U.S. Fish & Wildlife Service

Arcata Fisheries Date Series Report DS 2015-45

Klamath and Trinity River
Intra-Gravel Water Temperatures, 2014 and 2015

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November 2015

Funding for this study was provided by the Klamath River Habitat Assessment Study administered by the Arcata Fish and Wildlife Office.

The Arcata Fish and Wildlife Office Fisheries Program reports its study findings through two publication series. The **Arcata Fisheries Data Series** was established to provide timely dissemination of data to local managers and for inclusion in agency databases. The **Arcata Fisheries Technical Reports** publishes scientific findings from single and multi-year studies that have undergone more extensive peer review and statistical testing. Additionally, some study results are published in a variety of professional fisheries journals.

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

The correct citation for this report is:

Magneson, M.D. 2015. Klamath and Trinity River intra-gravel water temperatures, 2014 and 2015. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Arcata Fisheries Technical Report Number DS 2015-45, Arcata, California.

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Abstract.— Temperature recorders were used to monitor water temperatures in spawning gravels (intra-gravel) and in the water column above spawning gravels (surface) in the Klamath and Trinity Rivers from September 2014 to late June 2015. Water temperature recorders were installed in areas having 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 early winter and cooler in the spring than surface water temperatures. Findings of this study are important given the influence of intra-gravel water temperatures within redds on the development of salmonid embryos and the resulting influence on timing of emergence.

Introduction

Salmon prefer to select spawning sites with down-welling (Chapman 1988) and up-welling (hyporheic flow; Geist and Dauble 1998; Geist 2000; Malcolm et al. 2002) intra-gravel flows. Some researchers have reported surface water (water column) temperatures differ from intra-gravel temperatures (Crisp 1990; Geist 2000; Hanrahan 2007) and these differences might be important when describing the thermal environment experienced by developing eggs and embryos (Shepherd et al 1986). Conversely, a temperature differential was not observed between surface water temperature and intra-gravel water temperatures for artificial redds (Groves et al. 2008).

Water temperature is one of the most important variables in fish biology and influences survival and development of embryos and alevins (Crisp 1988, 1990; Carter 2005; Geist et al. 2006). Malcolm et al. (2008) reported interactions between water temperature and dissolved oxygen concentrations as critical controls of developmental timing and survival.

The Stream Salmonid Simulator (S3) juvenile Chinook Salmon production model uses water temperatures, estimated by the model RBM10 (Yearsley et al. 2001), to determine timing of egg development and eventual emergence as free-swimming fry. However, the RBM10 model estimates spatially-specific temperatures in the water column, which may not accurately reflect the temperatures experienced by eggs as they develop within a redd. The purpose of this study was to determine if there is a difference between intra-gravel and water column water temperatures in the Klamath Basin as differences will influence the S3 model's estimates of emergence timing of free-swimming fry.

Study Area

The Klamath River originates in southern Oregon, east of the Cascade Mountain Range and flows 423 kilometers through southern Oregon and northern California bisecting the Cascade and Coast mountain ranges before entering the Pacific Ocean (National Resource Council 2008; Magneson 2015). The upper half of the watershed, upstream of Iron Gate Dam, is relatively flat with a series of wide valleys, several lakes, and six reservoirs. The lower half of the watershed is mostly mountainous with a narrow river canyon (Figure 1).

Climatic conditions vary throughout the watershed with coastal areas having mild wet winters, moderate annual temperatures and coastal fog (Ayres Associates 1999). Further inland, temperature fluctuations increase and become more variable between hot summers and cold winters, and precipitation generally decreases. Air temperatures are greatly influenced by elevation and local topography.

The Klamath River Basin drains approximately 41,000 km^2 in Oregon and California (Ayres Associates 1999). Four major tributaries to the Klamath River downstream of IGD are, from upstream to downstream, the Shasta, Scott, Salmon, and Trinity rivers. The Scott River is the first tributary that typically increases flow in the Klamath River below IGD (Ayres Associates 1999) and the Trinity River is the Klamath River's largest tributary.

The Trinity River flows for 266 kilometers through mountainous terrain in northern California in a northwesterly direction to the Klamath River. The Trinity River has two reservoirs made by Trinity and Lewiston Dam, the lowermost dam (Magneson and Chamberlain 2015). From Lewiston Dam, the Trinity River flows for approximately 180 river kilometers (rkm) before joining the Klamath River at Weitchpec, CA. From Weitchpec, the Klamath River flows for 70 rkm before entering the Pacific Ocean (Figure 1).

