US Army Corps
of Engineers ®
Walla Walla District

Data Summary Memorandum

NWW FY21 Water Quality Monitoring at Yakima River delta (Lake Wallula)

Prepared in Support of the USACE Sustainable Rivers Program
FY21 Locks & Dams

CENWW-ECH

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1. INTRODUCTION

1.1 Study Area

The Yakima Delta study area is located at the confluence of the Columbia and Yakima Rivers, approximately Columbia River Mile 335, and the upstream end of Lake Wallula, the run-of-river reservoir created by McNary Dam (a U.S. Army Corps of Engineers [USACE] project) downstream. Bateman Island lies just east of the Delta, with an earthen causeway connecting the south side of the Delta to Bateman Island. Upstream inflow to the study area includes Columbia River below Priest Rapids Dam (a Public Utility District [PUD] project), and the Yakima River below Horn Rapids Dam (a U.S. Bureau of Reclamation [USBR] project). Downstream stage in the study area is influenced by McNary Dam (MCN) operations and Snake River outflows below Ice Harbor Dam (a U.S. Army Corps of Engineers [USACE] project) to Lake Wallula. The Lake Wallula zone of backwater influence extends about 2 miles up the Yakima River (Figure 1.1-1).

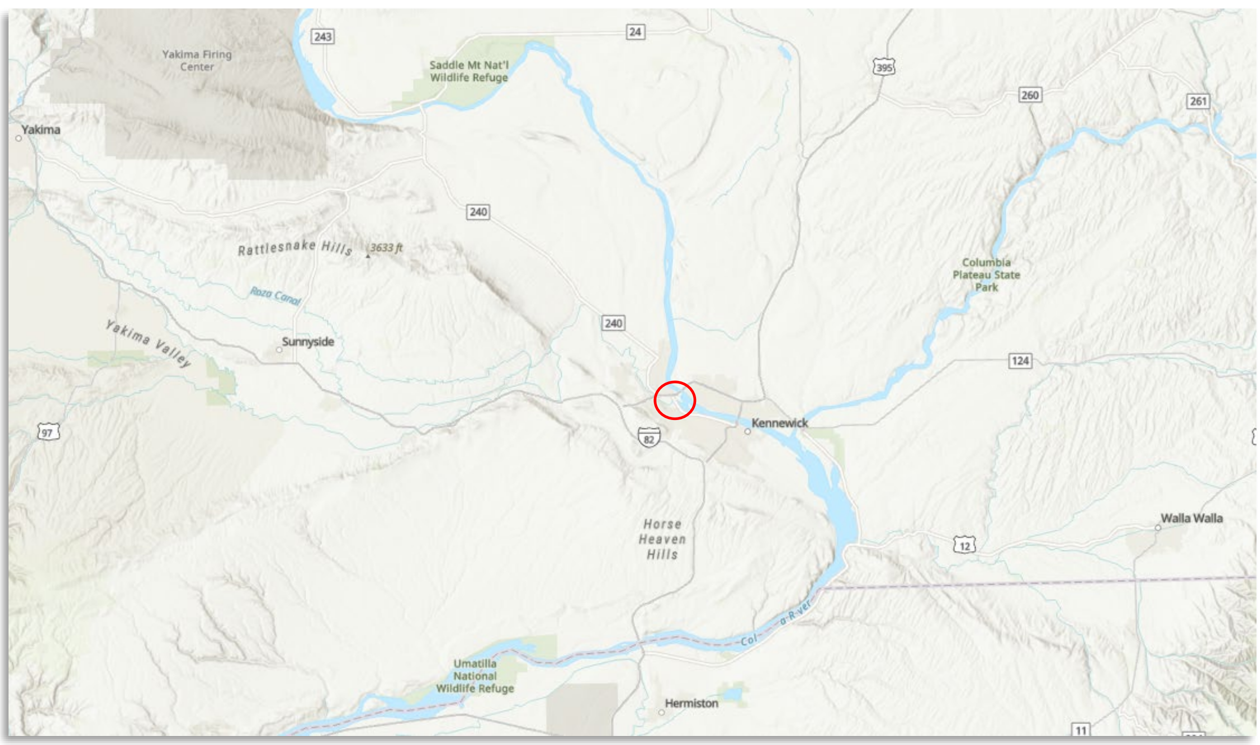

Figure 1.1-1 Regional map depicting study area.

1.2 Background

The Yakima River delta is located at the confluence with the Columbia River (46.250° N, 119.235°W) near the town of Richland, WA and at the upstream end of Lake Wallula, the reservoir pool created by McNary Dam. Completed in 1953, McNary Dam is a run-of-river project where total project inflows and total project outflows are approximately equal within a daily interval. Hydrology in the Yakima delta is influenced by a combination of upstream flows from the Columbia and Yakima Rivers, lateral flows from the Snake River, and the Lake Wallula stage controlled by MCN downstream. The Lake Wallula backwater can extend as much as ~2 miles up the Yakima River channel which influences the energy regime, fine sediment deposition, and flow mixing with the Columbia River. MCN pool operations are relatively dynamic with a normal operating range of 5 feet, and as a run-of-river project must account for large volume inflows, hydropower load following, and seasonal Federal Columbia River System Biological Opinion (BiOp) constraints at the daily to sub-daily scale.

The Yakima River and delta has historically been plagued by high temperatures and degraded water quality (Holroyd 1998). The Columbia River and the backwater on the western side of Bateman Island (Figure 1.2-1) are listed by the Washington State Department of Ecology as “impaired” on the State’s 303(d) list (Federal Clean Water Act) for temperature, dissolved gas, and pH and categorized as polluted. Summer in-stream temperatures make the lower Yakima River inhospitable to salmonid species, and low dissolved oxygen levels threaten all aquatic life in the river. Aquatic invasive vegetation (AIV) found within the delta includes: flowering rush (*Butomus umbellatus*), European milfoil (*Miriophyllum spicatum*) and water stargrass (*Heterantera dubia*) which dramatically impact dissolved oxygen and pH. The warmest waters in the lower Yakima River are found within the delta, specifically within the stagnant pools located west of Bateman Island. Previous sampling identified Yakima flows entering the delta area at average temperatures of 80°F, rapidly warming to as much as 90°F in the delta area (Appel et al. 2011, Wassell et al., 2014). Flow from the Columbia river is somewhat cooler with average summer temperatures of 67°F, but can exceed 70 °F at times. These extreme temperatures are a migration barrier to late-migrating salmon, including sockeye, summer Chinook, and fall Chinook. Temperature and water quality data for the Yakima delta is limited both spatially and temporally and is a significant data gap in the characterization of baseline conditions and simulation of mitigation alternatives.

Figure 1.2-1 Overview map of Yakima Delta Study Area

1.3 Scope

For this study, Walla Walla District (NWW) completed 3 monitoring tasks.

1. Deployment and retrieval of fixed location temperature strings.
2. Bi-monthly water quality surveys at select locations
3. Reconnaissance Thermal Mapping via a fixed-wing unmanned aircraft system (UAS)

The WY21 monitoring plan included the establishment of 18 sites distributed within the study area (Figure 1.3-1; Table 1.3-1). Temperature strings were deployed to ten of the eighteen sites to record hourly temperature data between May and September. The remaining sites were used for bi-monthly water quality surveys. The monitoring layout was developed to measure temperature and water quality parameters within 4 distinct subareas at various depths throughout the water column.

This study added value by:

1. providing a better understanding of temperature trends and water quality parameters in the Yakima Delta area
2. identifying relationships between system drivers and temperature response, and
3. filling a critical data gap for the coincident CAP1135 feasibility study

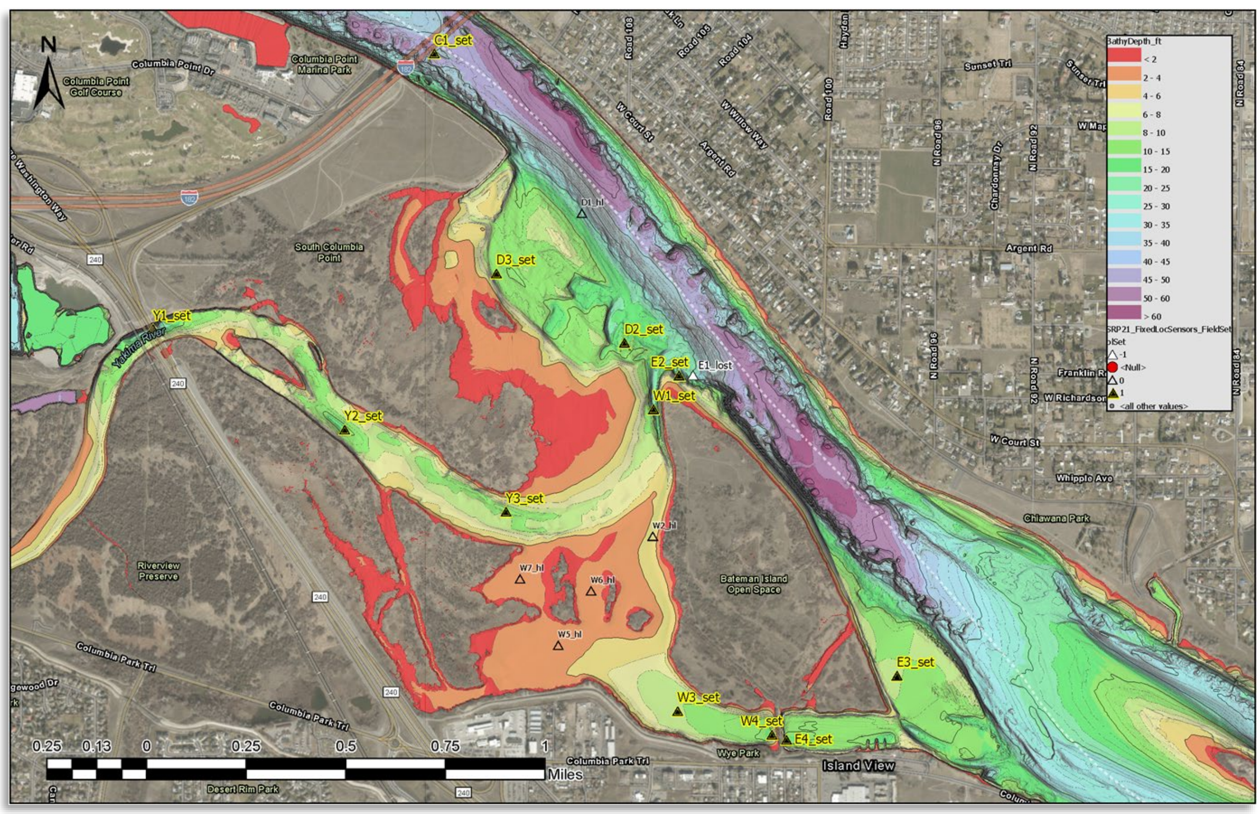

Figure 1.3-1 Map of field monitoring sites in the study area.

Table 1.3-1 List of field monitoring sites in the study area

Reach	Site Name	Location (WGS84)	# of Sensors	Sensor Elevations (ft NAVD88)	Status
Yakima	Y1	46.254N - 119.258W	6	{327, 330, 332, 337, 338}	
	Y2	46.250N - 119.248W	3	{333, 337, 340}	
	Y3	46.247N - 119.239W	3	{333, 337, 340}	
West Bateman	W1	46.251N - 119.232W	3	{328, 334, 340}	
	W2	46.246N - 119.232W	0		Lost
	W3	46.240N - 119.231W	3	{341, 343, 344}	
	W4	46.239N - 119.226W	3	{333, 337, 340}	
	W5	46.242N - 119.237W	0		
	W6	46.244N - 119.235W	0		
	W7	46.245N - 119.239W	0		
Delta	D1	46.258N - 119.235W	0		
	D2	46.253N - 119.233W	3	{337,340, 344}	
	D3	46.256N - 119.240W	2	{335, 339}	Reset
Columbia	C1	46.264N - 119.243W	8		Lost
East Bateman	E1	46.252N - 119.230W	0		
	E2	46.252N - 119.230W	0		
	E3	46.241N - 119.219W	2	{337, 341}	
	E4	46.239N - 119.225W	3	{333, 337, 340}	

2. DATA SUMMARY

This section summarizes monitoring data collected and related timeseries including:

- Water Temperature string data
- Synoptic Survey data
- UAS Thermal Mapping
- Meteorological Conditions
- Riverine Conditions
- Hydraulic Conditions

2.1 Water Temperature String Data

Water temperature sensors were installed at ten of the eighteen monitoring sites, at incremental depths through the water column. The deep and shallow sensors were typically set at 2-3 feet off the channel bottom and below the water surface, respectively. The sensors used were the Onset U22-001 HOBO Water Temp Pro v2 with a nominal accuracy of ±0.2°C and hourly recording interval. The U22-001 temperature string sensors were deployed at select elevations and attached to cables set between buoys w/120-150 lbs concrete anchors. The anchoring allowed each sensor to remain at a fixed elevation and did not vary with reservoir stage.

2.1.1 Water Temperature Summary

Water temperatures in the study area between May and September were characterized by two predominant signals. The first, and most stable was the cooler signal at sensors mainly influenced by Columbia River flows. The second, and more dynamic signal, was the warmer signal at sensors influenced by Yakima River flows. The third signal was the response in the mixing areas around Bateman Island which varied with: timing, location, and depth (Figures 2.1-1 and 2.1-2; Table 2.1-1).

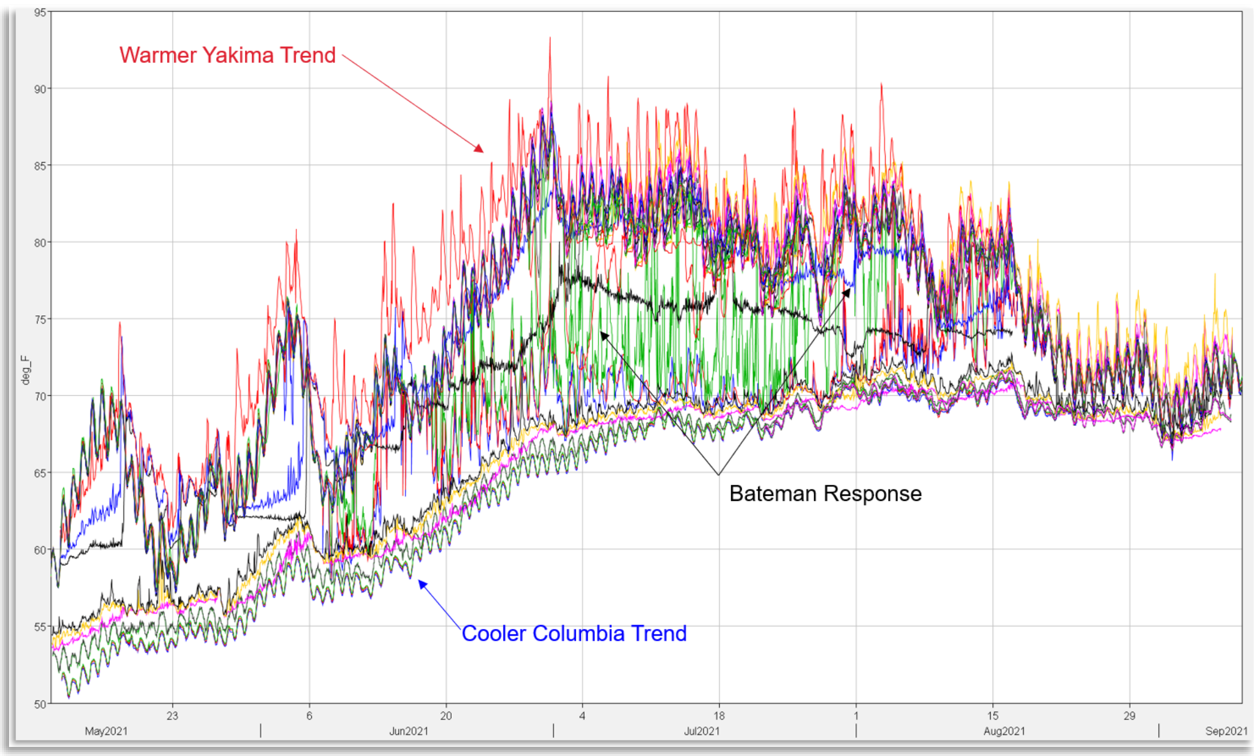

Figure 2.1-1 Timeseries of temperature string data between May and September 2021.

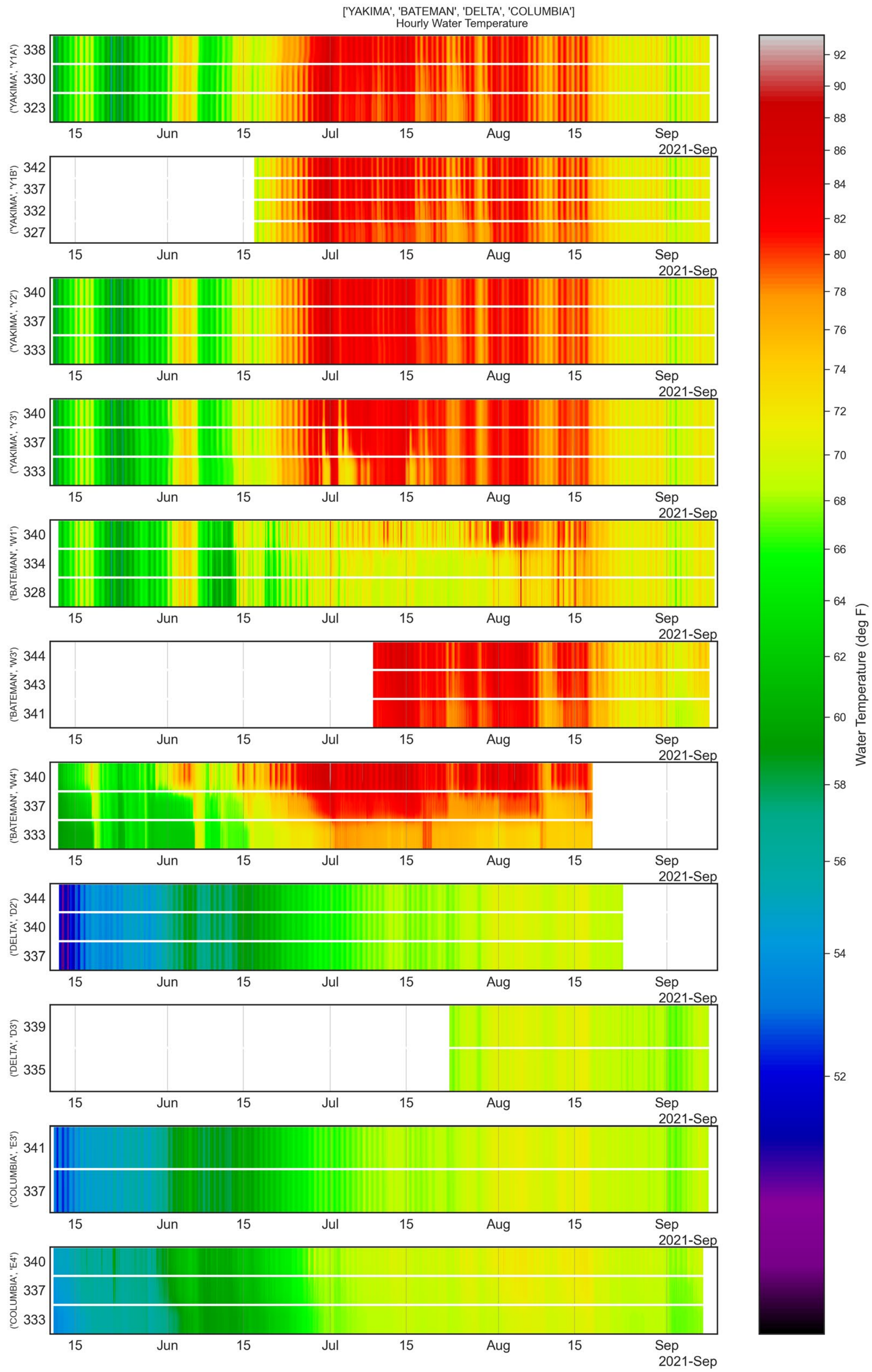

Figure 2.1-2 Timeseries heatmap of temperature string data between May and September 2021.

Table 2.1-1 Summary of temperature string data between May and September 2021.

Reach	Site	n	min	mean	std	25%	50%	75%	max
Yakima	Y1A	8718	56.9	73.7	7.0	68.7	74.0	79.9	88.9
	Y1B	8072	67.0	77.3	4.6	73.0	78.3	80.7	89.1
	Y2	8781	57.0	73.9	7.2	68.9	74.0	80.3	88.4
	Y3	8784	57.2	73.6	6.9	69.0	73.6	79.8	87.3
Bateman	W1	8715	57.2	70.0	4.7	67.9	70.5	72.5	84.5
	W3	4470	67.2	78.2	4.7	73.7	79.6	81.9	87.8
	W4	7098	58.9	73.9	7.5	67.4	74.9	79.8	93.3
Delta	D2	7491	50.3	63.4	6.2	57.5	66.1	68.9	71.2
	D3	2298	66.4	69.2	1.1	68.4	69.1	70.1	71.6
Columbia	E3	5796	51.9	64.7	5.8	59.3	67.7	69.1	71.8
	E4	8625	53.4	65.3	5.5	60.2	68.3	69.5	72.9

2.1.2 Water Temperature Distributions

Distributions of measured water temperature across the ten sites varied with location and season. All sites generally exhibited cooler temperatures during May with a rapid warming trend in early to mid-June associated with the 2021 Pacific Northwest (PNW) regional heat dome where local air temperatures in the study area exceeded 110°F.

Temperatures in the Yakima River (sites Y1, Y2, and Y3) were generally bimodal with seasonal peaks around 71°F and 80°F. On the West side of Bateman Island, sites W3, and W4 also exhibited the same pattern. Conversely, water temperatures at the Delta sites (D2 and D3) were generally below 75°F. Sites E2, E3, and E4 were also bimodal, with the early spring peak around 55° - 60°F and the summer peak, around 70°F. Joint distributions of temperature with hourly rate of change were also plotted, illustrating that the heating/cooling trends are generally symmetrical, regardless of water temperature (Figures 2.1-3 and 2.1-4).

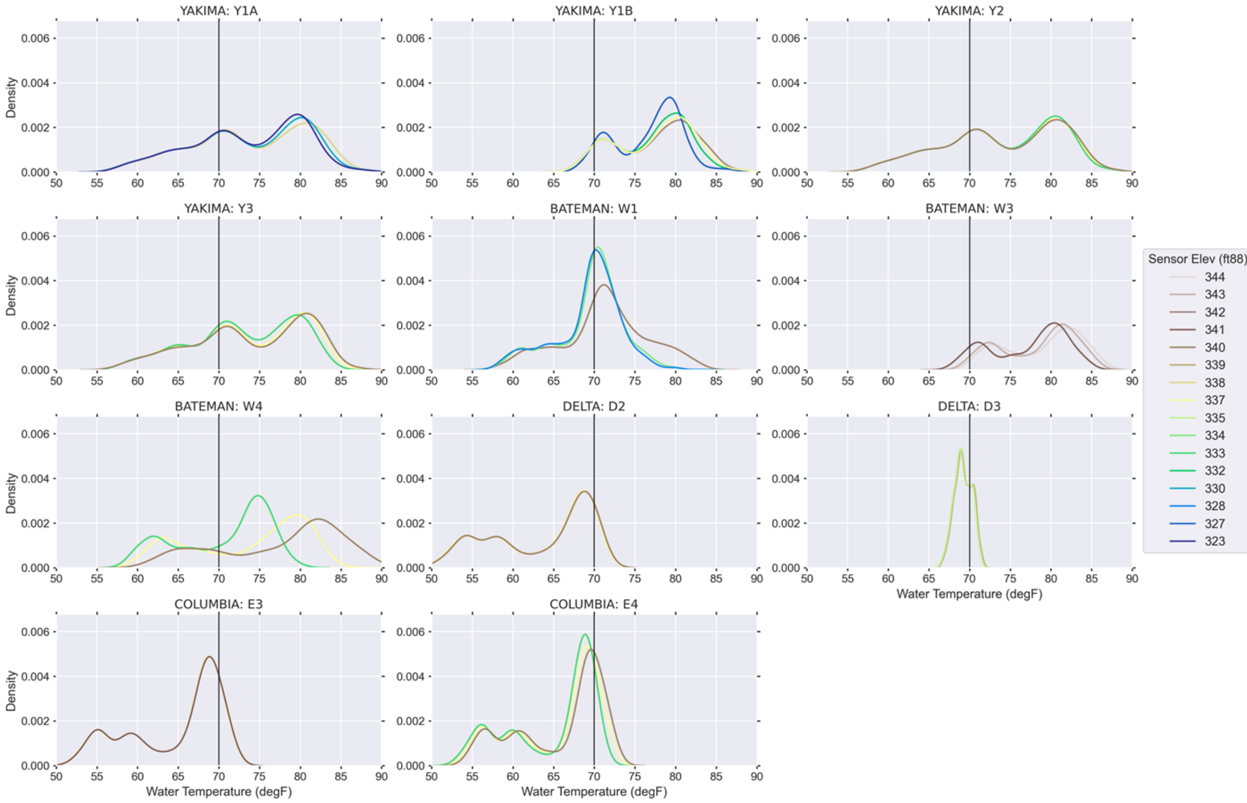

Figure 2.1-3 Water temperature distribution by depth.

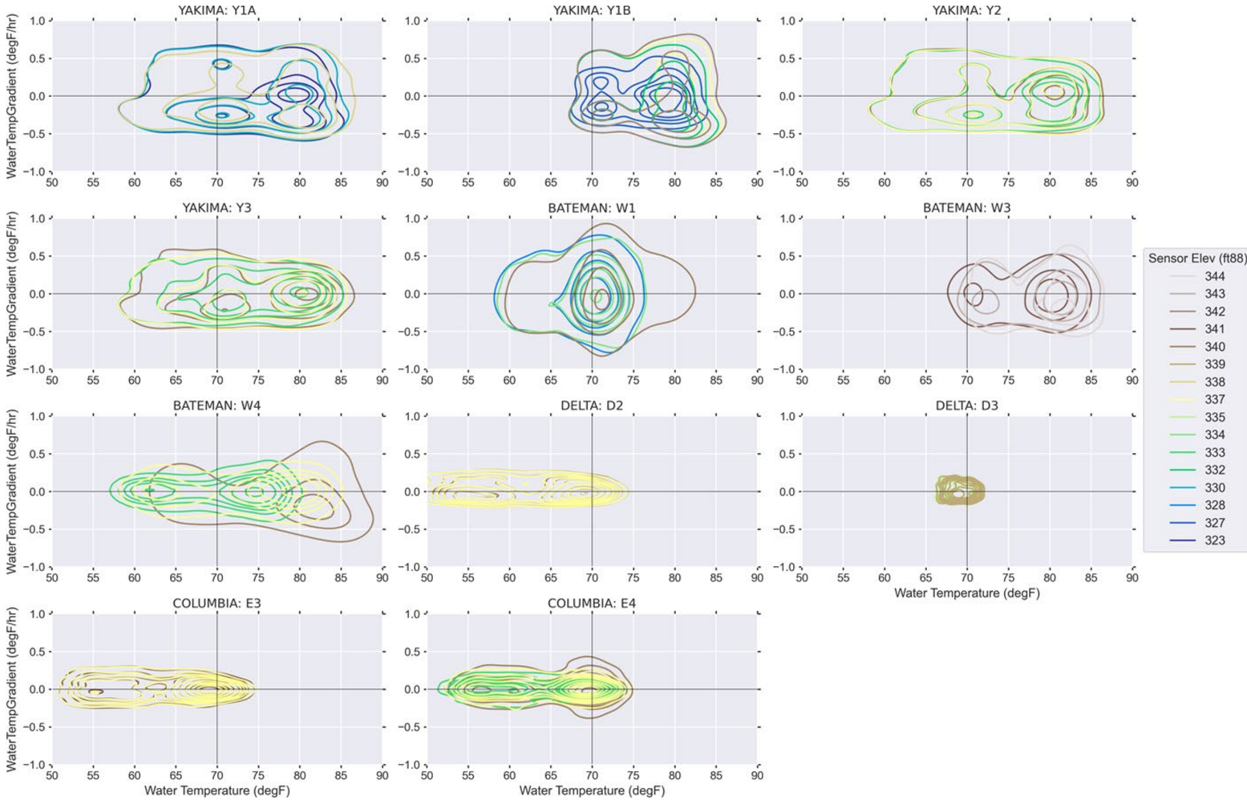

Figure 2.1-4 Water temperature distribution and gradient by depth.

2.1.3 Water Temperature Diurnal Patterns

Diurnal patterns in water temperature were also measured at all sites with the daily high temperatures typically occurring in the late afternoon. The daily water temperature range was larger at the Yakima and Bateman sites, than at the Delta and Columbia sites (Figures 2.1-5 and 2.1-6).

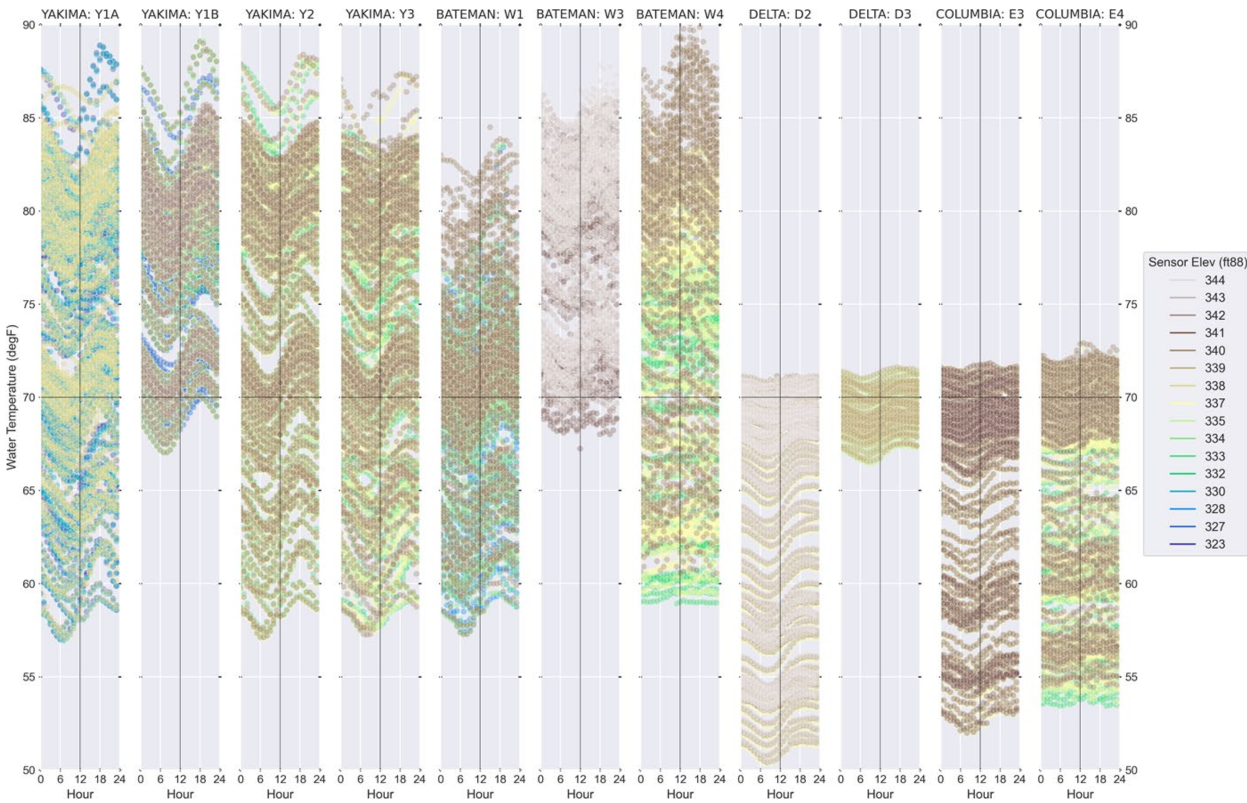

Figure 2.1-5 Water temperature vs. hour of day by depth. *Note strong diurnal signal in Yakima & Bateman reaches, and weak diurnal signal for Delta and Columbia reaches*.

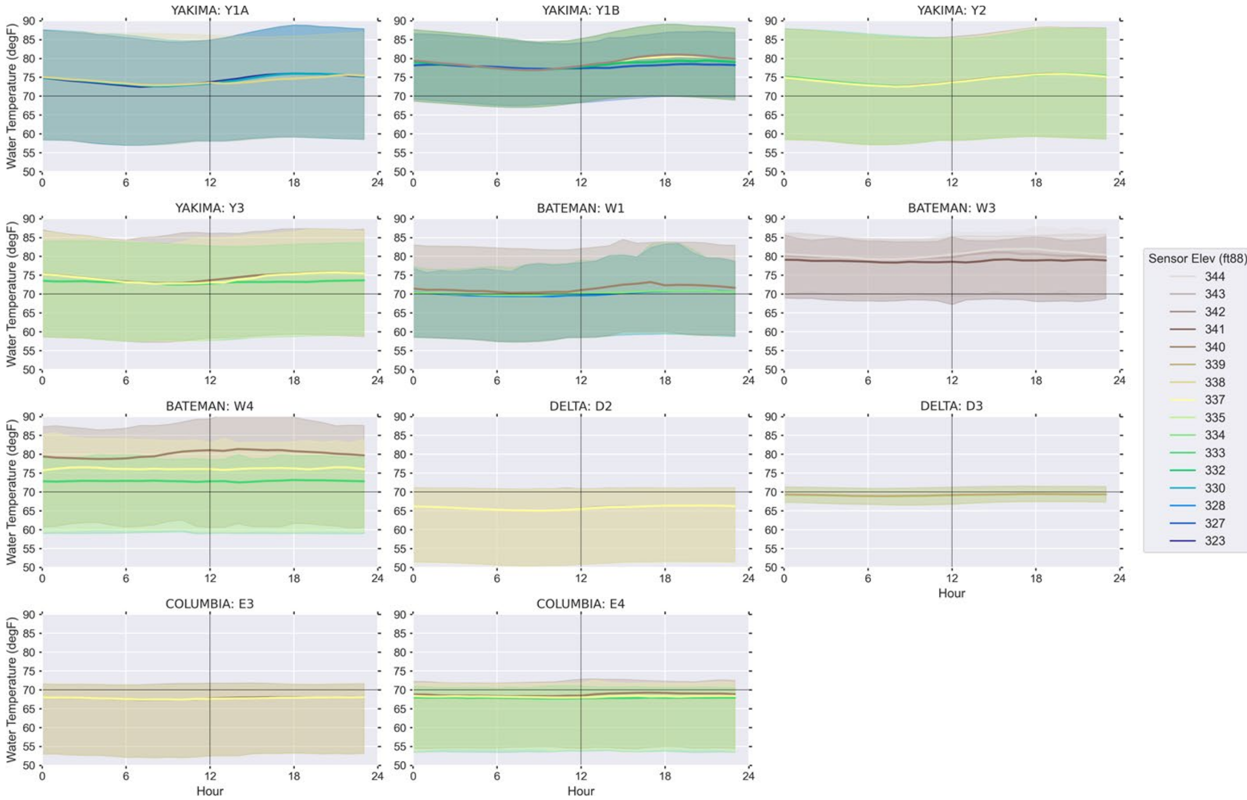

Figure 2.1-6 Median Water temperature and range vs. hour of day by depth.

2.2 Synoptic Survey Data

Seven synoptic surveys were conducted in the study area to measure additional water quality parameters at select stations (Table 2.2-1). This included two monthly events in June-August, and one event in September using a standard stepped-depth interval sampling. The last four events required a multi-day effort due to an abundance of aquatic invasive vegetation (AIV) which impeded both transport and monitoring. The equipment used was a HydroLab DS5X Sonde w/Surveyor 4A Data Logger which measured: temperature, conductivity, pH, dissolved oxygen as LDO, and turbidity.

Two field methods were used for the synoptic sonde survey. At sites with fixed buoy's, the sampling boat was tethered to the site to prevent moving out of the profile zone. The sonde was then lowered down through the water column at one-foot increments. The technician would monitor the readings until they stabilized, and then record the measurements before proceeding to the next depth. For sites without installed buoys, a drift technique was used based on predetermined GPS coordinates. The boat or canoe would start at the GPS sampling location and collect stepped interval data as per the stationary method, flowing slowly with the current to minimize the influence of position change within the depth profile.

Table 2.2-1 Summary of Synoptic Survey Dates

Event#	Date(s)	# of Sites Sampled
1	6/7/21	11
2	6/18/21	10
3	7/8/21	11
4	7/19/21 & 7/22/21	11
5	8/9/21 – 8/11/21	14
6	8/23/21 – 8/24/21	15
7	9/8/21 – 9/9/21	15

General trends in the measured sonde data include (Figures 2.2-1 to 2.2-5; Photo 2.2-1):

- Incremental decrease of water temperature with depth sans a strong indication of temperature stratification except during select events at W1 and W4.
- Consistent dissolved oxygen measurements through the depth profile at all sites except: W1, W3, W4, and E4.
- Near-zero dissolved oxygen concentrations at W4 site during multiple events.
- High dissolved oxygen during September with the formation of air bubbles observed associated with AIV.
- Change in temperature, conductivity, and pH with depth at site W1 indicative of vertical stratification between the mixing Yakima and Columbia River water.

