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Klamath and Trinity River Intra-Gravel Water Temperatures, 2015 and 2016

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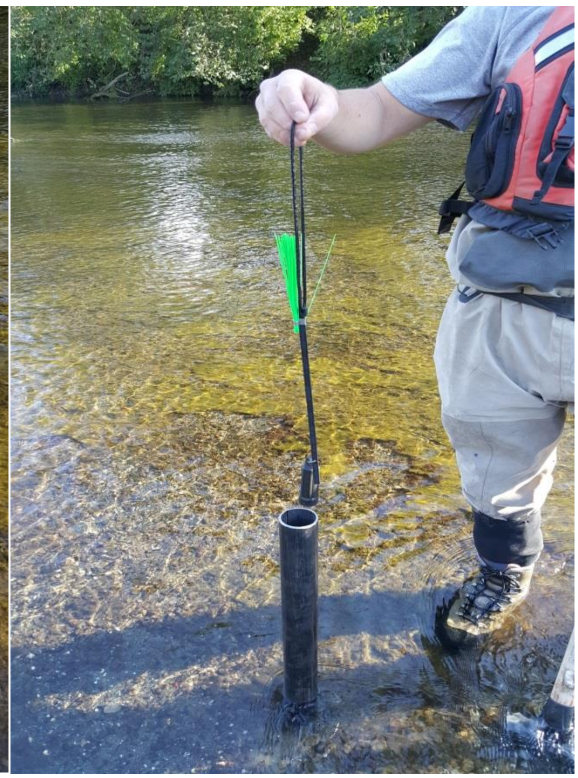

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Key words: Intra-Gravel, Klamath River, Trinity River, Chinook Salmon, Water Temperature

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Klamath and Trinity River Intra-Gravel Water Temperatures, 2015 and 2016

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Abstract.— Digital loggers were used to monitor water temperatures in spawning gravels and in the surface water column adjacent to spawning gravels in the Klamath and Trinity rivers from July 2015 to April or August 2016. Loggers were installed in areas with high densities of Chinook Salmon redds to assess potential differences in predicted embryo incubation and subsequent emergence timing calculated using intra-gravel versus surface water temperatures. In general, intra-gravel water temperatures were warmer in the fall and winter and cooler in the spring and summer than surface water temperatures. However, both within- and among-site variation in the magnitude of deviation from surface temperatures was observed. Some of this variation was not easily explained and was beyond the resolution of this study. Estimated emergence timing based on intra-gravel water temperatures ranged from 0 to 26 days earlier than what would be expected based on surface water temperatures. These findings are important given the influence of intra-gravel temperatures on the development of salmonid embryos and the resulting influence on emergence timing.

Introduction

Like other aquatic ectotherms, Pacific salmon (*Oncorhynchus* spp) are highly sensitive to variation in water temperature, which influences their development, growth, foraging, spawning, and survival (Brett 1971; Beschta et al. 1987; McCullough 1999). In many watersheds along the Pacific Coast of North America, including the Klamath River basin, water temperatures have increased due to habitat alteration, water withdrawals, and climate change (NRC 1996; Bartholow 2005; Isaak et al. 2011), resulting in deleterious impacts to salmon populations (NRC 1996; McCullough 1999; NRC 2004). Monitoring water temperatures is an important component of assessing the status of salmon-supporting ecosystems and the effects of management actions and other human activities on salmon development, growth, and survival. However, the common practice of placing temperature loggers longitudinally along a river or river network may not capture important fine-scale temperature variation within a river channel, such as that between surface flow and hyporheic (intra-gravel) flow.

Salmon often select spawning sites with down-welling (Chapman 1988), up-welling (Geist and Dauble 1998; Geist 2000; Malcolm et al. 2002), or both types (Neumann and Curtis 2016) of intra-gravel flow. Surface water (water column) temperatures can differ from intra-gravel temperatures (Crisp 1990; Geist 2000; Hanrahan 2007) and these differences may be important when describing the thermal environment experienced by developing eggs and embryos (Shepherd et al. 1986). In contrast, a difference was not observed between surface and intra-gravel water temperatures for artificial redds (Groves et al. 2008). Given the lack of intra-gravel water temperature data in the Klamath and Trinity rivers, the Arcata Fish and Wildlife Office (AFWO) set out to evaluate potential differences between intra-gravel and surface water temperatures in the Klamath basin. In particular, this information was needed to inform a Chinook Salmon (*O. tshawytscha*) production model that is being developed for the Klamath River basin (Stream Salmonid Simulator or S3 Model).

The Stream Salmonid Simulator uses water temperatures, estimated by the sub-model RBM10 (Jones et al. 2016), to determine timing of egg development and emergence as free-swimming fry. However, RBM10 estimates spatially-specific temperatures in the surface water column, which may not accurately reflect temperatures experienced by eggs within a redd. The purpose of this study was to determine if there were differences between intra-gravel and water-column water temperatures in the Klamath basin. If differences exist, they will influence the S3 model's estimates of emergence timing of free-swimming Chinook Salmon fry. This report describes results from the second and final year of monitoring of intra-gravel water temperatures. The results from the first year of monitoring are found in Magneson (2015).

Study Area

The Klamath River basin is the third largest watershed (41,000 km^2) draining to the Pacific Ocean in the conterminous USA and has an atypical structure compared to most watersheds. The Klamath River originates in the Cascade Mountains of southern Oregon and then flows into the upper Klamath basin, a large, low relief plateau that historically contained extensive shallow lakes and wetlands (NRC 2004; VanderKooi et al. 2011). The Klamath River then cuts through the southern end of the Cascade Mountains and is impounded by a series of six dams. These dams mark the transition from upper to lower basin and divide the watershed by preventing fish passage and altering flows and sediment transport. Below the dams, the Klamath River enters the Klamath-Siskiyou Mountains and flows for approximately 235 river kilometers (rkm) to its confluence with the Trinity River. In contrast to the upper basin, the lower basin is high relief and the Klamath River and its tributaries primarily flow through confined canyons (NRC 2004; VanderKooi et al. 2011). Overall the watershed has a Mediterranean climate with warm, dry summers and cool, wet winters. However, the climate changes dramatically from east to west and also at finer scales according to elevation, topography, and aspect. The upper basin is generally semi-arid and river flows are primarily driven by snowmelt and groundwater, while the lower basin is more mesic and river flows are primary driven by rainfall and snowmelt (NRC 2004; Williams and Curry 2011). All water temperature sampling sites were located in the lower Klamath basin.

The Trinity River, the Klamath River's largest tributary, flows through mountainous terrain in a northwesterly direction to the Klamath River. The Trinity River has two reservoirs made by Trinity and Lewiston dams. From the lower most dam the Trinity River flows for 180 rkm before joining the Klamath River at Weitchpec, California. From Weitchpec, the Klamath River flows for 70 rkm before entering the Pacific Ocean (Figure 1).