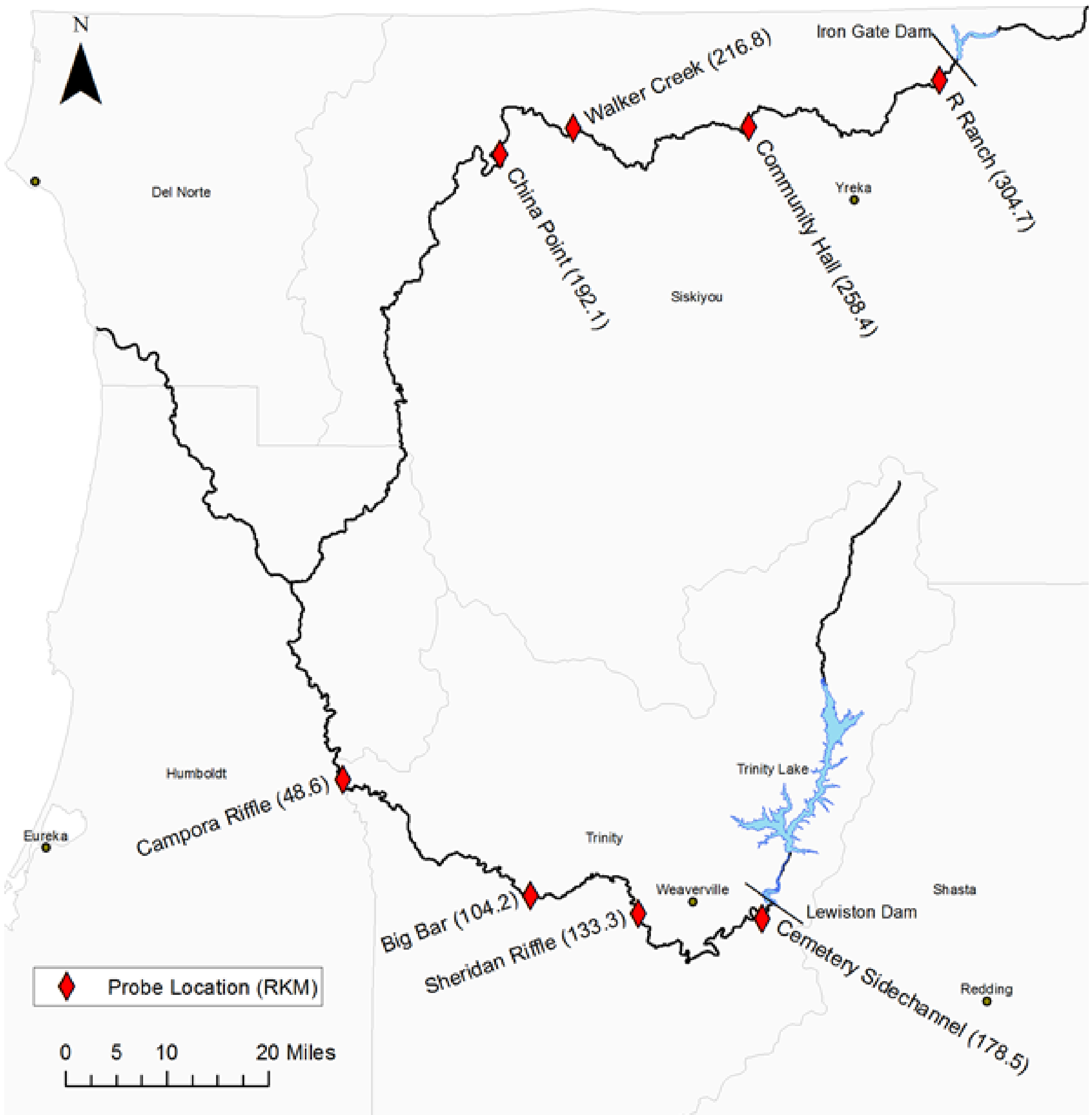

Figure 1. Klamath and Trinity River intra-gravel and surface water temperature monitoring sites during September 16, 2014 to June 19, 2015.

Methods

Data loggers (HOBO Water Temp Pro v2 Model Number U22 001; Onset Computer Corporation, Bourne, Massachusetts) were used in this study and set to record at 30-min intervals. Prior to and after deployment, each probe was tested to verify operation within the manufacturer's accuracy specification of ± 0.2 degrees Celsius (˚C). The instruments proved accurate and reliable for all tests conducted during this study and no "probe drift" adjustments to temperature data were necessary. A copy of the AFWO quality assurance protocol for data logger operation and validation is available upon request.

Surface water temperatures were collected by attaching a temperature logger to one end of a piece of chain with the other end attached to the river bank. These loggers were placed along the stream margin in water < 1.0 m deep in the fall during low flows and in the vicinity (< 100 m) of the intra-gravel temperature loggers. Surface water temperature from Lewiston California Data Exchange Center (CDEC) water quality station LWS (rkm 180.7) was used as a surrogate for the surface logger at Cemetery Side Channel because the logger at Cemetery Side Channel was dewatered after December 5, 2014. These two sites were compared by examining their difference for the time that they overlapped (September 26 to December 5, 2014) and it was determined the differences were small enough (range -0.11 to 0.64°C; $\bar{x}$ = 0.14°C) so that data from the Lewiston site could be used as a surrogate for Cemetery Side Channel surface temperature. For Appendices A and B, surface daily mean water temperature was subtracted from intra-gravel daily mean water temperature to show differences in daily mean temperature over time. At Big Bar the surface water temperature logger was damaged and data was not able to be recovered and compared to data from the intra-gravel water temperature loggers there.

Intra-gravel temperature loggers were placed within the gravels at various locations in the rivers that had high redd densities the previous year. Data loggers were attached to one end of a plastic cable tie with stainless steel wire threaded through a small hole (Zimmerman and Finn 2012). The upper end of the cable tie had a green colored stake whisker attached to make re-locating the temperature logger easier. 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 temperature loggers in the substrate, 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 into the substrate. Water temperature loggers were placed in the substrate in mid to late-September of

2014 and retrieved in mid-June of 2015 (Table 1). Four water temperature logger installation sites were selected on both the Klamath and Trinity rivers (Figure 1).

Sites were selected based on having high redd densities the previous year; being readily accessible; and being distributed throughout the primary extent of mainstem spawning. One surface and four intra-gravel loggers were installed at each site. Coordinates of logger locations were recorded using a Pro XH GPS, Zephyr Geodetic™ antenna, and TerraSync™ survey software (Trimble Navigation Limited, Sunnyvale, CA, U.S.A.) on a tablet computer. For extraction, a GPS was used to navigate to each logger’s coordinates, and visual identification of stake whiskers were used to relocate the loggers. A clamming shovel was used to clear substrate away from the water temperature logger so it could be more easily extracted.

Logger data were downloaded using HOBOware Pro by Onset® and imported into MS Excel for graphical analysis. Only sites retaining a functional surface (or surrogate) and intra-gravel water temperature logger were used in this analysis. Accumulated thermal units (ATU) were used to cast differing intra-gravel and surface daily mean water temperatures into a biologically-relevant metric: fry emergence time. Incubation times for fall Chinook Salmon eggs were determined by starting at the peak spawning survey week (approximately when 50% of spawning had occurred; Shepherd et al. 1986), and calculating ATUs using daily mean temperatures. The peak emergence time for juvenile fall Chinook Salmon was assumed to be around 1,000 ATU (Geist 2006).

Results and Discussion

On the Klamath River, 10 (7 intra-gravel, 3 surface) of the 20 temperature loggers were recovered, and on the Trinity River 13 (9 intra-gravel, 4 surface) of the 20 temperature loggers were recovered (Table 1). Temperature logger fidelity varied by site, and high flow events are hypothesized to have caused some temperature loggers to wash away and prevent their recovery. This hypothesis is supported by the fact that the fewest temperature loggers were recovered from the most downstream sites in each river, which experienced higher flow variability than sites located further upstream near dams that functioned to regulate flows.

Klamath River

RRanch (rkm 304.7)

Both intra-gravel and surface water temperatures tended to decrease in the fall and early winter and then increase in the spring (Figure 2). Surface water temperatures at RRanch were similar or slightly cooler from late September until late January and then were then similar or slightly warmer from late January until late June than intra-gravel water temperatures (Appendix A). The estimated ATU was slightly less for

Table 1. Intra-gravel and surface water temperature study sites on the Klamath and Trinity rivers from September 16, 2014 to June 19, 2015.

