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HYPORHEIC WATER QUALITY AND SALMONID EGG SURVIVAL IN THE SAN JOAQUIN RIVER

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ABSTRACT

Poor survival of salmonid eggs during what was considered the time of potential spring-run Chinook spawning and egg incubation (September-November) was observed in hyporheic incubated eggs in the San Joaquin River below Friant Dam. Water temperatures appropriate for salmon egg survival did not occur consistently except for a short period towards the end of the study in November. These relatively high water temperatures may have been responsible for much of the observed poor egg survival. Hyporheic temperatures appeared to be mostly controlled by air temperature and there was very little correlation of water temperature with flow. Spatially, appropriate temperatures occurred at the furthest downstream station earlier in the season than did temperatures at upstream sites closer to the reservoir. Periphyton and fine sediment seemed to control groundwater/surface water interactions to some degree and low DO was sometimes associated with what appeared to be groundwater intrusion that was more common at upstream stations with large amounts of periphyton. High flows resulted in both increases and decreases in hyporheic DO concentrations. Negative impacts occurred differentially at locations in the same riffle. Lower DO often occurred with low flows at the end of the study. Some of the incubated eggplates attracted invertebrate benthos documented as harmful to fish eggs in other studies. This study has revealed that variability in hyporheic conditions is high within the studied section of the San Joaquin River.

INTRODUCTION

The San Joaquin River Restoration Program (SJRRP) is a long-term effort to restore flows and a self-sustaining Chinook salmon (*Oncorhynchus tshawytscha*) fishery to the San Joaquin River, California from Friant Dam to the confluence of Merced River, while reducing or avoiding adverse water supply impacts. With completion of the Friant Dam in 1942, spring-run salmon were quickly extirpated from the San Joaquin River, while fall-run population size declined greatly in the upper part of the San Joaquin drainage (Fisher 1994). Presently salmon are absent from this portion of the San Joaquin River and attempts are being made to identify factors limiting successful restoration. The present study was designed to assess hyporheic water quality associated with egg incubation conditions below Friant Dam for spring-run Chinook salmon in advance of salmon re-introduction efforts.

During spawning activity and redd construction, Chinook salmon eggs are buried in the river substrate, at depths from ca. 30 cm (e.g., DeVries 1997) to 45 cm (Geist 2000). The incubation period often lasts 40-50 days before hatching occurs (SJRRP 2010). After hatching, alevins remain buried in the gravel while development continues with mostly yolk-sac derived nutrition. In the nearby Sacramento River Basin, spring-run Chinook salmon alevins remain in the gravel for 2 to 3 weeks after hatching and then emerge into the water column (Fisher 1994). This long contact time with the redd environment for these early life history stages of salmon indicates its importance to salmon populations. Redd water quality is not necessarily totally predicated on surface water quality and conditions may differ markedly from those found at the surface (e.g., Soulsby, et al. 2001). Potential limiting factors for embryo development and emergence of fry from redds include: suitable water temperatures, concentrations of dissolved oxygen (DO), presence of fine

sediments, and appropriate groundwater-surface water (GW-SW) interactions (Malcolm et al. 2006). Some benthic invertebrates may also impact salmon by consuming eggs and fry (McDonald 1960, Brown and Diamond 1984).

In the Central Valley of California, spawning of the spring-run Chinook salmon peaks in mid-September, while fall-run spawning peaks in mid-October (Fisher 1994). Potential exposure periods for intragravel life-history stages of Chinook salmon in the San Joaquin River Basin extend from late August through March (Fisher 1994, SJRRP 2010). It is likely that San Joaquin River water quality in August/September represents the most critical high water temperatures and low DO to which salmon eggs would be exposed, thus making studies at this time of year important.

Optimal temperatures for successful egg incubation are $\leq 13^{o}C$ (from Table 3-1, SJRRP 2010), while intragravel DO criteria concentrations set for the protection of salmonids (EPA 1986) include mean values of 6.5 mg/L and 1-day minimum of 5.0 mg/L ambient DO. More recently, Brown and Hallock (2009) reviewed intragravel DO water quality standards of Pacific Northwest government agencies. The review included western states, tribes, and the Canadian province of British Columbia and found that 1-day minimum criteria ranged from 5 to 8 mg/L. This range of values agrees with the results of Malcolm et al. (2003) who reported negligible survival where mean DO's were < 7.6 mg/L.

Fine sediment in redds is often thought to impact egg and fry survival. However, Kondolf (2000) suggests difficulties in finding a universally applicable sediment threshold. Perhaps as a result, different particle sizes have been promulgated as impacting salmon. Particles less than 6.4 mm were recognized as having potential to infiltrate redds, forming a layer in the stream gravels that sometimes prevents emergence of fry (Lisle 1989). Kondolf (2000), in a review of the literature, found that salmonid emergence and survival was decreased by 50% when fine sediments (<6.4 mm) exceeded 30%. Bryce et al. (2010) suggested that hatching success will decline to unsustainable levels when bedded sand and fine sediments (< 2 mm) are between 11% and 18% by volume or mass. A mixture of sizes of fine sediments may also be important to Chinook salmon embryo survival and Tappel and Bjornn (1983) developed equations from incubation studies that used sizes of < 0.85 mm and <9.5 mm to predict survival in gravel mixtures.

Malcolm et al. (2006) suggest that causal relationships between some of these limiting factors are unclear and indicate that highly dynamic GW-SW interactions may explain much about embryo survival in the redd environment. There are strong hydrological influences on GW-SW interactions and potentially flow could be used as a management tool for influencing conditions within the hyporheic (e.g., Malcolm et al. 2004). Often high flows increase the proportion of surface water in the hyporheic, while during low flows groundwater may dominate (Malcolm et al. 2004).

Recent spot checks of DO from hyporheic samplers in the San Joaquin River (Nelson and Reed 2011) indicated that DO may be very low (ca. 2mg/L) at some locations and that there may be diurnal variation in these values. Below Friant Dam on the San Joaquin, it appears that dense periphyton growth may play a role in these DO shifts. In-stream photosynthesis causes highest DO to occur in the late afternoon, with lowest readings often recorded just before daybreak.

Intragravel DO monitoring to date has only occurred during daylight hours and it is important to consider DO concentrations at different periods that may impact early life-stage salmonids.

The present paper addresses San Joaquin River intragravel continuous DO and temperature monitoring, periphyton biomass, salmonid egg survival, and how these parameters compare spatially and under differing conditions of flow. These data should aid in determination of the quality of spawning habitat below Friant Dam and will also help evaluate the effects of restoration flow releases on DO and water temperatures in egg incubation habitats. It should be recognized that there are likely parameters that are unrecognized and yet important to egg and alevin survival within the spawning gravels. In this regard little has changed since Charles Darwin (1859) pointed out in *On the Origin of Species* that, "What checks the natural tendency of each species to increase in number is most obscure…. We know not exactly what the checks are in even one single instance" (67).

Since spring-run spawning would potentially occur from late August through early October (e.g., Fisher 1994) on the San Joaquin River, rainbow trout (*Oncorhynchus mykiss*) eggs were used for this study because of the limited availability of Chinook salmon eggs at an appropriate time. Spring-run egg availability is very limited and fall-run would not be available until the first run on the Feather River in October.

METHODS

Study Sites—Sites were at increasing distance downstream of Friant Dam (Figure 1). Site A was 4.8 km below the dam; B, 9.6 km; and C, 14.0 km. Sites selected were at riffle/run areas believed to be appropriate for Chinook salmon spawning. The studied section of the river was assumed, because of cool water from the dam, to have the highest likelihood for appropriate water temperatures for egg and alevin survival and development. Study sites were also chosen based on sediment grain-size with larger substrates considered most suitable for spawning. Specific locations sampled at each site are presented in Appendix A.

Equipment was installed during September. Site visits and monitoring occurred in September, October, and November when equipment and eggplates were removed for analyses.

Equipment installation--Each location within a riffle was excavated by hand for installation of equipment. A 19-L bottomless bucket was placed at the selected spot in the stream and substrate material was then removed and placed into a separate container. As material was removed, the bucket was lowered in the resulting hole to stabilize the sides. Buckets were left in place overnight to avoid critical delays that might have occurred if time was expended on digging holes immediately before egg introduction. Excavated material was salvaged and returned to the same location after monitoring equipment and eggplates had been placed in the hole. During removal and replacement of substrate, some fine sediment was lost in the current. This was considered desirable as it mimics, to some degree, what would occur during spawning by salmon. Continuous DO and temperature monitoring equipment were installed at 3 intragravel locations (ca. 30 cm depth) and at a single surface water location at each of the 3 sites. Airstone and tubing (for discrete hyporheic sample withdrawal) were also installed at these locations. An additional 3 intragravel locations at each site lacked DO sensors but had an airstone and tubing along with HOBO temperature loggers installed to increase spatial representation and to allow

for additional data collection. Eggplates with rainbow trout eggs were installed at all locations (six locations per site). Fine sediment traps were also placed within the gravel at most locations. Periphyton samples for biomass evaluation were collected from all locations during each of three sampling occasions. Periphyton were typically collected just upstream and within 1-m of each location.

Eggplates--Eggs and milt were obtained from fish spawned at the San Joaquin Hatchery Facility in September. Eggs were fertilized and water hardened at the hatchery and egg incubation plates were loaded. Six plates remained at the hatchery (initial controls), 18 eggplates were used in the river, and 6 returned to the hatchery (final controls) after all eggplates were installed in the San Joaquin River. Controls were used to estimate handling and travel mortality. Eggs were fertilized and processed within 48 hrs.

Eggplates were similar to Greenberg's (1992) design. Eggplates consisted of two 15.2-cm square polyvinyl chloride (PVC) plates placed together with mesh glued to the two outer sides. Eggs were placed in holes drilled in the sheets and retained between the two plates. Plastic strap ties were used to secure plates together. Eggplates had 32 ovals measuring 11 mm wide and 27 mm long and spaced in four rows of eight ovals each (Figure 2). A single egg was placed in each oval. The mesh, which was glued to the eggplates, was silver-gray fiberglass insect screening with 1.5 x 1-mm rectangular openings.

Upon retrieval of eggplates, number of live fish present and number that hatched were counted. Larval fish and contents of eggplate were preserved in 70% alcohol and then fish total length was measured in the laboratory. Macroinvertebrates associated with eggs were collected and identified. Functional feeding group status (Merritt and Cummins 1996) of invertebrates was determined to aid in interpretation of potential impact of invertebrates to eggs and alevins.

Continuous monitoring—Dissolved oxygen sensors (precise to 0.01 mg/L) (Aquistar®) utilized fluorescence of a stable, immobilized ruthenium-based film matrix, and optical transmission to measure oxygen concentration in the fluid outside of the sensor. Measurement was based on photons of light responding to oxygen outside of the sensor. This design eliminates the need for water flow and frequent cleaning. Water temperature was also recorded from the sensor. The sensor was very small (4 cm diameter) and easily fit into the constrained study environment.

Sensors were connected via cable to control boxes on the shore. Control boxes recorded data (DO and temperature) and powered both the control box and the sensor. Logging period was set for every 15 minutes during the 2 months of the study. A control box communications port allowed for downloading of data as the study progressed. This occurred on a weekly basis when sensor cables were also checked to ensure that they remained hidden and free of debris.

Continuous hyporheic water temperatures were measured in locations that lacked a DO/temperature sensor using HOBO® Water Temp Pro loggers. These were buried at the same depth as DO/temperature sensors.

Flow and additional water temperature data were obtained from USGS gage 11251000 below Friant, California. This site was upstream of our Site A. In addition to trends in streamflow, we examined trends in air temperature over the study area using air temperature measurements

record by the Bureau of Reclamation at Friant Dam (California Data Exchange Center, site FRT, latitude 36.995^{o}N, longitude 119.692^{o}W) (Figure 1).

Water samples—In September and November, hyporheic pore water samples were collected via a fused glass air stone attached to eggplates. Plastic tubing, connected to the air stone, led to the surface and allowed for collection of pore water *in situ*. The air stone was used to prevent clogging of the tubing by sand or other particles during collection. A 60- ml plastic syringe was connected to tubing to withdraw pore water samples and was also used to collect surface water samples associated with each riffle location. The tubing was initially cleared by withdrawing and discarding 10-mls of fluid, followed by collecting 15-ml for DO determination. A final volume of 60-mls was collected for measurement of temperature (^{o}C) and conductivity (µS/cm). The same procedure was followed for collection of surface water samples. The collection of small volumes is suggested as important for clearly delineating environmental conditions at a given substrate depth (e.g., Malcolm et al., 2009).

A spectrophotometric method (Chemetrics, Inc.) was used for spot DO measurements. The Rhodazine-D™ colorimetric method minimizes atmospheric interaction with the water sampled (White et al. 1990). The sampling system uses partially evacuated oxygen-free glass ampules containing Rhodazine-D™ that are broken along a prescored capillary tip while they are submerged in the water to be analyzed. A portable spectrophotometer which accepts the glass ampule is then used to measure DO after the spectrophotometer has been zeroed using a blank. Water temperature and conductivity were measured with a hand-held meter with a probe that requires a very minimal immersion depth (WTW Multiline P4).

Water velocity and depth at each location were also measured at this time.

Periphyton--Periphyton samples for biomass evaluation were collected proximal to all sample locations. Periphyton samples were collected from rocks with a sampling device made from a modified 30-ml syringe with an inside diameter of 2.06 cm (Porter et al. 1993). Samples were then filtered onto glass-fiber filters. Ash-free-dry-mass was determined using standard methods (Eaton et al. 1995) where filters were dried for 48 hr at 105^{o}C, dry weight determined on an analytical balance, filters ashed at 500^{o}C for 1 hr, and the mass of the residue (ash weight) determined. Ash-free-dry-weight (g/m^{2}) (AFDW) was calculated by subtracting the ash weight from the dry weight of the sample and dividing by the periphyton sample area. Sampling occurred during September, October, and November.

Sedimentation traps--Traps consisted of 500 ml topless nalgene containers (opening was 3.4 cm in diameter) containing 100 marbles (15 mm diameter) as a base substrate. Sedimentation traps were buried in eggplate locations for estimation of fine sediment infiltration. Traps were collected when eggplates were harvested and capped as they were retrieved (Figure 3). Information on particle size of substrate material was obtained from size gradations of dried mineral samples from traps. Samples were oven dried for 24 hrs at 105^{o} C. A set of sieves placed in a mechanical shaker for 15 min was used to sift each diameter class, which were then weighed separately.

Analyses—ANOVA followed by Tukey's test was used to compare hatch numbers of rainbow trout eggs and differences in larval trout lengths between sites and hatchery controls. ANOVA was also used to examine differences in daily DO amplitudes, periphyton biomass, and sediment

between sites. If tests (Shapiro-Wilk) indicated non- normal data, it was transformed prior to analysis using ln(X+1).

Temperature and DO data were compared graphically, while air, surface, and hyporheic temperature response to flow were analyzed using coefficient of variation (CV), multivariate correlation, or quantifying hourly phase changes. Temperature response to a mid-October flow (termed the fall pulse attraction flow) was analyzed by comparing differences between surface and hyporheic water temperatures and with CV calculated from 48 hrs worth of data from a time period prior to the flow (9/29-9/30), during the flow (10/14-10/15), and post-flow (10/29-10/30). The goal was to determine how surface temperatures and flows affected conditions within the hyporheic. Coefficient of variation was used as an indicator of GW intrusion since, in many cases, groundwater exhibits a less variable thermal profile relative to SW influenced zones (e.g., Malcolm et al. 2004). The 25^{th} and 75^{th} quartiles of the proportion of hyporheic CV vs. the surface water CV were calculated to compare hyporheic temperatures at each location. The temporal phase shift of the three distinct 48-hour periods beginning 9/29, 10/14, and 10/29, were evaluated graphically by hour.

Multivariate exploration with correlations was conducted using a standard correlation matrix for temperature and flow. During each of three distinct 10-day periods – the September flow of 10 cms, the October high flow pulse of 20 cms, and the November low flow period of 3 cms, a standard multivariate correlation matrix was generated for correlations between hyporheic temperatures and surface temperatures with air temperature and streamflow. The correlations were estimated based on hourly measurements for each of the three 10-day periods using a pairwise method. A pairwise method simply performs correlations for all rows for each pair of columns containing values (measurements for that hour). The result is a matrix of correlation coefficients that summarizes the strength of the linear relationships between each pair of response variables (hyporheic and surface temperatures) to either air temperature or flow.