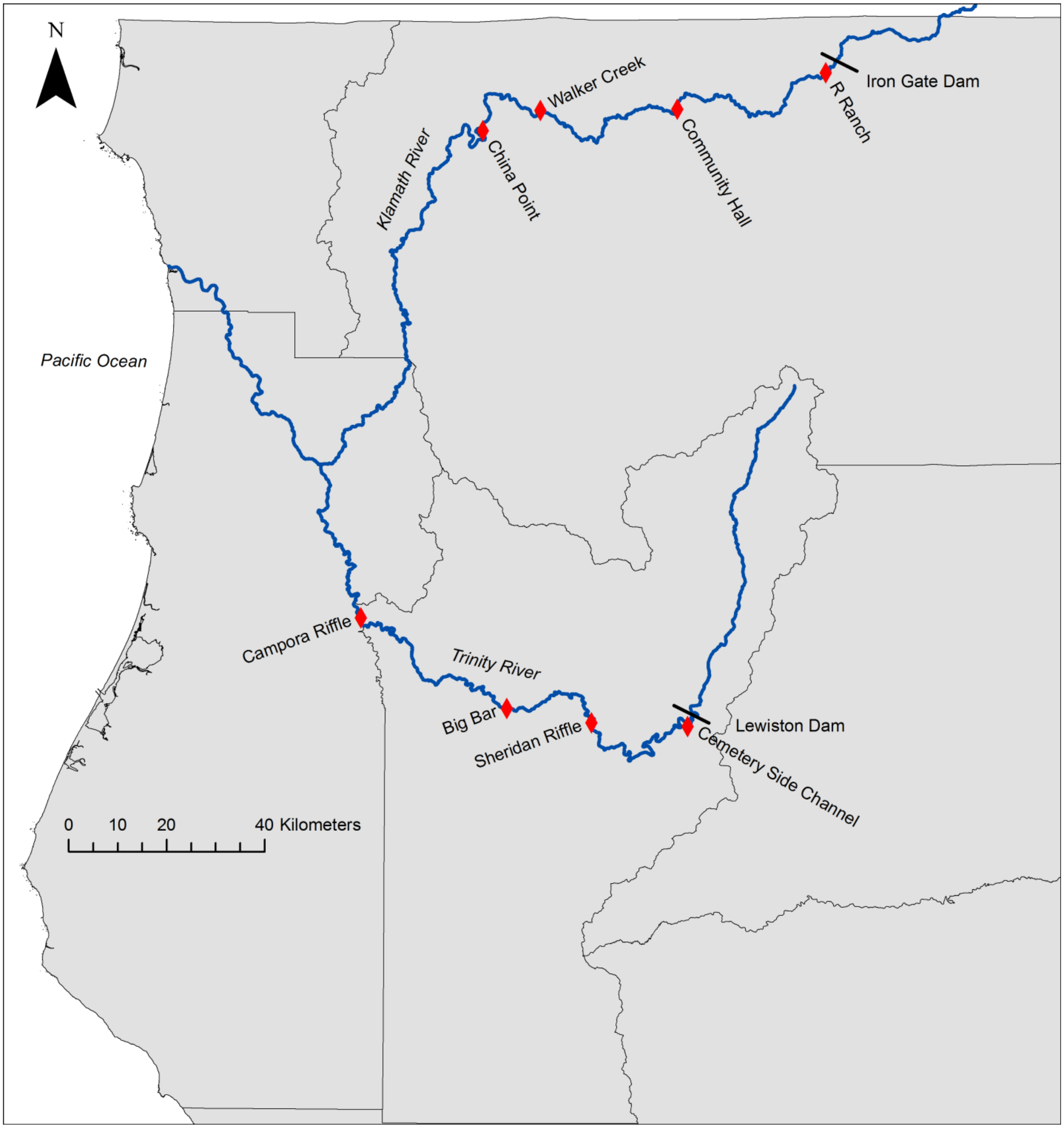

Figure 1. Klamath and Trinity River intra-gravel and surface water temperature monitoring sites from summer 2015 to summer 2016. The red diamonds represent the sampling sites.

Methods

Data loggers (HOBO Water Temp Pro v2 Model Number U22 001; Onset Computer Corporation, Bourne, Massachusetts) were used to record water temperatures and were set to record at 30-min intervals. Prior to and after deployment, each logger was tested to verify operation within the manufacturer's accuracy specification of ± 0.2 °C. The loggers proved accurate and reliable for all tests conducted during the study and no "logger drift" adjustments to temperature data were necessary.

Surface water temperatures were monitored by attaching a temperature logger to an end of a piece of chain with the other end attached to the river bank. These loggers were placed along the river margin in water < 1.0 m deep during late-summer, low-flow conditions and in the vicinity (< 100 m) of the intra-gravel temperature loggers. Intra-gravel temperature loggers were placed within the river bed at various locations at sites known to have high densities of Chinook Salmon spawning. Temperature loggers were attached to one end of a plastic cable tie with stainless steel wire threaded through a hole in the end of each logger (Zimmerman and Finn 2012). A green stake whisker was attached to the upper end of the cable tie to assist in re-locating the temperature logger. The sensor end of the temperature logger was placed approximately 28 cm into the substrate, leaving the stake whiskers just above the substrate surface. The depth of 28 cm was based on the range of egg pocket depths observed by Evenson (2001) for Chinook Salmon redds in the Trinity River.

To install intra-gravel loggers, a steel probe nested inside an aluminum pipe was pounded vertically into the substrate with a sledge hammer (Zimmerman and Finn 2012). The steel probe was then removed from the pipe and a wooden dowel was used to push the logger into the bottom of the pipe. The pipe was then carefully lifted out of the substrate, with pressure applied on the dowel to hold the temperature logger in place. The dowel was then carefully removed from the substrate, leaving the temperature logger buried in the substrate.

Four water temperature monitoring sites were selected on both the Klamath and Trinity rivers (Figure 1). Sites were selected based on having high redd densities in recent years, being readily accessible, and to ensure distribution throughout the primary extent of mainstem river spawning. Water temperature loggers were deployed in mid-July 2015 and retrieved in late April or early August 2016 (Table 1). One surface and four intra-gravel loggers were installed at each site. The location of each logger was recorded using a Pro XH GPS, Zephyr Geodetic™ antenna, and TerraSync™ survey software (Trimble Navigation Limited, Sunnyvale, CA, USA) on a tablet computer. For extraction, the GPS was used to navigate to each logger's location, and loggers were visual identified by the stake whiskers. A clamming shovel was used to clear substrate away from the water temperature logger so that it could be more easily extracted.

Logger data were downloaded using HOBOware Pro by Onset® and imported into Microsoft Excel and the R software for statistical computing for analysis and visualization. Only sites retaining both functional surface and intra-gravel water temperature loggers were analyzed. Accumulated thermal units (ATUs) were used to convert intra-gravel and surface daily mean water temperatures into a biologically-relevant metric: fry emergence time. Incubation times for fall Chinook Salmon eggs can be estimated by starting at the peak spawning survey week (approximately when 50% of spawning has occurred; Shepherd et al. 1986), and summing ATUs using daily mean temperatures. The peak emergence time for juvenile fall Chinook Salmon was assumed to be at 1,000 ATUs (Geist 2006). We began summing ATUs on November 1st, which approximates the peak of Chinook Salmon spawning at these sites and in the basin in general (Magneson and Colombano 2014; Magneson 2015). We calculated the number of days to 1,000 ATUs for all loggers, and for each intra-gravel logger we calculated the mean daily absolute deviation from its respective surface logger temperatures along with the maximum daily deviation above and below the surface logger temperatures.

Table 1. Intra-gravel water temperature study sites and logger details for the Klamath and Trinity rivers from July 2015 through August 2016. Coordinate system: NAD_1983_StatePlane_California_I_FIPS_0401_Feet (US Survey Feet)

Klamath River				
Site/Logger	Installed	Extracted	Northing	Easting
R Ranch				
Surface	7/15/2015	8/8/2016	2577713	6433628
Gravel1	8/13/2015	8/8/2016	2577687	6433627
Gravel2	7/15/2015	8/8/2016	2577653	6433627
Gravel3	7/15/2015	8/8/2016	2577675	6433641
Community Hall				
Surface	7/15/2015	8/8/2016	2554669	6333624
Gravel1	7/15/2015	8/8/2016	2554685	6333625
Gravel2	7/15/2015	8/8/2016	2554696	6333601
Gravel3	7/15/2015	8/8/2016	2554692	6333612
Walker Creek				
Surface	7/15/2015	8/8/2016	2554535	6242602
China Point				
Gravel1	7/15/2015	8/8/2016	2542276	6203424
Trinity River				
Site (Logger #)	Installed	Extracted	Northing	Easting
Cemetery Side Channel				
Surface	7/16/2015	4/20/2016	2141603	6335648
Gravel1	7/16/2015	4/20/2016	2141578	6335742
Sheridan Riffle				
Surface	7/16/2015	4/20/2016	2144315	6271494
Gravel1	7/16/2015	4/20/2016	2144478	6271457
Gravel2	7/16/2015	4/20/2016	2144490	6271378
Gravel3	7/16/2015	4/20/2016	2144532	6271462
Big Bar				
Surface	7/16/2015	8/1/2016	2154821	6215688
Gravel1	7/16/2015	8/1/2016	2154953	6215554
Gravel2	7/16/2015	8/1/2016	2154975	6215525
Campora				
Surface	7/16/2015	8/8/2016	2216690	6117621

Results

Out of 40 temperature loggers deployed in July 2015, 20 were re-located and retrieved in April or August 2016 (Table 1). On the Klamath River, both surface and intra-gravel temperature loggers were retrieved at two of four sites (R Ranch and Klamath Community Hall). On the Trinity River, both surface and intra-gravel temperature loggers were retrieved at three of four sites (Cemetery Side Channel, Sheridan Riffle, and Big Bar). Loggers we were unable to re-locate were likely washed away during winter high-flow events or were excavated by spawning salmon. At all five sites, daily-mean water temperatures exhibited typical seasonal patterns, with minimum temperatures occurring in December or January and maximum temperatures occurring in July or August. Across all intra-gravel loggers, the mean deviation from surface water temperatures was 0.42 ^{o}C (Table 2). The mean estimated emergence timing based on intra-gravel water temperatures ranged from 0 to 26 days (mean = 8.5 days) earlier than what would be expected based on surface water temperatures.