Klamath River Mainstem						
Site (logger #)	Location	Name	Installed	Extracted	Northing	Easting
Rranch[a]						
10566551	surface	RRSurface	9/16/2014	6/19/2015	4639376	543934
10566530	intergravel	RRgravel1	9/16/2014	6/19/2015	4639372	543931
10566547	intergravel	RRgravel2	9/16/2014	6/19/2015	4639369	543930
Klamath Community Hall[b]						
10566525	surface	KCCsurface	9/17/2014	6/19/2015	4632008	513548
10566544	intergravel	KCCgravel1	9/17/2014	6/19/2015	4632012	513544
10566538	intergravel	KCCgravel2	9/17/2014	6/19/2015	4632017	513534
10566539	intergravel	KCCgravel3	9/17/2014	6/19/2015	4632020	513531
Walker Creek (upstream)[c]						
10566546	surface	WCsurface	9/17/2014	6/19/2015	4631649	485817
10566542	intergravel	WCgravel1	9/17/2014	6/19/2015	4631656	485803
10566541	intergravel	WCgravel2	9/17/2014	6/19/2015	4631649	485814
China Point[d]						
Trinity River Mainstem						
Site (logger #)	Location	Name	Installed	Extracted	Northing	Easting
Cemetery Side Channel (upstream)[e]						
10579786	surface	CSCsurface	9/26/2014	6/18/2015	4506169	515625
10579784	intergravel	CSCgravel1	9/26/2014	6/18/2015	4506764	496044
10579793	intergravel	CSCgravel2	9/26/2014	6/18/2015	4506145	515633
10579788	intergravel	CSCgravel3	9/26/2014	6/18/2015	4506153	515635
Sheridan Riffle						
10579799	surface	SRsurface	9/26/2014	6/18/2015	4506764	496044
10579783	intergravel	SRgravel1	9/26/2014	6/18/2015	4506817	496041
10579791	intergravel	SRgravel2	9/26/2014	6/18/2015	4506835	496037
10579794	intergravel	SRgravel3	9/26/2014	6/18/2015	4506839	496043
10579785	intergravel	SRgravel4	9/26/2014	6/18/2015	4506815	496034
Big Bar[f]						
10579790	surface	BBsurface	9/26/2014	6/18/2015	4509763	478982
10579789	intergravel	BBgravel1	9/26/2014	6/18/2015	4509804	478961
10579782	intergravel	BBgravel2	9/26/2014	6/18/2015	4509811	478966
Campora Riffle[g]						
10579781	surface	Camporasurface	9/26/2014	6/18/2015	4528284	448909

[a] Could not relocate two intra-gravel water temperature loggers.
[b] Could not relocate one intra-gravel water temperature logger.
[c] Could not relocate two intra-gravel water temperature loggers.
[d] Could not relocate one surface and four intra-gravel water temperature loggers.
[e] Could not relocate one intra-gravel water temperature logger.
[f] Surface water temperature logger malfunctioned and could not relocate two intra-gravel water temperature loggers.
[g] Could not relocate four intra-gravel water temperature loggers.

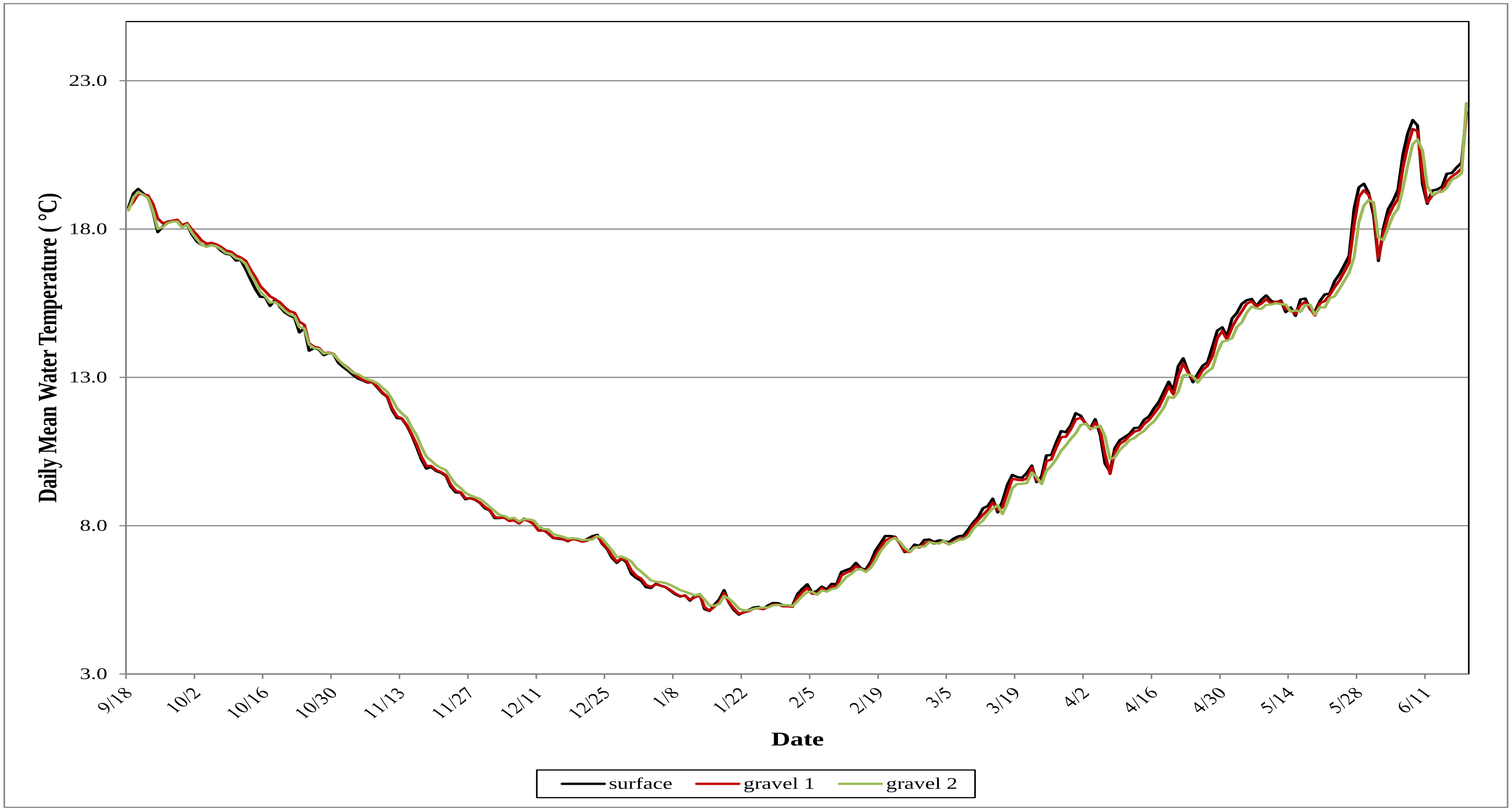

Figure 2. Daily mean intra-gravel and surface water temperatures on the mainstem Klamath River at RRanch (rkm 304.7) from September 18, 2014 to June 19, 2015.