The small amount of collected information and absence of DO sensors from half of the locations precluded statistical analysis of environmental variables impact on egg survival.

RESULTS

Egg survival—Numbers of rainbow trout eggs that hatched were significantly lower in egg plates placed in the river (Sites A, B, and C) compared to initial and final controls (ANOVA, $F=37.6$, $P<0.0001$) (Figure 4). Mean hatch numbers at the river sites ranged from 2.3 to 3.3 per eggplate. Average numbers that hatched in initial (15.7 per eggplate) and final (11.5 per eggplate) controls maintained in the hatchery (hatchery water temperature $15^{o}C$) were higher. Hatch date at the San Joaquin Hatchery Facility was October 10^{th} and hatching at the river sites may have been near this date. Similar to eggs in the initial and final controls, a larger group of eggs, which provided eggs for eggplates, at the fish hatchery also experienced relatively high losses (pers. comm. Paul Adelizi, 10/11/2011). Survival of larval trout from hatch to when eggplates (all 0 hatch data omitted) were retrieved, was mostly low at San Joaquin River sites (Site A= 28%, Site B= 88%, Site C= 27%), but ranged from 76-89% in controls. Especially striking were two sites at Site A (A1 and A6) that both had 7 eggs hatch but only a single surviving larval fish when plates were retrieved. At the river sites the best larval fish survival was at Site B where a total of 14 fish were alive at retrieval, whereas only 4 and 5 were alive at Sites A and C. Total survival in initial

and final controls was 83 and 52. If we consider hatch of the initial-control to be base-line, then 73% of the eggs hatched in the final control and the best hatch rate from the river corresponded to 21%.

Mean length of larval fish differed significantly between sites (ANOVA, F=3.52, P=0.0088) Figure 5). Mean lengths were greatest in the initial (23.4 mm/fish) and final (23.2 mm/fish) controls and lowest at Site C (21.9 mm/fish). Significant differences from controls were only detected at Site C.

The most common invertebrate that invaded eggplates in the river (no invertebrates were found in controls) was the chironomid larvae *Phaenopsectra* (Table 1). *Polypedilum* was the next most abundant chironomid. The flatworm *Dugesia* and amphipod *Crangonyx*, were also found in eggplates (Table 1), and were the only potential predators of eggs or alevins detected.

Flow—In the early part of the study, during September, flows were maintained at approximately 9 cms. Except for a few spikes ($\pm$ 5 cms) in early October, flow was not increased until October 11. Flow was maintained at a new level of ca. 20 cms until October 21st, when it was lowered to 10 cms. On November 6th, flows were dropped to between 2 and 3 cms for the rest of the study.

Temporal/longitudinal variability in water temperature—Surface water temperatures appeared to respond to longitudinal warming and to changes in flow (Figure 6). Highest temperatures were observed at Site C and lowest temperatures observed at the gage and Site A through most of the monitored period. Site B temperatures were intermediate. However, when flows were decreased in November, temperatures at Site C were lowest. The lower water volume may have allowed for a greater response to ambient air temperatures at this downstream station, while temperatures at the gage and Site A were still influenced by the nearby reservoir. During the high flows of mid-October, it appeared that differences between the sites were diminished (Figure 6). Higher water volumes likely affected the capacity of ambient air temperatures to influence water temperatures.

Prior to increases (9/29-9/30), flows were held relatively constant at ~9 cms. The temporal dynamics of hyporheic water temperatures strongly followed surface temperature patterns with daily maximums occurring between 16:00-17:00 at Sites A, B, and C. Hyporheic temperatures generally did not lag behind diurnal surface temperature patterns by more that approximately 30 minutes. Due to increasing air temperatures during the 9/29 – 9/30 period, the thermal maxima on 9/29 exhibited a gradual recessional limb rather than a more distinct decrease to nighttime thermal minima. The gradual recessional limb on 9/29 is consistent between surface and hyporheic temperatures, further suggesting the two are closely in phase and driven largely by atmospheric conditions during this period.

For the period 10/14-10/15, flows were increased and held relatively constant at ~20 cms. The temporal dynamics of hyporheic temperatures somewhat followed surface temperature patterns with daily maximums occurring between 15:00pm-16:00 at Site A, and between 16:00-17:00 at Sites B and C. Hyporheic temperatures were typically in phase with respect to timing, with a few exceptions. Site A4 exhibited a 4-5 hour lag to peak thermal maxima compared to surface temperatures. Site B4 exhibited almost no diurnal signal and suggests influence of groundwater

during the high flow period. Sites C5 and C6 exhibited a 3-4 hour lag to peak thermal maxima compared to surface temperatures.

During the post high flow period, 10/29/11-10/30/11, flows were reduced to approximately 10 cms. Temporal dynamics of hyporheic temperatures followed surface temperatures with daily maximums occurring between 4:00-5:00pm at Sites A, B, and C. Sites A4 and A5 exhibited the most distinct lag to peak thermal maxima compared to surface temperatures, on the order of approximately 3 hours. Sites B1 and B4 exhibited a 1-hour lag to peak compared to surface temperatures. Site C hyporheic temperatures did not lag behind surface temperatures by more than 30 minutes, and were generally in phase with surface diurnal minima and maxima.

Hyporheic temperatures relative to surface water temperatures and flows are presented in Figures 7-12 for the three sites. Figures 7-9 show data logged with DO/temperature sensors, while Figures 10-12 represent those using self-contained HOBO loggers. Surface temperatures represented in all graphs are from the single surface DO/temperature sensor at each site. Visually it appeared that there was a response to the high flows in mid-October (Figure 7-12) with minimum surface water temperatures settling at approximately 13.5^{o}C at all of the locations within sites.

The temporal dynamics of surface temperatures strongly followed air temperature patterns with maximums occurring in September and minimums occurring in November (Figure 13). In parallel, hyporheic temperatures were highest in September and lowest in November. Towards the end of the observation period, differences in surface water temperatures and hyporheic temperatures became less distinct, indicating the decreasing day length and lower maximum air temperatures over the course of the experiment.

Site and temporal temperature/flow effects—Temperature responses varied by site and with flow. For the period 09/29/11 - 09/30/11 minimum hyporheic temperature at Site A was 13.3°C, at Site B 14.3°C, and at Site C was 15.3°C. Maximum temperature at Site A was 16.4°C, at Site B 16.84°C, and at Site C was 17.77°C. Hyporheic temperature varied between the six monitored locations by 3.1°C at Site A, 2.6°C at Site B, and 2.4°C at Site C.

Surface water temperature for the same time period varied by more than 2.9°C (range 13.3 to 16.3) at Site A, 2.3°C (range 14.6 to 16.9) at Site B, and 2.0°C (range 15.8 to 17.7) at Site C. With the exception of Site A, the range of temperature variations observed at the 18 hyporheic locations was lower than the range of surface water temperatures. It should be noted that hyporheic temperature variation was measured from 18 locations (6 at each site), while surface water temperatures were measured from only a single location at each site. The range of temperatures from spot measurements of surface water temperatures at locations was very small (see *Surface water temperature range* section).

During the high flow period 10/14/11 - 10/15/11 minimum hyporheic temperature at Site A was 13.4°C, at Site B was 13.4°C, and at Site C was 13.2°C. Maximum temperature at Site A was 14.9°C, at Site B was 15.4°C, and at Site C was 15.7°C. Hyporheic temperature varied by 1.5°C at Site A, 2.1°C at Site B, and 2.5°C at Site C.

Surface water temperature (10/14-10/15) varied by 1.4°C (range 13.4 to 14.8) at Site A, 2.1°C (range 13.4 to 15.5) at Site B, and 2.1°C (range 13.6 to 15.7) at Site C. With the exception of Site B, the range of temperature variations observed in the 18 hyporheic locations was greater than the range of surface water temperatures. The range of surface and hyporheic temperatures were diminished during the high flow period for all sites, indicating either greater hydraulic conductivity between surface waters and hyporheic waters, or lesser influence from atmospheric conditions due to increased flow volume.

During the period 10/29/11 - 10/30/11 when the high flow pulse was diminished, minimum hyporheic temperature at Site A was 12.9°C, at Site B was 12.9°C, and at Site C was 13.2°C. Maximum temperature at Site A was 15.3°C, at Site B was 15.0°C, and at Site C was 15.5°C. Hyporheic temperature varied by 2.4°C at Site A, 2.0°C at Site B, and 2.3°C at Site C.

Surface water temperature (10/29-10/30) varied by 2.5°C (range 12.83 to 15.29) at Site A, 2.1°C (range 12.9 to 15.1) at Site B, and 1.6°C (range 13.6 to 15.4) at Site C.

With the exception of Site C, the range of temperature variation observed at the 18 hyporheic locations was again greater than the range of surface water temperatures following the high flow period. Streamflow during the early period (09/29/11-09/30/11) and the late period (10/29/11-10/30/11) was nearly the same, at approximately 10 cms (350 cfs). However, the range of temperatures at all three sites was greater in the end of September than in the end of October for both hyporheic and surface water.

Location and GW/SW effects --Temperatures at the various hyporheic locations appeared to have a variety of patterns. In many locations it appeared that maximum hyporheic temperatures were mostly lower than surface water temperatures. However, there were exceptions. At Site A, hyporheic temperatures were generally cooler than surface temperatures, with the exception of A3 (Figure 7b) and A5 (Figure 10b) during the initial September flows and during mid-October high flows. During the three periods for which data were compared, temperatures at A3 were indeed, on average, slightly higher than surface water temperatures. Hyporheic temperatures ranged from an increase over surface water temperatures of 0.08^{o}C from 10/29-10/30 to an increase of only 0.03^{o}C from 9/29-9/30. In all cases, hyporheic temperatures were lagged with respect to diurnal variation of surface temperatures.

Table 2 presents CV for the various locations with an emphasis on which measurements were relatively extreme (i.e., > 75th and <25th percentiles). We suggest that this gives some evidence of which locations provided a surface-dominated response versus those with a potential groundwater signal. It seems that locations with GW signals are most common at the most upstream site, while these signals are uncommon downstream at Site C, and are intermediate at Site B (Table 2).

From 9/29-9/30 the CV at Site A ranged from 4.66 at A1 (lowest) to 6.97 at the surface (highest) (Table 2). In two cases (A1 and A6) the hyporheic temperature variability was much lower than surface water variability (Table 2). During mid-October high flows, hyporheic temperatures at locations A4 (Figure 7c), A1 (Figure 10a), and A6 (Figure 10c) demonstrated decreased variability suggesting groundwater inflow (also see Table 2). Variability at A4 was much less during the mid-October flows and CV at A4 was calculated as 1.50 for the period 10/14-10/15 while the other locations ranged from 2.35 to 3.40 (Table 2). Following high flows, from 10/29-

10/30, CV at A1 was 3.03 and A4 was 3.57, while the remaining locations exhibited CVs from 4.22 to 5.76 (Table 2). It appears that A1, A4, A5, and A6 all had exceptionally low hyporheic temperature variability at some point during the studied periods.

Both A1 and A5 are lagged with respect to diurnal temperature variability during the late period, but A1 and A6 are lagged during the early period. During high flows, all hyporheic temperatures are slightly lagged behind surface temperatures.

At Site B, hyporheic temperatures more closely mimicked surface temperatures with hyporheic temperatures similar or only slightly cooler than surface temperatures (Figures 8 and 11). As the season progressed, however, B1 (hyporheic 0.02^{o}C warmer than surface temperatures) from 10/14-10/15 and then both B1 (0.10^{o}C warmer) and B2 (0.06^{o}C warmer) from 10/29-10/30, became, on average, slightly warmer than surface water temperatures. Location B4 (Figure 11b), however, had a dramatic temperature response to increased flows in mid-October and exhibited a CV of 0.4 (Table 2) during the high flow period, suggesting a diminished influence of surface conditions. This diminished variability continued during the late period of 10/29-10/30 and was also exhibited at location B1 (Table 2). During the late period of 10/29-10/30, hyporheic temperatures became slightly cooler than surface temperatures, but continued to mimic surface diurnal variability.

B4 is lagged with respect to diurnal variability during all three periods. B6 is lagged behind surface temperatures during the high flow and late period, but more closely mimics surface variability during the early period.

At Site C, hyporheic temperatures most closely mimicked surface water temperatures in terms of magnitude and variability (Figures 9 and 12). Site C5 exhibited the lowest CV of 2.84 (Table 2, and also see Figure 12c) during high flows, while the rest of the hyporheic temperatures at site C appeared to be little influenced by flow regime change.

C5 is lagged with respect to diurnal variability during all three periods. However, the most significant lag occurs by C5 during the high flow period. Site C1 also exhibits a lagged diurnal signal during the high flow and late period, but hyporheic temperatures were most closely in phase with surface temperatures during the early period.

In general, hyporheic temperatures exhibited a decrease in the amplitude of diurnal temperature fluctuations relative to surface water temperatures. Hyporheic temperatures, however, varied quite a bit on a daily basis. Temperatures were cooler than surface water temperatures most times and then sometimes warmer than surface water temperatures within a short period. As an example we present data from Site B showing the diurnal change in hyporheic temperature relative to surface water temperature (Figure 14). The three regimes presented have very different fluctuating temperature patterns. Mean hyporheic temperatures, however, for the period presented were very similar, ranging from 15.75 to 15.81^{o}C. Mean surface water temperature for the same period was 15.84^{o}C.

Surface water temperature range—Comparisons of surface and hyporheic temperatures may have been confounded by the single surface water sensor used for temperature derivation. Limited spot measurements of surface water temperatures at the various locations indicated that there was some spatial variability, with an average temperature range of 0.53^{o}C calculated from

all sites, locations and all sampling dates. Spot temperatures were also collected at surface water DO/temperature probes. These measurements were always within the range generated from all locations within a site on a given date. These data, however, do suggest that the differences from continuous monitoring data indicating warmer temperatures in the hyporheic may be an artifact from collecting surface temperature data from only a single location.

Air temperature— Comparisons of hyporheic temperature response to flow over time may have been confounded by the relative influence of air temperature from September thru November.

The correlation coefficients for each site and each of three periods is shown in a graphical format in Figure 15 and summarizes the strength of the linear relationships between each pair of response variables (hyporheic temperatures) with flow and air temperature for the early period, the high flow period, and the later low flow period.

In general, hyporheic temperatures were more closely correlated to air temperatures during September and October, with weaker correlation during the low-flow period during November. Hyporheic temperatures were more closely correlated to flow during the high flow period in October, and less so during the September and November low flow periods. While higher flow volume could mean less air temperature influence, hyporheic temperature was not consistent during this period of time. Based on the results of this study, the timing of high flows (20 cms) and low flows (3 cms) will be important in terms of its relative influence to hyporheic temperatures.

Spot measurements of variables—Dissolved oxygen measurements from September and November indicated little difference between surface and hyporheic measurements (Table 3). Differences in mean values between the groups ranged from 0.1 to 2.2 mg/L. Overall, specific conductance measurements were similar between surface and hyporheic measurements with surface measurements averaging 22.5 µS/cm (range 20.0-26.0) while hyporheic measurements averaged 23.6 µS/cm (range 20.0-35.0). Larger differences were measured when comparing velocity and depth between the two months (Table 3). Mean velocities and depths decreased greatly at Site C in November (Table 3).

Continuous DO measurements—Hyporheic DO concentrations differed graphically between locations at Site A (Figure 16). A2 appeared to be closely tied to surface water DO, while DO at A3 and A4 were typically lower than those measured at the surface (Figure 16). The response of DO to the increased mid-October flow event was variable, with increases observed at both A2 and A3 (Figure 16a and 16b), while a decrease in DO was seen at A4 that was roughly coincident with the increased flow (16c). This appeared to be coupled with the decreased temperature variability that occurred at A4 (Figure 7c). Especially low DO occurred in the hyporheic during the extremely low flows in mid-November (Figure 16). Lowest measured DO was between 5 and 6 mg/L.

