US Army Corps of Engineers ®
Walla Walla District

YAKIMA RIVER DELTA ECOSYSTEM RESTORATION

Final Feasibility Report with Integrated Environmental Assessment

Appendix E

Hydrologic and Hydraulic Assessment

Contents

Figures

1 Introduction

The U.S. Army Corps of Engineers (USACE) Walla Walla District (CENWW) in collaboration with the Washington Department of Fish and Wildlife (WDFW) has completed a feasibility study for restoring aquatic habitat and ecosystem functionality to the Yakima Delta in Kennewick and Richland, Washington under Section 1135 of the Continuing Authorities Program (CAP). The purpose of this hydrologic and hydraulic (H&H) assessment was to quantify the hydrologic and thermal loading to the Yakima Delta study area and the corresponding hydrodynamic mixing and temperature response. The H&H assessment established provisional baseline conditions and provided relative comparisons for two discrete measures previously screened through the USACE smart planning process (ER 1105-2-100).

The Yakima Delta study area is located at the confluence of the Columbia and Yakima Rivers, approximately Columbia River Mile 335 (Figure 1-1), and the upstream end of Lake Wallula, the run-of-river reservoir created by McNary Dam (a USACE project) downstream. Bateman Island lies just east of the Delta and is connected to the right bank of the Columbia River with an earthen causeway that that blocks active flow around the south side of the island and hydraulicly shelters a local marina to the east. To the north of Bateman Island, the delta is characterized by a shallow shelf with dynamic mixing of Yakima and Columbia River flows depending on their magnitude and ratio. The bounding inflows to and outflows from the Yakima Delta study area are influenced by regional regulation, which is coordinated with but generally outside of direct USACE operational authority.

Figure 1-1. Yakima Delta study area

The Tentatively Selected Plan (TSP) for this feasibility study as of January 2023 is the complete removal of the causeway (Measure 7, see Section 4.2) intended to reduce temperatures in the areas west and south of Bateman Island by increasing the conveyance and mixing fraction of cooler Columbia River water to offset the warmer temperatures of the incoming Yakima River. Without the causeway in place, more Columbia River flow is predicted to dynamically mix around Bateman Island, following relic channels around the south side of the island, and at times extending up to ~1000 feet west depending on the flow magnitude and ratio. For both baseline conditions and the TSP, water surface elevations in the Yakima Delta study area will remain equilibrated with Lake Wallula stage, independent of the degree of flow mixing.

2 Regional Conditions

The Yakima Delta study area is located at the confluence of the Yakima and Columbia Rivers which is also near the upstream extent of Lake Wallula, a run-of-river reservoir created by McNary Dam (MCN) located approximately 43 river miles downstream. Riverine conditions in the Yakima Delta study area are notably influenced by Lake Wallula pool levels upstream of MCN, which is operated in concert with regionally coordinated operations of the greater Federal Columbia River Power System (FCRPS).

Inflows to the Yakima Delta study area include outflow from Priest Rapids Dam (PRDW) 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 operations through a series of coordinated run-of-river hydropower projects below Grand Coulee Dam (GCD), while Yakima River flows are more representative of a spring freshet followed by a descending hydrograph limb as upstream irrigation demands increase through the summer hydroperiod.

Despite being over forty miles downstream from the Yakima River Delta, the backwater conditions created by MCN within Lake Wallula are a notable driver of water surface elevations and dampened hydraulic energy within the study area. The MCN pool elevations operate over a typical range of 3 to 5 feet to regulate not only Columbia and Yakima River inflows, but also inflows from the Snake River which joins the Columbia about ten miles downstream of the study area. In addition to the regional river network, MCN operations are also essential to real-time balancing of hydropower grid ties and thus can be highly variable at sub-weekly and sub-daily scales. At upper end of the MCN operational stage range, the Lake Wallula backwater can extend as much as ~2 miles up the Yakima River channel which influences the stage, energy regime, fine sediment deposition, and flow mixing with the Columbia River.

