts surface water flow through the gravel. Additionally, the high percentage of fines (between 15 and 20%) is detrimental to eggs and emerging fry.

Bulk samples from the restored Upper Sunrise 2010/2011 site are not armored, but gravel size is not always ideal. One sample is slightly too fine (Figure 2.14i), and the other is slightly too coarse (Figure 2.14ii). D_{50} values are within suitable spawning habitat range, although bulk sample 2 is on the coarser edge of that acceptable range. The steep slope of the size distribution curves indicates that the gravels are well sorted after restoration (Figure 2.15i, 2.15ii). This will allow good flow through the hyporheic zone, but the new gravel may be too well sorted. A wider range of grain sizes (more fines, more cobbles) would create more complexity at the site.

All three sites have functional grain size distributions one to three years after the gravel was emplaced. Grain sizes are appropriate for spawning, although older sites are growing coarser with time. At this rate, the sites will return to their coarse, armored condition within a matter of a few years.

Chapter 3: GRAIN MOBILITY

3.1 Background

The stability of gravels and natural bed load mobility during high stream flow events is also important to the success of salmonid reproduction (Nawa et al., 1990; DeVries, 2000). Although small amounts of bed mobility may be beneficial by helping to reduce armoring and improve permeability (Horner, 2005), major scour or burial of redds due to flood events is a contributing factor to high mortality rates (Schuett-Hames et al., 1996). Partial scour of material above the egg pocket can also be destructive. Partial scour allows for the finer sediments to become suspended and inter-gravel flow can be impeded as these fines infiltrate back into the substrate (Schutt et al., 1996).

Bedload transport and stream morphology are dependent on a variety of factors (Muskatirovic, 2008). Hydraulic and hydrological cycles influence stream channels of gravel-bed rivers, causing them to be non-uniform and continually changing. Armoring of the surface layer also affects bedload transport. Gravel bed rivers tend to have courser-grained surface layers than subsurface layers, and armoring (Figure 3.1) is natural part of fluvial processes. Armoring becomes more severe when a dam restricts sediment supply on a river. Grains aren't added to the stream because the dam blocks sediment flow, so material downstream from the dam becomes coarser and coarser. Grain mobility is highly variable on regulated rivers due to episodic and seasonal water releases (Muskatirovic, 2008).

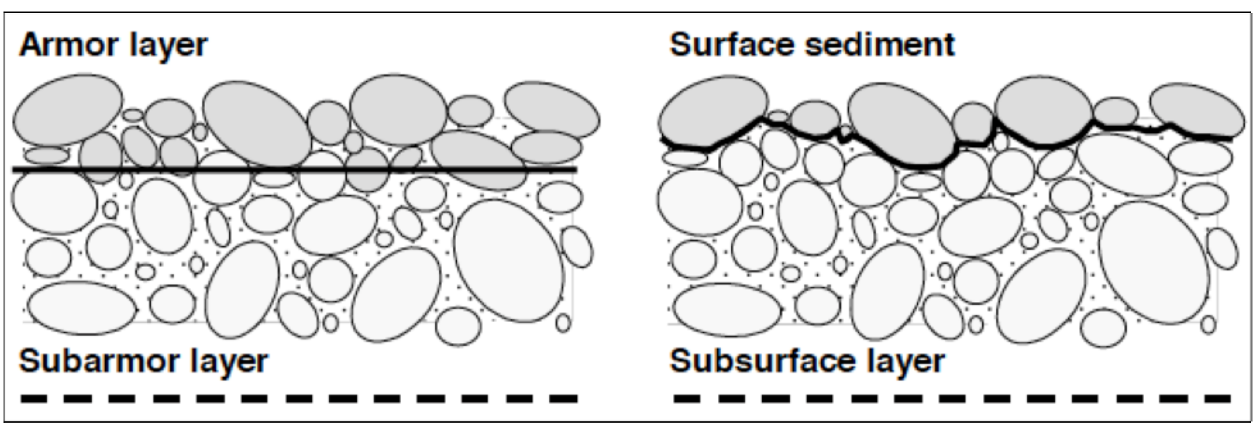


Figure 3.1: Stratigraphy of an armored bed distinguishing between armor layer, sub armor layer, surface sediment, and subsurface layer. (From Bunte and Apt, 2001)

Grain transport is distinguished by two modes (Muskatirovic, 2008; Turowski et al., 2010; Frey et al., 2011). During bedload transport, sediments move by sliding, rolling, or saltating (brief "hops" into the water column) along the bed of the stream. During suspended load transport, grains are moved by suspension in the water column and are supported by turbulent forces; particles can move considerable distance in this mode (Turowski et al., 2010; Frey et al., 2011). The mobility of the grain and whether the grain moves via suspended load or bedload transport depends on particle size, density, and ambient hydraulic conditions (Turowski et al., 2010).

Bedload transport can be divided into three stages [(Jackson and Beschta, 1982; Ashworth and Ferguson, 1989; Warburton, 1992) found in Frey et al., 2011]. Stage 1 is when smaller grains are advected away or percolate downward into the sediment. This leads to armoring of the surface layer, and thus overall transport is greatly reduced (Frey et al., 2011). Size segregation, stage 1, is consistent with the pre-restored conditions of the site on the Lower American River, CA. Stage 2 involves partial transport of local bed material leading to the collection of material in 'patches'. Grains tend to be the same size and individual grain motion is interrupted by encounters with grains of similar sizes, thus reducing the overall bedload mobility (Frey et al., 2011). In Stage 3, grain transport extends down some depth and entrains most or all grains that are exposed in the surface layer. Transport may occur in low amplitude wave-like features, or bedload sheets; kinetic sieving may occur where smaller grains move downward in the bed by filling the voids opened by general motion (Frey et al., 2011). High stream velocity is involved in Stage 3 transportation, although sand-sized material may be a significant part of the total bed load. Stage 2 and Stage 3 may occur on the American River at higher flows. A 1-dimensional model by Ayers Associates predicted stage 3 bed mobility at approximately 40,000 cfs. on the Lower American River, CA.

During a flood event, scour and fill cause changes in bed topography over a short period of time (Leopold, 1964; Haschenberger, 1999). The exchange of sediment between the streambed and the water column controls the vertical and horizontal sorting of sediment; therefore, the mean depth of scour can in turn dictate the rates of bed material transport (Haschenberger, 1999). Previous studies have shown that the physical factors influencing the process of scour and fill vary (Carling, 1987; Haschenberger, 1999; Bigelow, 2005; DeVries, 2000). Some studies indicate that scour and fill are controlled by shear stress levels (Carling, 1987; Haschenberger, 1999; Bigelow,

2005) while other studies show the correlation between sediment supply and particle size and the amount of scour and fill present (DeVries, 2000). Complexities, including heterogeneous grain size and sorting, unsteady and non-uniform stream flow, variable streambed configurations, and local sediment supply affect scour and fill rates and overall bed load transport (Haschenberger, 1999).

3.2 Methods

Background

Tracer rocks are rocks of predetermined size that are collected from the river and painted colors by size increments. The colored rocks are deployed back into the river, starting locations are recorded with a GPS, and individual rock movements are recorded with time. Tracer rocks are used to show grain mobility during river flow events.

The dynamic processes of scour and fill are difficult to measure in a stream bed. Geomorphic and biological studies (Madej,1984; Tripp and Poulin, 1986; Lisle and Eads, 1991; Hassen, 1990; Laronne et al., 1994; Harvey and Lisle, 1999) have used scour chains to measure scour and fill, based on research pioneered by Leopold et al. (1964). Scour chains allow accurate, direct measurement of maximum scour and fill depths over a period of time (Lisle and Eads, 1991; Nawa and Frissell, 1993). Scour chain measurements can help assess physical impacts on intragravel hyporheic habitats. Bed-load transport during peak flows can be assessed by measurement of discreet scour and fill events along a stream channel (Nawa and Frissell, 1993).

Tracer Rocks

Tracer rocks were deployed at the 2008 Upper Sailor Bar site immediately after gravel augmentation, and the tracer rocks were tracked for two subsequent years. Tracer rocks were deployed at the Upper Sunrise 2010/11 site immediately after gravel augmentation and were monitored throughout the remaining year. Yellow, blue, and red tracer rocks (Figure 3.2) were deployed along three transects in each restoration area. The starting position of individual tracer rocks was mapped with high resolution GPS.

All tracer rock transects were linear and perpendicular to the direction of stream flow. At each site, tracer rock transects were placed across the upstream, middle, and downstream portions of the restoration area. Clusters of tracer rocks of three sizes were deployed every six to twelve feet along each transect. The largest size rocks (2 ½ - 3 inch) were yellow, the middle size rocks (1 ¼ to 1 ¾ inch) were blue, and the smallest size rocks (5/8 to 7/8 inch) were red. These colors were chosen for easy identification and clear differentiation of the different types of tracer rocks. Rocks of each size were deposited at all drop locations. After each winter season and until tracer rocks were unrecoverable, tracer rocks were located and re-mapped using GPS to compare movement patterns with original locations of each transect.

(i) **(ii)**

Figure 3.2i: Painted tracer rocks of different sizes are yellow (2 ½ -3 inch), blue (1 ¼ to 1 ¾ inch), and red (5/8 to 7/8 inch). ii) Yellow tracer rocks have moved approximately 15 cm.

Scour Chains

Scour chains (Figure 3.3) were used at Upper Sailor Bar 2009 site and Upper Sunrise 2010/2011 site to measure scour and fill of the augmented gravels. Between 10 and 25 scour chains were installed in a grid across each restoration site, and a high resolution GPS unit was used to record the location of each chain.

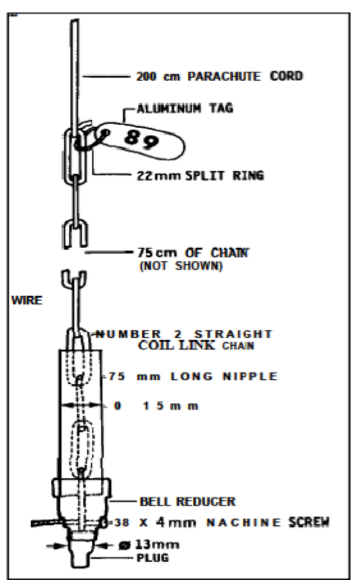


Figure 3.3: Scour chain with anchor constructed from galvanized pipe fittings (From Nawa and Frissell, 1993).

A number 2 straight linked chain, 1 meter in length, was used at each scour chain location. A nylon cord was attached to the opposite end to make it easier find the chain at times of data retrieval (Figure 3.4). The assembled scour chain was inserted into a steel pipe with the anchor secured against the end of the pipe, and the pipe was driven into the streambed. A post hole pounder was used to drive the pipe vertically into the streambed approximately 40- 50 cm. The pipe was then carefully pulled out, allowing the chain to be partially buried in the gravel. The initial length of the exposed chain was measured and recorded for each site. Scour or fill depth was determined by measuring the difference between the length of chain lying over the original bed surface and that lying over the final bed surface (Figure 3.4), (Lisle and Eads, 1991).

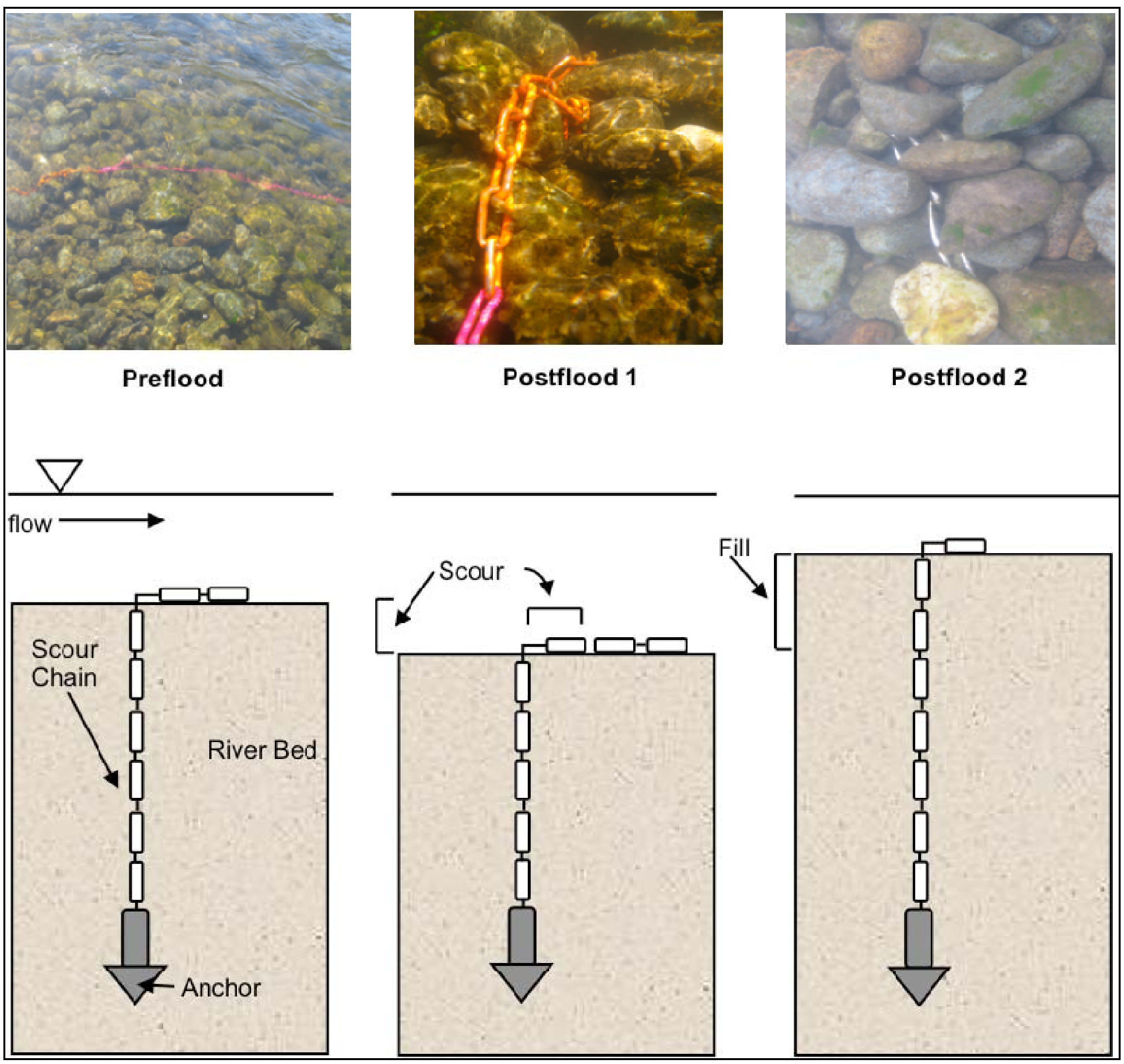


Figure 3.4: Schematic of scour chains in the riverbed with net scour and net fill events.

3.3 Results

Tracer Rocks

Tracer rock locations were initially recorded after installation and were then monitored after high discharge events. After successive monitoring, the percentage of recovery decreased because of several factors, including algal and sediment deposition on painted particles, particle burial, and loss of particles within the deeper parts of the channel.

Results of grain movement are presented on maps of each restoration site, with different colored points representing original location of tracer rock transects and location of tracer rocks identified after the winter seasons.

<u>Upper Sailor Bar 2008 Site</u>

Figure 3.5 shows lines of tracer rock transects installed after gravel addition. The green line is the original transect of tracer rocks. Yellow dots represent rocks relocated after eight months of flow, with a peak flow of 5000 cfs. Tracer rocks located after the second year of flow are shown in Figure 3.6. The furthest downstream transect lost 1/3 of the tracer rocks over a one year period, with the highest loss along the southern edge of the gravel addition. Field crews commented that this edge of the gravel was eroded soon after construction finished due to high stream velocity. The middle and upper transects also lost considerable numbers of tracer rocks due to burial or movements by fish during the salmon redd building process; this was witnessed on multiple occasions by the field crew. Substantial numbers of yellow and blue rocks were located 8 months after the gravel addition was completed. The upper transect recovered 19 large (yellow, 2 1⁄2 -3 inch) rocks, 12 intermediate-sized (blue, 1 1⁄4 - 1 3⁄4 inch) and 6 small- sized (red, 5/8 – 7/8 inch) rocks. The middle transect recovered 17 large rocks, 9 blue rocks and 7 red rocks. Only 5 tracer rocks were recovered from the lower transect.

After 8 months and flows of up to 5000 cfs, most of the larger yellow tracer rocks did not move. There was minor movement of yellow rocks in the high velocity portion of the gravel addition. The middle transect showed a similar pattern, and tracer rocks from the downstream transect were either buried or washed away. Medium-sized (blue) tracer rocks were mobile in the upper and middle transects, with individual rocks moving up to 20 meters. Red tracer rocks moved the furthest and yielded the smallest number of rocks due to burial or removal from the area. Most grain mobility occurred near the thalweg adjacent to the southern bank.

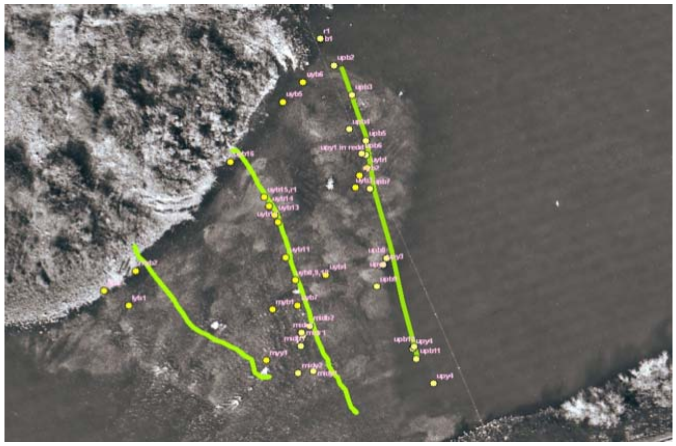


Figure 3.5: Post gravel addition map of Upper Sailor Bar 2008 site showing tracer rock transects (green) installed after gravel addition, yellow points indicate rocks located after high flow conditions (5000 cfs) in June 2009.

Figure 3.6 shows tracer rocks located in June 2010, eighteen months after the gravel was added. Recovery was lower, but tracer rock movements still show patterns after this extended time. Field crews located 26 out of 120 yellow rocks, 4 out of 120 blue rocks, and 2 out of 120 red rocks after 18 months and flows of up to 5000 cfs. There was minor movement of yellow rocks (up to 3 ½" diameter) along the higher velocity southern edge of the gravel addition, the middle transect showed a similar pattern, and tracer rocks from the downstream transect were mostly missing and presumed eroded away. Figure 3.6 shows that only a few of the tracer rocks located in June 2010 had moved from the previous June.

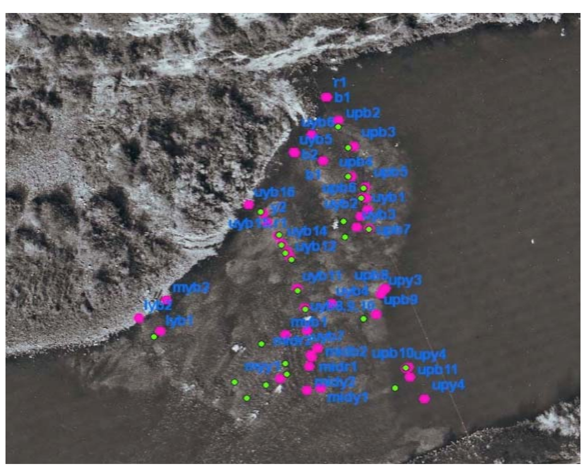


Figure 3.6: Post gravel addition map of the Upper Sailor Bar 2008 site showing one year of tracer rock movement (pink) and a second year of tracer rock movement (green).

Upper Sunrise 2010/2011 Site

Figure 3.7 shows tracer rock transects installed after the gravel addition in 2011. Pink dots represent the position of tracer rocks immediately after installation, and green dots represent the location of tracer rocks in May 2012, after the winter season and discharge of 3000 cfs. Most tracer rocks were recovered and had not moved more than a few 10's of cm downstream. One large yellow tracer rock moved upstream from the middle transect (probably placed there by humans), and one medium blue rock moved downstream near the thalweg. These isolated movements show that the site was not affected in a significant way by the winter flows.

Figure 3.7: Post gravel addition map of Upper Sunrise 2010/2011 site showing tracer rock transects (pink) installed after gravel addition, green points indicate rocks located after winter season (3000 cfs) in May 2012.

Scour Chains

Scour chain lengths were initially recorded after installation and were monitored after subsequent winter seasons and high discharge events. Several chains could not be recovered; loss of chains could be due to either heavy burial or erosion during storm events. Measurements are summarized in tables and presented on maps.

Upper Sailor Bar 2009 Site

Information from the Upper Sailor Bar 2009 Site (Table 3.1) is limited; many chains could not be recovered, and data only exists for 6 out of 25 original chains. The chains that were located and measured in 2010, 2011, and 2012 show chain lengths increasing though time, indicating scour at the site. This site has experience net erosion over the study period of 2.5 years. Poor recovery at this site limits our ability to estimate the volume of sediment removed, but gravel loss at the site may approach 20%.

Table 3.1: Upper Sailor Bar 2009 Site original chain lengths after installation in October 2009 and increased chain lengths in 2012.

Chain	Original Length (cm) 2009 October	Length (cm) 2012 February	Change
J1	41	47	scour 6 cm
J2	18.5	59.5	scour 41 cm
J6	34	50	scour 16 cm
J7	23	43	scour 20 cm
J12	34.5	37	scour 2.5 cm

Upper Sunrise 2010/2011 Site

Scour chains were installed in October 2010, after restoration at the Upper Sunrise 2010/2011 Site. Scour chain measurements were taken in May 2012 after a relatively low flow winter season with a max discharge of approximately 3000 cfs. Figure 3.8 shows a scour and fill map of the site where red represents erosion and green represents deposition. Gray triangles on the map are discreet measurements at each chain, where the size of the triangle indicates the magnitude of gravel scour or fill. There are areas of high scour near the southern border of the new gravel, and areas with high amounts of fill near the island and northern bank.

3.4 Discussion

Tracer rocks were more mobile at the 2008 site. This is largely because winter flows peaked at 5,000 cfs in winter 2009, so bed material was mobilized in the year that followed gravel addition. This resulted in scour and loss of tracer rocks near the thalweg (along the south bank).

After the third season, most tracer rocks at the 2008 site were not recovered and may have been eroded away or buried.

Upper Sunrise 2010/2011 Augmentation Site
Chain Scour and Fill

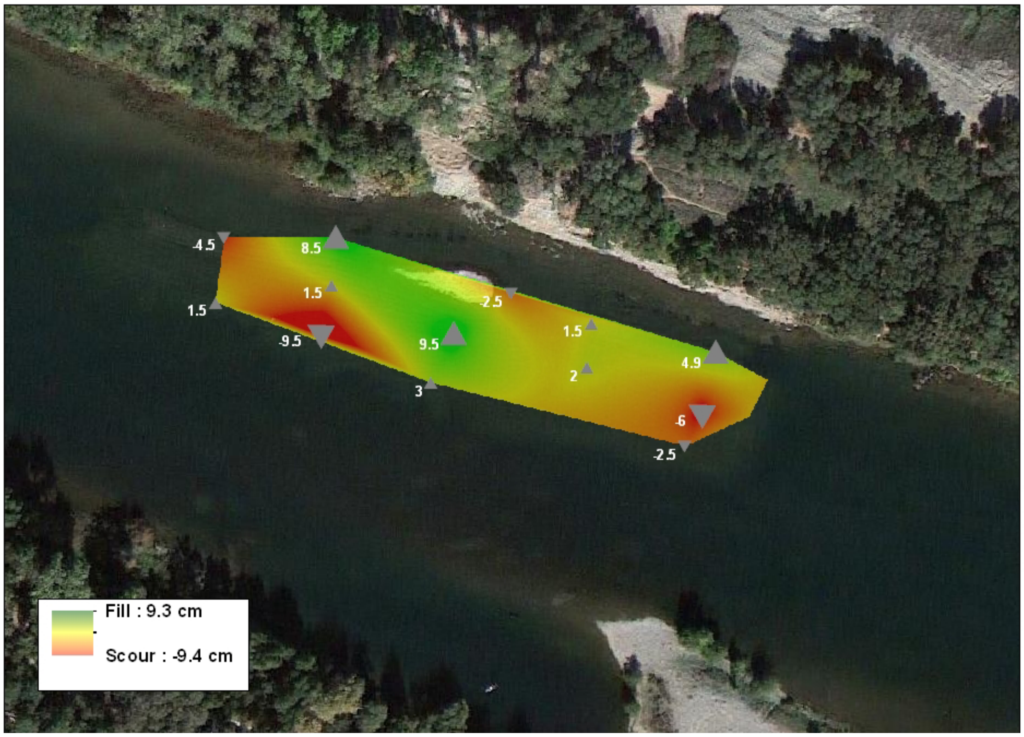


Figure 3.8: Scour and fill map of the Upper Sunrise 2010/2011 restoration site, with measurements made in May 2012.