Klamath River

R Ranch (rkm 304.7)

Three intra-gravel loggers were retrieved at R Ranch. Intra-gravel water temperatures were typically slightly warmer than surface water temperatures during fall and winter and were typically slightly cooler than surface water temperatures during spring and summer (Figure 2). Mean deviations from surface water temperatures across the sampling period ranged from 0.18 ^{o}C to 0.61 ^{o}C among the three intra-gravel loggers. Daily-mean intra-gravel water temperatures were up to 1.41 ^{o}C warmer than surface water temperatures and as low as 1.88 ^{o}C cooler than surface water temperatures. The threshold of 1,000 ATUs was reached by the intra-gravel loggers between 2 and 12 days before the surface logger. Summary statistics for each logger are found in Table 2. Appendix A has a map of logger placements at R Ranch, with logger placements from the previous year included for comparison.

Klamath Community Hall (rkm 258.4)

Three intra-gravel loggers were retrieved at Klamath Community Hall. Seasonal patterns in differences between intra-gravel and surface water temperatures at Klamath Community Hall were similar to those at R Ranch (Figure 3). Mean deviations from surface water temperatures across the sampling period ranged from 0.43 ^{o}C to 0.69 ^{o}C among the three intra-gravel loggers. Daily-mean intra-gravel water temperatures were up to 3.31 ^{o}C warmer than surface water temperatures and as low as 2.20 ^{o}C cooler than surface water temperatures. The threshold of 1,000 ATUs was reached by the intra-gravel loggers between 7 and 26 days before the surface logger. Summary statistics for each logger are found in Table 2. Appendix B has a map of logger placements at Klamath Community Hall, with logger placements from the previous year included for comparison.

Trinity River

Cemetery Side Channel (rkm 178.5)

Only a single intra-gravel logger was retrieved at Cemetery Side Channel. Intra-gravel water temperatures deviated only slightly from surface water temperatures and there was little evidence of a seasonal pattern in the deviations (Figure 4). The mean deviation from surface water temperatures across the sampling period was 0.03 ^{o}C for the lone intra-gravel logger. Daily-mean intra-gravel water temperatures were up to 0.20 ^{o}C warmer than surface water temperatures and as low as 0.15 ^{o}C cooler than surface water temperatures. The threshold of 1,000 ATUs was reached by the intra-gravel and surface loggers on the same day. Summary statistics for each logger are found in Table 2. Appendix C has a map of logger placements at Cemetery Side Channel, with logger placements from the previous year included for comparison.

Sheridan Riffle (rkm 133.3)

Three intra-gravel loggers were retrieved at Sheridan Riffle. Intra-gravel water temperatures were typically warmer than surface water temperatures during fall and winter and were typically cooler than surface water temperatures during early spring, although there were exceptions (Figure 5). Mean deviations from surface water temperatures across the sampling period ranged from 0.27 ^{o}C to 0.99 ^{o}C among the three intra-gravel loggers. Daily-mean intra-gravel water temperatures were up to 3.64 ^{o}C warmer than surface water temperatures and as low as 2.23 ^{o}C cooler than surface water temperatures. The threshold of 1,000 ATUs was reached by the intra-gravel loggers between 1 and 20 days before the surface logger. Summary statistics for each logger are found in Table 2. Appendix D has a map of logger placements at Sheridan Riffle, with logger placements from the previous year included for comparison.

Big Bar (rkm 104.2)

Two intra-gravel loggers were retrieved at Big Bar. Intra-gravel water temperatures were typically slightly warmer than surface water temperatures during late summer through fall, and varied between being warmer and cooler than surface water temperatures for the remainder of the sampling period (Figure 6). Mean deviations from surface water temperatures across the sampling period ranged from 0.10 ^{o}C to 0.12 ^{o}C between the two intra-gravel loggers. Daily-mean intra-gravel water temperatures were up to 0.79 ^{o}C warmer than surface water temperatures and as low as 0.61 ^{o}C cooler than surface water temperatures. The threshold of 1,000 ATUs was reached by the intra-gravel loggers between 1 and 2 days before the surface logger. Summary statistics for each logger are found in Table 2. Appendix E has a map of logger placements at Big Bar.

Table 2. Mean and maximum daily deviations (^oC) from surface water temperatures and days to 1,000 accumulated thermal units (starting November 1) for intra-gravel water temperature loggers deployed in the Klamath and Trinity rivers from July 2015 through August 2016.

Site/Logger	Mean absolute deviation	Max above surface	Max below surface	Days to 1,000 ATUs	Deviation from surface days
Klamath River					
R Ranch					
Surface				143	
Gravel1	0.18	0.56	-0.62	141	-2
Gravel2	0.61	1.41	-1.88	131	-12
Gravel3	0.30	0.67	-1.22	139	-4
Community Hall					
Surface				142	
Gravel1	0.69	3.31	-0.48	116	-26
Gravel2	0.43	1.84	-1.53	135	-7
Gravel3	0.68	2.94	-2.20	126	-16
Trinity River					
Site/Logger	Mean absolute deviation	Max above surface	Max below surface	Days to 1,000 ATUs	Deviation from surface days
Cemetery Side Channel					
Surface				125	
Gravel1	0.03	0.20	-0.15	125	0
Sheridan Riffle					
Surface				135	
Gravel1	0.65	3.30	-2.23	124	-11
Gravel2	0.27	1.97	-1.37	134	-1
Gravel3	0.99	3.64	-2.11	115	-20
Big Bar					
Surface				135	
Gravel1	0.12	0.79	-0.61	134	-1
Gravel2	0.10	0.58	-0.40	133	-2
Mean of all					
Gravel	0.42				-8.5

