

DESIGNING SALMONID SPAWNING RESTORATION HABITAT TO BE DYNAMIC AND  
NATURAL: HETEROGENEOUS GEOCHEMICAL AND PHYSICAL FEATURES

A Thesis

Presented to the faculty of the Department of Geology  
California State University, Sacramento

Submitted in partial satisfaction of  
the requirements for the degree of

MASTER OF SCIENCE

in

Geology

by

Margaret Katy Janes

FALL  
2013

© 2013

Margaret Katy Janes

ALL RIGHTS RESERVED

DESIGNING SALMONID SPAWNING RESTORATION HABITAT TO BE DYNAMIC AND  
NATURAL: HETEROGENEOUS GEOCHEMICAL AND PHYSICAL FEATURES

A Thesis

by

Margaret Katy Janes

Approved by:

\_\_\_\_\_, Committee Chair  
Dr. Timothy Horner

\_\_\_\_\_, Second Reader  
Dr. Kevin Cornwell

\_\_\_\_\_  
Date

Student: Margaret Katy Janes

I certify that this student has met the requirements for format contained in the University format manual, and that this thesis is suitable for shelving in the Library and credit is to be awarded for the thesis.

\_\_\_\_\_, Department Chair \_\_\_\_\_  
Dr. Timothy Horner Date

Department of Geology

Abstract  
of  
DESIGNING SALMONID SPAWNING RESTORATION HABITAT TO BE DYNAMIC AND  
NATURAL: HETEROGENEOUS GEOCHEMICAL AND PHYSICAL FEATURES

by  
Margaret Katy Janes

The Lower American River has historically provided natural spawning habitat for approximately one third of Northern California's salmon population. However, since the construction of Folsom and Nimbus Dams, downstream reaches have become sediment starved and periodic high outflow from the dam has caused channel armoring and incision, thereby degrading the natural spawning habitat. Restoration work on spawning sites in the Lower American River has consisted primarily of importing gravel to create riffles during periods of moderate flow. This is an effort to mitigate armoring of the riverbed and to rehabilitate salmonid spawning habitat by providing suitable grain size for all stages of spawning (redd construction, incubation, and emergence). Since restoration activities began, all rehabilitated sites have not been equally used for spawning. This study attempts to examine and compare the physical parameters of each site in order to ascertain which characteristic create more suitable rehabilitated habitat. To do this, we compared physical parameters of enhanced areas and a natural spawning area to redd density using principle component analysis and ANOVA statistical analysis. We found that some augmentation sites are more heterogeneous than others, and this correlates with higher spawning use ( $F=30.81, p=0.009$ ). With time, salmonids alter the spawning sites, creating small ridges and valleys perpendicular to flow. This creates more variable subsurface flow and generates hyporheic flow through the new gravel. This may have an effect on spawning as the

more seasoned additions have a higher frequency of spawning than the newer augmentations. In order to efficiently rehabilitate a site and expedite the “seasoning process”, creating variance through gravel contours during the gravel augmentation process may be effective as it mimics the small scale biophysical interactions.

\_\_\_\_\_, Committee Chair  
Dr. Timothy Horner

\_\_\_\_\_  
Date

## PREFACE

The Department of Geology of the University of California, Sacramento allows for a publication ready manuscript for a scientific journal to be presented as a thesis for the requirement of a Master of Science in Geology. Data for this study is from a larger report submitted to the Bureau of Reclamation in June of 2012 by the author.

## ACKNOWLEDGEMENTS

We thank Kevin Cornwell, John Hannon and Jamie Kneitel for the contributions of valuable comments on many aspects of the manuscript. We also thank Jay E. Heffernan and the CSUS field staff that collected data for this study. Support from the Bureau of Reclamation, U.S. Fish and Wildlife Service through the Central Valley Project Improvement Act Restoration Funds and Sacramento Water Forum are gratefully acknowledged.

A statement of appreciation, appropriately stated, is perhaps the most difficult part of preparing any type of paper. However without reservation, I would like to express my sincere appreciation to Dr. Tim Horner for his interest, encouragement, and most useful suggestions in relation to both this piece of work and to my whole graduate education. My continued education into the methods of scientific research has been extremely adequate as a result of such an attitude as he has expressed.

A sincere note of thanks should also be given to others associated with my research. These include Kelly Janes and the gravel team for their invaluable knowledge of methods applied in this project and to the countless hours spent in the water. To my man and my kid and my parents for the love and support given to me despite the hours spent away from one another.



## TABLE OF CONTENTS

	Page
Preface .....	vii
Acknowledgements.....	viii
List of Tables .....	x
List of Figures.....	xi
Chapter	
1. INTRODUCTION .....	1
2. STUDY AREA .....	5
3. METHODS .....	8
Redd Surveys .....	8
Water Quality Parameters .....	8
Vertical Flux (Hyporheic Pressure Head).....	9
Surface Water Depth, Velocity, and Direction of Flow.....	9
Data Analysis.....	9
4. RESULTS .....	11
Water Quality Parameters .....	11
Vertical Flux (Hyporheic Pressure Head).....	12
Surface Water Depth, Velocity, and Direction of Flow.....	13
5. DISCUSSION .....	19
6. CONCLUSION.....	26
References.....	27

LIST OF TABLES

Tables	Page
1. Chinook salmon redd counts and percentage of total spawning .....	11
2. Physical parameters recorded during the 2012 spawning season .....	12

## LIST OF FIGURES

Figures	Page
1. Locations of four gravel enhancement sites and one natural high use spawning site.....	5
2. Chinook salmon redd locations on 26 November 2012.....	15
3. Vertical flux maps .....	16
4. Surface water depth, velocity, and direction of flow maps.....	17
5. Flow chart illustrating eight discrete steps in evaluating statistical analysis .....	18
6. Redd count versus parameter data with corresponding correlation coefficients. ....	19
7. Principal component analysis biplot of high use and low use spawning areas.....	20
8. Principal component analysis biplot of parameter variance of high use and low use spawning areas.....	21
9. Redd count versus area variance with corresponding correlation coefficients.....	22
10. Mean Chinook salmon use as a function of high and low variance of combined parameters .....	23
11. Interaction plot for the group means of Chinook salmon use as a function of high and low variance for each parameter .....	24
12. Surface water depth and mean flow versus upwelling and downwelling map.....	25

## 1. Introduction

The protection and rehabilitation of salmonid spawning habitat, has become increasingly necessary. Salmonid species have been shown to be critical indicators of good water quality, healthy ecosystems and beneficial watershed management practices (DeVries 1997). Compared to historical levels, there has been a significant decline in salmonid population, which has resulted in the United States National Marine Fisheries Service to list steelhead (*Oncorhynchus mykiss*) and some runs of Chinook salmon (*Oncorhynchus tshawytscha*) as threatened or endangered under the Endangered Species Act ((NOAA) 1994; NOAA 1998). Degradation of habitat is identified as a primary contributing agent and is believed to be a result of anthropogenic influences on the spawning habitat (Nelson, Dweyer et al. 1987; Bjornn and Reiser 1991; Heaney, Foy et al. 2001; Soulsby, Youngson et al. 2001; Horner, Titus et al. 2004; Kondolf, Williams et al. 2008). Dams, urbanization, artificial levees, channel modification and input from hatcheries impact the natural balance of the riparian system and limit the quantity and quality of spawning gravel needed by resident salmonid populations (Vyverberg , Snider et al. 1997; Soulsby, Youngson et al. 2001; Hannon and Deason 2005). Because degradation of spawning habitat may be a principal cause of declining populations of salmon, there has been a recent emphasis on the evaluation and restoration of spawning sites on rivers of the northwestern region United States (DeVries 1997; Merz and Setka 2004a; Kondolf, Williams et al. 2008).

Salmonids use gravel bed rivers as spawning habitat and for the incubation of embryos (Merz and Setka 2004a; Merz, Setka et al. 2004b; Kondolf, Williams et al. 2008). Natural gravel bed streams are typically characterized by pool-riffle sequences, have abundant bedload material, and are generally coarse-grained. These characteristics provide a naturally heterogeneous environment. Female salmon spawn by excavating a pit to build a redd (nest) in the stream gravels. After spawning, the female salmon will bury the eggs by moving gravels and forming an

egg pocket (Bjornn and Reiser, 1991; Wu, 2000). This morphology deflects surface water through the shallow gravel, and creates localized flow through the redd. On the American River in Northern California, salmonids construct redds that are 20 to 40 cm deep into the gravel streambed (DeVries 1997; Monaghan and Milner 2009). This region is called the hyporheic zone, and is the shallow environment that serves as the interface between stream water on the surface and groundwater in the subsurface. This zone is the interface where chemicals, nutrients and organic matter are exchanged between surface and subsurface environments.

The hyporheic environment is highly variable and has physical and chemical gradients that have measurable effect on habitat and egg survival (Malcom, Soulsby et al. 2003). From a hydraulic standpoint, the sedimentary deposits produced by gravel bed streams are heterogeneous and anisotropic (Tucker 1981). 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; Bencala 2000). In addition, bed topography of the riverine system facilitates discrete points of water exchange through the hyporheic zone. Vertical flux is induced by either upwelling of water from the hyporheic gravel to the surface stream or downwelling of surface water into the hyporheic environment. The pools and riffles that form naturally in the streambed create points of high and low pressure which expedite the movement of water through the streambed (Harvey and Bencala 1993); pools create deeper, backup water and higher pressure on the upstream side, and water is forced through the riffles to the low-pressure areas on the downstream side (Kondolf, Williams et al. 2008). As a result, vertical flux through the hyporheic zone is controlled by the differences in pressure head and may be a key factor in salmonid redd site selection (Geist and Dauble 1998).