The 2010/11 site shows less tracer rock mobility, but maximum winter and spring flows have only peaked at 3000 cfs in the months that followed the gravel addition. These tracer rocks may be more mobile in a year with higher winter and spring flows.

Scour chain measurements at the 2008 site are sparse but tell the story of overall erosion after three winter seasons. 20% of the gravel may have been removed by scour at this site. Scour and fill patterns at the 2010/2011 site show scour along the upstream edge of the new gravel and in the deeper, faster water of the mid-channel region. Deposition occurs near the gravel bar (island) and the north bank. The island appears to create a buffer zone that reduces stream velocity and causes a broad band of sediment to be deposited. Woody debris also appears to have a positive effect on limiting scour.

Chapter 4: Surface Water Depth and Velocity

4.1 Background

Surface water depth and velocity are key variables in salmonid spawning site selection. Surface water velocities can hinder successful spawning if they are too high or too low. Low surface water velocities decrease the volume of water flowing in the subsurface, which reduces the amount of dissolved oxygen in the gravel. Surface water velocities between 0.5-2.0 m/s are optimal for spawning gravel exchange (Chapman et al., 1986). Higher surface water velocities add stress to the spawning females by making them work harder to stay in one location, thus reducing their normal 10-14 day stay on the redd (Chapman, 1986, Hannon, 2000). Additional stresses on spawning salmonids are detrimental at this critical moment in their reproductive life cycle.

Salmonid spawning has been reported at depths greater than 7 meters, although the optimal depth for salmonid redd construction ranges from the fin height of the spawning salmon to about 2 meters of water depth (Chapman, 1986; Hannon, 2000).

4.2 Methods

Surface water velocity measurements were conducted following USGS stream gaging procedures (USGS, 1980). Surface water depth and velocity were measured using a Price AA current meter attached to a topset wading rod. In the field, cup revolutions (R) from the current meter are counted for 60 seconds and then converted to surface water velocity (USGS, 1980). The velocity is given in feet per second and converted to meters per second.

$$V=2.2048(R)+0.0178 \qquad (4.1)$$

On some field days a Marsh/McBirney current velocity meter was used to measure surface water velocity. Results from the two methods are comparable.

Surface water depth and velocity measurements were taken at each mini-piezometer site in the new gravel, and at 10 – 40 additional points across the new gravel. The additional measurements were made to sample the sites at a higher density. This higher density allows smaller trends and variability to show across the sites. Velocity measurements were made at depths of 60% from the surface and 80% from the surface. The 60% depth measurement is used to represent the average velocity of the column of surface water, and the 80% depth is taken as a "snout velocity" of the salmonid.

A Brunton compass was used to measure flow direction wherever stream velocity was measured. Flow directions were incorporated into maps that show depth and velocity across the site.

4.3 Results

Background

Depth and Velocity data are reported in tables that summarize the range, mean and variance at each site. Variance give a value of how the data distributes itself about the mean, and is useful because is appropriates more meaning to samples that are farther from the mean, and therefore may be more significant. Additionally, the covariance of different parameters can then be used to measure how they change together. Variance was calculated using equation 4.2, an embedded equation in MS Excel. In this equation x is the discreet data measurement and n is the total number of measurements taken; this was used to assess variability at each site.

$$\frac{\Sigma(x-\bar{x})^2}{(n-1)} \qquad (4.2)$$

Depth and velocity data are also reported on contour maps that include the direction of surface water flow.

Upper Sailor Bar 2008 Site

Surface water depth and velocity were measured at 8 established mini-piezometer sites in December of 2011 at a flow rate of 2150cfs, and a summary of results is reported in Table 4.1. More detailed measurements with denser spacing were collected at 34 locations across this site in February of 2012 at a river discharge rate of 1640 cfs (Figure 4.1), and the summary of results is also reported in Table 4.1.

Table 4.1: Summary and statistical comparison of mean, range, standard deviation and variance of the Sailor Bar 2008 Site's surface water depth and velocity from December 2011 and February 2012.

Upper Sailor Bar 2008	Date of Measurement and Flow	Range	Mean	Standard Deviation	Variance	Number of Measurements
Velocity @ 80% Depth	12/16/11 2150cfs	0.03-1.00m/s	**0.44m/s**	0.32	**0.106**	8
Velocity @ 60% Depth	12/16/11 2150cfs	0.04-1.08m/s	**0.53m/s**	0.35	**0.125**	8
Depth	12/16/12 2150cfs	0.30-1.00m	**0.63m**	0.21	**0.046**	8
Velocity @ 60% Depth	2/1/12 1640cfs	0.01-1.30m/s	**0.48m/s**	0.3	**0.092**	34
Depth	2/1/12 1640cfs	0.27-0.88m	**0.50m**	0.21	**0.045**	34

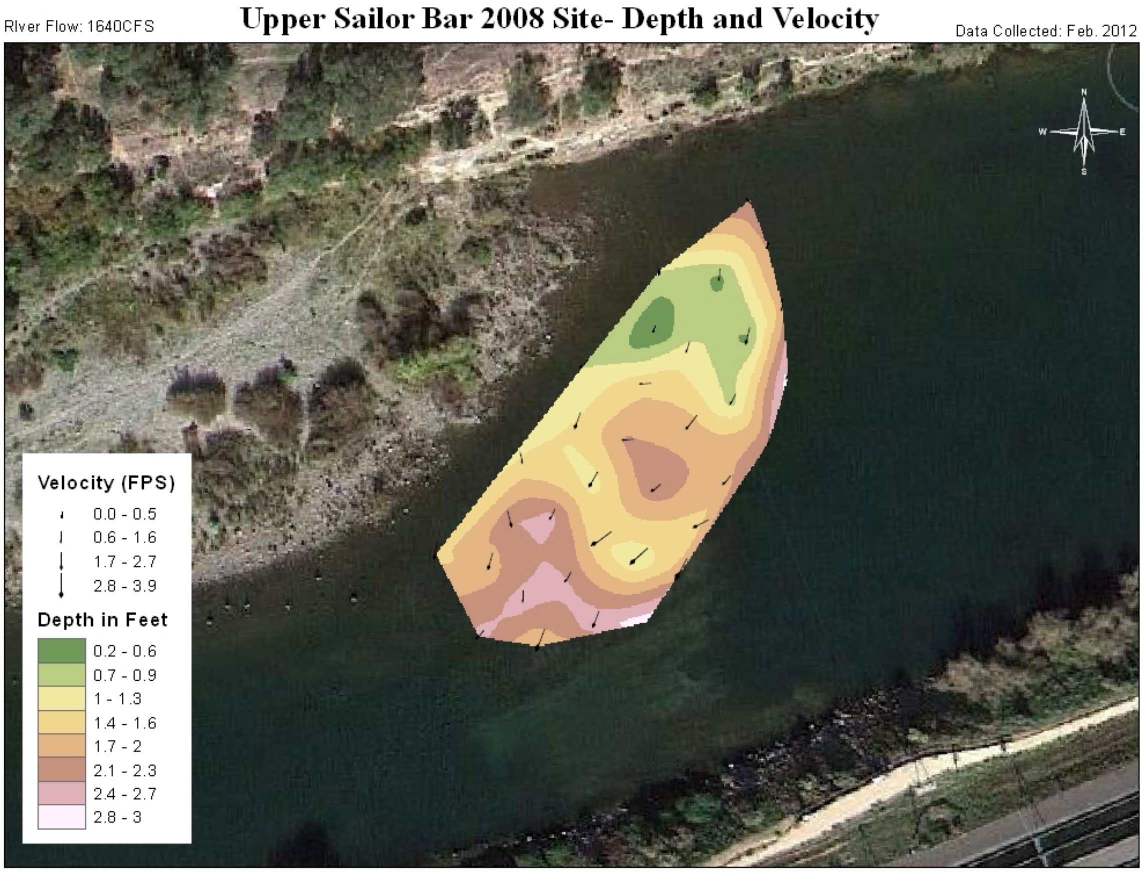


Figure 4.1: Depth, velocity, and direction of flow map for the Upper Sailor Bar 2008 site at 1640 cfs, February 2012.

Upper Sailor Bar 2009 Site

Surface water depth and velocity were measured at established mini-piezometer sites in December of 2011 at a flow rate of 2040 cfs and the results are reported in Table 4.2. Surface water depth and velocity were measured with denser spacing throughout the site at 40 locations in February of 2012 (Figure 4.2), at a flow rate of 1640 cfs. A summary of the results is reported in Table 4.2.

Table 4.2: Summary and statistical comparison of mean, range, standard deviation and variance of the Sailor Bar 2009 site's surface water depth and velocity from December 2011 and February 2012.

Lower Sailor Bar 2009	Date of Measurement and Flow	Range	Mean	Standard Deviation	Variance	Number of Measurements
Velocity @ 80% Depth	12/9/11 2040cfs	0.36-0.73m/s	**0.52m/s**	0.12	**0.016**	8
Velocity @ 60% Depth	12/9/11 2040cfs	0.41-0.98m/s	**0.68m/s**	0.22	**0.049**	8
Depth	12/9/12 2040cfs	0.24-0.94m	**0.58m**	0.2	**0.042**	8
Velocity @ 60% Depth	2/2/12 1640cfs	0.01-1.18m/s	**0.50m/s**	0.33	**0.111**	40
Depth	2/2/12 1640cfs	0.06-0.91m	**0.43m**	0.24	**0.06**	40

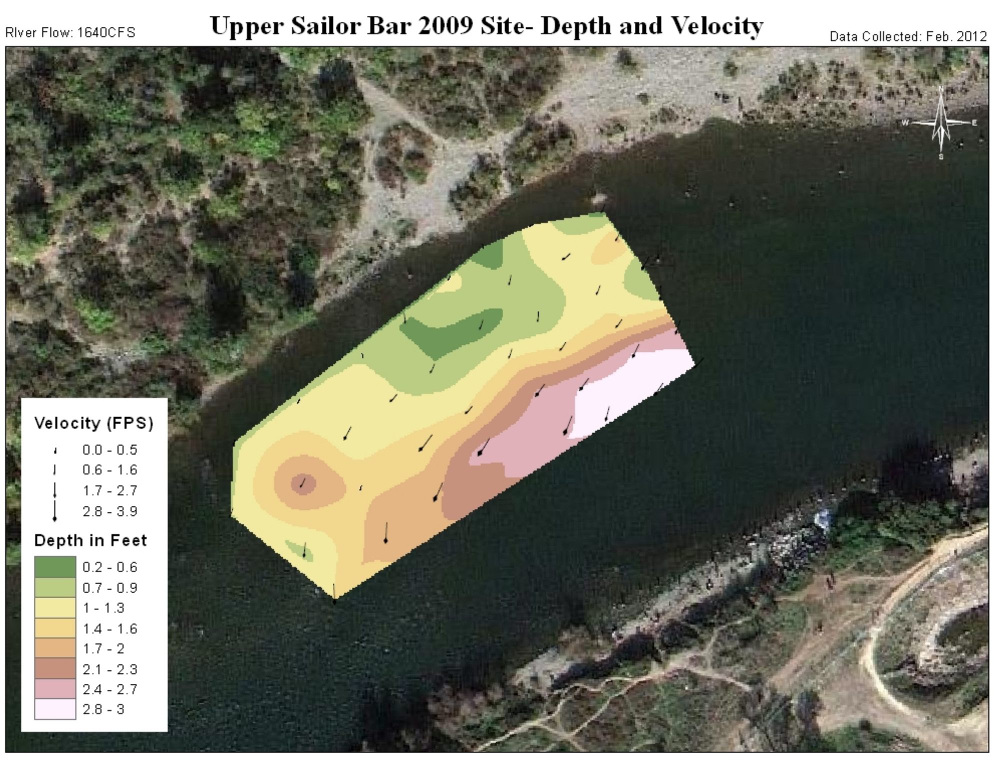


Figure 4.2: Depth, velocity, and direction of flow map for the Sailor Bar 2009 site at 1640 cfs, February 2012.

Upper Sunrise 2010/2011 Site

Surface water depth and velocity were measured twice at established mini-piezometer sites. The first measurements were in December of 2011 at a flow of 2040 cfs while Fall-run Chinook were spawning, and the results are reported in Table 4.3. Surface water depth and velocity were measured at 65 locations throughout the site in February of 2012 (Figure 4.3). Steelhead were spawning in the river at that time, flows were 1640cfs, and the results are reported in Table 4.3.

Table 4.3: Summary and statistical comparison of mean, range, standard deviation and variance of the Upper Sunrise 2011 site's surface water depth and velocity from December 2011 and February 2012.

Upper Sunrise 2010/2011	Date of Measurement and Flow	Range	Mean	Standard Deviation	Variance	Number of Measurements
Velocity @ 80% Depth	12/8/11 2040cfs	0.15-0.67m/s	**0.38m/s**	0.14	**0.02**	14
Velocity @ 60% Depth	12/8/11 2040cfs	0.16-0.76m/s	**0.46m/s**	0.17	**0.029**	14
Depth	12/8/11 2040cfs	0.15-0.82m	**0.63m**	0.21	**0.045**	14
Velocity @ 60% Depth	2/9/12 1640cfs	0.01-0.98m/s	**0.51m/s**	0.2	**0.041**	65
Depth	2/9/12 1640cfs	0.06-1.12m	**0.66m**	0.25	**0.065**	65

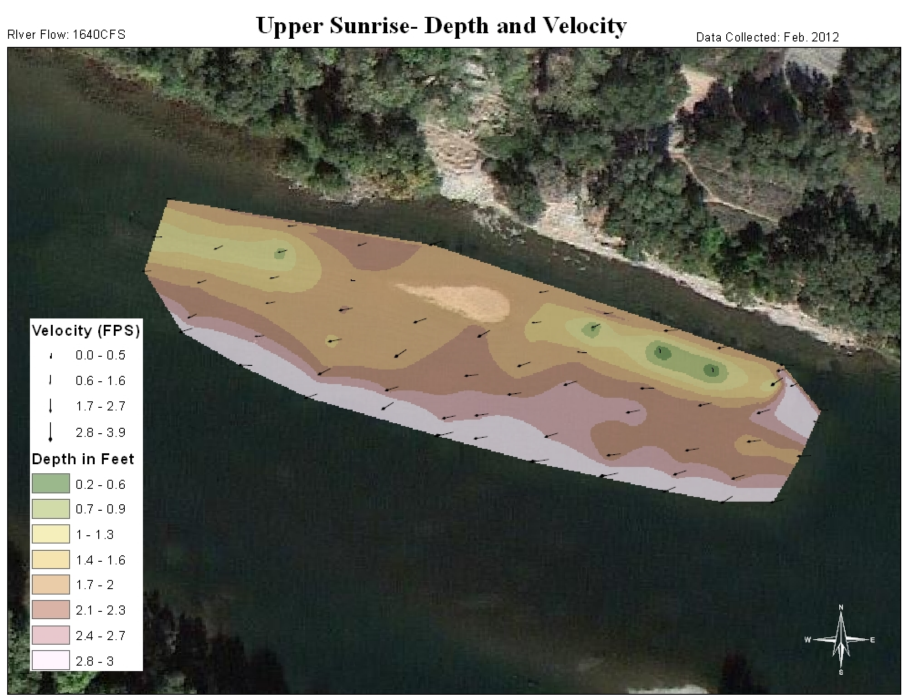


Figure 4.3: Depth, velocity, and direction map for the Upper Sunrise 2010/11 site at 1640 cfs, February 2012.

4.4 Discussion

Mean surface water velocities were similar for the three restoration sites, and there was low variability within each site. Variance of the surface water velocity was higher at the 2008 and 2009 sites, and lowest at the 2010/11 site. Variance is shown by the red bars in Figure 4.4. The range of velocities is also highest for the 2008 and 2009 gravel additions (0.01 m/s-1.30 m/s and 0.01 m/s-1.18 m/s respectively), while the 2010/2011 site has a slightly smaller range of velocities (0.01 m/s- 0.98 m/s). Many of these stream velocities are lower than the optimal range quoted for salmonids (Chapman, 1986).

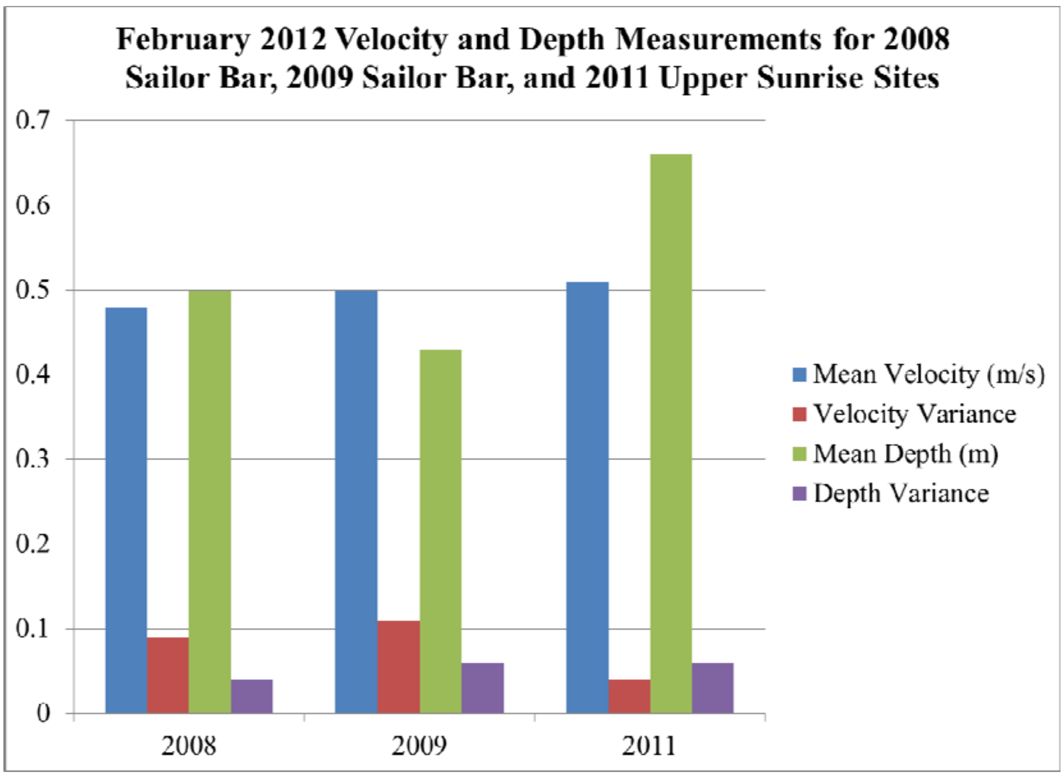


Figure 4.4: Comparison of mean velocity and variance, with mean depth and variance for the 3 augmentation sites on the American River.

The 2010/2011 site is also deeper than the other sites, with a mean water depth of 0.66 m. Depth is shown by the green bars in Figure 4.4. All depths are within the optimal depth range that is cited for spawning, although observations of redds on the American River show that much of the spawning is in shallow water, and spawning gravels with depths greater than 0.6 meters were often unused.

The Upper Sailor Bar 2008 site is characterized by a hummocky bed with small-scale gravel waves perpendicular to flow. These waves developed after the new gravel was added, and are largely a result of fish manipulating the gravel at the site. This hummocky topography enhances flow through the gravel, and is a result of generations of large fish spawning in the same places. The effect is most pronounced near the upper edge of the new gravel. A pool is located immediately upstream of the augmentation site, and this may serve as a refuge. The 2008 gravel addition site has a wide variety of depth, velocity and flow directions as a result of this hummocky bed topography (Figure 4.1)

The Upper Sailor Bar 2009 site has shallow and deep spots, but the gravel waves that form these features are at an angle to flow, and are more subtle, with longer wavelength than the 2008 site. This site does not have an upstream pool that would serve as a quick retreat or velocity refuge. The 2009 gravel addition has significant variability in depth and velocity, but the direction of flow is not as variable as the 2008 site (Figure 4.2).

Flow direction and velocity are very consistent at the Upper Sunrise 2010/2011 site. Flow crosses the new gravel bar at a slight angle, and gradually deepens toward the thalweg. Much of the surface water flow bypasses the bar and flows toward the south bank. Surface water velocities are consistently across the new gravel, with lower velocities at the downstream tail of the site and higher velocities at the head and mid points. The direction of flow is uniform throughout the site with little variation. Bed material is also very consistent, both in size and distribution across the 2010/11 site.

Chapter 5: GRAVEL PERMEABILITY

5.1 Background

Survival of eggs in redds depends largely on the oxygen available to them in the surrounding gravel pore water (Terhune, 1958). Gravels that are highly permeable allow the exchange of oxygenated water as well as other nutrients between the river water and the hyporheic zone (Barnard & McBain, 1994). Higher permeability in the gravel results in a greater supply of oxygenated water to the eggs (Terhune, 1958). Subsurface flow may also be an attractor as adult salmon select spawning areas (Leman, 1989).

Intergravel flows are strongly affected by the properties of the riverbed sediments (Figure 5.1). Gravel-bed rivers that commonly function as salmon spawning habitat are constructed of intertwined longitudinal gravel bars, and the flow splits and rejoins frequently as it passes over these features. Natural river sediment is highly heterogenous in these environments, with interfingered lenses of sand, silt and gravel. This variability in bed topography and sediment size creates permeability differences in the subsurface of gravel bed rivers (The Environment Agency, 2009).

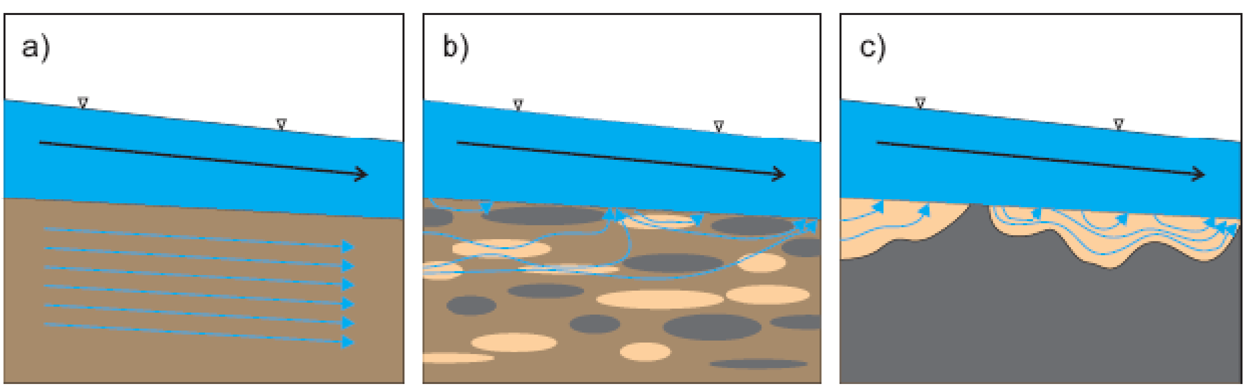


Figure 5.1: Hyporheic flow is dependent on the properties of the sediment underlying the river. a) No variability within the sub straight causes laminar flow and does not promote the interaction or mixing between the river water and the ground water. b) A system where the river gravels are heterogeneous leads to good hyporheic mixing and flow. c) When the system encounters an impermeable layer no hyporheic flow takes place. (The Environment Agency, 2009)

5.2 Methods

Background- Tracer Tests and Gravel Permeability Measurements

Tracer tests were used to examine gravel permeability at newly restored sites on the American River. Tracers were injected at a depth of 30 cm in the gravel because this is where Salmonid species typically lay their eggs (Wickett, 1954). Tracers were monitored with time, and seepage velocity was calculated from the travel times of the tracers. This approach is relatively new, but surface and subsurface tracers have been used in many other North American rivers (Wagner and Bencala, 1996).