Site B hyporheic DO also varied with location (Figure 17). All three of the monitored locations responded to the increased flow with increased hyporheic DO. Two of the locations (Figure 17b and 17c) had hyporheic DO higher than that measured at the surface. This pattern, however, changed at B5 (Figure 17c) after the high flows were completed when DO became lower in the hyporheic. Lowest hyporheic DO was 6 mg/L recorded at A5. During the lowest flows, surface DO plummeted, perhaps indicating that the sensor was exposed to lentic conditions.

Hyporheic DO at site C was sometimes higher than surface water measurements (Figure 18). In two of the three sites (Figure 18a and 18b) DO remained at relatively high concentrations throughout the study period. DO at C6 (Figure 18c), however, declined dramatically to 2.12 mg/L in association with the high flow period in October, and then declined again with the lower flows in November (Figure 18c).

Diurnal variation in DO—Patterns for a portion of data are presented in Figures 19-21). Data suggests that hyporheic DO concentrations tracked surface concentrations for this time period. However, there appeared to be differences between locations in gradients between surface and hyporheic DO. The large gradients such as at location A4 in Figure 19c may indicate slow intragravel flow or intermittent exposure to groundwater (also suggested by temperature CV, Table 2). Other locations, such as A2 (Figure 19a), B2 and B5 (Figure 20b-20C), and C2 and C6 (Figure 21a and 21c) seem to indicate a very tight linkage between surface water and hyporheic water. The diurnal variation suggests a linkage with periphyton biomass since peaks in DO occurred during daytime hours in the afternoon, while the minima was in the morning, just before dawn (Figures 19-21). Mean daily DO amplitudes were relatively small, with mean amplitudes at Site A for the period 9/23-11/6 of 1.45 mg/L, at Site B of 1.25 mg/L, and at Site C of 1.18 mg/L. Mean amplitudes differed significantly ($F=10.1$, $P=0.0001$) with Site A differing significantly from both Sites B and C, while the two furthest downstream sites did not differ from each other (Tukey HSD, P value=0.05). It seems unlikely that the diurnal shifts were related to water temperature since peak DO was associated with warmest water temperatures (Figure 22).

Periphyton biomass—Periphyton biomass (Figure 23) appeared to vary dramatically between the first two sites (A and B) and Site C, the furthest downstream site. Mean values differed between all sites (ln (X+1) transformation, $F=45.7$, $P<0.0001$) with Site A (mean biomass=264 g/m^2), Site B (mean biomass=169 g/m^2), and Site C (mean biomass=5.6 g/m^2) all differing significantly from each other (Tukey HSD test, $P<0.05$).

Sediment—The amount of fine sediment (by weight, fraction retained on < 2 mm screen) collected in sediment traps ranged from 8.1-87.6 kg/m^2. No significant differences in weight of fine sediment were detected between sites ($F= 0.65$, $P=0.5394$). Average weight for the three sites was 17.3 kg/m^2 at Site A, 29.5 kg.m^2 at Site B, and 30.7 kg/m^2 at Site C.

DISCUSSION

Temperature

Hyporheic water temperatures were likely too high for successful hatching of rainbow trout eggs. Maximum temperatures at the time when eggplates were transferred (late September) ranged from ca. 16.5 to 18.0^{o}C at the three sites. Hatching success of rainbow trout eggs has been found to be highest (90%) at 10-12°C and declines to 0% survival at 18.5°C (Figure 2a, Humpesch 1985).

On the basis of a literature review, McCullough et al. (2001) concluded that temperatures in the range of 7-10°C are optimal for incubation and embryonic development of rainbow trout; temperatures above 16°C result in very poor (7%) survival. For salmon eggs incubated at 16°C,

mortality occurring post emergence can be much more severe than that occurring prior to emergence because of physiological difficulty in completing yolk absorption (Jewett 1970, as cited by CDWR 1988). The SJRRP (2010) considers temperatures $\geq 15.6^{o}$ C as lethal for egg incubation.

The optimal temperature for successful Chinook salmon egg incubation of $\leq 13^{o}$C (Table 3-1, SJRRP 2010) did not occur at San Joaquin River sites until November. Of interest in this study is that initially the furthest downstream site had the warmest temperature, while at the end of the study the most upstream site had the warmest temperature. Optimal temperatures of $\leq 13^{o}$C (for salmon egg incubation) were only present (consistently) towards the end of the study and only occurred at the furthest downstream site.

We observed diminished variability of temperatures toward the end of the experiment. The mobilization and deposition of fine sediment during the high flow period may have diminished permeability between gravels in the hyporheic during the later study period. Diminished permeability has been correlated to lower conductivity, longer residence time of intragravel pore water, resulting in buffered connectivity to surface water.

Dissolved oxygen

Critical concentrations of DO for some salmonid (steelhead trout) eggs increase with increasing temperature (Rombough 1988). Critical oxygen concentrations for steelhead trout were found to be highest immediately before hatching and ranged from 7.5 to 9.7 mg/L depending upon water temperature (Rombough 1988). Rombough (1988) suggests that one half of the critical level could be considered the incipient lethal level. This would correspond to a DO value of around 5 mg/L at a temperature of 15^{o}C observed around the time of hatching. In most cases hyporheic DO in the San Joaquin River was higher than this value.

The average DO value for **no production impairment** of salmonid eggs in gravel has been set by the Environmental Protection Agency (EPA 1986) at > 8 mg/L, and hyporheic measurements in the San Joaquin River were often below this level. Measurements at the **slight to severe production impairment** (< 6 mg/L DO) level also occurred. However, in many cases these values happened post-hatch (if spring Chinook spawn in September) when alevins may be able to move and avoid areas of low DO. The low DO that we observed in November could impact other runs of Chinook salmon. The Washington State Department of Ecology (WDOE 2002) has found that growth is reduced by 25% when salmon eggs are incubated at 6 mg/L DO. WDOE (2002) notes that field studies on emergence consistently cite intragravel oxygen concentrations of 8 mg/L or greater as being necessary for superior health and survival, oxygen concentrations below 6-7 mg/L result in a 50% reduction in survival through emergence, and oxygen concentrations below 5 mg/L result in negligible survival. Continuous measurements of DO in the San Joaquin River hyporheic indicated that 2 of the 9 hyporheic locations monitored for DO achieved concentrations close to or below 5 mg/L.

Invertebrates

Invertebrates were present in many of the eggplates used in the San Joaquin River. The chironomids *Phaenopsectra* along with *Polypedilum* are often considered shredders or

detritivores and were likely feeding on decomposing eggs or alevins in the eggplates. *Polypedilum* has been previously documented as a detritivore that feeds on decomposing salmon eggs (Elliott and Bartoo 1981). Chironomids were especially abundant in salmon egg baskets 30 cm down in the substrate of Deer Creek, California (Bowen and Nelson 2003). The flatworm *Dugesia* was also found in eggplates and Newburg (1974) found this organism to be an important predator of fish eggs. Another potential predator, the amphipod *Crangonyx* also occurred in eggplates. While amphipods are often considered to be detritivores, this presumed role has been challenged (Dick et al. 2005). MacNeil et al. (1997) indicate that amphipods may be active predators of freshwater fish and Schwartz (1991) considered *Crangonyx* to be a facultative predator. *Crangonyx* has only been detected in hyporheic samples in this part of the San Joaquin River (Nelson and Reed 2011). Both *Dugesia* and *Crangonyx* were relatively common in San Joaquin River hyporheic samples (Nelson and Reed 2011) and were found at all of the present study sites. In studies of *Dugesia* impacts on walleye (*Stizostedion vitreum*) eggs, baskets without *Dugesia* experienced survival rates of 61-81%, while those with *Dugesia* were lower at 32-34% (Newburg 1974).

Sediment

Reduced redd interstitial velocities, which may affect salmonid egg survival (see Malcolm et al. 2011), were observed in a Canadian river whenever a runoff event resulted in more than 7 kg/m^2 of sand (particle size < 2mm) being deposited (Zimmermann and La Pointe 2005). All of the values recorded from our study were greater than this value. Some of the low DO values that appeared in redds after the mid-October high flow may have partially been the result of sediment entering redds. Sear (1993) found that higher discharge and velocities resulted in infiltration of fines deeper into redds. Mean weight of sand found in sediment traps at the two furthest downstream stations were close to 30 kg/m^2. Not all of this was from sediment transport because some fine sediment entered the traps when they were initially buried in the hyporheic. Sediment may also impact near-surface interstices and prevent alevins from emerging from gravels (Lisle and Lewis 1992). Gravel cleaning operations have decreased fine sediments and resulted in hyporheic DO concentrations being maintained at high levels (Meyer et al. 2008).

Periphyton biomass

There was a range of periphyton biomass (AFDW) at the three sites with highest values at Site A and lowest at Site C. Mean values recorded at Site A (260 g/m^2) and Site B (169 g/m^2) were fairly high, while biomass from Site C (5.6 g/m^2) was much lower. Mean daily DO amplitudes differed between the sites, with highest amplitudes at the two furthest upstream sites. The largest difference, however, was only 1.45 mg/L DO indicating very little response to periphyton biomass. Reaeration in these riffle areas was probably sufficient to make up for most of the DO deficit that occurred at night from plant respiration. Periphyton biomass in the San Joaquin was roughly similar to that found to cause a 9 mg DO/L daily variation observed in a river in Switzerland, where dry plant biomass was > 300 g/m^2 (Kaenel et al. 2000). This river, however, was nutrient enriched which may have played some role in the large diurnal changes in oxygen concentrations.

It is possible that the large amounts of periphyton at the two upstream sites could inhibit the exchange of surface water into the hyporheic environment by forming a somewhat impenetrable mat over the substrate. Sloughing of periphyton has been observed to decrease river bed

permeability on occasion (Ibisch and Borchardt 2002). The lower amounts of sediment collected from traps at Site A, while not significantly different from the other sites, may be suggestive of resistance to infiltration of deeper sediments by fine sediment, perhaps also because of a shield of periphyton (e.g., Ibisch et al. 2009).

Flow/groundwater-surface water interactions

Flow was manipulated in the San Joaquin River so that high flows during the study occurred in mid-October. It is generally believed that high flows increase the relative contribution of surface water in the hyporheic zone (e.g., Greig et al. 2007). Data from the present study do not support this assumption, as narrowed hyporheic temperature measurements indicated the increased presence of groundwater during high flows at several of the monitored San Joaquin River locations. Dissolved oxygen also declined at some locations as flow increased in mid-October, also suggesting the presence of anoxic GW. Long contact with the GW influences the hyporheic environment and may lead to salmonid embryo death or sublethal effects such as delayed emergence or small body size (Malcolm et al. 2011).

Low flow in November appeared to impact the hyporheic environment, with lower DO occurring at this time. The decreased water depths and velocities that occurred in conjunction with these lower flows may have affected the ability of surface water to enter the shallow hyporheic zone. Wickett (1958) in a review of environmental factors affecting salmon production indicated that oxygen concentrations in redds vary with surface water velocity. Often, decreased river stage will result in an increase in the percent of low DO GW found in the hyporheic zone (Arntzen et al. 2006). The sensitivity of egg survival to fine sediments, which may be introduced to redds under high flow conditions, may increase under low flow conditions (Reiser and White 1990).

Others have found negligible relationships between river discharge and GW/SW exchange (Hanrahan 2008), suggesting that larger scale processes, including such things as pool-riffle sequences, may control hydrological exchanges between SW and GW. Hanrahan (2008) further suggests that there may be differences between high gradient and low gradient rivers in susceptibility to flux reversals related to whether the hydraulic gradient is dominated by longitudinal or lateral forces. A variety of causes at locations in the San Joaquin River result in the differing impacts to salmonid embryos and alevins. The end result seems to be increased hyporheic GW which could lead to mortalities in some cases. Timing of GW exposure could be paramount to the level of impact.

Formation of hummocks from aquatic plants may also alter GW/SW interactions. Sand deposition in association with plants at the surface may form patterns of deeper bed water upwelling through river substrates (White 1990). This sort of convective pattern could explain some of the patterns observed in our study where it seemed that GW induced temperature profiles were observed more commonly at the upstream sites that contained large amounts of periphyton.

Conclusions

Temperature, at the time of year studied, seems a critical impediment to egg survival in this system. The assumed egg incubation initiation for spring-run Chinook salmon of August in the San Joaquin River Basin (Fisher 1994, SJRRP 2010) is probably infeasible given the observed

temperatures. A recently discovered memorandum (Department of Fish and Game 1951) suggests that the historical timing of runs may have been very different from that assumed for the present study and states that spring-run fish spawned in October and November, while spawning of the fall-run occurred as late in the spawning season as January. This timing certainly is supported by the temperature data that we collected. Perhaps of some importance to salmon restoration is the flip-flop observed in surface water temperatures where sites closest to the dam were coolest in September and warmest in November. Winter-warm conditions often occur below deep-release reservoirs (Ward 1976). This observation is likely dependent upon the flow regime and its response to air temperature (e.g. Webb et al. 2003) but might also indicate that further downstream sites are more conducive to salmon egg survival rather than, as is often assumed, locations closer to the dam.

Dissolved oxygen in the hyporheic was relatively high except in response to either high flows which increased GW interactions at some locations or in response to low flows late in the season which almost universally decreased hyporheic DO's, perhaps as a response to decreased velocities. These decreased velocities likely decrease the proportion of SW in the hyporheic. Flows of ca. 10 cms, observed early in the study, appeared to largely maintain DO in a desirable range. In some cases it appeared that the return to 10 cms post- high flow improved DO that had declined during high flows. The large amounts of periphyton may indirectly impact DO in the hyporheic by decreasing interactions with SW and driving GW upward into the shallow hyporheic. Salmonid life history information seems to suggest that high DO is especially important at the time of egg hatching. While alevins are also sensitive to low DO, they may successfully move away from deleterious environments, ultimately allowing for successful emergence of larval salmon.

To support salmon egg survival in this system it seems that a flow of 10 cms during spawning and until hatch is desirable. Higher and lower flows may have deleterious effects, with some of the impact of flows amplified by periphyton at the upstream sites and intrusion of fine sediment post high flow. Mechanical disturbance of periphyton prior to spawning may be necessary if more exchange of SW to GW is desired. This could be a difficult task as the large flows of 200 cms from early in 2011 did not appear to impact periphyton biomass to any great degree (personal observation). After hatching, flows could probably be reduced for a time, if extremely low embryo-damaging winter-time temperatures can be avoided. It should be recognized that a range of flows is likely healthy for the system overall. However, the limited data we have suggests the significance of avoiding higher flows we observed during the studied period to increase egg survival. Decisions would need to be made on whether attractant flows for adults or increased egg survival were of more importance at that time of year. Timing of flows would need to be adjusted to take into consideration both spring and fall-runs if recovery of both populations is deemed feasible. Timing of pulse flows may also need to adjust according to air temperatures. As shown by this study, the influence of cooling from air temperature changes over the course of the study and may outweigh the heating or cooling caused by a high or low flow pulse, (i.e. a dry, warm November may counteract the cooling effect of a 20-cms pulse to surface water and hyporheic temperatures). To generalize relational trends between air surface water and hyporheic temperature, 10-day averages cluster all 18 sites for three distinct periods. During September 10-cms flows the mean air temperature was 25 ^{o}C, mean surface water temperature was 15.5^{o}C, and mean hyporheic temperature was 15.5^{o}C. During the October 20-cms flow mean air temperature was 22^{o}C, mean surface water temperature was 14.4^{o}C, and mean

hyporheic temperature was 14.4°C. The November 3-cms flow resulted in mean air temperature of 12.5°C, surface water temperature of 13.4°C, and mean hyporheic temperature of 13.5°C. Over time, air temperatures from September to November declined by approximately 13°C, with a greater decline from October to November. Both surface and hyporheic water temperatures declined on the order of approximately 1°C per month from September to November. Primary controls to subsurface temperature include air temperature, flow volume, and temperature of upstream surface and reservoir water. Air temperature was significantly higher than surface and hyporheic water temperatures in September, while air temperature was only slightly lower than water temperatures in November. The effect that air temperature has upon water temperature will depend largely on flow volume at any given time period.

It may be of value to conduct subsequent studies that are similar but expanded to obtain information on different water year types (flow regimes) with different air temperatures to further evaluate the relationships between flow, temperature, and conditions in the hyporheic environment. It is unclear what impact invertebrates may have on salmon eggs or alevins and further study is needed in this area. Also needed are studies than examine the ability of salmon larvae to emerge from the San Joaquin sediments. This study has revealed variability in hyporheic conditions is high and potentially has important consequences for stream ecology and for future hyporheic studies.