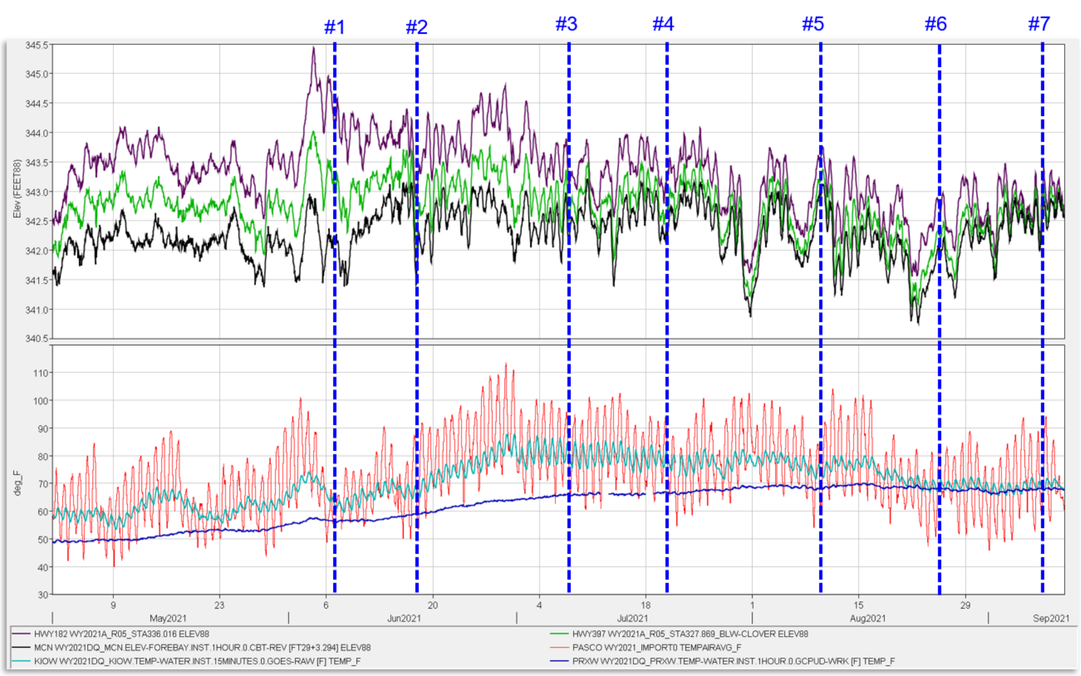

Table 2.2-1 Timeline of synoptic survey events relative to reservoir elevations (top panel), incoming water temperature and air temperature (bottom panel).

Photo 2.2-1 Synoptic Survey field photos 2.2.1 (USACE photos)

Water Temperature

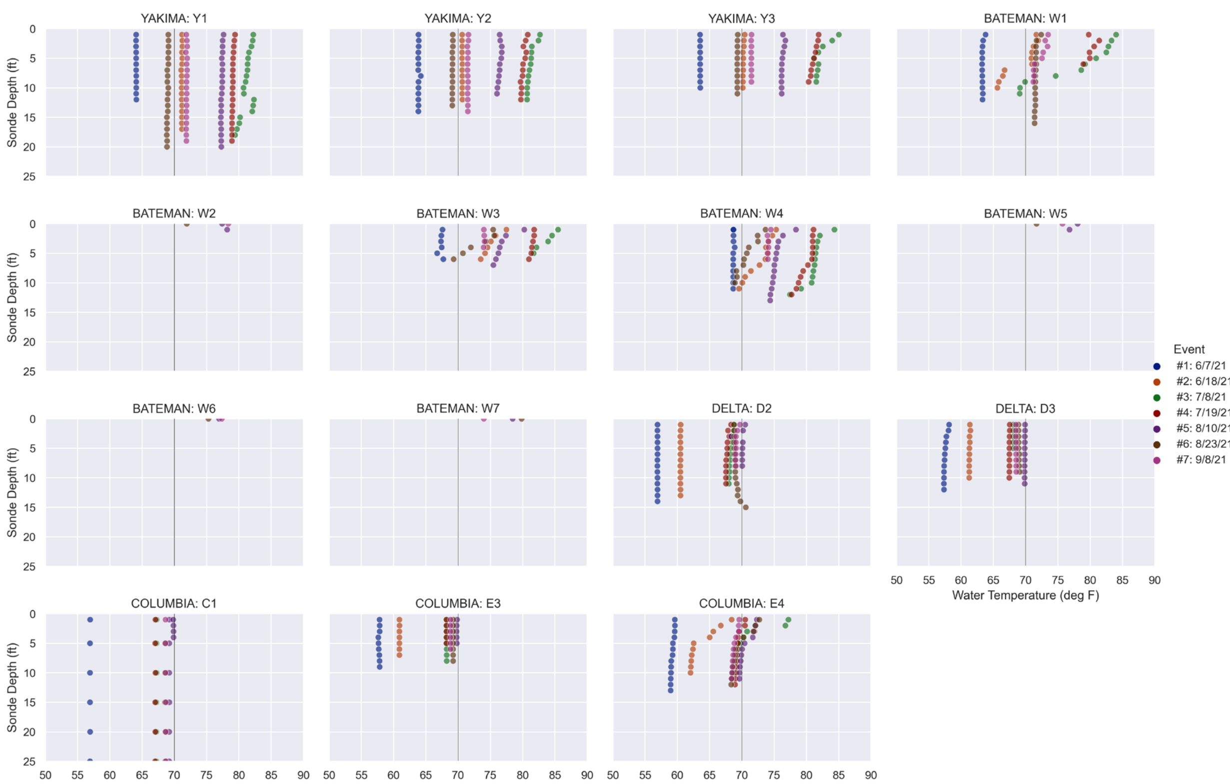

Figure 2.2-2 Synoptic survey data - water temperature vs. depth by event

2.2.2 Dissolved Oxygen

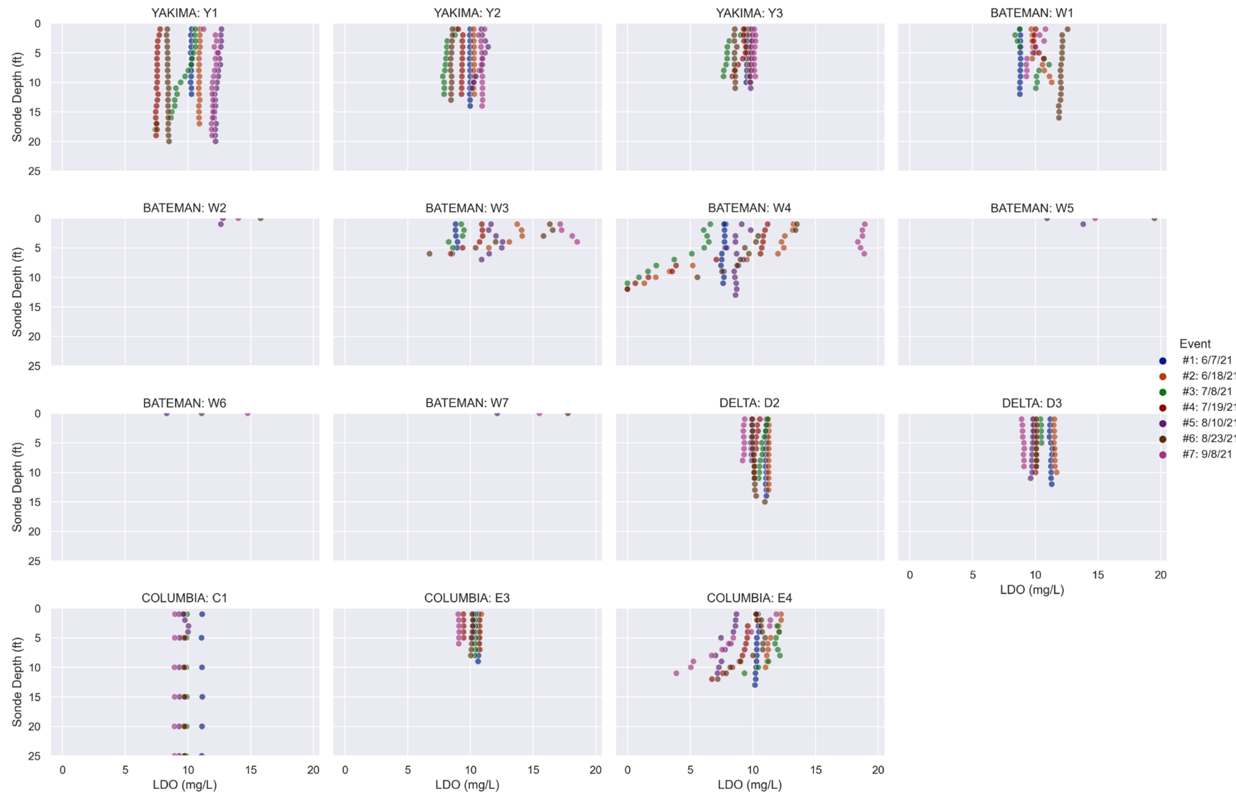

Figure 2.2-3 Synoptic survey data - dissolved oxygen vs. depth by event

2.2.3 Conductivity

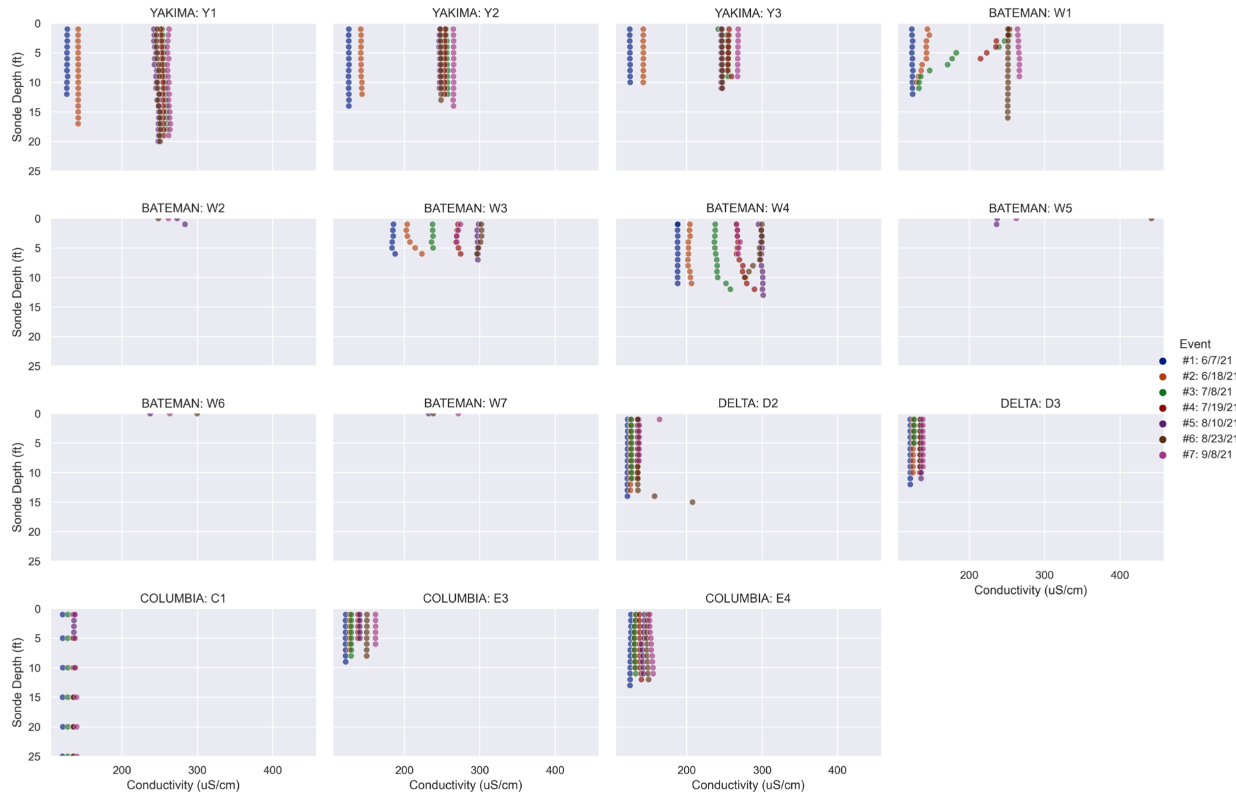

Figure 2.2-4 Synoptic survey data - conductivity vs. depth by event

2.2.4 pH

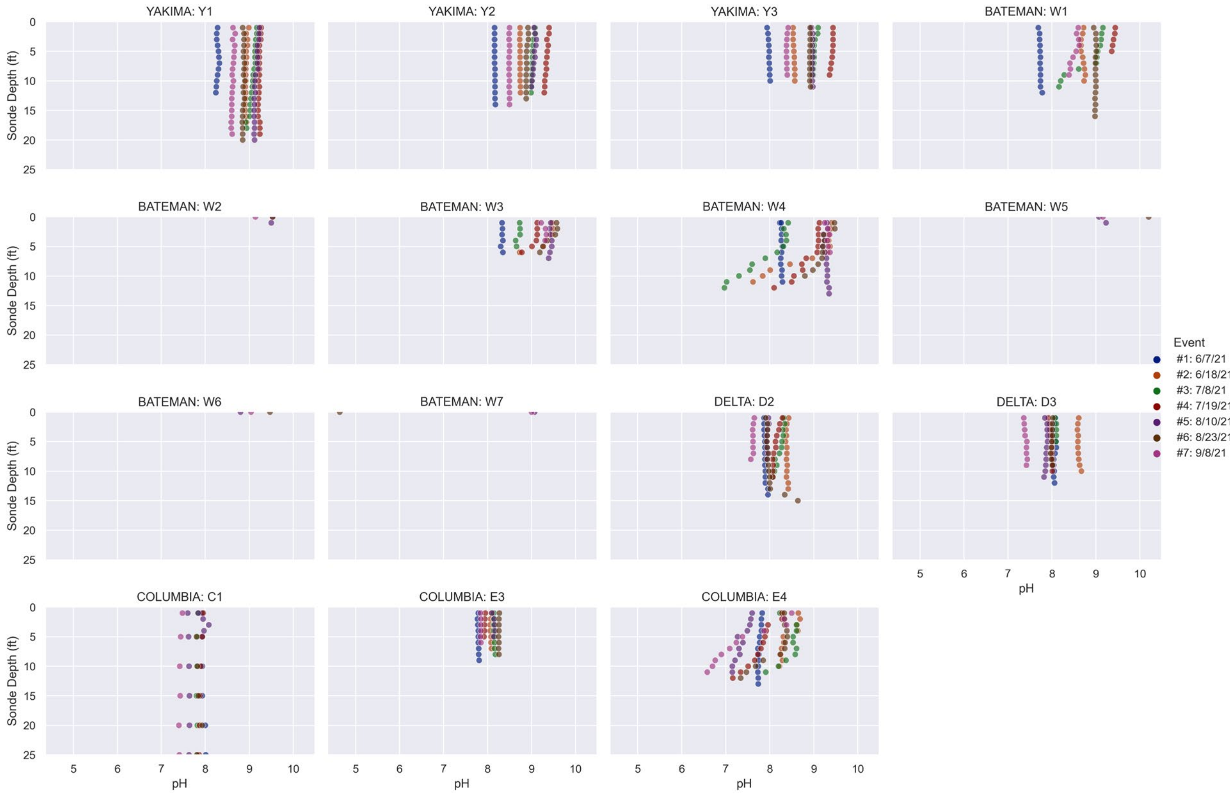

Figure 2.2-5 Synoptic survey data - pH vs. depth by event

2.3 UAS Thermal Mapping

NWW resourced the Portland District (NWP) UAS (Unmanned Aerial System) team to perform reconnaissance level temperature mapping in the study area. NWP conducted three sorties on 10-Aug-2021 over study sub-areas (Figure 2.3-1) to coincide with a MCN week-high pool condition and synoptic survey #5. The UAV surveys were conducted in accordance with Federal Aviation Administration (FAA) flight plan requirements and regulations, using an eBeeX fixed wing UAS flying at a nominal height of ~360 feet above ground level. The eBeeX carried a SenseFly-Duet-T thermal camera with a visible spectrum (RGB) resolution of 20 MP and a thermal resolution of 1 megapixel (Figures 2.3-2 to 2.3-7).

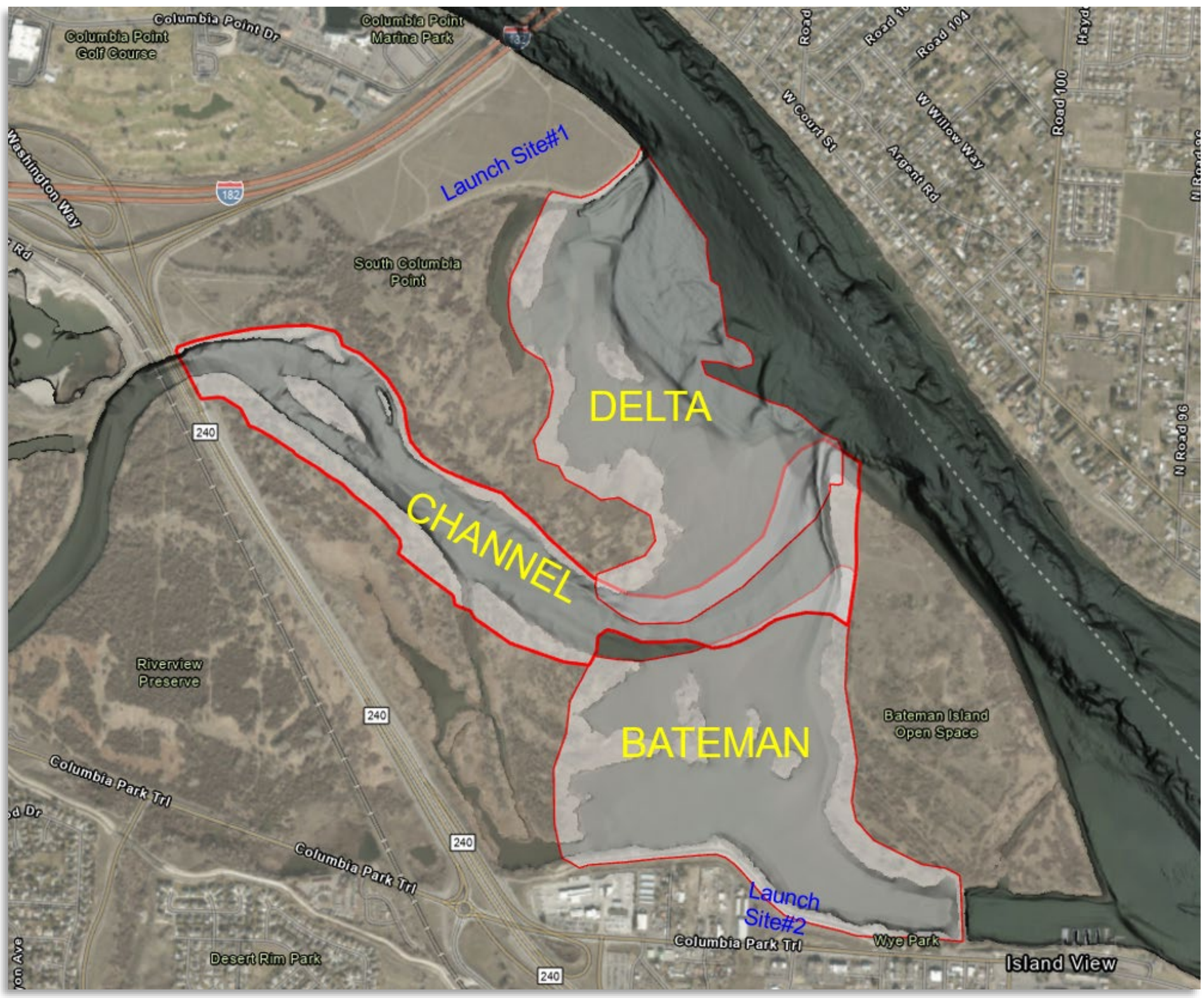

Figure 2.3-1 Three UAS flight areas on 10-Aug-2021.

2.3.1 Delta Area

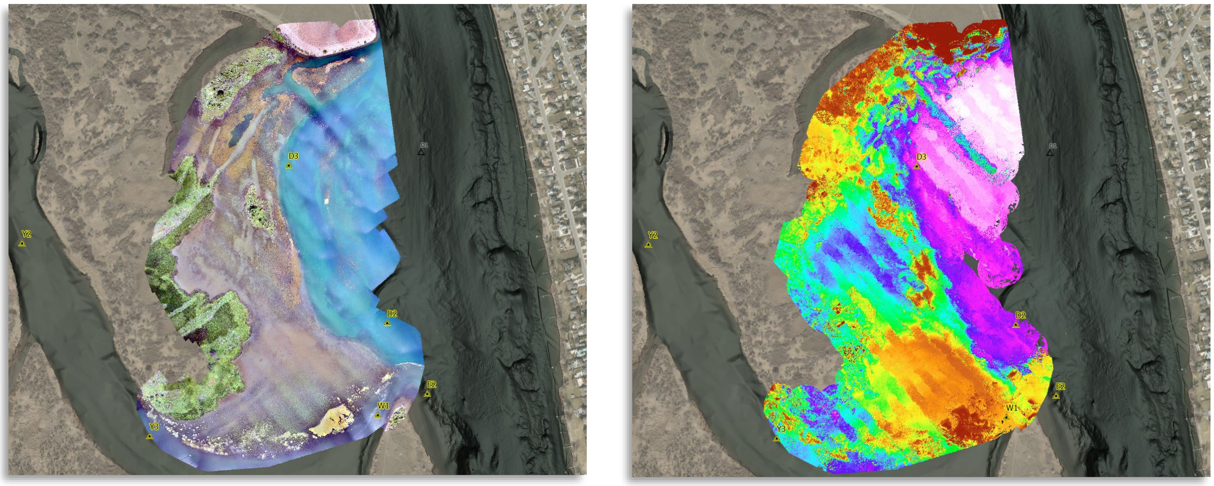

Figure 2.3-2 UAS Thermal Mapping in the Delta Area on 10-Aug-2021. *Left photo is RGB orthometric and right photo is surface temperature.*

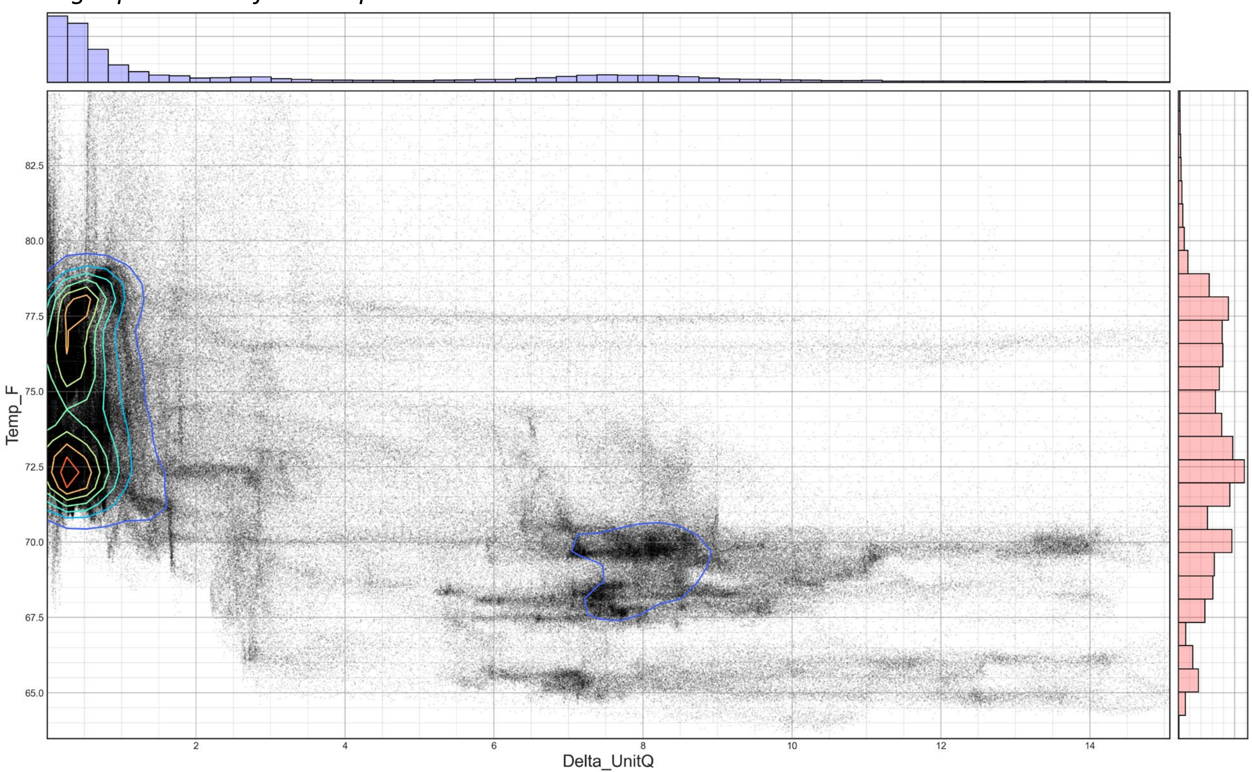

Figure 2.3-3 Distribution of UAS Water Surface Temperature versus Unit Discharge in the Delta Area on 10-Aug-2021. *Note inverse trend above 2 cfs/ft.*

2.3.2 Yakima River Area

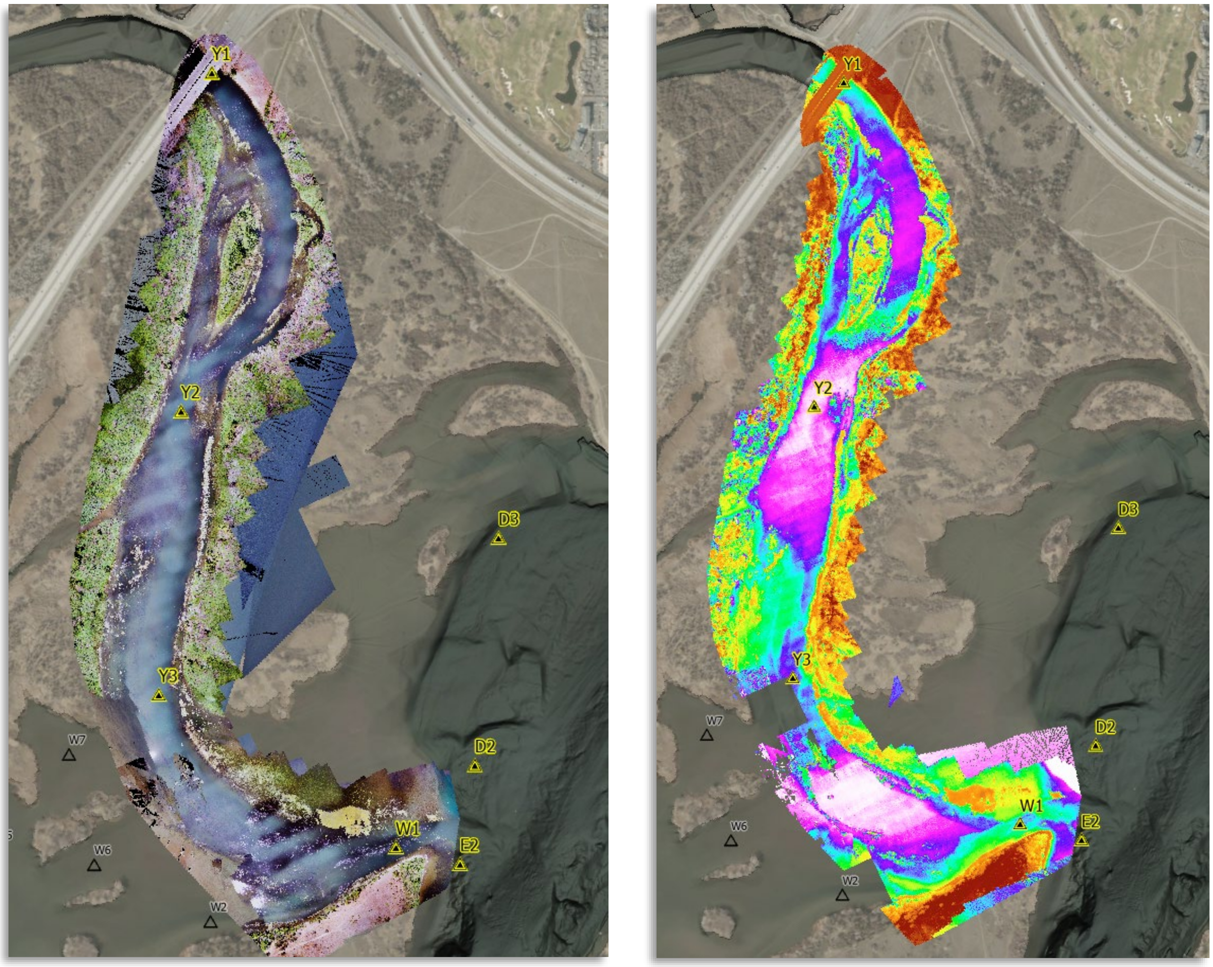

Figure 2.3-4 UAS Thermal Mapping in the Yakima River on 10-Aug-2021. *Left photo is RGB orthometric and right photo is surface temperature.*

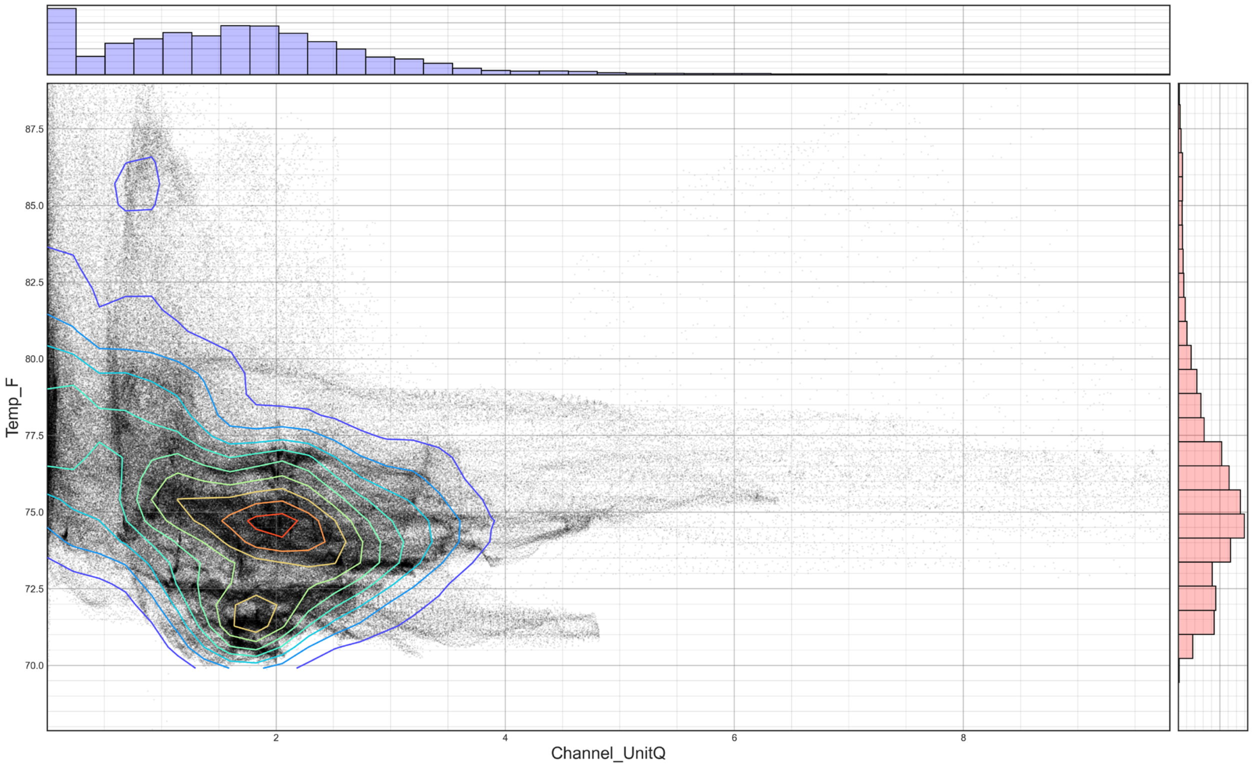

Figure 2.3-5 Distribution of UAS Water Surface Temperature versus Unit Discharge in the Yakima River Area on 10-Aug-2021. *Note inverse trend above 2 cfs/ft.*

2.3.3 West Bateman Area

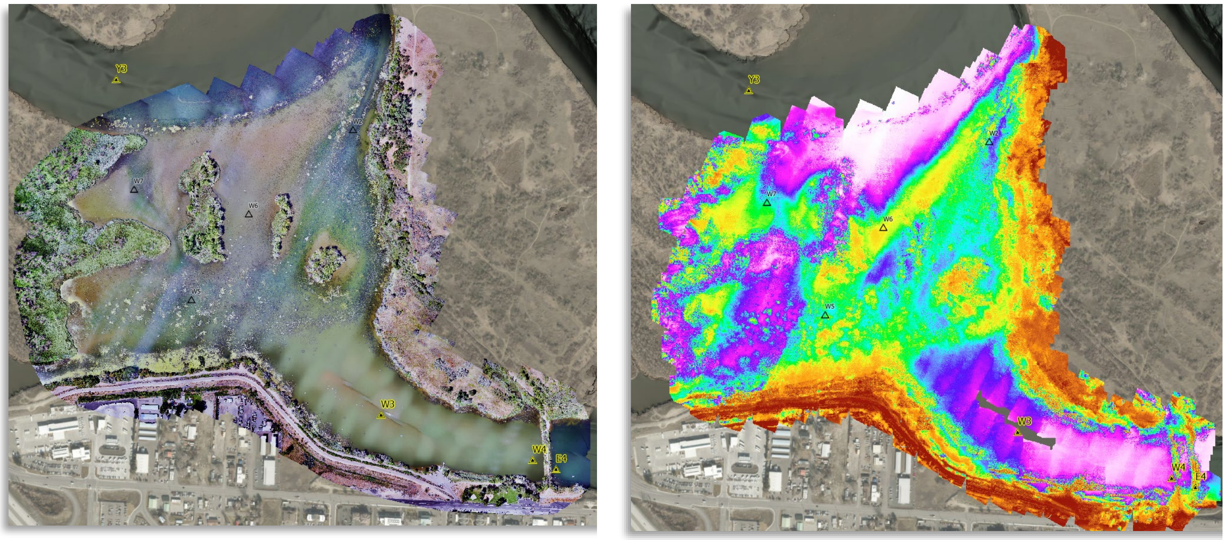

Figure 2.3-6 UAS Thermal Mapping West of Bateman Island on 10-Aug-2021. *Left photo is RGB orthometric and right photo is surface temperature.*

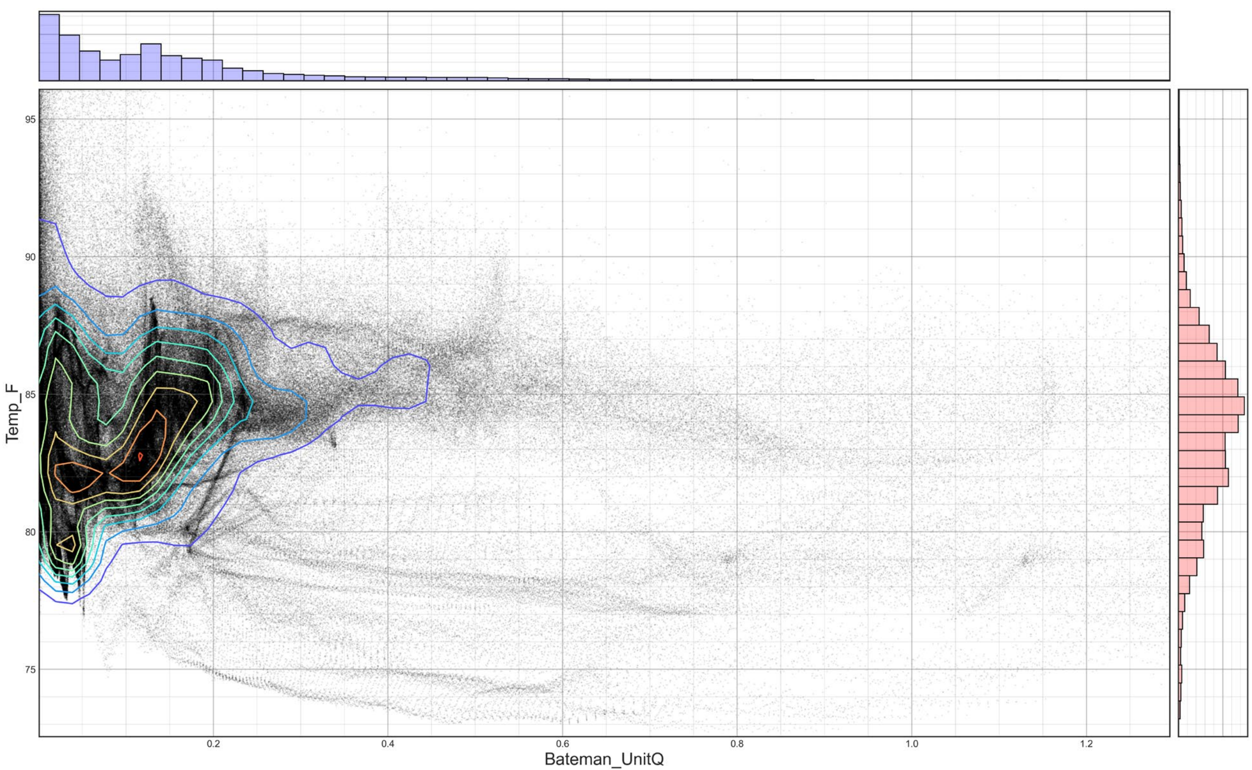

Figure 2.3-7 Distribution of UAS Water Surface Temperature versus Unit Discharge in the West Bateman Area on 10-Aug-2021. *Note inverse trend above 2 cfs/ft.*

2.4 Meteorological Data

Hourly meteorological data for the study period was downloaded from the Washington State University (WSU) AgWeatherNet for Pasco, WA in Franklin County, WA (http://weather.wsu.edu/?p=88650).