Methods

Salt water tracer tests were used to determine inter-gravel velocity. These tests used a main injection well and several monitoring wells. Tracer movement was observed using 1 ¼ inch diameter steel standpipes. The standpipes were 4 feet long with a pointed plug at the bottom to make insertion into the gravel easier. At the bottom of the standpipes there are 8 machined apertures, each 4 inches long and .030 inches wide, cut every 45 degrees parallel to the primary axis of the device. Approximately five standpipes are inserted 30cm into the gravel at ≈ 30cm intervals aligned parallel to flow of the river (Figure 5.2). After installation, the true separation of the standpipes is measured and recorded. The standpipes are then purged to develop the well and clear the standpipe apertures of silt and clay that might inhibit tracer flow.

Figure 5.2: Standpipes are pounded into the river gravel aligned parallel to flow direction spaces at approximately 30cm intervals.

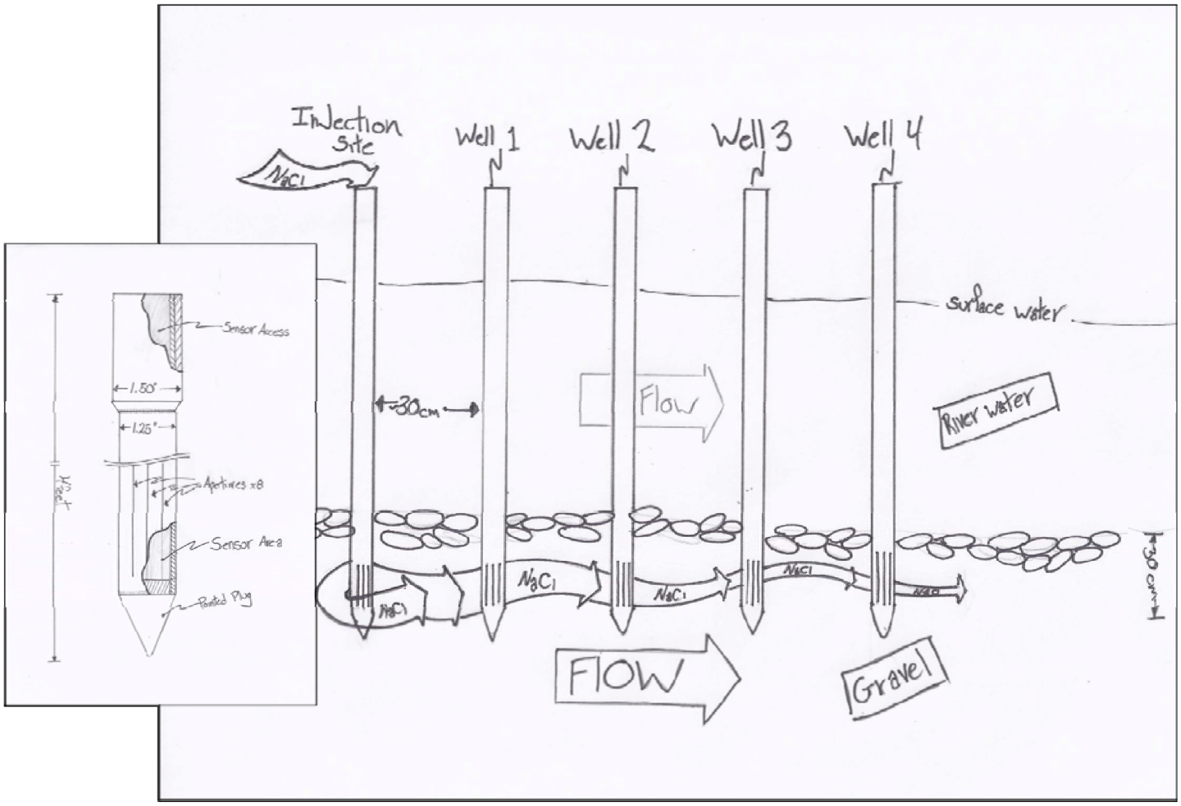


Figure 5.3: Cross section of injection well and standpipes with theoretical flow of NaCl saturated tracer water.

Orion electrical conductivity meters were used to measure tracer content in each standpipe. These meters were calibrated within 30 minutes prior to the tests. Electrical conductivity (E.C.) probes were inserted into the four downstream standpipes, with the E.C. probe tip in the center of the machined screened interval. Water that flows through the gravel will pass through the apertures at the bottom of the standpipe and flow over the E.C. probe tip (Figure 5.3). A baseline E.C. measurement was taken to start the test, then super-saturated NaCl solution was added to the upstream standpipe using a graduated cylinder. The NaCl solution had electrical conductivity properties several orders of magnitude higher than natural waters in the American River.

The time of the test start was recorded, and 2000 ml of salt solution was slowly introduced into the leading standpipe. Values shown on each E.C. meter in each downstream well were recorded every 15 seconds. Recording continued for 45 minutes or until the electrical conductivity meters returned to their baseline measurements.

Results were entered into MS Excel and plotted as a graph of electrical conductivity vs. time. For each standpipe, the time to the midpoint of the tracer peak was used to indicate travel time in the gravel. The distance between standpipes was measured in the field (Δd), and velocity (V_{s_n}) was calculated for each segment of the subsurface flow using equation 5.1. The travel velocities for each segment were then averaged to give a single flow velocity at the site. This method uses meter-scale tracer tests to estimate seepage velocity in spawning gravel.

$$V_{s_n} = \frac{\Delta d}{\Delta T}. \qquad (5.1)$$

Some tracer tests reported no change in EC for the entire duration of the test, and were discarded. Other tests had variable recovery of the tracer, with some downstream wells recording tracer hits and other downstream wells missing the tracer. Data from incomplete tracer tests were only used when at least two wells in a series encountered the spike in electrical conductivity. Tracer test results and missing tracers indicate complex flow patterns in the subsurface. Lateral or vertical components to subsurface flow may not be captured by these tests.

Results from a tracer-test that worked especially well can be seen in SWT 4 (Figure 5.5). Arrival peaks for the plume are evenly spaced on the plot of E.C. vs. time, so the velocity calculations are consistent for each segment of the test. This test also illustrates the natural dilution over of the NaCl solution over the duration of the test. It is also important to note that the wells used for seepage velocity calculations do not need to be consecutive.

5.3 Results

Background

Inter gravel seepage velocity measurements were conducted at three gravel augmentation sites on the Lower American River in Fall 2011 and Spring 2012. These experiments were to understand the rates of subsurface flow at a depth where salmonid eggs are laid in the gravel. Dams erected on the American River have created unnatural flows cycles and sediment starvation , which has led to altered bed material and low gravel permeability.

Upper Sailor Bar 2009 Site

Seepage velocities were measured at three locations on the 2009 Upper Sailor Bar gravel addition site (Figure 5.4). Two of those tests provided useful data (Figure 5.5). SWT 10 recorded no change in E.C. measurements over the duration of the test and results were discarded. The ninth test, SWT 9, had an average seepage velocity of 0.20 cm/sec, and the tenth test showed a seepage velocity of 0.72 cm/sec. The Sailor Bar 2009 gravel augmentation site has variable surface water depth and velocity, so it is reasonable that subsurface flows are also variable.

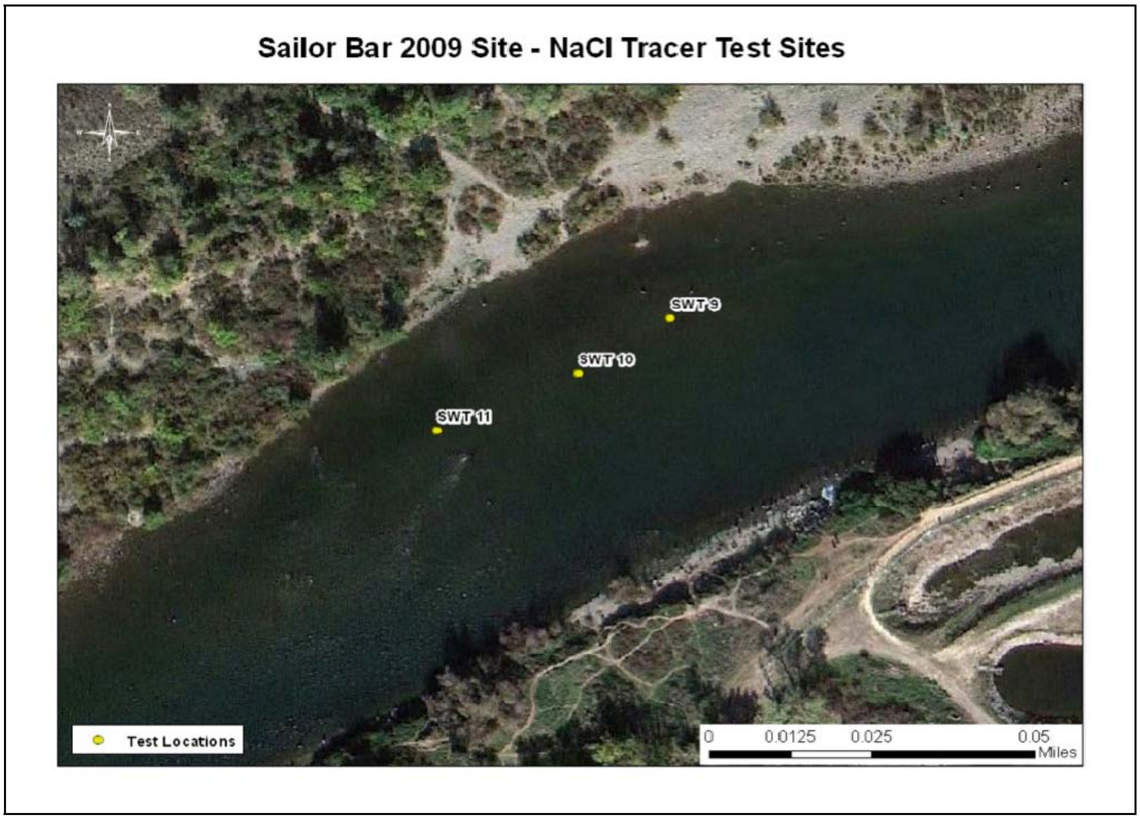


Figure 5.4: Map showing locations for salt tracer tests at the Upper Sailor Bar 2009 Augmentation site.

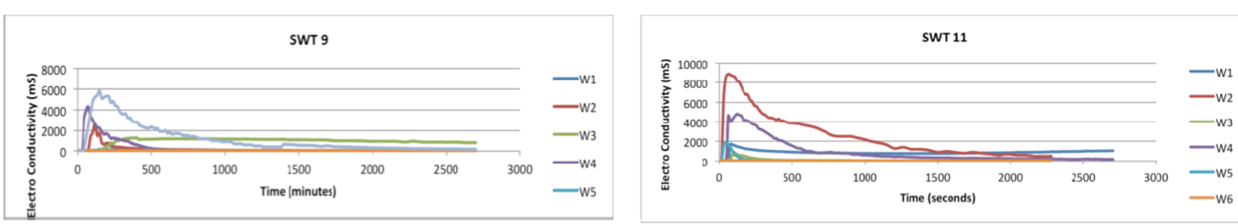


Figure 5.5: Salt water tracer results for Sailor Bar 2009 Augmentation sites. Excludes SWT 10 due to unusable results.

Upper Sunrise 2010/2011Site

Eight salt water tracer (SWT) tests were conducted at the 2010/11Upper Sunrise site. These measurements were completed in 2011 and 2012, roughly one year after the new gravel was added. Five of the tracer tests provided useful data. SWT 1 and SWT 6 were discarded with no change in E.C. reading . SWT 2 was classified as unusable due to the simultaneous arrival of the peak concentration at wells one and two and inconsistent data from the remaining wells. The three tests that were classified as unusable (SWT 1, SWT 2, and SWT 6) were all conducted at the upstream edge of the augmentation site (Figure 5.6). Figure 5.7 shows the graphed results of the usable tests (SWT 3, SWT 4, SWT 5, SWT 7 and SWT 8). The five successful tests yielded seepage velocities between 0.53 cm/sec and .23 cm/sec, with a mean value of .34 cm/sec for the 2009 Upper Sunrise site (Figure 5.7).

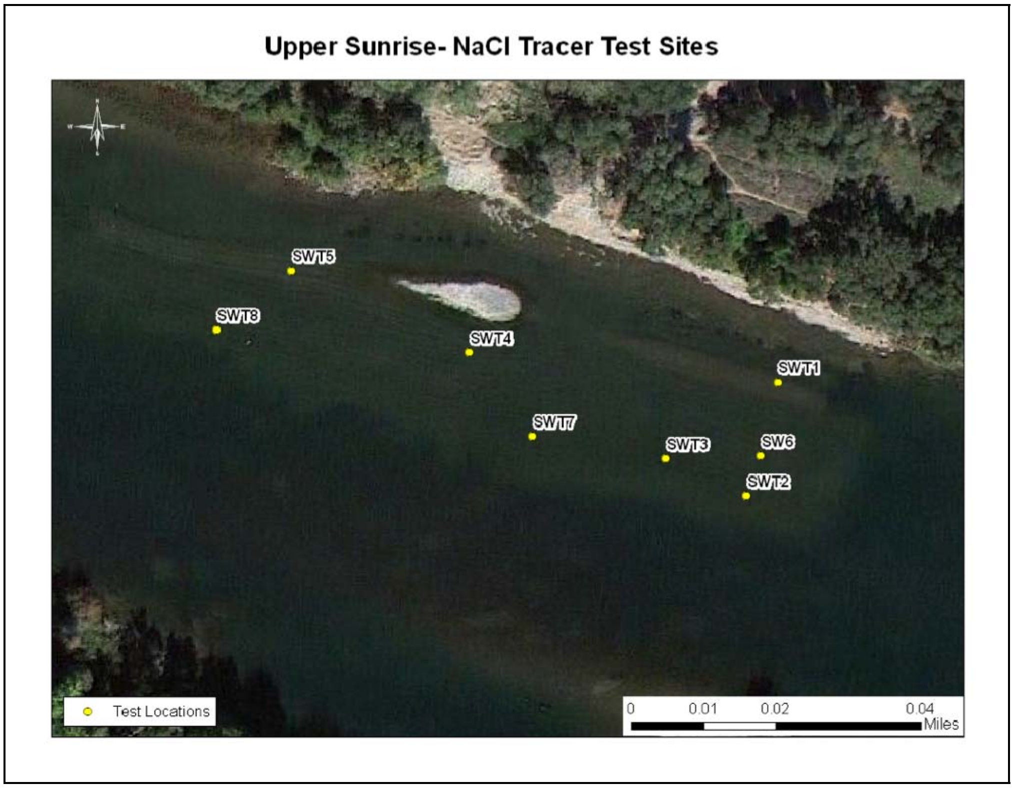


Figure 5.6: Map showing locations for salt tracer tests at the upper Sunrise 2010/2011 Augmentation site. This Photo was taken in October 2011. The newly added gravel is clearly visible as the lighter area on the northern side of the river.

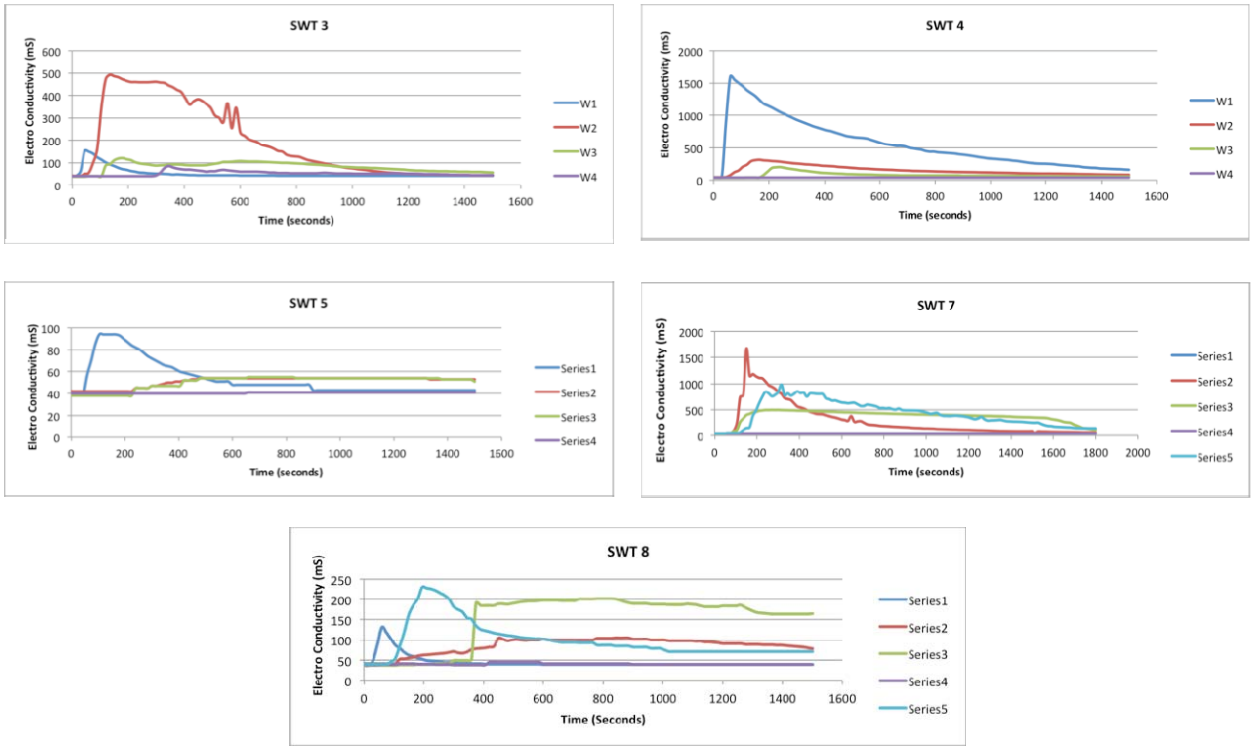


Figure 5.7: Salt water tracer results for Supper Sunrise 2010/2011 Augmentation sites. SWT 1, 2, and 6 are not included due to unusable results.

5.4 Discussion

Seepage velocity tests conducted on the Lower American River show that intra gravel velocity is rapid at the restored sites (Figure 5.8). At the Upper Sunrise 2010/2011 site, seepage velocities vary between 0.3 and 0.5 cm/sec. This site has consistent depth velocity and substrate, so permeability is relatively uniform across the site. The failed tests (SWT 1, 2 and 6) were all located at the upstream edge of the augmentation. It is interesting to note that inter gravel flow velocities are closely related to stream velocity, with higher stream velocities leading to higher intra gravel flow velocities.

Two seepage velocities obtained from the Upper Sailor Bar 2009 gravel addition site are less similar, with values of 0.20 and 0.72 cm/sec. This is partially due to the statistics of low numbers, but this site may be more variable in the subsurface. The variability of the inter-gravel velocities can be attributed to other attributes of this site. Stream velocities, gravel contours, water depth and substrate size are also more variable at the site. Based on limited data, seepage velocity or permeability may be more variable at the 2009 site than the 2010/11 site.

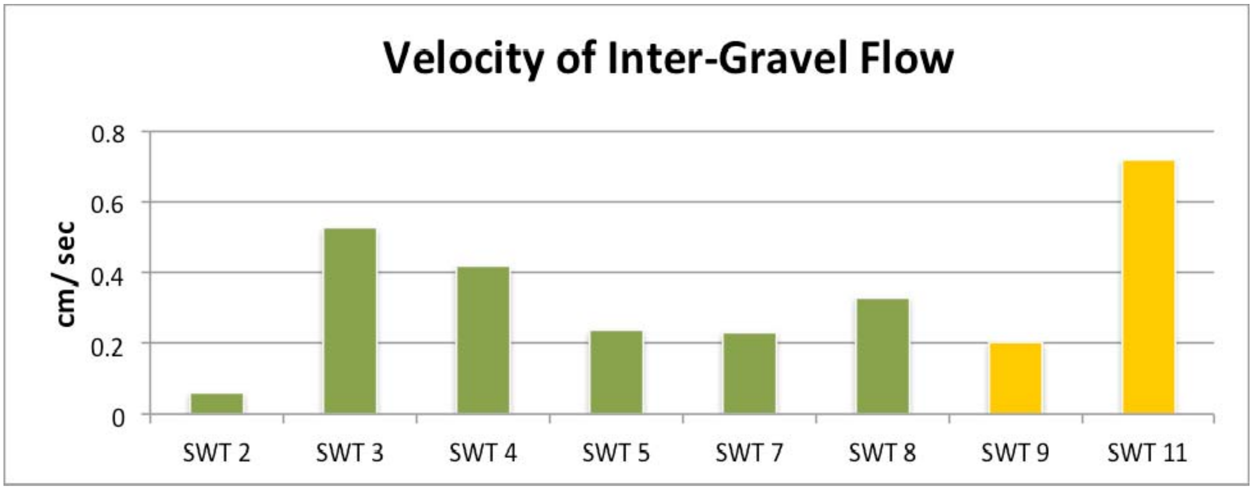


Figure 5.8: Histogram showing velocities in cm/sec for successful salt water tracer tests conducted on the Lower American River at the Upper Sunrise 2010/2011 augmentation site (green) and the Sailor Bar 2009 augmentation site (yellow). SWT 2 was discarded due to inconsistent results.

Chapter 6: Hyporheic Pressure Head

6.1 Background

Vertical flux through the hyporheic zone is controlled by the differences in pressure heads and may be a key factor in salmonid redd site selection (Geist and Dauble, 1998). Upwelling conditions are commonly associated with salmonid redds due to the increase of water exchange around the redd which replenishes oxygen and removes waste (Becker and others, 1983). Vronskiy and Leman propose that hyporheic exchange is critical and upwelling and downwelling may not be as important (Geist and Dauble, 1998).

Riffle and pool sequences can be effective (Figure 6.1) in creating upwelling and downwelling zones (Grieg et al., 2007). Effectively, this is what a female salmonid creates on a smaller scale when constructing a redd.