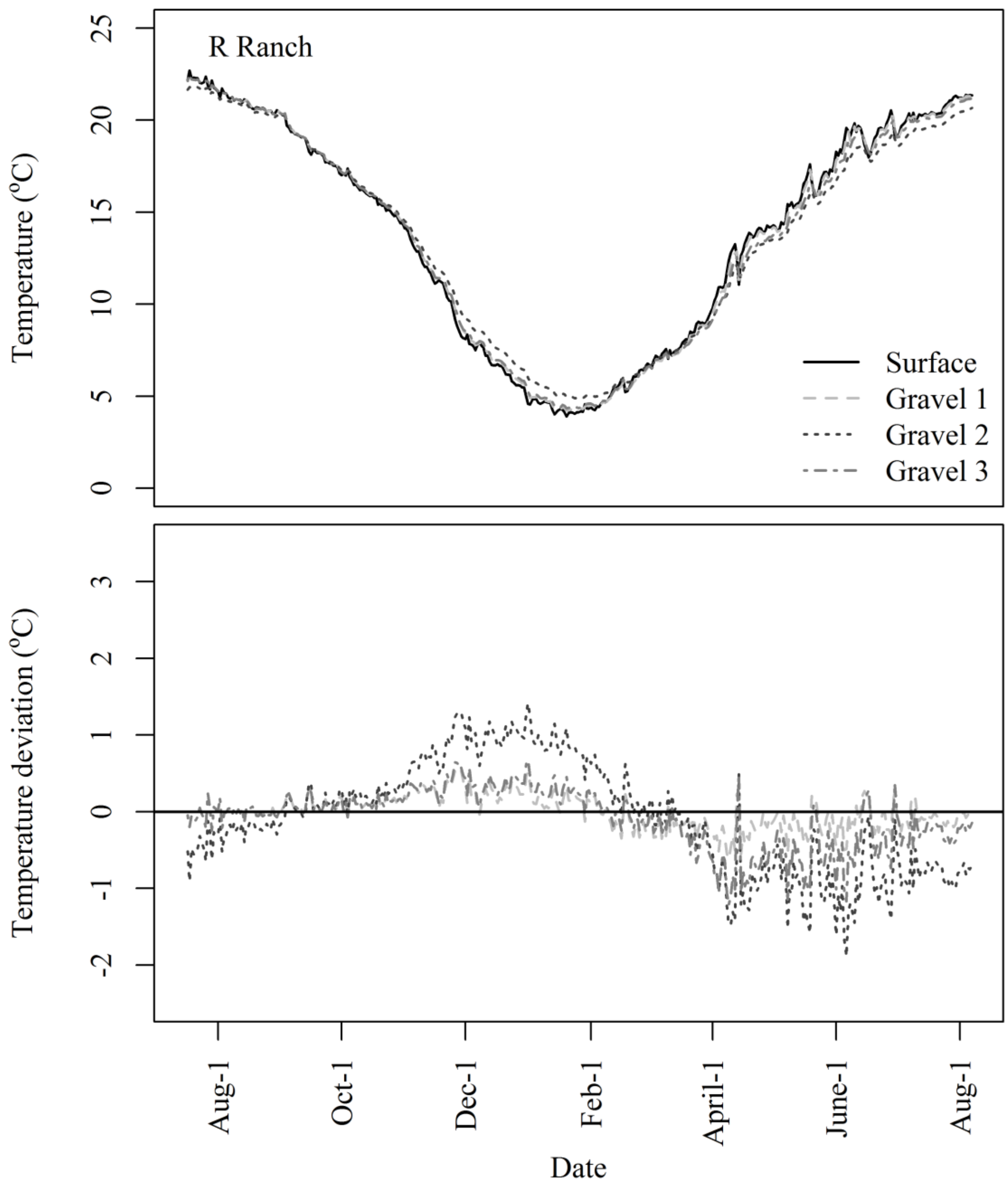

Figure 2. Daily-mean intra-gravel and surface water temperatures in the mainstem Klamath River at R Ranch (rkm 304.7) from July 2015 to August 2016 (top), and daily mean deviations of intra-gravel water temperatures from surface water temperatures for the same period (bottom).

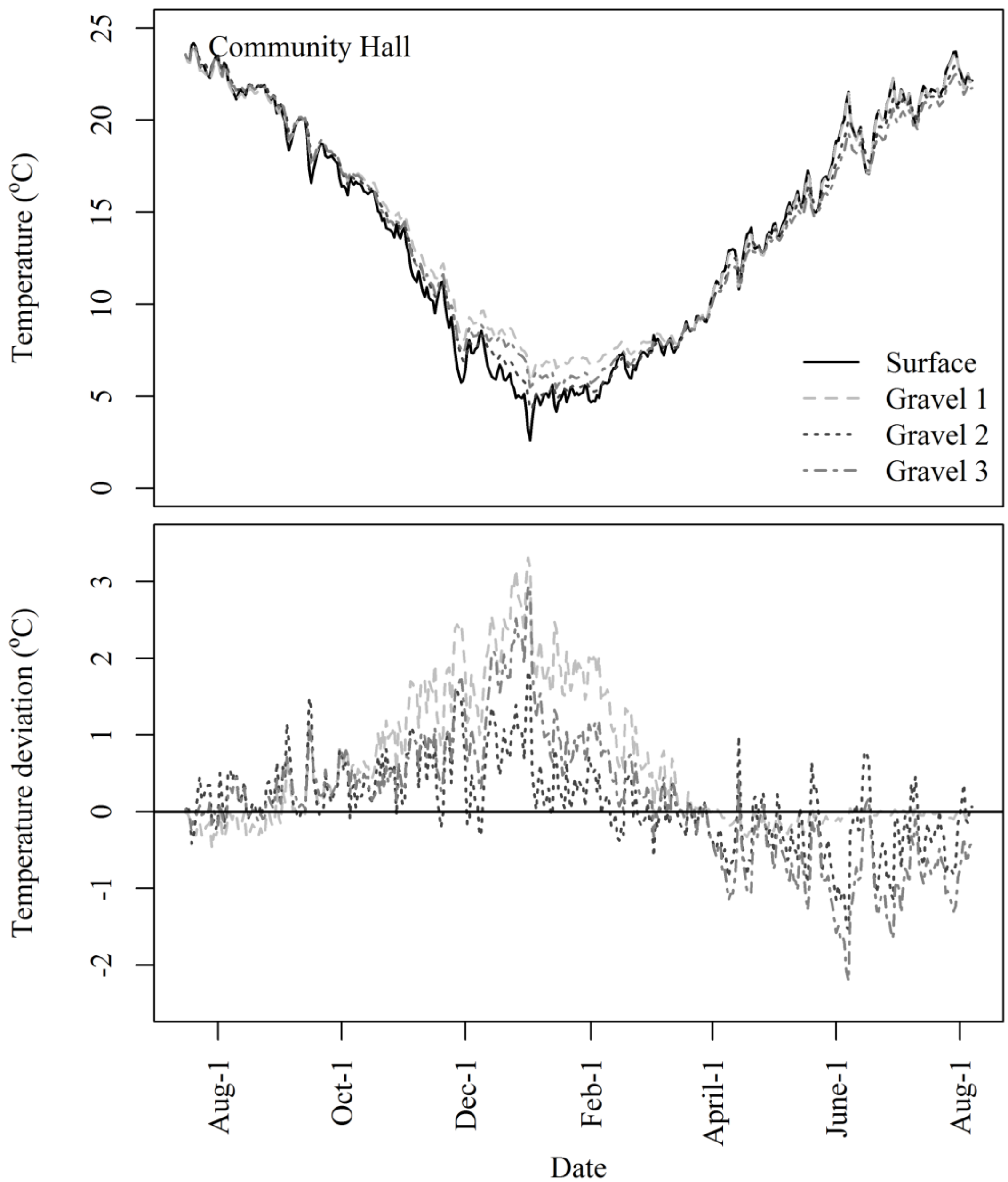

Figure 3. Daily-mean intra-gravel and surface water temperatures in the mainstem Klamath River at Klamath River Community Hall (rkm 258.4) from July 2015 to August 2016 (top), and daily mean deviations of intra-gravel water temperatures from surface water temperatures for the same period (bottom).