The weather station is located at 46.25° N -119.13° W (WGS84) at an elevation of 404 ft MSL. Datasets of interest for this assessment include air temperature and solar radiation (Figures 2.4-1 and 2.4-2; Table 2.4-1).

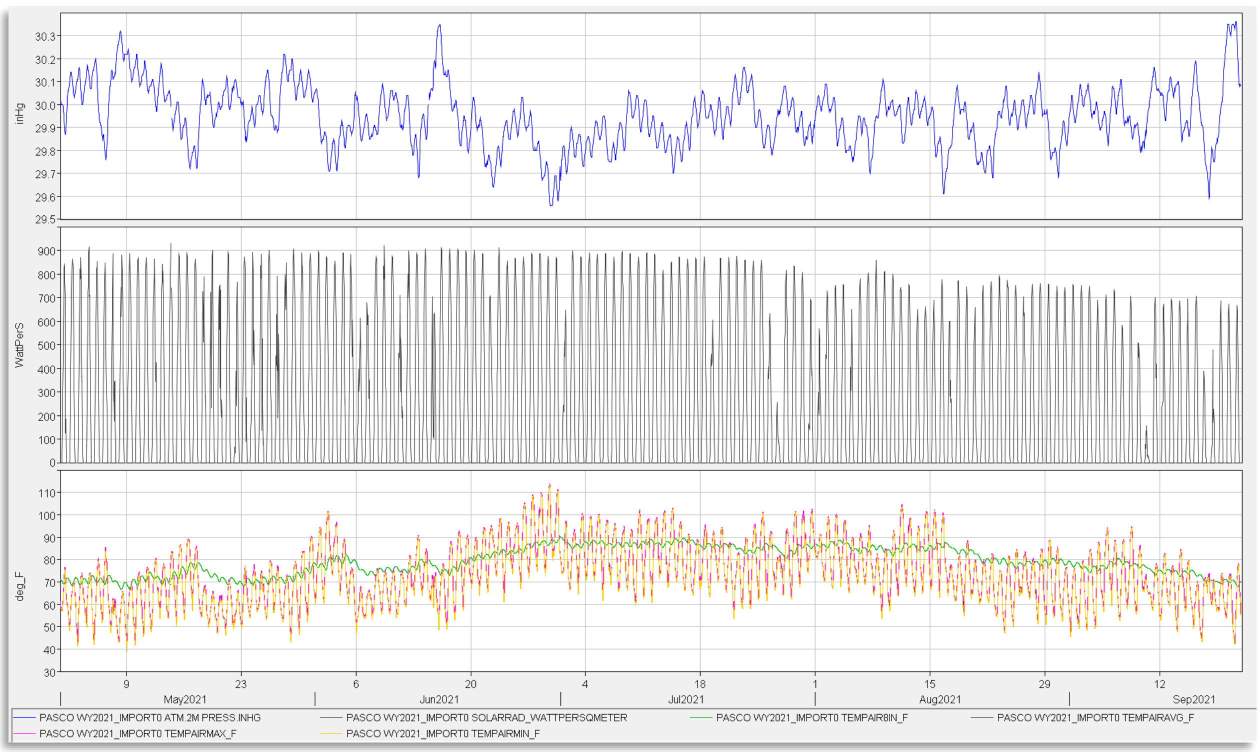

Figure 2.4-1 Timeseries of Meteorological Conditions between May and September 2021

Table 2.4-1 Summary of WY2021 Meteorological Conditions in study area.

Metric	n	min	mean	std	25%	50%	75%	max
Air Temperature (°F)	8760	42.2	75.1	13.0	113.5	65.4	74.4	84.5
Dewpoint (F)	8757	21.8	46.7	8.1	68.2	41.0	47.5	52.7
Relative Humidity (%)	8757	9.0	40.7	17.6	92.1	26.2	38.3	53.9
Solar Radiation (W/m^2)	8757	0.0	274.7	308.5	930.0	0.0	128.0	569.0
Atmospheric pressure (in Hg)	8757	29.6	29.9	0.1	30.4	29.9	29.9	30.0
Wind Speed (mph)	8757	0.3	4.9	2.9	19.5	2.8	4.3	6.3

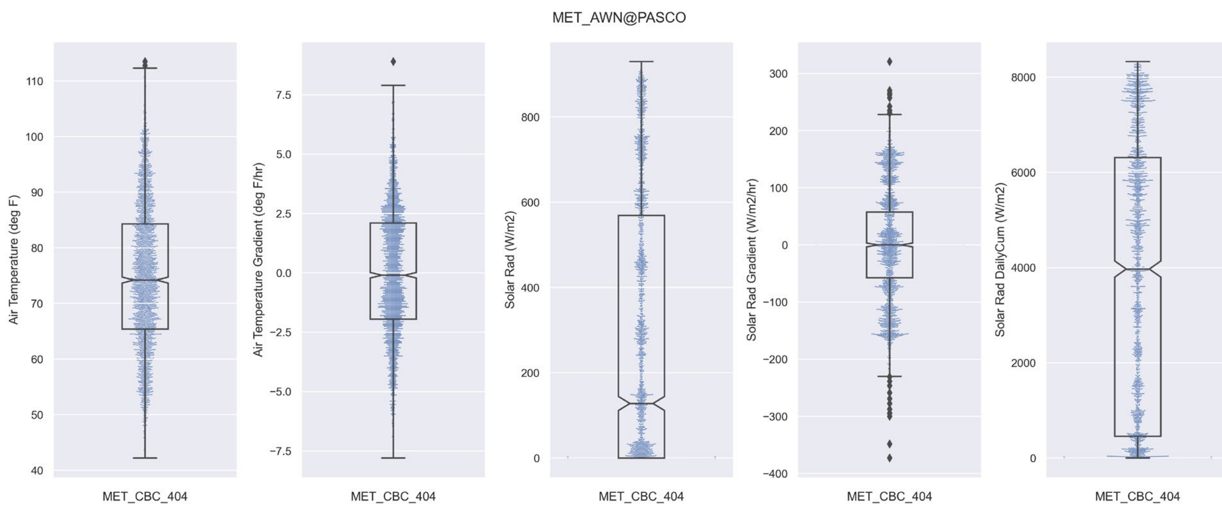

Figure 2.4-2 Distributions of Meteorological Conditions between May and September 2021

2.5 Riverine Conditions

The MCN reservoir (Lake Wallula) is influenced by regional riverine conditions of the greater Federal Columbia River Power System (FCRPS). Inflows to the study area include outflow from Priest Rapids Dam (PRD) on the Columbia River and outflow from Horn Rapids Dam (HRD) on the Yakima River. The flow and temperature of both systems are characterized by regional seasonality, larger volume and cooler water in the spring versus smaller volume and warmer water in the summer and fall. Columbia River flows can be highly variable between May and November due to upstream hydropower operations through a series of run-of-river projects, while Yakima River flows are more representative of a spring freshet followed by a descending hydrograph limb as irrigation demands increase through the summer. Riverine conditions in the Yakima Delta study area are also influenced by McNary (MCN) pool operations which fluctuate ~3-5 feet. While the MCN forebay stage varies year-round without significant seasonality, the lowest stages in WY2021 occurred during July and August for inflows below 150kcfs (Figures 2.5-1 to 2.5-4; Table 2.5-1).

Unit value timeseries of riverine data for the WY2021 study period was obtained from Northwestern Division (NWD) Data Query version 2.1 @

http://nww-wmops.nww.usace.army.mil/common/dataquery/www/

and the U.S. Geological Survey (USGS) National Water Information System @

https://waterdata.usgs.gov/nwis

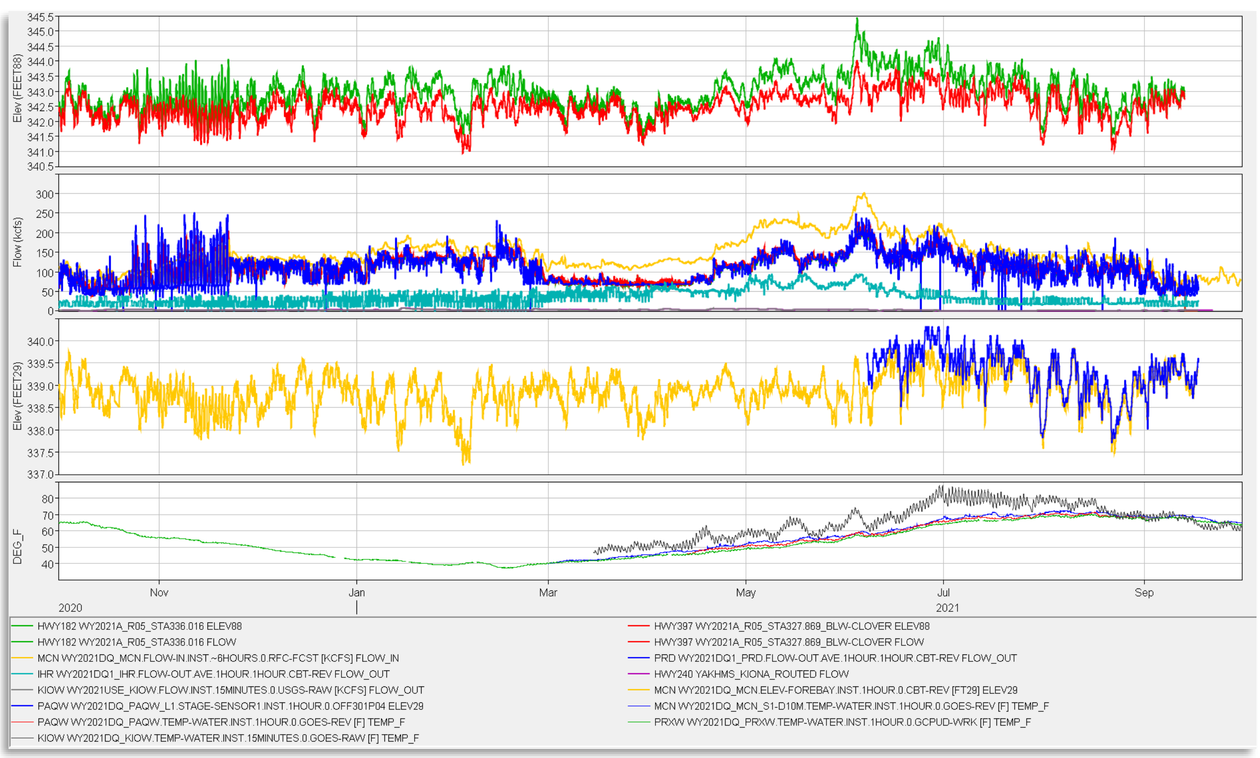

Figure 2.5-1 WY2021 timeseries plot illustrating flow, stage, and temperature at various regional stations of influence. *Note seasonality of inflow magnitude and temperature.*

Table 2.5-1 Summary of WY2021 Riverine Conditions.

Metric	n	min	mean	std	25%	50%	75%	max
Yakima River Flow @ Kiona (kcfs)	8763	1.01	2.31	1.07	1.39	1.85	3.16	5.42
Yakima River Temperature @ Kiona (°F)	8736	54.4	72.0	7.1	66.9	72.1	77.9	87.7
Columbia River Flow blw PRD (kcfs)	8763	0.00	124.88	35.82	101.90	126.80	147.20	246.60
Columbia River Temperature blw PRD (°F)	8619	49.4	62.8	6.2	56.8	65.9	68.0	70.1
Columbia River Stage blw Yakima (feet NGVD29)	6810	337.7	339.3	0.5	339.0	339.4	339.7	340.3
Columbia River Temperature blw Yakima (°F)	6186	56.6	66.5	3.9	65.3	67.9	69.1	71.3
MCN Inflow (kcfs)	8763	68.69	171.33	47.38	135.14	160.75	209.23	301.47
MCN Forebay Elevation (feet NGVD 29)	8763	337.5	339.0	0.4	338.8	339.0	339.3	339.9
MCN Forebay Temperature (°F)	8718	52.6	65.0	6.0	59.0	68.1	69.7	72.4

2.5.1 McNary Pool

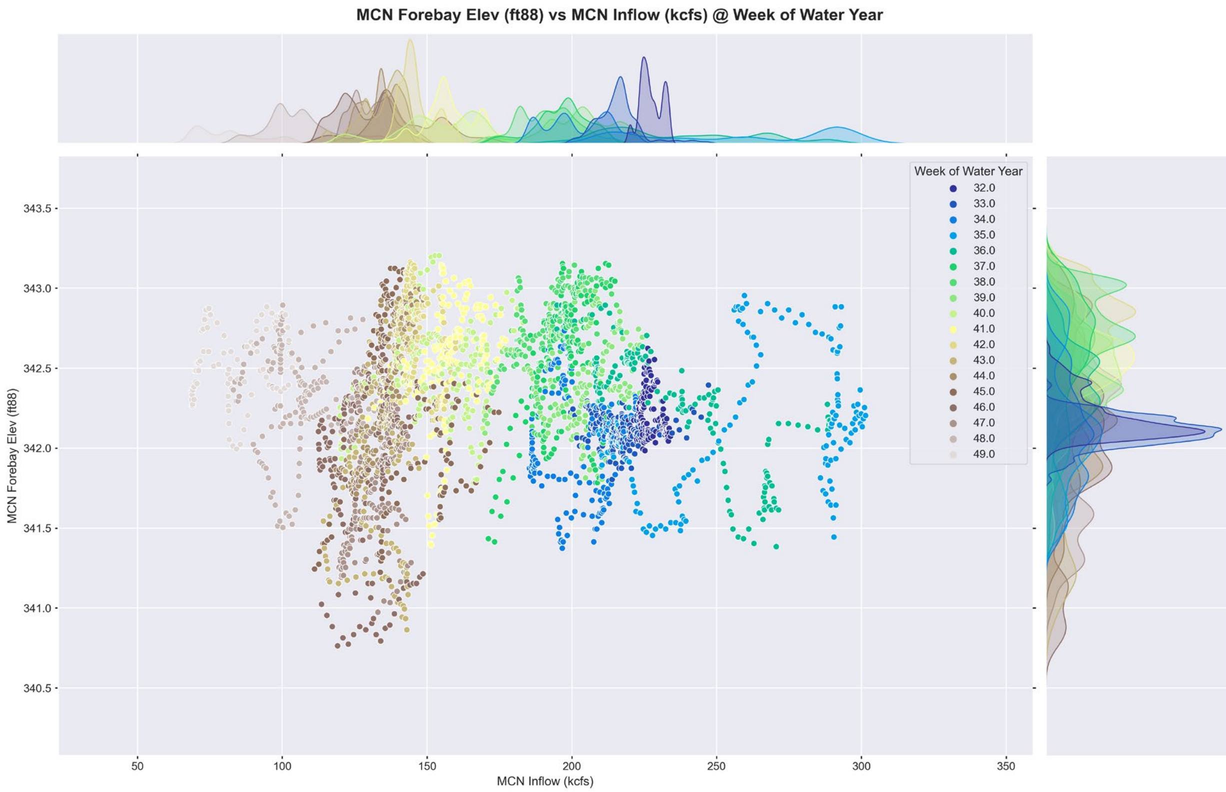

Figure 2.5-2 McNary forebay elevation (feet NAVD88) versus inflow between May and September 2021. *Note seasonality of inflow and year-round variability of MCN stage.*

2.5.2 Yakima River

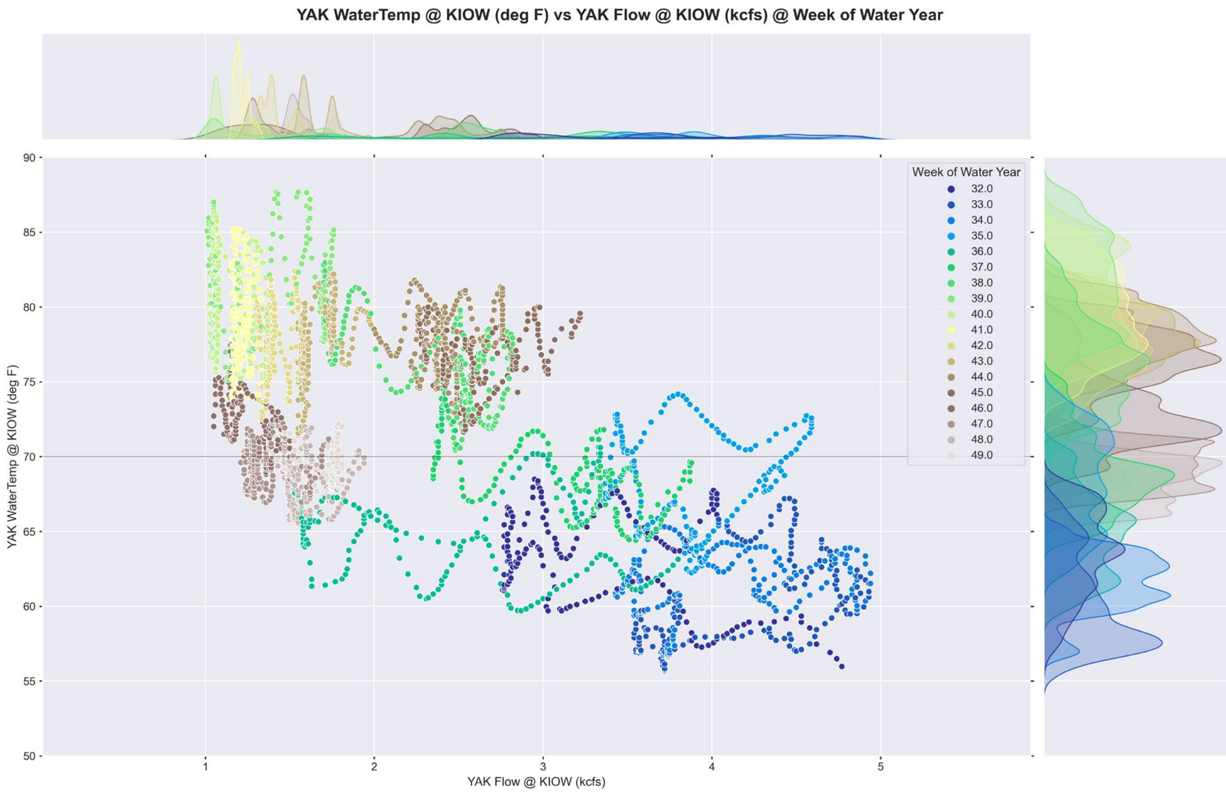

Figure 2.5-3 Yakima River temperature versus flow at Kiona gage between May and September 2021. *Note cooler inflowing temperatures from Yakima basin associated with the spring freshet followed by rapid heating in June.*

2.5.3 Columbia River

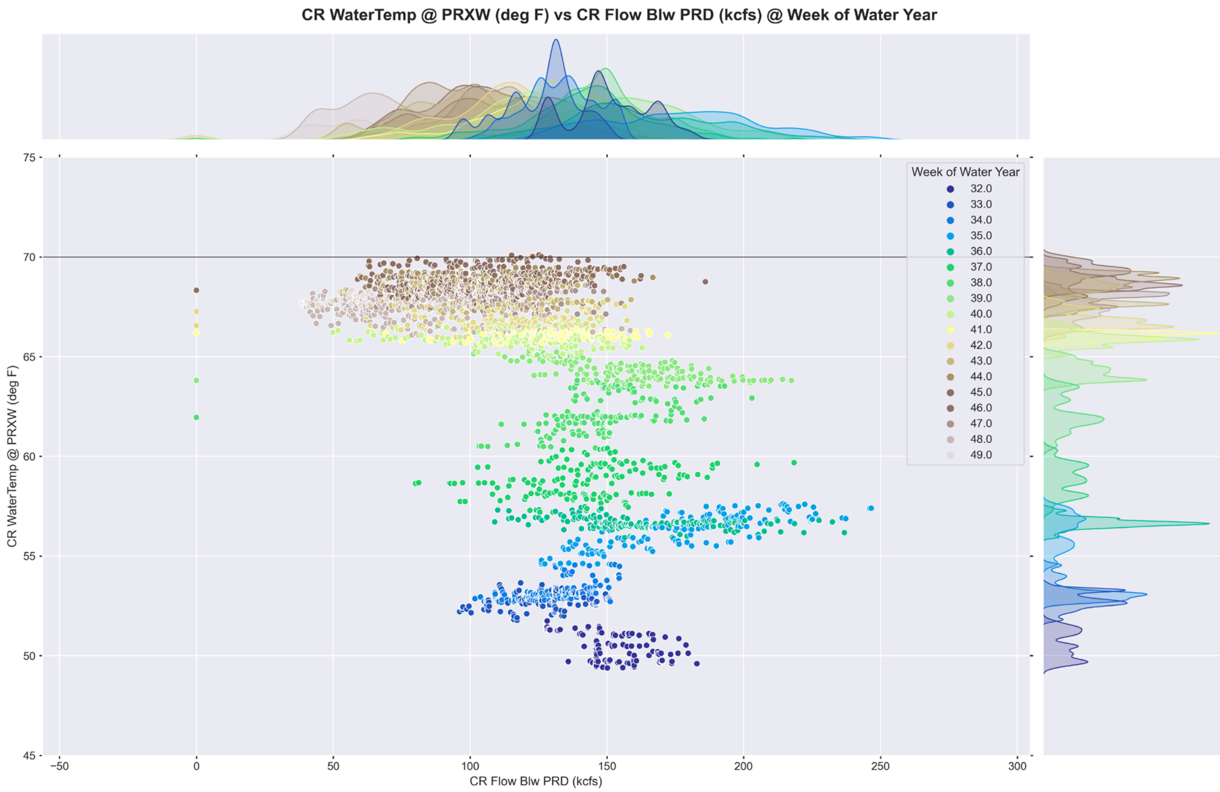

Figure 2.5-4 Columbia River temperature vs. flow below Priest Rapids Dam between May and September 2021. *Note seasonality of inflowing temperature.*

2.6 Hydraulic Conditions

Local hydraulic conditions were estimated using a HEC-RAS2D model of the study area with a nominal grid size of 25'. The model was calibrated to historical stage data and run for the May through September 2021 study period using regional routed inflows for the Yakima and Columbia Rivers, and downstream stage routed from the MCN forebay elevation. A key hydraulic parameter of interest is the degree of flow mixing between the incoming cooler Columbia River and warmer Yakima River. While the RAS2D model does not currently compute flow source tracing, it did provide hourly timeseries of spatially varying depth and velocity for comparison with measured temperatures (Figures 2.6-1 to 2.6-4; Table 2.6-1).

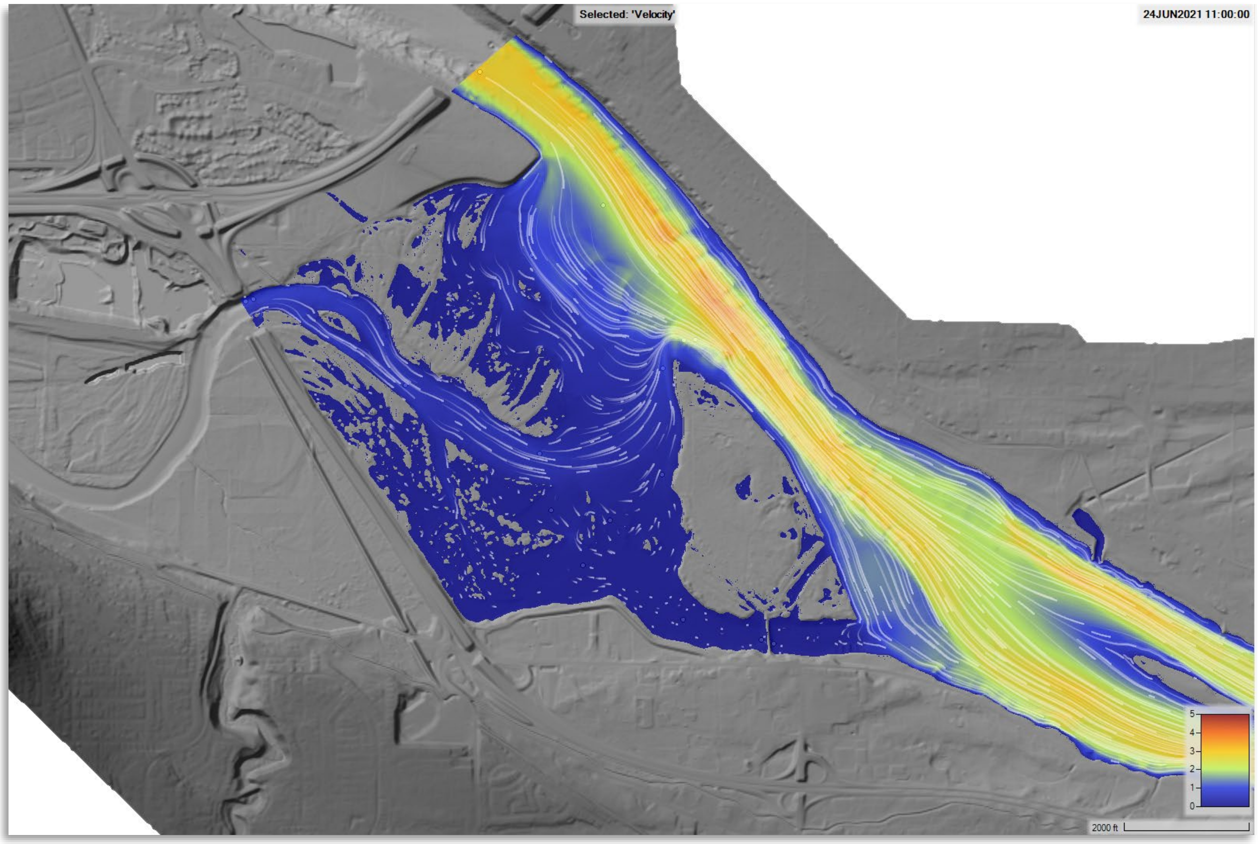

Figure 2.6-1 Example HEC-RAS 2D model output for velocity on 24 June 2021. *Note relatively low velocities southwest of Bateman Island.*

Table 2.6-1 Summary of WY2021 hourly Hydraulic Conditions across monitoring sites.

Metric	n	min	mean	std	25%	50%	75%	max
Stage (feet NAVD 88)	8763	342.1	345.2	1.3	344.3	345.2	346.0	350.0
Hydraulic Depth (ft)	8763	0.7	14.4	6.6	9.7	15.1	18.1	28.8
Invert Depth (ft)	8763	0.7	14.9	7.0	9.8	15.7	19.3	30.1
Velocity (ft/sec)	8763	0.00	0.88	0.59	0.39	0.81	1.23	3.16
Shear Stress (lbf/ft^2)	8763	0.00	0.05	0.05	0.01	0.03	0.06	0.32
Unit Discharge (ft^2/sec)	8763	0.0	7.7	8.6	1.7	4.1	9.9	44.4

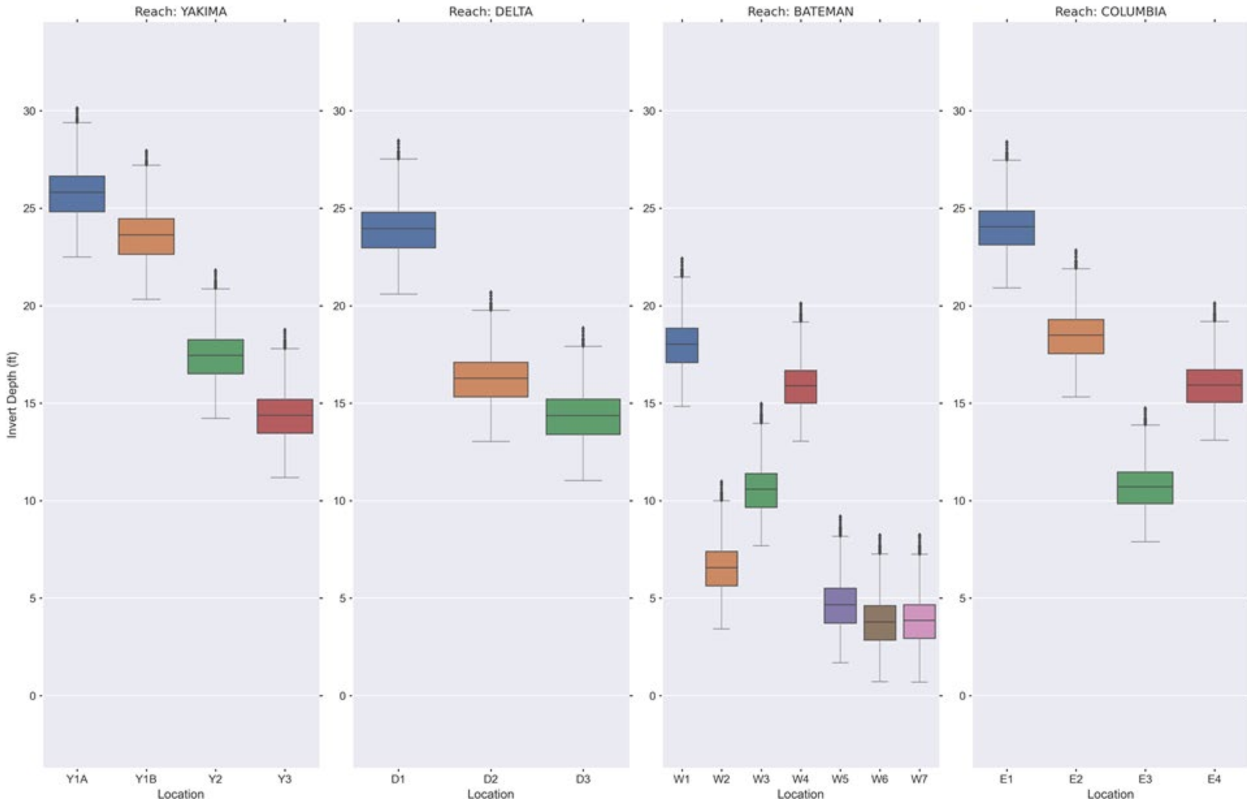

Figure 2.6-2 Distribution of depth at monitoring sites.

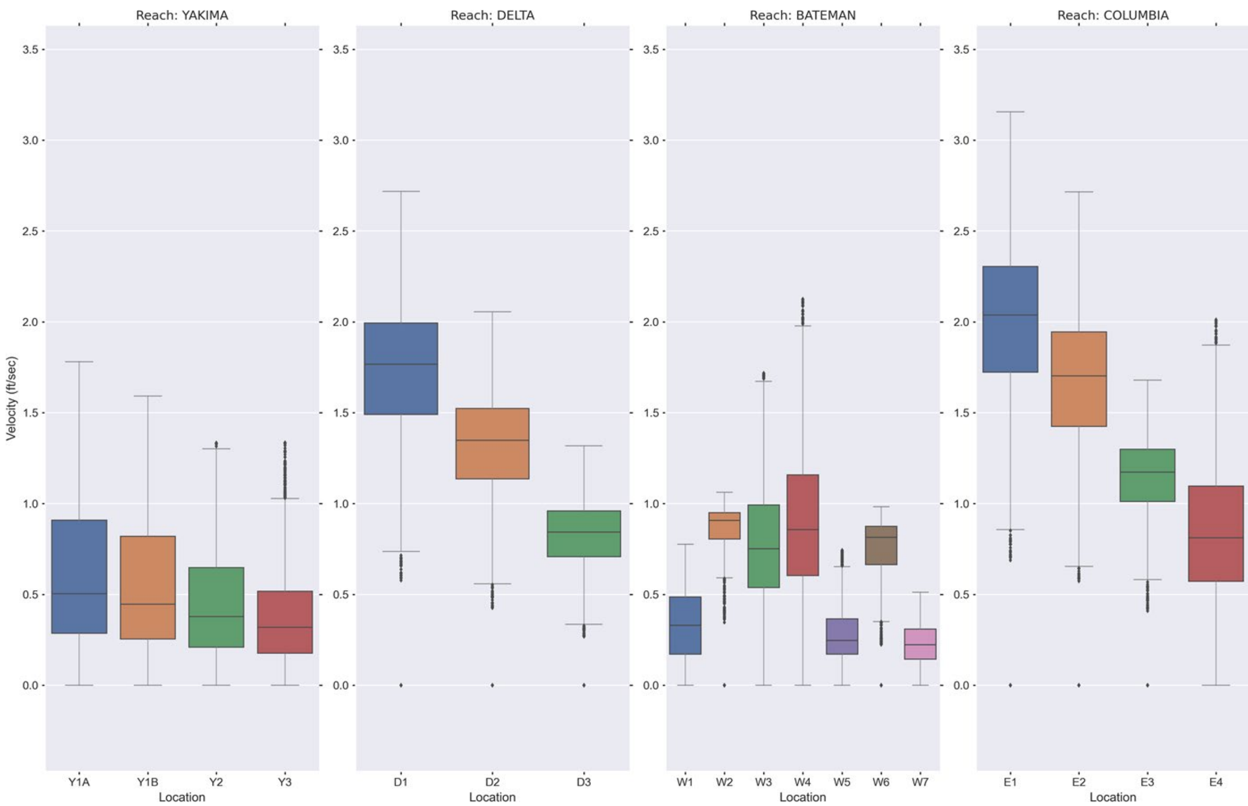

Figure 2.6-3 Distribution of velocity at monitoring sites.

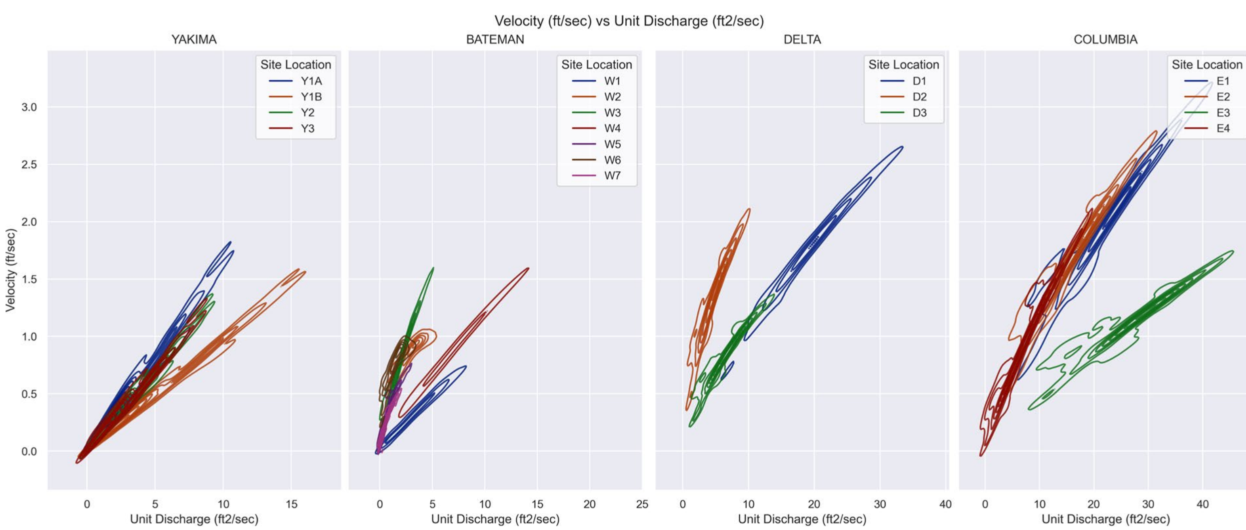

Figure 2.6-4 Rating distributions for velocity at monitoring sites.

3. TRENDS SUMMARY

A cursory graphical summary of the May through September monitoring data was conducted to evaluate trends & correlations with various conditions including:

- Regional river conditions
- Meteorological conditions
- Local hydraulic conditions

Note that due to the relatively brief timeframe of the collected data and funding allocated to reporting, the extent of this trends summary is intended to be an initial reconnaissance review, and neither statistically exhaustive nor robust. Additional analyses and model development are proposed (see Section 4) for future tasks to integrate this data with coincident and regional water temperature studies.

3.1 Timeseries

The measured timeseries of water temperature at multiple sites by depth provided insight to both seasonal and localized trends. Most sensors generally tracked with the trend of the majority inflow (either Yakima or Columbia River) with various deviations.

Figures 3.1-1 to 3.1-22 below illustrate various temporal trends including:

- Water temperature stratification at: Y1, Y3, W1, & W4
- Water temperature trending with baseline inflow temperature.
- Daily warming of upper water column.
- June/July heat dome influence at depth
- Flow mixing at W1 and Y3.