the intra-gravel temperatures than for surface temperatures, (range = 0-1 days; $\bar{x}$ = 0.5 days; Table 2). Substrate at the RRanch study site was more embedded than at downstream sites, which may help to explain the reduced intra-gravel flows.

Klamath River Community Hall (rkm 258.4)

At the Klamath Community Hall site, daily mean water temperatures were cooler for the surface loggers than the intra-gravel probes from late September until early March, and then warmer than most intra-gravel water temperatures (Figure 3; Appendix A), with the magnitude of the difference varying between loggers. One intra-gravel water temperature logger (Gravel 1) recorded daily mean water temperatures 1.8°C warmer than surface water temperatures (January 27). Conversely, in the latter part of the monitoring period daily mean water temperatures were as much as 1.8°C cooler than that recorded by the surface water temperature logger (June 8). Intra-gravel temperatures were more variable between loggers at the Community Hall site than at the RRanch site. The difference in predicted time-to-emergence based on surface versus intra-gravel ATU estimates ranged from 2 to 10 days ($\bar{x}$ = 5.3 days; Table 2), with the estimated ATU being lower for intra-gravel than surface temperatures.

Walker Creek (rkm 216.8)

At the Klamath River site located just upstream of Walker Creek, surface daily mean water temperatures were mostly cooler than intra-gravel daily mean water temperatures from late September until early March and then became slightly warmer than intra-gravel daily mean water temperatures into June (Figure 4; Appendix A). Intra-gravel daily mean water temperatures for the Gravel 2 logger were more variable than the Gravel 1 logger and the surface logger. The Gravel 2 logger recorded daily mean temperatures as much as 1.5°C warmer than the surface water temperature logger (February 16). Intra-gravel water temperatures were not as variable at this site as they were at the Klamath River Community Hall site, but were more variable than at the RRanch site. The difference between predicted time-to-emergence based on surface versus intra-gravel ATU estimates ranged from 1 to 6 days ($\bar{x}$ =3.5 days; Table 2), with the intra-gravel ATU being lower than the surface estimate.

Trinity River

Cemetery Side Channel (rkm 178.5)

In the pool tail out at the Cemetery Side Channel site, the surface temperature logger was out of the water after December 5, so a surrogate CDEC surface water temperature logger located at Lewiston was used. The intra-gravel daily mean water temperatures was warmer than the Lewiston surface daily mean water temperature for all three intra-gravel loggers except in late October and for two intra-gravel

Table 2. Differences in peak spawning and emergence dates based on accumulated thermal units (ATU) between intra-gravel and surface water temperature loggers at study sites on the Klamath and Trinity Rivers in 2014 and 2015.

Site	Name	Peak Spawning date	Peak emergence date	Difference surface vs gravel dates (days)	ATU (°C)
		Klamath River Mainstem			
RRanch	surface	27-Oct	1-Mar		996.6
	gravel 1	27-Oct	1-Mar	0	995.7
	gravel2	27-Oct	28-Feb	1	997.3
Klamath River Community Hall	surface	27-Oct	1-Mar		996.5
	gravel 1	27-Oct	19-Feb	10	996.8
	gravel 2	27-Oct	27-Feb	2	996.3
	gravel 3	27-Oct	25-Feb	4	996.0
Walker Creek	surface	20-Oct	16-Feb		998.5
	gravel 1	20-Oct	15-Feb	1	999.3
	gravel 2	20-Oct	10-Feb	6	997.9
		Trinity River Mainstem			
Cemetery Side Channel	Surface[a]	3-Nov	12-Feb		997.4
	gravel 1	3-Nov	9-Feb	3	1001.1
	gravel 2	3-Nov	10-Feb	2	998.0
	gravel 3	3-Nov	10-Feb	2	996.9
Sheridan Riffle	surface	20-Oct	4-Feb		999.9
	gravel 1	20-Oct	31-Jan	4	995.2
	gravel 2	20-Oct	3-Feb	1	1,000.1
	gravel 3	20-Oct	2-Feb	2	999.2
	gravel 4	20-Oct	25-Jan	10	1,001.6

[a]Lewiston surface water temperature was used as surrogate.

loggers (Gravel 1 and 3) in early November (Figure 5; Appendix B). The difference between surface and intra-gravel ATU ranged from 2 to 3 days ($\bar{x}$ = 2.3 days; Table 2) and was lower when estimated using the intra-gravel water temperatures.

Sheridan Riffle (rkm 133.3)

At the Sheridan Riffle site (rkm 133.3) the surface daily mean water temperatures were slightly cooler than intra-gravel daily mean water temperatures until early March, and then slightly warmer than most intra-gravel loggers until early June

Figure 3. Daily mean intra-gravel and surface water temperatures on the mainstem Klamath River at Klamath River Community Hall (rkm 258.4) from September 18, 2014 to June 19, 2015.

Figure 4. Daily mean intra-gravel and surface water temperatures on the mainstem Klamath River at Walker Creek (rkm 216.8) from September 18, 2014 to June 19, 2015.