Riffle and pool sequences can be effective in creating upwelling and downwelling zones (Greig, Sear et al. 2007). This upwelling and downwelling is what a female salmonid creates on a

smaller scale when constructing a redd. Incubating eggs are exposed to conditions in the hyporheic environment, and are dependent on intragravel flow to deliver dissolved oxygen and remove metabolic waste (Coble 1961; Youngson, Malcolm et al. 2004; Merz and Setka 2004a; Greig, Sear et al. 2007; Kondolf, Williams et al. 2008). Low dissolved oxygen content and high temperatures are a primary factor in egg mortality and low overall fitness of eggs and alevin (Nawa and Frissell 1993; DeVries 1997; Malcom, Soulsby et al. 2003; Horner, Titus et al. 2004; Youngson, Malcolm et al. 2004; Merz and Setka 2004a; Kondolf, Williams et al. 2008). Minimum oxygen requirements are between 4.25 milligrams per Liter (mg/L) and 6.00 mg/L, or a saturation percent between 54 and 70%, and dissolved oxygen saturation 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 will be dominated by well-oxygenated water (Jones and Mulholland 2000; Malcom, Soulsby et al. 2003).

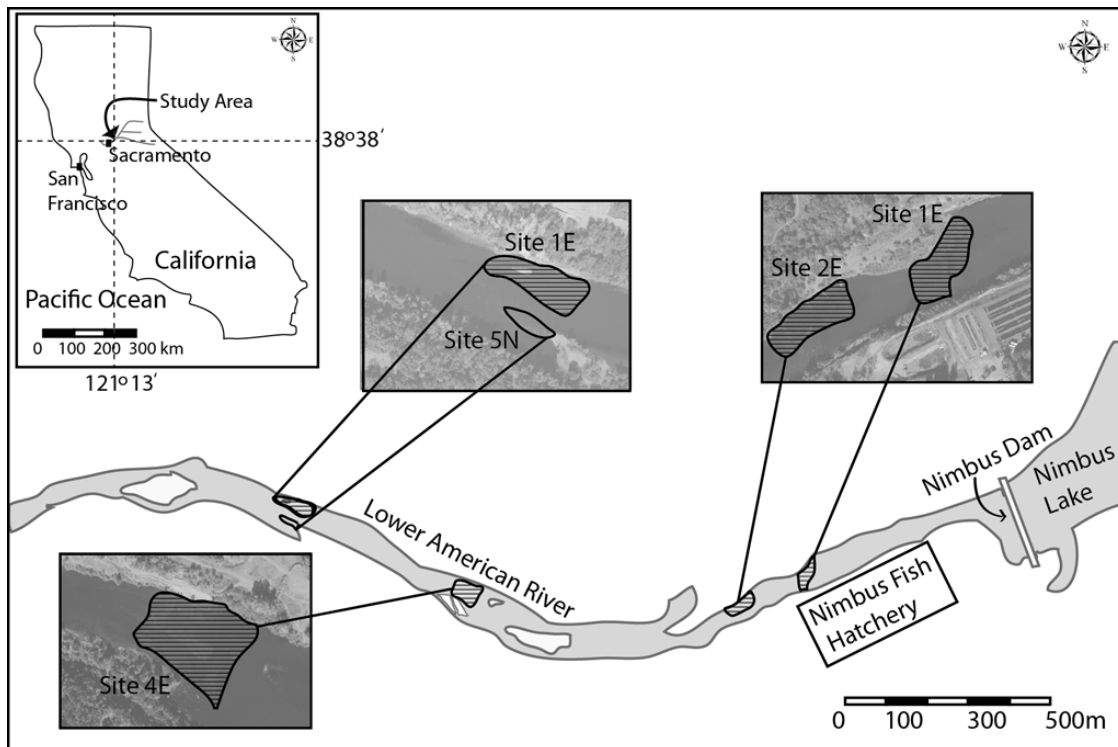
Surface water depth and velocity are key variables in salmonid spawning site selection. Surface water velocities can hinder successful spawning if they are too high or too low; surface water velocities between 0.5-2.0 meters/second (m/s) are optimal for spawning gravel exchange (Chapman, Weitkamp et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

Although little work has been done to evaluate the effectiveness of restoration projects. Merz et al. (2004a) showed that gravel enhancement can be an effective means for improving spawning

habitat. Work on multiple rehabilitated sites in the American River, a regulated California river, has shown that physical parameters became more suitable for spawning habitat as a result of gravel additions (Horner and Janes 2013). Although previous work on each site shows positive effects from rehabilitation projects, not all sites are being used equally. One factor in the success of rehabilitation projects may be habitat heterogeneity. Habitat heterogeneity is positively correlated with biodiversity (Palmer, Ambrose et al. 1997; Geist and Dauble 1998; Pretty, Harrison et al. 2003; Tews, Brose et al. 2004; Wheaton, Pasternack et al. 2004a; Wheaton, Pasternack et al. 2004b), therefore heterogeneity incorporated into gravel enhancement sites can generate specific ecologic benefits. This study examines and compares the physical properties of gravel enhancement site to ascertain the combination of characteristics that creates more suitable rehabilitated habitat. The success of a rehabilitation site was measured by high redd site selection by salmonids. To do this, we assessed hydraulic and geomorphic parameters of restored areas and a natural unrestored area (control) and compared physical conditions to salmonid redd site selection. Physical parameters that were measured in the study included surface water depth, velocity and flow direction, vertical flux, and intragravel water quality. Furthermore, multivariate statistics were used to test the hypothesis that higher salmonid use is correlated to higher heterogeneity within a site.

## 2. Study Area

The Lower American River lies below Nimbus Dam (Figure 1), 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, Titus et al. 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, Titus et al. 2004). 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 natural flow regime (Monaghan and Milner 2009).



**Figure 1.** Locations of four gravel enhancement sites (Site 1E, Site 2E, Site 3E, Site 4E) and one natural high use spawning site (Site 5N) within the lower American River, California.



The American River watershed (Figure 1) has an area of 4,890 square kilometers. The watershed's headwaters begin at the crest of the Sierra Nevada, at an elevation of approximately 3000 meters. The terminus of the river is at its confluence with the Sacramento River, at an elevation close to sea level (National Research Council 1995). The drainage basin can be separated into an upper segment and a lower segment. The upper segment, above Folsom and Natoma Lakes, consists of multiple forks with steep gradients and high energy flows through steep canyon walls. The lower segment lies below dams and has a gradient of approximately 0.06, with lower energy flows across alluvium plain material (National Research Council 1995).

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).

California's Central Valley has a Mediterranean climate that is characterized by warm, dry summers and cool, wet winters. Precipitation ranges from 10 – 40 centimeters per year (cm/yr) in the lower segments of the watershed to 200 cm/yr in the higher elevations of the American River Basin (NOAA 2009).

Regional stream flow in the watershed is highly seasonal, and prior to construction of Folsom and Nimbus dams yearly peak flows have ranged from 10,000 to 180,000 cubic feet per second (cfs). After dam construction, yearly peak river flows range from 1,000 cfs to 135,000 cfs (USGS 2012). Folsom Dam is operated for flood control, water supply for irrigation, and recreation.

Restoration work is part of the Central Valley Project Improvement Act (CVPIA section b.13) mandate to evaluate and improve gravel conditions below federal dams. Restoration work, under this Act, began in the mid-1990's with assessment (Vyverberg, Snider et al. 1997; Horner, Titus et al. 2004) of physical conditions in the American 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 natural spawning occurs along a six-mile stretch just below Nimbus Dam, where the river has a gradient of approximately 0.06 and surface gravel has low permeability. These sites have 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 , Snider et al. 1997; Horner, Titus et al. 2004).

Based on the results of early studies, remedial actions are aimed at artificially improving spawning habitat at different sites by gravel enhancement projects. This approach allows for later comparison of treatment effectiveness. Gravel augmentations consist of adding thousands of cubic meters of presorted gravel to each site, often involve placement of gravel as specific bed features (typically riffles and bars), for spawning-bed enhancement. For this study, five sites were evaluated on the lower American River. Four were enhanced sites (1E thru 4E) and the fifth (5N) was a natural (control) site that receives high spawning use (Figure 1). Site 1E was enhanced in 2008, site 2E was enhanced in 2009, Site 3E was enhanced in 2010 and again in 2011, and Site 4E was enhanced in 2012. The natural spawning site (Site 5N) lies adjacent to Site 3E, and was also assessed for this study.

### **3. Methods**

#### *Redd Surveys*

On 26 November 2012 a low level air flight was used to survey redd abundance and distribution. This aerial survey was implemented by the U.S. Bureau of Reclamation, and produced high resolution three-band (red, blue, green) digital images of the lower American River. Photographs were downloaded into ArcGIS 10.0 (ESRI 2012, Redlands, CA) and salmon redd locations were recorded and mapped at each site in this study.