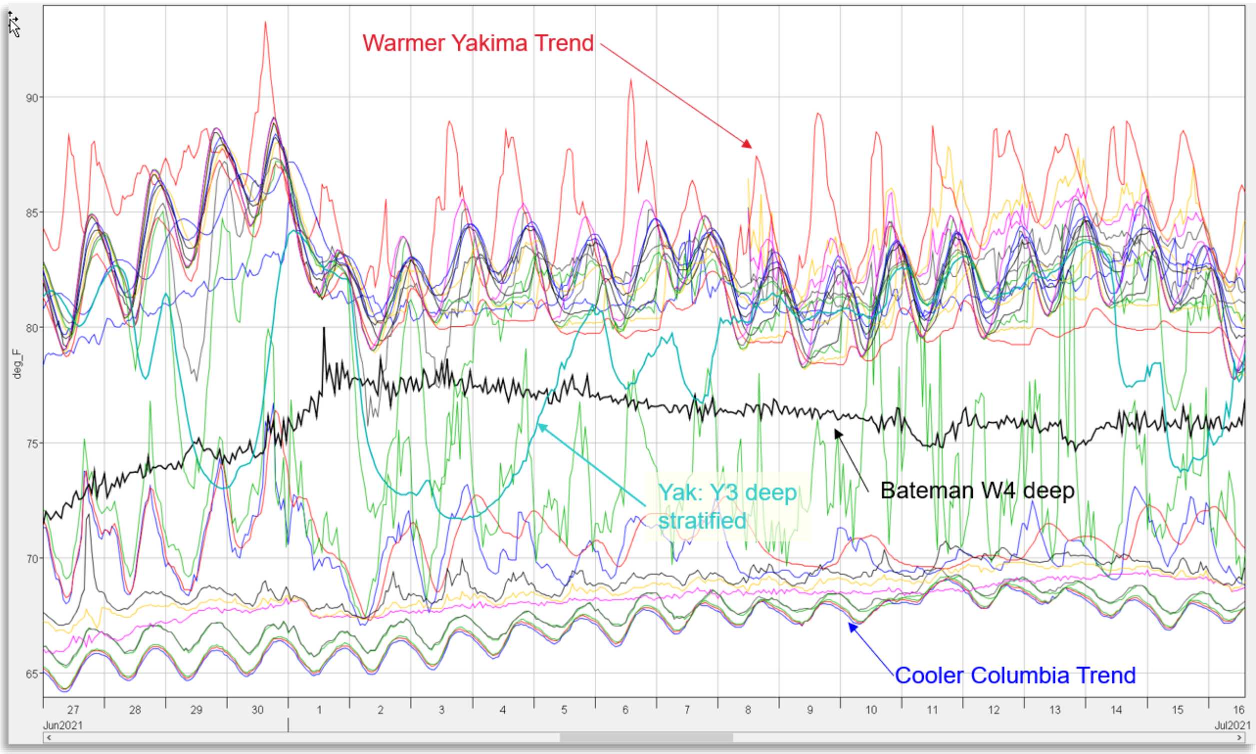

Figure 3.1-1 Water temperature timeseries for first half of July 2021.

3.1.1 Yakima Timeseries

Measured water temperatures in the Yakima River consistently tracked with inflowing water temperature with a large diurnal temperature range. Various departures were identified in the Yakima temperature data, in-particular, at Y1, where temperatures at depth stratified and remained warm for two weeks following the June/July heat-dome, and Y3, where temperature stratification occurred coincident with a flow direction change, potentially indicating increased mixing of Columbia River water in the lower Yakima.

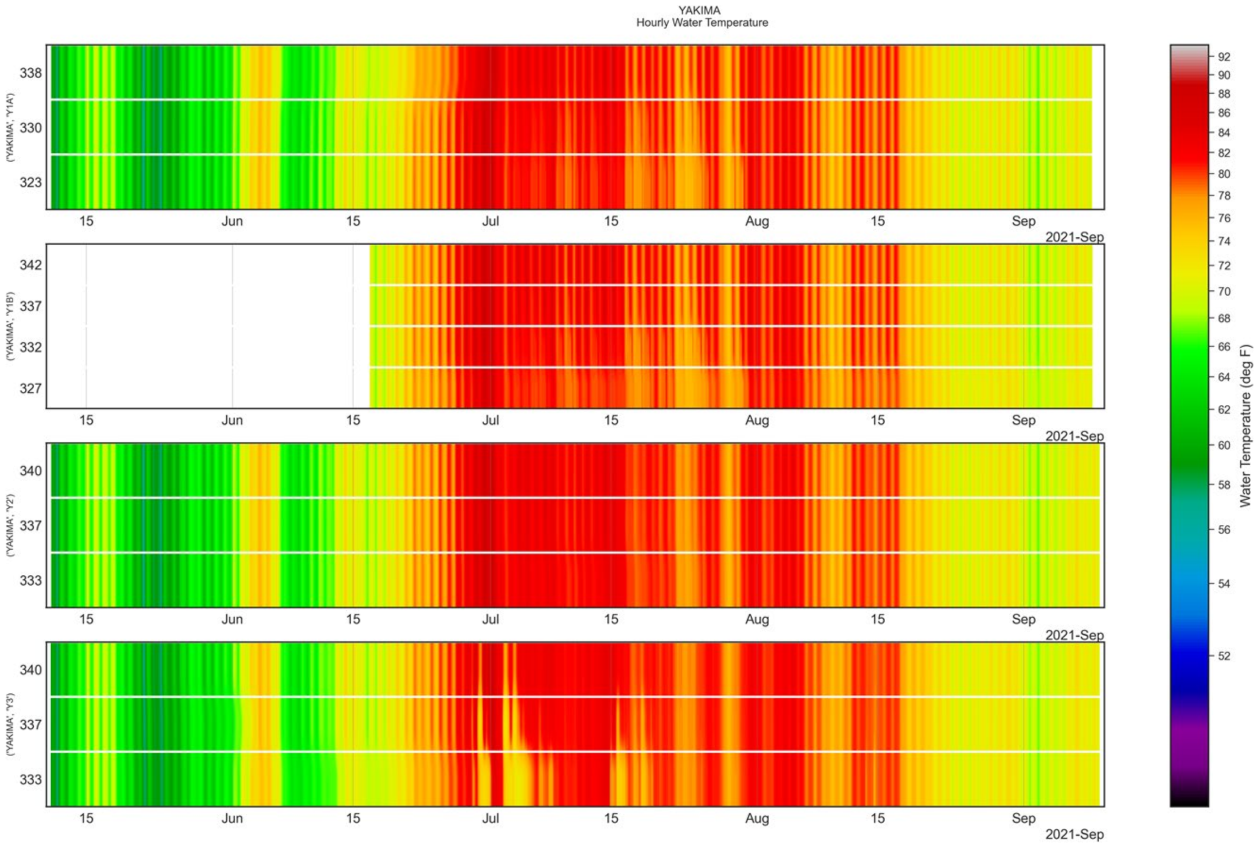

Figure 3.1-2 Timeseries of Yakima hourly temperature string data between May and September 2021.

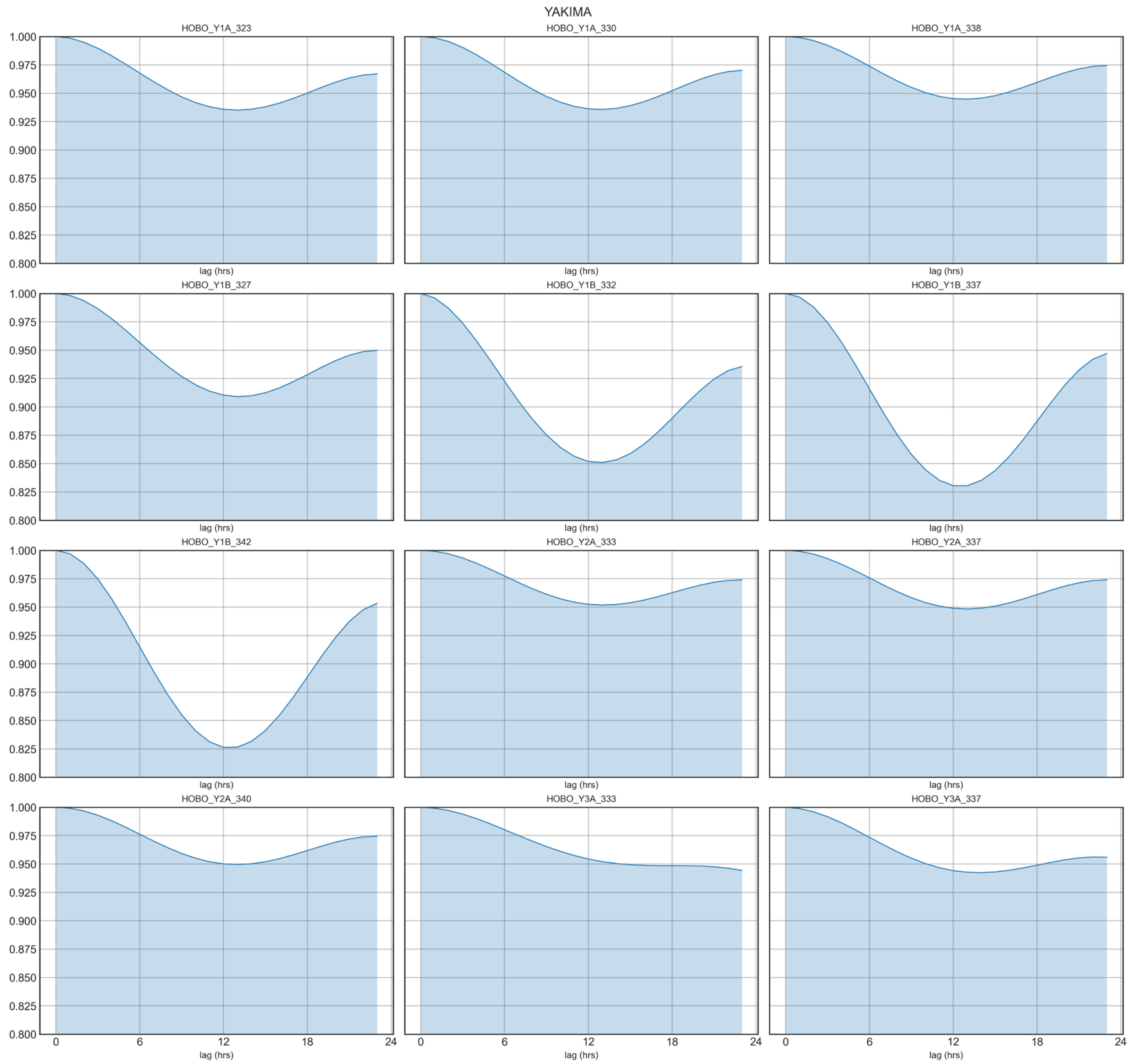

Figure 3.1-3 Pearson correlation coefficients of Yakima hourly temperature string data between May and September 2021 for 1 to 24 hour lag.

3.1.1.1 Yakima – Y1

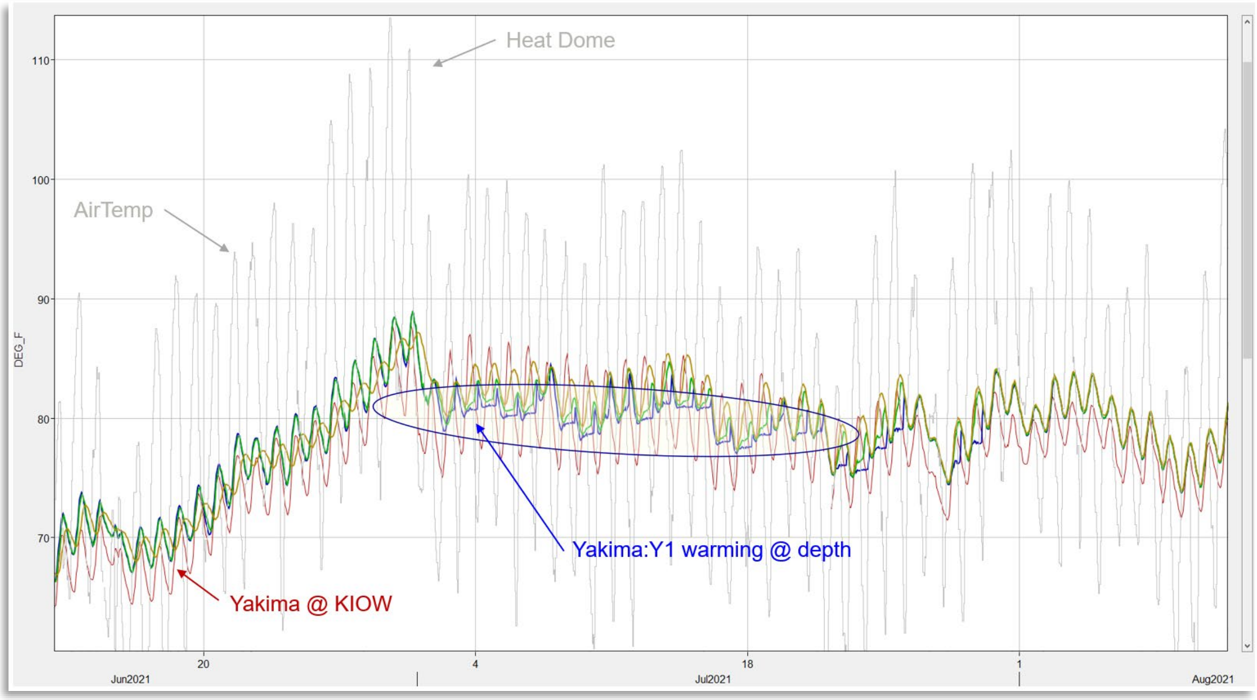

Figure 3.1-4 Water temperature stratification at Yakima River Y1 during heat dome in early July 2021.

3.1.1.2 Yakima – Y3

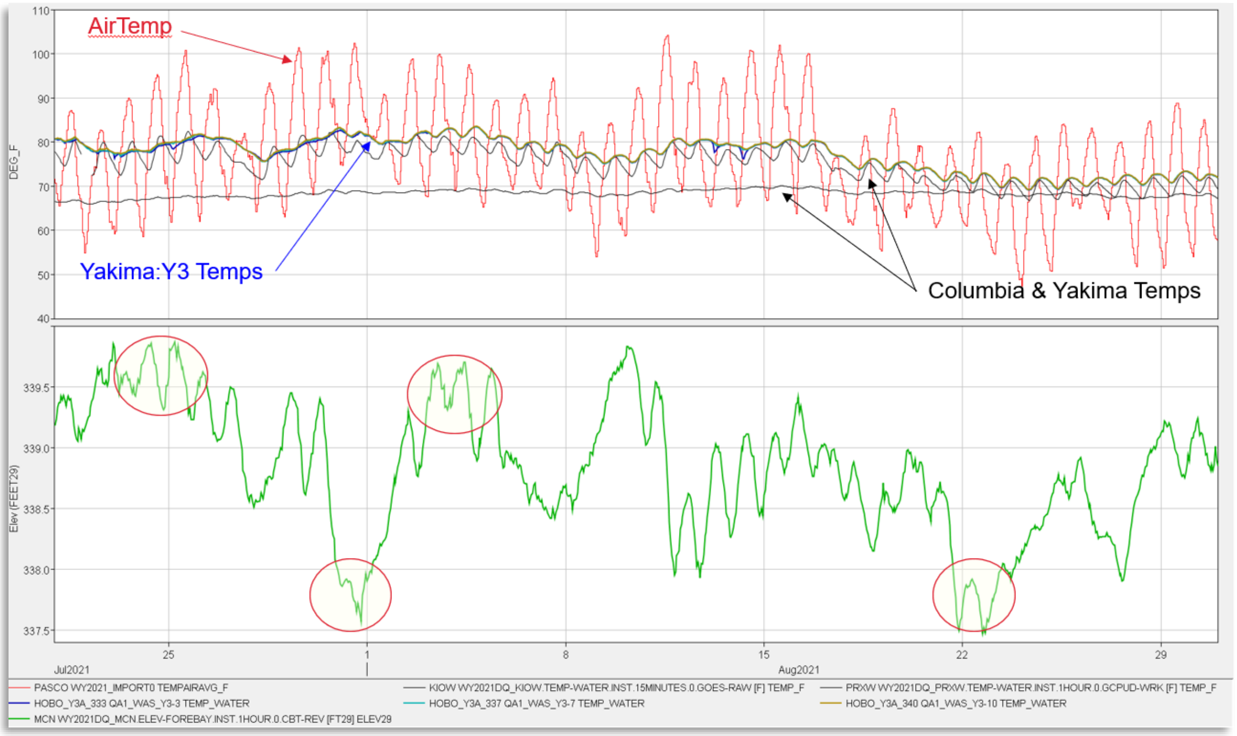

Figure 3.1-5 Water temperature timeseries at Yakima River Y3 for late July and early August 2021 and MCN pool levels. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow.*

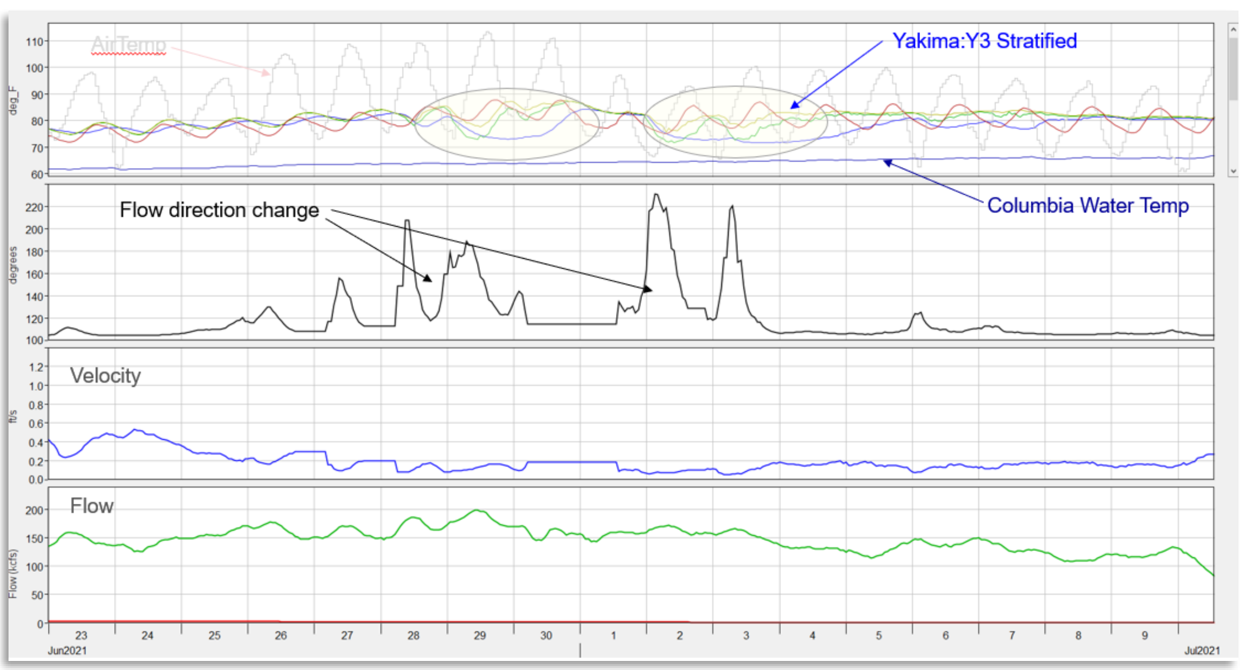

Figure 3.1-6 Water temperature stratification at Yakima River Y3 during heat dome in early July 2021.

3.1.2 Bateman Timeseries

Measured water temperatures in the Bateman reach are predominately influenced by the warmer inflowing Yakima River temperature, especially to the south and west of Bateman Island, where Columbia River water does not frequently mix most likely due to the causeway.

At site W1, water temperature trended with the Yakima baseline temperature through May and June; following the Yakima freshet, flow direction at W1 changed and the W1 flow stratified, tracking with cooler Columbia River temperature at depth, while the top of the water column tracked with Yakima baseline temperature.

Site W3 was replaced in early July following theft and spanned a shallow range with measured water temperatures trending with the upper water column at W4.

At station W4 on the west side of the causeway, spring temperatures in May and June were notably stratified, with the deepest measurements remaining near constant for multiple days in a row, followed by an abrupt transition of ~8-12°F in <6 hours. The stratification pattern continued into July and August, and was associated with coincident observations of decreased Luminescent Dissolved Oxygen (LDO) at depth. While groundwater exchange through the causeway could help to explain the consistent pattern of cooler water at depth, no significant difference in hydraulic head across the causeway was estimated by the hydraulic model and other means of indirect passage such as an abandoned culvert are undocumented. In addition, the synoptic survey data indicates notable differences in water quality parameters between the W4 and E4 sites.

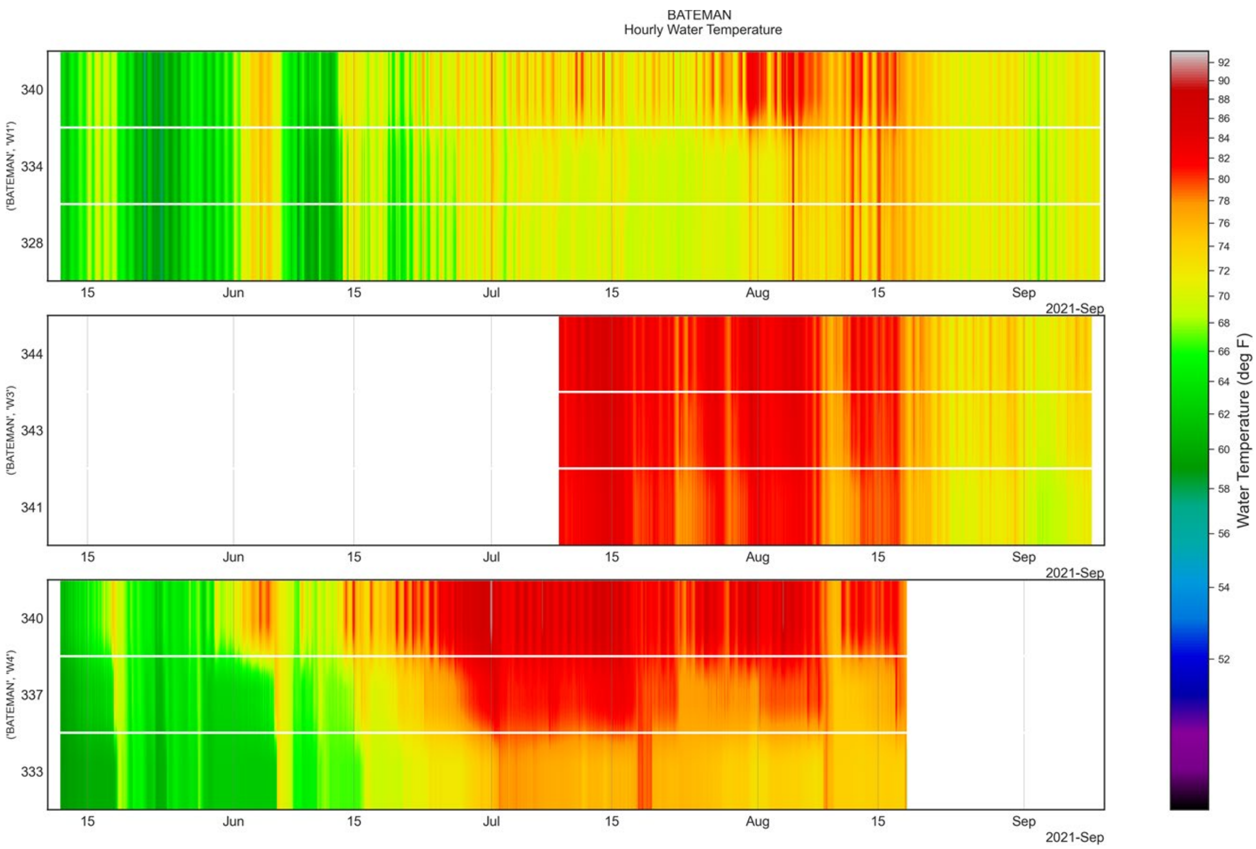

Figure 3.1-7 Timeseries of West Bateman hourly temperature string data between May and September 2021.

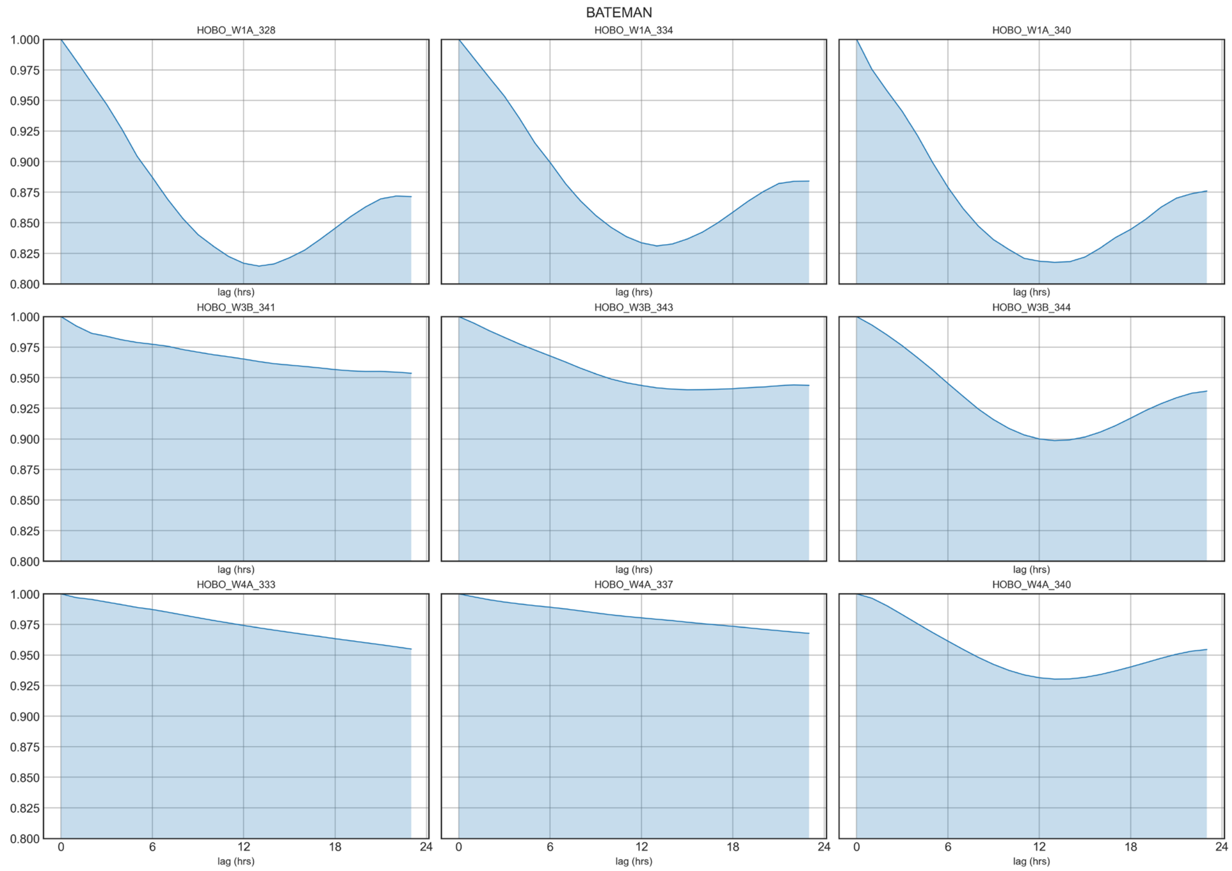

Figure 3.1-8 Pearson correlation coefficients of Bateman hourly temperature string data between May and September 2021 for 1 to 24 hour lag.

3.1.2.1 Bateman – W1

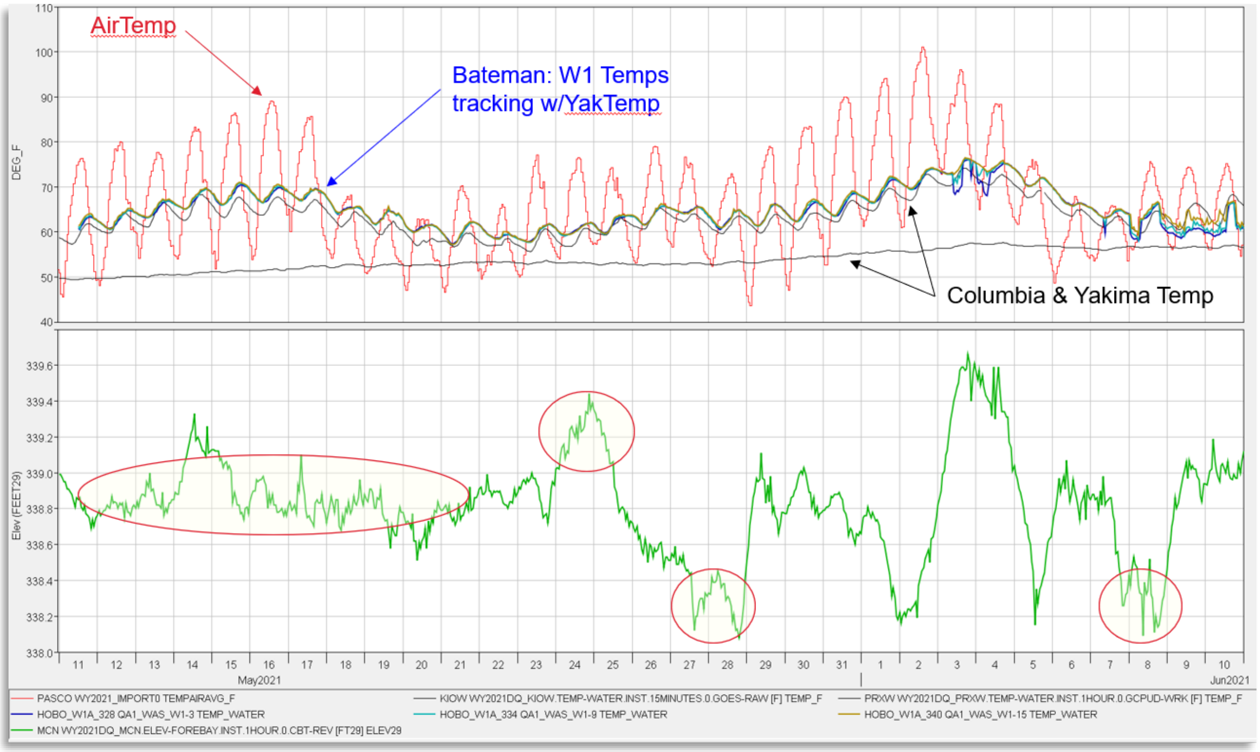

Figure 3.1-9 Water temperature timeseries at West Bateman Reach W1 for May and June 2021 with McNary pool elevation. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow.*

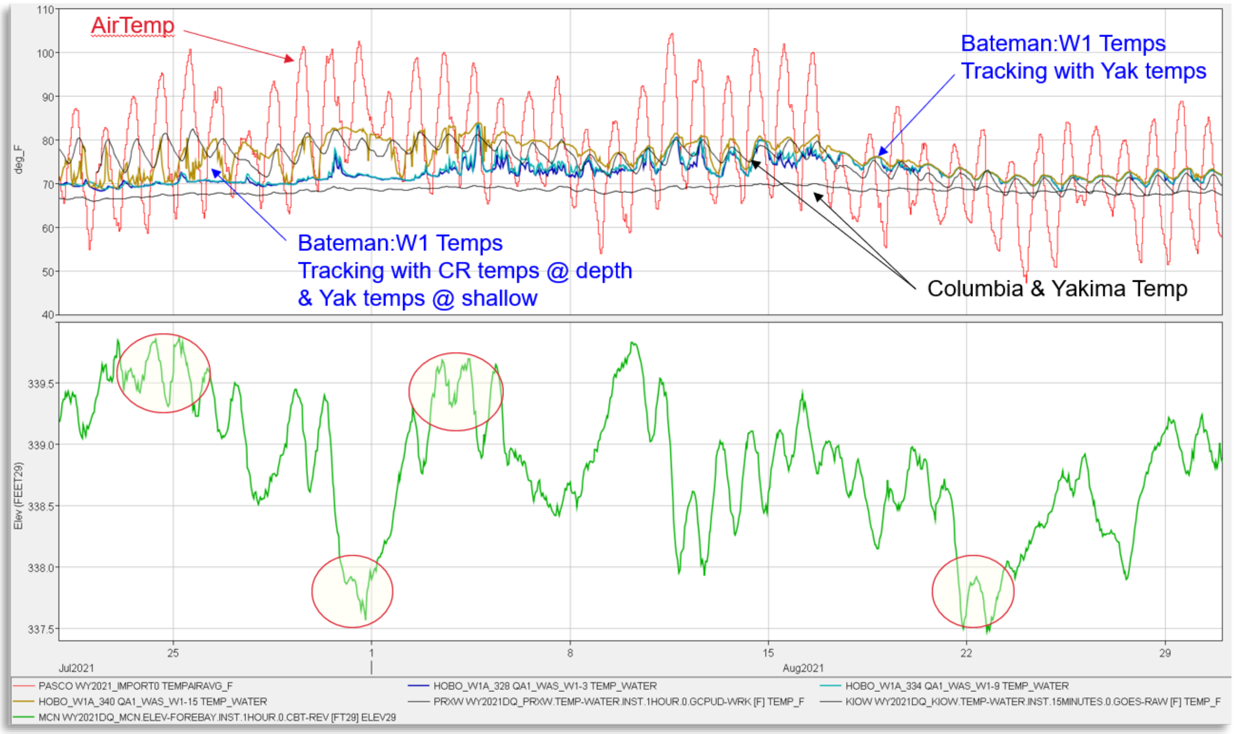

Figure 3.1-10 Water temperature timeseries at West Bateman Reach W1 for late July and early August 2021. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow*

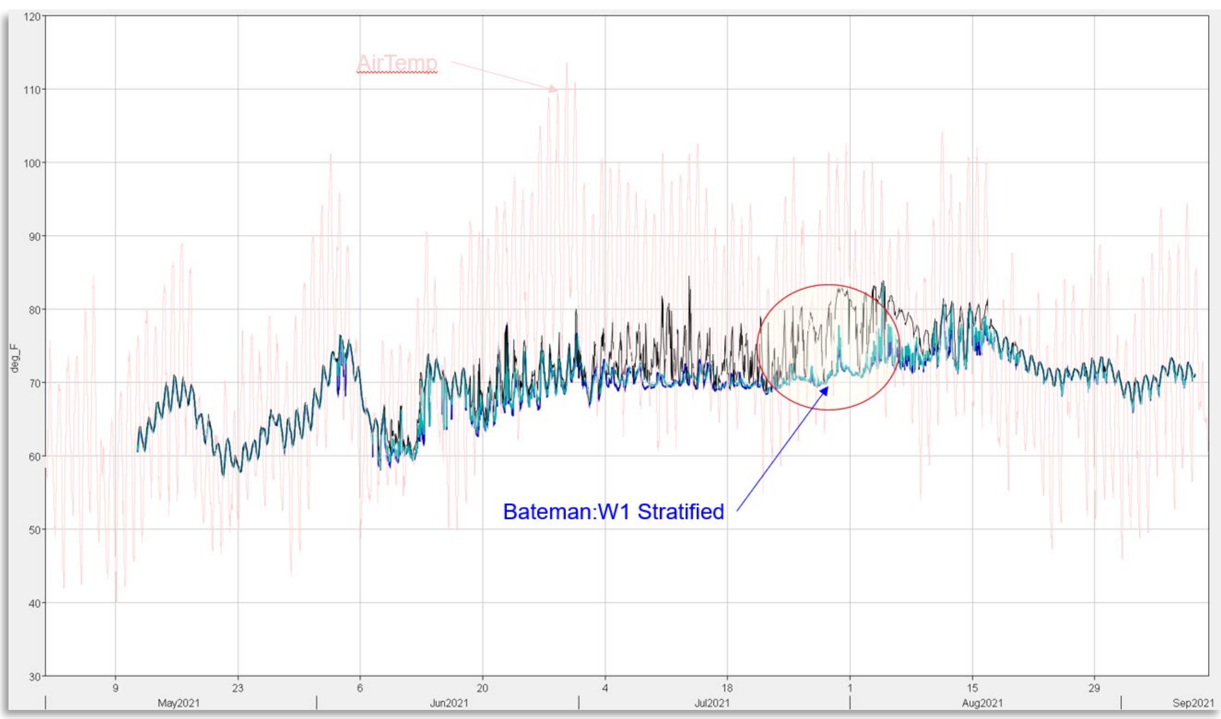

Figure 3.1-11 Water temperature stratification at Bateman Reach W1 following heat dome in late July 2021.

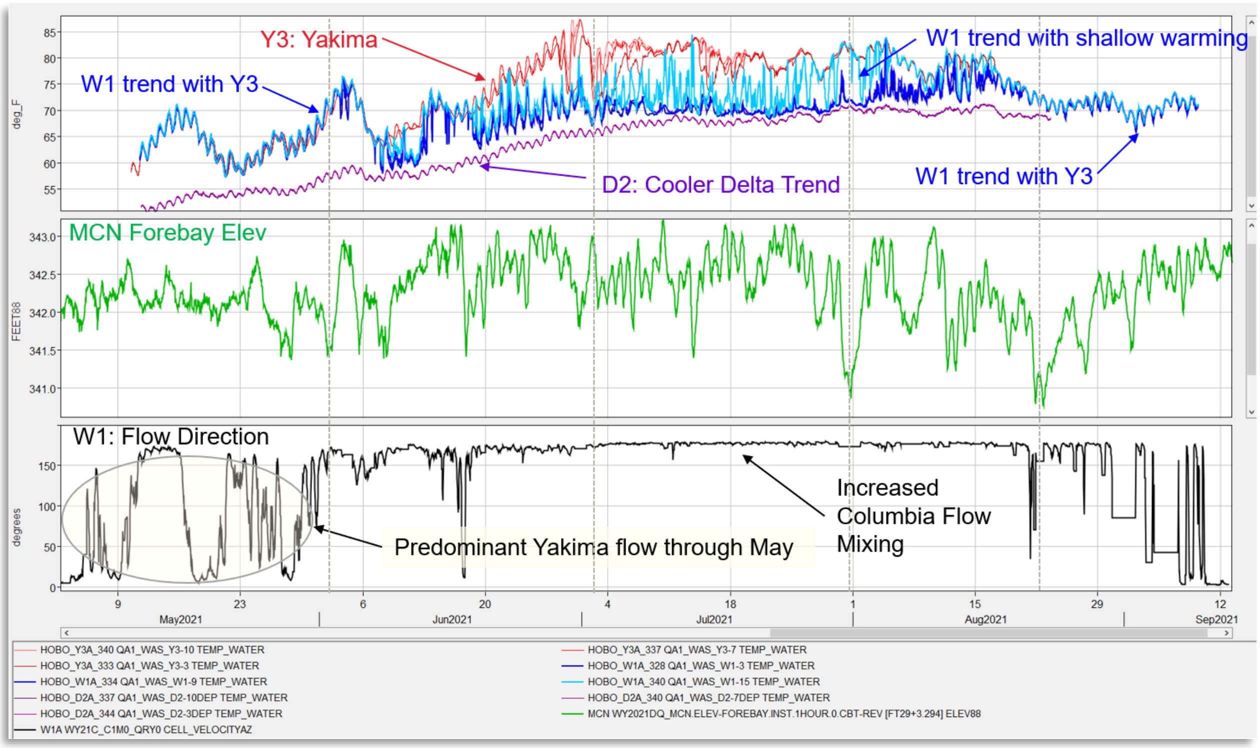

Figure 3.1-12 Water temperature timeseries at West Bateman Reach W1 with MCN forebay elevation and flow direction.