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REFERENCES

Arntzen, E.V., D.R. Geist, and P.E. Dresel. 2006. Effects of fluctuating river flow on groundwater/surface water mixing in the hyporheic zone of a regulated, large cobble bed river. River Research and Applications 22:937-946.

Bowen, M.D. and S.M. Nelson. 2003. Environmental variables associated with a Chinook salmon redd in Deer Creek, California. California Fish and Game 89(4):176-186.

Brown, A.F. and M. Diamond. 1984. The consumption of rainbow trout (*Salmo gairdneri* Richardson) eggs by macroinvertebrates in the field. Freshwater Biology 14:211-215.

Brown, C. and D. Hallock. 2009. Washington State Dissolved Oxygen Standard: A Review and Discussion of Freshwater Intragravel Criteria Development. Publication No. 09-03-039. Environmental Assessment Program, Washington State Department of Ecology, Olympia, Washington 98504-7710.

Bryce, S.A., G. A. Lomnicky, and P. R. Kaufmann. 2010. Protecting sediment-sensitive aquatic species in mountain streams through the application of biologically based streambed sediment criteria. J. N. Am. Benthol. Soc. 29(2):657–672.

California Department of Water Resources (CDWR). 1988. Water temperature effects on chinook salmon (*Oncorhynchus tshawytscha*) with emphasis on the Sacramento River: a literature review. Northern District Office Report, Red Bluff, California. 42 p.

Darwin, Charles (1859). *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (1st ed.). London: John Murray. ISBN 1-4353-9386-4. http://darwin-online.org.uk/content/frameset?itemID=F373&viewtype=text&pageseq=1. Retrieved 16 February 2012.

Department of Fish and Game. 1951. Fish and game water problems of the upper San Joaquin River: Potential values and needs. State of California memorandum pp.1-11.

DeVries, P. 1997. Riverine salmonid egg burial depths: review of published data and implications for scour. Canadian Journal of Fisheries and Aquatic Sciences 54: 1685-1698.

Dick, J.T.A., M.P. Johnson, S. McCambridge, J. Johnson, V. E. E. Carson, D. W. Kelly, and C. MacNeil. 2005. Predatory nature of the littoral amphipod *Echinogammarus marinus*: gut content analysis and effects of alternative food and substrate heterogeneity. Marine Ecology Progress Series 291:151–158.

Eaton, A.D., L.S. Clesceri, and A.E. Greenburg (eds.). 1995. Standard methods for the examination of water and wastewater. Baltimore, Maryland, American Public Health Association, United Book Press, Inc.

Elliott, S.T. and R. Bartoo. 1981. Relation of Larval Polypedilum (Diptera: Chironomidae) to Pink Salmon Eggs and Alevins in an Alaskan Stream. The Progressive Fish-Culturist. 43(4): 220-221.

Environmental Protection Agency (USEPA). 1986. Ambient Water Quality Criteria for Dissolved Oxygen. Office of Water. EPA 440/5-86-003. 35pp. Available online at: <http://www.epa.gov/cgi-bin/claritgw?op-Display&document=clserv:OAR:0579; &rank=4&template=epa>. Website accessed July 5, 2004.

Fisher, F.W. 1994. Past and present status of Central Valley Chinook salmon. Conservation Biology 8: 870-873.

Geist, D.R. 2000. Hyporheic discharge of river water into Chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 57:1647-1656.

Greenberg, L.A. 1992. Field survival of brown trout eggs in a perforated incubation container. North American Journal of Fisheries Management 12:833-835.

Greig, S.M., D.A. Sear, and P.A. Carling. 2007. A review of factors influencing the availability of dissolved oxygen to incubating salmonid embryos. Hydrological Processes 21:323-334.

Hanrahan, T.P. 2008. Effects of river discharge on hyporheic exchange flows in salmon spawning areas of a large gravel-bed river. Hydrological Processes 22:127-141.

Humpesch, U.H. 1985. Inter- and intra-specific variation in hatching success and embryonic development of five species of salmonids and *Thymallus thymallus*. Arch. Hydrobiol. 104(1):129-144.

Ibisch, R.B. and D. Borchardt. 2002. Effects of periphyton biomass and suspended solids on river bed permeability and hyporheic oxygen balances. Verh. Internat. Verein. Limnol. 28:1875-1979.

Ibisch, R.B., I. Seydell, and D. Borchardt. 2009. Influence of periphyton biomass dynamics on biological colmation processes in the hyporheic zone of a gravel bed river (River Lahn, Germany). Advanc. Limnol. 61:87-104.

Kaenel, B.R., H. Buehrer, and U. Uehlinger. 2000. Effects of plant management on stream metabolism and oxygen balance in streams. Freshwater Biology 45:85-95.

Kondolf, G.M. 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society 129:262-281.

Lisle, T.E. 1989. Effects of woody debris on anadromous salmonid habitat, Prince of Wales Island, southeast Alaska. North American Journal of Fisheries Management 6: 538-550.

Lisle, T.E. and J.Lewis. 1992. Effects of sediment transport on survival of salmonid embryos in a natural stream: a simulation approach. Can. J. Fish. Aquat. Sci. 49:2337-2344.

MacNeil, C., J. T. A. Dick, and R. W. Elwood. 1997. The trophic ecology of freshwater *Gammarus* spp. (Crustacea:Amphipoda): problems and perspectives concerning the functional feeding group concept Biol. Rev. 72:349-364.

McCullough, D.A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon**.** U.S. Environmental Protection Agency EPA 910-R-99-010 Seattle, Washington

McCullough, D., S. Spalding, D. Sturdevant, and M. Hicks. 2001. Issue Paper 5: Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids. U.S. Environmental Protection Agency. EPA-910-D-01-005.

McDonald, J.G. 1960. A possible source of error in assessing the survival of Pacific salmon eggs by redd sampling. The Canadian Fish Culturist 26:27-30.

Malcolm, I.A., A. Youngson, and C. Soulsby. 2003. Survival of salmonid eggs in gravel bed streams: effects of groundwater-surface water interactions. River Research and Applications 19(4):303-316.

Malcolm, I.A., C. Soulsby, A.F. Youngson, D.M. Hannah, I.S. McLaren, and A. Thorne. 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival. Hydrological Processes 18:1543-1560.

Malcolm, I.A., C. Soulsby, and A.F. Youngson. 2006. High-frequency logging technologies reveal state-dependent hyporheic process dynamics: implications for hydroecological studies. Hydrological Processes 20:615-622.

Malcolm, I.A., C. Soulsby, A.F. Youngson, and D. Tetzlaff. 2009. Fine scale variability of hyporheic hydrochemistry in salmon spawning gravels with contrasting groundwater-surface water interactions. Hydrogeology Journal 17:161-174.

Malcolm, I.A., A.F. Youngson, C. Soulsby, C. Imholt, and R.J. Fryer. 2011. Is interstitial velocity a good predictor of salmonid embryo survival? Transactions of the American Fisheries Society 140:898-904.

Meritt , R. W. and K. W. Cummins (Eds.), 1996: An introduction to the aquatic insects of North America, 3rd ed. Kendall/Hunt Publishing Company, Dubuque, Iowa.

Meyer, E.I., O Niepagenkemper, F. Molls, and B. Spänhoff. 2008. An experimental assessment of the effectiveness of gravel cleaning operations in improving hyporheic water quality in potential salmonid spawning areas. River Research and Applications 24:119-131.

Nelson S.M. and G.K. Reed. 2011. Observations on the Hyporheic Environment along the San Joaquin River below Friant Dam. Bureau of Reclamation, Technical Service Center. Technical Memorandum No. 86-68220-11-03.

Newburg, H.J. 1974. Planarians as a mortality factor on spawned fish eggs. The Progressive Fish-Culturist 36:4, 227-230.

Porter, S.D., T.F. Cuffney, M.E. Gurtz, and M.R. Meador. 1993. Methods for collecting algal samples as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 93-409, 39 pp.

Reiser, D.W. and R.G. White. 1990. Effects of streamflow reduction on Chinook salmon egg incubation and fry quality. Rivers 1(2):110-118.

Rombough, P.J. 1988. Growth, aerobic metabolism, and dissolved oxygen requirements of embryos and alevins of steelhead, *Salmo gairdneri*. Can. J. Zool. 66:651-660.

San Joaquin River Restoration Program (SJRRP). 2010. Conceptual Models of Stressors and Limiting Factors for San Joaquin River Chinook Salmon Fisheries. Exhibit A. Management Plan: A Framework for Adaptive Management in the San Joaquin River Restoration Program.

Schwartz, S.S. 1992. Benthic predators and zooplanktonic prey: predation by *Crangonyx shoemakeri* (Crustacea; Amphipoda) on *Daphnia obtusa* (Crustacea; Cladocera). Hydrobiologia 237:25-30.

Sear, D.A. 1993. Fine sediment infiltration into gravel spawning beds within a regulated river experiencing floods: ecological implications for salmonids. Regulated Rivers: Research and Management 8:373-390.

Soulsby, C., I.A. Malcolm, and A.F. Youngson. 2001. Hydrochemistry of the hyporheic zone in salmon spawning gravels: a preliminary assessment in a degraded agricultural stream. Regulated Rivers: Research & Management 17:651-665.

Tappel, P. D. and T. C. Bjornn. 1983. A new method of relating size of spawning gravel to salmonid embryo survival. North American Journal of Fisheries Management 3: 123-135.

Ward, J.V. 1976. Comparative limnology of differentially regulated sections of a Colorado mountain river. Arch. Hydrobiol. 78(3):319-342.

Washington State Department of Ecology (WDOE). 2002. Evaluating Criteria for the Protection of Freshwater Aquatic Life in Washington's Surface Water Quality Standards: Dissolved Oxygen. Draft Discussion Paper and Literature Summary. Publication Number 00-10-071. 90pp.

Webb, B.W., P.D. Clack, and D.E. Walling. 2003. Water-air temperature relationships in a Devon river system and the role of flow. Hydrological Processes 17:3069-3084.

White, A.F., Peterson, M.L., and R.D. Solbau. 1990. Measurement and interpretation of low levels of dissolved oxygen in ground water. Ground Water. 28(4):584–590.

White, D.S. 1990. Biological relationships to convective flow patterns within stream beds. Hydrobiologia 196:149-158.

Wickett, W.P. 1954. The oxygen supply to salmon eggs in spawning beds. J. Fish. Res. Bd. Canada 11(6):933-953.

Zimmermann, A.E. and M. LaPointe. 2005. Intergranular flow velocity through salmonid redds: sensitivity to fines infiltration from low intensity sediment transport events. River Research and Applications 21:865-881.

Table 1. Invertebrates found in eggplates from the San Joaquin River.

Site	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	Total all plates
EPHEMEROPTERA																			
Baetidae																			
Baetis sp.													1						1
DIPTERA																			
Chironomidae																			
Orthocladiinae																			
Cricotopus sp.																	1		1
Parakiefferiella sp.													1						1
Chironomini																			
Phaenopsectra sp.	5		7	4	1		2	5		1	4	27	3	2	2	10	8	6	87
Polypedilum sp.								10					1						11
Tanytarsini																			
Tanytarsus sp.												2				1	1		4
TURBELLARIA																			
Dugesiidae																			
Dugesia sp.					3	2					2	1		1		1	1		11
OLIGOCHAETA																			
Lumbriculidae			1		1														2
AMPHIPODA																			
Crangonyctidae																			
Crangonyx sp.									1					1				2	4
Total number of taxa	1	0	2	1	3	1	1	2	1	1	2	3	4	3	1	3	4	2	
Total number of organisms	5	0	8	4	5	2	2	15	1	1	6	30	6	4	2	12	11	8	

Table 2. Coeficient of variation (CV) of temperature measurements from select flow periods on the San Joaquin River. The proportion of hyporheic CV's to surface CV's is also presented. Percentiles were calculated from proportion data and percentiles ≥ 75th and ≤ 25th determined. Hyporheic temperature CV's corresponding to the percentile data are presented with those < 25th in red and > 75th in green. Those data with exceptionally small CV's may represent GW influenced sites while those with exceptionally large CV's may be more SW oriented.

	Low flow/September CV	Proportion hyporheic/ surface water CV	High flow/Mid-October CV	Proportion hyporheic/ surface water CV	Low flow/Late-October CV	Proportion hyporheic/ surface water CV
Site A						
Surface	6.97		3.58		5.79	
A1	**4.66**	0.67	**2.35**	0.66	**3.03**	0.52
A2	6.93	0.99	3.40	0.95	5.76	0.99
A3	6.46	0.93	3.20	0.89	4.95	0.85
A4	5.4	0.77	**1.50**	0.42	**3.57**	0.62
A5	6.79	0.97	3.02	0.84	**4.22**	0.73
A6	**4.92**	0.71	**2.55**	0.71	**4.28**	0.74
Site B						
Surface	4.48		4.90		4.18	
B1	4.4	0.98	4.21	0.86	**3.05**	0.73
B2	**4.69**	1.07	4.69	0.96	4.14	0.99
B3	**4.69**	1.07	4.66	0.95	**4.22**	1.01
B4	4.04	0.92	**0.41**	0.08	**3.14**	0.75
B5	**4.53**	1.03	4.88	1.00	4.14	0.99
B6	**4.56**	1.04	4.44	0.91	4.09	0.98
Site C						
Surface	3.47		4.78		3.62	
C1	**3.55**	1.02	4.71	0.99	3.53	0.98
C2	**3.52**	1.01	4.67	0.98	3.59	0.99
C3	**3.58**	1.03	4.72	0.99	**3.66**	1.01
C4	**3.72**	1.07	**4.95**	1.04	**3.85**	1.06
C5	**3.51**	1.01	**2.84**	0.59	3.61	1.00
C6	**3.75**	1.08	4.31	0.90	3.24	0.90

Table 3. Range of variables measured in September and November at 5-6 locations at each site. These data are from spot measurements collected on single days at each site.

Variables		Sites					
		A		B		C	
		September	November	September	November	September	November
Temperature (^{o}C)	Surface	14.8 (14.2-15.2)	13.5 (13.4-13.6)	16.6 (16.2-16.9)	14.1 (13.9-14.4)	18.4 (18.2-18.8)	15.0 (14.9-15.2)
	Hyporheic	15.0 (14.4-15.6)	13.8 (13.6-13.9)	17.1 (16.5-17.7)	14.2 (14.0-14.4)	18.7 (18.4-19.0)	15.0 (14.8-15.2)
Dissolved oxygen (mg/L)	Surface	9.9 (9.0-10.4)	8.8 (8.3-9.3)	10.8 (10.2-11.4)	9.5 (8.0-10.3)	11.2 (11.1-11.4)	10.8 (10.3-11.2)
	Hyporheic	10.4 (9.1-12.2)	6.6 (3.4-8.3)	10.9 (10.2-11.2)	9.8 (6.5-12.6)	11.1 (10.3-11.7)	11.1 (10.2-13.7)
Conductivity (µS/cm)	Surface	21.2 (21.0-22.0)	24.8 (24.0-25.0)	21.2 (21.0-22.0)	25.0 (25.0-25.0)	21.7 (21.0-22.0)	25.3 (25.0-26.0)
	Hyporheic	23.2 (20.0-33.0)	25.4 (24.0-28.0)	23.0 (21.0-33.0)	25.3 (25.0-27.0)	23.5 (21.0-32.0)	25.5 (25.0-27.0)
Velocity (m/S)	Surface	0.67 (0.09-1.00)	0.21 (0.15-0.30)	0.55 (0.27-0.82)	0.12 (0.03-0.21)	0.64 (0.36-0.91)	0.06 (0.06-0.09)
Depth (cm)	Surface	30.2 (26.6-33.0)	13.5 (10.0-22.0)	18.9 (11.4-27.3)	9.7 (8.0-14.0)	27.8 (22.2-32.3)	10.3 (8.0-16.0)

Figure 1. Sample sites along the San Joaquin River.