#### *Water Quality Parameters*

Water quality measurements were taken from surface water and from subsurface water at a depth of 30 cm in the gravel. Subsurface water samples were collected using mini-piezometers that were installed in a network in the gravel addition areas and georeferenced using a high-resolution global positioning system (GPS). Mini-piezometers were installed after completion of the gravel additions. Each mini-piezometer was sampled by initially pumping water with a peristaltic pump until it was clear. Water was then pumped into a sealed flow-through cell where dissolved oxygen, temperature, and turbidity measurements were made as water was continually pumped. Pumping continued for three to five minutes until each of the measurements had stabilized or approximately two liters of water was pumped from the subsurface. A sealed flow-through cell was used to minimize the interaction of the subsurface water with the atmosphere. After each sample was collected, the water was drained from the flow through cell before sampling the next piezometer. Dissolved oxygen was measured in mg/L and %, temperature was measured in degrees Celsius ( $^{\circ}\text{C}$ ), and turbidity was measured in NTU. All meters were calibrated within 30 minutes prior to the start of data collection. Surface water was sampled using the same procedure at the beginning and end of each day to assess surface water conditions and check for

meter drift.

#### *Vertical Flux (Hyporheic Pressure Head)*

Upwelling and downwelling are important for hyporheic exchange, and measuring hyporheic pressure head reveals upwelling and downwelling conditions in the subsurface. A bubble manometer board attached to a baffle was used to compare pressure head differences between the river and 30cm gravel depth (Zamora 2006). Higher pressure heads in the river compared to the gravel subsurface indicate a downwelling condition (losing) where the surface water is mixing into the subsurface. Higher pressure heads in the gravel subsurface compared to the river indicate an upwelling (gaining) condition where the subsurface water is mixing into the surface water. Each pressure head measurement was georeferenced

#### *Surface Water Depth, Velocity, and Direction of Flow*

Surface water velocity measurements were conducted following USGS stream gaging procedures (USGS 1980). Surface water depth and velocity were measured using a Marsh-McBirney Flo-Mate model 2000 flowmeter attached to a top set wading rod, each measurement location was georeferenced. The velocity was recorded in meters per second (m/s).

Surface water velocity measurements were taken 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 water and the 80% depth is a “snout velocity” of the salmonid. A Brunton compass was used to measure the direction of flow at each discreet location point.

#### *Data Analysis*

Statistical analysis was performed with the statistical program R (R Core Team, 2012,

Vienna, Austria). Descriptive statistics and a correlation matrix were created to build a model of physical parameter variance versus salmon use. Principle components analysis (PCA) was used to reduce the number of physical condition variables in the data set. This identified environmental variables that are important for spawning site selection. Next each site was split into multiple areas (top of enhanced riffle, mid riffle, and bottom of the riffle) and a second PCA was performed using each area's parameter variance versus area's salmon redd count. This highlighted the importance of variance to redd site selection. After correlations were determined, Jenks natural breaks (Jenks 1967) classification method was used to partition the variance data into two class intervals and mean salmon use was plotted for high variance and low variance conditions. Lastly, to quantify the interaction between parameters, parameter variance, and salmon utilization, a factorial analysis of variance (ANOVA) was employed using the area's parameter variance model. All statistical significance tests were conducted from the perspective of null hypothesis significant testing with  $\alpha = 0.05$ .

#### 4. Results

Physical parameter data was collected at study sites during the fall salmon run between October and November 2012, and Chinook salmon redd distribution data was collected 26 November 2012. Redd counts were variable between the sites (Table 1). The five study sites supported 0.14 to 4.56% of the total lower American River 2012 Chinook salmon fall run spawning (Figure 2). Site 1E had the highest percentage of redds within the site (4.56%), Site 5N had the second highest percentage of redds (3.12%) and the highest density of redds per square meters, followed by the third highest percentage of redds at Site 4E (2.93%). Site 2E and Site 3E had the lowest percentage of redds respectively (1.69% and 0.14%).

**Table 1.** Chinook salmon redd counts and percentage of total spawning on the Lower American River, CA at each restoration site and the natural spawning site during the fall run in 2012. Data collected 26 November 2012.

Site	Redds	
	Count	Percentage
1E	165	4.56%
2E	61	1.69%
3E	5	0.14%
4E	106	2.93%
5N	113	3.12%
Total Redds LAR, 2012	3619	

#### *Water Quality Parameters*

Water quality measurements were evaluated while Chinook Salmon were spawning (November 2012) and are summarized in Table 2. Gravel additions result in significant increase in dissolved oxygen content at all sites (Horner and Janes 2013) and are within a suitable spawning habitat range. In the single sampling event used for this study dissolved oxygen levels were moderately high at Site 1E and Site 5N while Site 2E, Site 3E and Site 4E all had extremely high levels of dissolved oxygen that approached saturation. Mean turbidity measurements were

inversely proportional to dissolved oxygen patterns with high mean turbidity at Site 1E and Site 5N, and lower mean turbidity measurements at Site 2E, Site 3E, and Site 4E.

### *Vertical Flux (Hyporheic Pressure Head)*

Vertical Flux was measured as a pressure difference in the gravel and is the driving force behind upwelling and downwelling (Table 2); results were contoured in ArcGIS (Figure 3). At Site 1E (Figure 3a), downwelling was most common as water exited an upstream pool and flowed over the restoration site. Site 1E was dominated by upwelling in the lower half of the restoration site with a tendency of upwelling towards the channel center (thalweg) of the channel. Site 2E (Figure 3b) is dominated by upwelling conditions but there are small areas of downwelling along the northern bank. The strongest upwelling is towards the thalweg. Site 3E (Figure 3c) has minimal bedforms that produce bands of upwelling and downwelling. Downwelling occurs along

**Table 2.** Physical parameters recorded during the 2012 spawning season at each area of the four gravel enhancement sites and one natural spawning site including intragravel flow, surface water flow, and intragravel water quality. Mean measurements ( $\pm$  standard deviation) are provided for each area of the riffle.

Site	Riffle Section	Redds	Water Flow			Intragravel Water Quality		
			Mean Vertical Flux (cm)	Mean Water Depth (m)	Mean Stream Velocity ( $m*s^{-1}$ )	Mean DO (ppm)	Mean Temperature ( $C^{\circ}$ )	Mean Turbidity (NTU)
1E	Upper	102	0.3 $\pm$ 0.3	0.7 $\pm$ 0.5	0.14 $\pm$ 0.1	8.1 $\pm$ 1.3	14.4 $\pm$ 0.1	120 $\pm$ 60
1E	Mid	37	0.0 $\pm$ 0.3	0.6 $\pm$ 0.4	0.47 $\pm$ 0.3	6.5 $\pm$ 2.7	14.5 $\pm$ 0.1	156 $\pm$ 213
1E	Lower	26	1.0 $\pm$ 1.0	0.4 $\pm$ 0.1	0.73 $\pm$ 0.4	9.3 $\pm$ 0.2	14.4 $\pm$ 0.0	160 $\pm$ 260
2E	Upper	22	0.0 $\pm$ 1.0	0.6 $\pm$ 0.3	0.43 $\pm$ 0.3	8.4 $\pm$ 1.9	14.4 $\pm$ 0.1	115 $\pm$ 180
2E	Mid	21	0.8 $\pm$ 0.8	0.4 $\pm$ 0.0	0.35 $\pm$ 0.2	9.9 $\pm$ 0.1	14.4 $\pm$ 0.1	15 $\pm$ 9
2E	Lower	18	0.3 $\pm$ 0.3	0.3 $\pm$ 0.1	0.53 $\pm$ 0.1	9.0 $\pm$ 0.9	14.7 $\pm$ 0.1	105 $\pm$ 107
3E	Upper	3	0.8 $\pm$ 0.0	0.9 $\pm$ 0.1	0.50 $\pm$ 0.2	10.2 $\pm$ 0.3	15.3 $\pm$ 0.6	31 $\pm$ 22
3E	Mid	1	0.3 $\pm$ 0.3	0.7 $\pm$ 0.1	0.61 $\pm$ 0.1	6.9 $\pm$ 3.3	14.8 $\pm$ 0.2	72 $\pm$ 67
3E	Lower	1	0.3 $\pm$ 0.3	0.6 $\pm$ 0.1	0.56 $\pm$ 0.1	7.8 $\pm$ 2.7	14.9 $\pm$ 0.2	40 $\pm$ 31
4E	Upper	24	0.3 $\pm$ 0.3	0.6 $\pm$ 0.1	0.55 $\pm$ 0.2	9.6 $\pm$ 0.1	14.9 $\pm$ 0.2	9 $\pm$ 7
4E	Mid	44	0.0 $\pm$ 0.0	0.5 $\pm$ 0.0	1.13 $\pm$ 0.2	9.7 $\pm$ 0.3	15.1 $\pm$ 0.1	23 $\pm$ 16
4E	Lower	28	0.3 $\pm$ 0.8	0.5 $\pm$ 0.1	1.30 $\pm$ 0.3	9.3 $\pm$ 0.5	15.0 $\pm$ 0.2	22 $\pm$ 20
5N	Upper	68	0.0 $\pm$ 1.0	0.3 $\pm$ 0.1	0.40 $\pm$ 0.2	6.9 $\pm$ 0.8	14.5 $\pm$ 0.2	123 $\pm$ 82
5N	Lower	45	0.8 $\pm$ 1.0	0.4 $\pm$ 0.2	0.61 $\pm$ 0.2	7.0 $\pm$ 0.5	14.7 $\pm$ 0.2	157 $\pm$ 110

**Note:** Vertical Flux measured by upwelling and downwelling; DO, dissolved oxygen

a ridge parallel to the northern bank of the site and upwelling occurs towards the thalweg. Site 4E (Figure 3d) shows the most heterogeneity with upwelling and downwelling at apparently discreet points across the site and many neutral pressure head measurements (indicating a lack of vertical exchange) throughout the site. Site 4E generally has downwelling at the head of the new riffle and upwelling at the downstream edge of the site. Site 5N (Figure 3c) is a heavily used natural spawning area, and is dominated by upwelling with a discreet point of downwelling in the upstream northeast location of the site.