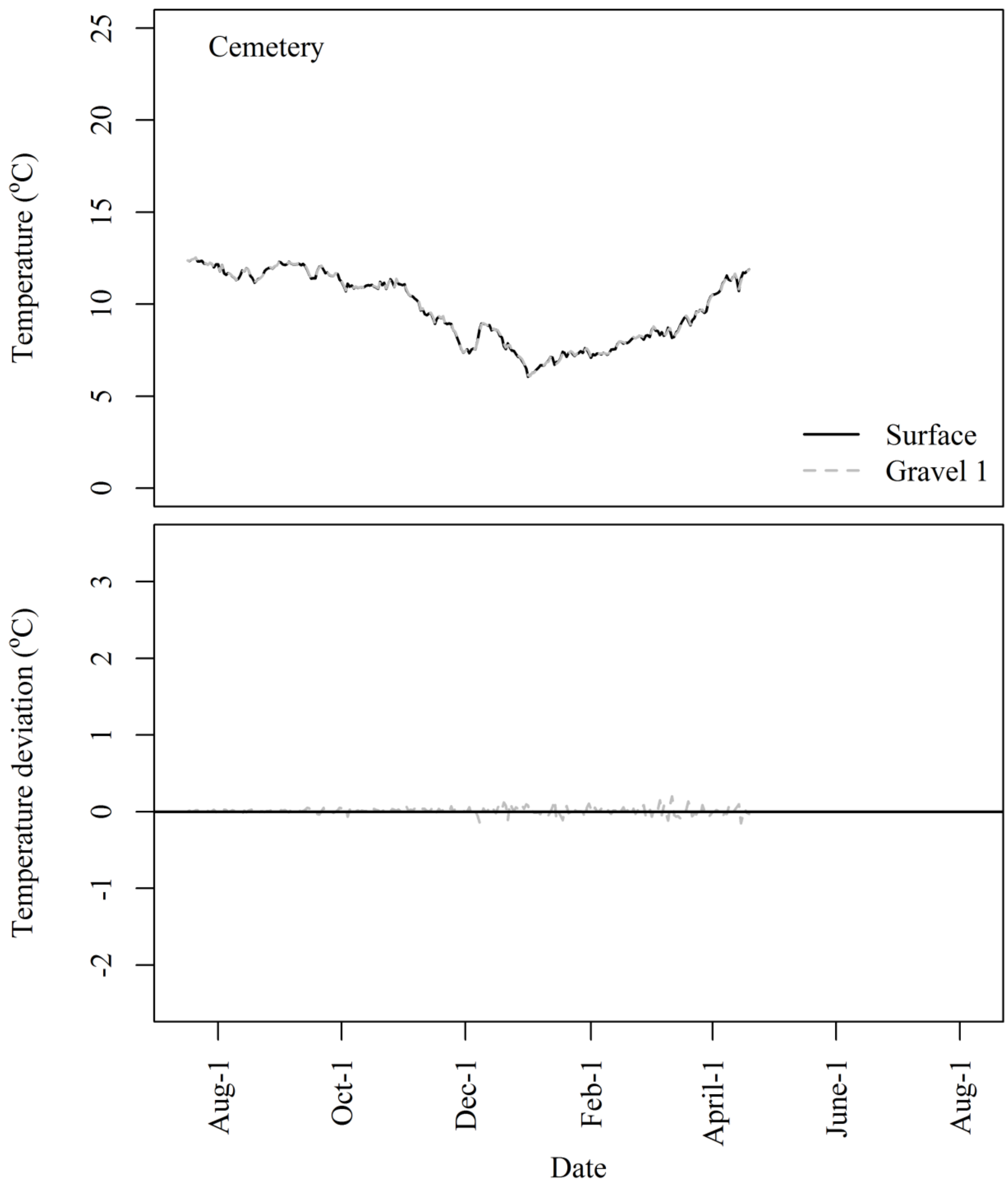

Figure 4. Daily-mean intra-gravel and surface water temperatures in the mainstem Trinity River at Cemetery Side Channel (rkm 178.5) from July 2015 to April 2016 (top), and daily mean deviations of intra-gravel water temperatures from surface water temperatures for the same period (bottom).

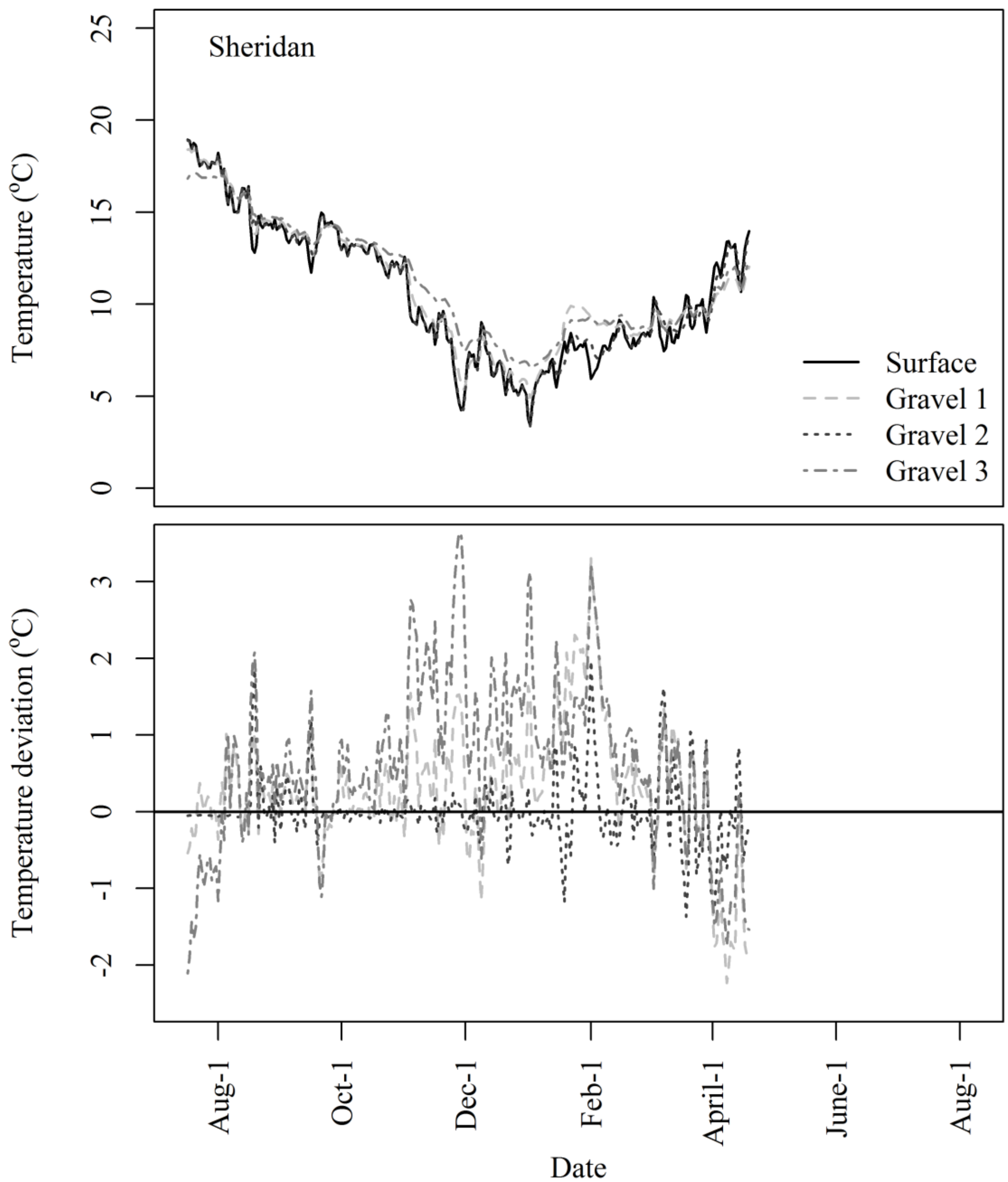

Figure 5. Daily-mean intra-gravel and surface water temperatures in the mainstem Trinity River at Sheridan Riffle (rkm 133.3) from July 2015 to April 2016 (top), and daily mean deviations of intra-gravel water temperatures from surface water temperatures for the same period (bottom).