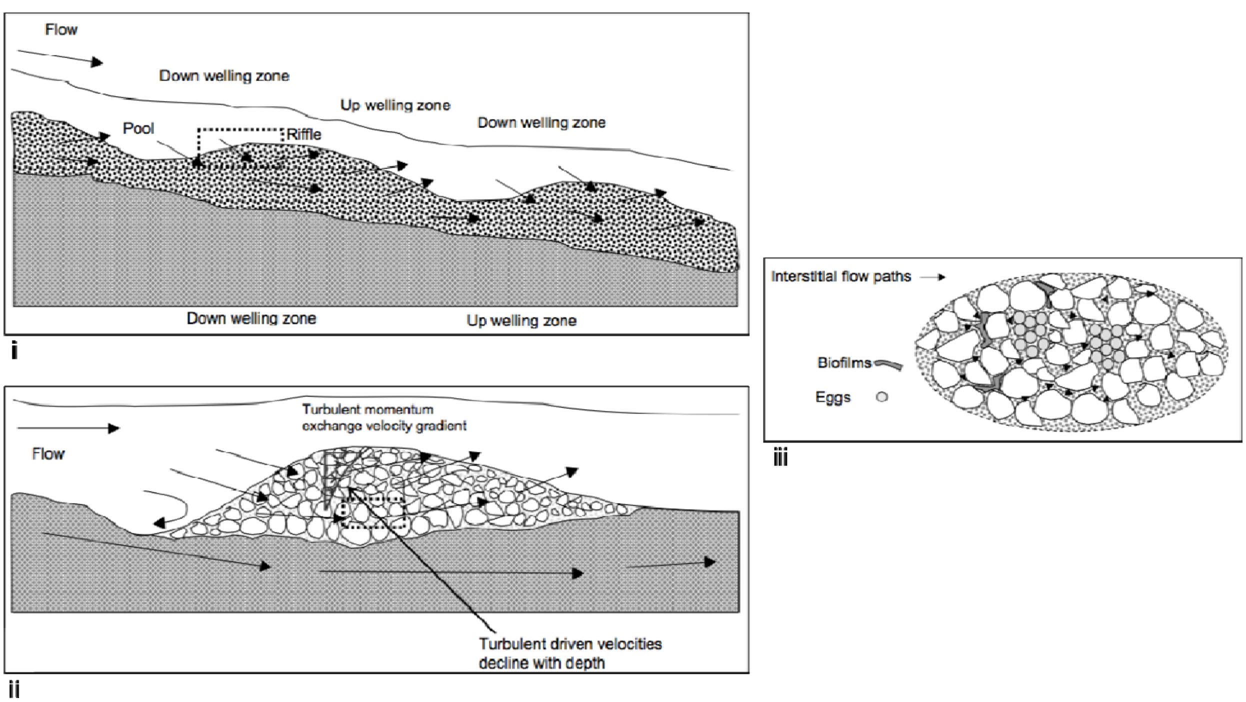
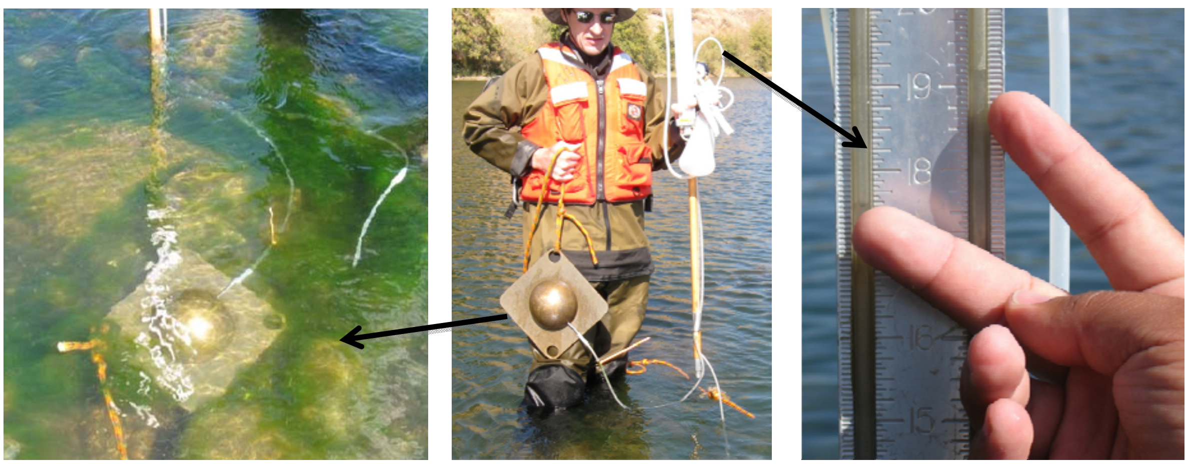


Figure 6.1: Subsurface flows; i. Reach-scale surface subsurface exchange. (ii). meter-scale exchange through a redd (ii). (iii). Micro-scale flow paths in the egg pocket. From Grieg et al., 2007.

6.2 Methods

Background

Pressure differences are used to reveal upwelling and downwelling conditions in the subsurface. A bubble manometer board (Figure 6.2) is attached to a baffle that blocks river current (Figure 6.2i). The manometer board compares pressure head differences between the river and at 30 cm depth in the gravel (Zamora, 2006). Higher pressure heads in the river vs. the gravel indicates a downwelling condition (losing stream). This flushes surface water into the shallow gravel. Higher pressure head in the gravel subsurface vs. the river indicates an upwelling condition (gaining stream). This contributes subsurface water from the hyporheic zone to the stream.



i **ii** **iii**

Figure 6.2: Dr. Tim Horner holding manometer board and baffle. Baffle (i) in water next to piezometer and ii) connected to manometer board. Pressure head reading on the manometer board (iii) showing downwelling conditions where the pressure measurement on the left is (subsurface) is lower than the river pressure measurement on the right. This indicates downwelling conditions.

Methods

A manometer board was used to measure pressure differences between surface water and subsurface water from the hyporheic zone. A manometer board has a glass tube in the shape of an inverted "U" attached to a graduated board (Zamora, 2006). Tubing from one end of the glass tube is attached to a baffle on the bottom of the streambed, and measures river pressure head. The baffle was used to remove the effect of stream flow from the pressure measurement of the stream pressure. The tubing from the other end of the glass tube was attached to the piezometer, and measurements from this tube represent intra gravel water pressure at a depth of 30 cm in the gravel. The top of the manometer was then attached to a small pump, and air was evacuated from the system. Pressure levels were compared between the sides of the manometer board (Fig. 6.2iii), and vertical gradient is calculated by dividing the manometer difference by the 30 cm vertical distance between the piezometer and the river bottom.

6.3 Results

Upwelling conditions were recorded as a positive number, while downwelling conditions were recorded as a negative number. The size of the marker on each map indicates the magnitude of upwelling or downwelling. Hyporheic pressure head measurements were conducted in November 2011 at a flow of 2640 cfs.

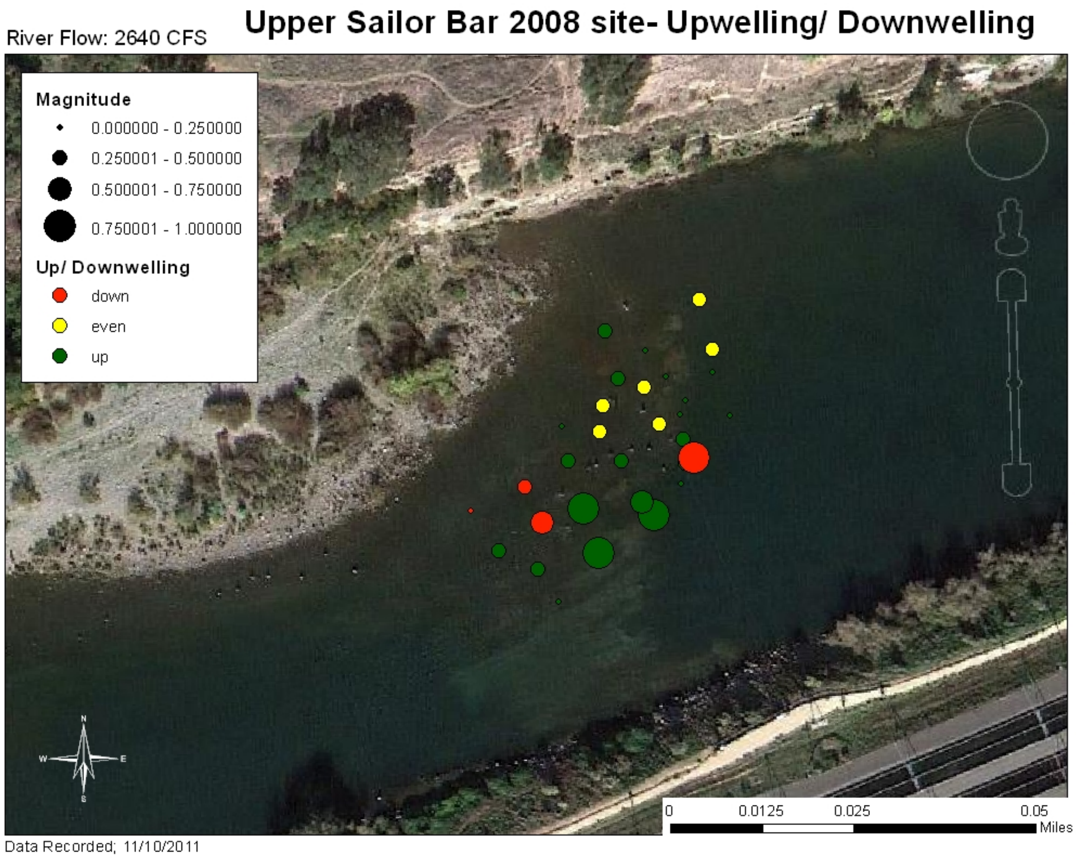


Figure 6.3: Sailor Bar 2008 upwelling and downwelling conditions at 2640cfs, data recorded on November 10, 2011.

<u>Upper Sailor Bar 2008 Site</u>

The Upper Sailor Bar 2008 Site showed a wide range of pressure head measurements, and had the highest variance in pressure head measurements (Table 6.1). The 2008 gravel addition showed a mixture of upwelling and downwelling conditions throughout the site (Figure 6.3). The large upwelling conditions are along a hummocky gravel wave, and downwelling conditions are found in deeper areas (micro pools).

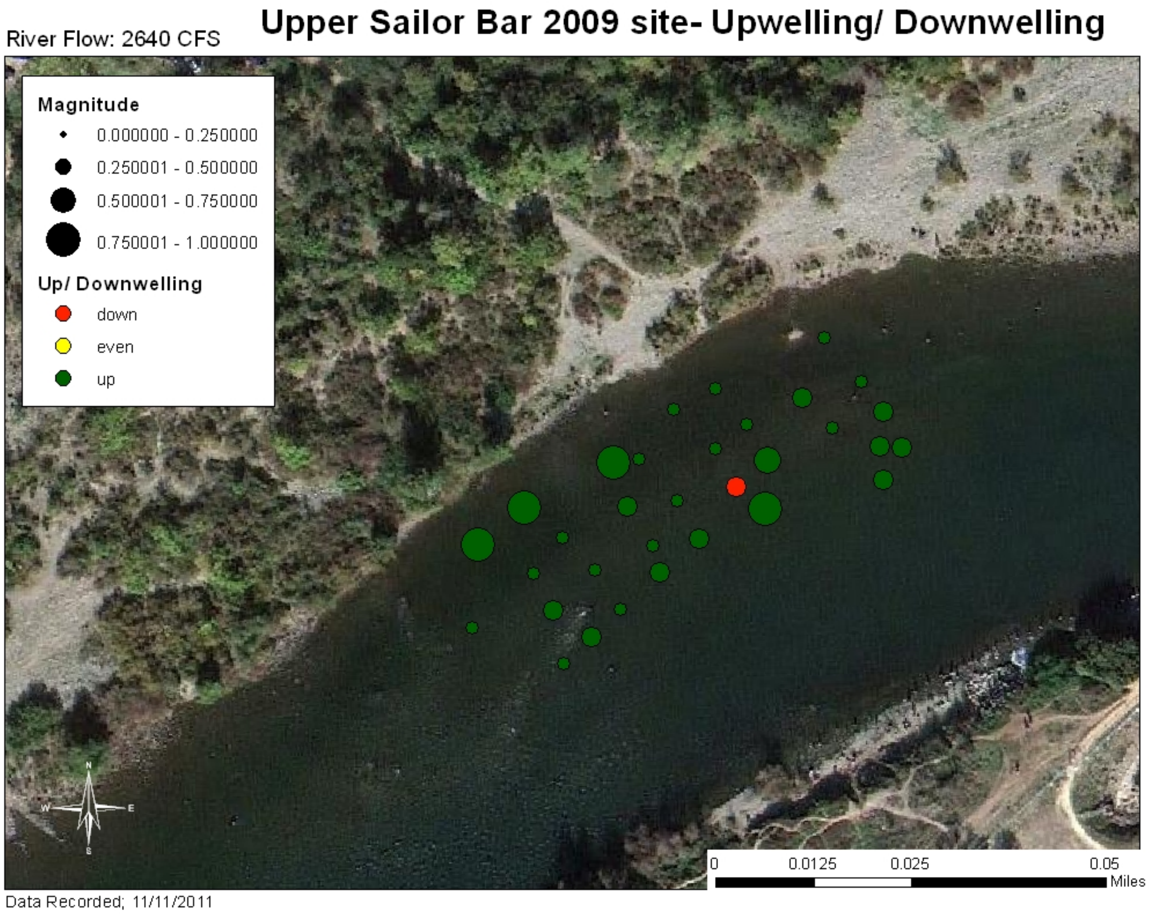


Figure 6.4: Sailor Bar 2009 upwelling and downwelling conditions at 2640 cfs, data recorded on November 11, 2011.

<u>Upper Sailor Bar 2009 Site</u>

The Upper Sailor Bar 2009 Site showed a wide range of pressure head measurements (with a moderately-high standard deviation) and upwelling conditions across the site. Many upwelling measurements are moderately strong. This translates to moderately-high variance (Table 6.1). The single downwelling measurement is related to small-scale flow diversion around a large boulder (Figure 6.4).

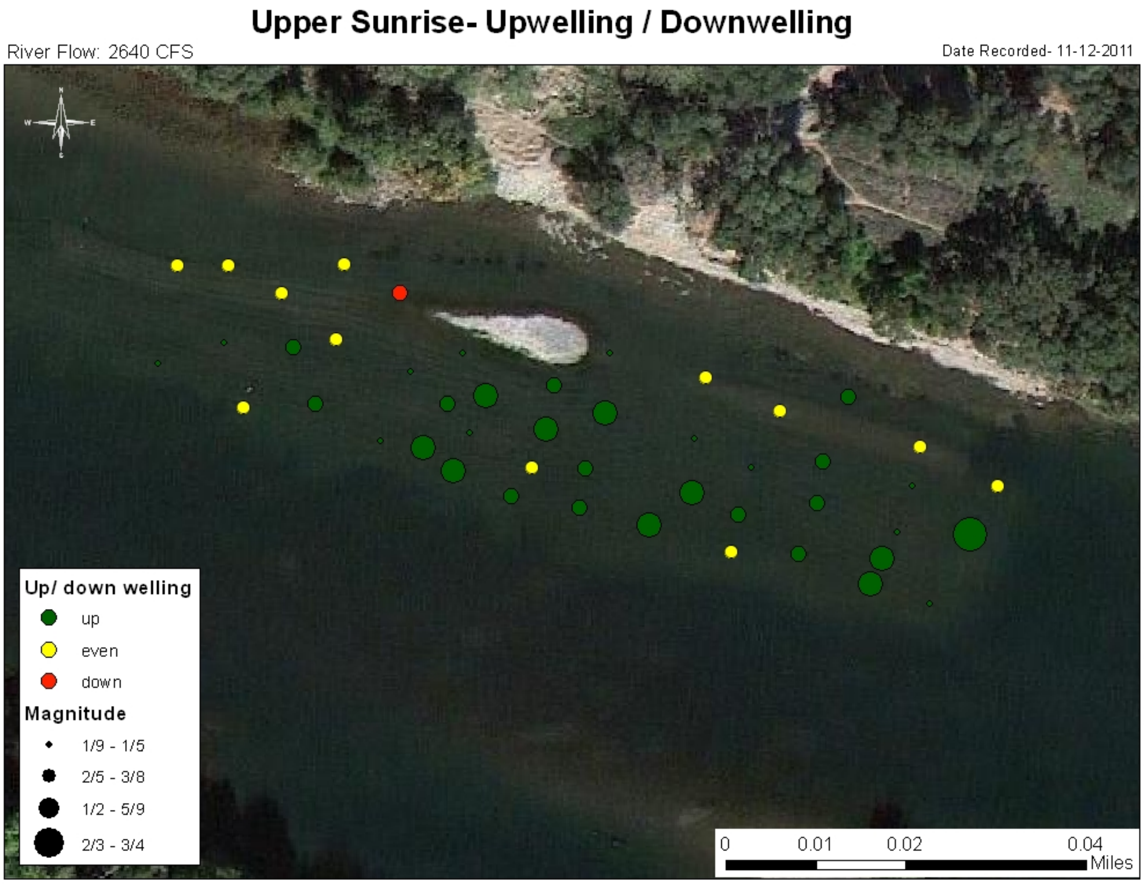


Figure 6.5: Upper Sunrise 2011 upwelling and downwelling conditions at 2640 cfs, data recorded on November 12, 2011.

<u>Upper Sunrise 2010/2011 Site</u>

The 2011 Upper Sunrise site has a moderate range of pressure head measurements (with a low standard deviation), and magnitudes are relatively low (Figure 6.5). Upwelling and neutral measurements are most common. This homogeneity is reflected in the low variance at the site (Table 6.1).

Results are compared in Table 6.1, which includes the range of measurements recorded, their mean and the variance within each site. Variance was calculated in the same fashion as described in chapter 4.

Table 6.1: Summary and comparison of pressure head measurements with the manometer board at all three gravel augmentation sites.

Site	Date of Measurement	Range inches	Mean inches	Standard Deviation	Variance	Number of Measurements
Upper Sailor Bar 2008	11/10/11	-1.5	0.22	0.45	0.2	31
Lower Sailor Bar 2009	11/11/11	-1.5	0.37	0.32	0.104	33
Upper Sunrise 2010/2011	11/12/11	-1	0.2	0.2	0.041	46

There is a difference between each site concerning upwelling and downwelling locations and magnitude. Upper Sailor Bar 2008 site showed the most heterogeneity as indicated by the largest variance (Table 6.1) and the presence of both upwelling and downwelling zones throughout the augmentation site. The large upwelling conditions were along a gravel ridge, whereas the downwelling conditions existed in deeper micro-pools.

The Upper Sailor Bar 2009 site was dominated by upwelling conditions, but did show considerable variability in magnitude of upwelling. This site had moderately high variance.

The Upper Sunrise 2010/2011 site was also dominated by upwelling conditions, but shows lower variance in the magnitude of upwelling. This site also had many neutral pressure head measurements that indicate lack of vertical exchange.

Chapter 7: TEMPERATURE

7.1 Background

Temperature in the hyporheic zone is a controlling variable for successful salmonid reproduction and survival (Horner, 2005). Temperature profiles are also used to understand hyporheic flow patterns at salmon rehabilitation sites. In the connected system, the exchange of water between the stream and the shallow subsurface plays a key role in influencing temperatures in the stream and their underlying sediments (Stonestrom and Constanz, 2003).

Groundwater temperature is relatively constant (Stonestrom and Constanz, 2003) whereas stream water temperature varies diurnally and seasonally (Ingebritsen and Sanford, 1998; Fetter, 2001). This produces a temperature gradient that can be used interpret subsurface flow patterns. Heat flows between two points by advection and by thermal conduction through the stationary solids and fluid (Zamora, 2006). Heat carried by moving water can serve as a tracer to determine water movements between groundwater and surface water; heat transfer signals are different in gaining and loosing streams (Stonestrom and Constanz 2003). Comparing the temporal patterns between stream water and shallow stream gravel creates a picture of vertical flow through the hyporheic zone (Figure 7.1).

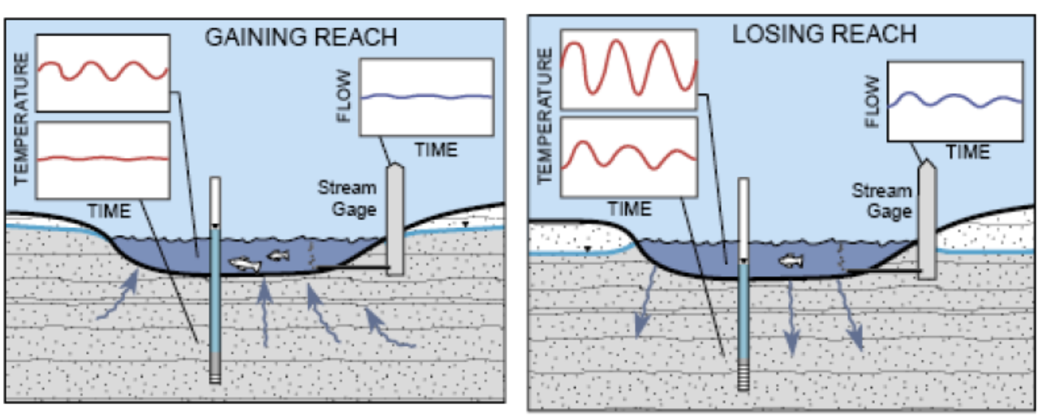


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Figure 7.1: Stream flow and temperature histories for gaining and losing reaches of a stream coupled to local groundwater system. Temperature fluctuations in and beneath the gaining reach are therefore muted compared to temperatures in and beneath the losing reach (i). Groundwater is buffered from temperature fluctuations at the land surface (ii). (from Zamora, 2006)

7.2 Methods

Data obtained from vertical strings of temperature loggers was used to track temperature in the hyporheic zone. Temperature logger housings (small pvc wells) were installed at the Upper Sunrise 2010/2011 Site in 2010 and again in 2011 to provide a continuous record of heat flow between the surface and subsurface. The housings were composed of a 4 foot long pvc pipe with a rigid wire that holds a string of Hobo Water Temp Pro v2 data loggers (Figure 7.2i). Temperature loggers were affixed at 0 foot, 1 foot, 2 foot, 3 foot and 4 foot intervals in the pvc pipe (Figure 7.2ii), and installed vertically in the new gravel. Temperature loggers were calibrated in a 0° Celsius ice bath prior to installation to ensure that the loggers were functioning correctly. Temperature loggers were set to record at 30 minute intervals. Well casings were installed to the desired depth of four feet using a slide hammer and sledge hammer .

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ii

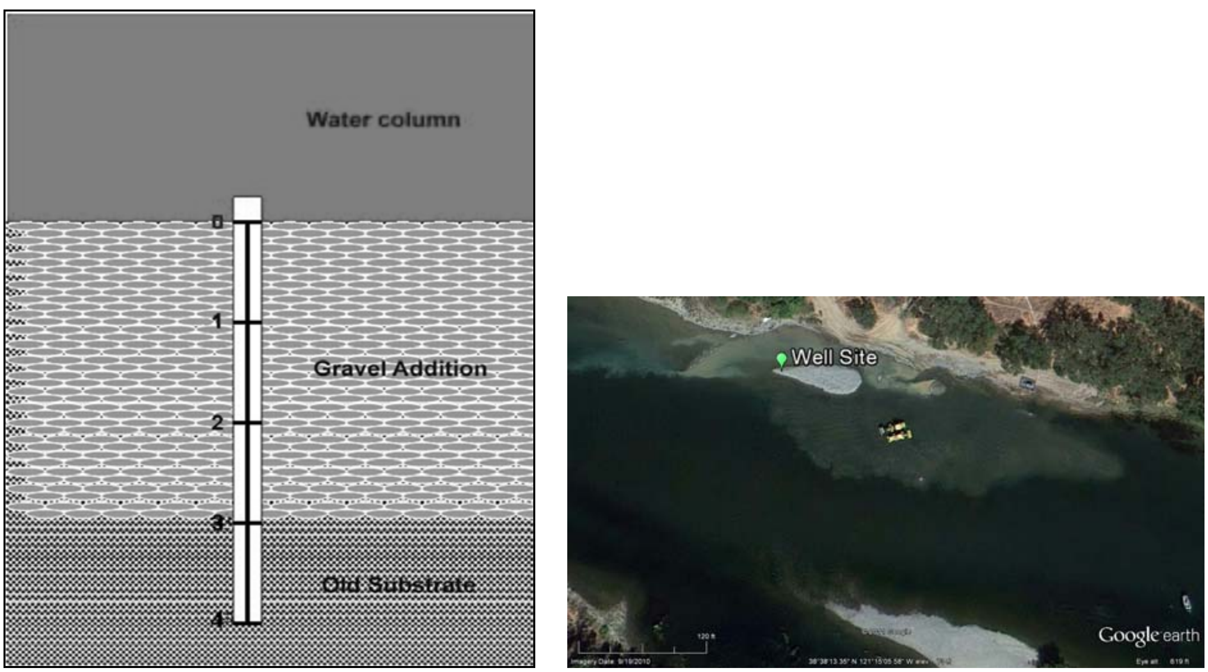
Figure 7.2: i) Hobo water Temp Pro v2 data logger. ii). String of temperature loggers affixed at 0 foot (gravel river interface), 1 foot, 2 foot, 3 foot and 4 foot intervals.

7.3 Results

Upper Sunrise 2010/2011 Site

Temperature Analysis from November 2010 to July 2011

On November 26, 2010, two temperature logger housings (wells) were installed in the gravel restoration site (Figure 7.3i) at the Upper Sunrise project area (Figure 7.3ii). High discharge during the early data collection period scoured out one of these wells and no data were retrieved (Horner, 2011). The other well recorded temperature data until July 14, 2011, when the loggers were accidently removed by a fisherman. Early data were downloaded on January 13, 2010, and the remaining data were downloaded after the loggers were recovered by the fisherman.



i ii

Figure 7.3: i) Temperature loggers are installed in stream gravel at one foot intervals. ii) Upper Sunrise temperature logger site installed in November 2010).

Figure 7.4 provides a plot of water temperature verses time for 7.5 months of data. The plot can be broken into two distinct periods; the first period recorded decreasing temperatures over time, and the second period recorded increasing temperatures. The slope of the temperature profile changed from decreasing to increasing temperatures on January 20, 2011.