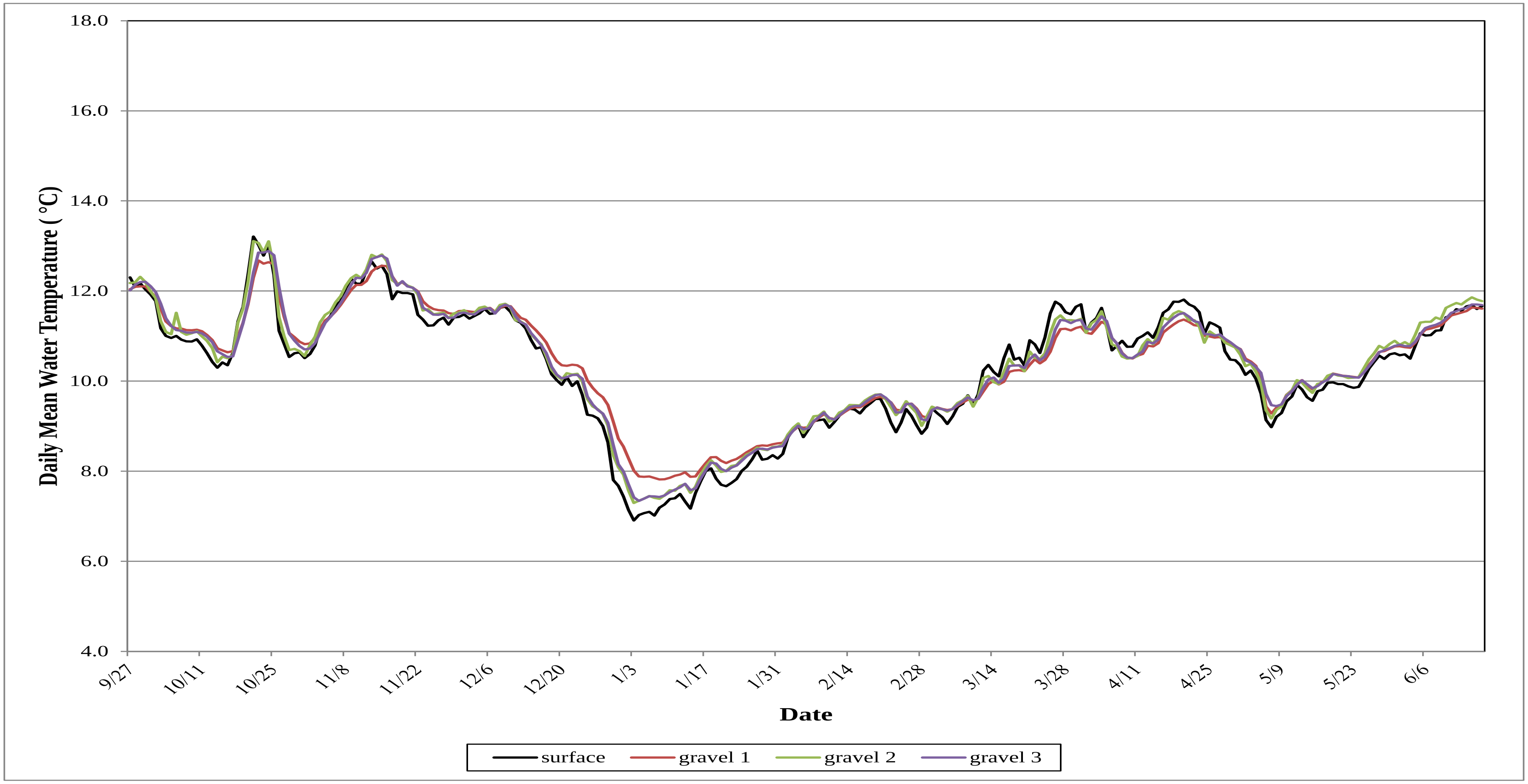

Figure 5. Daily mean intra-gravel and surface water temperatures on the mainstem Trinity River at Cemetery Side Channel (rkm 178.5) from September 27, 2014 to June 17, 2015. Note: Surface water temperature at Lewiston (rkm 180.7) was used as a surrogate for Cemetery Side Channel surface water temperature.

(Figure 6; Appendix B). Intra-gravel logger Gravel 4's daily mean water temperatures appeared to be more variable than the other intra-gravel water temperature loggers, and daily mean water temperatures were as much as 4.5°C warmer and 2.6°C cooler than the surface temperature logger on December 31 and April 19, respectively. The difference between intra-gravel and surface ATU ranged from 1 to 10 days ($\bar{x}$ = 4.3 days; Table 2) and was lower for intra-gravel ATU.

Summary

Both intra-gravel and surface daily mean water temperatures decreased in the fall and early winter and increased in the spring. Daily mean water temperatures collected by surface loggers tended to be lower than intra-gravel water temperatures in the fall and early winter, then shifted to being higher than intra-gravel temperatures in the spring. However, most juvenile salmonids had already emerged from redds by late spring when the observed shift occurred. The difference in water temperatures between the surface loggers and the adjacent intra-gravel loggers varied and was likely due to differences in intra-gravel (hyporheic) flow. Possible inconsistencies in gravel conditions (e.g. porosity, embeddedness, percent fines, etc.) at specific intra-gravel logger placements may have contributed to observed variability in water temperatures at sites, and may have been less if loggers had been deployed in egg pockets within redds.

In general, intra-gravel water temperatures were warmer than surface water temperatures in the fall and early winter, which is assumed to increase the developmental rate of eggs (Murray and Beacham 1987) and lessen the subsequent time to emergence. To account for these differences, the S3 model developers should adjust water column temperatures predicted by the RBM10 model to better reflect conditions influencing egg development and subsequent time-to-emergence in the Klamath Basin.

Acknowledgements

I would like to thank Dr. Nicholas Som and Nicholas Hetrick of the Service's Arcata Fish and Wildlife Office for providing comments on an earlier draft of this report. I would also like to thank Service employees Aaron David, Andrew Goodman, Derek Rupert and Travis Webster of Service's Arcata Fish and Wildlife Office for field support. We would also like to thank RRanch for allowing us river access through their property.