3.1.2.2 Bateman – W3

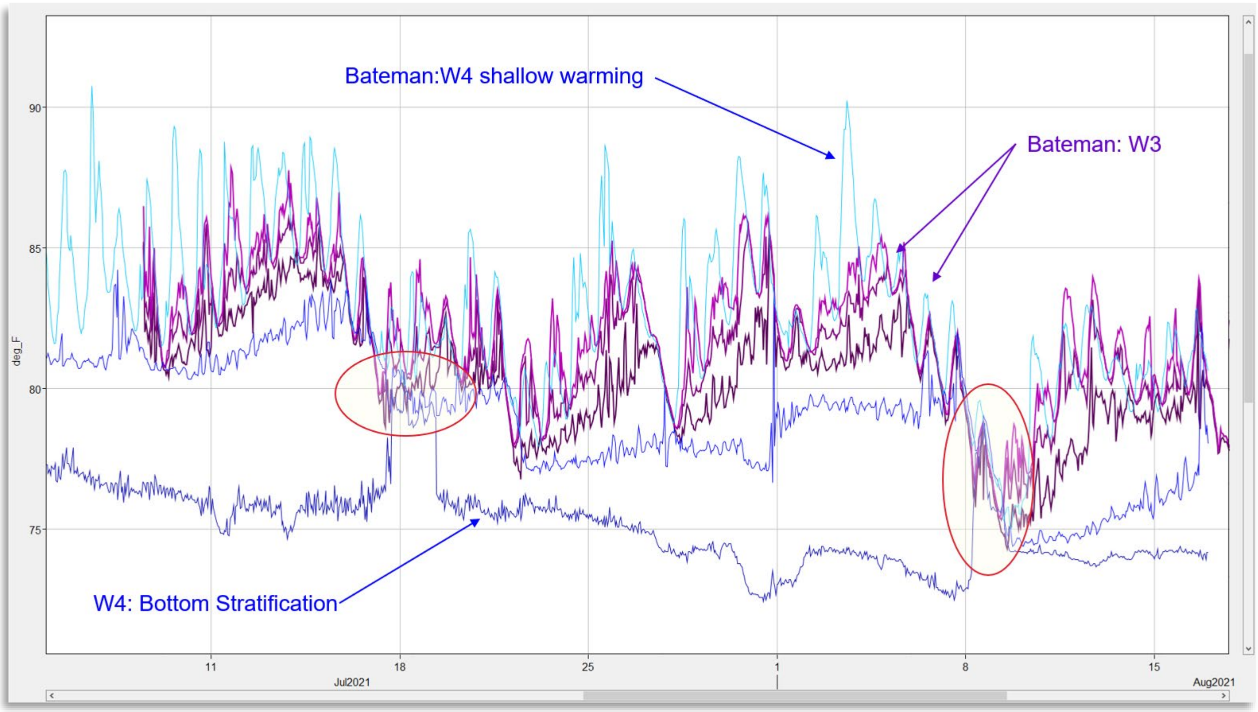

Figure 3.1-13 Water temperature timeseries at West Bateman Reach W3 with W4 for comparison. *Note abrupt changes in W4 temperature highlighted.*

3.1.2.3 Bateman – W4

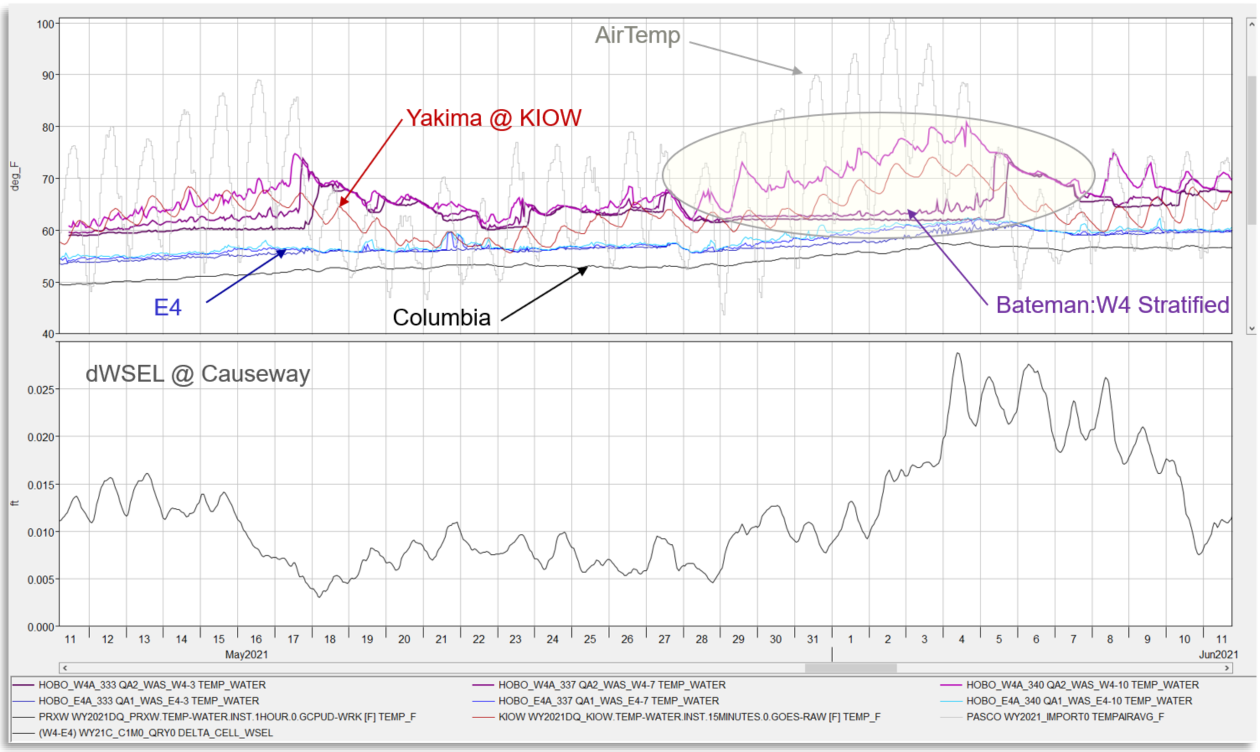

Figure 3.1-14 Water temperature timeseries at West Bateman Reach W4 for May and early June 2021. *Bottom figure is the water surface elevation differential in feet between the East and West sides of the causeway.*

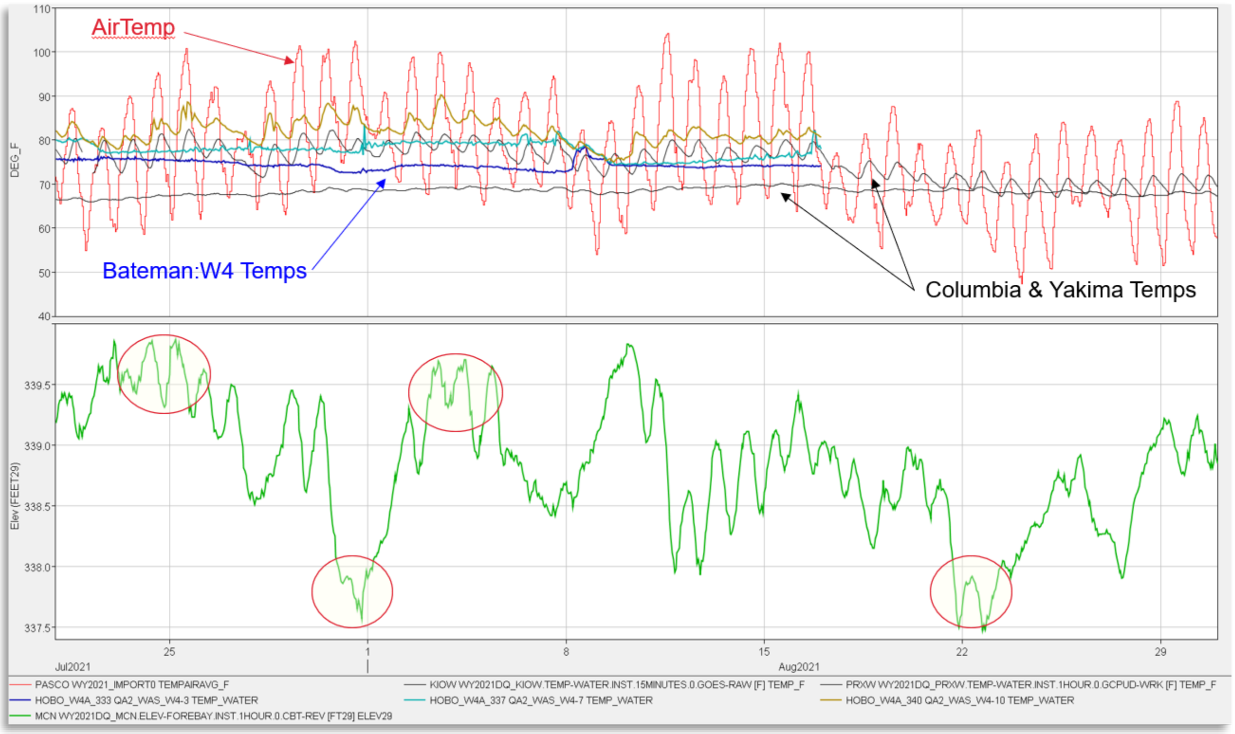

Figure 3.1-15 Water temperature timeseries at West Bateman Reach W4 for late July and early August 2021. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow.*

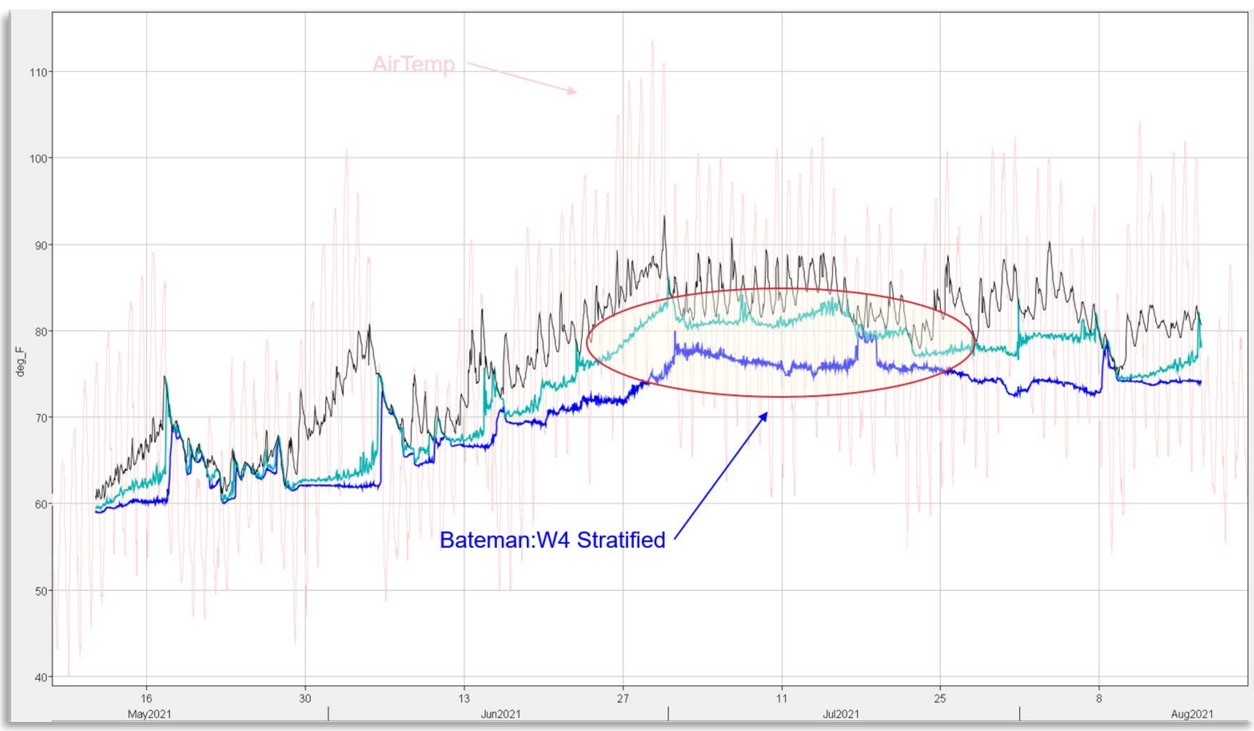

Figure 3.1-16 Water temperature stratification at Bateman Reach W4 during heat dome in early July 2021.

3.1.3 Delta Timeseries

Measured water temperatures in the Delta and East side of Bateman Island consistently trended with inflowing Columbia River water temperature with a minor diurnal temperature range. Only minor departures were identified in the temperature data at D2 and D3.

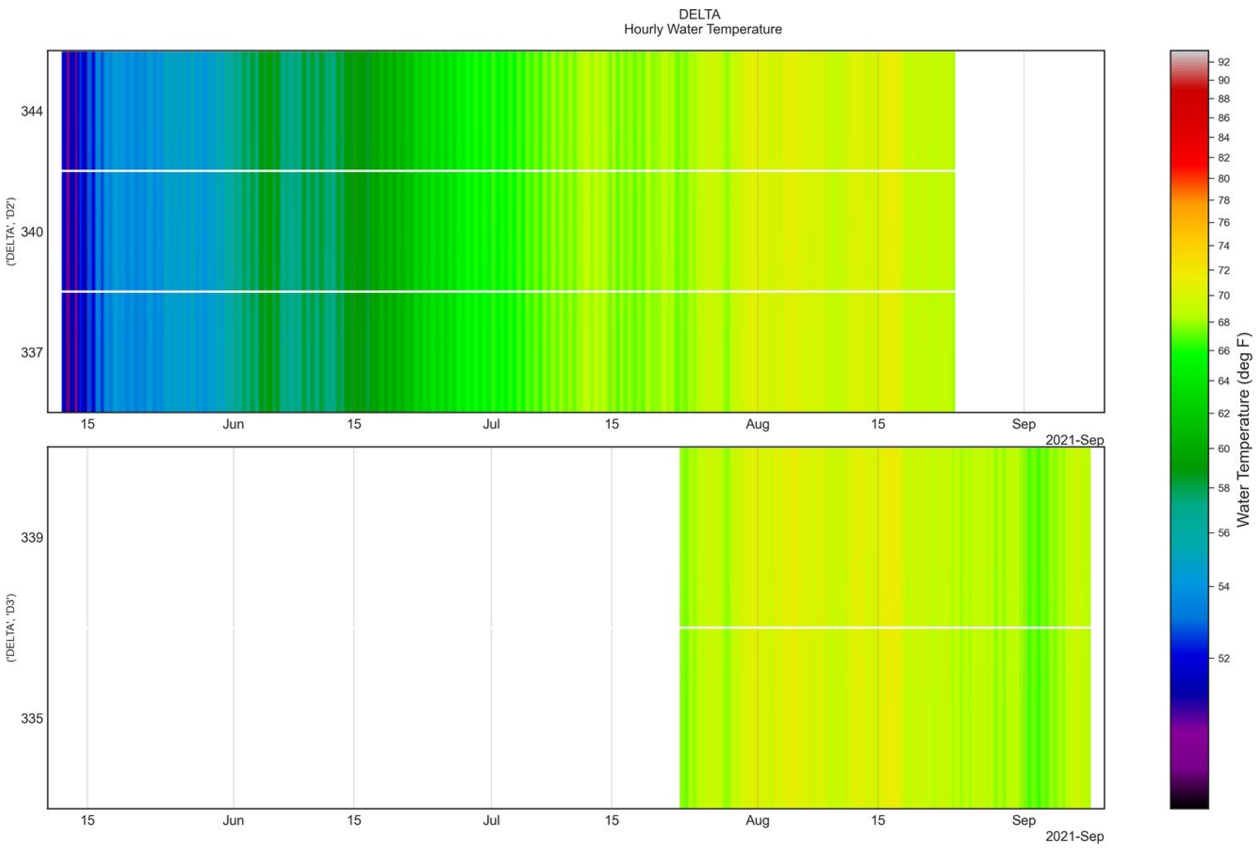

Figure 3.1-17 Timeseries of Delta temperature string data between May and September 2021.

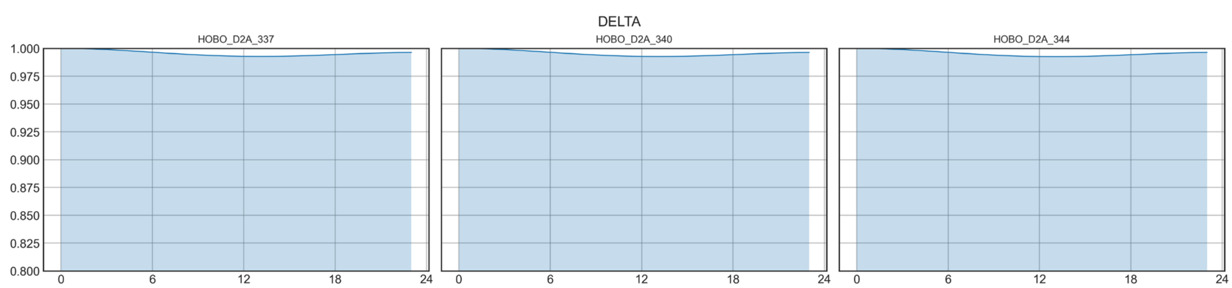

Figure 3.1-18 Pearson correlation coefficients of Delta hourly temperature string data between May and September 2021 for 1 to 24 hour lag.

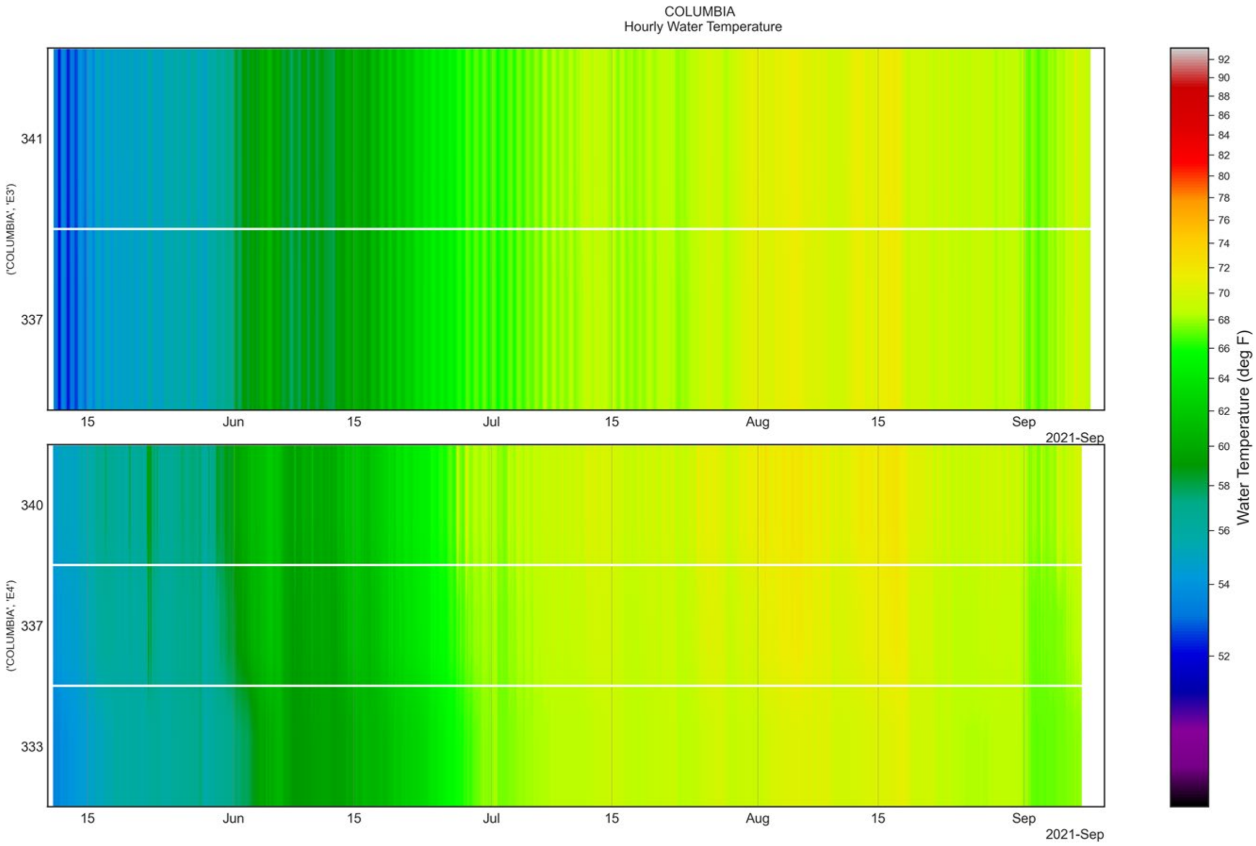

Figure 3.1-19 Timeseries of East Bateman hourly temperature string data between May and September 2021.

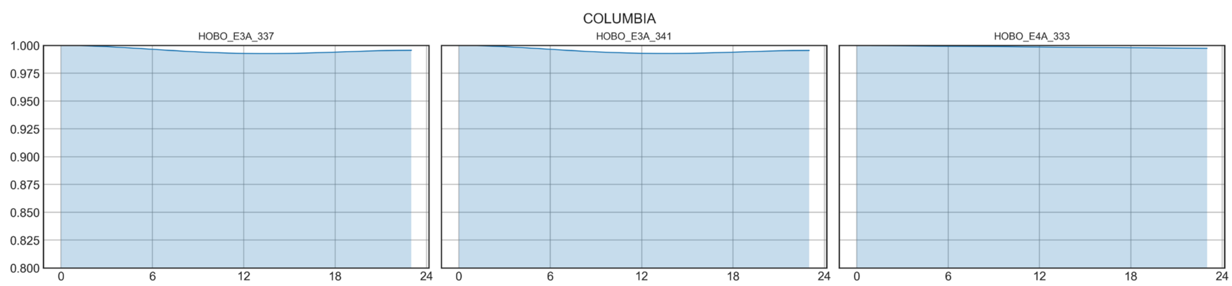

Figure 3.1-20 Pearson correlation coefficients of Columbia hourly temperature string data between May and September 2021 for 1 to 24 hour lag.

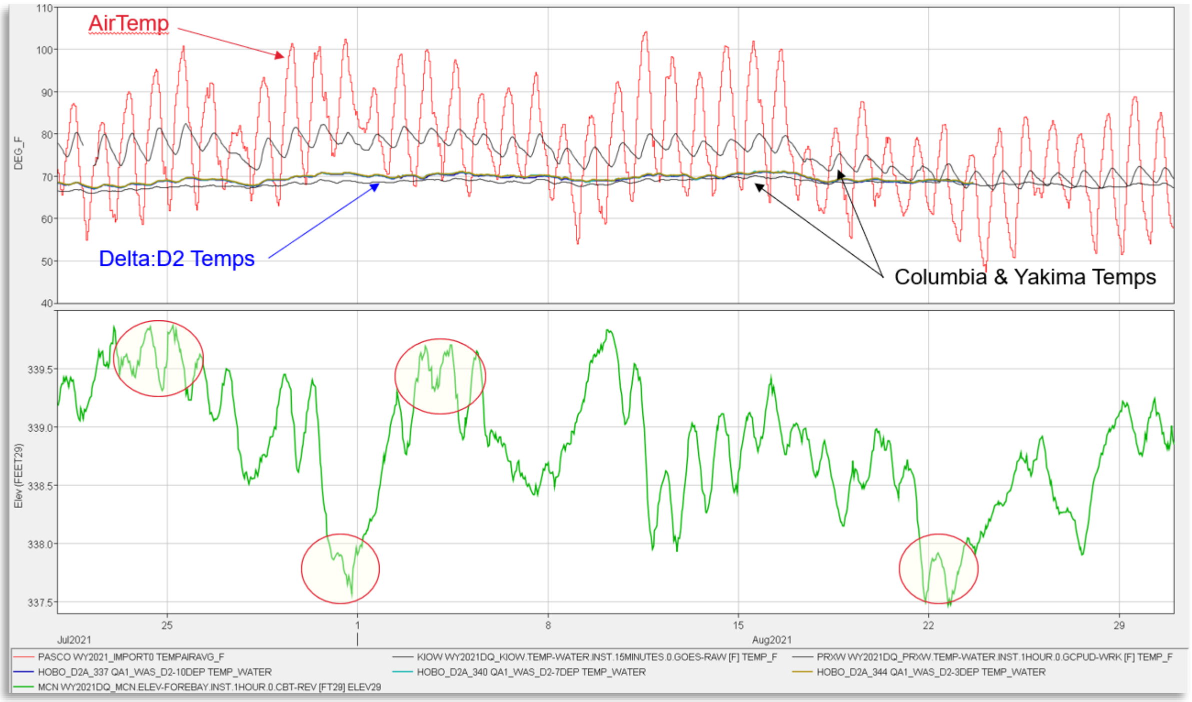

Figure 3.1-21 Water temperature timeseries at Delta Reach D2 for late July and early August 2021. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow.*

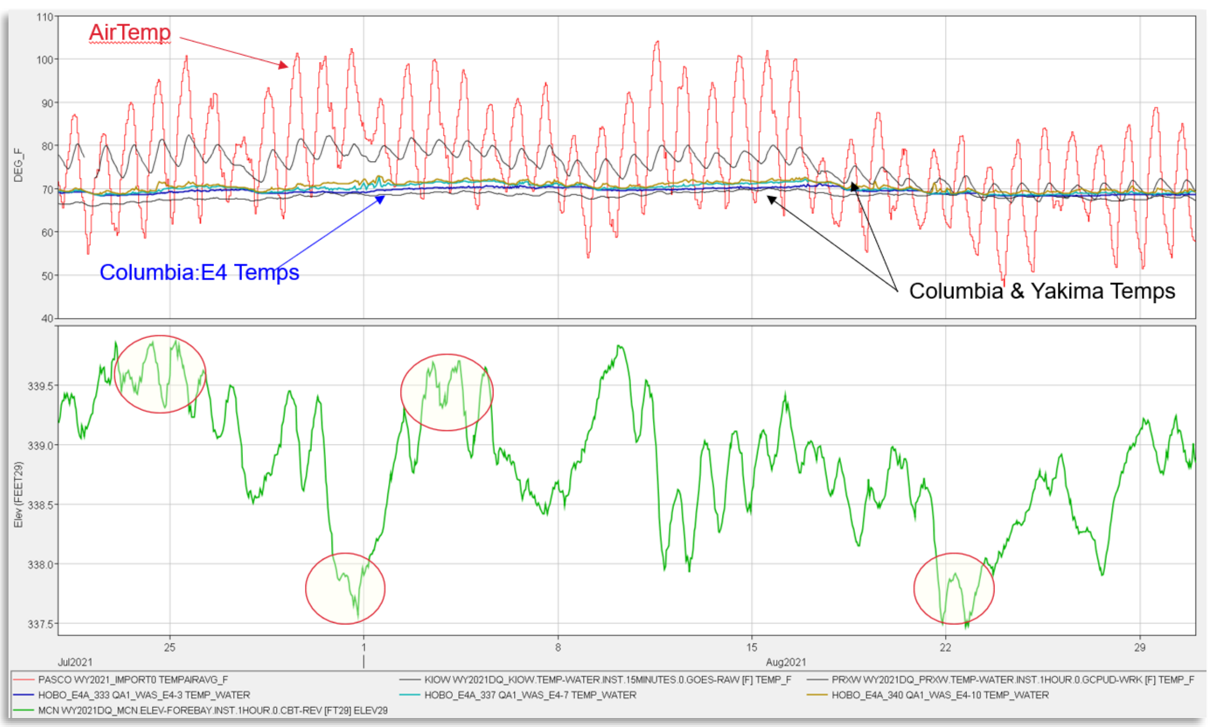

Figure 3.1-22 Water temperature timeseries at Columbia Reach E4 for late July and early August 2021. *Note consistent temperature trends independent of both high and low MCN pool levels highlighted in yellow.*

3.2 Water Temperature vs Parameter Distributions

Bivariate distributions of measured water temperature paired with various exogenous conditions were plotted to provide insight into seasonal and depth trends. The plots are presented as smoothed kernel density estimates for paired timeseries. The strongest correlations at all sites were to the baseline water temperatures of either the Yakima or Columbia River inflows. Deviations from the baseline trend were observed at multiple sites depending on location and depth. Figures 3.2-1 to 3.2-11 and Tables 3.2-1 to 3.2-9 below illustrate various correlation trends with external conditions including: river conditions, hydraulic conditions, and meteorological conditions.

3.2.1 River Conditions

Although minor thermal stratification at select stations on warm days coincided with low pool levels, the reverse trend was inconsistent. In general, measured water temperatures were not observed to have a distinctive signature relative to MCN forebay stage, with symmetrical bivariate distributions. All sites indicated a strong signal to the incoming flow water temperature of either the Yakima or Columbia River. All sites also exhibited a weak inverse trend for lower water temperature with increased flow; this however is a seasonal trend, and higher flows of the post-freshet period did not coincide with lower relative temperatures.

3.2.1.1 Columbia River Flow and Temperature

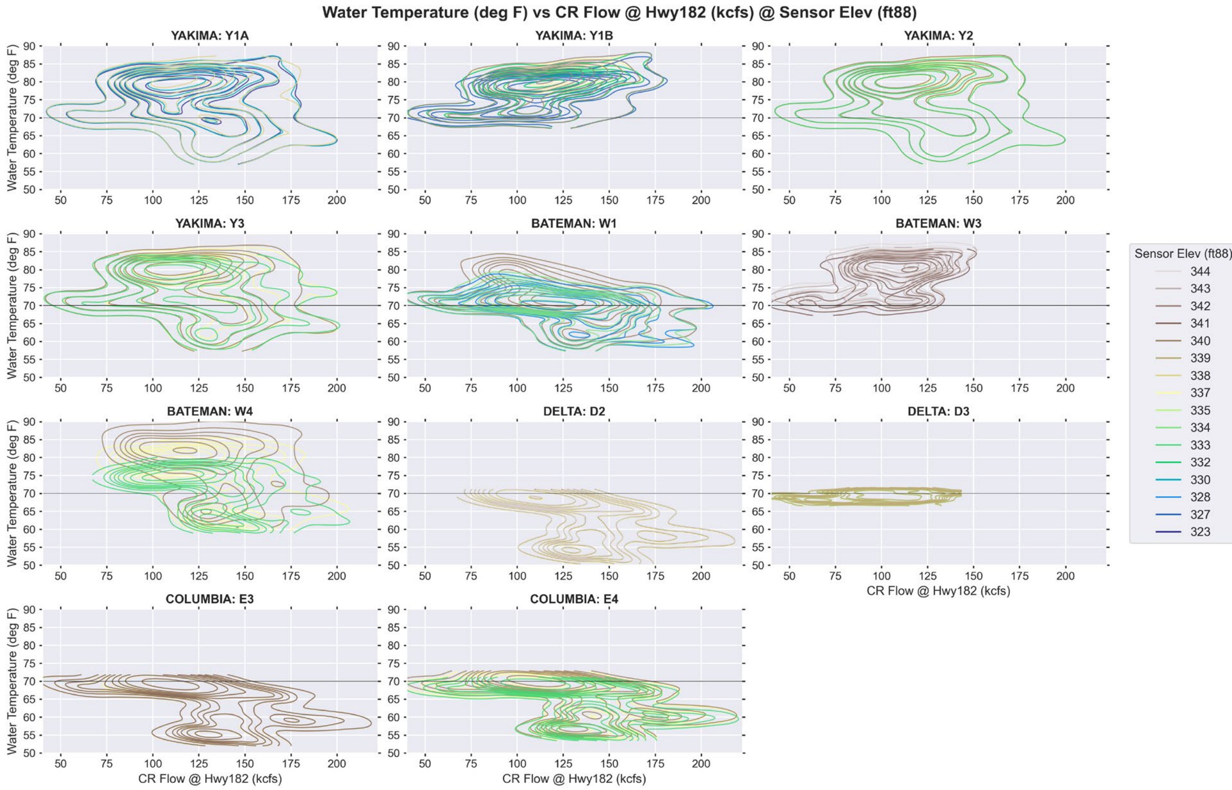

Figure 3.2-1 Water Temperature by Depth vs Columbia River Flow

Table 3.2-1 Spearman Rank Correlation Coefficients for Water Temperature vs CR Flow @ Hwy182 by Sensor@ Elevation

Yakima

Y1A_323	-0.169
Y1A_330	-0.167
Y1A_338	-0.170
Y1B_327	0.355
Y1B_332	0.353
Y1B_337	0.365
Y1B_342	0.368
Y2A_333	-0.156
Y2A_337	-0.156
Y2A_340	-0.155
Y3A_333	-0.288
Y3A_337	-0.224
Y3A_340	-0.187

Bateman

W1A_328	-0.440
W1A_334	-0.424
W1A_340	-0.443
W3B_341	0.327
W3B_343	0.318
W3B_344	0.319
W4A_333	-0.402
W4A_337	-0.334
W4A_340	-0.285

Delta

D2A_337	-0.647
D2A_340	-0.646
D2A_344	-0.645
D3B_335	0.115
D3B_339	0.107

Columbia

E3A_337	-0.652
E3A_341	-0.655
E4A_333	-0.593
E4A_337	-0.589
E4A_340	-0.605

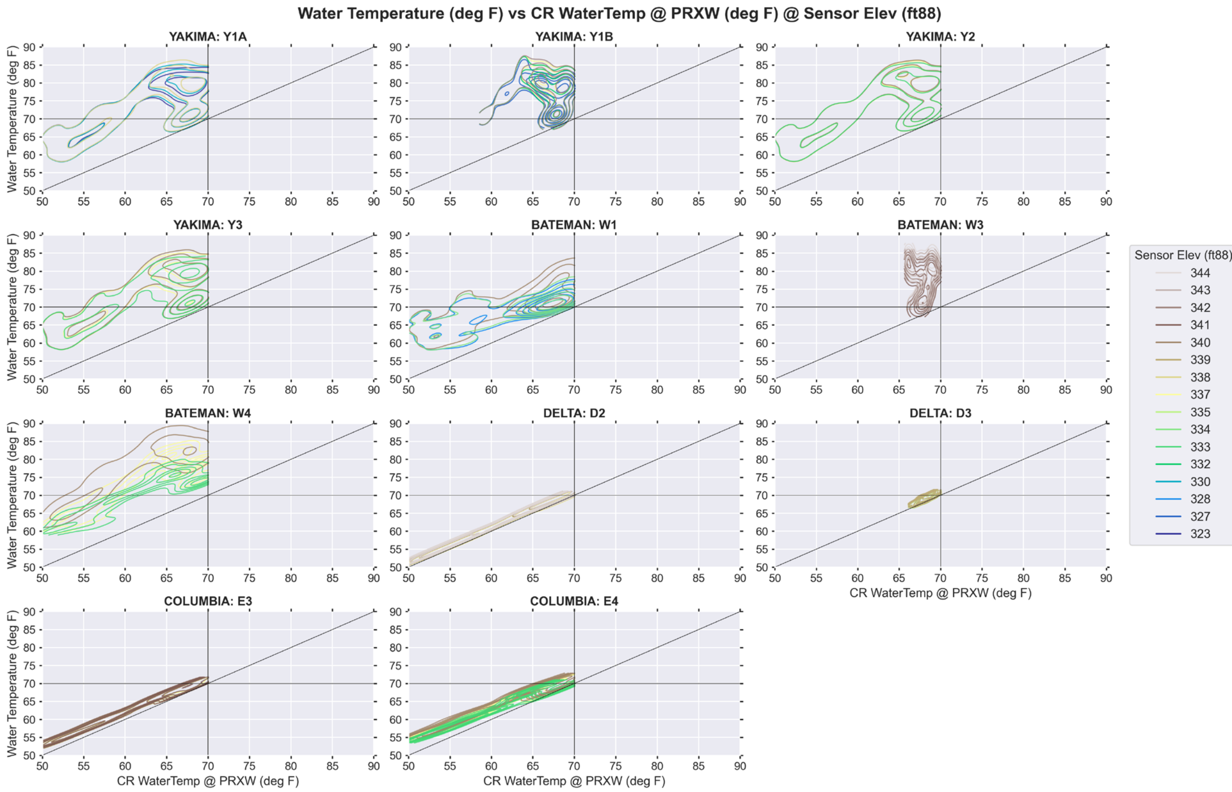

Figure 3.2-2 Water Temperature by Depth vs Columbia River Temperature

Table 3.2-2 Spearman Rank Correlation Coefficients for Water Temperature vs CR Temp @ PRXW by Sensor@ Elevation