#### *Surface Water Depth, Velocity, and Direction of Flow*

Mean surface water depth and velocities were within optimal spawning range for all restoration sites (Table 2). Mean surface water velocities generally increased in the lower sections of the riffles for the higher use sites (Site 1E, Site 4E, and Site 5N) as water streamed over the new gravel. Stream velocities were relatively consistent across Site 2E and Site 3E.

Bed topography varied at these sites. Site 1E is characterized by a hummocky bed with small-scale gravel waves perpendicular to flow (Figure 4a). These waves developed after new gravel was added, and were 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 located immediately upstream of the enhanced site, may serve as a refuge for spawning females. Site 1E has a wide variety of depth, velocity and flow directions as a result of this hummocky bed topography.

Site 2E (Figure 4b) 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 Site 1E site. This site does not have an upstream pool that would serve as a quick retreat or velocity refuge. Site 2E

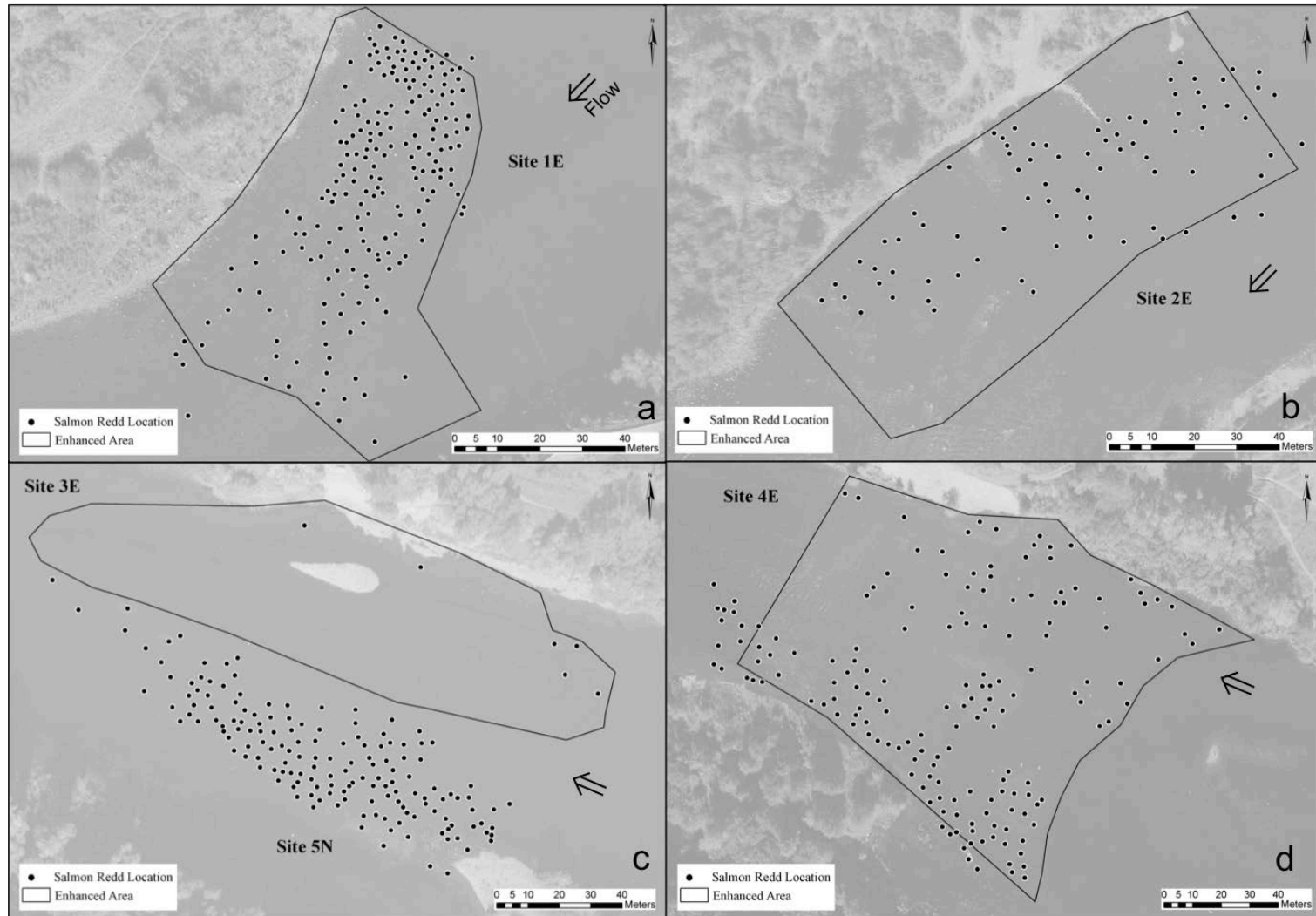


has minor variability in depth and velocity and the direction of flow is not as variable as the Site 1E.

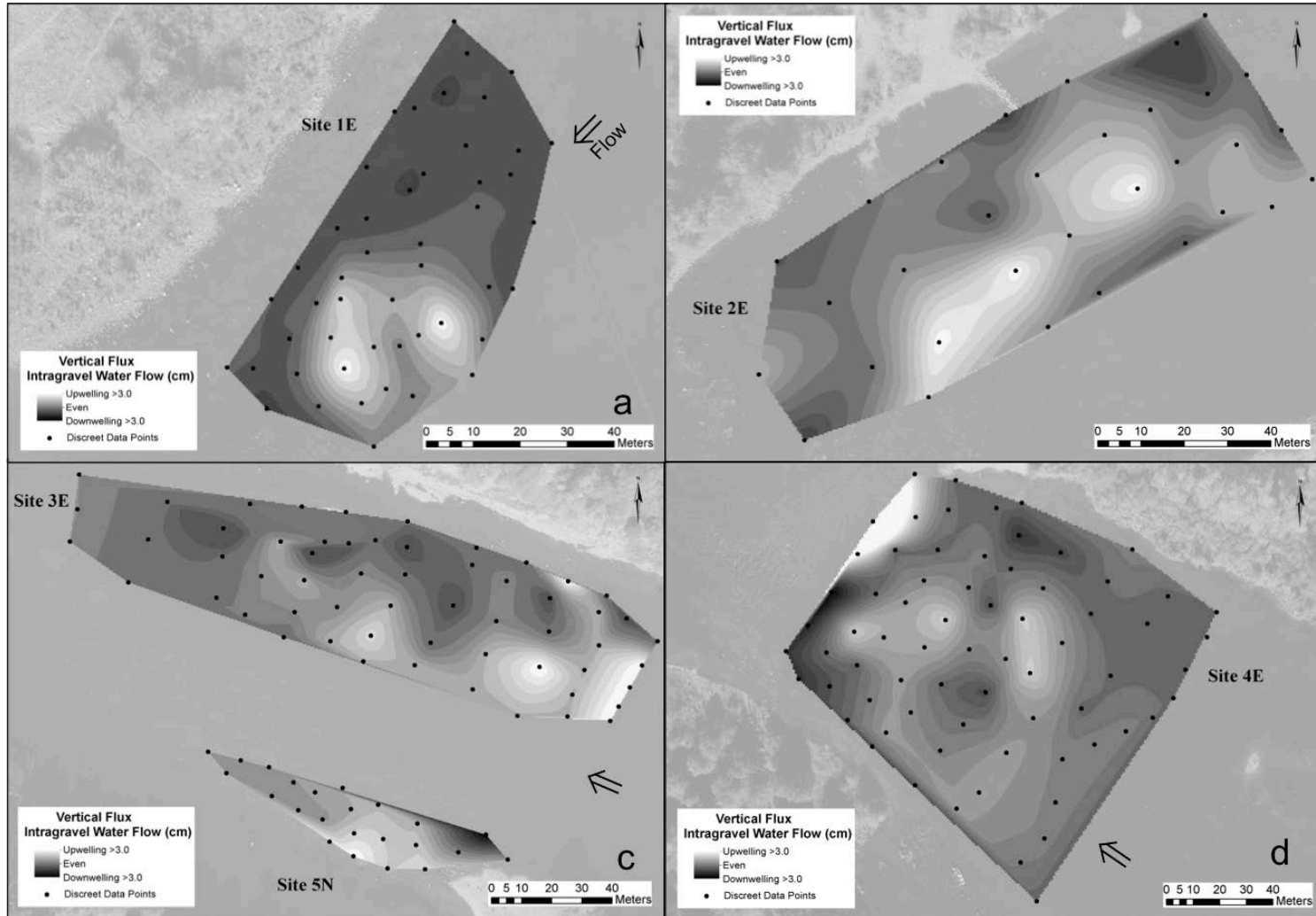
Flow direction and velocity are very consistent at Site 3E (Figure 4c). Flow crosses the new gravel bar at a slight angle, and the stream gradually deepens toward the thalweg. Much of the surface water flow bypasses the bar and flows toward the south bank. Surface water velocities are consistent across the new gravel, with higher velocities at the head and mid points and lower velocities at the downstream tail of the site. The direction of flow is uniform throughout the site with little variation.

Site 4E (Figure 4d) has slightly hummocky bed topography, but lacks the gravel waves that form from fish manipulation occurring over years of use. The hummocky profile forms a larger sequence of micro riffles and pools. Surface water velocities at Site 4E are consistently higher towards the bottom of the restoration site and lack variability in direction of flow as water is funneled towards a smaller outlet downstream. At this site most flow is perpendicular to micro-ridges. Additionally, a small channel south of the enhanced site may serve as a refuge location for spawning females or juvenile rearing habitat.