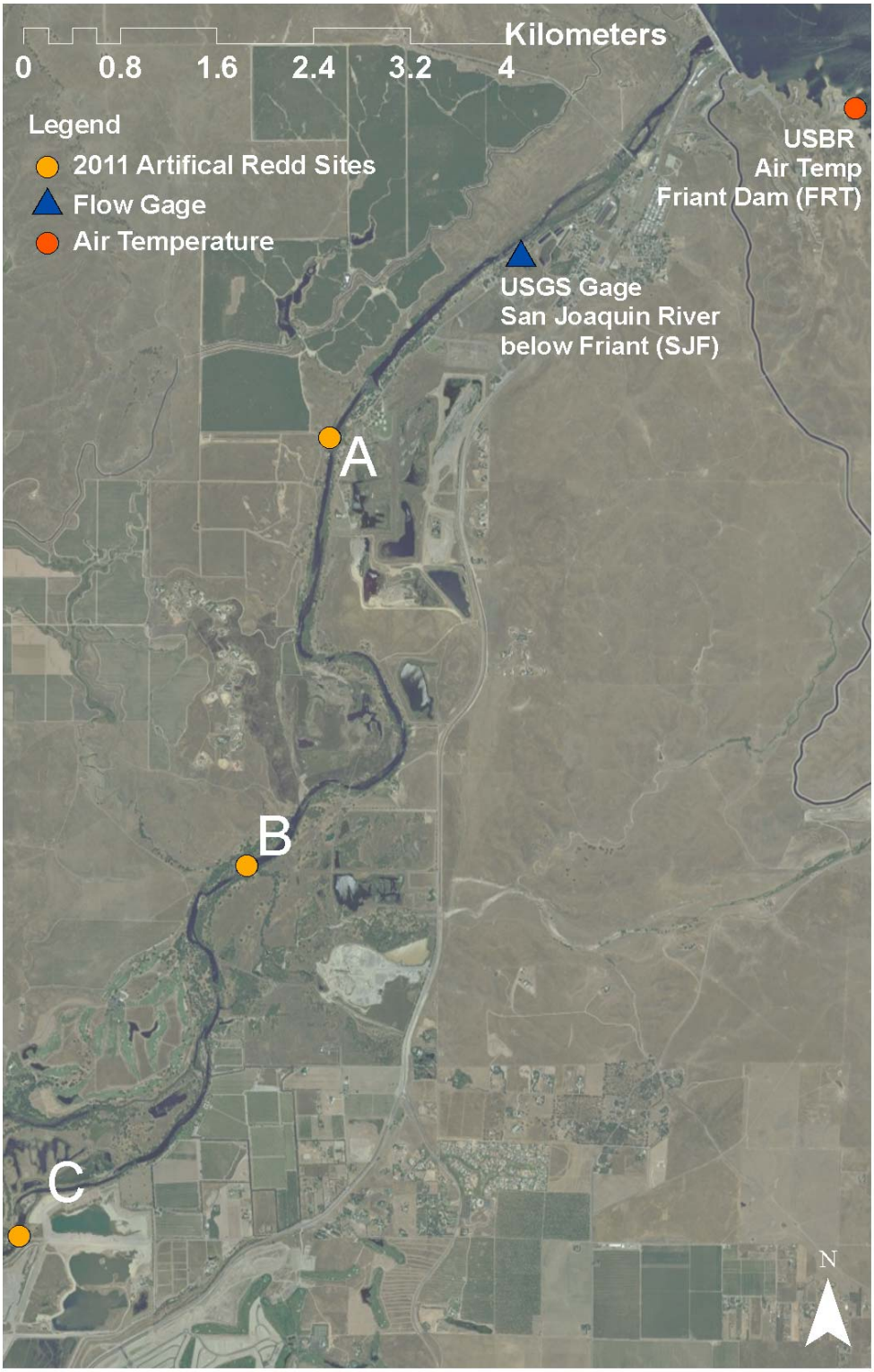


Figure 2. Eggplate design with half of eggplate shown. Note the presence of dead eggs and larval rainbow trout.

Figure 3. Sediment trap collected from a hyporheic location on the San Joaquin River.

Figure 4. Comparison of number of rainbow trout that hatched in egg plates at sites along the San Joaquin River and at hatchery controls (initial and final). Controls included those that were left at the hatchery (initial) and those returned to the hatchery (final) after all river sites were stocked. Letters associated with bars indicate whether there was a statistically significant difference in numbers that hatched. Bars with the same lower-case letters indicate no significant difference (Tukey HSD test, P>0.05). Numbers that hatched in the river all differed significantly from controls. Each egg plate had 32 eggs and there were six plates associated with each treatment. Variability is presented as standard error.

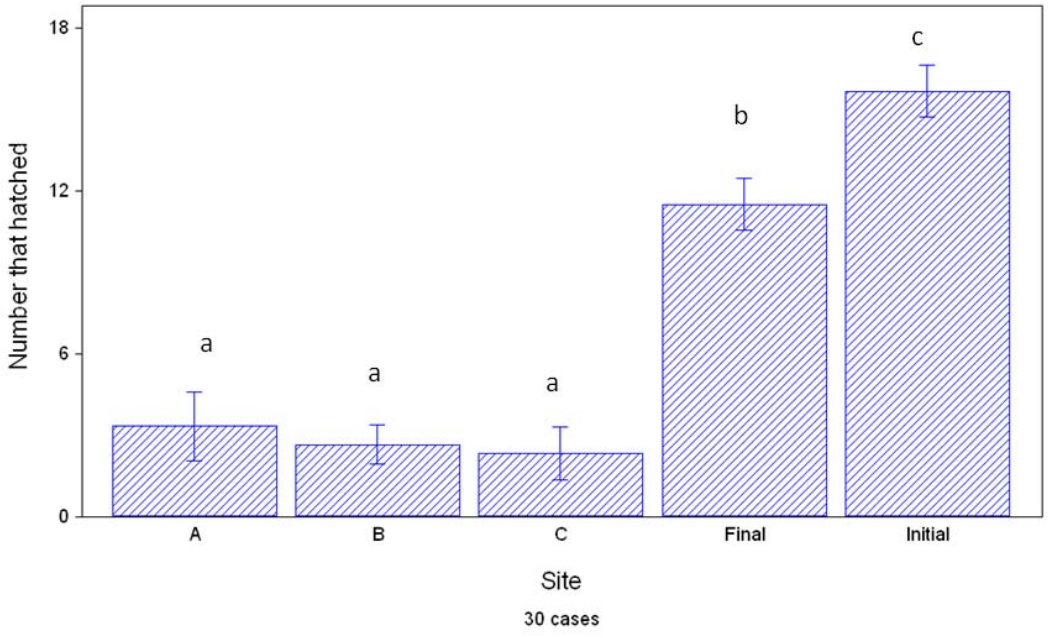


Figure 5. Box and whisker plots of rainbow trout lengths from egg plates. Only those larvae from Site C differed significantly in length from the initial and final controls. Plots with the same lower-case letters indicate no significant difference (Tukey HSD test, P>0.05).

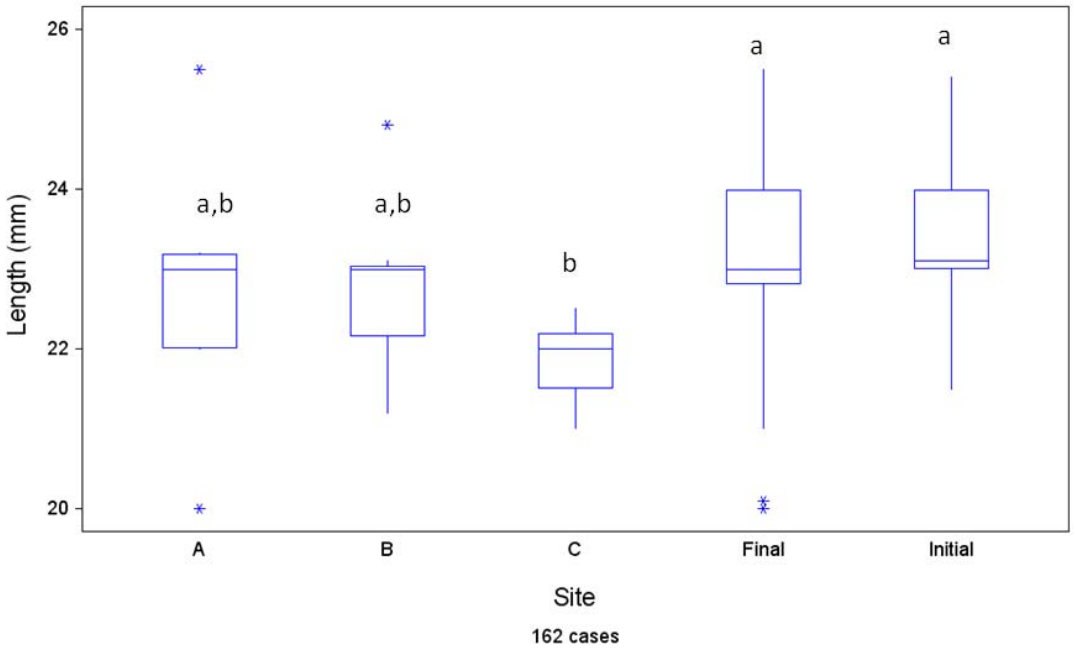


Figure 6. Surface water temperatures and flow over time at four locations in the San Joaquin River.

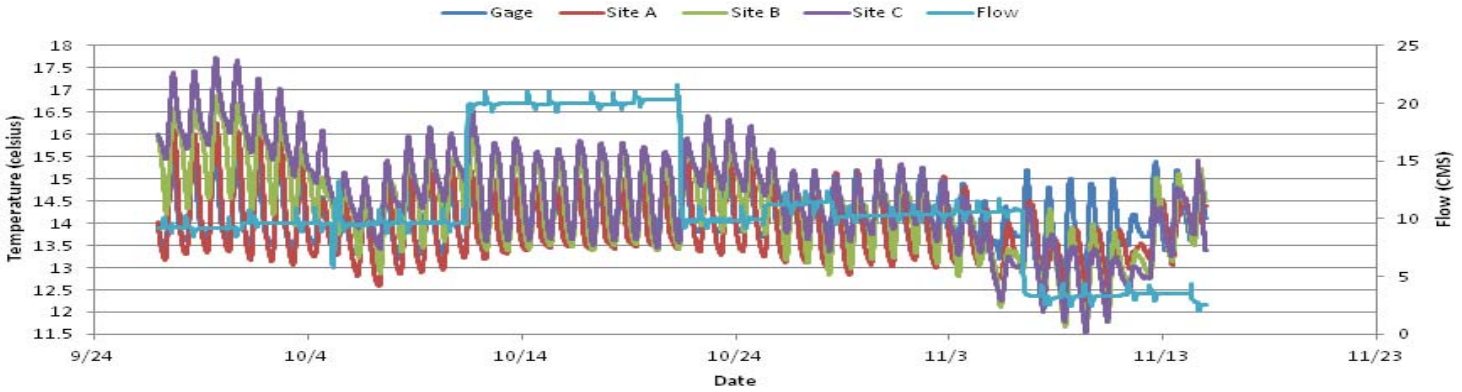


Figure 7. Surface and hyporheic water temperatures at Site A relative to flow. Temperature at these three locations measured with DO/temp sensor.

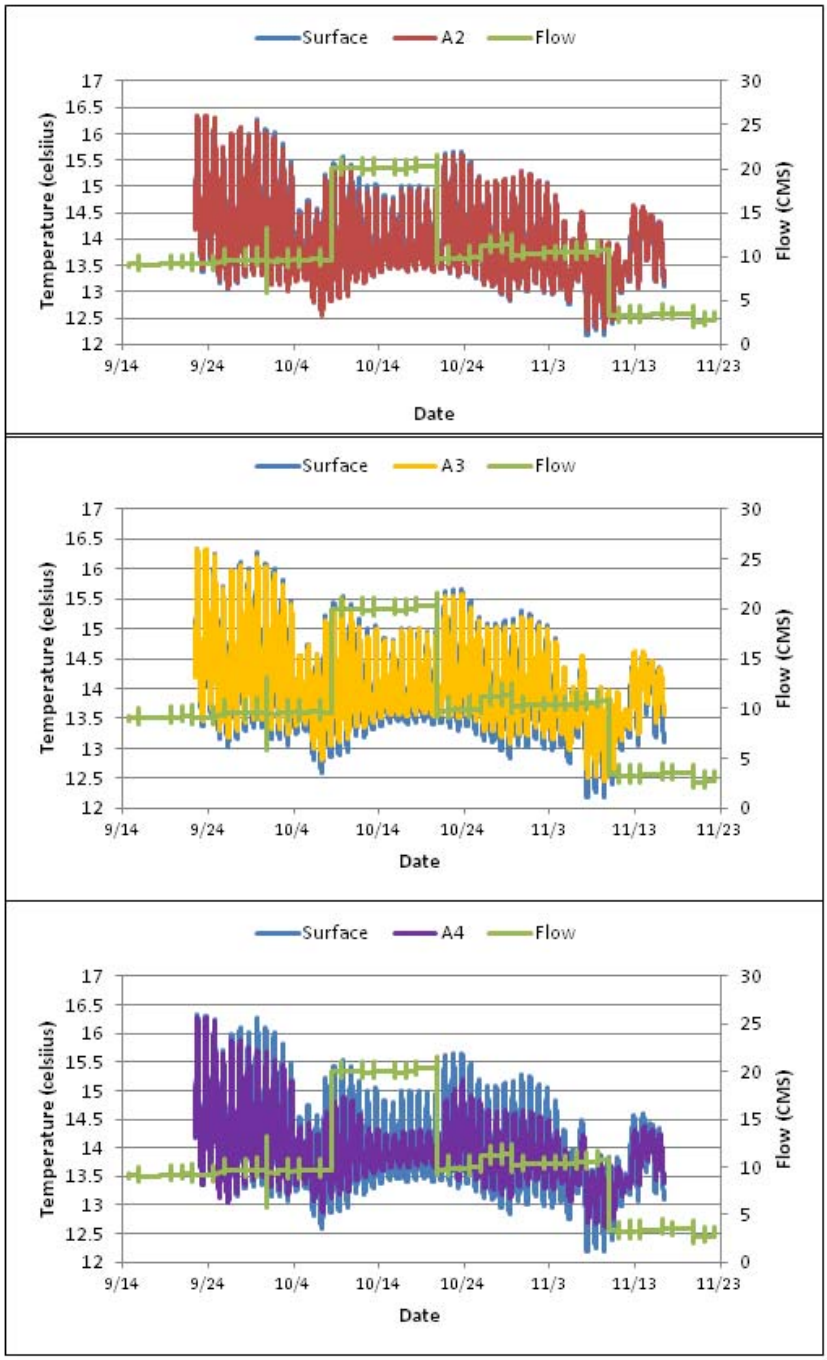


Figure 8. Surface and hyporheic water temperatures at Site B relative to flow. Temperature at these three locations measured with DO/temp sensor.