Yakima

Y1A_323	0.599
Y1A_330	0.589
Y1A_338	0.589
Y1B_327	-0.052
Y1B_332	-0.060
Y1B_337	-0.082
Y1B_342	-0.093
Y2A_333	0.573
Y2A_337	0.575
Y2A_340	0.573
Y3A_333	0.669
Y3A_337	0.611
Y3A_340	0.586

Bateman

W1A_328	0.769
W1A_334	0.757
W1A_340	0.772
W3B_341	-0.054
W3B_343	-0.019
W3B_344	-0.015
W4A_333	0.756
W4A_337	0.723
W4A_340	0.733

Delta

D2A_337	0.988
D2A_340	0.988
D2A_344	0.988
D3B_335	0.869
D3B_339	0.869

Columbia

E3A_337	0.981
E3A_341	0.980
E4A_333	0.942
E4A_337	0.942
E4A_340	0.949

3.2.1.2 Yakima River Flow and Temperature

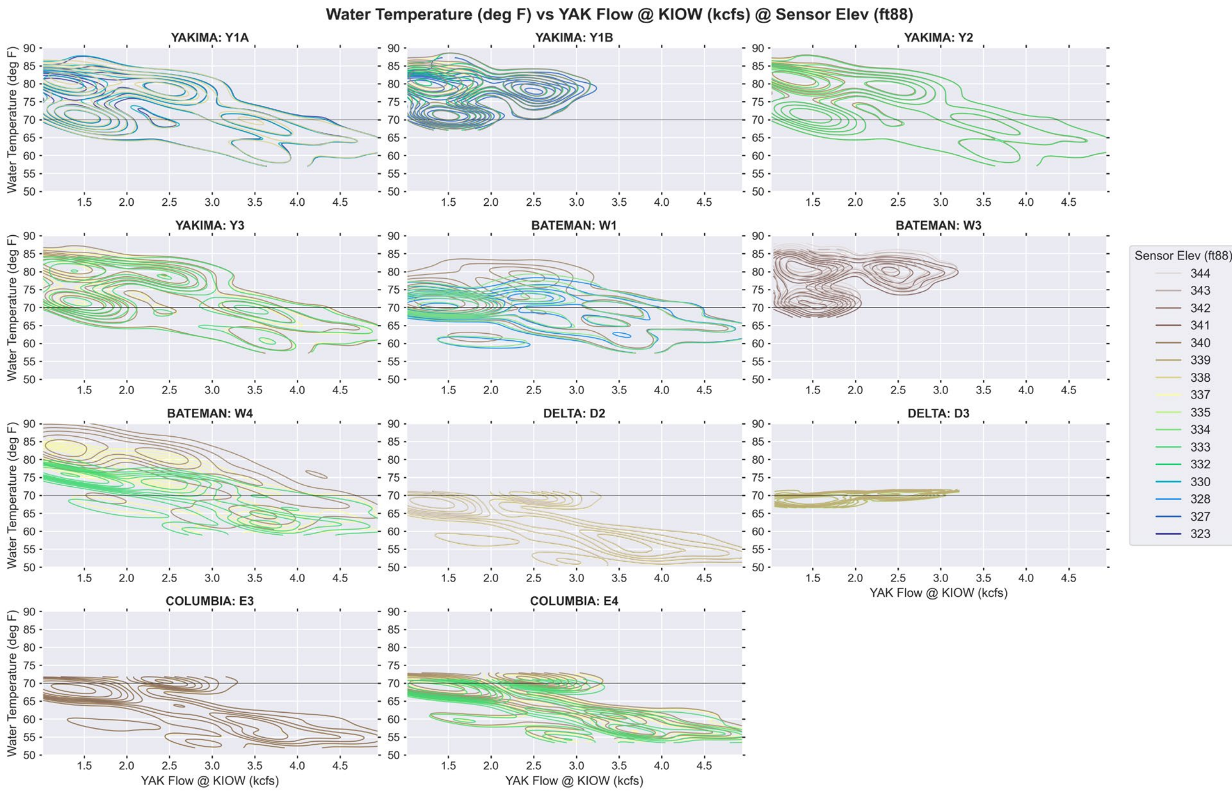

Figure 3.2-3 Water Temperature by Depth vs Yakima River Flow

Table 3.2-3 Spearman Rank Correlation Coefficients for Water Temperature vs Yakima River Flow @ KIOW by Sensor@ Elevation

Yakima

Y1A_323	-0.590
Y1A_330	-0.612
Y1A_338	-0.639
Y1B_327	-0.174
Y1B_332	-0.162
Y1B_337	-0.210
Y1B_342	-0.234
Y2A_333	-0.630
Y2A_337	-0.632
Y2A_340	-0.636
Y3A_333	-0.546
Y3A_337	-0.606
Y3A_340	-0.631

Bateman

W1A_328	-0.336
W1A_334	-0.349
W1A_340	-0.399
W3B_341	-0.074
W3B_343	-0.029
W3B_344	-0.024
W4A_333	-0.852
W4A_337	-0.844
W4A_340	-0.746

Delta

D2A_337	-0.589
D2A_340	-0.589
D2A_344	-0.589
D3B_335	0.602
D3B_339	0.605

Columbia

E3A_337	-0.539
E3A_341	-0.541
E4A_333	-0.585
E4A_337	-0.579
E4A_340	-0.569

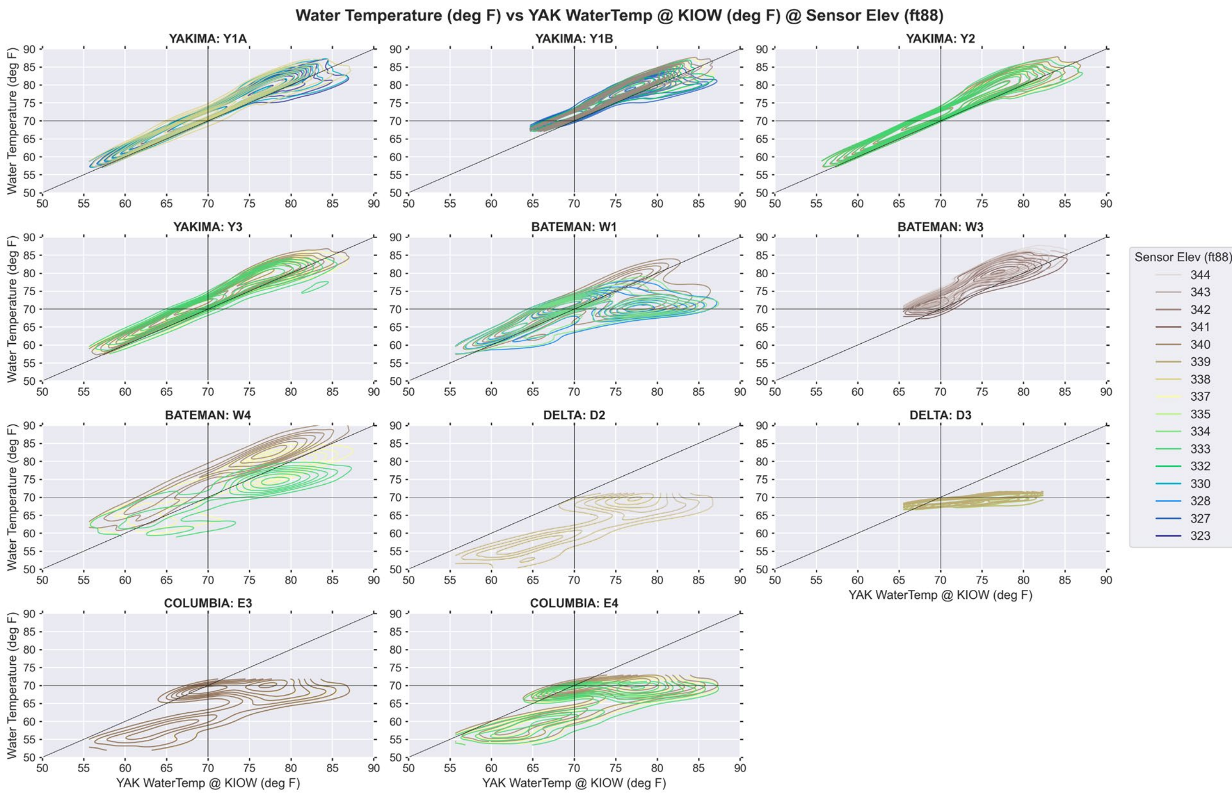

Figure 3.2-4 Water Temperature by Depth vs. Yakima River Temperature

Table 3.2-4 Spearman Rank Correlation Coefficients for Water Temperature vs Yakima River Temperature @ KIOW by Sensor@ Elevation

Yakima

Y1A_323	0.963
Y1A_330	0.966
Y1A_338	0.965
Y1B_327	0.870
Y1B_332	0.913
Y1B_337	0.948
Y1B_342	0.963
Y2A_333	0.961
Y2A_337	0.970
Y2A_340	0.971
Y3A_333	0.906
Y3A_337	0.951
Y3A_340	0.965

Bateman

W1A_328	0.581
W1A_334	0.607
W1A_340	0.747
W3B_341	0.854
W3B_343	0.898
W3B_344	0.932
W4A_333	0.804
W4A_337	0.859
W4A_340	0.931

Delta

D2A_337	0.733
D2A_340	0.732
D2A_344	0.731
D3B_335	0.759
D3B_339	0.766

Columbia

E3A_337	0.654
E3A_341	0.663
E4A_333	0.715
E4A_337	0.736
E4A_340	0.742

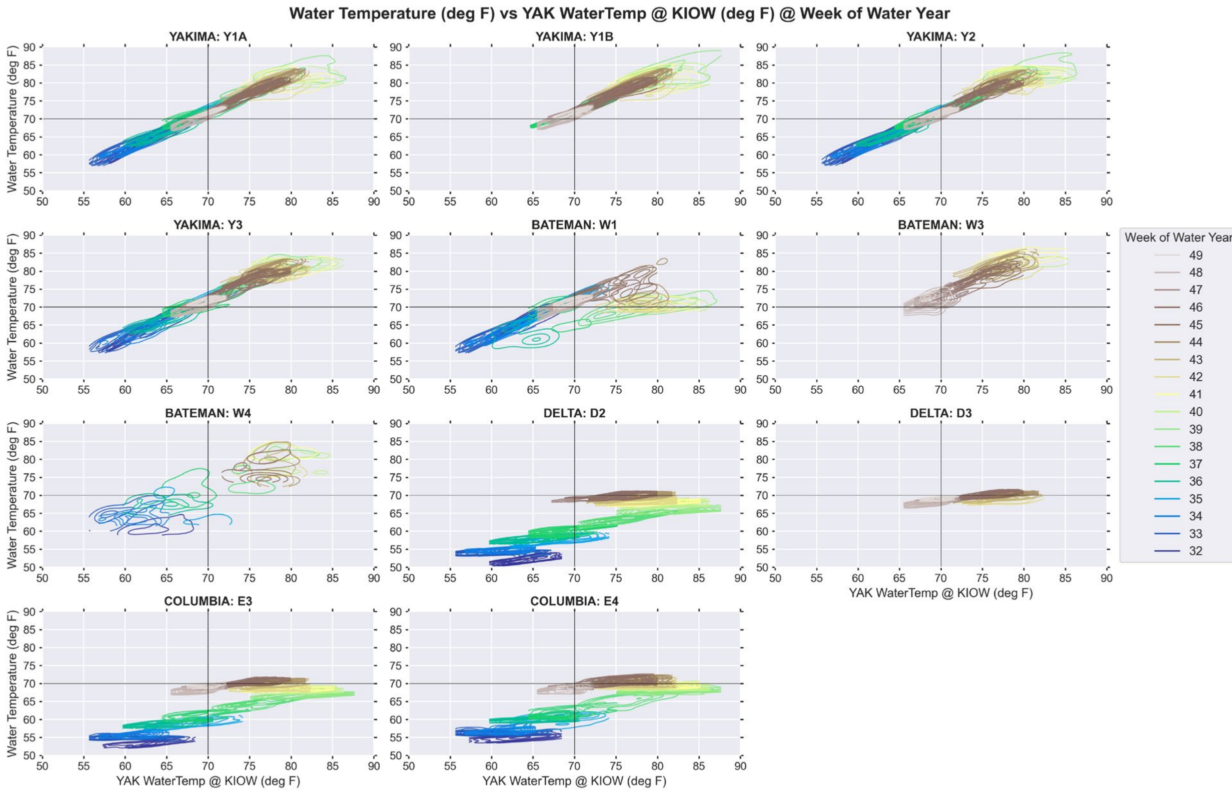

Figure 3.2-5 Water Temperature vs. Yakima River Temperature by Week

3.2.1.3 MCN Forebay Elevation

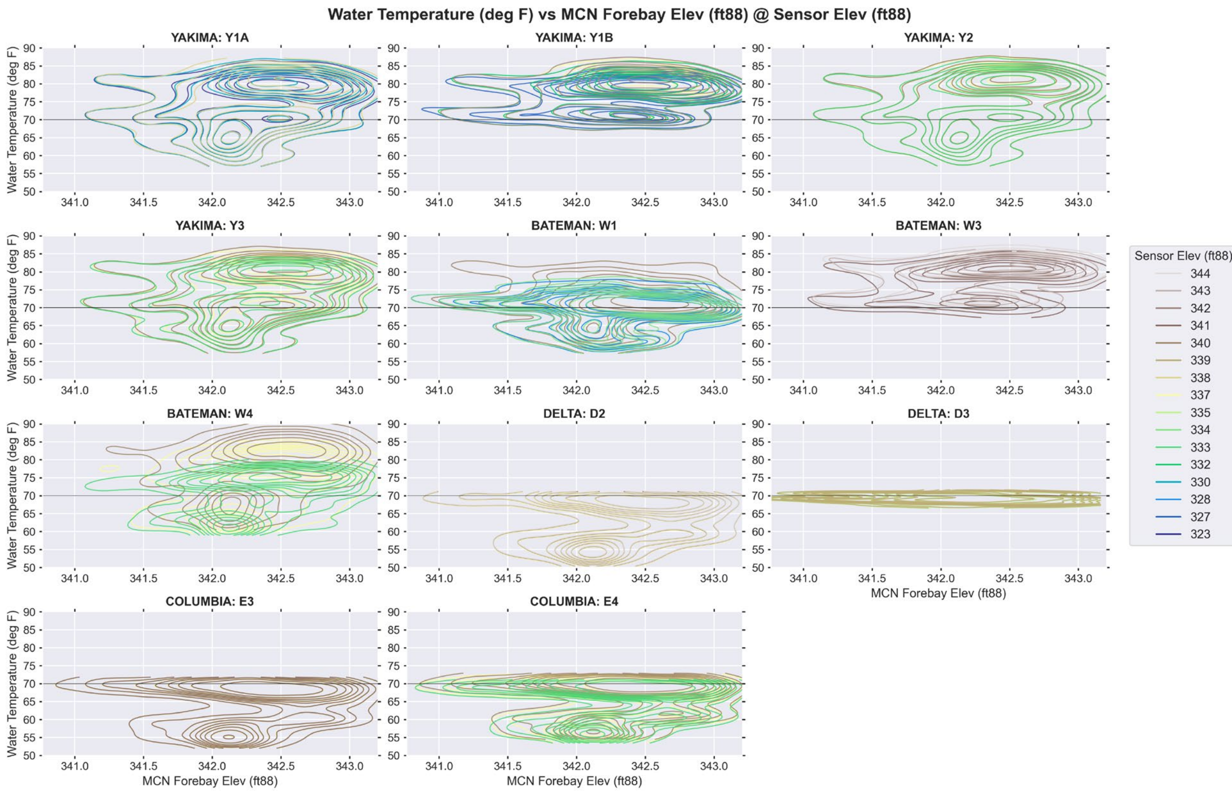

Figure 3.2-6 Water Temperature by Depth vs MCN Forebay Elevation

Table 3.2-5 Spearman Rank Correlation Coefficients for Water Temperature vs MCN Forebay by Sensor@ Elev.

Yakima

Y1A_323	0.256
Y1A_330	0.265
Y1A_338	0.276
Y1B_327	0.124
Y1B_332	0.125
Y1B_337	0.129
Y1B_342	0.133
Y2A_333	0.281
Y2A_337	0.273
Y2A_340	0.275
Y3A_333	0.254
Y3A_337	0.262
Y3A_340	0.272

Bateman

W1A_328	-0.066
W1A_334	-0.049
W1A_340	0.038
W3B_341	0.193
W3B_343	0.212
W3B_344	0.220
W4A_333	0.346
W4A_337	0.293
W4A_340	0.299

Delta & Columbia

D2A_337	0.048
D2A_340	0.047
D2A_344	0.046
D3B_335	-0.140
D3B_339	-0.132

E3A_337	-0.016
E3A_341	-0.011
E4A_333	0.052
E4A_337	0.057
E4A_340	0.039

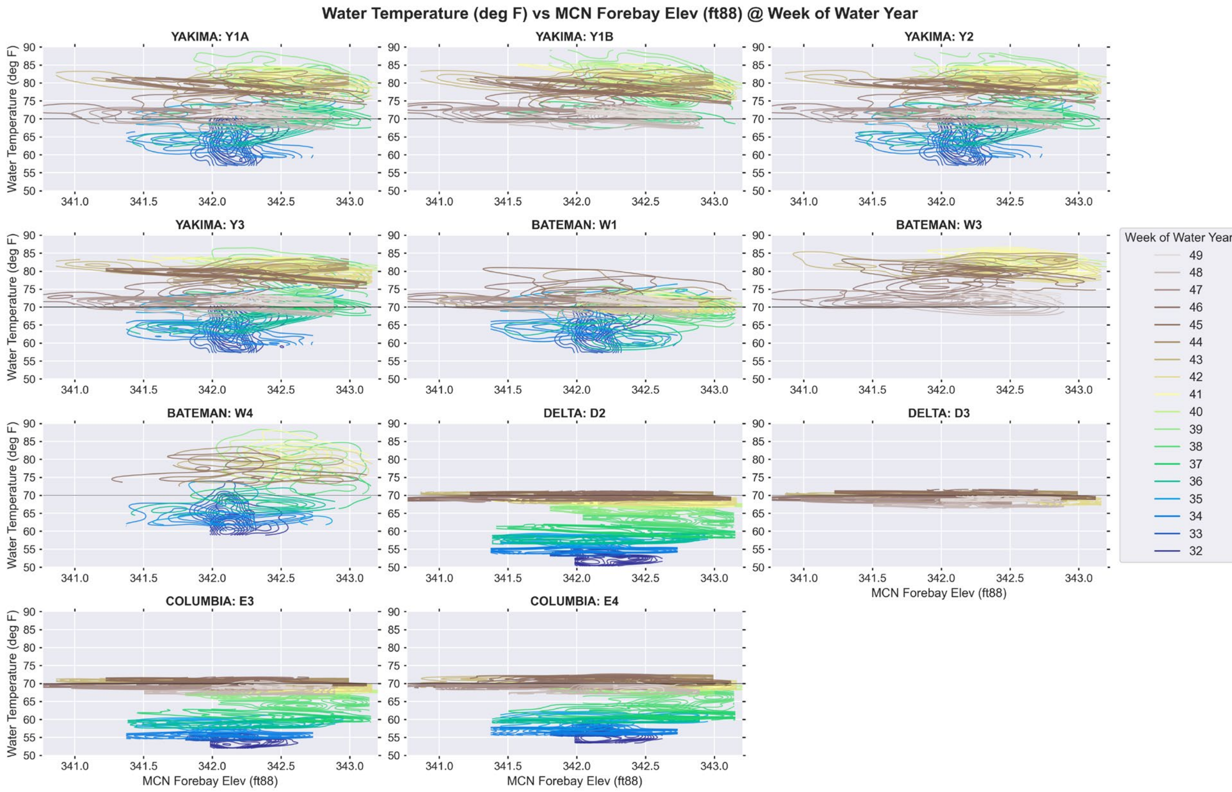

Figure 3.2-7 Water Temperature vs MCN Forebay Elevation by Week

3.2.2 Hydraulic Conditions

As would be expected, temperature sensors set in deeper water were found to remain cooler than those in shallow water. However, the temperature range distribution at most sites was found to be consistent regardless of depth, indicating equivalent diurnal heating and cooling trends at many stations. With the exception of higher local velocities and unit-discharge associated with the spring freshet and cooler incoming river baseline temperatures, they do not appear to be strongly corelated with water temperature. Flow mixing patterns between the cooler Columbia water in the delta and the warmer Yakima water on the west and north sides of Bateman Island do appear to influence water temperatures. Flow mixing and water temperature patterns in the delta are inconsistent, depending upon both the flow and temperature ratios as well as the MCN downstream stage. In general, the shallow areas on the south west side of Bateman Island did not appear to mix with Columbia River water most likely due to the causeway.

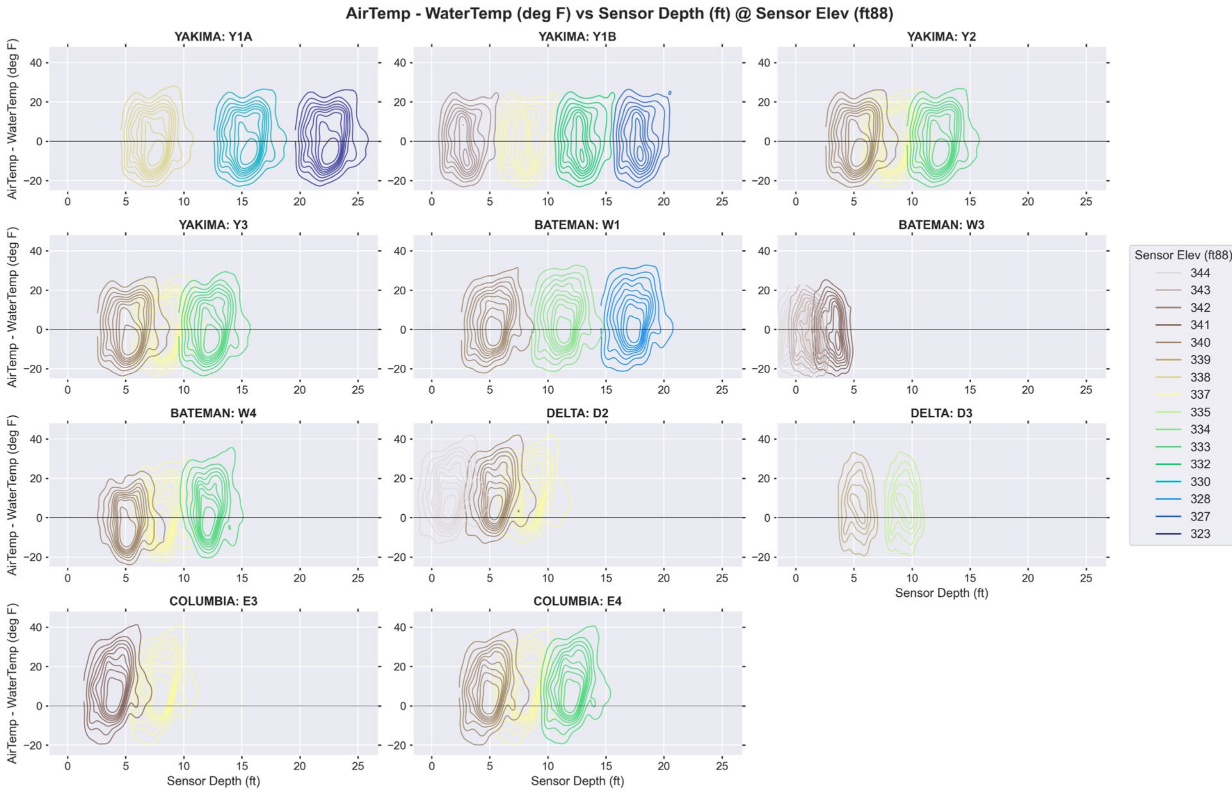

Figure 3.2-8 (Air Temp – Water Temp) vs. Sensor Depth

Table 3.2-6 Spearman Rank Correlation Coefficients for Water Temperature vs Water Depth by Sensor@ Elev.

Yakima

Y1A_323	-0.218
Y1A_330	-0.216
Y1A_338	-0.221
Y1B_327	0.342
Y1B_332	0.340
Y1B_337	0.352
Y1B_342	0.357
Y2A_333	-0.173
Y2A_337	-0.176
Y2A_340	-0.174
Y3A_333	-0.285
Y3A_337	-0.224
Y3A_340	-0.187

Bateman

W1A_328	-0.467
W1A_334	-0.451
W1A_340	-0.444
W3B_341	0.398
W3B_343	0.395
W3B_344	0.397
W4A_333	-0.368
W4A_337	-0.313
W4A_340	-0.265

Delta

D2A_337	-0.657
D2A_340	-0.657
D2A_344	-0.656
D3B_335	0.058
D3B_339	0.057

Columbia

E3A_337	-0.668
E3A_341	-0.668
E4A_333	-0.592
E4A_337	-0.589
E4A_340	-0.608

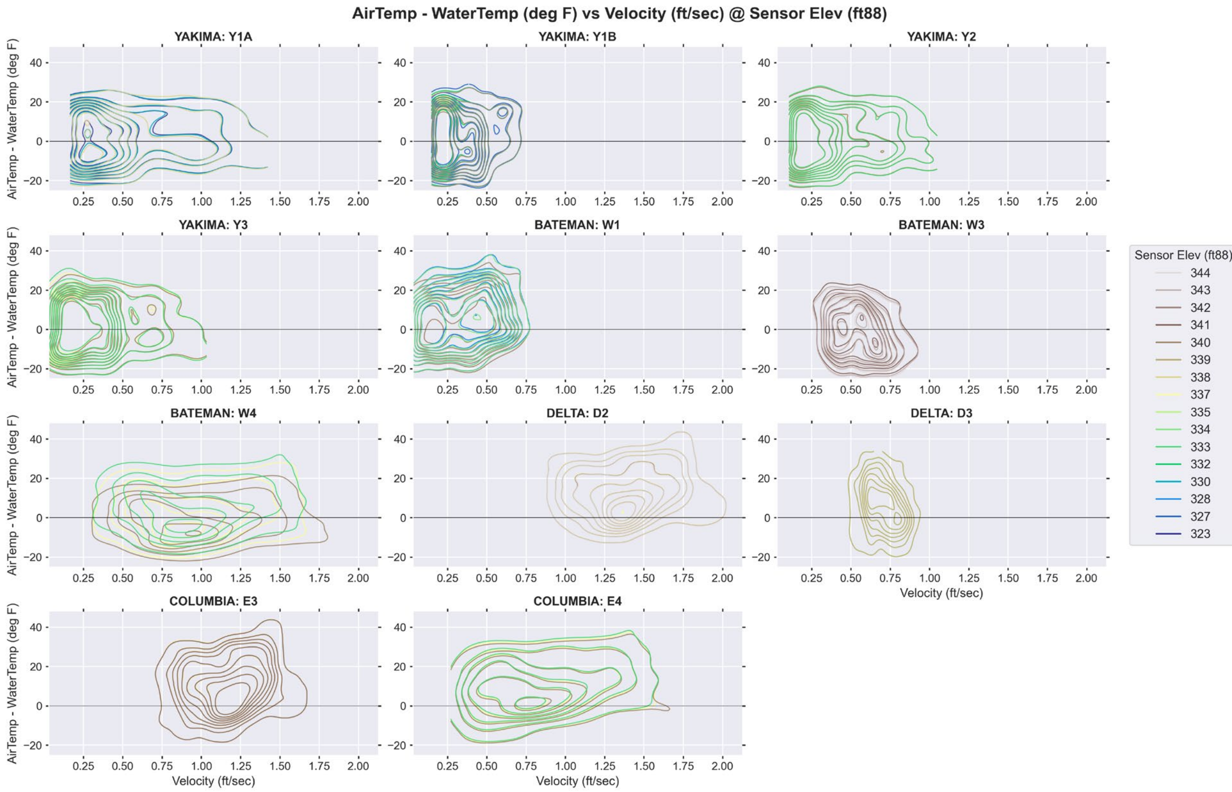

Figure 3.2-9 (Air Temp – Water Temp) vs. Velocity

Table 3.2-7 Spearman Rank Correlation Coefficients for Water Temperature vs Velocity by Sensor@ Elev.

Yakima

Y1A_323	-0.755
Y1A_330	-0.769
Y1A_338	-0.788
Y1B_327	-0.468
Y1B_332	-0.473
Y1B_337	-0.509
Y1B_342	-0.522
Y2A_333	-0.777
Y2A_337	-0.782
Y2A_340	-0.784
Y3A_333	-0.734
Y3A_337	-0.750
Y3A_340	-0.768

Bateman

W1A_328	-0.050
W1A_334	-0.019
W1A_340	0.068
W3B_341	0.371
W3B_343	0.367
W3B_344	0.368
W4A_333	-0.441
W4A_337	-0.372
W4A_340	-0.321

Delta

D2A_337	-0.626
D2A_340	-0.626
D2A_344	-0.625
D3B_335	0.066
D3B_339	0.059

Columbia

E3A_337	-0.659
E3A_341	-0.662
E4A_333	-0.636
E4A_337	-0.633
E4A_340	-0.650

3.2.3 Meteorological Conditions

While water temperature was found to be positively correlated with air-temperature with a lagged diurnal pattern, the bivariate distributions were often symmetrical, except for shallow sensors at sites W1 and W4. Sites with a strong Columbia River influence were less correlated with air temperature. Solar radiation was not found to be correlated with water temperature trends at any of the sites, with symmetrical diurnal distributions.

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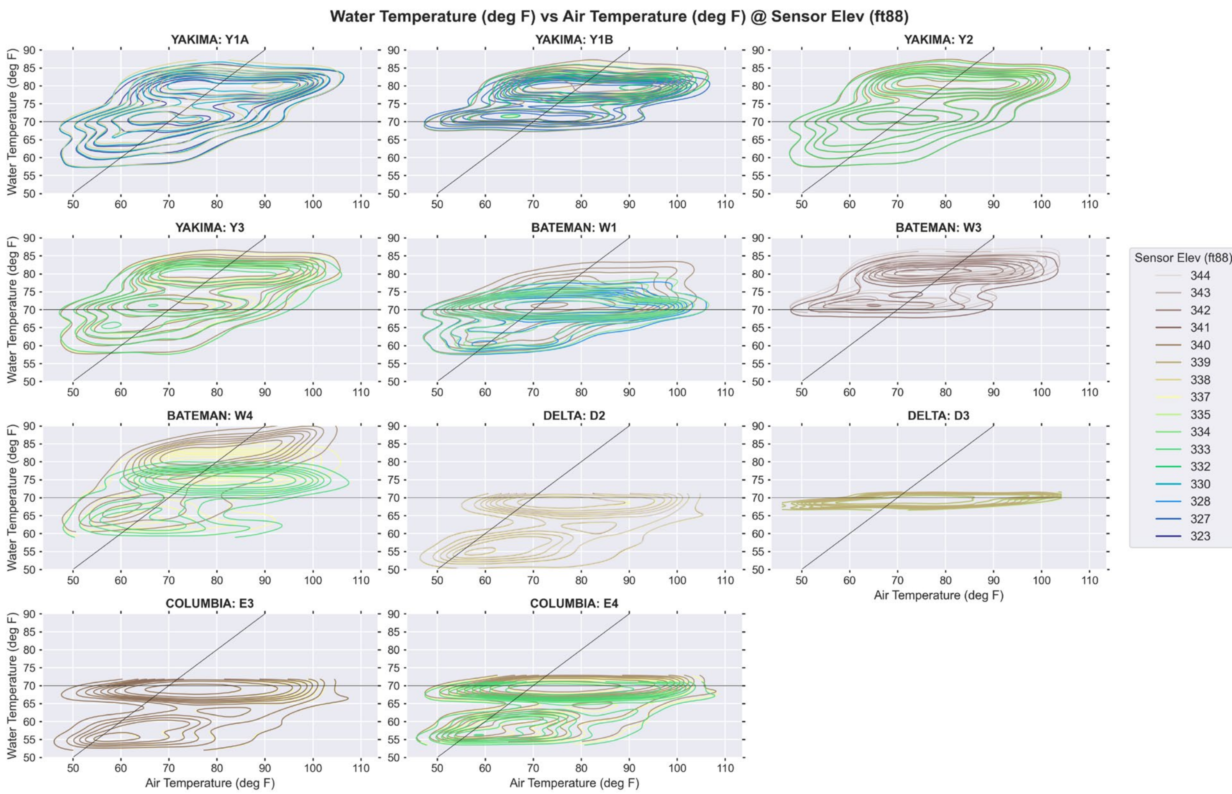

Figure 3.2-10 Water Temperature vs. Air Temperature

Table 3.2-8 Spearman Rank Correlation Coefficients for Water Temperature vs Air Temperature by Sensor@ Elevation

Yakima

Y1A_323	0.580
Y1A_330	0.558
Y1A_338	0.534
Y1B_327	0.380
Y1B_332	0.425
Y1B_337	0.424
Y1B_342	0.442
Y2A_333	0.549
Y2A_337	0.553
Y2A_340	0.555
Y3A_333	0.499
Y3A_337	0.535
Y3A_340	0.554

Bateman

W1A_328	0.335
W1A_334	0.362
W1A_340	0.490
W3B_341	0.440
W3B_343	0.482
W3B_344	0.504
W4A_333	0.401
W4A_337	0.465
W4A_340	0.680

Delta

D2A_337	0.407
D2A_340	0.406
D2A_344	0.403
D3B_335	0.392
D3B_339	0.411

Columbia

E3A_337	0.318
E3A_341	0.332
E4A_333	0.347
E4A_337	0.361
E4A_340	0.394

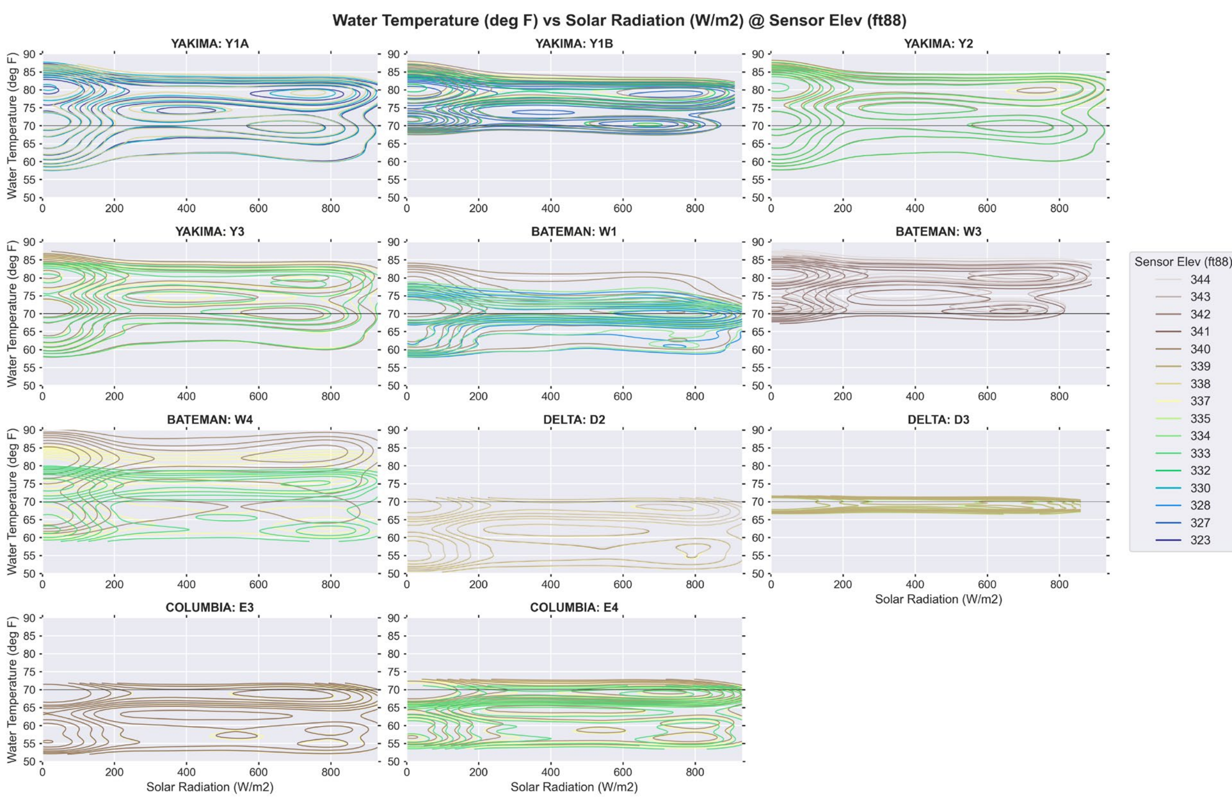

Figure 3.2-11 Water Temperature vs. Solar Radiation

Table 3.2-9 Spearman Rank Correlation Coefficients for Water Temperature vs Solar Radiation by Sensor@ Elevation

Yakima

Y1A_323	-0.087
Y1A_330	-0.108
Y1A_338	-0.112
Y1B_327	-0.095
Y1B_332	-0.132
Y1B_337	-0.171
Y1B_342	-0.165
Y2A_333	-0.084
Y2A_337	-0.101
Y2A_340	-0.097
Y3A_333	-0.092
Y3A_337	-0.100
Y3A_340	-0.087

Bateman

W1A_328	-0.179
W1A_334	-0.153
W1A_340	-0.094
W3B_341	0.012
W3B_343	-0.015
W3B_344	-0.044
W4A_333	-0.002
W4A_337	-0.007
W4A_340	0.044

Delta

D2A_337	-0.098
D2A_340	-0.099
D2A_344	-0.103
D3B_335	-0.136
D3B_339	-0.121

Columbia

E3A_337	-0.111
E3A_341	-0.101
E4A_333	-0.061
E4A_337	-0.084
E4A_340	-0.097

3.3 Reach Conditions

This section includes bivariate the distribution plots from section 3.2 above, grouped by reach. In addition, paired plots of intra site and sensor distributions were developed to summarize cross-correlation between the datasets.