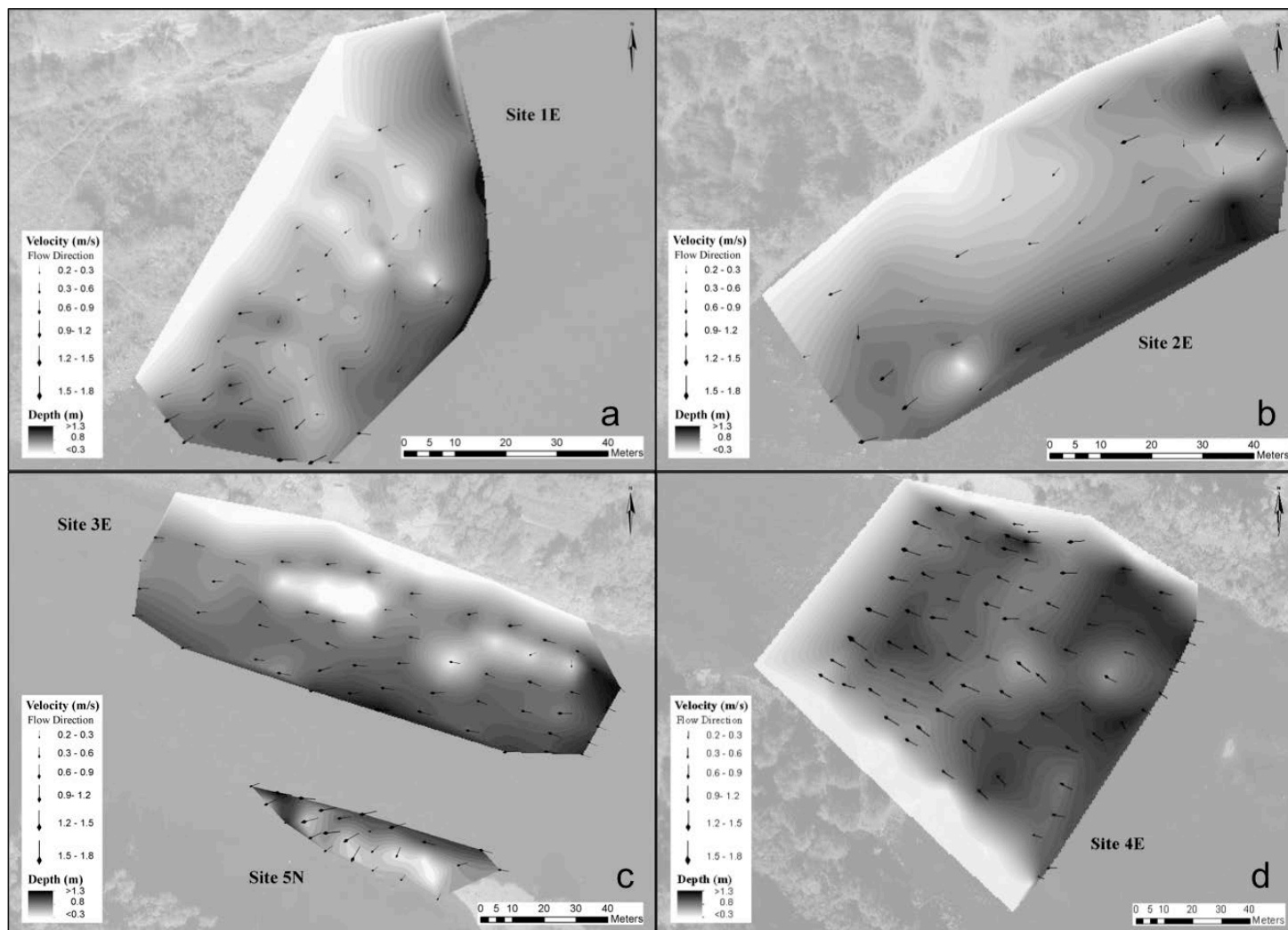
Site 5N (Figure 4c) is characterized by a hummocky bed profile with micro pool and riffles that appears to be the result of fish manipulation of the gravel. The site has a wide variety of surface water velocity and direction of flow, and most flow is perpendicular to the main gravel bar. The site also has a deep pool dominated by large woody debris that may act as a refuge for fish during spawning and emergence stages.



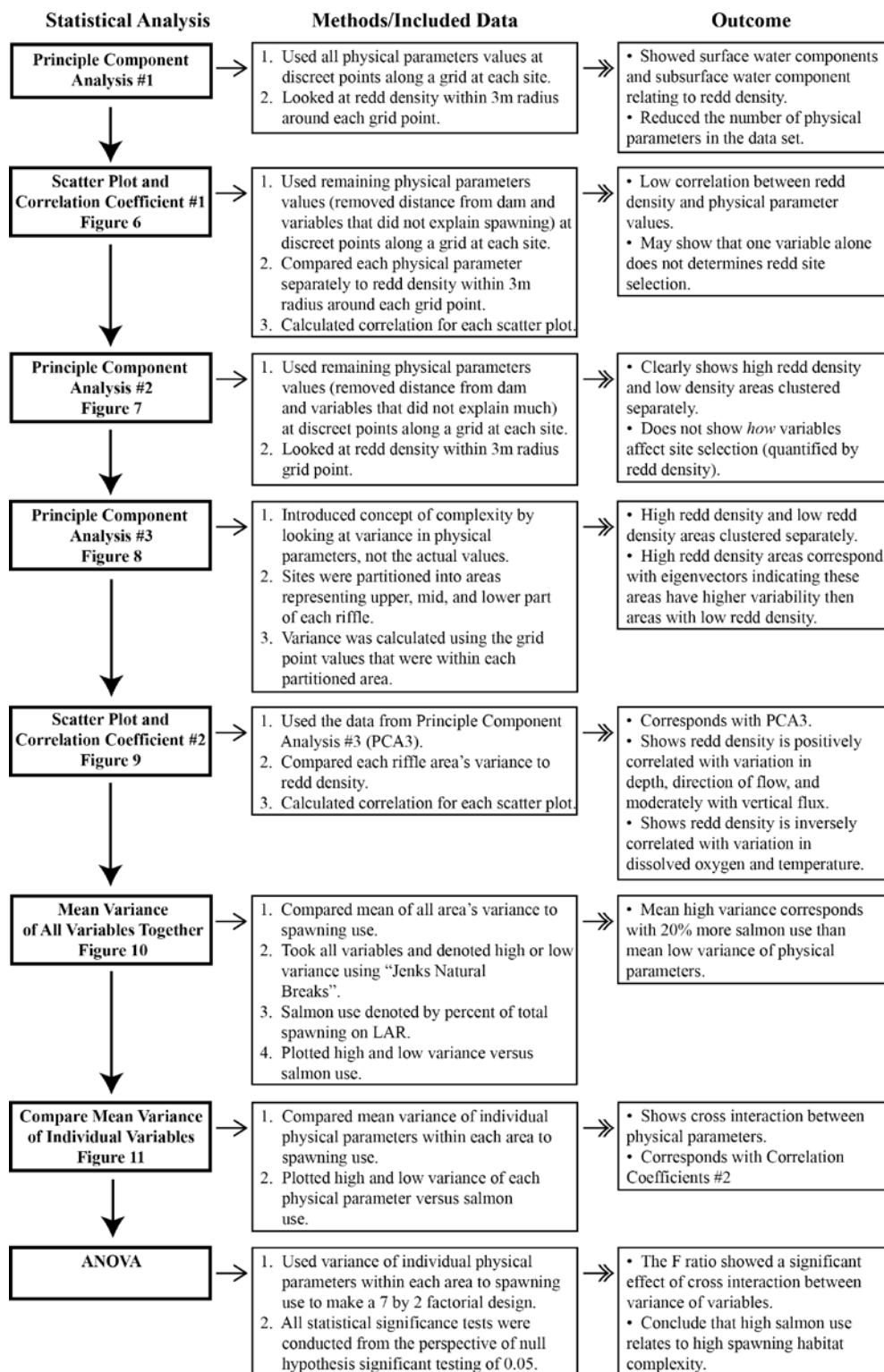
**Figure 2.** Chinook salmon redd locations on 26 November 2012 for the four gravel enhancement sites: Site 1E (a), Site 2E (b), Site 3E (c), Site 4E (d), and the natural spit unenhanced site, Site 5N (c); (high-resolution fly-over photos courtesy John Hannon, U.S. Bureau of Reclamation)



**Figure 3.** Vertical flux maps plotted as upwelling and downwelling measurements for the four enhanced sites: Site 1E (a), Site 2E (b), Site 3E (c), Site 4E (d), and the natural spawning site, Site 5N (c); (high-resolution photos courtesy John Hannon, U.S. Bureau of Reclamation)



**Figure 4.** Surface water depth, velocity, and direction of flow maps for the four enhanced sites: Site 1E (a), Site 2E (b), Site 3E (c), Site 4E (d), and the natural spit unenhanced site, Site 5N (c); (high-resolution photos courtesy John Hannon, U.S. Bureau of Reclamation)

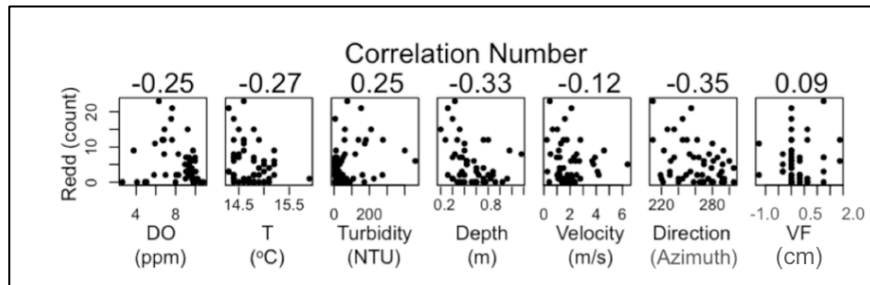


**Figure 5:** Flow chart illustrating eight discrete steps in evaluating statistical analysis of potential Chinook salmon use.