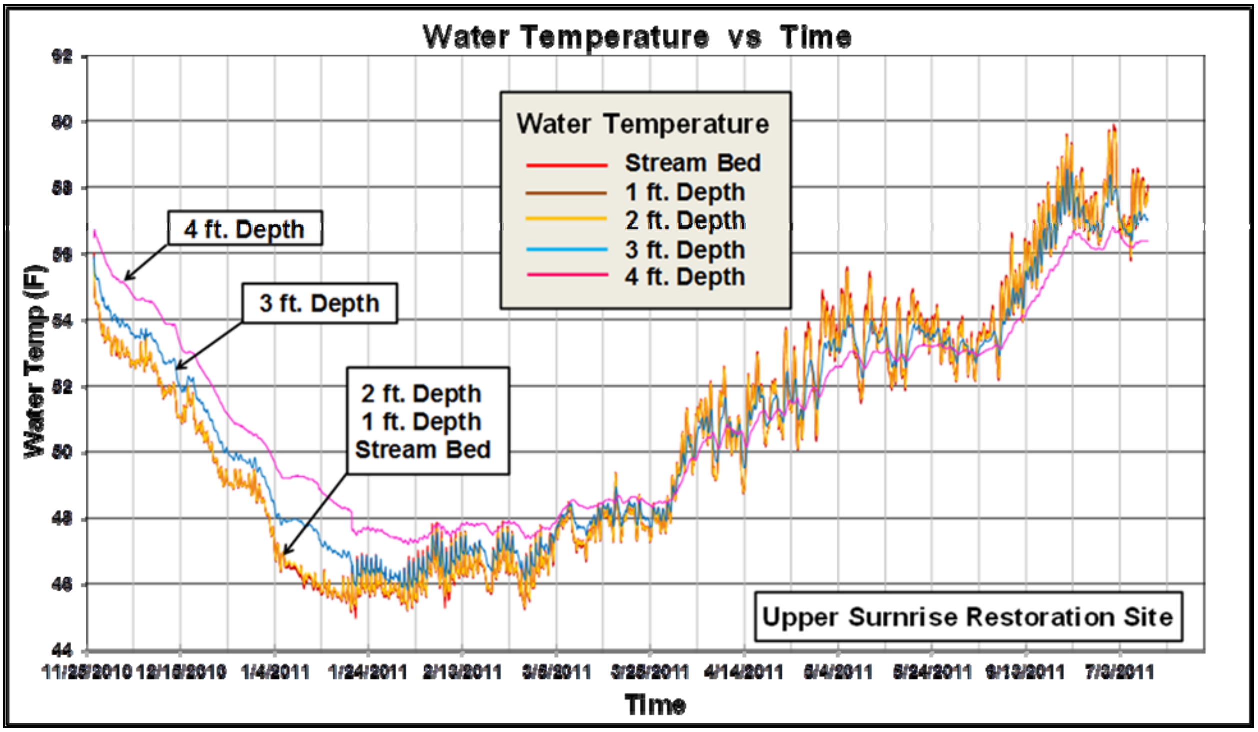


Figure 7.4: Temperature was recorded in vertial wells installed in the stream gravel, and compared between the stream bottom and 1 ft, 2 ft, 3 ft and 4 ft depths in the gravel. Temperature loggers recorded from November 26, 2010 to July 14, 2011.

The temperature signal also inverts during the study period. In the early part of 2011 surface water was coldest, and temperature increased with increasing depth in the subsurface. This is the normal pattern during the cold winter months. This pattern reversed on April 1, when surface water became warmer than hyporheic water. From this time onward through the hot summer months, temperature was highest at the surface and decreased into the subsurface.

The difference in temperature also varies with time. At times all curves are nearly superimposed, indicating similar temperature through the gravel. At other times there is a difference of up to 1.5° between adjacent loggers.

Three of the temperature loggers recorded similar temperature for all parts of the study. The logger that was deployed on the stream bed had an almost identical temperature record to the 1 ft and 2 ft deep loggers. This is probably caused by the new gravel. A blanket of new gravel was laid down at the site, and this material has high permeability. Temperature records show high heat exchange and high permeability in the upper 2 ft of sediment. This is probably the signal from the highly permeable new gravel.

The magnitude of diurnal temperature variations changed with time. These daily fluctuations are the smallest spikes on the temperature curve, and maintained maximum peak-to-trough values of approximately 0.5 °F until January 20, when the peak-to-trough amplitudes abruptly increased to approximately 1 or 2 °F. The amplitude of the daily variation increased again in April 2011. These jumps in amplitude may be related to weather patterns or solar heating at the surface.

The curves from the two deepest loggers (three- and four-foot depth in the gravel) also changed character on January 20. During the initial two-month period, the three-foot depth logger recorded very minor to no diurnal temperature fluctuations, and the four-foot deep logger showed essentially no fluctuations (Horner et al. 2011). After January 20, the three-foot deep logger began recording diurnal fluctuations of an increased magnitude that tracked relatively well with the shallow data (zero-, one- and two-foot depth), though marginally offset and with smaller amplitudes. During the same period, the four-foot depth logger also recorded very minor diurnal fluctuations that continued off and on for the remaining months.

Upper Sunrise 2010/2011 Augmentation Site

Temprature Logger site

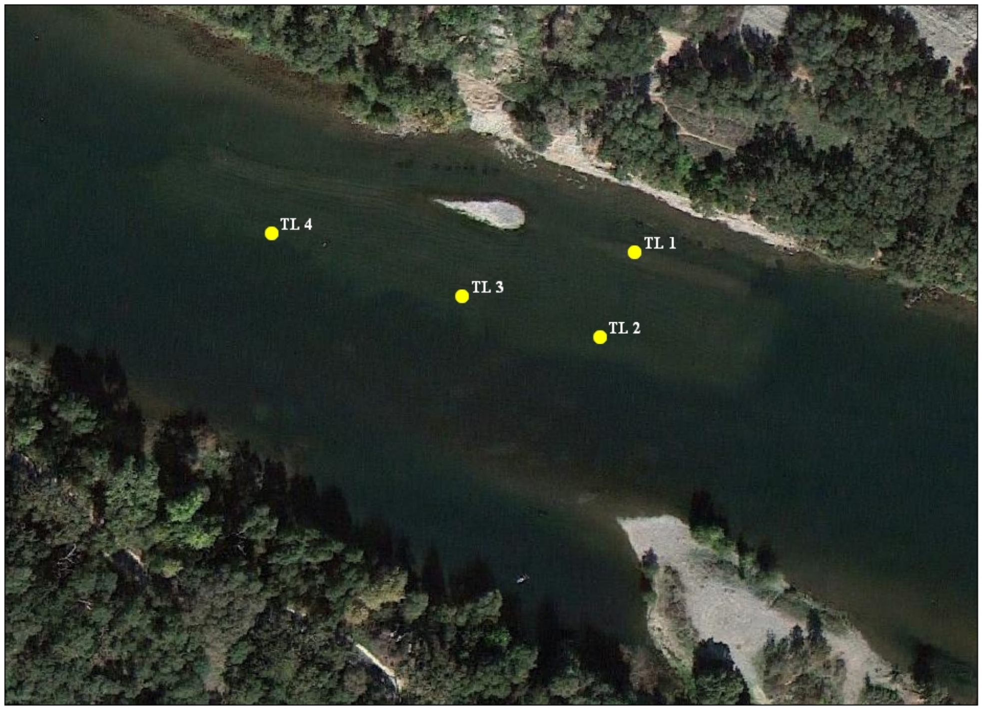


Figure 7.5: Temperature logger locations for the Upper Sunrise 2010/2011 gravel addition site. Temperature loggers were installed in the 2011/2012 season, and monitored for up to seven months.

Temperature Analysis from October 2011 to May 2012

On October 26, 2011 well TL#1 was installed in the new gravel at the 2011 Upper Sunrise restoration site (Figure 7.5). On April 6, 2012 wells TL#3 and TL#4 were installed at the same site. Data were recorded from October 2011 through May 2012 in TL#1, and April through May 2011 in TL#3 and TL#4. Flows started at 3500cfs, then fell slowly to 1000cfs by March 2012. Flows spiked at 8000 cfs on May 1, 2012 then fell to 3000 cfs by May 16, 2012 (Figure 1.3). Data from TL#1 was downloaded on April 6, 2012 and the loggers were re-launched. Additional data was downloaded from TL#1, TL#3 and TL#4 on May 16, 2012.

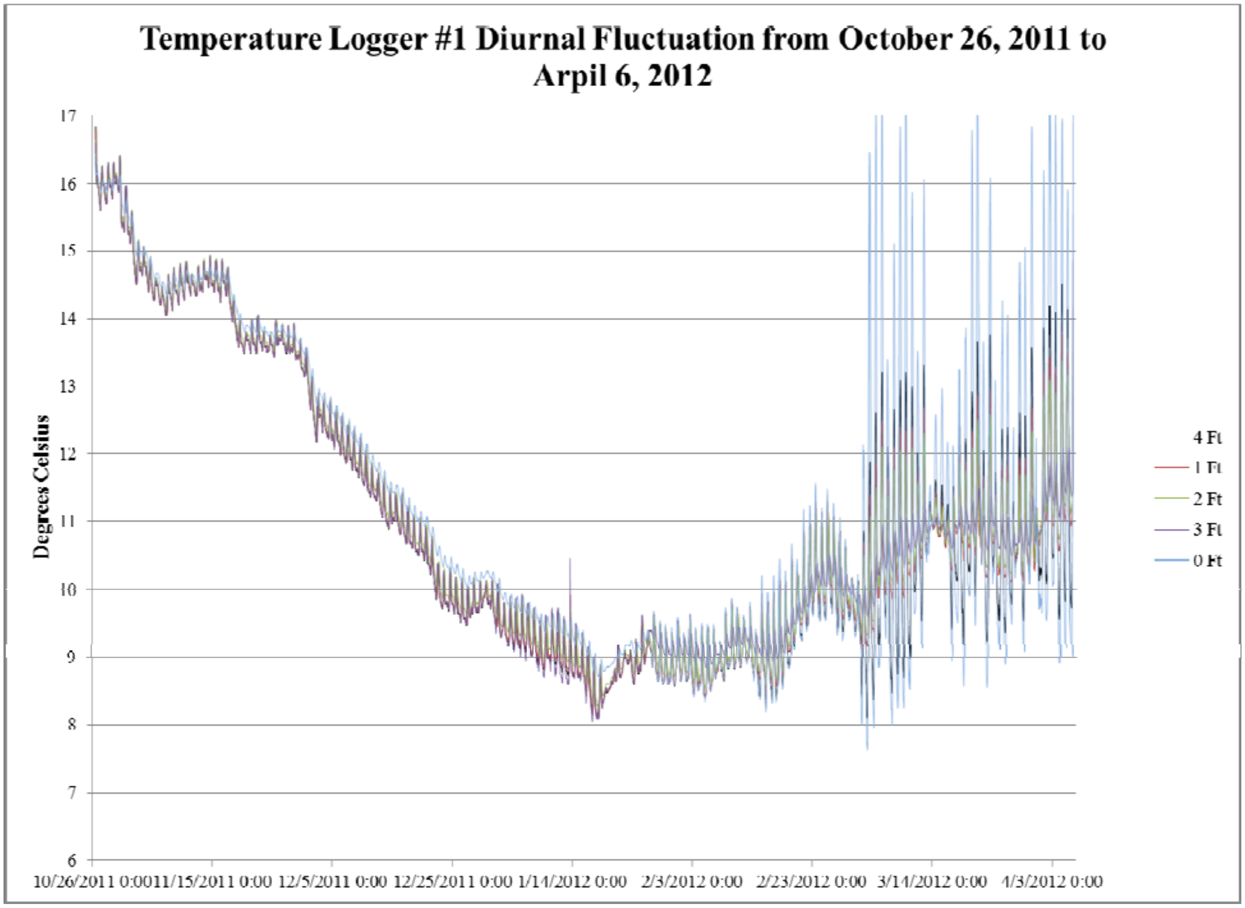


Figure 7.6: Temperature Logger #1 (TL#1) daily temperature fluctuations from October 2011 to April 2012.

The data from TL#1 is displayed in Figure 7.6 and shows temperature verses time from October 2011 to April 2012. Surface temperature variations are propagated to a depth of four feet in the gravel. This indicates downwelling conditions in permeable material. Flows were reduced to ~1000 cfs in March 2012, and at that time the 0 foot logger became dewatered, as shown by the huge spikes in daily temperature. The one ft and two ft loggers also show large temperature swings after that time, possibly from conduction in the well.

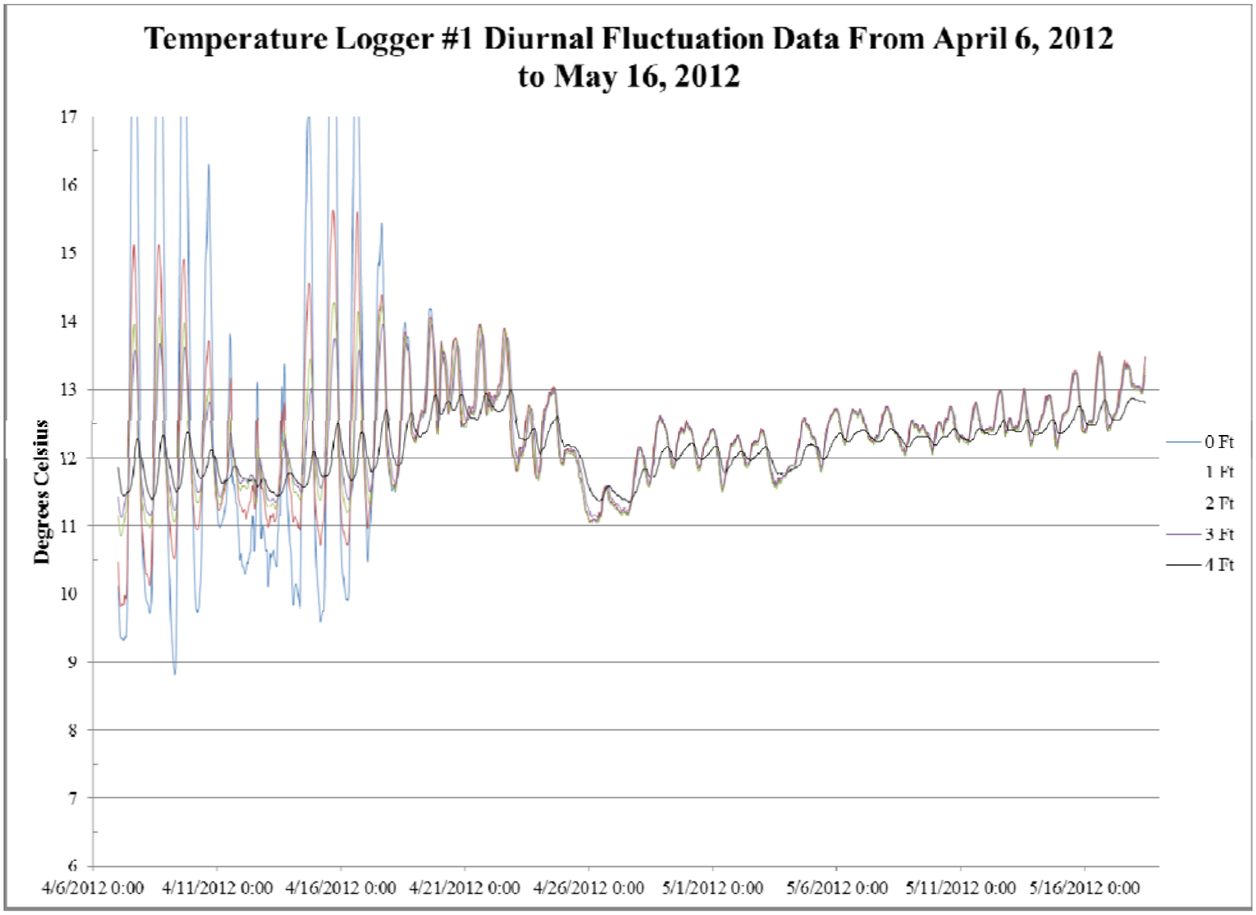


Figure 7.7: Temperature Logger #1 (TL#1) daily temperature fluctuations from April 2012 to May 2012. The logger housing was dewatered from March to mid April 2012.

TL#1 was re-launched in April 2012, and data from the shallow well is displayed in Figure 7.7. Large daily spikes show that the site location was dewatered until April 20, 2012. When the well became submerged again, the daily temperature signal propagated to a depth of 3 feet in the gravel with minimal lag time (figure 8.8) indicating high permeability and downwelling conditions up to 3 feet deep in the gravel. The temperature signal is slightly damped at the 4 foot level, and the diurnal fluctuation is not as prominent. This indicates less exchange with surface water. It seems likely that the top three feet consist of permeable new gravel at this location.

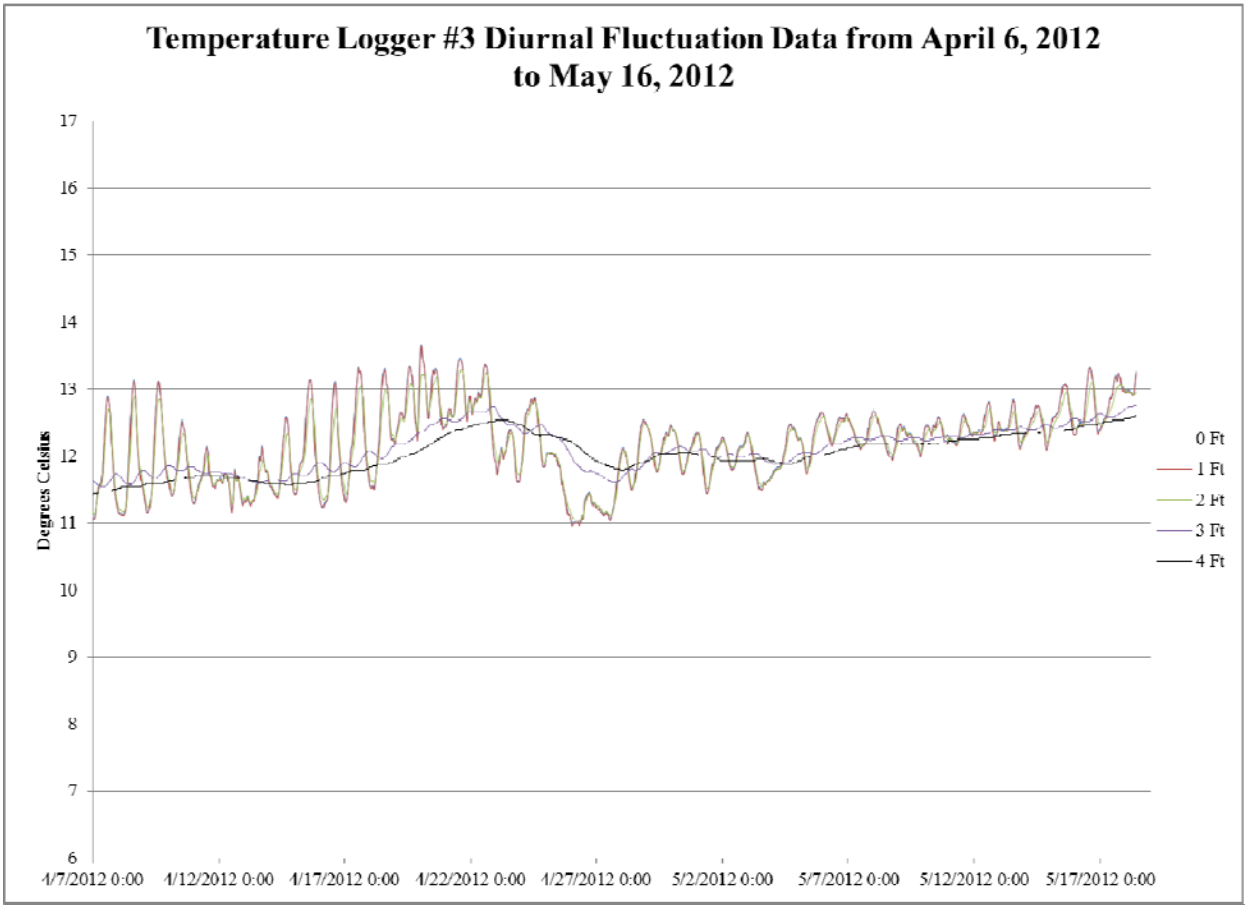


Figure 7.8: Temperature Logger #3 (TL#3) daily temperature fluctuations from April 2012 to May 2012. Upwelling conditions are indicated by the damped 3 and 4 foot signals.

The data from TL#3 is displayed in figure 7.7 for the time period from April 2012 to May 2012. The diurnal temperature signal is propagated to a depth of 2 feet in the gravel with minimal lag time. At the 3 and 4 foot level the diurnal temperature signal is not visible, indicating lack of exchange at this depth. A deeper groundwater signal may be present at this site, with subtle response that lags the surface signal by several days. It seems likely that the top two feet of permeable material represent new gravel, and the bottom two feet of the temperature loggers are installed in older, less permeable streambed material.

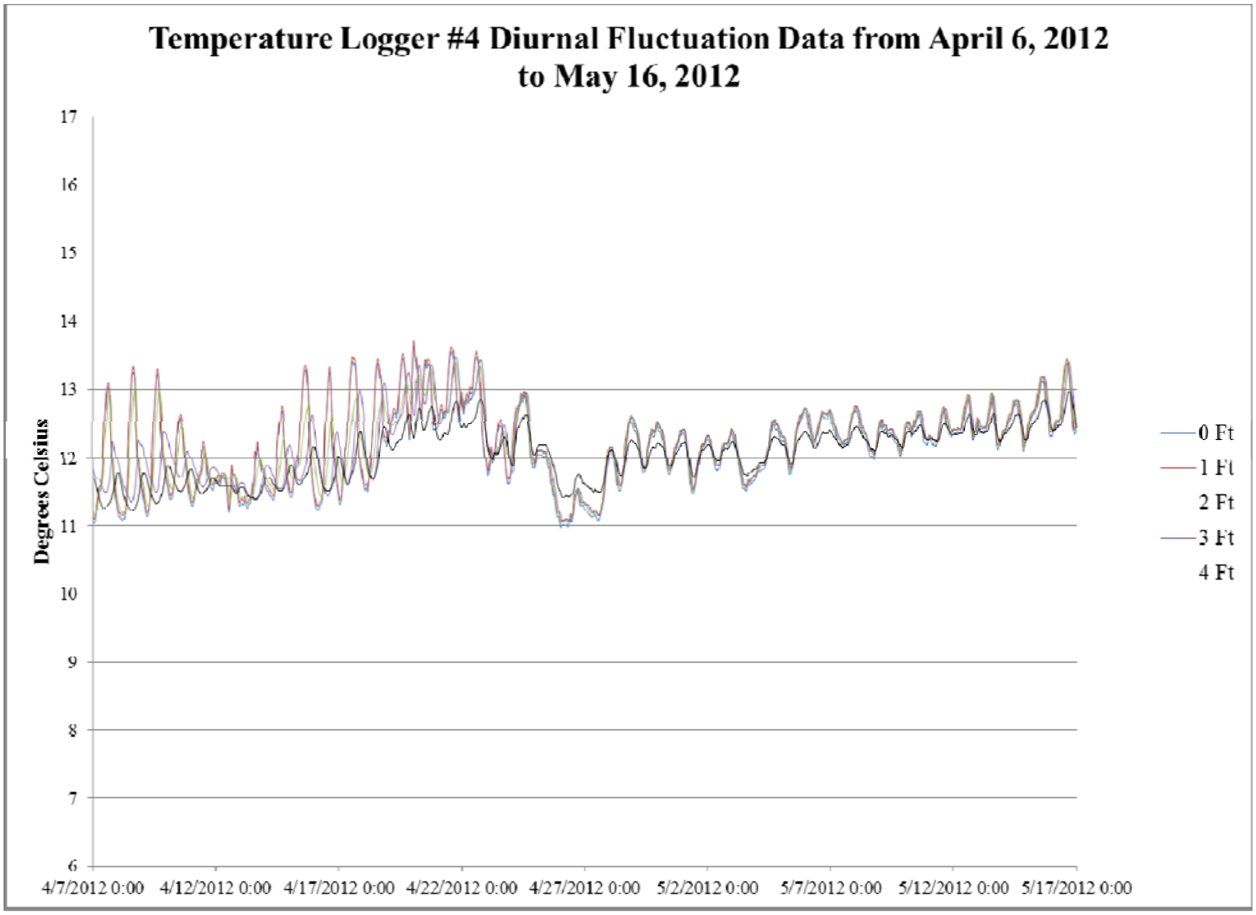


Figure 7.9: Temperature Logger #4 (TL#4) daily temperature fluctuations from April 2012 to May 2012. Downwelling conditions are indicated by the strong daily signals at the 4 foot interval. Loggers are placed at 0 foot, 1 foot, 2 foot, 3 foot, and 4 foot interval (figure 8.2).