3.3.1 Yakima

The intra-site/sensor distribution plots in Figures 3.3-1 to 3.3-8 for the three Yakima stations illustrate a high degree of correlation between all sites and depths with a bimodal signal as per Figure 2.1-5 above. One exception is the deepest Y3 sensor which trended cooler than the upstream Y1 & Y2 sites due to intermittent mixing of cooler Delta water during discrete times.

The Y3 timeseries indicated some rapid temperature changes at depth which appear to result from a flow pattern change which increases the mixing of delta water (see Figure 3.1-12 above). Comparison between the lower Yakima (Y3) and south delta (D2) sites, illustrates a positive seasonal correlation with a bimodal distribution associated with the spring freshet and summer hydroperiods. With a stronger influence from the Yakima River baseline temperature, site Y3 consistently trended warmer than D2 at all depths with a nominal ~10°F offset. While no strong signal is present to indicate coincident water temperatures between D2 and Y3, areas of the bivariate distribution where Y3 bias is towards the 1:1 line may be indicative of increased flow mixing.

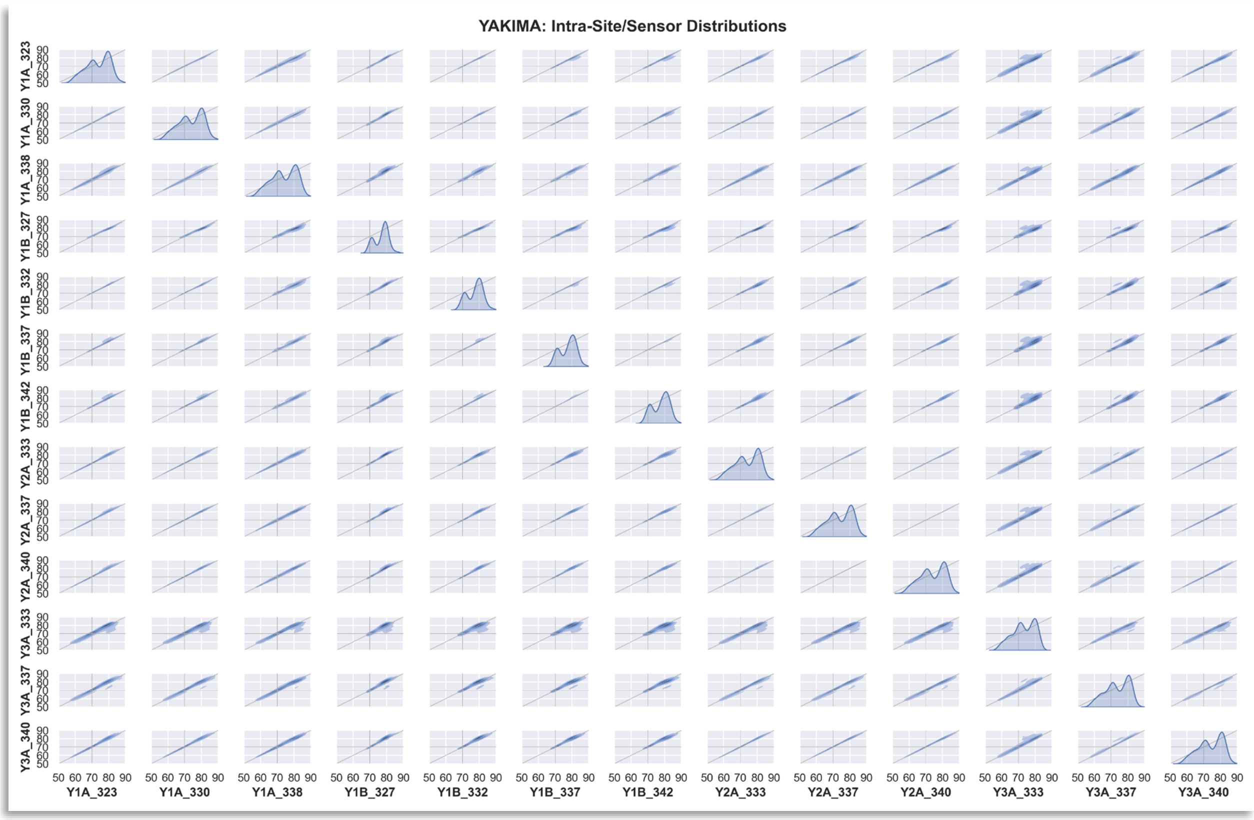

Figure 3.3-1 Intra-Site/Sensor Temperature Distributions for Yakima Reach

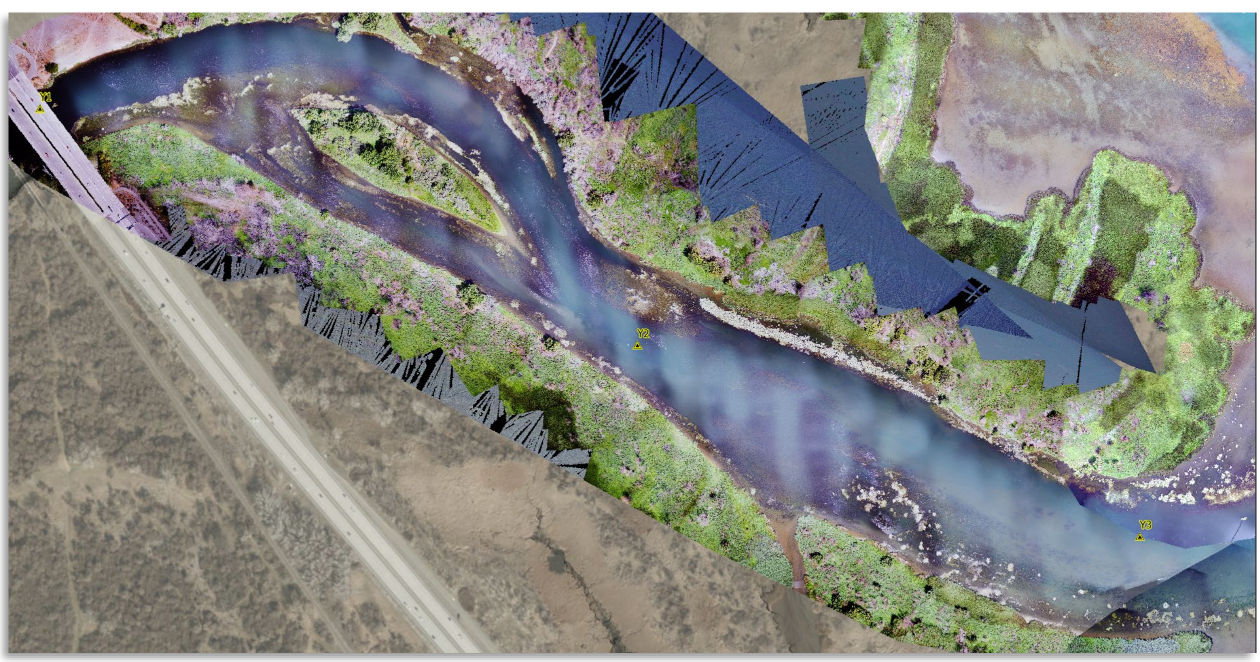

Figure 3.3-2 UAS Orthophoto at lower Yakima on 10-Aug-2021.

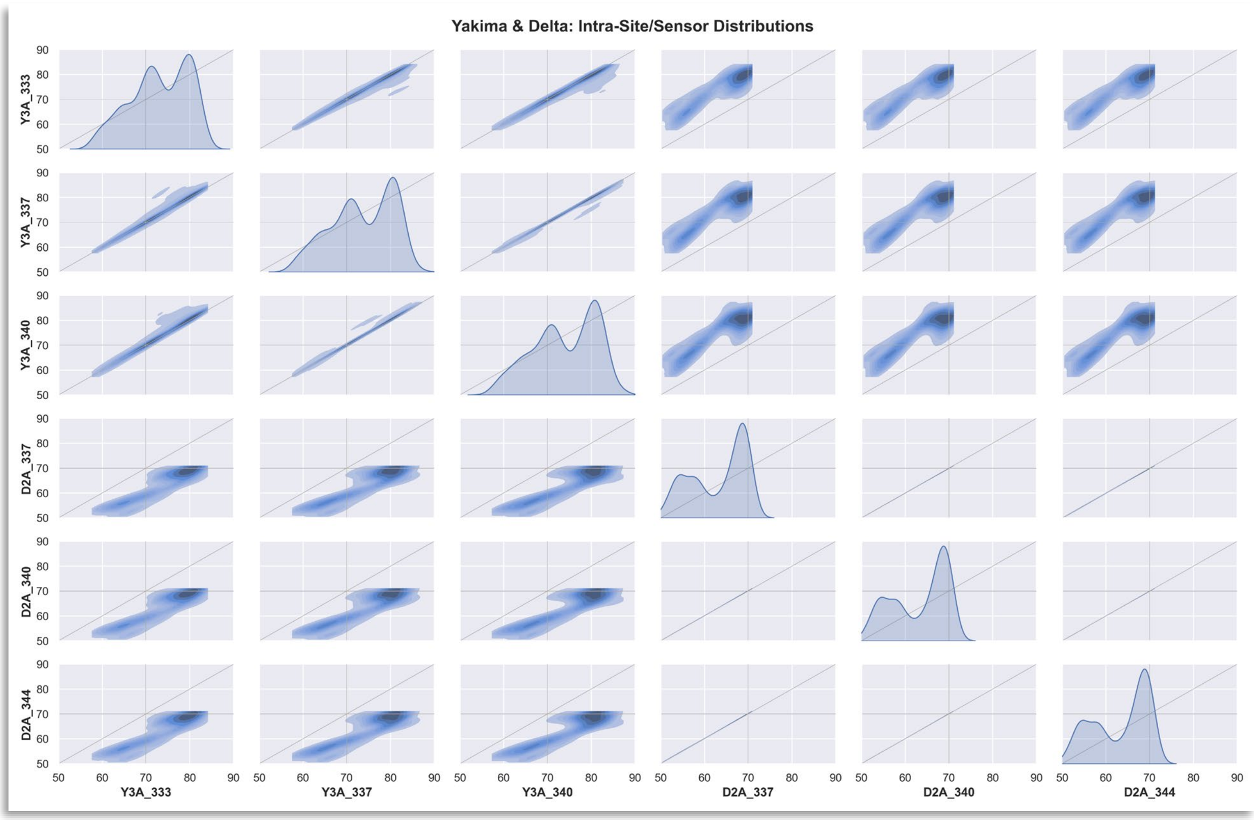

Figure 3.3-3 Intra-Site/Sensor Temperature Distributions for Delta (D2) & Lower Yakima (Y3) sites.

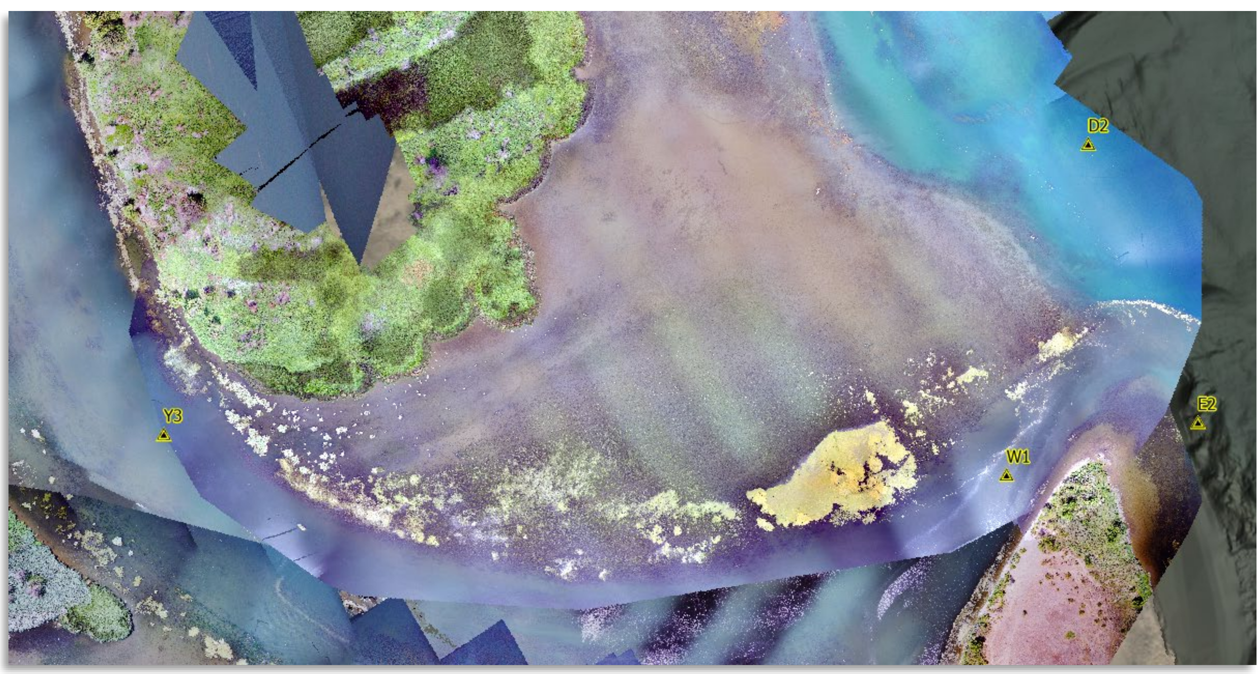

Figure 3.3-4 UAS Orthophoto at lower Yakima on 10-Aug-2021.

3.3.1.1 Yakima - Y1A

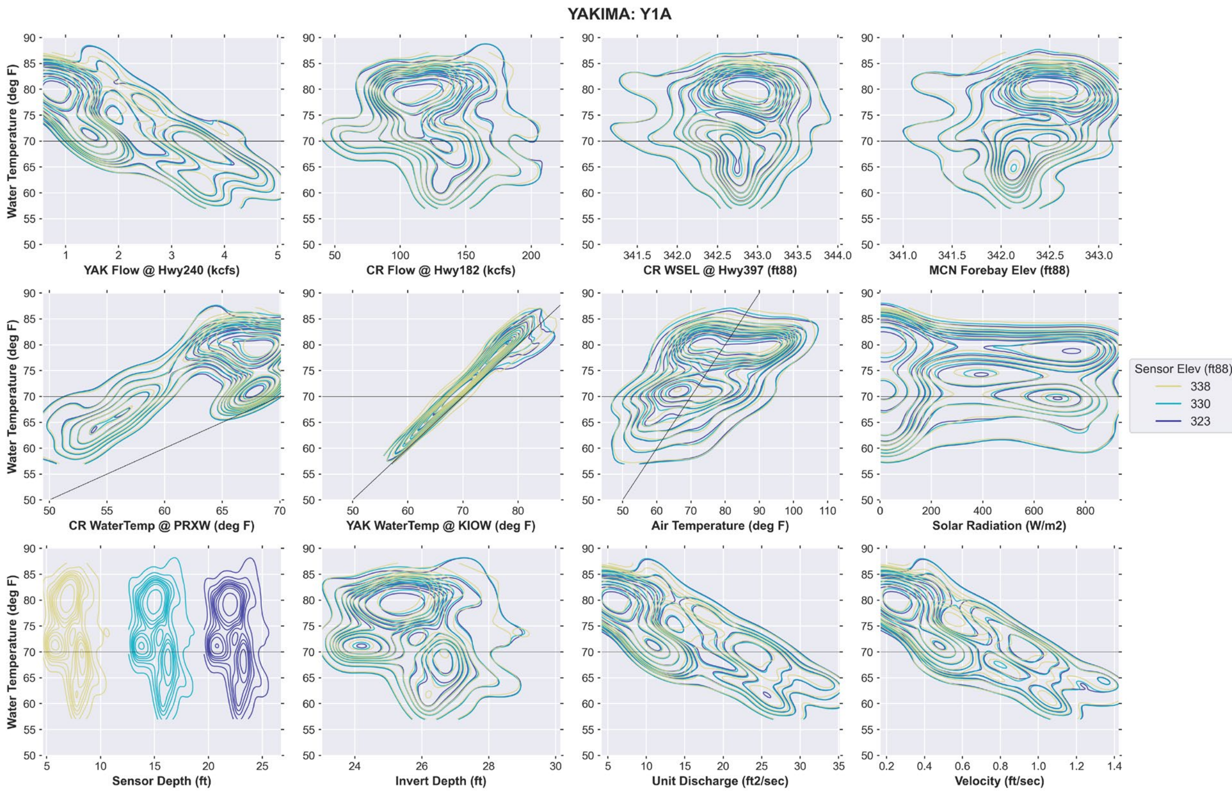

Figure 3.3-5Trends Summary – Yakima Reach – Y1A

3.3.1.2 Yakima - Y1B

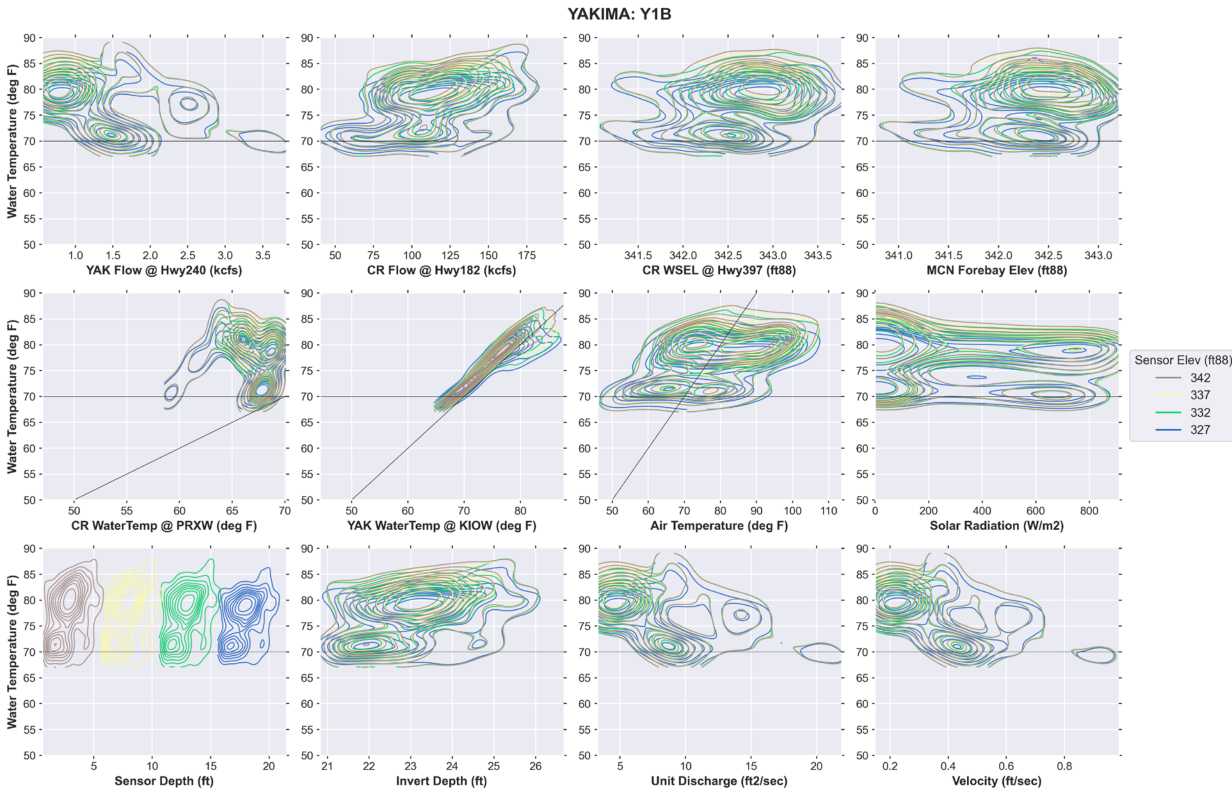

Figure 3.3-6 Trends Summary – Yakima Reach – Y1B

3.3.1.3 Yakima – Y2

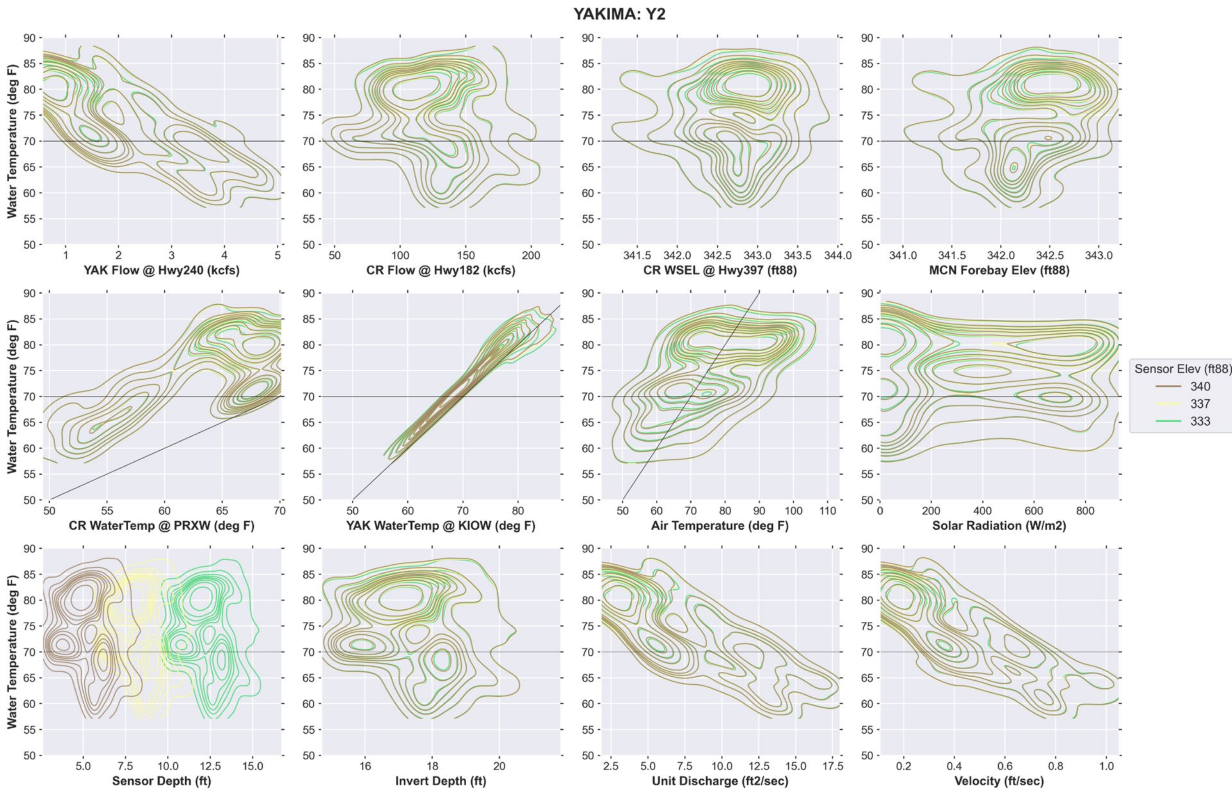

Figure 3.3-7 Trends Summary – Yakima Reach – Y2

3.3.1.4 Yakima – Y3

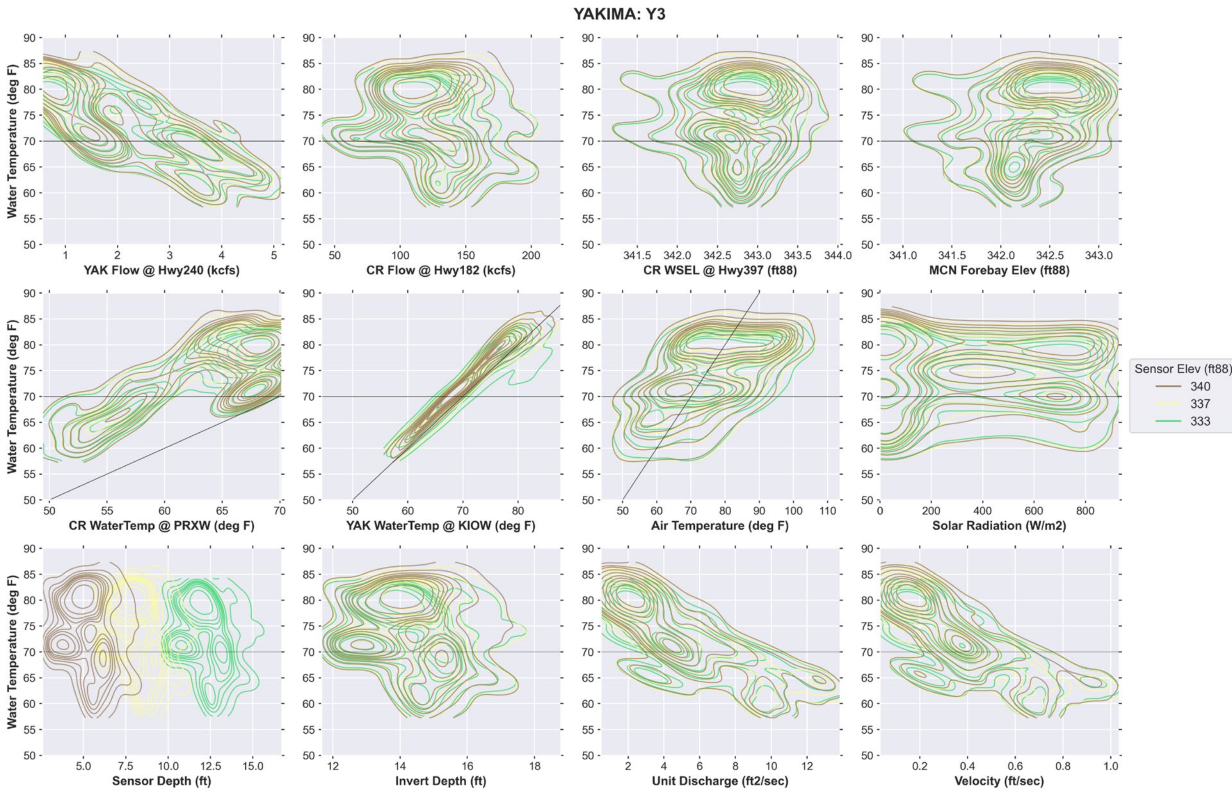

Figure 3.3-8 Trends Summary – Yakima Reach – Y3

3.3.2 Bateman

The intra-site/sensor distribution plots for the three Bateman stations (Figures 3.3-9 to 3.3-17) illustrate as much as 10°F coincident variability between stations and depths. The coincident variability was least between the W4 sensors below elevation 337 feet, and W3 sensors. Site W1 was consistently cooler than sites W3 and W4 with a unimodal distribution and median of ~70°F at all depths.

Comparisons between the North Bateman W1 site and the Lower Yakima Y3 sites indicates a high degree of correlation during the spring (first Y3 mode ~71°F), with W1 bias as much as 10°F cooler during the summer (second Y3 mode ~80°F)

Comparisons between the South Bateman W4 and the East Bateman E4 sites indicates a positive seasonal correlation with a bimodal distribution at each site indicative of the spring freshet and summer hydroperiods. As also evident in the timeseries, W4 consistently trended warmer than E4 at all depths. For the deepest sensors at 333' elevation , W4 generally maintained a ~5°F offset from E4. For the shallowest sensors at 340' elevation, the W4 offset trend was ~10°F.

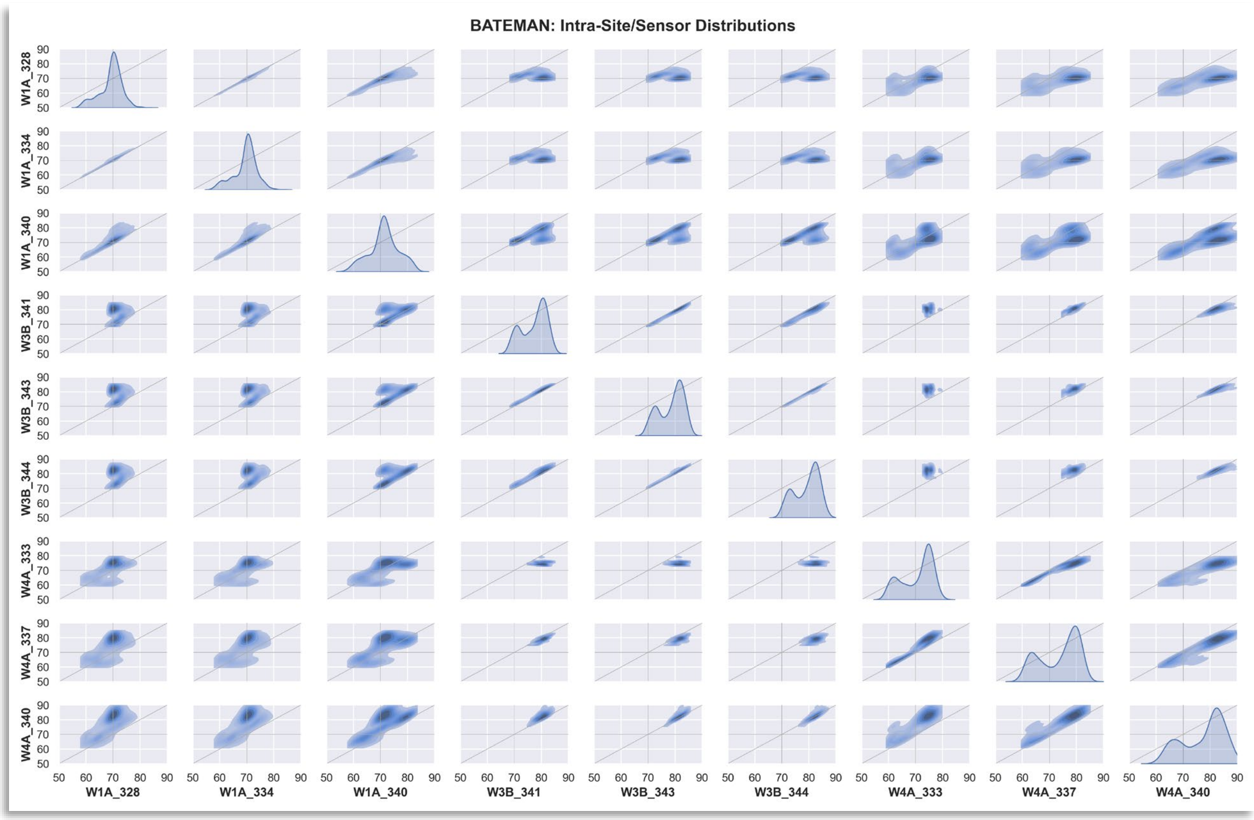

Figure 3.3-9 Intra-Site/Sensor Temperature Distributions for Bateman Reach

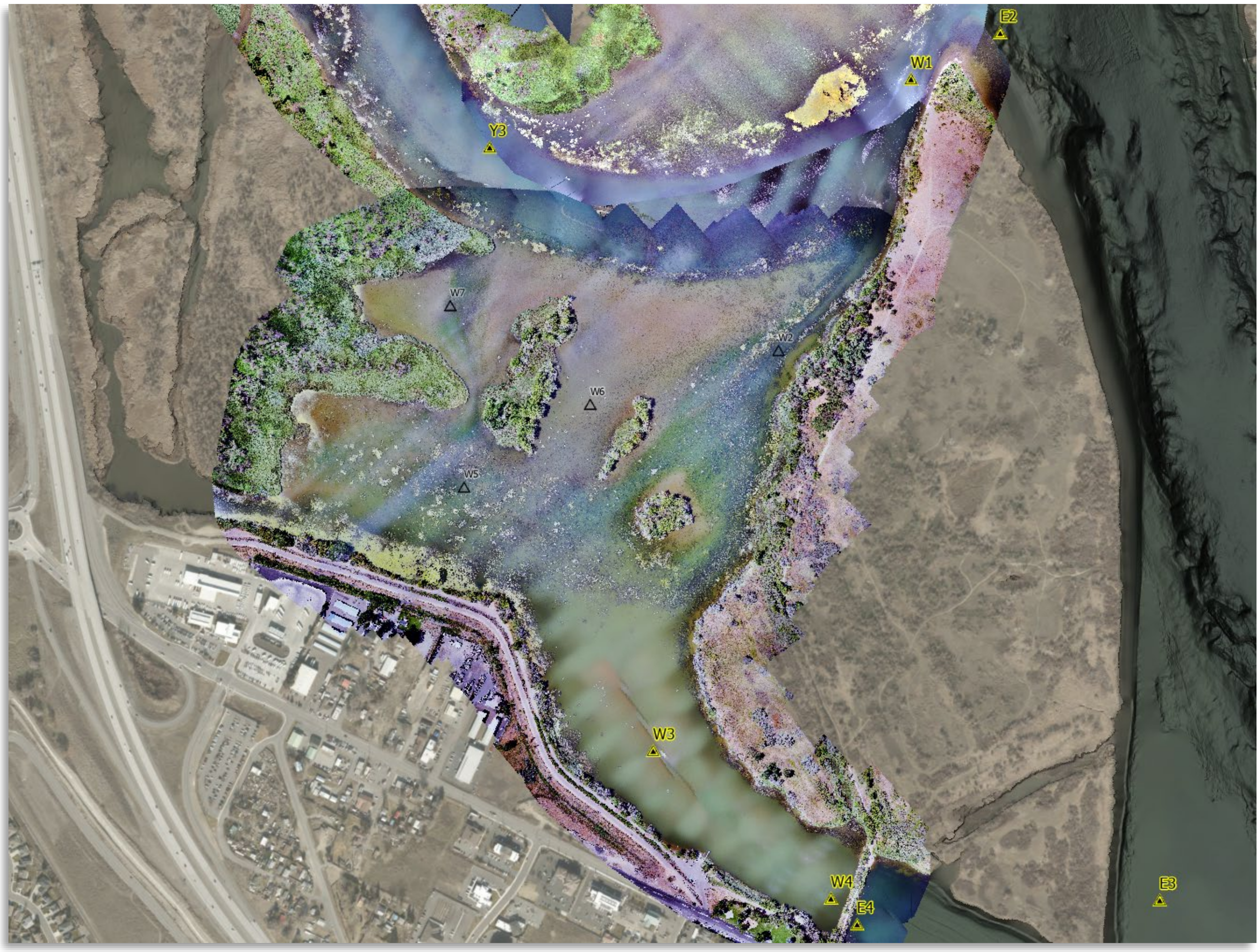

Figure 3.3-10 UAS Orthophoto at Bateman Island on 10-Aug-2021.

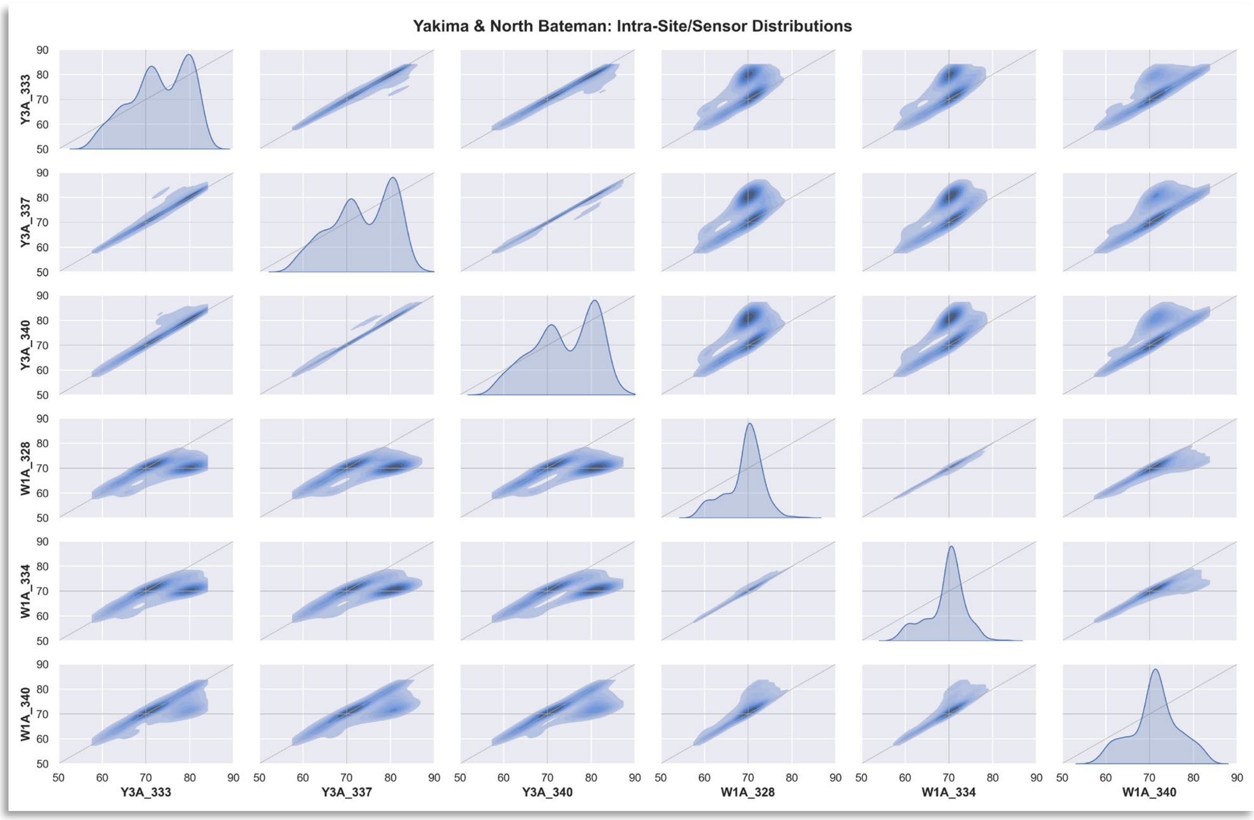

Figure 3.3-11 Intra-Site/Sensor Temperature Distributions for North Bateman (W1) and Lower Yakima (Y3) sites.