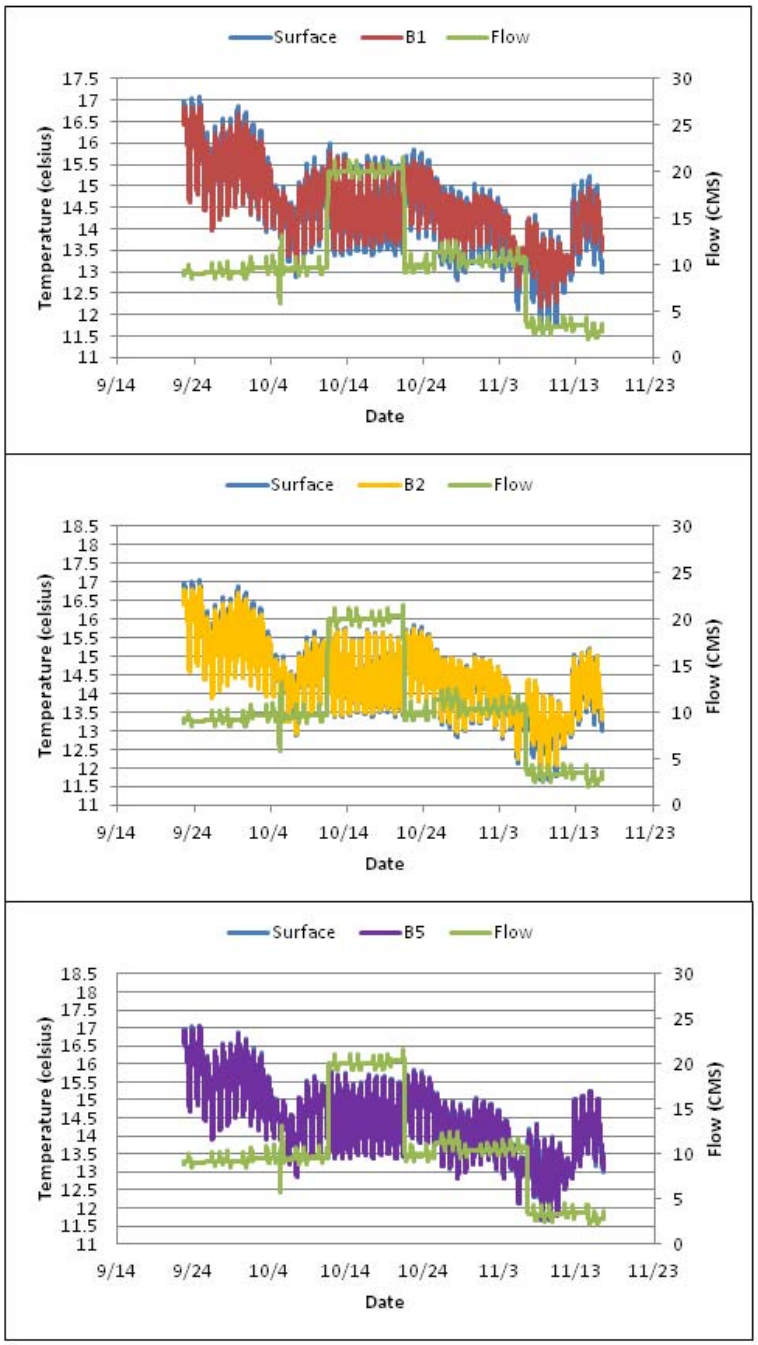


Figure 9. Surface and hyporheic water temperatures at Site C relative to flow. Temperature at these three locations measured with DO/temp sensor.

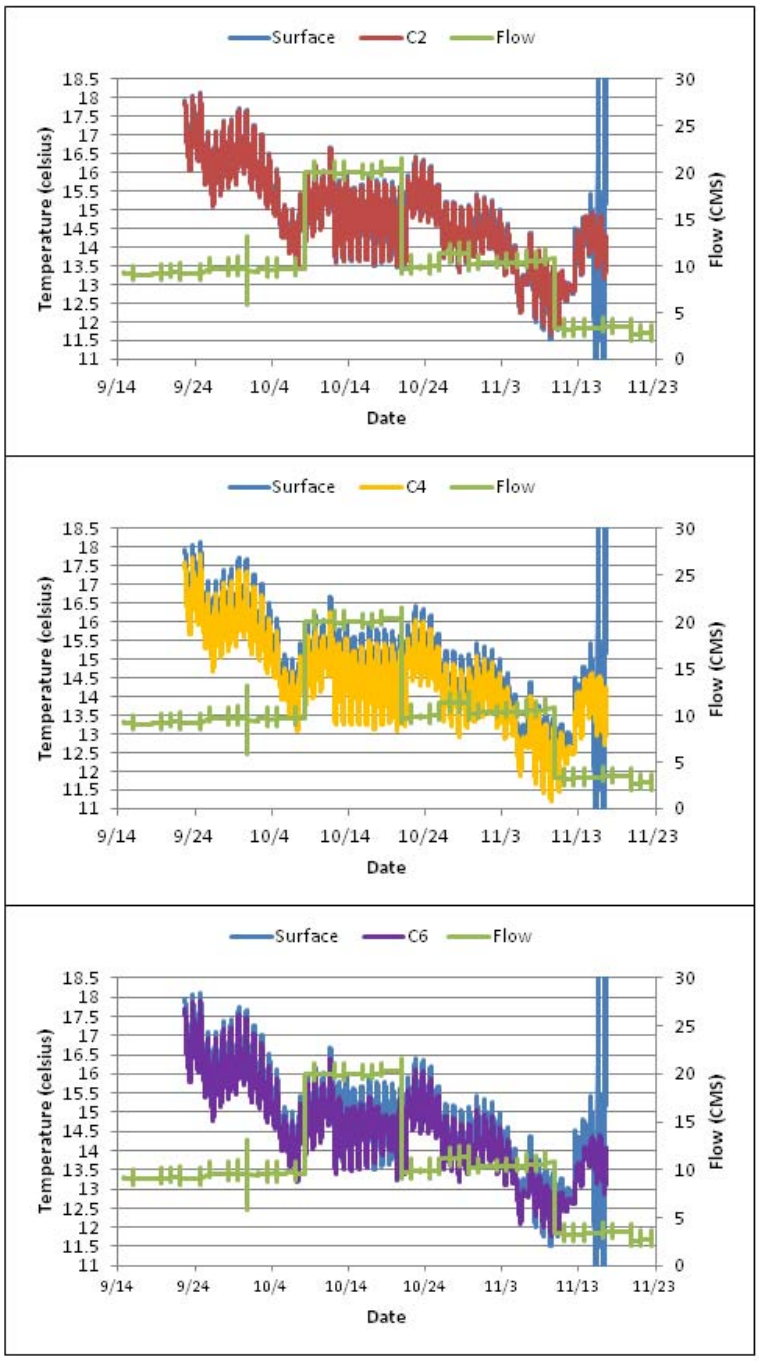


Figure 10. Surface and hyporheic water temperatures at Site A relative to flow. Temperature at these three locations measured with Hobo loggers.

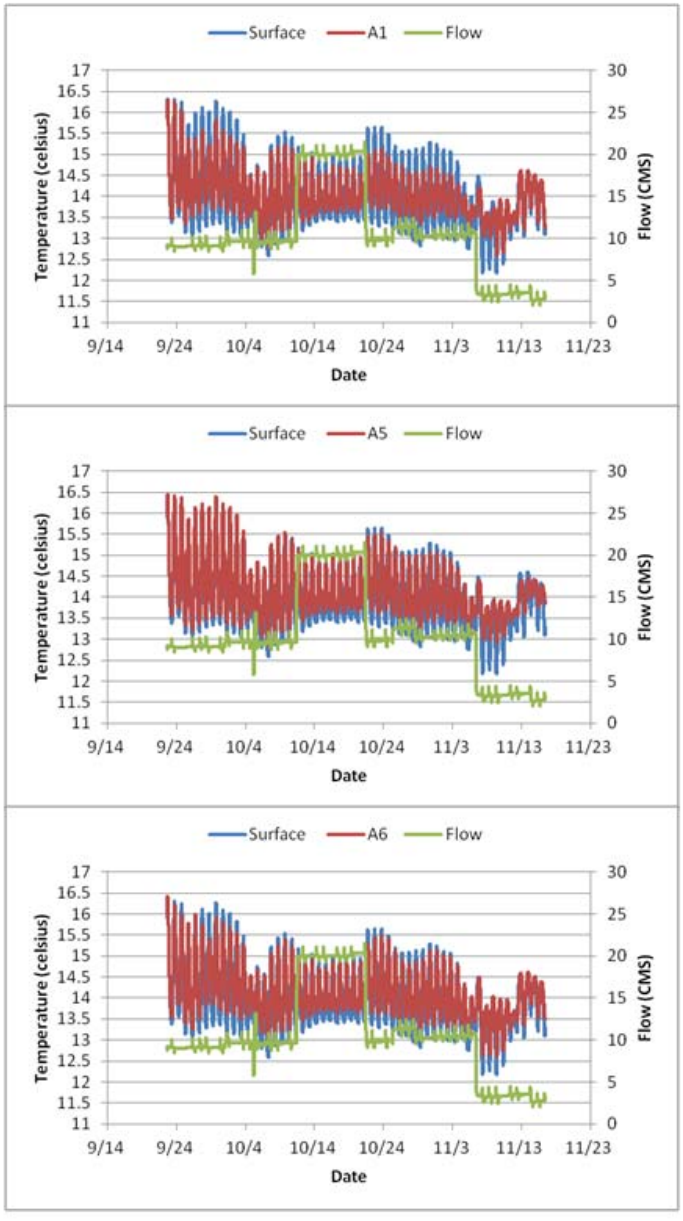


Figure 11. Surface and hyporheic water temperatures at Site B relative to flow. Temperature at these three locations measured with Hobo loggers.

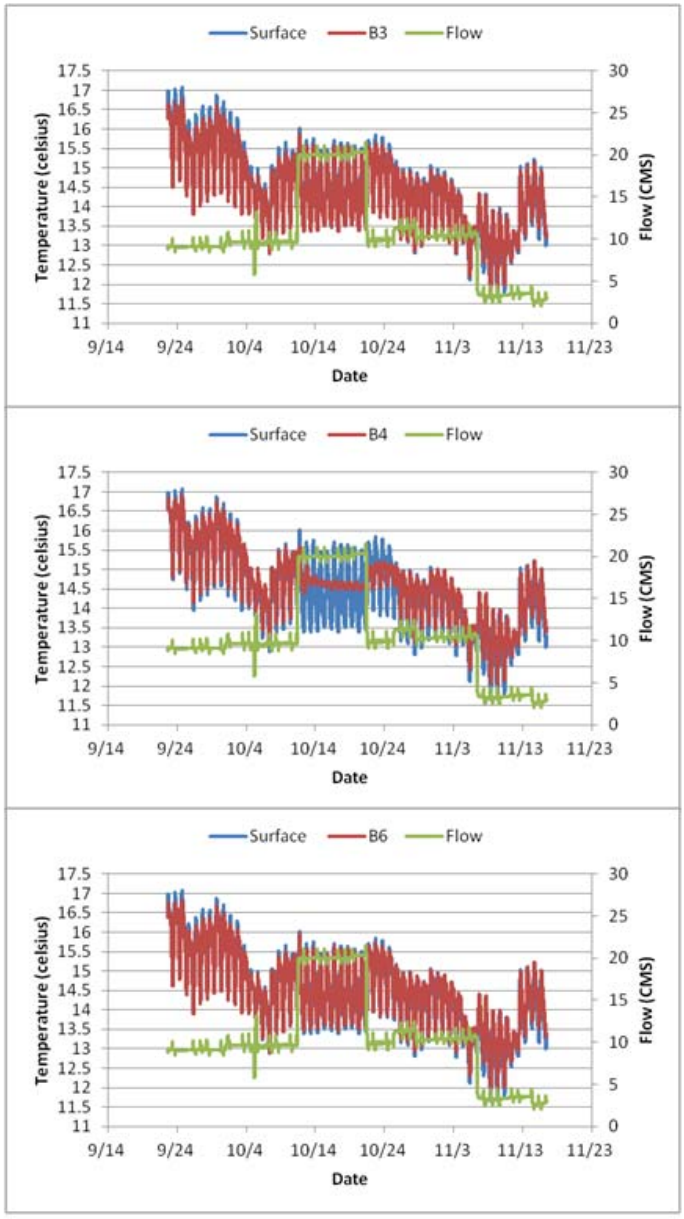


Figure 12. Surface and hyporheic water temperatures at Site C relative to flow. Temperature at these three locations measured with Hobo loggers.

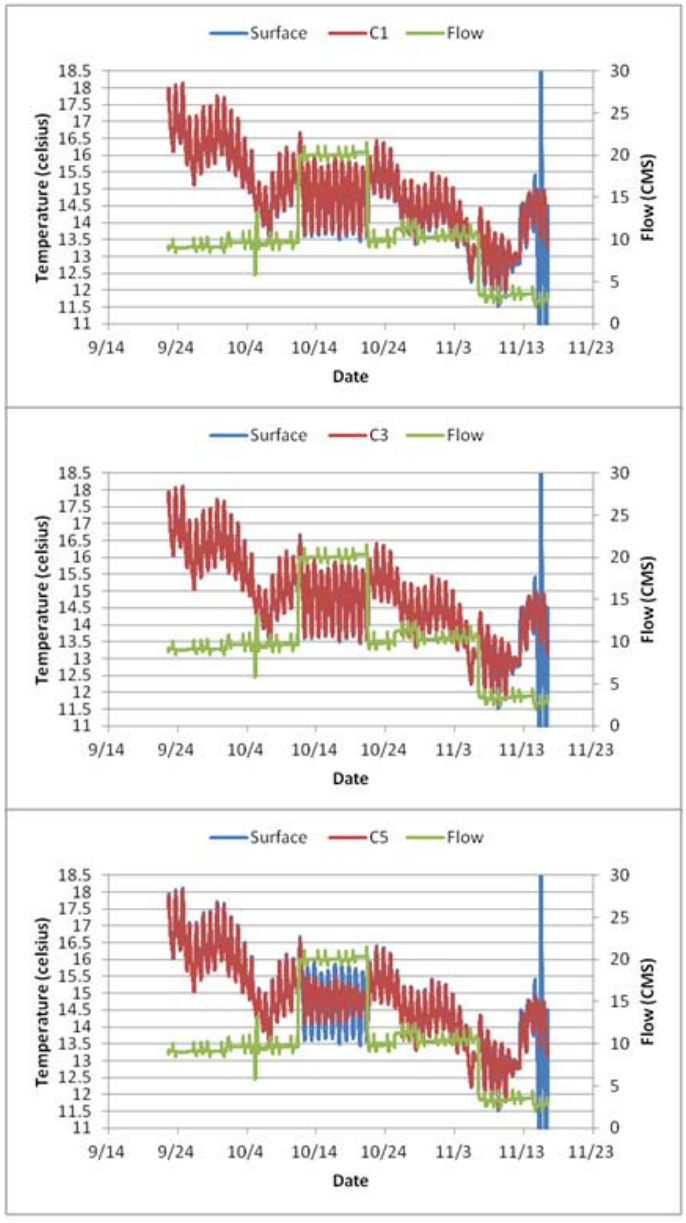


Figure 13. River water temperature in relation to flow and air temperature during low-flow September (a), high-flow October (b), and low-flow November (c) periods.

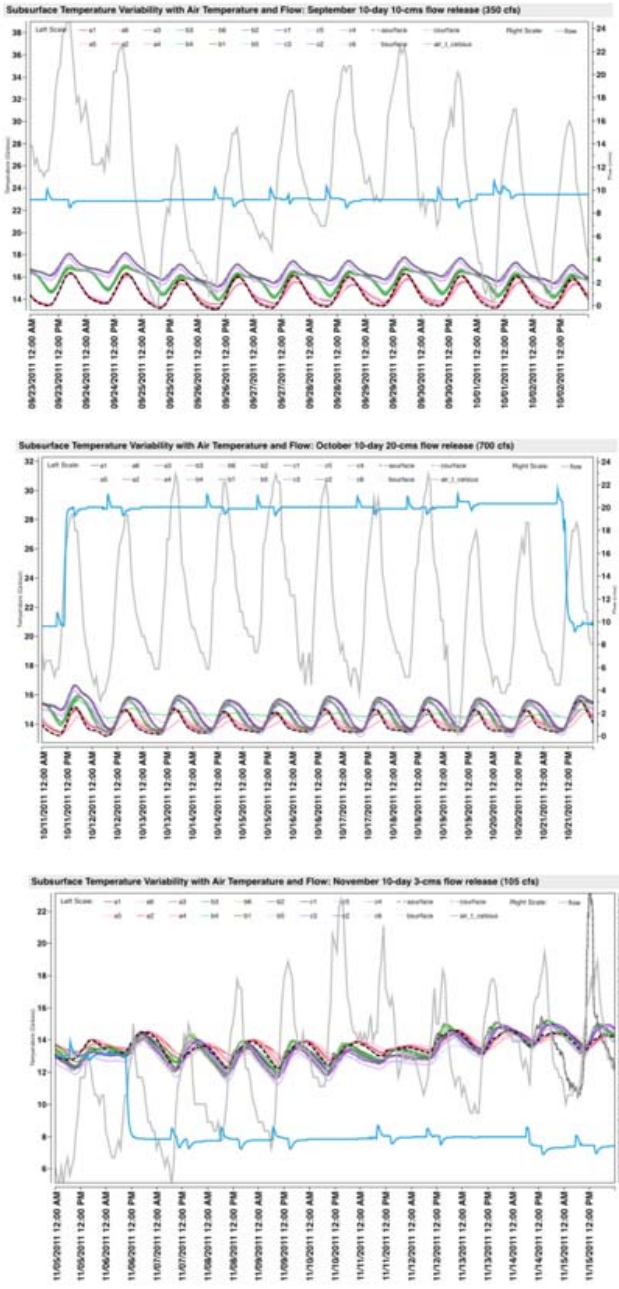


Figure 14. Diurnal change in temperatures for three hyporheic locations at Site B.