The data from TL#4 is displayed in Figure 7.8 for the time period from April 2012 to May 2012. The diurnal temperature signal is propagated to a depth of 4 feet in the gravel with minimal lag time at this site. The strong diurnal signal at 4 feet depth in the gravel indicates downwelling conditions deeper than 4 feet.

7.3 Discussion

Several trends are apparent from the temperature data, and information from temperature studies supports analysis of hyporheic flow patterns. Temperature loggers were installed in the shallow stream gravel, and diurnal variations were used as a tracer to monitor the depth of ground water/ surface water interaction. Changes in the diurnal cycle show that permeable material is present to a depth of 2 – 3 feet. Below that depth there is less exchange with the subsurface.

Temperature data provides a wide range of information about a site. Temperature analysis provided a record of when the stream was dewatered, and inversions in the temperature curve may provide cues for spawning salmonids that seasons are changing. Warmer surface water may be cooled by flow paths through the stream gravel, especially during the hot summer months. Summer temperatures are critical for young-of-the-year steelhead, so temperature data provides information about several aspects of habitat quality in the restored gravels.

Chapter 8: WATER QUALITY

8.1 Background

Incubating eggs are exposed to hyporheic environments and are dependent on intragravel flow to deliver dissolved oxygen and removal of metabolic waste (Youngson et al., 2004; Kondolf, 2008).

Low dissolved oxygen content is a primary factor in egg mortality and low overall fitness of eggs and alevin (Nawa et al., 1990; DeVries, 2000; Malcom et al. 2003; Youngson et al. 2004; Horner, 2004; Kondolf et al., 2008). Minimum oxygen requirements are between 4.25mg/L and 6.00 mg/L, or a saturation percent between 54 and 70% (Table 8.1). Dissolved oxygen saturation percentages and incubation periods are related to temperature (Davis, 1975). The incubation environment is a complex system with multiple factors that simultaneously act to influence outcomes (Wu, 2000). In general, redds located where downwelling occurs (Figure 8.1) will be dominated by well-oxygenated water (Jones and Mulholland, 2000; Malcom et al. 2002).

Table 8.1: Response of freshwater salmonid larvae and eggs to variable dissolved oxygen levels. (From Davis, 1975)

Response	Oxygen (mg/l)	Saturation at given temperature, °C (°F)					
		0 (32)	5 (41)	10 (50)	15 (59)	20 (68)	25 (77)
		Percent					
Function w/o impairment	7.75	98	98	98	98	100	100
Initial oxygen distress	6.00	76	76	76	79	87	95
Widespread oxygen impairment	4.25	54	54	57	64	71	78

Temperature is inversely related to dissolved oxygen levels, so cooler water usually has higher dissolved oxygen content. This is important for embryo development (Alderdice et al. 1958; Silver et al., 1963). Additionally, dissolved oxygen saturation is often inversely correlated with electrical conductivity levels. High electrical conductivity levels and low dissolved oxygen levels are characteristic of groundwater with long residence time and limited exchange with surface water. The dissolution of mineral ions results in a rise in conductivity, while the lowered oxygen is indicative of reduced conditions as a result of anaerobic bacterial activity in the subsurface (Youngson et al., 2004).

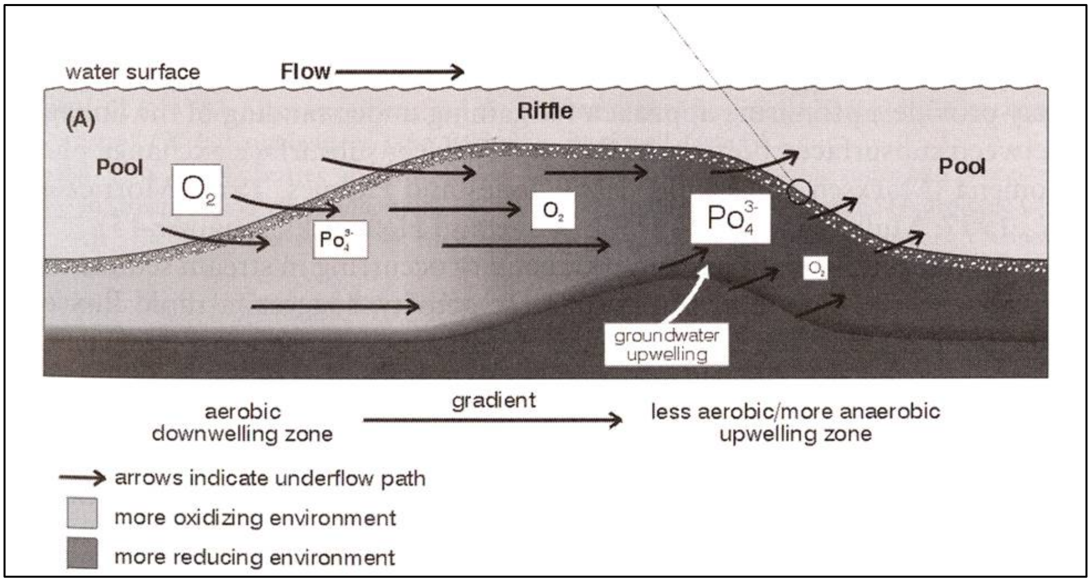


Figure 8.1: Conceptual model for flow through a pool tailout/riffle sequence. Notice the upwelling of groundwater- chapter 6. (From Jones and Mulholland 2000)

High turbidity can signal impaired spawning habitat if the turbidity is related to excess fine material. Intrusion and accumulation of fine sediment in the gravel can significantly reduce permeability (Wu, 2000; Soulsby et al., 2001; Bash et al., 2001); siltation has been identified by the Environmental Protection Agency (EPA) as the most important source of water quality degradation (Henley et al., 2000). Specifically, turbidity is caused by suspended inorganic and organic particulates, and can measured by a variety of light scatter or light absorbance techniques (APAH, 1992 in Henley et al., 2000). High turbidity can also affect macro-invertebrate density and diversity, therefore negatively impacting the food web at higher trophic levels. This can extend to fry and adult salmon if turbidity is extreme (Henley et al., 2000, Bash et al., 2001). Dredging on the lower American River extirpated salmon for many years, but strays repopulated the river in the 1930's.

Turbidity can be linked to positive-nutrient cycling (Horn and Goldman 1994). Certain elements are defined as nutrients because they are essential for life processes in aquatic organisms. Major nutrients include carbon, nitrogen, phosphorus, and silicon. Other potentially important nutrients include calcium, magnesium, sodium, potassium, and sulfur. Micronutrients, those required by plants and animals in very small quantities, might include manganese, copper, zinc, cobalt, and molybdenum (Horn and Goldman 1994).

8.2 Methods

Water quality measurements were made in surface water and at a depth of 30 cm in the stream gravel. Water quality measurements included dissolved oxygen (D.O.), turbidity, electrical conductivity (E.C.), and pH.

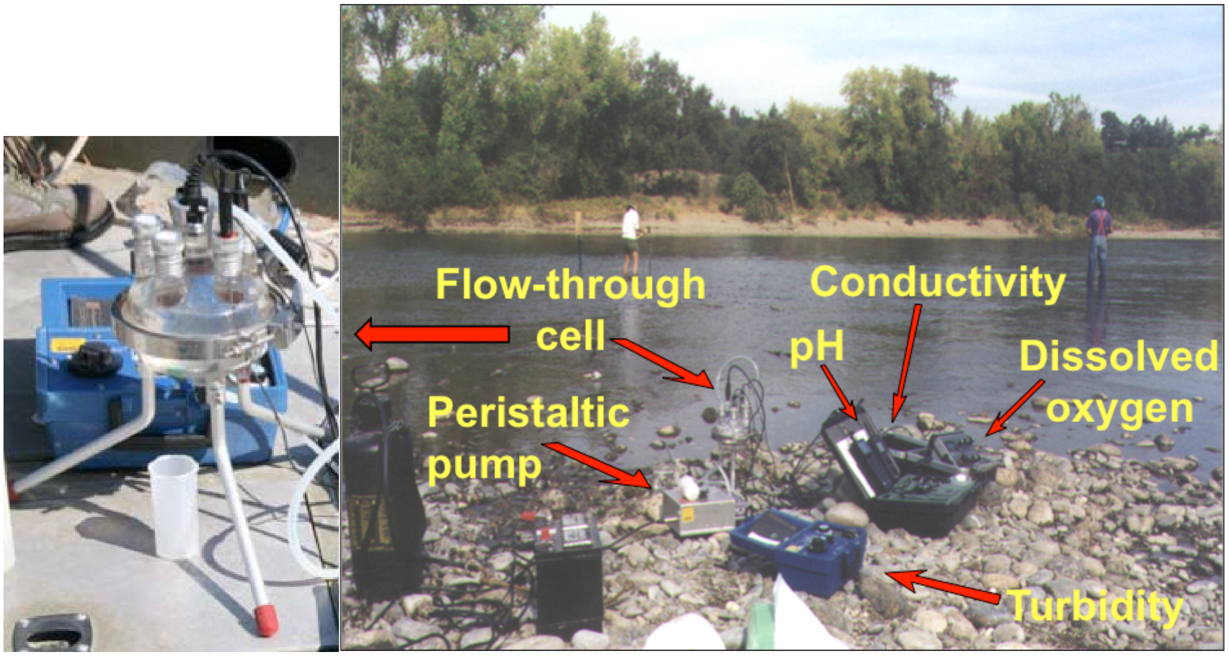
Subsurface water samples were collected using mini-piezometers (Figure 8.2), which were installed in a network across the gravel addition area. Mini-piezometers were installed and sampled both before new gravel was added at the restoration sites.

(i) (ii)

Figure 8.2: (i) Mini-piezometer tip with screen allows water samples to be removed from a discrete interval in the gravel. Mini-piezometers are installed at a depth of 30 cm in the gravel. (iI) Exposed sample tube in surface water.

Each mini-piezometer was sampled by pumping water with a peristaltic pump from the piezometer until it was clear. Water was then pumped into a sealed flow-through cell where D.O., turbidity,E.C. and pH and measurements were made. Pumping continued for three to five minutes until each of the measurements had stabilized. The sealed flow-through cell was used to minimize the interaction of the subsurface water with the atmosphere. Probes from the D.O., E.C., and pH meters were inserted into the ports in the flow-through cell. A rubber gasket was then tightened on each port to ensure an airtight seal. After each mini-piezometer was sampled, the water was drained from the flow-through cell before the next piezometer was sampled.

Dissolved oxygen was measured using a YSI model 95 D.O. meter (Figure 8.3). Turbidity was measured with a DRT turbidity meter. Electrical conductivity was measured with an Orion Model 128 Electrical Conductivity meter. An Orion 210 pH meter was used to measure pH. All meters were calibrated within 30 minutes prior to the start of data collection.



(i) (ii)

Figure 8.3: Hyporheic water from a depth of 30 cm is pumped by a peristaltic pump (i) through a flow-through cell so water is not contaminated by exposure to surface conditions. (ii) Parameters are measured by probes from each meter inserted into the ports of the flow-through cell.

8.3 Results

Background

Water quality was evaluated while salmon were spawning (October and November 2011). Water quality parameters were also measured during incubation periods (December 2011and January 2012), and when fry emerged. Measurements are summarized in tables and presented on maps. The mean value from each sampled site is included to summarize the site characteristics. The variance of each parameter is also included in each table. Variance give a value for the distribution of the data about the mean, and is useful because is appropriates more meaning to samples that are farther from the mean, and therefore may be more significant. Additionally, the covariance of different parameters can then be used to measure how they change together. Variance was calculated in the same fashion as described in chapter 4.

Upper Sailor Bar 2008 Site

8 mini piezometers were installed before gravel addition at the 2008 site. Figure 8.4 shows the location of the mini piezometers. Water quality data measured before restoration is

shown in Table 8.2. Mean dissolved oxygen measurements before the gravel addition were 4.5 mg/L with a range from 1.1 mg/L to 7.65 mg/L and a D.O. saturation ranged from 11.6% to 86.5%. D.O. levels were highly variable across the site. Surface water was sampled as an end-member in this system. When hyporheic water is similar to surface water, it indicates high rates of exchange.

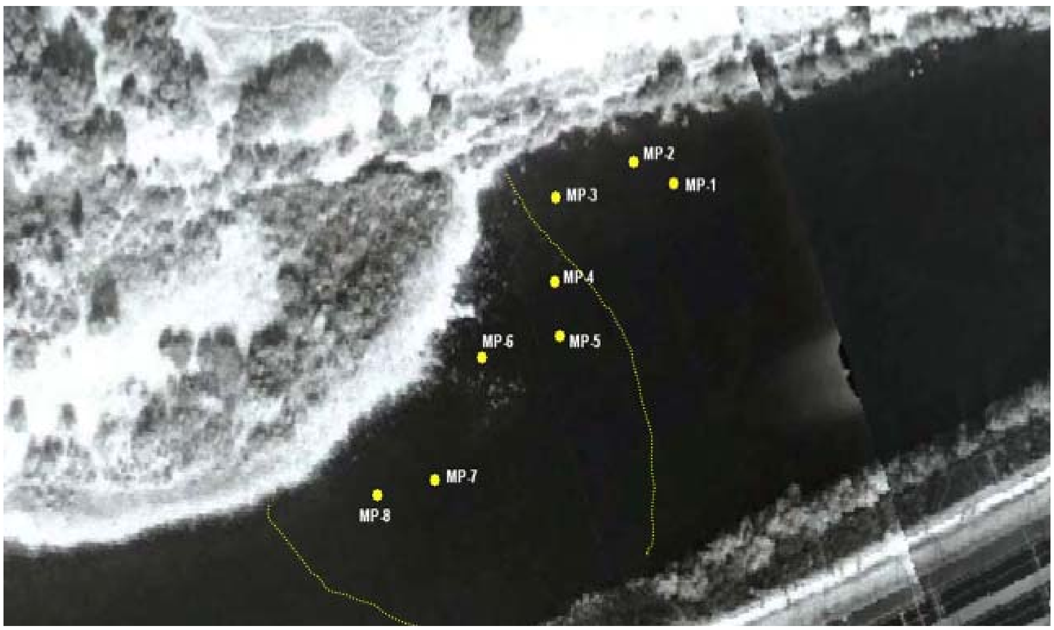


Figure 8.4: Piezometer locations at the Upper Sailor Bar 2008 site, before gravel addition. The area outlined in yellow received new spawning gravel.

Table 8.2: Water Quality parameters before gravel addition at the Upper Sailor Bar 2008 site. Parameters were collected in September 2008 at a flow of approximately 1500 cfs and average hyporheic water temperature of 22.00^{o} C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
MP-1	1.1	12.6	51.8	6.1	-
MP-2	7.45	84.9	37.2	6.6	-
MP-3	6.28	71.4	37.2	6.9	-
MP-4	7.62	86.5	52	7.3	-
MP-5	1.02	11.6	69.4	6.8	-
MP-7	5.38	62.2	54.6	6.9	-
MP-8	2.8	32.4	57.2	6.9	-
Variance	**8.16**	**1053.49**	**128.61**	**0.13**	-
Mean	**4.52**	**51.66**	**51.34**	**6.79**	-
Surface 1	9.3	111.2	36.6	7.3	-

A total of 7 mini piezometers was installed after the gravel addition, and 6 piezometers were added later to cover the site. Figure 8.5 shows the location of 13 mini piezometers in 2012, almost two years after the gravel addition. Post-restoration water quality data is shown in Table 8.3. After gravel augmentation, mean dissolved oxygen concentration was 7.46 mg/L with a range from 3.4 mg/L to 9.0 mg/L and D.O. saturation ranged from 31.5% to 84.3%.

Figure 8.5: Piezometer locations after gravel addition at the Upper Sailor Bar 2008 site.

Table 8.3: Measurements evaluate water quality parameters at the Upper Sailor Bar 2008 site. Parameters were collected in December 2011 at river flow of approximately 2150 cfs and an average hyporheic water temperature of 12.17° C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
MPC	8.2	75.6	37.8	7.1	40.0
MP1	6.7	62.1	39.4	7.0	82.5
MP5	8.0	74.4	37.0	7.0	11.6
MPb	3.4	31.5	68.0	7.3	110.5
MPk	8.9	84.3	37.1	7.3	40.0
Mpe	8.0	75.2	38.6	7.2	71.0
MP1	9.0	83.5	37.1	7.2	26.2
Variance	**3.77**	**334.58**	**130.81**	**0.02**	**1209.01**
Mean	**7.46**	**69.51**	**42.14**	**7.16**	**54.54**
Surface 1	9.3	83.3	36.6	7.3	2.4
Surface 2	9.1	85.2	36.9	7.3	3.8

Figure 8.6 shows D.O. levels on the Upper Sailor Bar 2008 site. Red dots represent D.O. percentages that are critically low for egg development and survival. Yellow dots represent D.O. percent levels that are reasonable for egg development and survival but not extreme. Green dots show high D.O. levels that are close to surface water levels and therefore could represent areas with especially good intragravel flow. Turbidity levels are highly variable (Table 8.3) at the 2008 restoration site. Figure 8.7 shows turbidity levels, with the darker colors representing higher values.

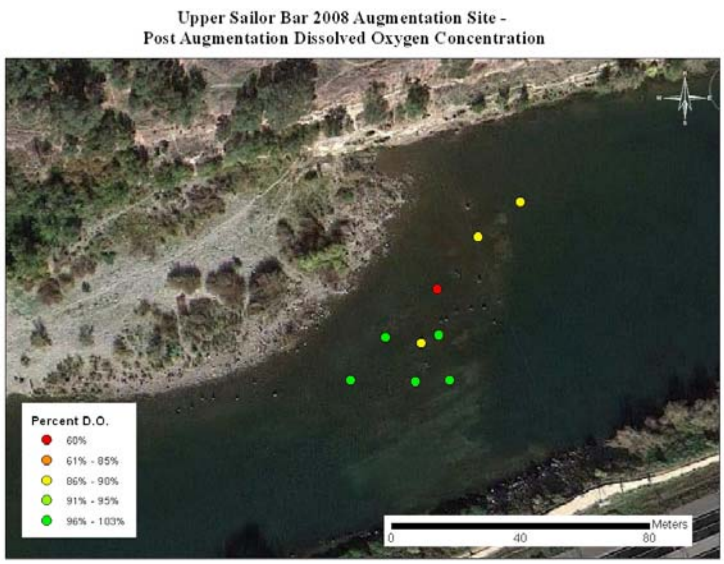


Figure 8.6: D.O. levels at the Upper Sailor Bar 2008 site collected in 2012.

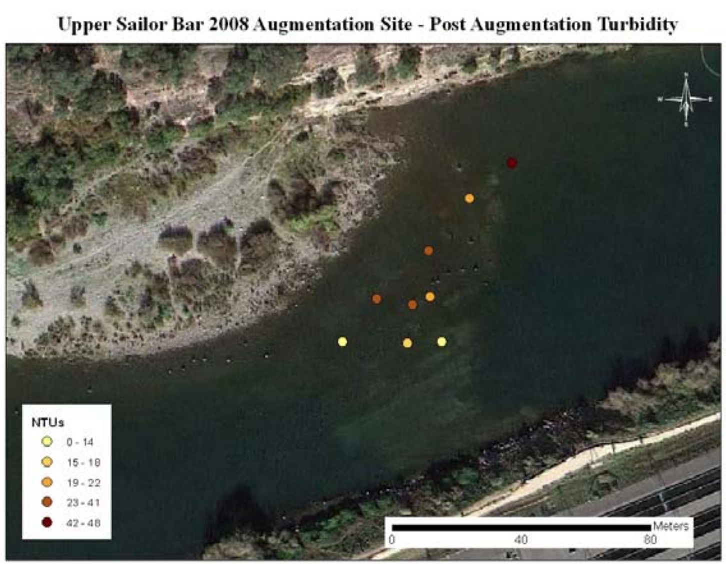


Figure 8.7: Turbidity levels at the Upper Sailor Bar 2008 Site collected in 2012.

Upper Sailor Bar 2009 Site

A total of 12 mini piezometers was installed in August 2009, before the gravel addition. Figure 8.8 shows the location of the mini piezometers, with mini-piezometers "Up 1" and "Up 2" used as upstream control sites. Mini-piezometers were sampled in September 2009, before gravel was added (Table 8.4). Dissolved oxygen values were very low prior to restoration , with mean D.O. of 3.58 mg/l for the 2009 study area. D.O was 3.8 mg/l in the upstream control area, and the mean D.O. of the surface water samples was 7.7 mg/l. This shows that gravel pore water was about 50% saturated with dissolved oxygen.

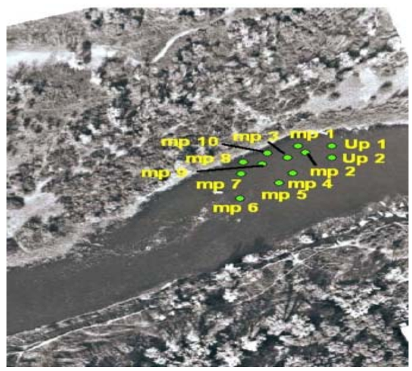


Figure 8.8: Piezometer locations at the pre gravel addition Upper Sailor Bar 2009 site.

Table 8.4: Water Quality parameters collected before gravel addition at the Upper Sailor Bar 2009 site. Parameters were collected in September 2009 at river flow of approximately 2000 cfs with an average hyporheic water temperature of 24.20 ^{o}C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
MP-1	3	32.5	56.8	6.7	35
MP-2	3.7	39.7	51.8	6.7	25
MP-3	1.5	16.1	56.1	6.5	13.5
MP-4	3.6	38.7	52.3	6.6	12.8
MP-5	3.3	35.4	54.3	6.6	8.41
MP-6	3.6	38.5	56.2	6.7	35.1
MP-7	3.3	35.5	54.7	6.5	7.3
MP-8	3.8	40.6	54.5	6.7	25
MP-9	2.1	22.6	60.4	6.8	58.8
MP-10	7.4	81.9	49.9	7	23.1
Variance	**3.05**	**380.14**	**9.37**	**0.03**	**297.96**
Mean	**3.58**	**38.66**	**54.80**	**6.68**	**23.00**
Surface 1	11.6	88.3	50.2	7.3	3.5
Surface 2	11.8	81.8	46.7	7.2	3.1

A total of 7 mini piezometers was installed after the gravel addition. Additional measurements were made to create a sampling network across the entire site. Figure 8.9 shows the location of the mini piezometers in 2012. Water quality data from the restored site is shown in Table 8.5. Mean dissolved oxygen was 8.06 mg/l in the new gravel, with a range from 6.0 mg/l to 9.0 mg/l and saturation percentages from 57.2% to 87.1%.

Figure 8.9: Piezometer locations after gravel addition at the Upper Sailor Bar 2009 Site.

Table 8.5: Current (2012) Water Quality parameters from the Upper Sailor Bar 2009 Site. Parameters were collected in December 2011 at approximately 2050 cfs with an average hyporheic water temperature of 13.23 °C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
pz1	8.7	82.2	36.1	7.3	33.1
mw2	6.0	57.2	34.4	6.8	101.7
pz2	7.7	73.9	36.4	7.2	41.5
pz3	8.2	78.3	36.3	7.3	155.8
mw4	7.8	74.4	36.1	7.2	102.8
jmw7	9.1	87.1	36.5	7.4	36.6
mw7	8.4	80.1	36.2	7.4	14.9
mw9	8.6	82.0	36.1	7.4	49.4
Variance	**0.91**	**81.95**	**0.45**	**0.04**	**2302.71**
Mean	**8.06**	**76.90**	**36.01**	**7.25**	**66.98**
Surface 1	11.2	104.9	35.6	7.3	1.6
Surface 2	8.6	81.8	36	7.4	2.2

Figure 8.10 shows D.O. levels on the Upper Sailor Bar 2009 Map. Red dots represent D.O. percentages that are critically low for egg development and survival. Yellow dots represent D.O. percent levels that are reasonable for egg development and survival but show low intra gravel flow. Green dots show high D.O. levels that are close to surface water levels and therefore could represent high levels of hyporheic exchange. D.O. saturation is less variable then the 2008 augmented site, while turbidity levels were highly variable (Table 8.5). Figure 8.11 shows turbidity levels with darker colors representing higher turbidity measurements. Higher turbidity levels tend to occur in deeper areas.