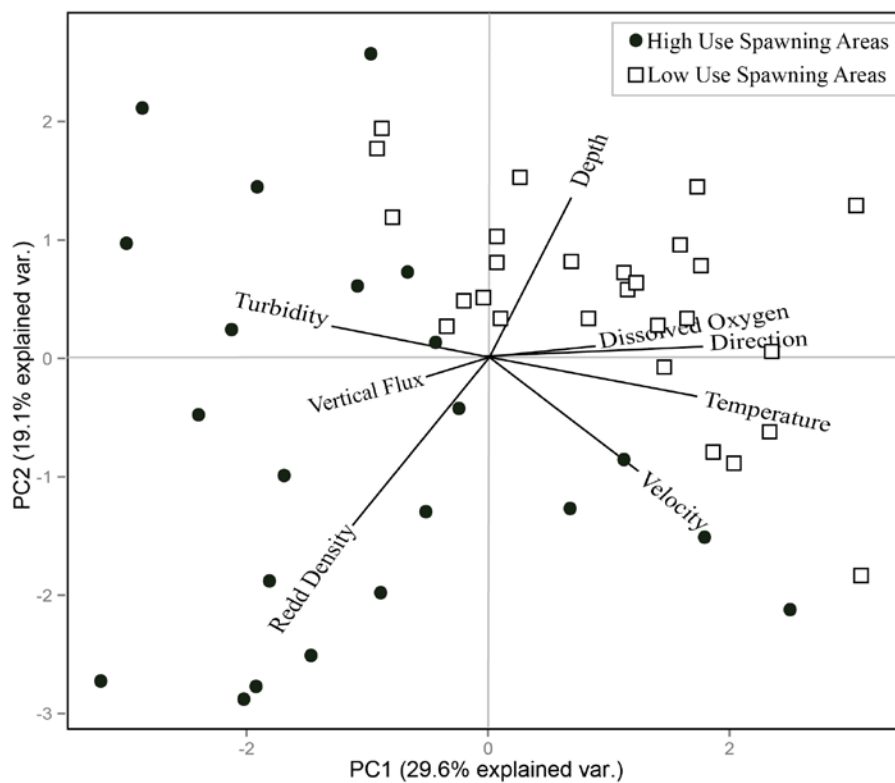
**Note:** LAR denotes Lower American River

## 5. Discussion

A conceptual diagram (Figure 5) summarizes the steps used for statistical analysis. Principle components analysis (PCA) was used as a first step (results not shown in this paper) to reduce the number of physical condition variables in the data set, and this identified environmental variables that are important for spawning site selection. PCA #1 showed surface water and subsurface components that could be measured using seven parameters (surface water-depth, velocity, direction of flow; and subsurface- vertical flux and water quality (dissolved oxygen, temperature, turbidity)). Redd counts versus individual physical parameter measurements indicate low

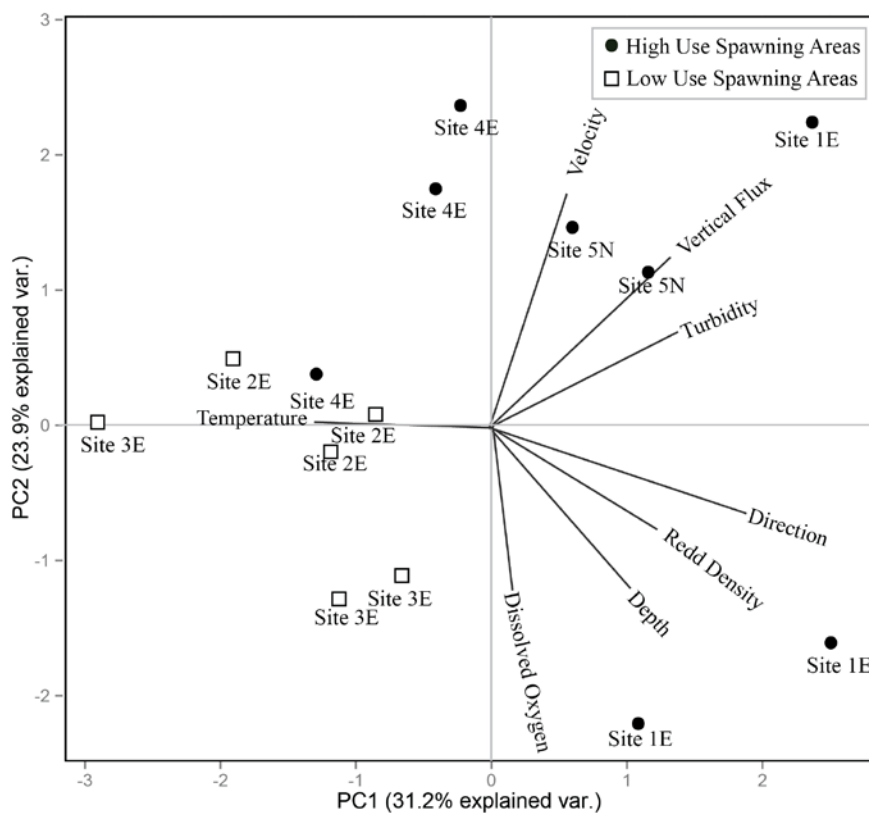


**Figure 6.** Redd count versus parameter data with corresponding correlation coefficients.  
**Note:** DO, Dissolved Oxygen; T, Temperature; VF, Vertical Flux



**Figure 7.** Biplot of sample scores on principal components (PC) 1 and 2 describing variation in the characteristics of the study sites. Plots of high use spawning areas and low use spawning areas are physical parameter values and redd counts within a three-meter radius around each grid point.

correlation (Figure 6), demonstrating that one physical parameter alone does not necessarily determine redd site selection. However, lower depths and temperatures as well as higher turbidity have weak correlation (0.3) with higher redd counts. PCA #2 (Figure 7) explain 48.7% of the variance, and although redd density is not clearly controlled by one physical parameter, there are significant groupings between high redd density clusters and low redd density clusters.

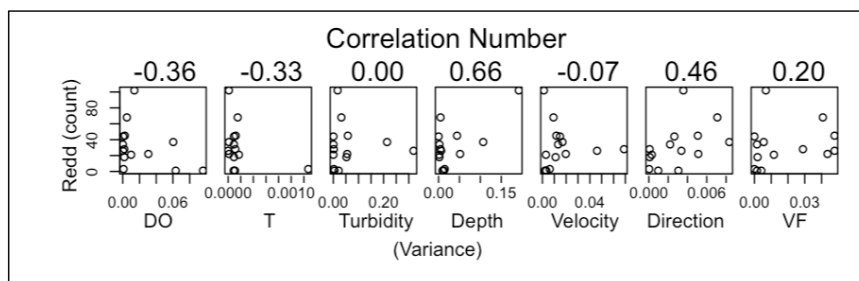


**Figure 8.** Biplot of sample scores on principal components (PC) 1 and 2 describing variation in the characteristics of the study sites. Plots of high use spawning areas and low use spawning areas are variance of physical parameters and values redds within each area (upper riffle, mid-riffle, lower riffle) the study sites (enhanced sites: Site 1E, Site 2E, Site 3E, Site 4E, and natural site: Site 5N).

Ecologists and biologists value complexity in habitat. To understand what drives redd site selection, PCA #3 used the variance in physical parameters instead of the actual physical parameter values and compared them to salmon use. To do this, each site was split into multiple areas (top of the restored riffle, mid riffle, and bottom of the riffle). Variance of each physical parameter of an area was determined and compared to the redd counts. The first two PC axis explained 54.9% of the total variance in physical conditions associated with the spawning locations and high redd density and low redd density plot separately (Figure 8). High redd densities correspond with parameters that show larger amounts of variability then the areas with



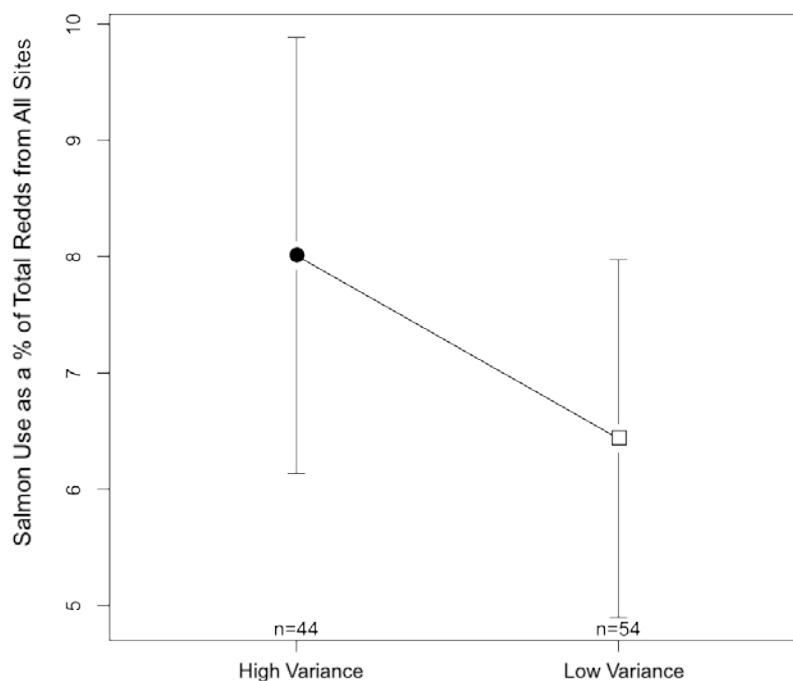
low redd densities. Redd density is also strongly positively correlated with variance in depth and direction of flow whereas redd density correlates negatively with variance in dissolved oxygen and temperatures (Figure 9). This is to be expected because fish need intragravel water to be high in dissolved oxygen and low in temperatures when spawning (Nawa and Frissell 1993; DeVries 1997; Malcom, Soulsby et al. 2003; Horner, Titus et al. 2004; Youngson, Malcolm et al. 2004; Merz and Setka 2004a; Kondolf, Williams et al. 2008) and variability in these parameters would be detrimental to fitness and survival.