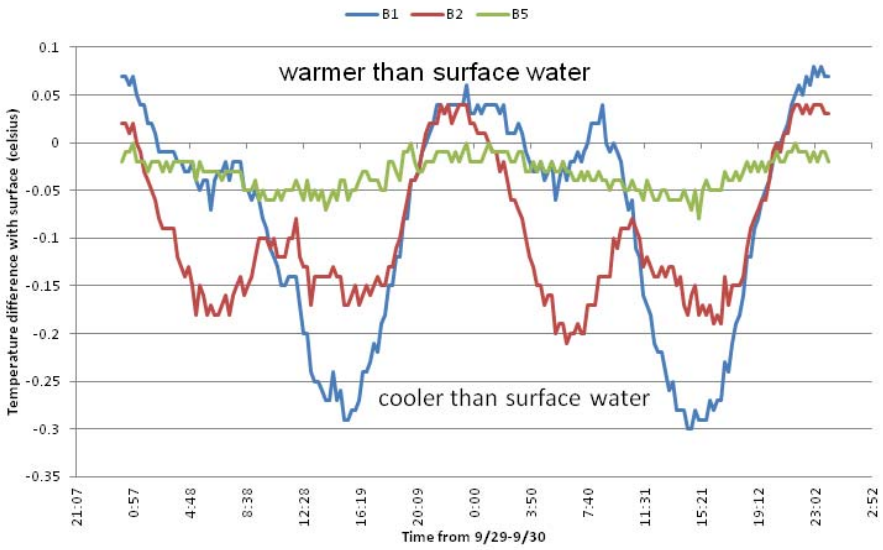


Figure 15. A plot of correlation coefficients that summarizes the strength of the linear relationships between each pair of response (*Y*) variables (hyporheic temperature) to flow and air temperature at each hyporheic and surface location. Thin lines represent this relationship with flow, while thick lines represent the relationship with air temperature.

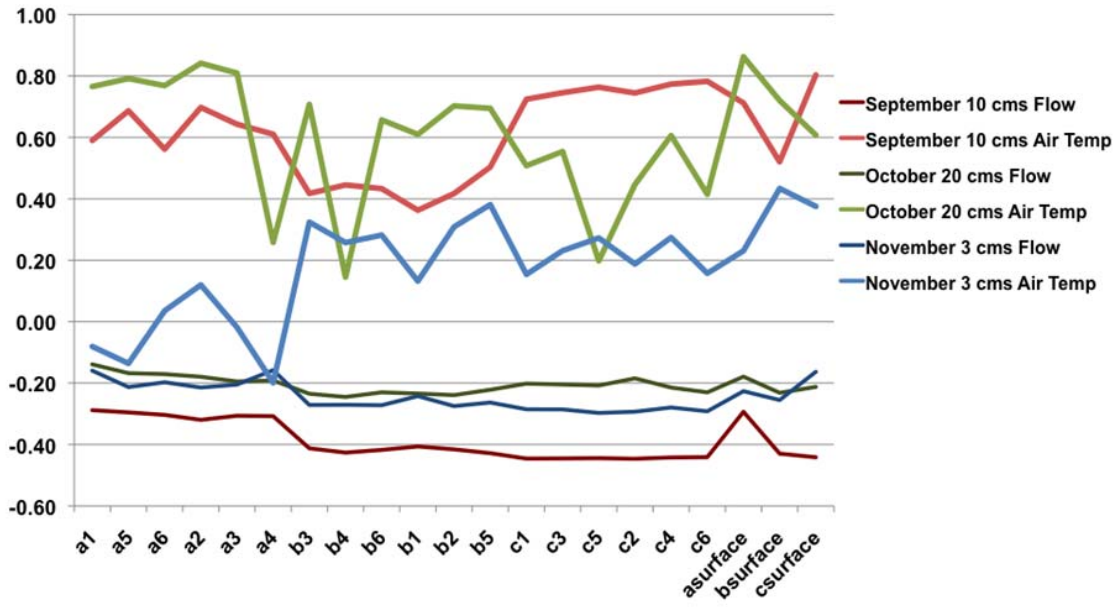


Figure 16. Continuously measured surface and hyporheic dissolved oxygen at Site A relative to flow.

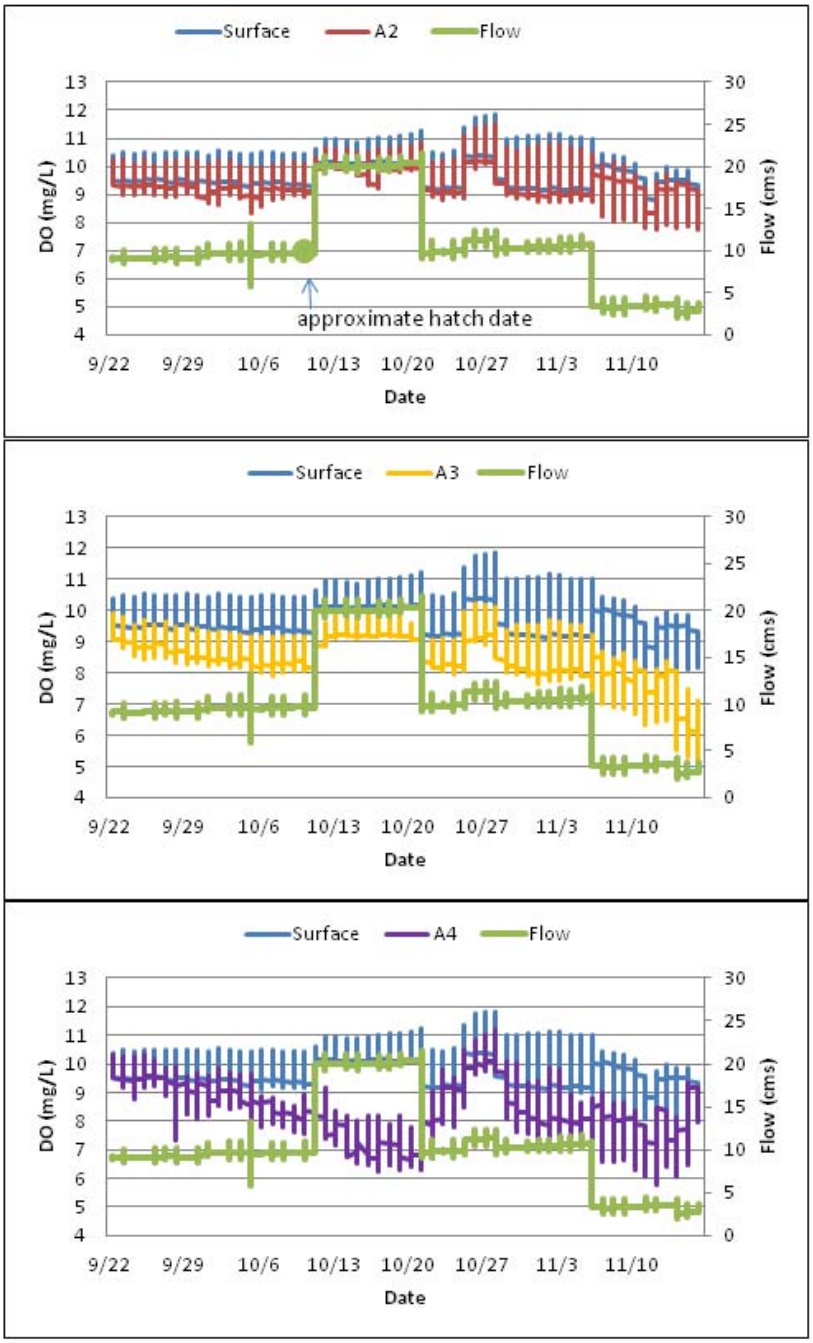


Figure 17. Continuously measured surface and hyporheic dissolved oxygen at Site B relative to flow.

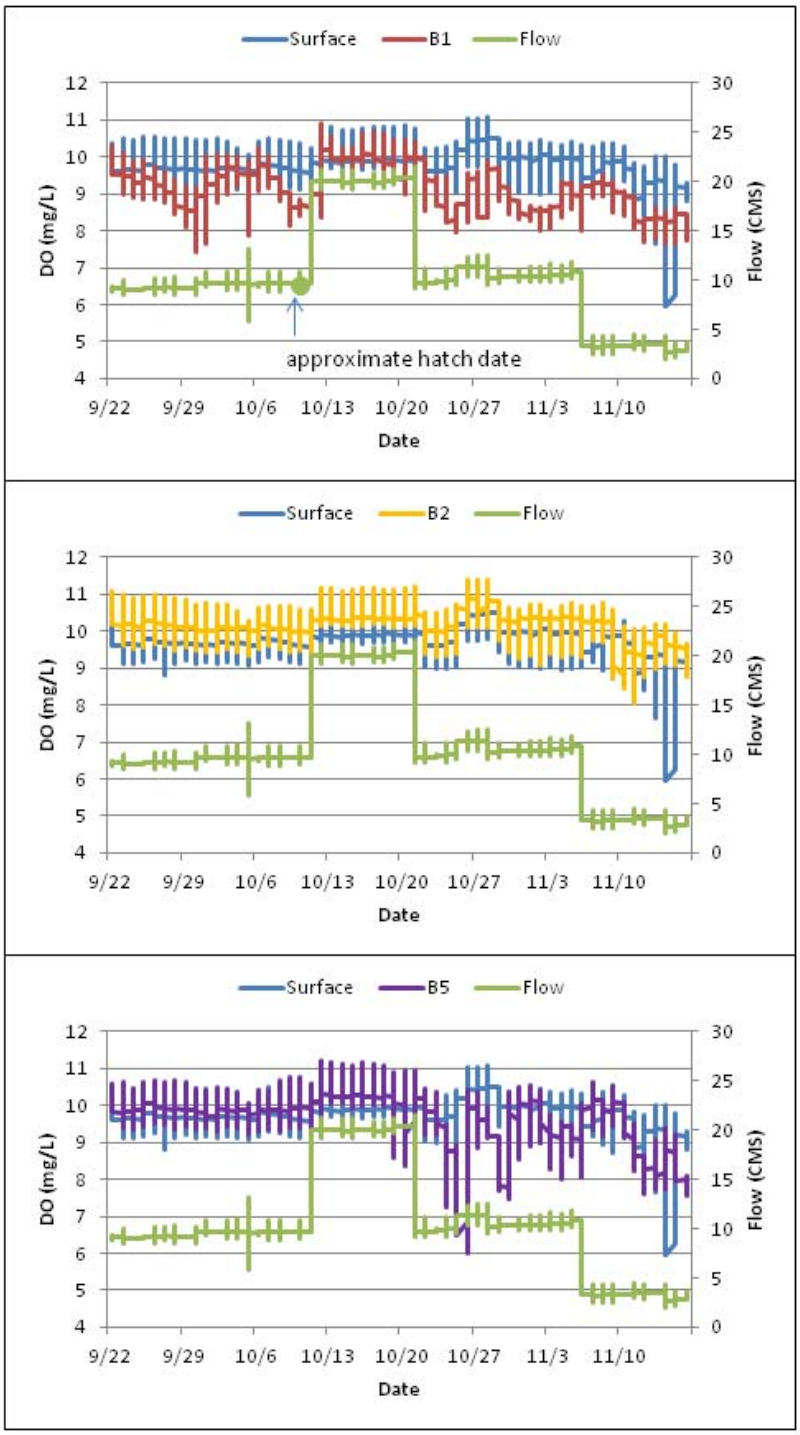


Figure 18. Continuously measured surface and hyporheic dissolved oxygen at Site C relative to flow.

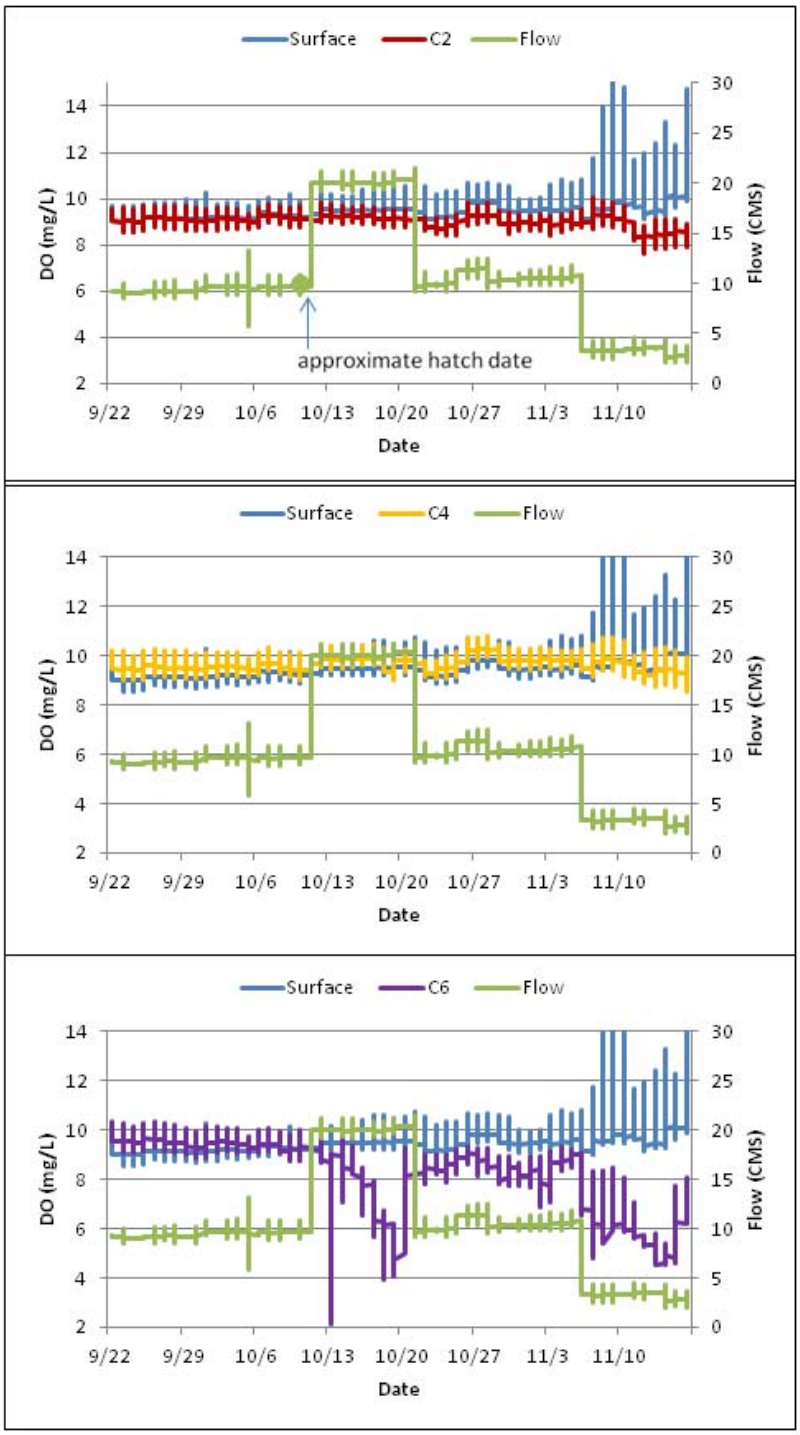


Figure 19. Diurnal patterns of dissolved oxygen at surface and hyporheic locations at Site A.