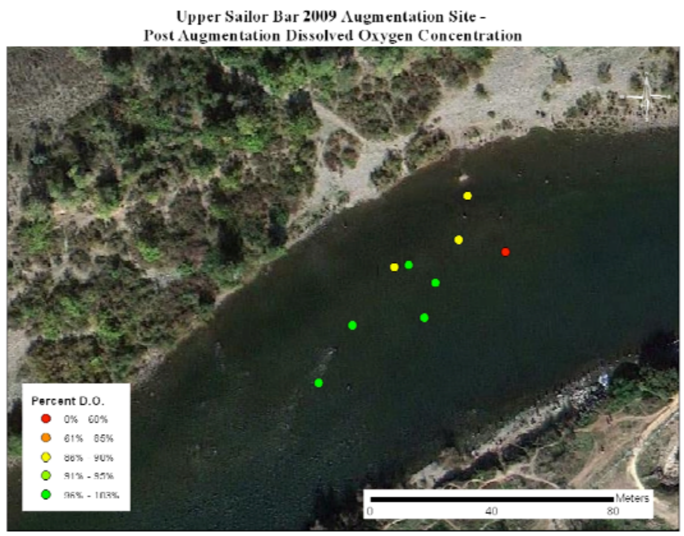


Figure 8.10: D.O. percent levels at the Upper Sailor Bar 2009 Site collected in 2012.

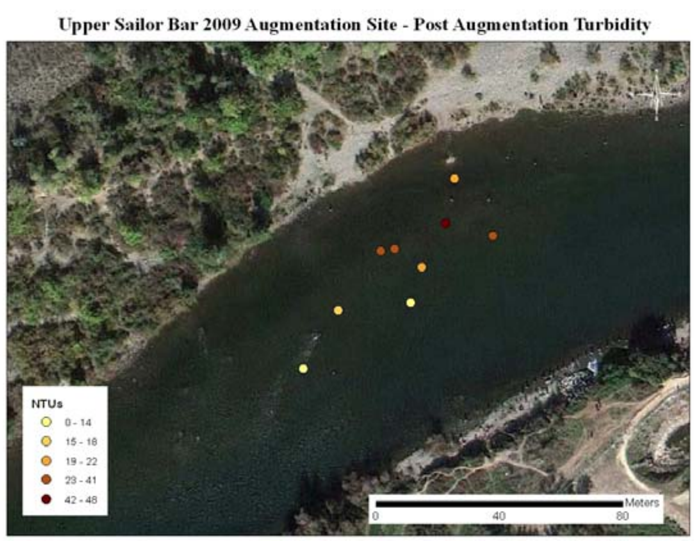


Figure 8.11: Turbidity levels at the Upper Sailor Bar 2009 Site collected in 2012.

Upper Sunrise 2010/2011Site

A total of 9 mini piezometers was installed before the gravel addition. Figure 8.12 shows the location of mini piezometers at the site. Water quality data from the un-restored site is shown in Table 8.6. Mean dissolved oxygen was 4.36 mg/l before the gravel addition (Figure 8.14) with a range from 1.05 mg/l to 8.82 mg/l and D.O. saturation levels from 11.1% to 83.5%.

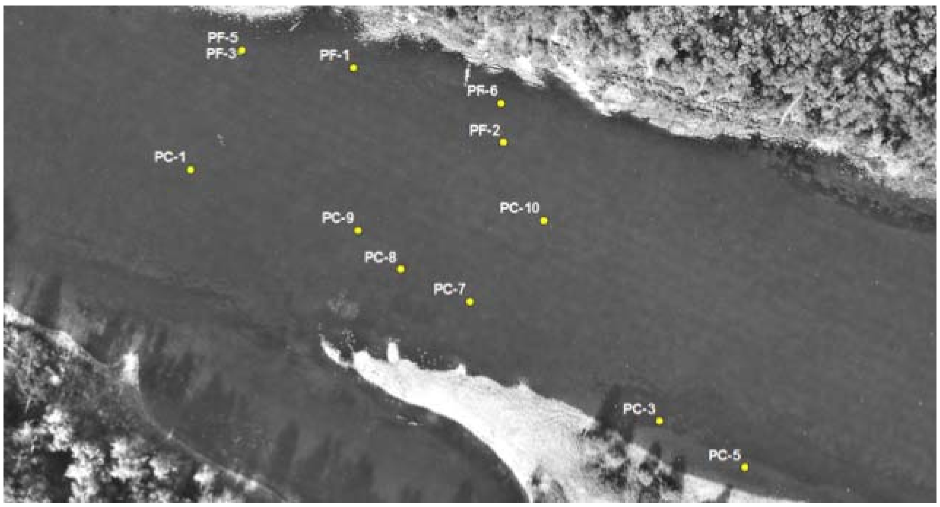


Figure 8.12: Piezometer locations at the pre gravel addition Upper Sunrise 2010/2011 Site.

Table 8.6: Water Quality parameters at the pre gravel addition Upper Sunrise 2010/2011 Site. Parameters were collected in August 2009 at approximately 1550cfs with an average hyporheic water temperature of 18.0^{o}C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
PF1	1.05	11.1	71.2	6.52	42.2
PF2	2.10	22.1	52.6	6.78	12.0
PF3	1.55	16.5	68.5	6.80	20.1
PF5	1.15	12.2	67.0	6.87	33.2
PC3	6.55	71.3	41.5	6.54	8.9
PC5	3.10	33.6	42.2	6.54	14.4
PC6	6.80	71.4	43.9	6.53	4.9
PC7	8.82	93.5	43.0	6.54	3.9
PC8	7.00	73.8	41.6	6.53	12.9
PC9	5.49	57.4	43.9	6.53	5.9
Variance	**8.30**	**933.24**	**154.53**	**0.02**	**161.00**
Mean	**4.36**	**46.29**	**51.54**	**6.62**	**15.84**
Surface1	9.34	96.80	41.10	6.97	
Surface2	9.56	101.20	46.30	6.54	3.50

After gravel addition, 16 mini piezometers were installed at the new site. Figure 8.13 shows the location of the mini piezometers after gravel addition, and water quality data from these sampling points is shown in Table 8.7. Mean dissolved oxygen was 8.85 mg/l at the restored site, and D.O. ranged from 8.5 mg/l to 9.1 mg/l with D.O. saturation levels that ranged from 80.3% to 85.2%.

Figure 8.13: Piezometer locations after gravel was added at the Upper Sunrise 2010/2011 site.

Table 8.7: Current (2012) Water quality parameters after gravel augmentation at the Upper Sunrise 2010/2011 site. Parameters were collected in December 2011 at flows of approximately 2040 cfs with an average hyporheic water temperature of 12.79^{o} C.

Location	D. O. (mg/L)	D.O. (% sat)	E.C. (uS)	pH	Turbidity (NTU)
SITE 1	8.9	84.3	36.9	7.4	4.3
SITE 2	8.8	83.3	36.3	7.4	4.4
SITE 3	8.9	84.3	36.3	7.4	3.9
SITE 4	9.0	85.4	36.8	7.5	8.9
SITE 5	8.9	83.9	36.5	7.4	7.8
SITE 6	8.7	82.4	36.8	7.4	5.2
SITE 7	9.0	85.2	36.6	7.3	10.9
SITE 8	9.0	84.7	51.2	7.5	23.3
SITE 9	8.8	82.8	36.2	7.4	21.5
SITE 10	8.8	83.3	36.8	7.4	16.6
SITE 11	9.1	86.2	36.7	7.4	11.5
SITE 12	8.6	81.3	36.4	7.3	4.0
SITE 13	8.5	80.3	36.9	7.4	4.5
SITE 14	8.9	84.1	36.9	7.4	3.9
Variance	**0.03**	**2.57**	**15.24**	**0.00**	**44.86**
Mean	**8.85**	**83.68**	**37.66**	**7.40**	**9.34**
Surface 1	9.6	91.1	36.2	7.5	4.7
Surface 2	9.1	86	36.3	7.4	1.9

Figure 8.14 shows D.O. levels across the Upper Sunrise 2010/2011 site. Red dots represent D.O. percentages that are critically low for egg development and survival. Yellow dots represent D.O. percent levels that are reasonable for egg development and survival but show low intra gravel flow. Green dots show high D.O. levels, with values that are close to surface water levels. This indicates good intra gravel flow and high rates of hyporheic exchange. D.O. levels are remarkably similar across the site. Figure 8.15 shows turbidity levels at the site, with color coding so that darker colors represent higher turbidity measurements. Turbidity levels are lower at the Upper Sunrise 2010/2011 site than any other site in this study. Turbidity levels also have low variance.

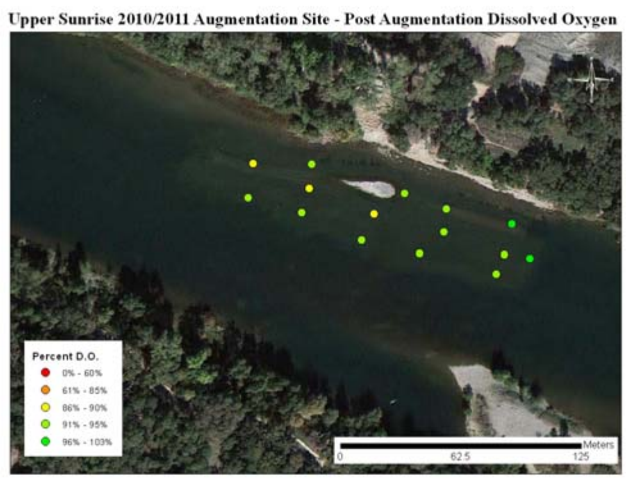


Figure 8.14: Dissolved oxygen levels at the 2010/11 Upper Sunrise site after gravel addition. Data were collected in 2012.

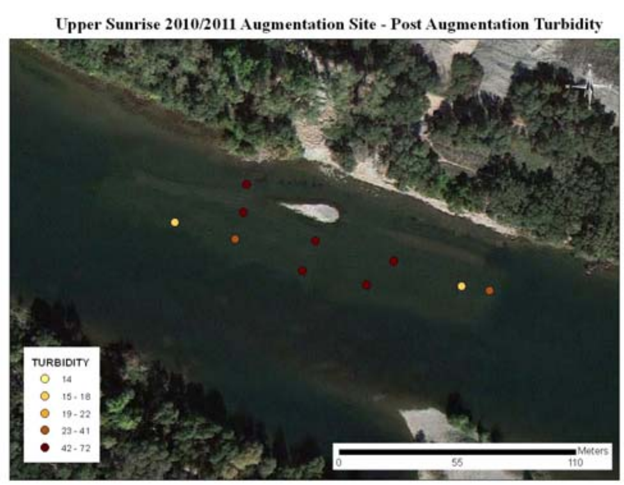


Figure 8.15: Turbidity levels at the 2010/11 Upper Sunrise site after gravel addition. Data were collected in 2012.

8.4 Discussion

Table 8.8 compares water quality parameters for pre and post-restoration conditions at each site. Values for post-restoration are from the most recent sampling event, in some cases three years after the initial gravel addition. Before restoration, all sites showed low levels of intra gravel flow, low D.O. content, and sub optimal conditions for spawning.

The ratio between surface and subsurface D.O. values is a good indicator of hyporheic exchange. When subsurface values approach surface water conditions it shows that oxygenated surface waters are being flushed into the subsurface. This is also expressed as a subsurface-subsurface D.O. ratio to help compare results from different seasons and different temperature regimes. Before restoration, gravel D.O. levels at all three sites averaged about 45% of the surface water value. After restoration, saturation levels averaged 79% of surface water values. This indicates a large increase in hyporheic exchange.

Turbidity was relatively low before restoration, but after restoration there were significant differences between the sites. The 2008 site had the highest turbidity, with a mean value of 55 NTU. This was also expressed by the high fine sediment concentration in bulk samples collected at the site. The 2009 site averaged 23 NTU, and the 2010/11 site had the lowest turbidity, with an average of 9 NTU. The site with the lowest turbidity had the cleanest, best-sorted gravel.

pH and E.C. are not usually critical to salmonid life stages, but they do provide information about surface/subsurface exchange. pH was slightly lower before restoration, with acidic values that may relate to organic material in the armored sediment. After restoration two sites were slightly basic, with values closer to surface water pH. E.C. dropped slightly after restoration, probably due to the cleaner, coarser gravel and fewer dissolved constituents.

Table 8.8: Comparison of water quality of each site pre-restoration and currently (2012). Comparisons include Mean surface and mean subsurface measurements of saturated dissolved oxygen, turbidity, electrical conductivity, and pH. Also included are the ratios between surface and subsurface measures, and the variance between the subsurface measurements within each measurement field.

	Pre Restoration			Current 2012		
	Upper Sailor Bar 2008	Upper Sailor Bar 2009	Upper Sunrise 2010/2011	Upper Sailor Bar 2008	Upper Sailor Bar 2009	Upper Sunrise 2010/2011
Mean Surface DO (%)	111.20	85.05	99.00	84.25	93.35	88.55
Mean Subsurface DO (%)	51.66	38.66	46.29	69.51	38.66	83.68
Subsurface Surface Ratio of DO	0.46	0.45	0.47	0.83	0.41	0.95
Subsurface Varience DO	8.16	380.14	933.24	334.58	81.95	2.57
Mean Surface Turbidity (NTU)	-	3.30	3.50	3.10	1.90	3.30
Mean Subsurface Turbidity (NTU)		23.00	15.84	54.54	23.00	9.34
Subsurface Surface Ratio ofTurbidity	-	6.97	4.53	17.59	12.11	2.83
Subsurface Varience Turbidity	-	297.96	161.00	1209.01	2302.71	44.86
Mean Surface EC (uS)	36.60	48.45	43.70	36.75	35.80	36.25
Mean Subsurface EC (uS)	51.34	54.80	51.40	42.14	54.80	37.66
Subsurface Surface Ratio of EC	1.40	1.13	1.18	1.15	1.53	1.04
Subsurface Varience EC	128.61	9.37	184.83	130.81	0.45	18.24
Mean Surface pH	7.30	7.25	6.76	7.30	7.35	7.45
Mean Subsurface pH	6.79	6.68	6.62	7.16	6.68	7.40
Subsurface Surface Ratio of pH	0.93	0.92	0.98	0.98	0.91	0.99
Subsurface Varience pH	0.13	0.03	0.02	0.02	0.04	0.00

Figure 8.16 shows dissolved oxygen ranges and mean values graphically. At each site values are color-coded with pre-augmentation D.O. in blue, post-augmentation in red, and the current (2012) values in green. Before augmentation, the blue bars at each site show a wide range of measurements with low overall mean D.O. content. D.O values before gravel addition were often low enough to cause egg mortality. Immediately after restoration, the dissolved oxygen levels were consistently higher. Over time, dissolved oxygen levels are still within an optimal range, but are dropping back towards original, non-restored levels.

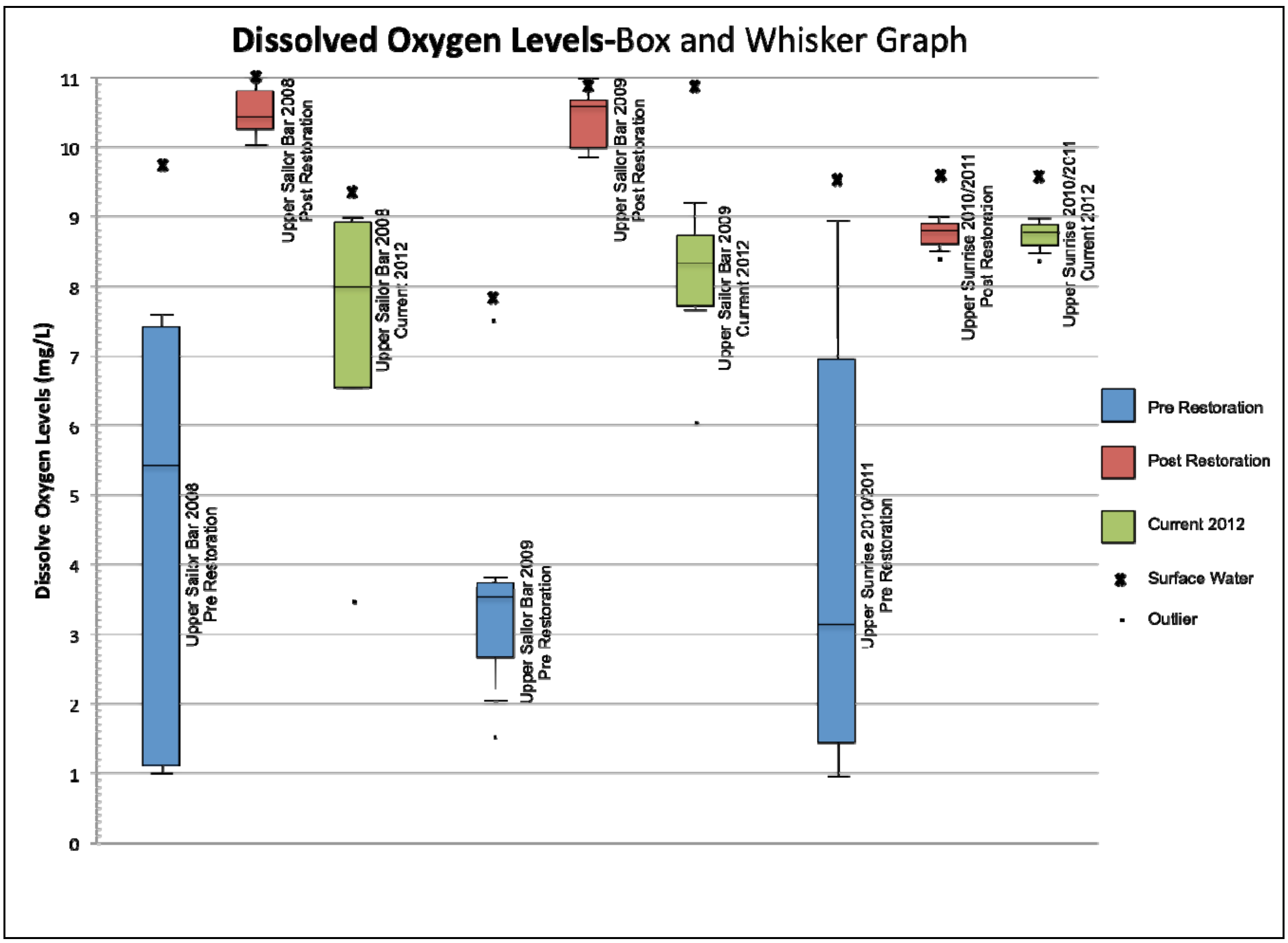


Figure 8.16: Box and Whisker graph of dissolved oxygen levels in mg/L for all sites. Pre-restored, post restoration and current measurements (2012).

Chapter 9: Conclusions and Recommendations

Gravel was added to sites on the American River, CA to rehabilitate salmonid spawning habitat. The goal was to provide suitable grain size for all stages of spawning (redd construction, incubation, and emergence) and to mitigate armoring of the riverbed. This report assesses three aspects of spawning habitat: grain size and its natural mobility, water flow in the surface and subsurface, and intra gravel water quality. These parameters were assessed by pebble counts and bulk sieve samples, scour chains and tracer rocks; surface water depth, velocity and direction , permeability, upwelling and down welling, temperature profiles, and dissolved oxygen, turbidity, electrical conductivity, temperature, and pH of hyporheic water. Each of these physical aspects is related (Figure 9.1), and it is important to examine how each might influence habitat suitability.

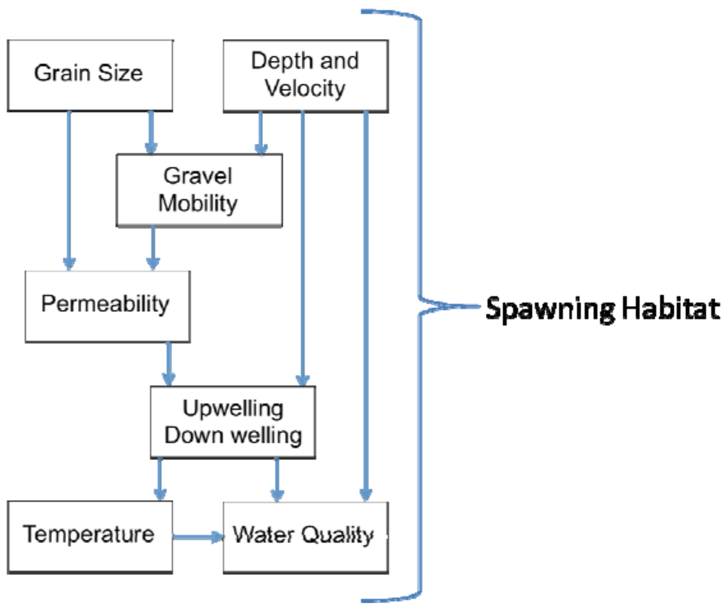


Figure 9.1: Flow chart showing interrelated parameters that affect spawning habitat. Arrows point towards the affected parameter.

Grain Size, Gravel Mobility and Permeability

Pebble count data was averaged for each site, and compared between pre-restored and restored conditions. These size distribution curves indicate that grains were out of suitable spawning habitat size range before restoration, and were within suitable spawning habitat gravel size after restoration. The trend over consecutive seasons is for grain size averages to get larger and closer to pre-restoration sizes.

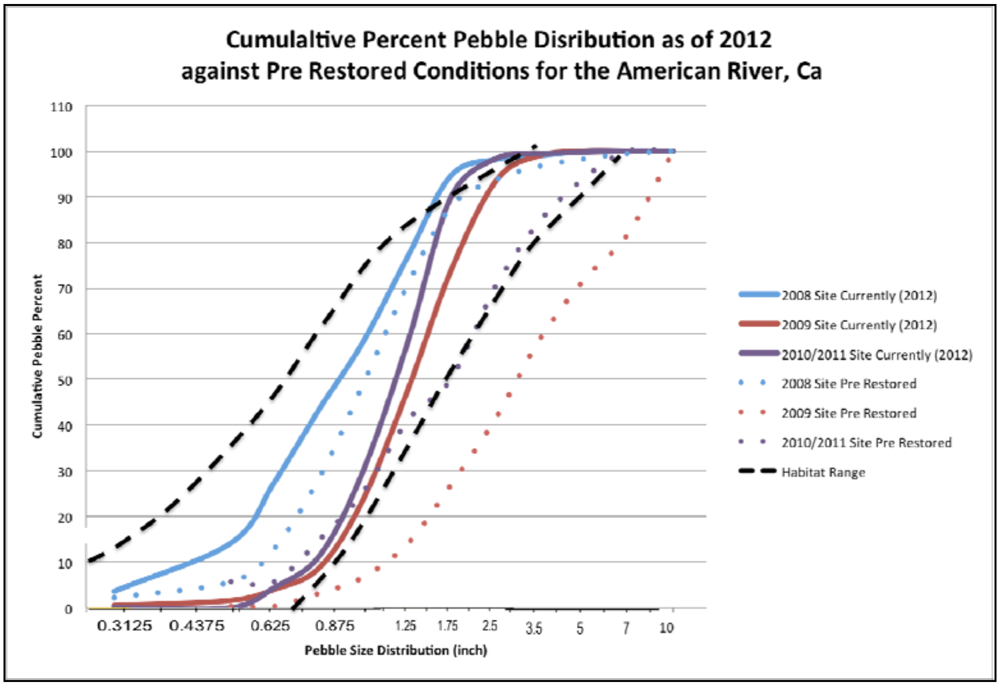


Figure 9.2: Comparison of cumulative pebble counts at each site presently (2012)

Bulk samples show cumulative grain size distribution, and are more accurate at assessing fine and coarse extremes. Bulk samples are large enough to be statistically accurate, and values from the cumulative frequency curve are used to estimate mean, median, and a variety of other sediment properties. Bulk samples from the 2010/2011 site show a distinct change from pre-restored to restored conditions. The site was initially armored and coarse, but also had a high percentage of fine material. After restoration, the gravel was well sorted and generally within the preferred size range. New gravel at the 2010/11 site may be too well sorted- it is lacking some coarse and some fine material compared to ideal conditions. The 2008 and 2009 sites also have improved mean grain size (Table 2.1), are better sorted, and are growing slightly coarser with time. This coarsening trend may be a problem in the near future.