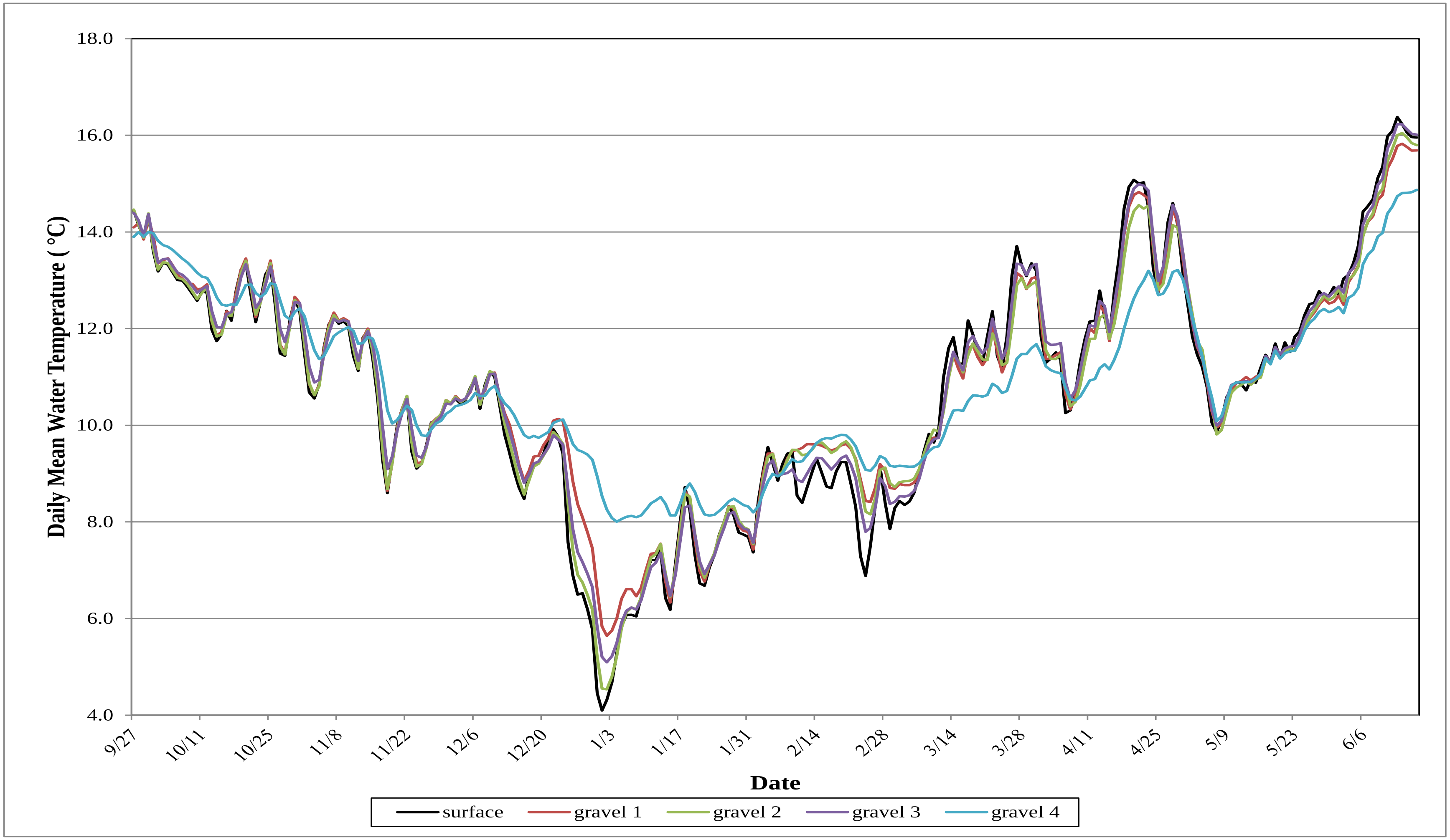

Figure 6. Daily mean intra-gravel and surface water temperatures on the mainstem Trinity River at Sheridan Riffle (rkm 133.3) from September 27, 2014 to June 17, 2015.