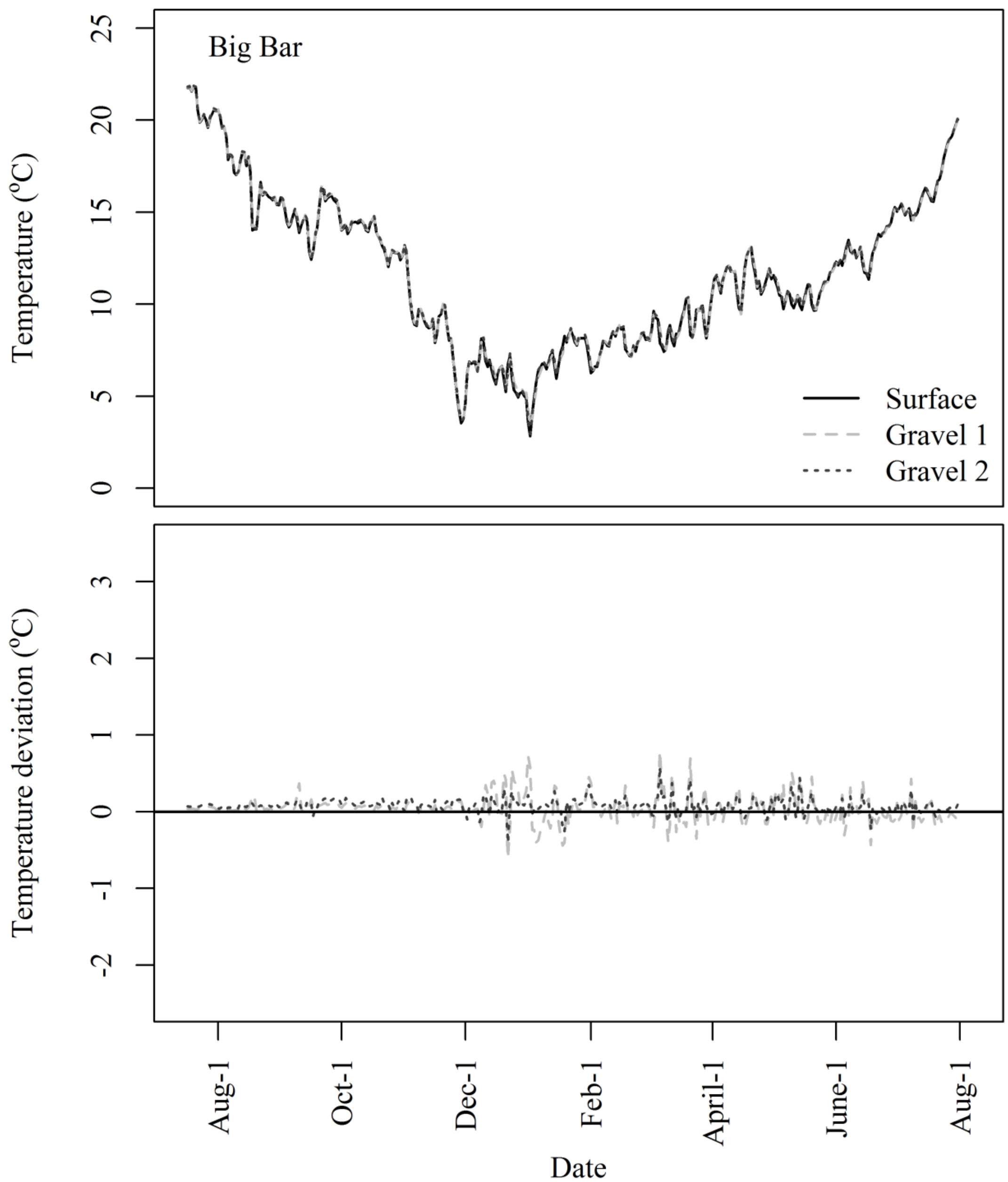

Figure 6. Daily-mean intra-gravel and surface water temperatures in the mainstem Trinity River at Big Bar (rkm 104.2) from July 2015 to August 2016 (top), and daily mean deviations of intra-gravel water temperatures from surface temperatures for the same period (bottom).

Discussion

Intra-gravel water temperatures were generally warmer than surface water temperatures during fall and winter and cooler during spring and summer at our sampling sites in the lower Klamath basin. Most pertinent to our focus, the period from mid-October to early March, when most Chinook Salmon spawning and egg incubation occurs in the Klamath basin, intra-gravel water temperatures were usually, though not exclusively, warmer than surface water temperatures. This observation suggests that incubating Chinook Salmon eggs experience warmer temperatures than would be predicted from surface water temperatures alone, and will develop and emerge faster than expected given surface water temperatures. In the first year of this study, Magneson (2015) observed a similar pattern. Our observations also align with research in other rivers, demonstrating that intra-gravel water temperatures are often more thermally stable than surface water temperatures (i.e., warmer in winter and cooler in summer relative to surface temperatures; Shepherd et al. 1986; Crisp 1990; Hanrahan 2007; Hannah et al. 2009).

The degree of deviation between intra-gravel and surface water temperatures did vary, however, among individual loggers within a site and among sites in the Klamath and Trinity rivers. Broadly, the relationship between intra-gravel and surface water temperatures is regulated by river channel bedform, substrate size and grading, and the relative amount of upwelling hyporheic flow vs. downwelling surface flow (Burkholder et al. 2008; Hannah et al. 2009 and references therein; C. Shea, USFWS, personal communication). Coarse substrates with large interstitial spaces tend to promote hydraulic connectivity between surface and intra-gravel flow, resulting in smaller temperature differences. Fine substrates with small interstitial spaces tend to reduce hydraulic connectivity and slow intra-gravel flow rates, resulting in divergence between surface and intra-gravel water temperatures. Channel bedforms and other geomorphic features which promote surface downwelling (e.g., riffle heads) tend to minimize differences between intra-gravel and surface water temperatures. In contrast, channel bedforms and other geomorphic features which promote hyporheic upwelling (e.g., riffle tails), tend to increase differences between intra-gravel and surface temperatures.

Intra-gravel loggers at three sites had generally small deviations from surface water temperatures (R Ranch on the Klamath River and Cemetery Side Channel and Big Bar on the Trinity River), while intra-gravel loggers at two sites had generally moderate deviations from surface temperatures (Community Hall on the Klamath River and Sheridan Riffle on the Trinity River). This result was also evident in the 2014-2015 study (excluding Big Bar, where loggers were not recovered), suggesting a consistent pattern.

Notably, R Ranch and Cemetery Side Channel are the sites closest to the downstream most dams on their respective rivers. Dams often trap fine sediment, resulting in coarsened sediment downstream (Kondolf 1997) and thus potentially increased connectivity between surface and hyporheic waters, which could explain the small differences between surface and intra-gravel water temperatures at these two sites. However, Big Bar is the furthest downstream of the three sites on the Trinity River considered in this report, which doesn’t support this explanation. As a partial alternative explanation, Cemetery Side Channel, which had the smallest surface – intra-gravel temperature differences of any site, was part of a constructed channel rehabilitation site. Rehabilitation activities included the addition of gravels containing no fines (sediments less than 2 mm), which could increase connectivity between surface and intra-gravel flow and thus potentially dampen temperature differences.

In both study years, the largest deviations from surface temperatures were observed at the Community Hall site on the Klamath River and the Sheridan Riffle site on the Trinity River. At Sheridan Riffle, a small tributary (Sheridan Creek) flows subsurface and enters the Trinity River on river right. Upwelling hyporheic flow from Sheridan Creek may moderate intra-gravel water temperatures at this site (D. Rupert and C. Shea, USFWS, personal communication). However, I am not aware of a similar input of hyporheic flow at the Klamath Community Hall site. Examination of maps of logger distribution at each site did not suggest obvious explanations for the variation in the amount of deviation from surface water temperatures among intra-gravel loggers within a site. Interestingly, at the Big Bar and Cemetery Side Channel sites on the Trinity River there was less of a clear seasonal pattern of deviations from surface temperatures than at Sheridan Riffle or the Klamath River sites, although again it is unclear what is driving these differences. These inferences are speculative, however, as this study did not seek to explain variation in surface – intra-gravel water temperature relationships among or within sampling sites.

While the observed variation in surface – intra-gravel water temperature relationships poses a challenge to predicting the emergence timing of salmon fry, it may be a potentially important facet of river ecosystem diversity. Within the Klamath Community Hall and Sheridan Riffle sites there was almost a three-week range in the number of days needed to reach 1,000 ATUs by different intra-gravel loggers. This fine-scale variation in intra-gravel temperatures may translate to variation in the emergence timing of Chinook Salmon fry. Habitat-mediated life-history diversity, such as temperature-driven differences in emergence timing, can increase salmon population resilience and reduce temporal variation in abundance (Hilborn et al. 2003; Moore et al. 2014).

In summary, intra-gravel water temperatures on both the Klamath and Trinity rivers were generally warmer than surface water temperatures during fall and winter and cooler during spring and summer. Because of these differences, Chinook Salmon fry likely emerge from the gravel earlier than would be predicted by surface water temperatures alone. The S3 model development should attempt to incorporate these differences in temperature to more accurately portray the rate of development of Chinook Salmon embryos and the emergence timing of fry. However, considerable variation in the magnitude of deviation between surface and intra-gravel water temperatures existed both within and among sites. To understand this fine-scale variation will likely necessitate a more detailed, intensive effort to map intra-gravel water temperatures. If future studies of intra-gravel water temperatures are undertaken, I suggest that a greater number of loggers be deployed at each site to increase the probability that multiple intra-gravel loggers are retrieved at each site. I also suggest that additional information be collected for each deployed logger, such as distance to shore, distance to the riffle crest, or surrounding substrate size, to be used as potential covariates in an analysis of deviations from surface water temperatures.