Table 2.1: Mean grain size range for each site comparing pre-restoration, post restoration, and current gravel size conditions. Data are from pebble counts.

Site	D_{50} range (inches)		
	Pre	Post	Currently
Upper Sailor Bar 2008	5/8 - 11/4	5/8 - 7/8	11/4
Lower Sailor Bar 2009	2 - 41/4	7/8 - 11/2	11/4
Upper Sunrise 2010/2011	7/8/05	7/8 - 11/2	11/4

Mean grain size at all sites is within the suitable habitat range, but there are some distinct differences between the sites. The Upper Sailor Bar 2008 site has a greater quantity of fines and organic material , and has the smallest D_{50} value at 0.875 inches. The Upper Sailor Bar 2009 site has the largest D_{50} value at over 1.25 inches (Figure 9.2). Both of these sites are moderately sorted and include some fine and coarse material.

Seepage rates are very high in the new gravel, with values from 0.20 to 0.72 cm/s. This is one of the most effective aspects of the gravel addition projects. Gravel is screened and washed before it is added to the channel, so a very controlled range of material is used as spawning gravel. New spawning gravel is well sorted and highly permeable. This is also shown in dissolved oxygen levels. Before gravel was added, hyporheic gravel averaged 45% saturated with dissolved oxygen. After restoration, dissolved oxygen levels averaged Adding gravel has increased the permeability and intra gravel flow rates are very high, improving spawning habitat.

Bed mobility patterns are confirmed by tracer rocks, and suggest that newly added, unseasoned gravel is subjected to higher rates of erosion then the more seasoned gravel of older sites. Although the majority of the new gravel persists for several seasons, data have shown up to 20% erosion at a site in a single season (Horner and others, 2010). All three restoration sites have some grain mobility, with channels forming across the sites and erosion at the top edge and outer edge of all sites.

Grain mobility is assessed primarily to observe if added gravels stay in place long enough to create long term suitable habitat. Islands and subsurface riffles at the 2008 site appear to create a buffer zone that slows water velocities, lowers erosion rates, and changes the flow direction of surface water. This heterogeneity may be beneficial, because salmonids tend to use the sites that have a range of physical properties.

Depth and Velocity, Hyporheic Pressure Head, and Water Quality

Velocity and depth patterns are different between the Upper Sailor Bar sites (Figure 9.3i and 9.4i) and the Upper Sunrise 2010/2011 site (Figure 9.5i). Mean depth is higher at the Upper Sunrise 2010/11 site than at the Upper Sailor Bar sites, and flow is less variable than the Upper Sailor Bar sites. Diversity of the physical habitat is attributed largely to the hummocky riverbed. Small-scale gravel waves have formed perpendicular to flow at the Upper Sailor Bar sites (Figure 9.3i), and this creates varied direction of flow which are not present at the Upper Sunrise 2010/2011 site (Figure 9.5i). The 2010/11 site was deeper, had more consistent depth and lacked small scale features that create variety in the spawning gravel (Figure 9.6).

Varying depth and velocity correspond with varying pool and riffle systems within a site (Figure 9.3i and 9.4i); and this strongly correlates with intra gravel flow (Figure 9.3ii, 9.4ii, and 9.5ii)) assessed through hyporheic pressure head differences (up and down welling measurements). Each site exhibited a majority of upwelling conditions albeit each site had it's own distinguishing patterns. The Upper Sailor Bar 2008 Site experienced a large variance of upwelling and down welling (Figure 9.3ii); this demonstrates a heterogenous environment. The Upper Sailor Bar 2009 Site has high variance in the magnitudes of upwelling (Figure 9.4ii). The Upper Sunrise 2010/2011 Site has the least amount of variance and demonstrates primarily upwelling conditions (Figure 9.5ii). Turbidity may be controlled by similar variables, because turbidity is higher in low velocity areas and lower in high velocity areas (Figure 9.3iv, 9.4iv, and 9.5iv).

Upwelling and downwelling allow adequate subsurface flow and delivery of oxygenated surface water to redds. High dissolved oxygen percentages (Figure 9.3iii, 9.4iii, and 9.5iii) are present where significant hyporheic exchange is present. This may be upwelling or downwelling because subsurface flow is so rapid the hyporheic water does not become oxygen- depleted. Low dissolved oxygen levels occur in old, armored gravel, and tend to occur where upwelling and downwelling are not significant (Figure 9.3ii, 9.4ii, and 9.5ii). All of the new gravel sites have some upwelling or downwelling, and do not appear to be limited by subsurface flow.

Pre restoration water quality conditions were not optimal for salmon spawning, while post restoration conditions show large improvement. Variance of each measurement, specifically dissolved oxygen and turbidity, is higher at the older Upper Sailor Bar Sites that also have a higher frequency of redds (Table 8.8). Heterogeneity results in availability of more appropriate habitat conditions in some areas and redd density suggests that salmonids tend to use the sites that have these heterogeneous qualities (Figure 9.6). Furthermore, plotting the dissolved oxygen levels from each site over time shows poor conditions pre restorations, improved conditions post restorations, and conditions dropping back towards original, non-restored levels (Figure 8.16). Despite these trends, conditions at all sites are within an optimal range for suitable spawning habitats.

Recommendations

Parameters studied in this report changed as a result of the addition of the gravel, and spawning habitat improved dramatically. Over time, these types of augmentations tend to become more dynamic and natural. Salmonids are currently using the sites with more heterogeneous physical environments. As the sites become more seasoned gravel mobilizes, and flows redistribute the material. Fish may be involved with this process at the high use sites. In order to stimulate this use, future projects could consider creating variability with gravel contours and changes in grain size. Channel-spanning features with large woody debris and gravel waves would create sub-habitat zones within the site.

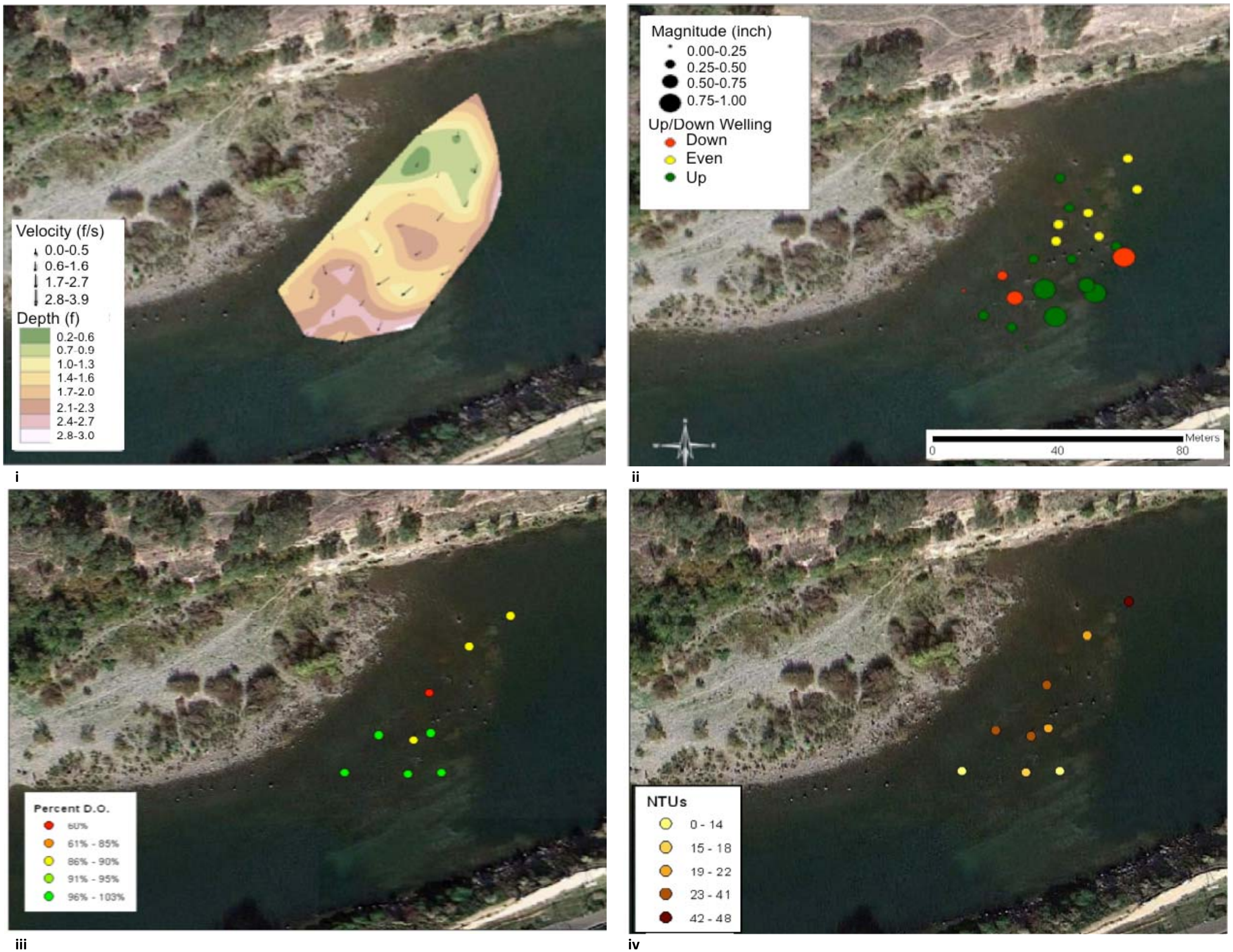


Figure 9.3: Upper Sailor Bar 2008 Site. Depth, velocity, and direction of flow map (i); upwelling and downwelling conditions map (ii); D.O. percent levels (iii); turbidity levels (iv).

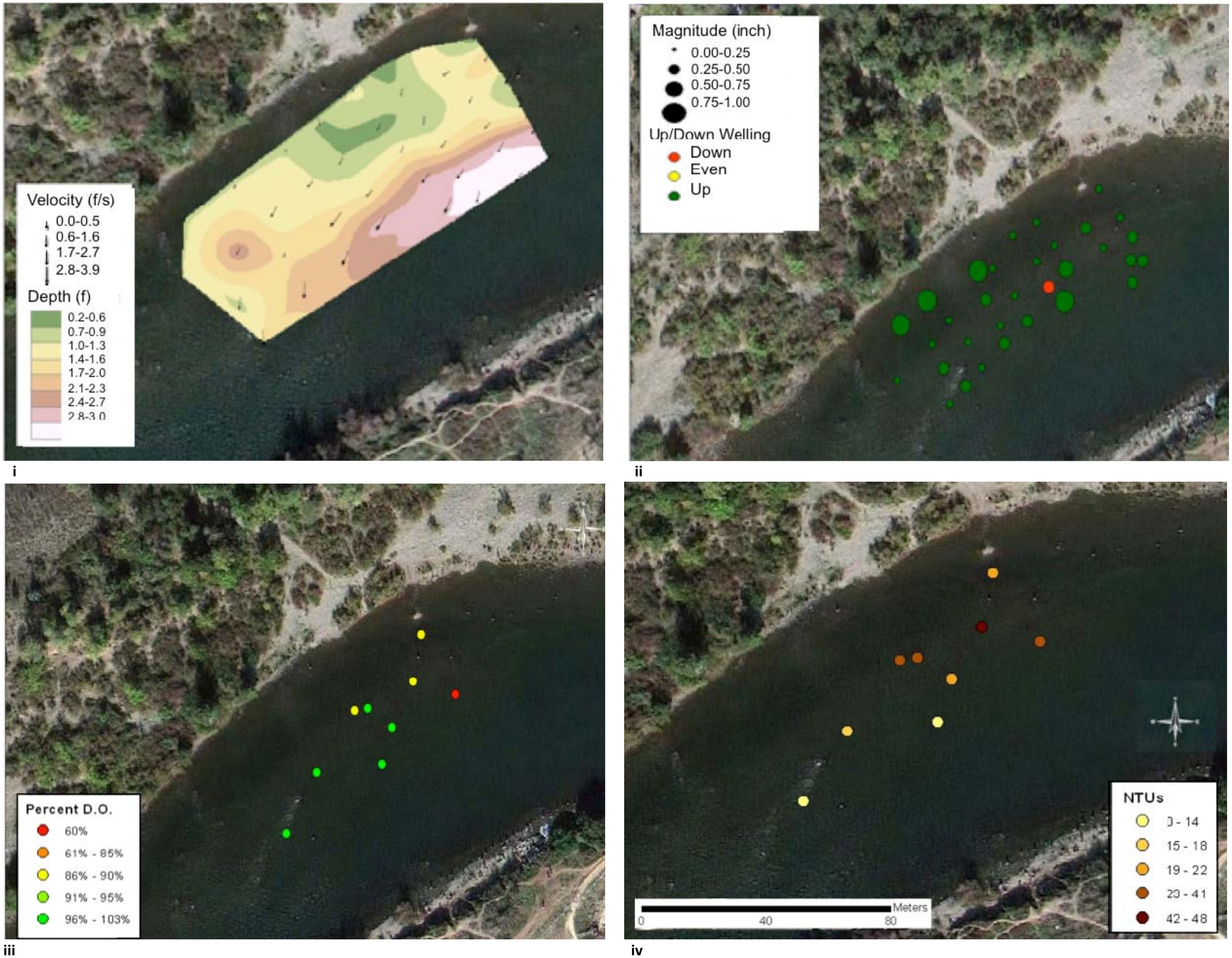
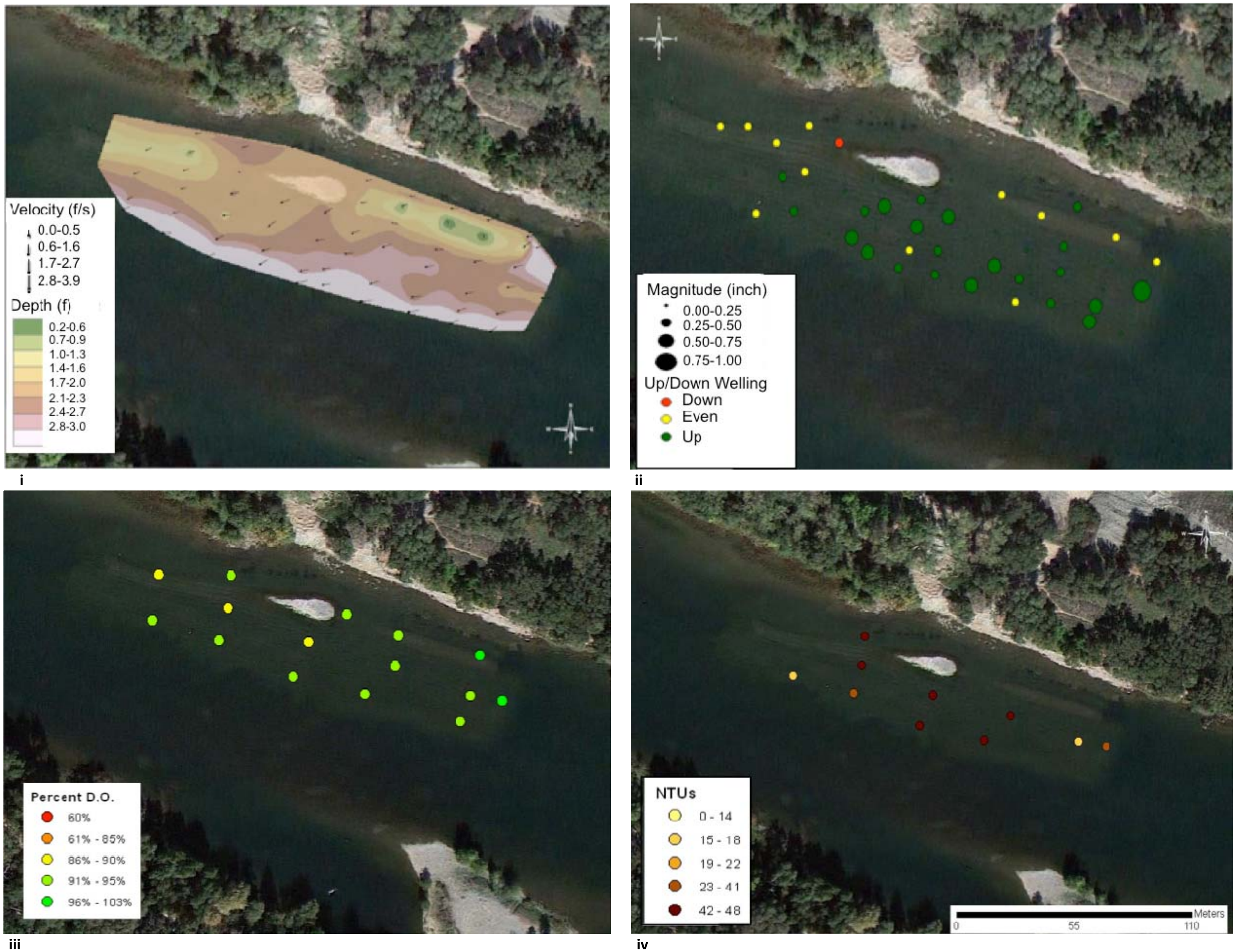
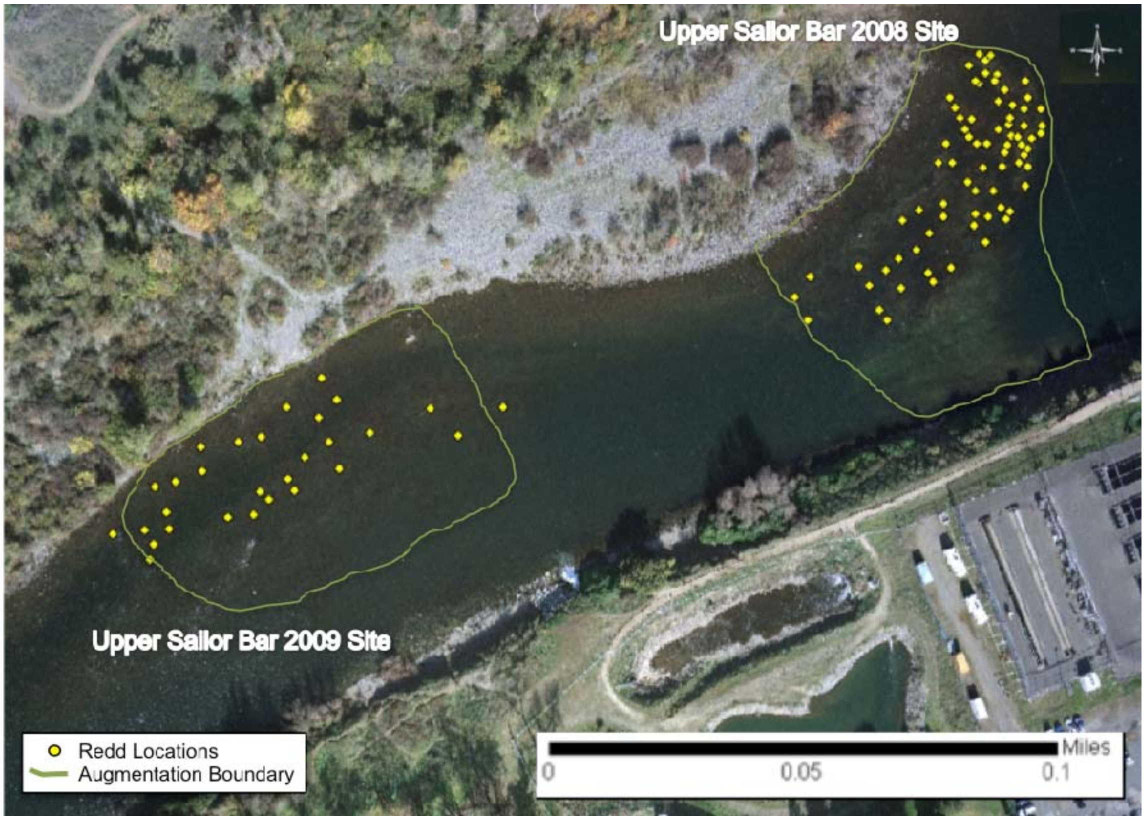


Figure 9.4: Upper Sailor Bar 2009 Site. Depth, velocity, and direction of flow map (i); upwelling and downwelling conditions map (ii); D.O. percent levels (iii); turbidity levels (iv).


Velocity (f/s)
0.0-0.5
0.6-1.6
1.7-2.7
2.8-3.9
Depth (f)
0.2-0.6
0.7-0.9
1.0-1.3
1.4-1.6
1.7-2.0
2.1-2.3
2.4-2.7
2.8-3.0
i
Magnitude (inch)
0.00-0.25
0.25-0.50
0.50-0.75
0.75-1.00
Up/Down Welling
Down
Even
Up
ii
Percent D.O.
60%
61% - 85%
86% - 90%
91% - 95%
96% - 103%
iii
NTUs
0 - 14
15 - 18
19 - 22
23 - 41
42 - 48
Meters
0
55
110
iv



i

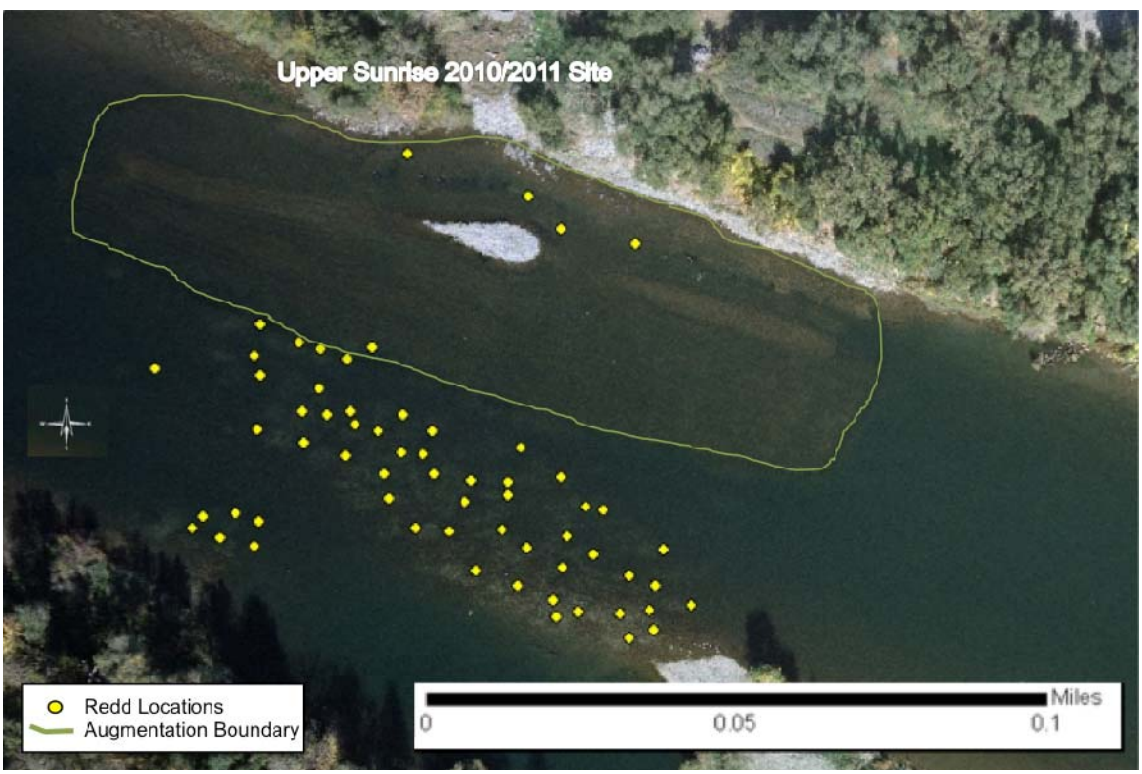


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Figure 9.6: (i) Salmon redd locations in Fall 2011 for Upper Sailor Bar Sites (ii) and Upper Sunrise Site (high-resolution flyover photos courtesy John Hannon).

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