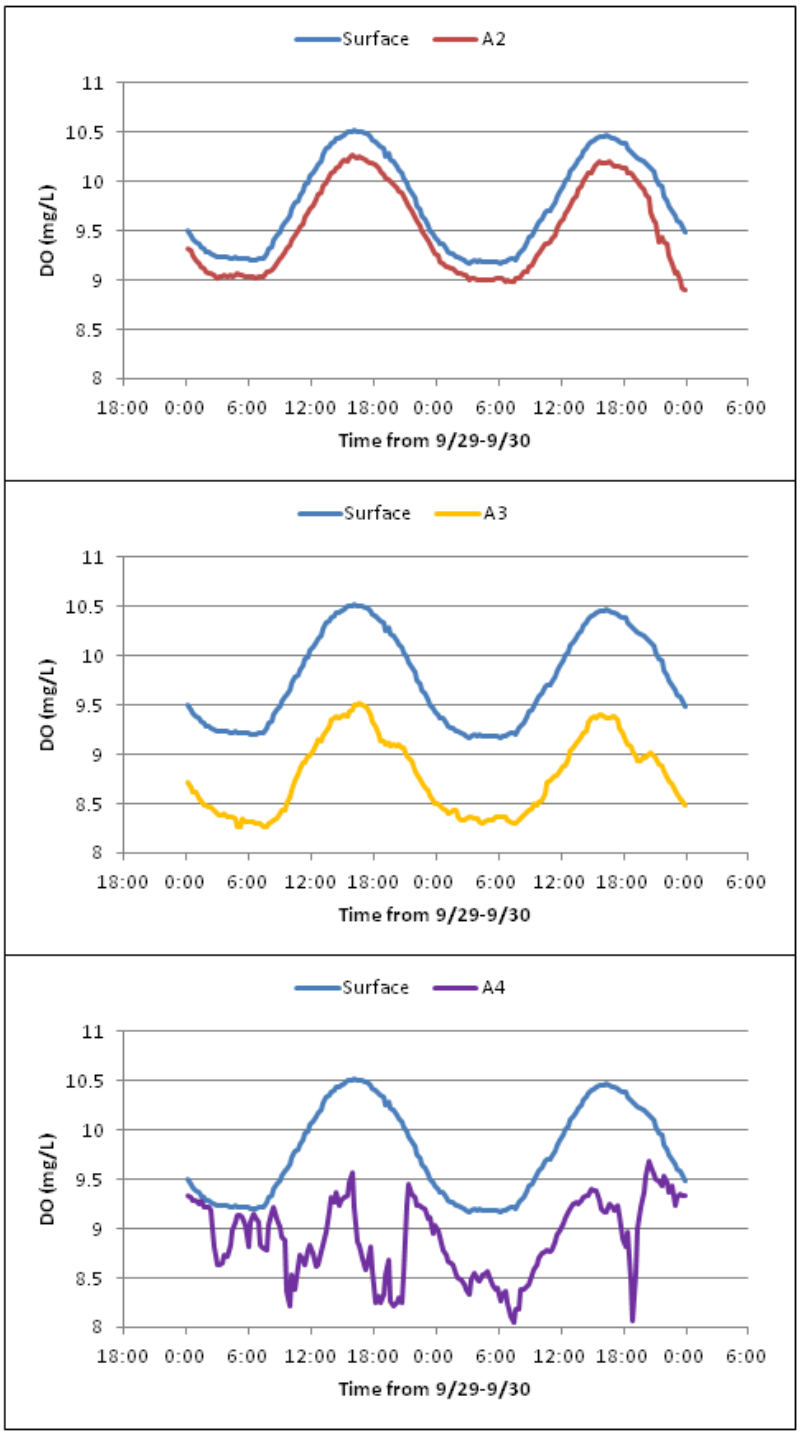


Figure 20. Diurnal patterns of dissolved oxygen at surface and hyporheic locations at Site B.

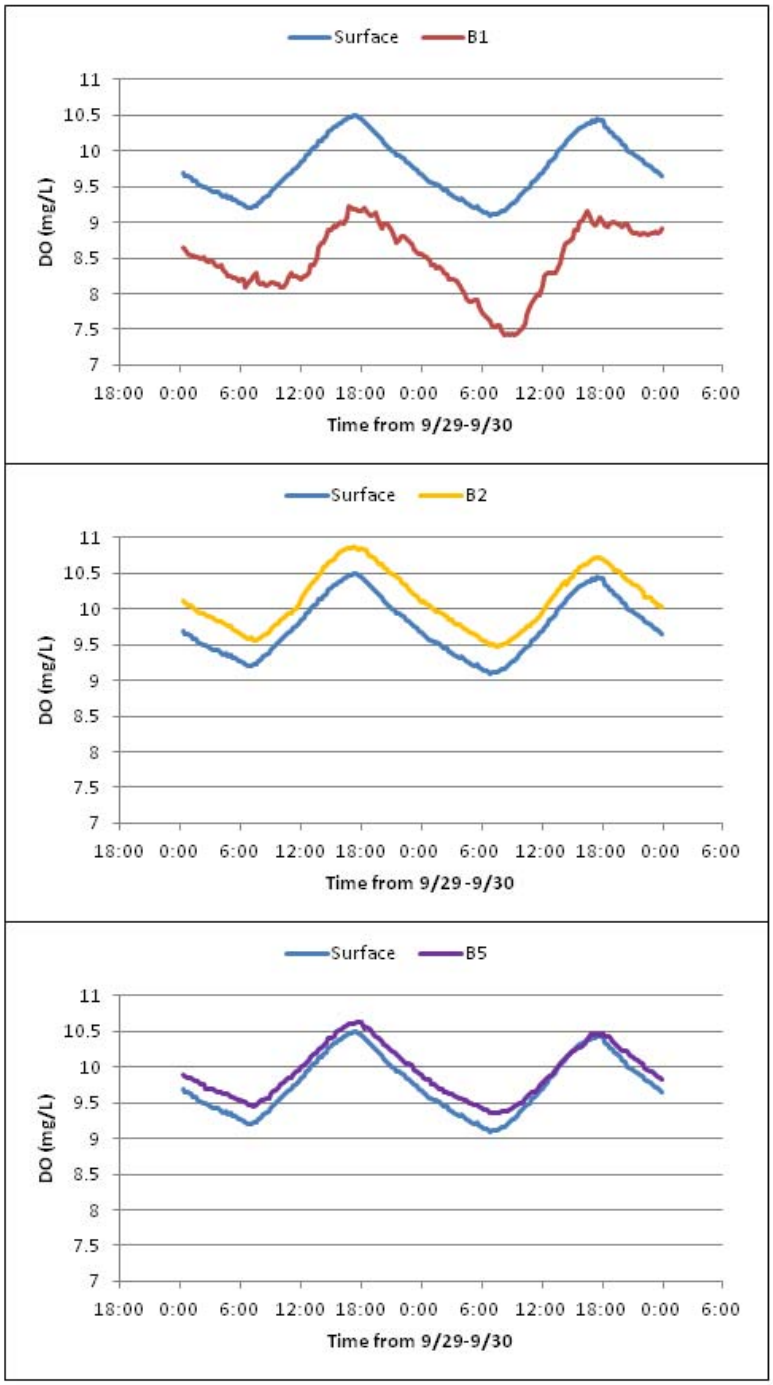


Figure 21. Diurnal patterns of dissolved oxygen at surface and hyporheic locations at Site C.

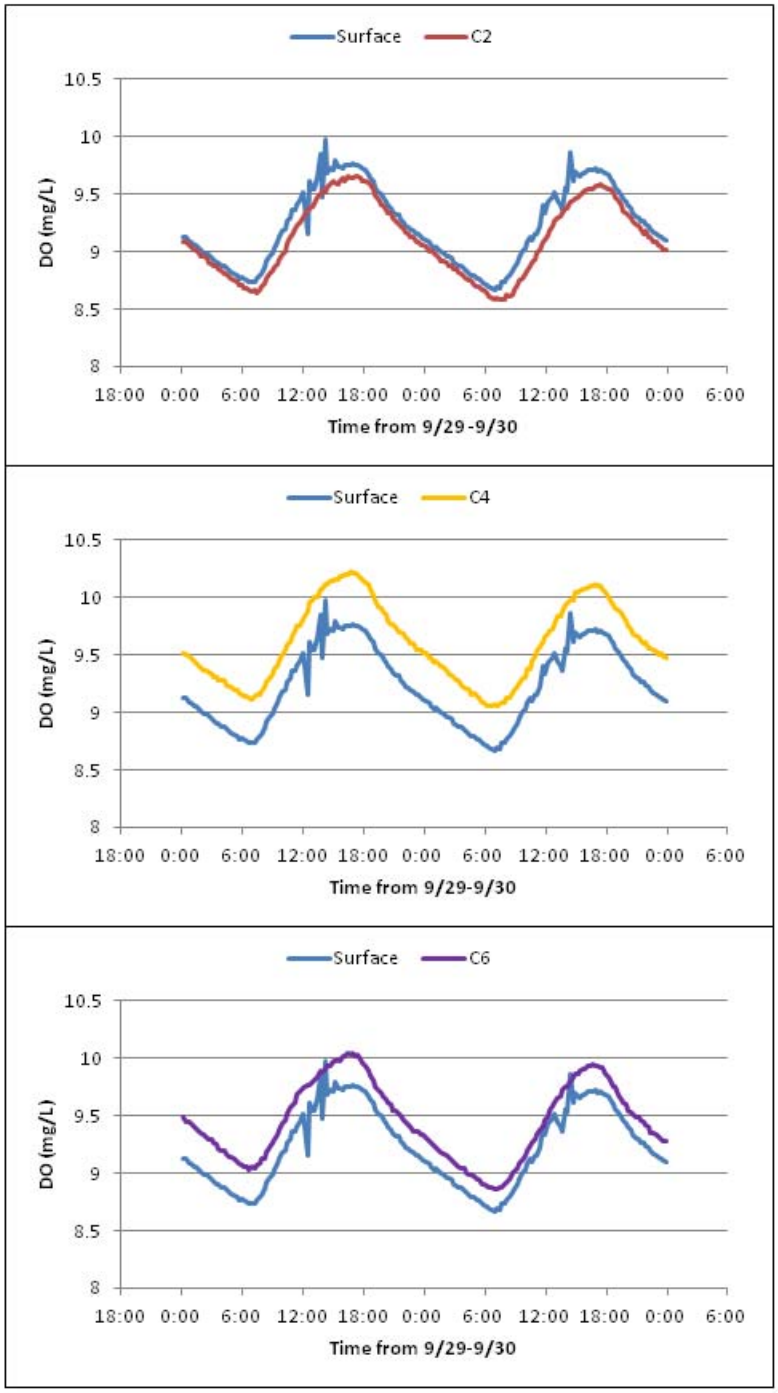


Figure 22. Comparison of temperature and DO amplitudes at Site C in the San Joaquin River.

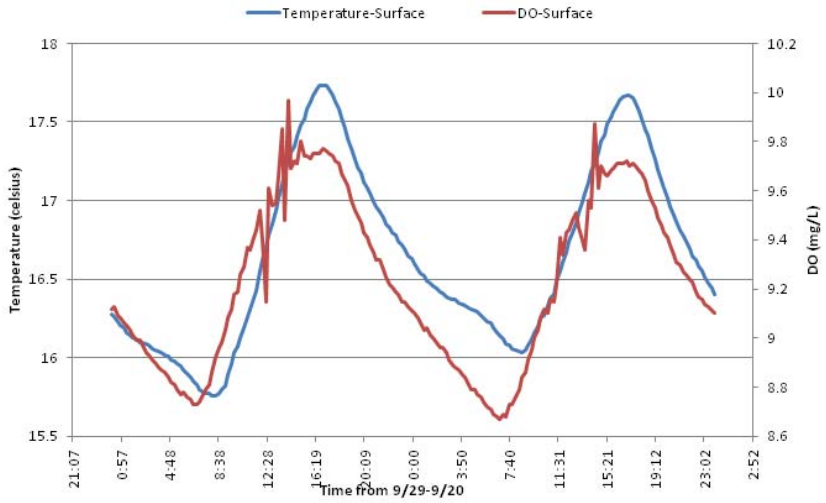
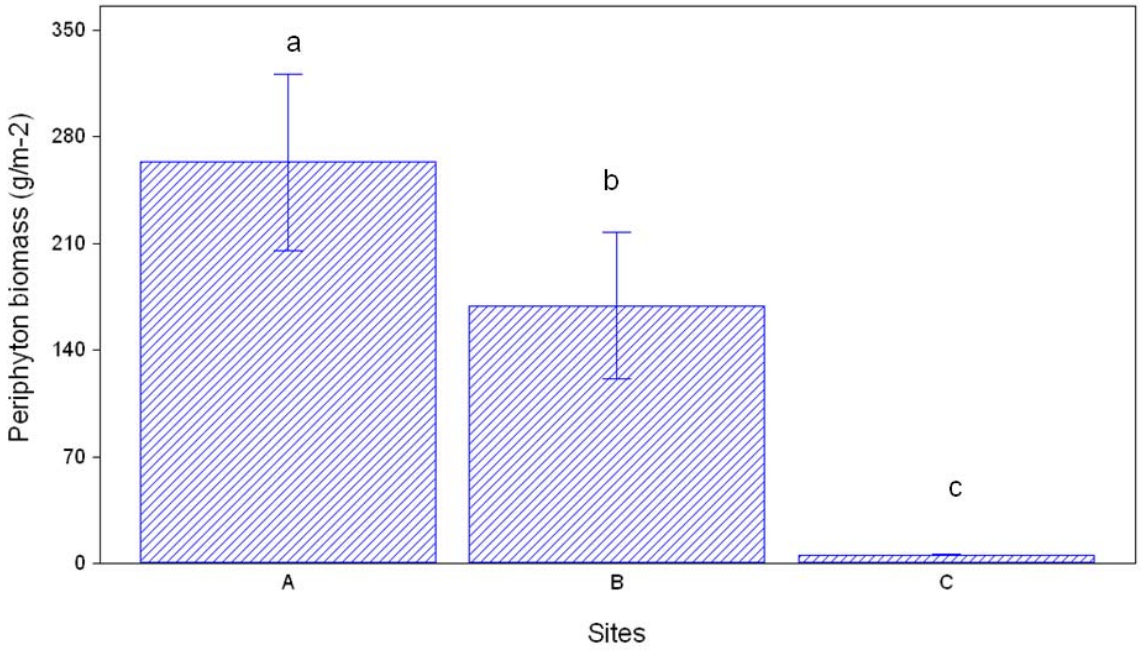


Figure 23. Mean periphyton biomass (AFDW) at sites along the San Joaquin River. Bars with the same lower-case letters indicate no significant difference (Tukey HSD test, P>0.05).



Appendix A

Locations examined at sites A, B, and C. Location designations are also provided for surface water sampling (SWS).


Kilometers
0
0.02
0.04
0.06
0.08
0.1
N
Legend
2011 Artificial Redd Sites
A1
A2
A3
A4
A SWS
A5
A6
Site A


Kilometers
0
0.02
0.04
0.06
0.08
0.1
N
Legend
2011 Artificial Redd Sites
Site B
B1
B2
B3
B4
B5
B6
B SWS


Kilometers
0
0.02
0.04
0.06
0.08
0.1
N
Legend
2011 Artificial Redd Sites
Site C
C2
C1
C SWS
C3
C5
C4
C6

PEER REVIEW DOCUMENTATION

PROJECT AND DOCUMENT INFORMATION

Project Name San Joaquin River Monitoring WOID AF941

Document **HYPORHEIC WATER QUALITY AND SALMONID EGG SURVIVAL IN THE SAN JOAQUIN RIVER**

Document Date June 2012 Date Transmitted to Client ____

Team Leader S. Mark nelson

Document Author(s)/Preparer(s) S. Mark Nelson, Gregory Reed, Erin N. Bray, Eric Guzman, and Matt Bigelow

REVIEW REQUIREMENT

Part A: Document Does Not Require Peer Review

Explain _____

Part B: Document Requires Peer Review: SCOPE OF PEER REVIEW

Peer Review restricted to the following Items/Section(s): Reviewer:

REVIEW CERTIFICATION

Peer Reviewer - I have reviewed the assigned Items/Section(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer: Erica Myers Review Date: May 2012
Signature see acknowledgements

Reviewer: _____ Review Date: _____
Signature

Preparer - I have discussed the above document and review requirements with the Peer Reviewer and believe that this review is completed, and that the document will meet the requirements of the project.

Team Member: S. Mark Nelson Date: 6-8-12
Signature