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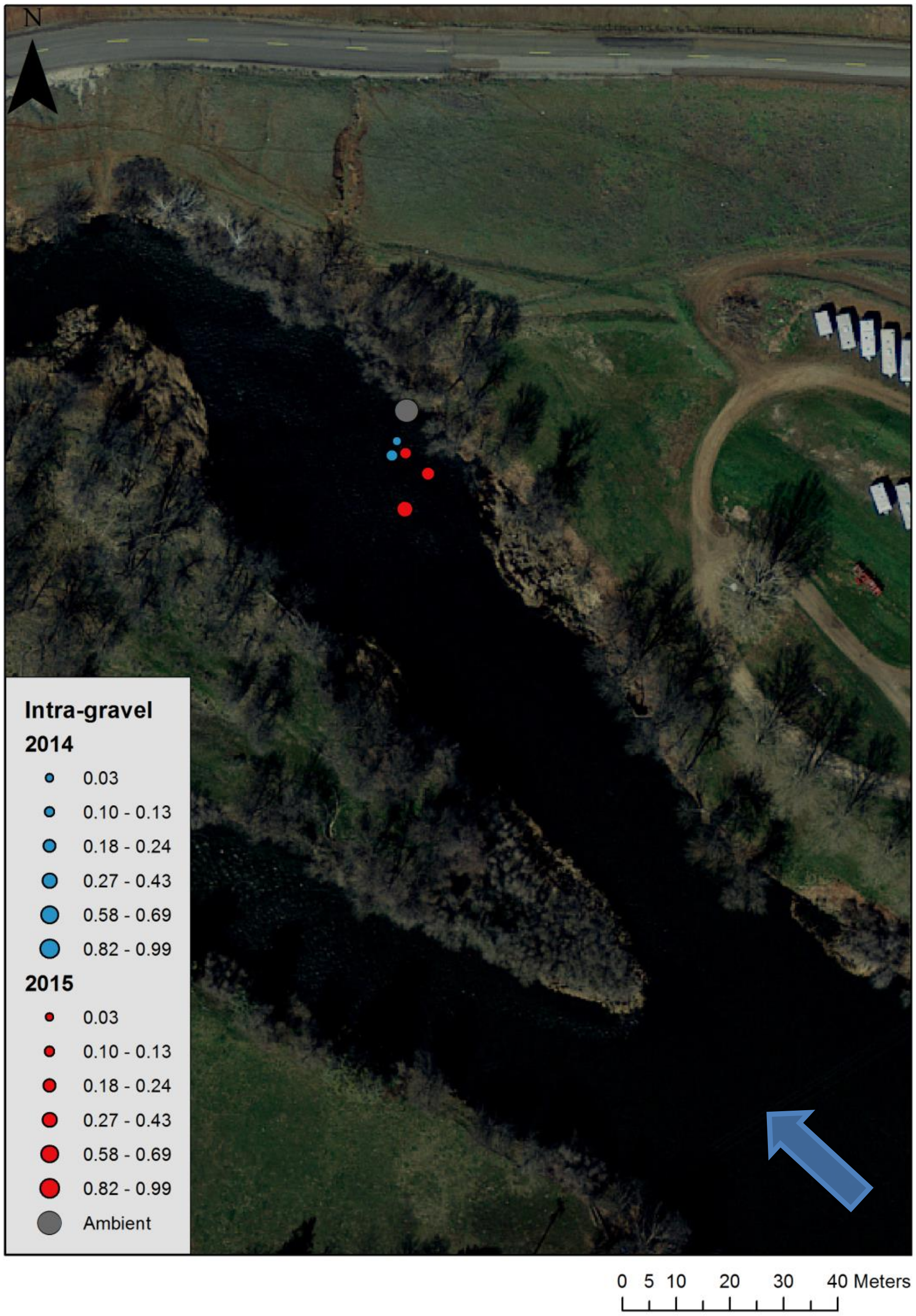
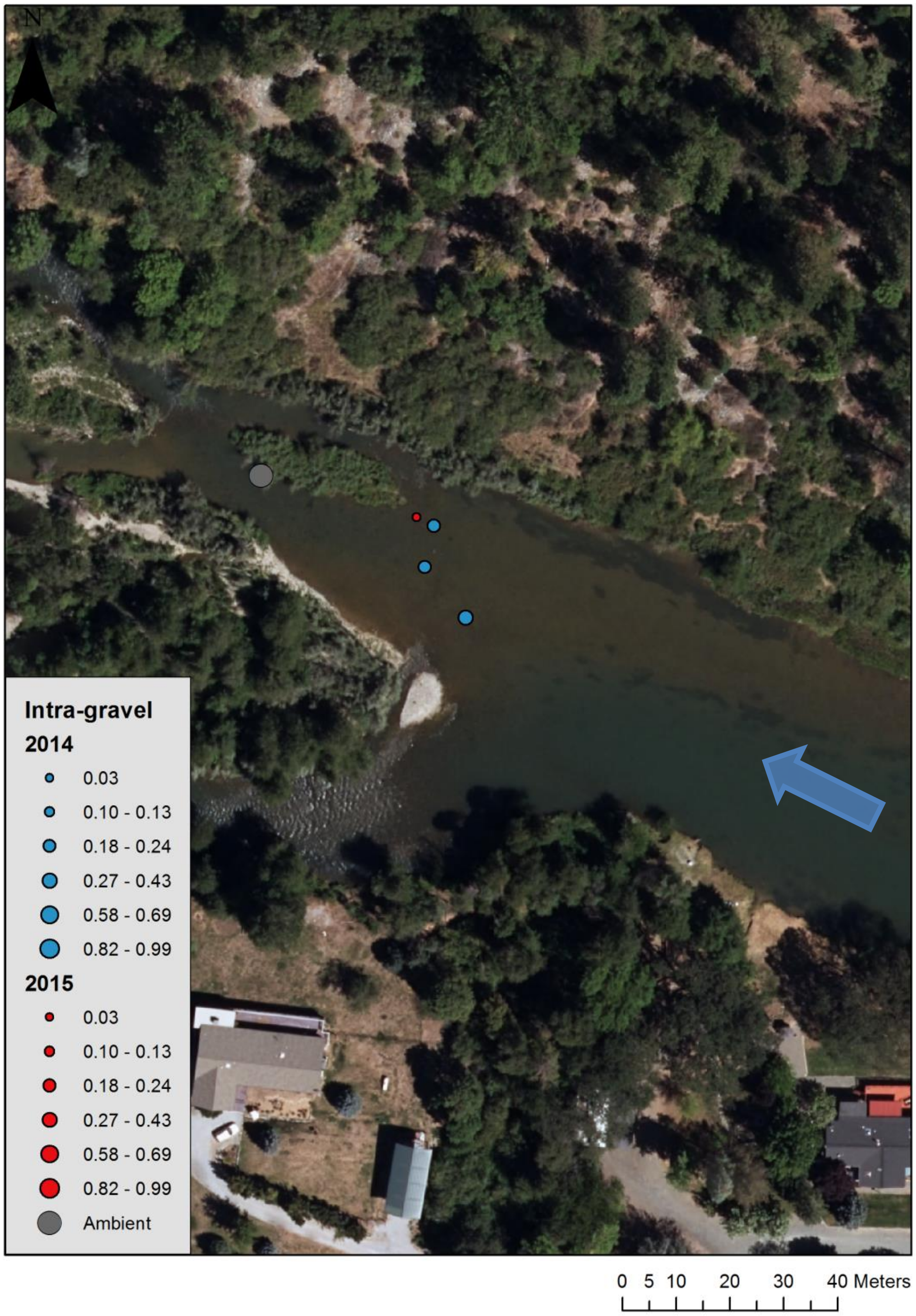
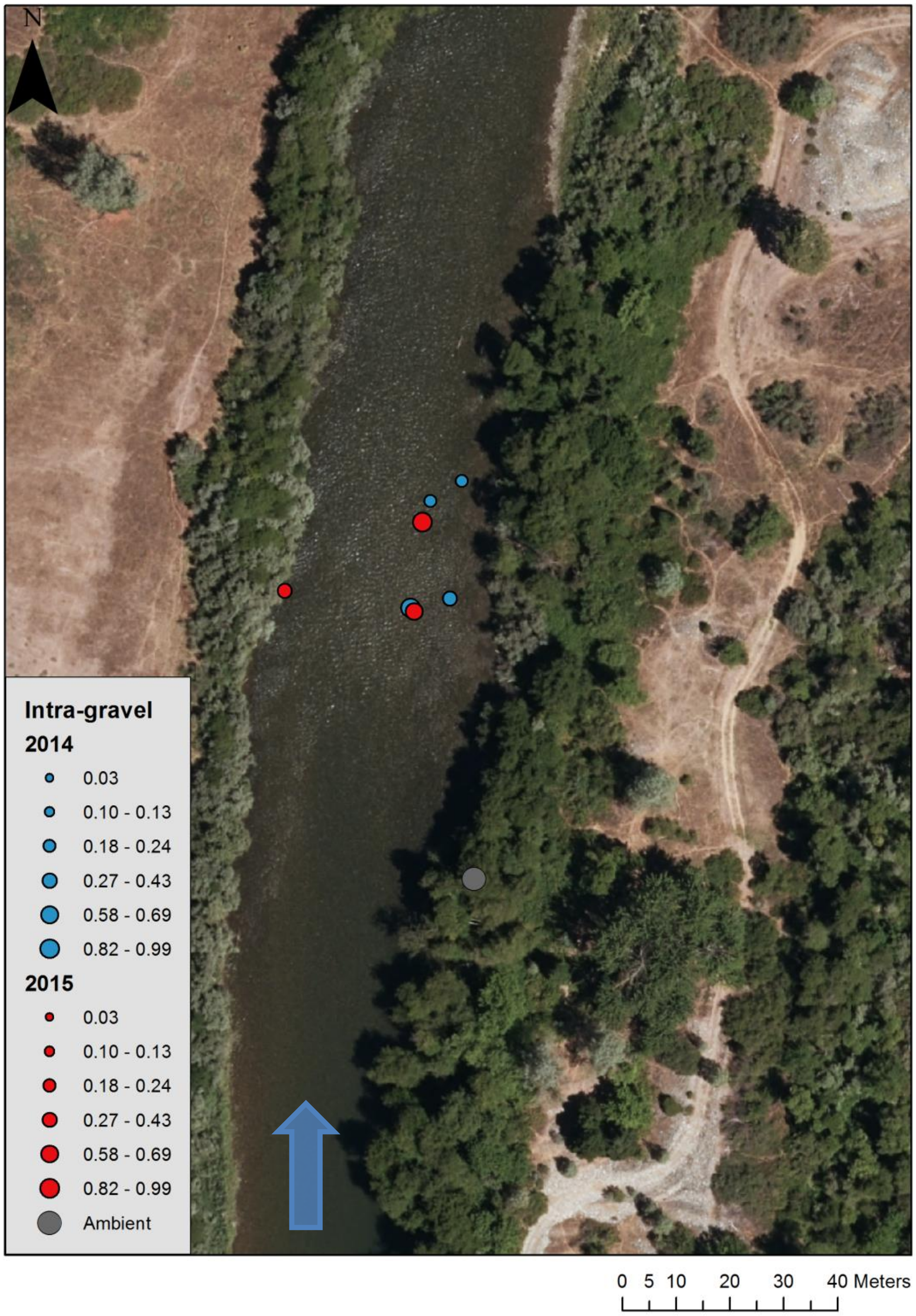