**Figure 9.** Redd count versus area (top of the restored riffle, mid riffle, and bottom of the riffle) variance with corresponding correlation coefficients.

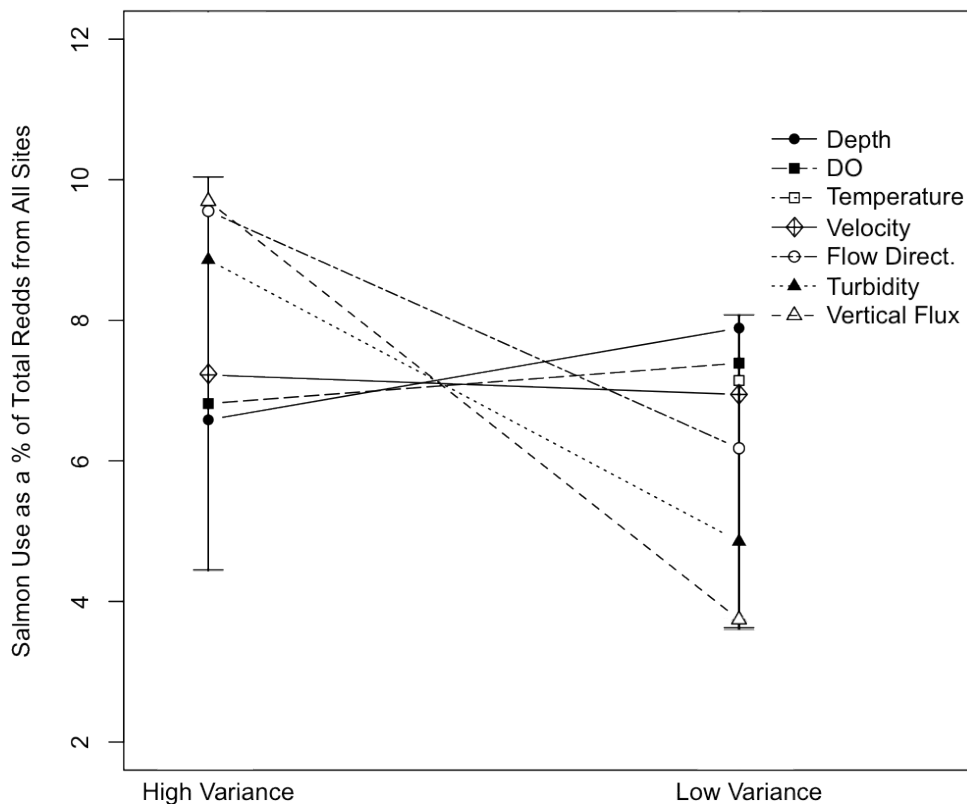
**Note:** DO, Dissolved Oxygen; T, Temperature; VF, Vertical Flux

Heterogeneity represented by variance yields higher salmon use (redd counts); higher mean variance (8.0%) provides greater salmon use than lower mean variance (6.5%) (Figure 10). Variable depth, velocity, and flow directions correspond with varying pool and riffle systems within a site and this in turn correlates strongly with intragravel flow assessed through vertical flux differences.



**Figure 10.** Mean Chinook salmon use as a function of high and low variance of combined parameters. Error bars depict 95% confidence intervals associated with each of the group means.

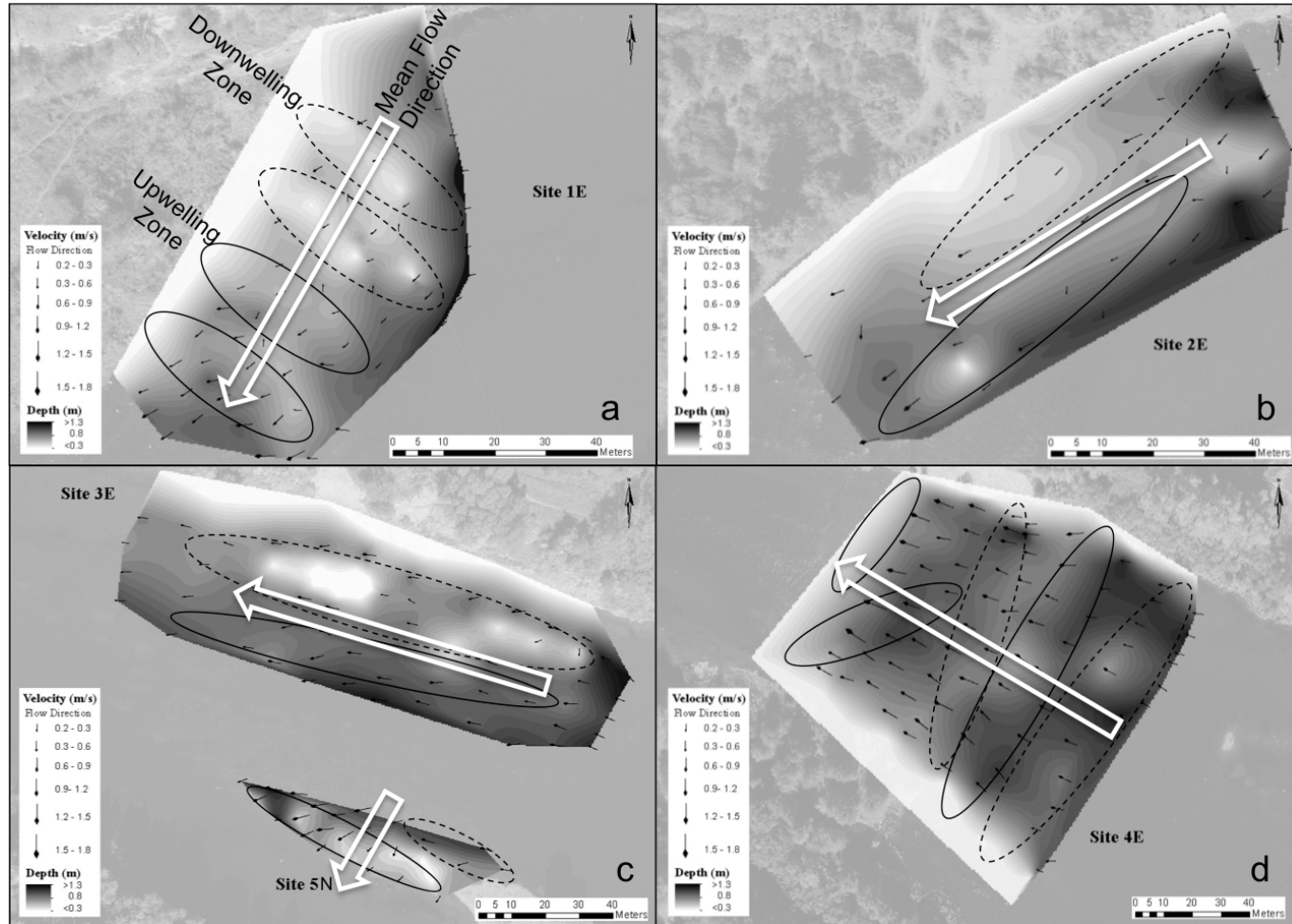
Regions of upwelling and downwelling appear to coincide with small-scale ridges and valleys within the larger enhanced riffle (Figure 11). For higher utilized sites (Site 1E, Site 4E, Site 5N), mean surface water flow is perpendicular to these ridges and valleys and consequently upwelling and downwelling regions. Mean surface water flow at lower utilized sites (Site 2E, Site 3E) is parallel to the ridges and valleys and regions of upwelling and downwelling. Additionally, high dissolved oxygen percentages are present where significant hyporheic exchange is present. This may be represented by upwelling or downwelling conditions because subsurface flow is so rapid the hyporheic water does not become oxygen-depleted. Crossover interaction between parameters and the individual variability constitutes complexity in the spawning environment (Figure 12). The interactions between each parameter as well as the amount of parameter variation influence salmon utilization.



**Figure 12.** Interaction plot for the group means of Chinook salmon use as a function of high and low variance for each parameter. Error bars depict 95% confidence intervals associated with each of the group means.

**Note:** DO, Dissolved Oxygen; Flow Direct., Flow Direction

The use of several physical-parameter variance measurements to construct a predictive model of elevated redd site selection worked well. The study is a seven (dissolved oxygen, temperature, turbidity, depth, stream velocity, direction of flow, and vertical flux) by two (high variance and low variance) factorial design using a significance level of 0.05 in the statistical analysis. The F ratio for the ANOVA showed a significant effect of cross interaction of parameter variance on salmon utilization ( $F=30.81$ ,  $p=0.009$ ) and accounted for 97.6% of the variation around the mean.