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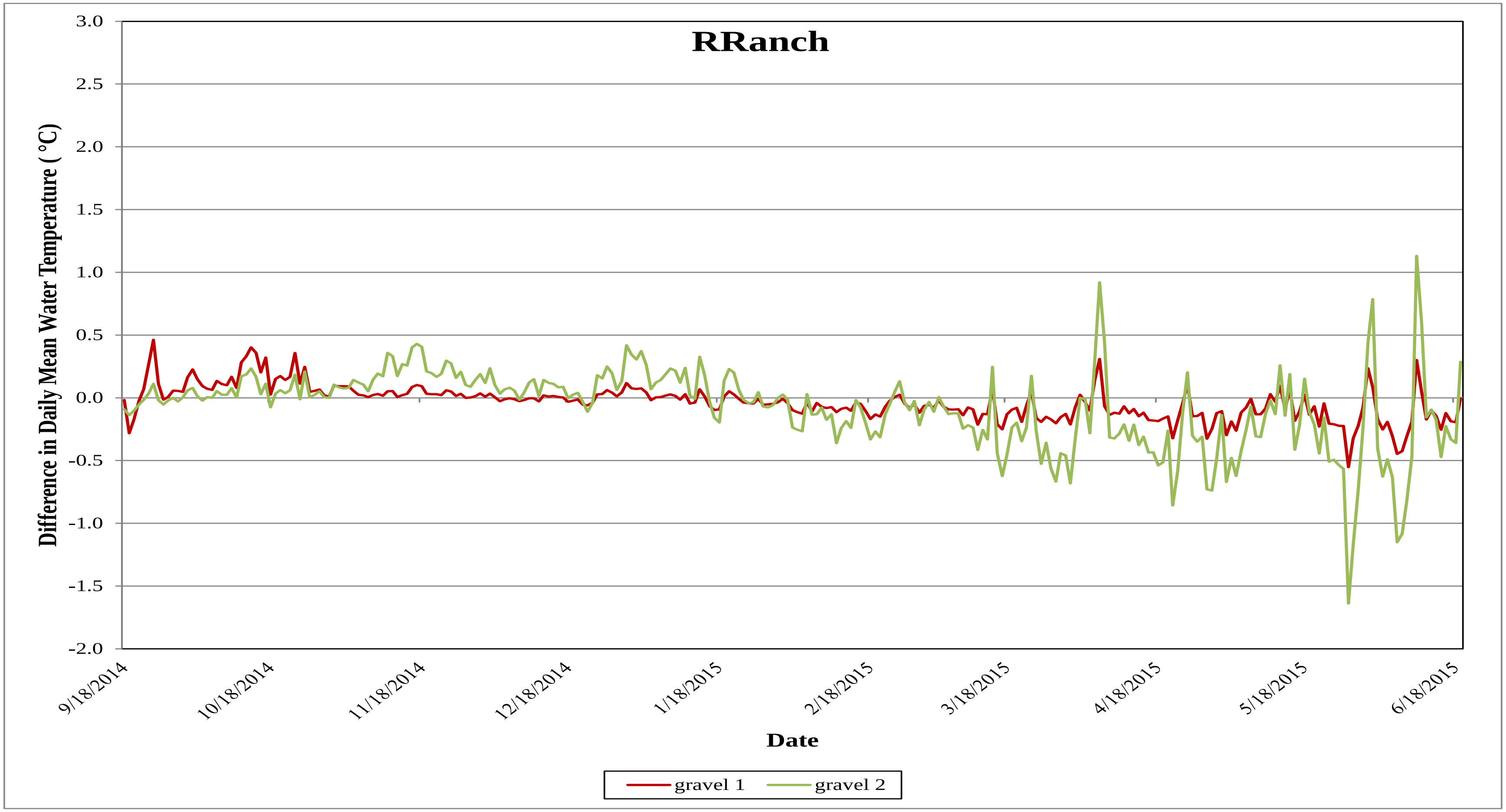
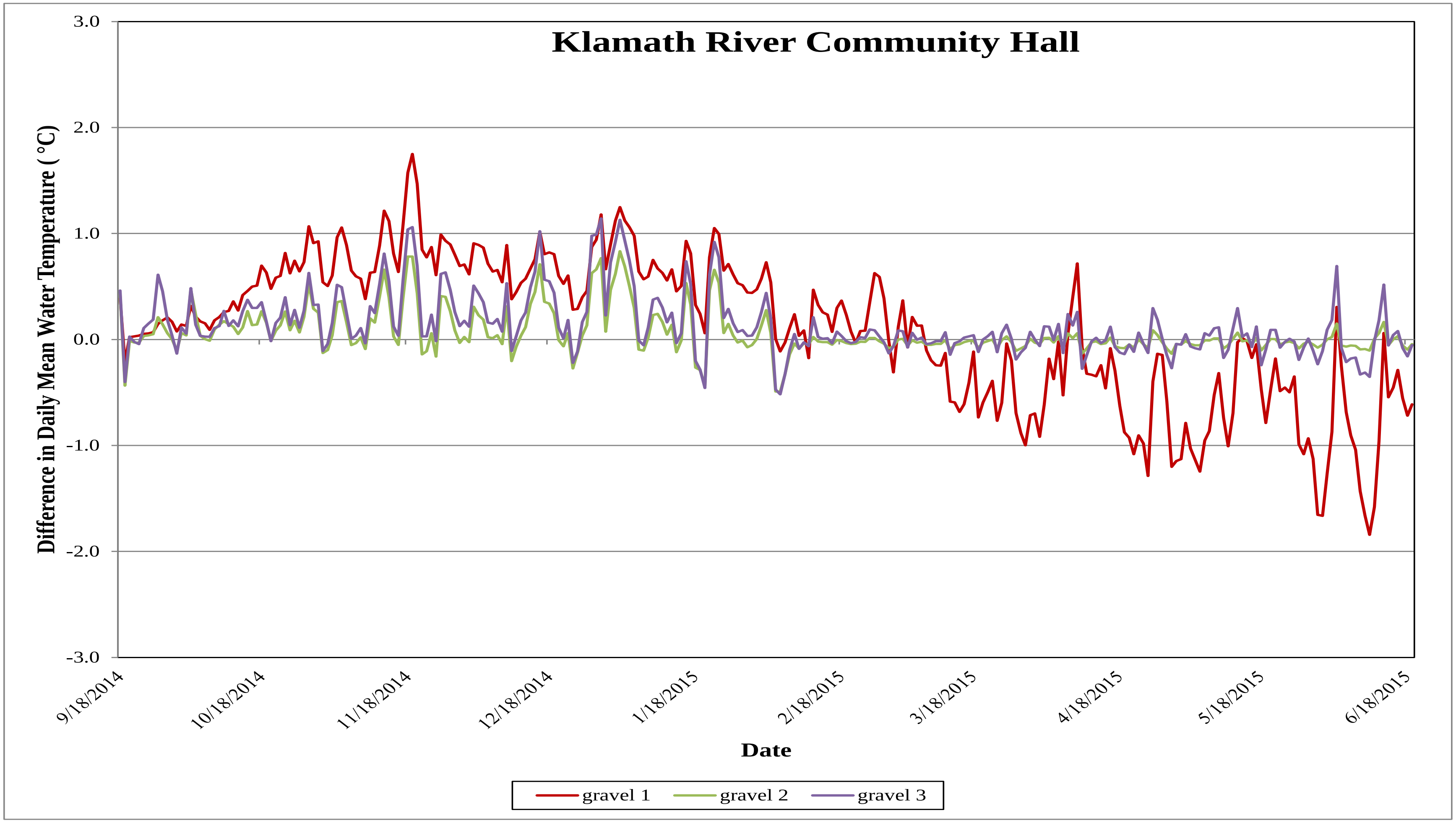
Appendix A. Difference between intra-gravel and surface daily mean water temperature (intra-gravel minus surface) at sites on the Klamath River.



Appendix A. (continued). Difference between intra-gravel and surface daily mean water temperature (intra-gravel minus surface) at sites on the Klamath River.