Figure 3.3-12 UAS Orthophoto at north end of Bateman Island on 10-Aug-2021.

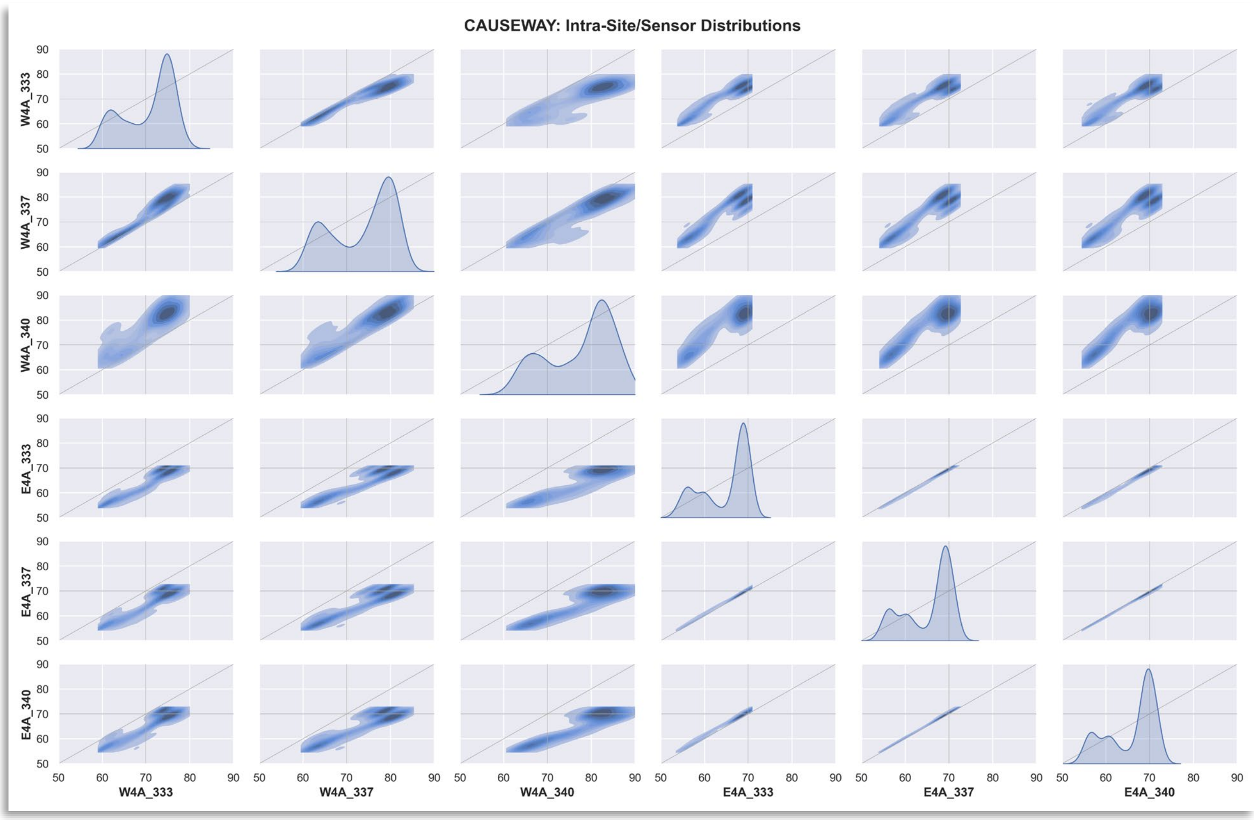

Figure 3.3-13 Intra-Site/Sensor Temperature Distributions at Causeway for Bateman W4 and Columbia E4

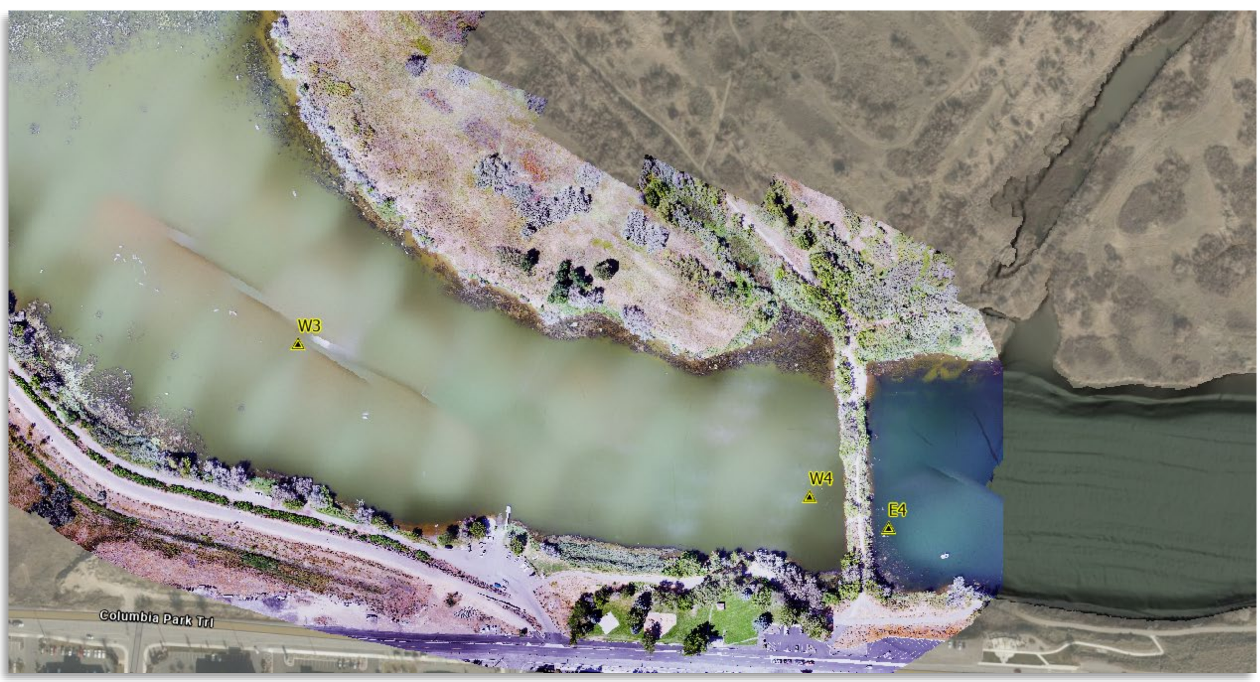

Figure 3.3-14 UAS Orthophoto at causeway on 10-Aug-2021.

3.3.2.1 Bateman – W1

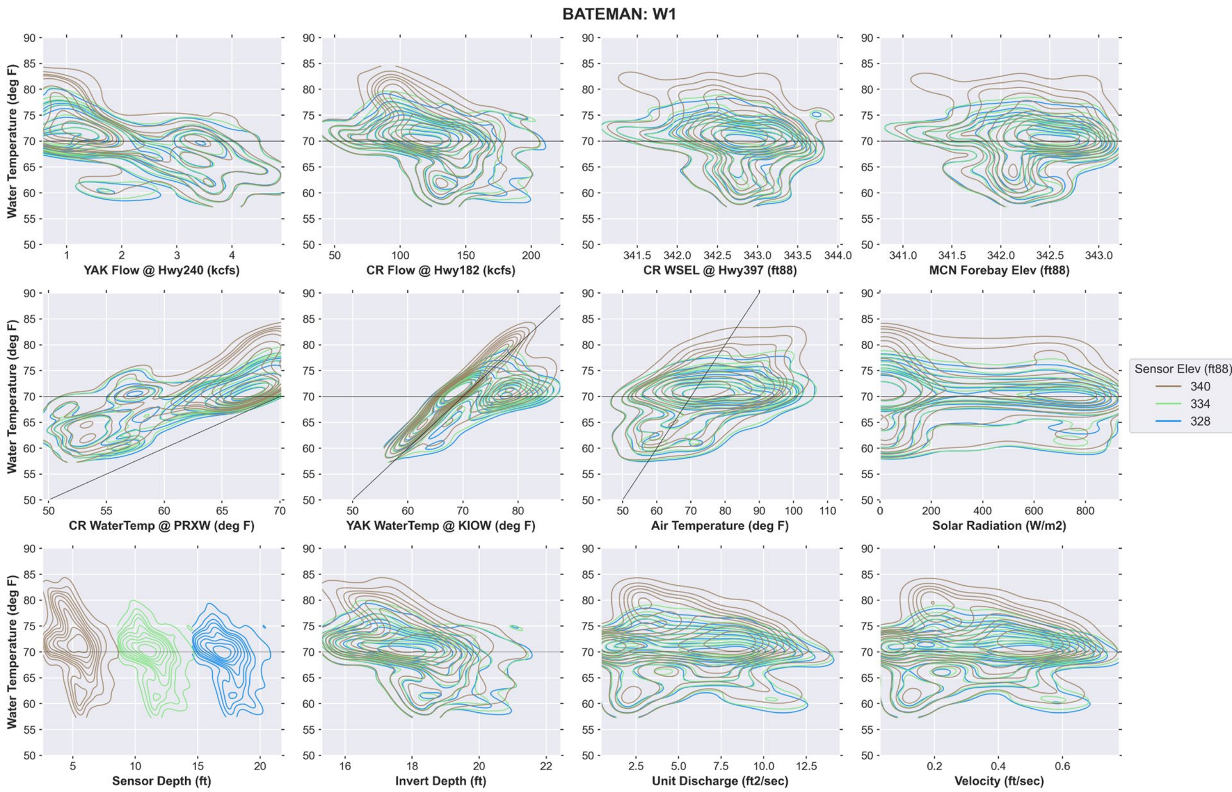

Figure 3.3-15 Trends Summary – Bateman Reach – W1

3.3.2.2 Bateman – W3

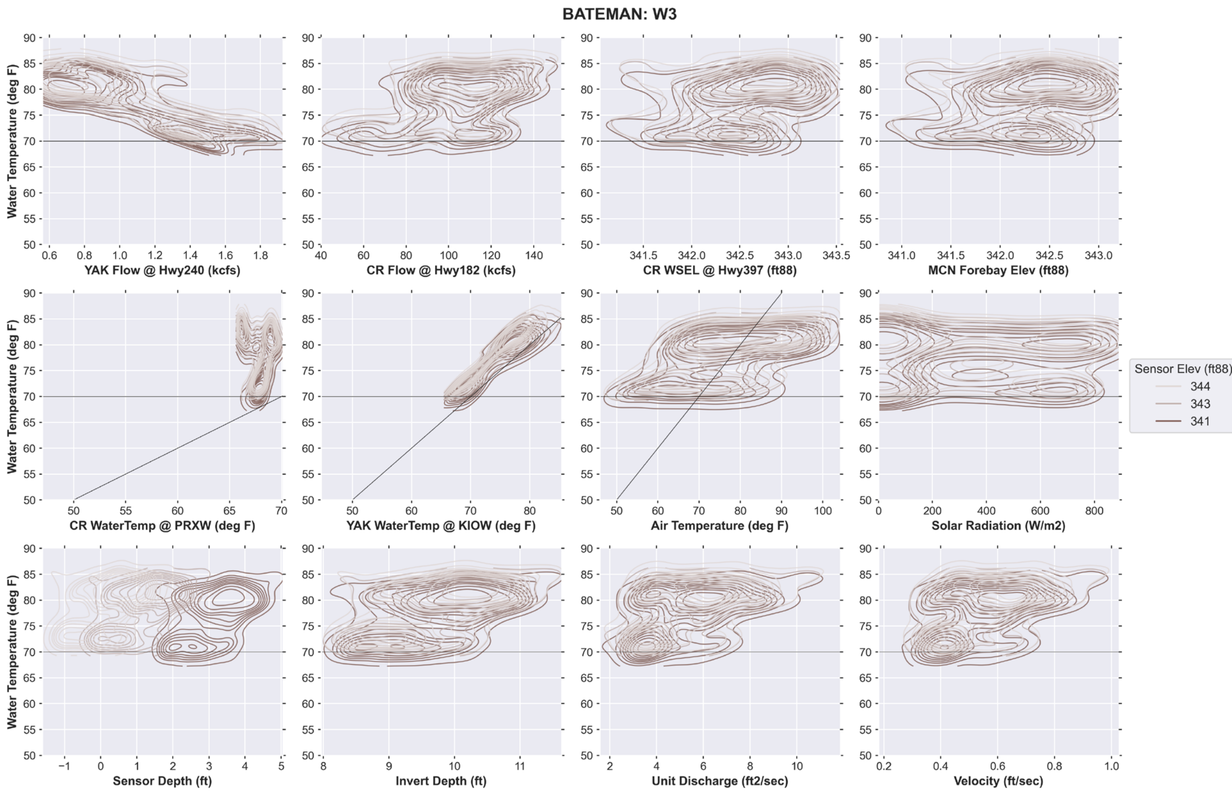

Figure 3.3-16 Trends Summary – Bateman Reach – W3

3.3.2.3 Bateman – W4

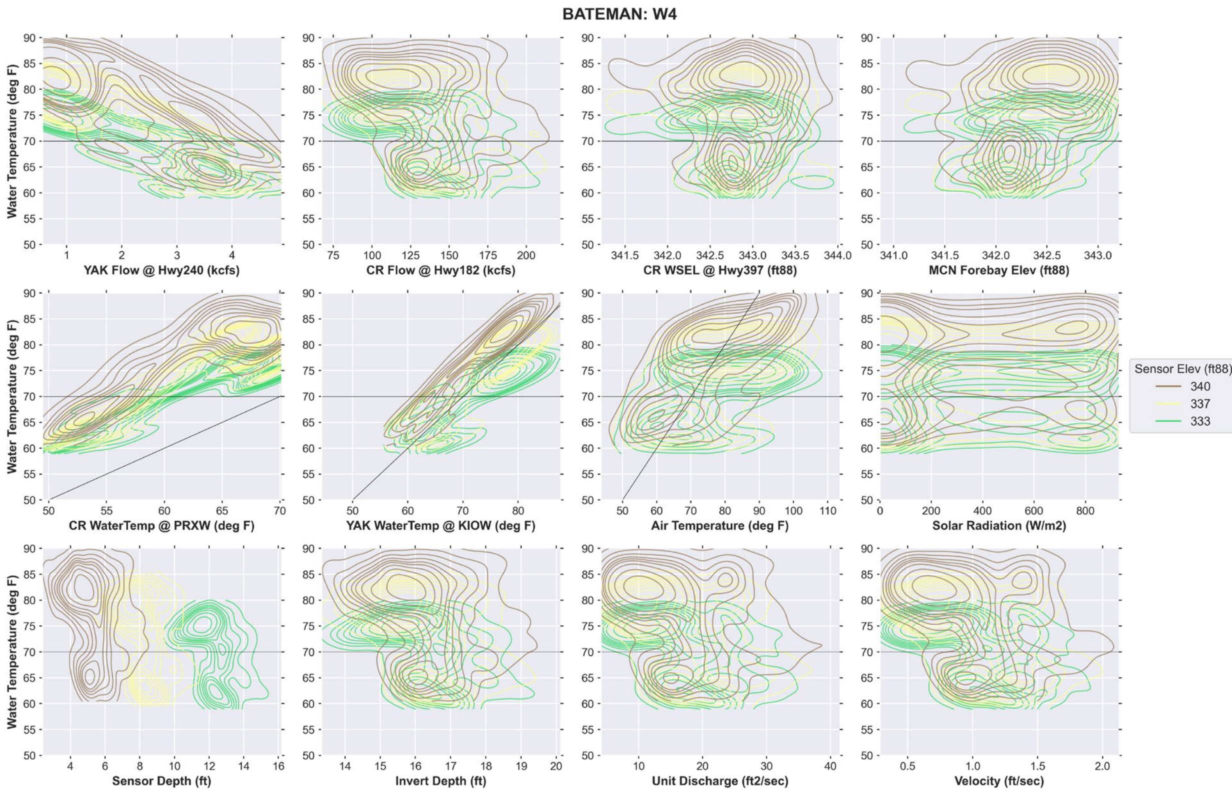

Figure 3.3-17 Trends Summary – Bateman Reach – W4

3.3.3 Delta & Columbia

The intra-site/sensor distribution plots for the Delta (D2 & D3) and Columbia reach (E3 & E4) stations indicates a high degree of correlation with very low variance (Figures 3.3-18 to 3.3-23). All four of these stations are strongly influenced by the baseline Columbia River water temperature and exhibit limited deviations due to other external factors.

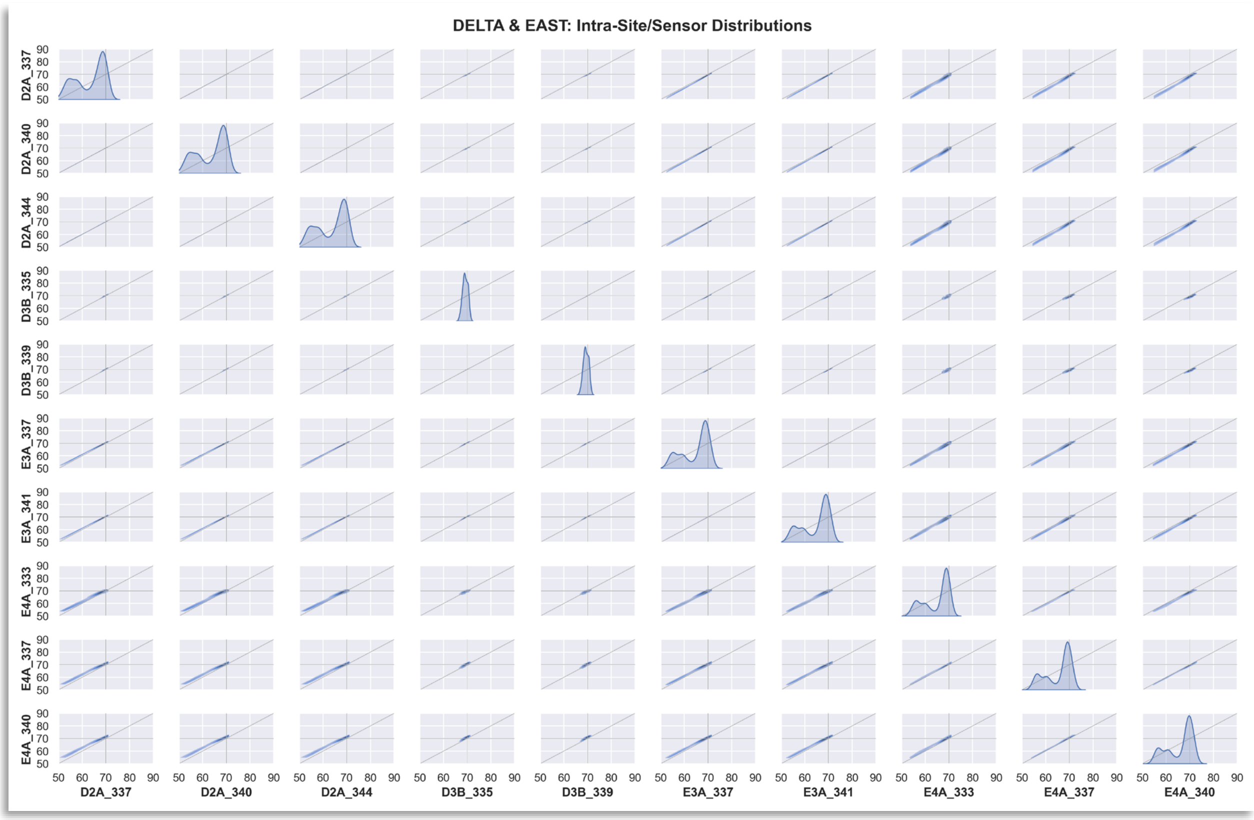

Figure 3.3-18 Intra-Site/Sensor Temperature Distributions for Delta & Columbia Reaches

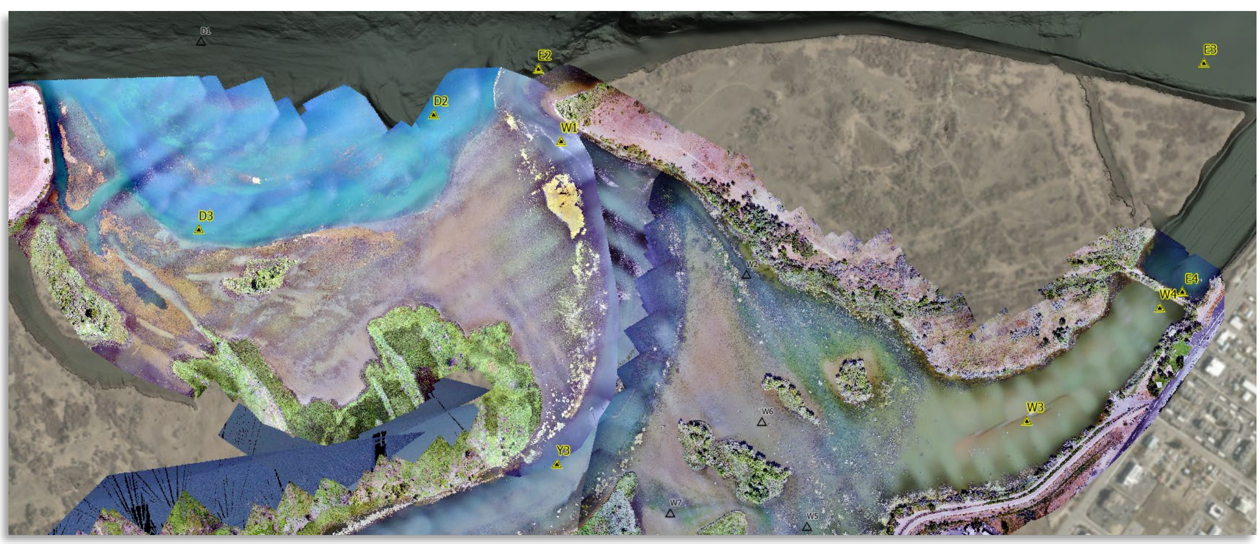

Figure 3.3-19 UAS Orthophoto at Delta and Columbia Reaches on 10-Aug-2021.

3.3.3.1 Delta – D2

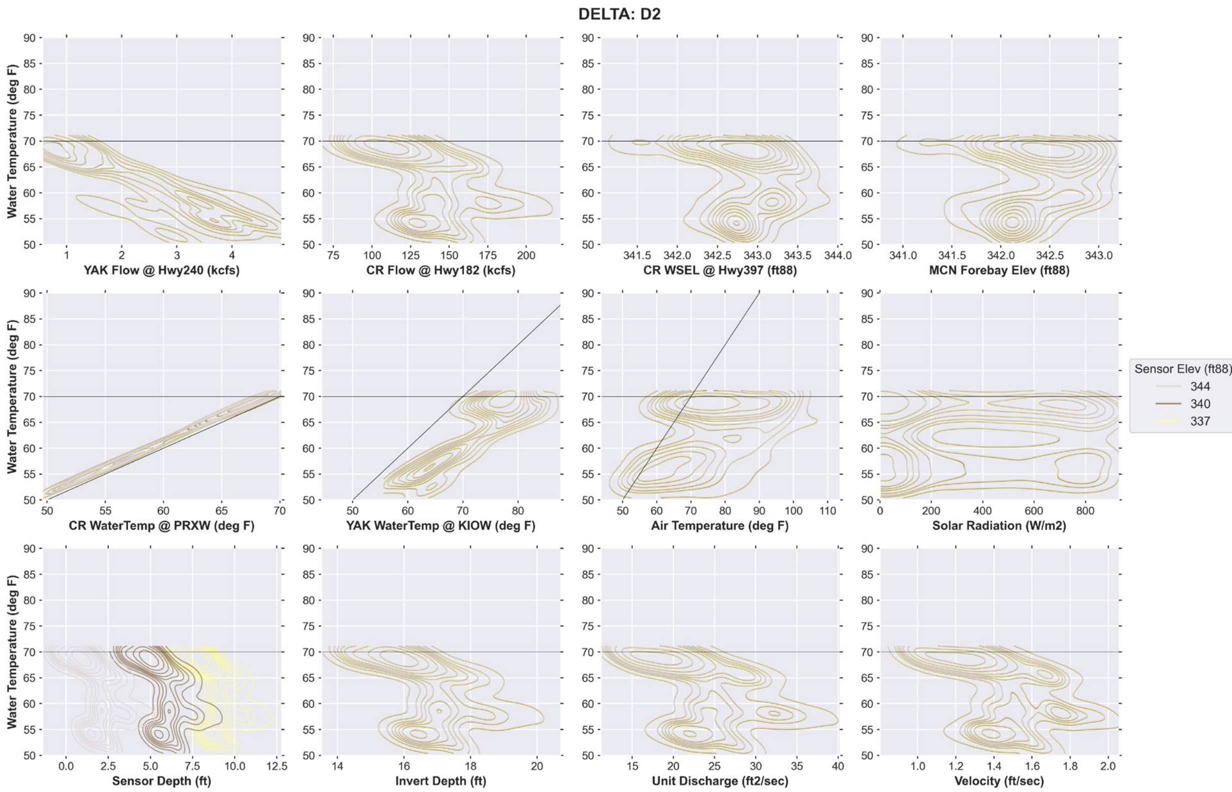

Figure 3.3-20 Trends Summary – Delta Reach – D2

3.3.3.2 Delta – D3

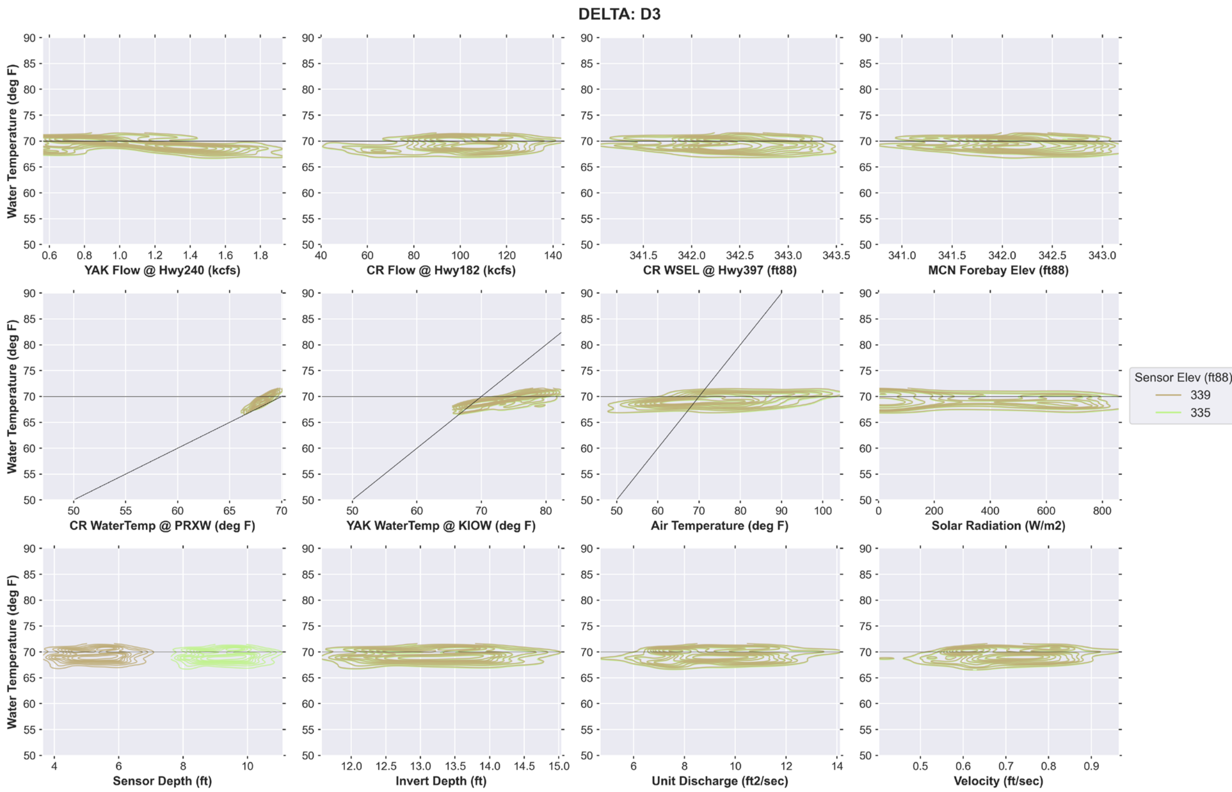

Figure 3.3-21 Trends Summary – Delta Reach – D3

3.3.3.3 Columbia – E3

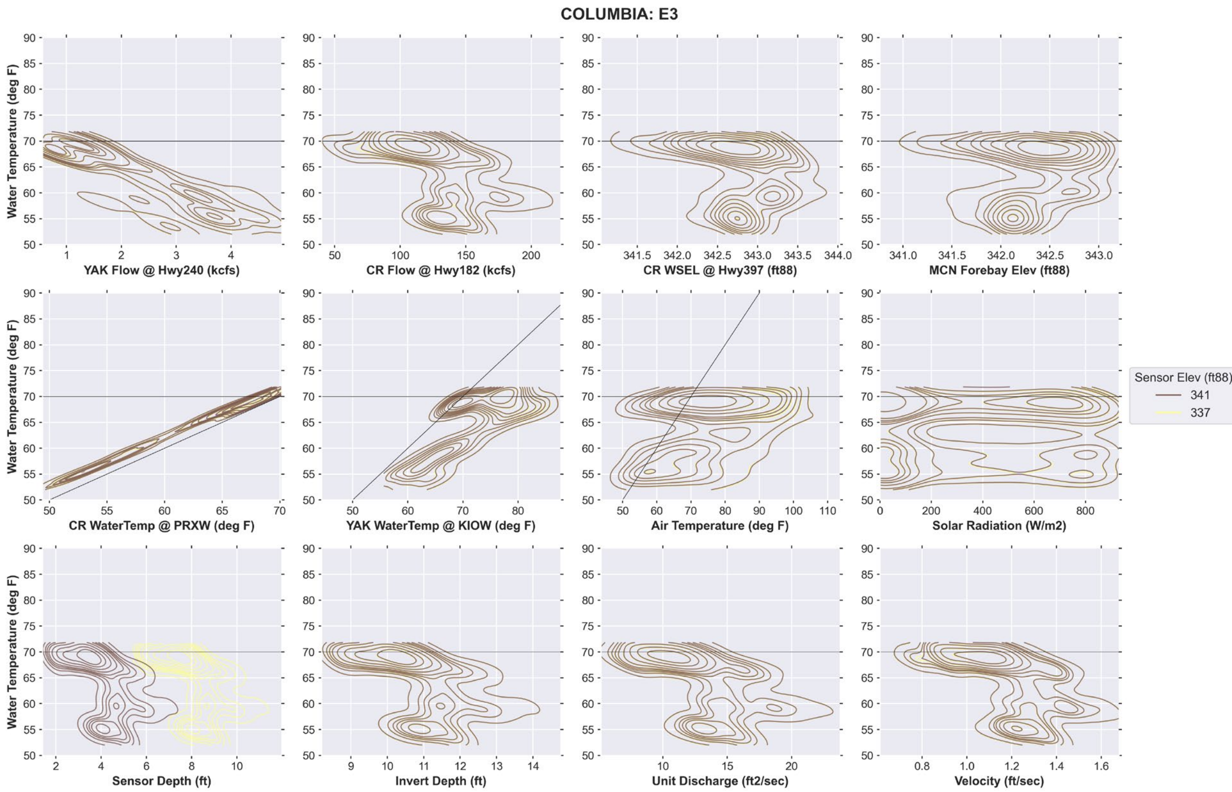

Figure 3.3-22 Trends Summary – Columbia Reach – E3

3.3.3.4 Columbia – E4

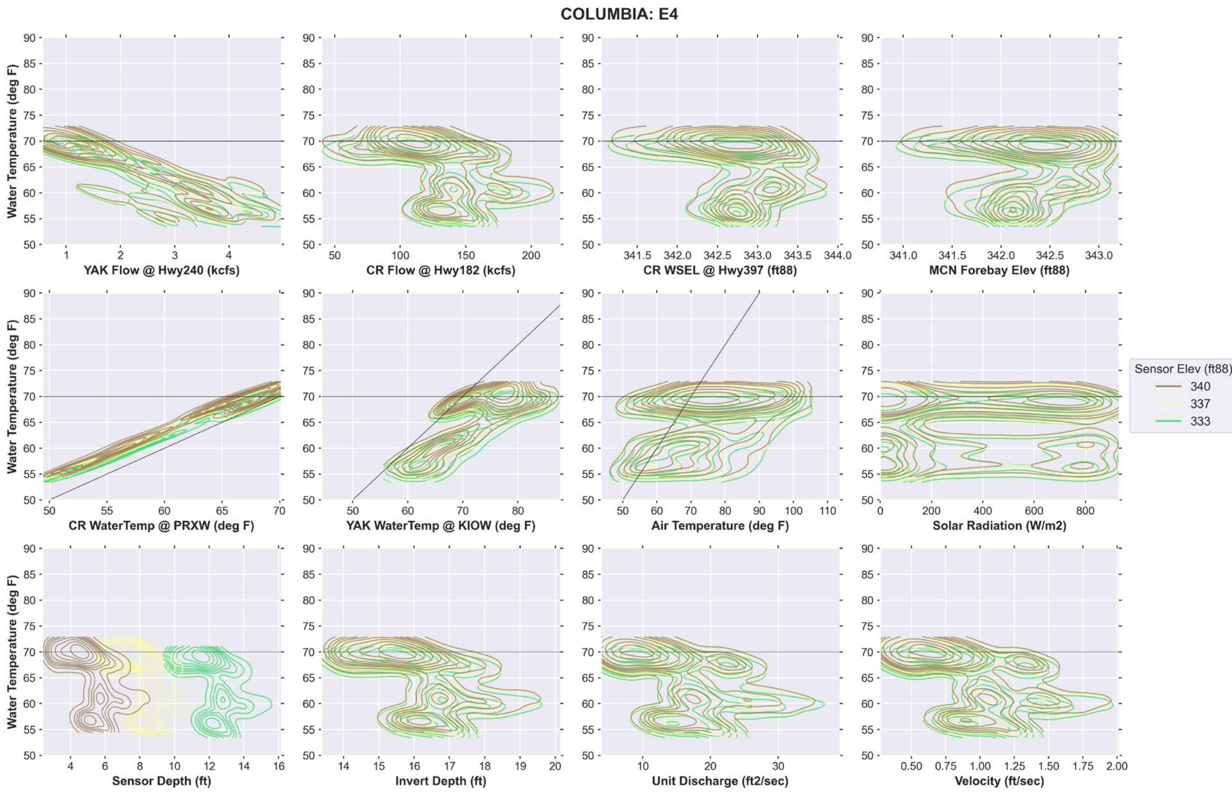

Figure 3.3-23 Trends Summary – Columbia Reach – E4

4. SUMMARY

4.1 General Trends

Measured water temperatures during the study period were characterized by a diurnal sinusoidal signal and bimodal seasonal signal. The strongest correlation trends were with the baseline temperature of the source flow (either Yakima River or Columbia River) and the influence of secondary parameters was present but minor. Dynamic mixing and stratification was identified at sites Y3 and W1, with no significant flow mixing West of Bateman Island, most likely due to the causeway. All sites also exhibited a seasonal inverse trend for lower water temperature with increased flow. Water temperature stratification was measured at: Y1, Y3 in the Yakima Reach and W1, W4 in the Bateman Reach. During the June/July regional heat dome, warming at depth without overnight cooling was observed. Measured water temperatures did not appear to be significantly affected by MCN forebay stage despite the coincidence of warm day thermal stratification with low pool levels.

4.2 Lessons Learned

Lessons learned on this study are summarized below.

- Sensors & Fieldwork:
  - Use hardened and tamper resistant sensor installations are necessary to mitigate against both theft and vandalism.
  - Pervasive AIV between July and October impacts boat travel through the study area.
  - The preferred timing for fieldwork is sensor deployment in March and retrieval in November.
- Thermal Mapping:
  - Flight and processing plans need to accommodate diurnal bias using multi-day mapping in similar time/weather windows.
  - Reduction of banding effects requires >50% overlap
  - Large areas of open-water without discernable pixel matching features are problematic for processing algorithms
  - Specialized software and licensing is required to process thermal images.

4.3 Future Tasks & timing

Recommended future tasks include both continued data collection and analysis for integration with related efforts and would ideally commence in FY23 Q1.

- Data Collection:
  - Temperature monitoring at six stations (Y1, C1, W1, W4, E1, and E4) using hardened installations.
  - Water quality monitoring at 3 stations (W1, W4, E4)
  - Stage monitoring at PAQW.
  - Include collection of phytoplankton, chlorophyll a, and aquatic macrophyte mapping to better understand their influence on dissolved oxygen and pH.

- Analyses:
  - Calibration of heat flux coefficients for multi-source flow-mixing and air temperature.
  - Develop hydraulic and water quality process model to develop parameter distributions.
  - Develop statistical forecast model for informing water management and integrate with regional NWD temperature regressions and parameterizations.

5. REFERENCES

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