**Figure 11.** Surface water depth and mean flow versus upwelling and downwelling map: Surface water depth, velocity, and direction of flow maps for the four enhanced sites: Site 1E (a), Site 2E (b), Site 3E (c), Site 4E (d), and the natural spit unenhanced site, Site 5N (c) overlaid by upwelling zones (solid ovals) and downwelling zones (dashed ovals). Mean direction of flow (white arrows) is perpendicular to ridges and valleys and vertical flux zones at high use sites 1E (a), 4E (d), and 5N (c) and parallel to ridges and valleys and vertical flux zones at low use sites 2E (b) and 3e (c); (high-resolution photos courtesy John Hannon, U.S. Bureau of Reclamation)

## 6. Conclusion

Physical parameters are used to characterize the suitability of riverine spawning habitat (Bjornn and Reiser 1991; Merz and Setka 2004a; Kondolf, Williams et al. 2008), including influences of the environment within the hyporheic zone (Geist and Dauble 1998). The interactions between these variables influence the heterogeneity of habitat creating micro-riffle and pool sequences that may encourage redd site selection (Geist and Dauble 1998).

Gravel enhancements provided a layer of appropriate sized, clean, loosely packed gravel 0.3 - 1.3 m deep over the enhanced sites. 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. Consequently, this provided parameters for suitable salmon spawning habitat to be within an appropriate range. However, salmonids tended to select sites with more heterogeneous physical environments.

Over time, these types of augmentations tend to become more dynamic and natural. 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. Diversity of the physical habitat is attributed largely to the hummocky riverbed. 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.

## References

- (NOAA), N. O. a. A. A. (1994). Endangered and Threatened Species: Status of Sacramento River Winter-run Chinook Salmon, Federal Register. **59**.
- Bencala, K. E. (2000). "Hyporheic zone hydrological processes." Hydrological Processes **14**: 2797-2798.
- Bjornn, T. C. and D. W. Reiser (1991). "Habitat requirements of salmonids in streams." American Fisheries Society Special Publication **19**: 83-138.
- Chapman, D. W., D. E. Weitkamp, et al. (1986). "Effects of riverflow on the distribution of Chinook salmon redds." Transactions of the American Fisheries Society **115**: 537-547.
- Coble, D. W. (1961). "Influences of water exchange and dissolved oxygen in redds on survival of steelhead trout embryos." Transactions of the American Fisheries Society **90**: 469-474.
- Davis, J. C. (1975). "Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review." Journal of Fisheries Research Board Canada **32**(12): 2295-2332.
- DeVries, P. E. (1997). "Riverine salmonid egg burial depths: review of published data and implications for scour studies." Canadian Journal of Fisheries and Aquatic Sciences **54**(8): 1685-1698.
- Fairman, D. (2007). A gravel budget for the Lower American River. Geology, CSUS. **MS**.
- Geist, D. R. and D. D. Dauble (1998). "Redd site selection and spawning habitat use by fall Chinook salmon: The importance of geomorphic features in large rivers." Environmental Management **22**: 665-669.
- Greig, S. M., D. A. Sear, et al. (2007). "Review of factors influencing the availability of dissolved oxygen to incubating salmon embryos." Hydrological Processes **21**: 323-334.
- Hannon, J. (2000). Steelhead spawning parameter, United States Bureau of Reclamation.
- Hannon, J. and B. Deason (2005). American River Steelhead (*Onchorhynchus Mykiss*) Spawning 2001 - 2005. Central Valley Project, American River, California Mid-Pacific Region, United States Bureau of Reclamation.

- Harvey, J. and K. E. Bencala (1993). "The effect of streambed topography on surface-subsurface water exchange in Mountain Catchments." Water Resources Research **29**: 89-98.
- Heaney, S. I., R. H. Foy, et al. (2001). "Impacts of agriculture on aquatic systems: lessons learnt and new unknowns in Northern Ireland." Mar. Freshw. Res. **52**: 151-163.
- Horner, C. T. and M. K. Janes (2013). Physical and geochemical characteristics of the Upper Sailor Bar 2008, Upper Sailor Bar 2009 and Upper Sunrise 2010/2011 gravel additions: 105.
- Horner, C. T., R. Titus, et al. (2004). Phase 3 Gravel Assessment on the Lower American River: Report to the U.S. Bureau of Reclamation Sacramento Office, California, USA.: 99.
- Ingebritsen, S. E. and W. E. Sanford (1998). Groundwater in Geologic Processes. New York, Cambridge University Press.
- Jenks, G. F. (1967). "The Data Model Concept in Statistical Mapping." International Yearbook of Cartography **7**(186-190).
- Jones, J. B. and P. J. Mulholland (2000). Streams and ground waters. San Diego, Academic Press.
- Kondolf, G. M., J. G. Williams, et al. (2008). "Assessing Physical Quality of Spawning Habitat." American Fisheries Society Symposium **65**: 1-26.
- Malcom, I. A., C. Soulsby, et al. (2003). "Heterogeneity in ground water-surface water interactions in the hyporheic zone of a salmonid spawning stream." Hydrological Processes **17**: 601-617.
- Merz, J. E. and J. D. Setka (2004a). "Evaluation of a Spawning Habitat Enhancement Site for Chinook Salmon in a Regulated California River." North American Journal of Fisheries Management **24**: 397-407.
- Merz, J. E., J. D. Setka, et al. (2004b). "Predicting benefits of spawning-habitat rehabilitation to salmonid (*Oncorhynchus spp.*) fry production in a regulated California river." Can. J. Fish. Aquat. Sci. **61**: 1433-1446.
- Monaghan, K. A. and A. M. Milner (2009). "The effect of anadromous salmon redd construction on macroinvertebrate communities in a recently formed stream in coastal Alaska." Journal of the North American Benthological Association **28**: 153-166.

National Research Council, N. (1995). Flood Risk Management and the American River Basin: An Evaluation. Washington, DC.

Nawa, R. K. and C. A. Frissell (1993). "Measuring scour and fill of gravel streambeds with scour chains and sliding-bead monitors." North American Journal of Fisheries Management **12**: 634-639.

Nelson, R. W., J. R. Dweyer, et al. (1987). "Regulated flushing in a gravel-bed river for channel habitat maintenance: a Trinity River [California, USA] fisheries case study." Environ. Manag. **11**: 479-494.

NOAA (1998). Endangered and Threatened Species: threatened status for two ESUs of steelhead in Washington, Oregon, and California, Federal Register. **53**.

NOAA (2009). Evaluation of 9 years of CPC Long Range Precipitation Forecasts in the Northern Sierra Nevada of California. M. Roos, California Department of Water Resources: 11-14.

Palmer, M. A., R. F. Ambrose, et al. (1997). "Ecological theory and community restoration ecology." Restoration Ecology **5**(4): 291-300.

Pretty, J. L., S. S. C. Harrison, et al. (2003). "River rehabilitation and fish populations: assessing the benefit of instream structures." Journal of Applied Ecology **40**(2): 251-265.

Schlemon, R. J. (1967). Landform-soil Relationships in North Sacramento County, California. Geography, U.C. Berkeley. **Ph.D.**

Soulsby, C., A. F. Youngson, et al. (2001). "Fine sediment influence on salmonid spawning habitat in a lowland agricultural stream: a preliminary assessment." Sci Total Environ **265**(1-3): 295-307.

Tews, J., U. Brose, et al. (2004). "Animal species diversity driven by heterogeneity/diversity: the importance of keystone structures." Journal of Biogeography **31**: 79-92.

Tucker, M. E. (1981). Sedimentary Petrology: An Introduction. Oxford, Blackwell Scientific Publishers.



USGS (1980). General Procedure for Gaging Streams: Techniques of Water-Resources Investigations of the United States Geological Survey, U.S. Department of Interior, Office of Water Data Coordination, U.S. Geological Survey.

USGS (2012). "11446500 American R A Fair Oaks CA." from [http://waterdata.usgs.gov/usa/nwis/uv?site\\_no=11446500](http://waterdata.usgs.gov/usa/nwis/uv?site_no=11446500).

Vyverberg , K., B. Snider, et al. (1997). "Lower American River Chinook Salmon Spawning Habitat Evaluation October 1994: California Department of Fish and Game Environmental Services Division. ." Technical Report No. 97-2: 112.

Wheaton, J. M., G. B. Pasternack, et al. (2004a). "Spawning Habitat Rehabilitation-II. Using hypothesis Testing and Development in Design, Mokelumne river, California, USA." International Journal of River Basin Management **2**(1).

Wheaton, J. M., G. B. Pasternack, et al. (2004b). "Spawning Habitat Rehabilitation-I. Concept, Approach, and Methods." International Journal of River Basin Management **2**(1).

Wu, F. (2000). "Modeling Embryo Survival affected by sediment deposition into salmonid spawning gravels." Water Resources Research **36**: 1595-1603.

Youngson, A. F., I. A. Malcolm, et al. (2004). "Long-residence groundwater effects on incubating salmonid eggs: low hyporeic oxygen impairs embryo development." Can. J. Fish. Aquat. Sci. **61**(12): 2278-2287.

Zamora, C. (2006). Estimating rates of exchange across the sediment/water interface in the Lower Merced River, CA. Geology, CSUS. **MS**: 102.