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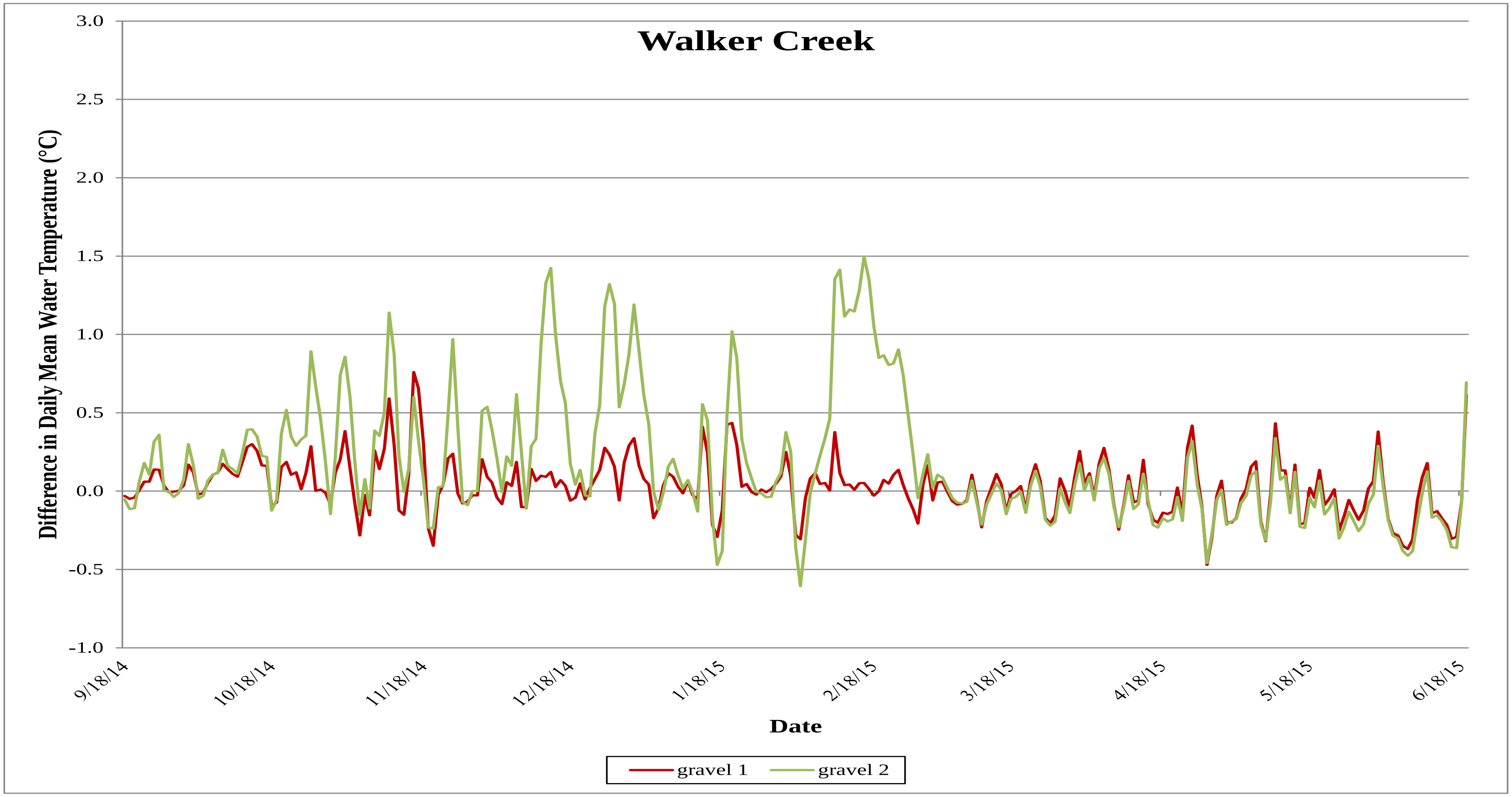
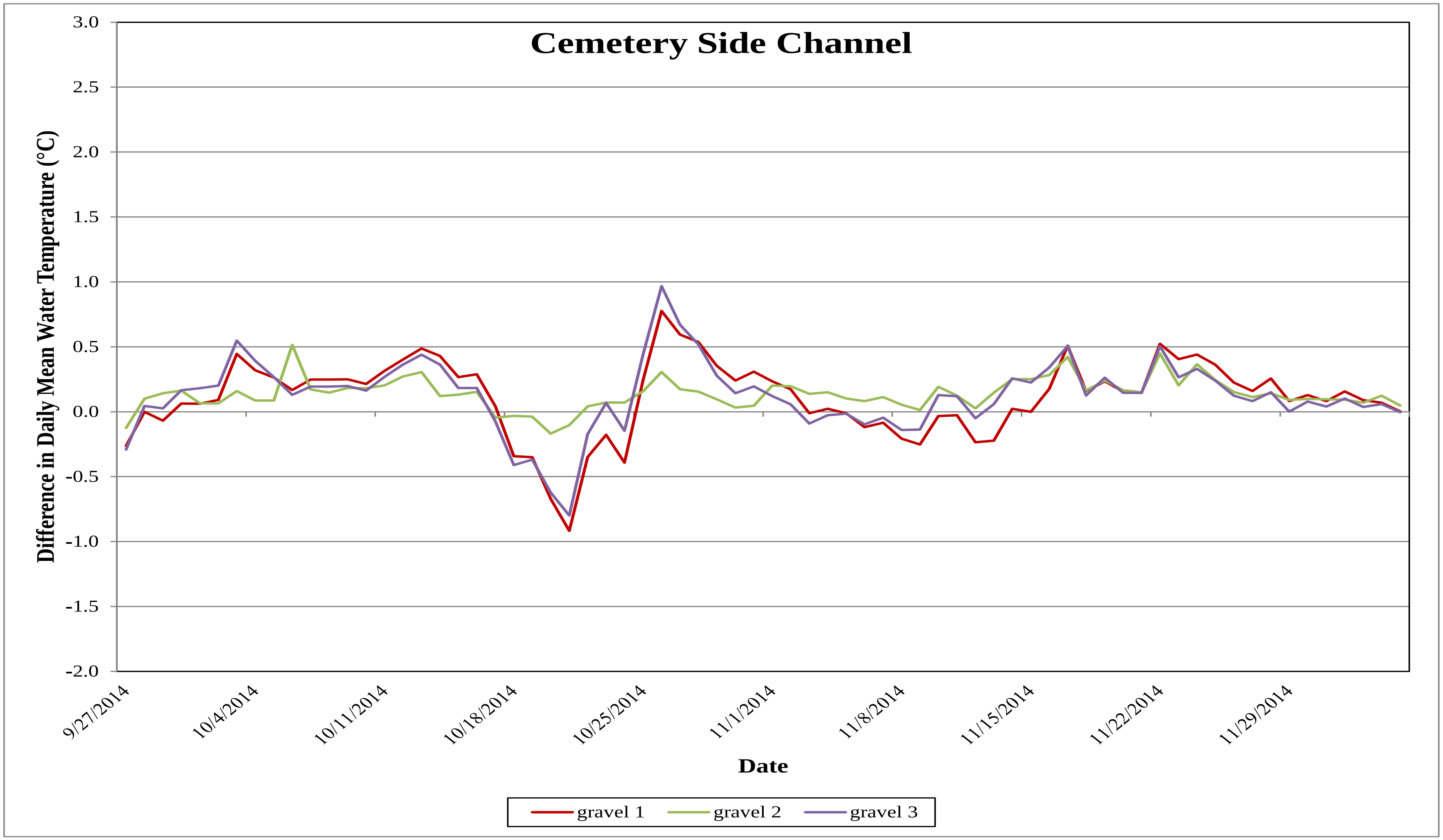


Appendix B. Difference between intra-gravel and surface daily mean water temperature (intra-gravel minus surface) at sites on the Trinity River.



Appendix B. (continued). Difference between intra-gravel and surface daily mean water temperature (intra-gravel minus surface) at sites on the Trinity River.