Appendix A. Map of intra-gravel and surface (ambient) water temperature loggers at R Ranch on the Klamath River for both study years. The size of intra-gravel logger symbols is proportional to the mean daily absolute deviation (in degrees C) of intra-gravel temperatures from surface temperatures. The blue arrow indicates the direction of river flow.

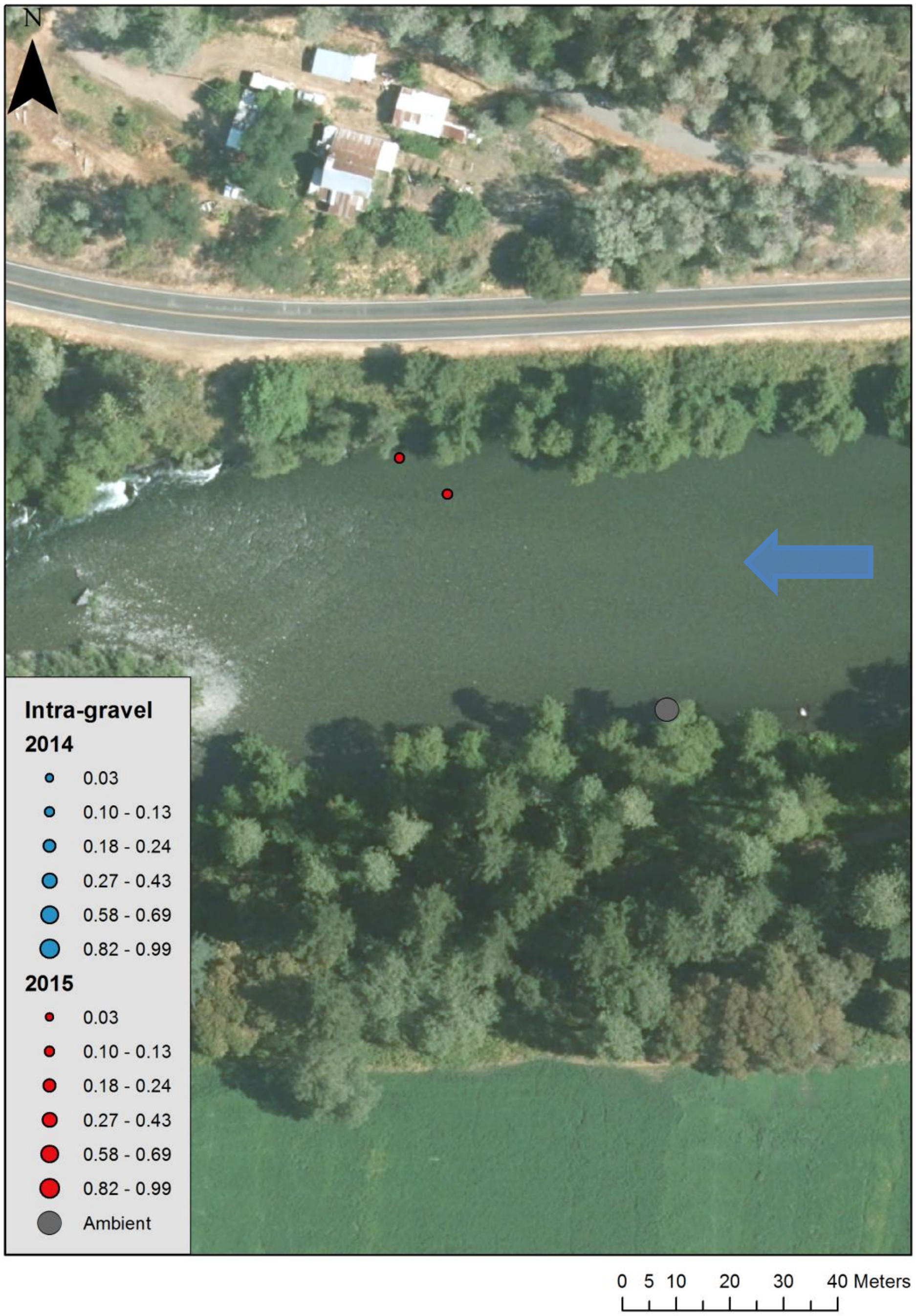
Appendix B. Map of intra-gravel and surface (ambient) water temperature loggers at Klamath Community Hall on the Klamath River for both study years. The size of intra-gravel logger symbols is proportional to the mean daily absolute deviation (in degrees C) of intra-gravel temperatures from surface temperatures. The blue arrow indicates the direction of river flow.



Appendix C. Map of intra-gravel and surface (ambient) water temperature loggers at Cemetery Side Channel on the Trinity River for both study years. The size of intra-gravel logger symbols is proportional to the mean daily absolute deviation (in degrees C) of intra-gravel temperatures from surface temperatures. The blue arrow indicates the direction of river flow.



Appendix D. Map of intra-gravel and surface (ambient) water temperature loggers at Sheridan Riffle on the Trinity River for both study years. The size of intra-gravel logger symbols is proportional to the mean daily absolute deviation (in degrees C) of intra-gravel temperatures from surface temperatures. The blue arrow indicates the direction of river flow.



Appendix E. Map of intra-gravel and surface (ambient) water temperature loggers at Big Bar on the Trinity River for the 2015-2016 study. The size of intra-gravel logger symbols is proportional to the mean daily absolute deviation (in degrees C) of intra-gravel temperatures from surface temperatures. The blue arrow indicates the direction of river flow.