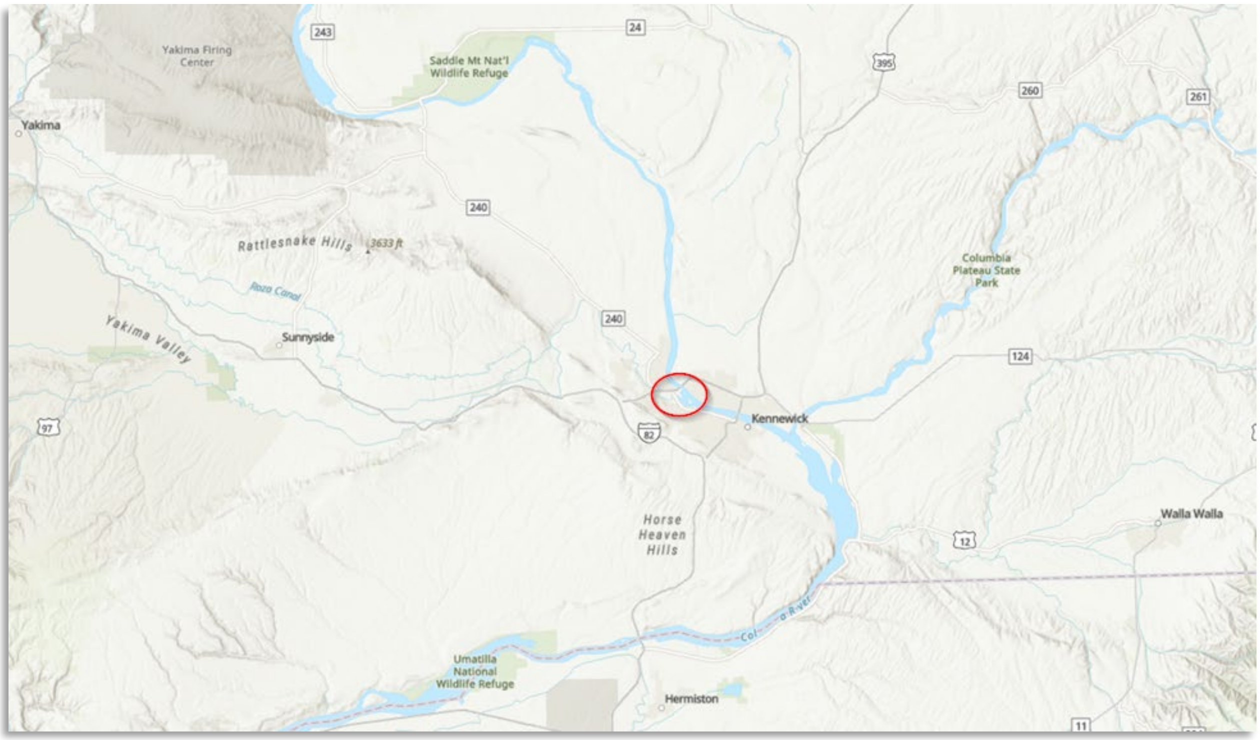


Figure 2-1. Vicinity map depicting the confluence of the Yakima, Columbia, and Snake Rivers and Yakima Delta study area.

Summary plots illustrating the seasonal quantiles for Columbia and Yakima River inflows and temperatures as well as downstream stage operations are presented in Figures 2-2 through 2-6 below. For all five plots, the dark line represents the day of the water year median while the dark shaded area represents the inter-quartile-range (IQR) from the 0.25 to the 0.75 quantile.

2.1 Columbia River

On the Columbia River, inflows to the study area are characterized by a typical spring freshet spanning from April to July (Figure 2-2). Columbia River temperatures typically reach a seasonal low < 40°F in February, which steadily increase to a seasonal high > 65°F (Figure 2-3). Downstream of the study area, the Lake Wallula stage can vary as much as five feet, however the IQR is typically within a one-foot range, and only increases slightly during the spring freshet (Figure 2-4)

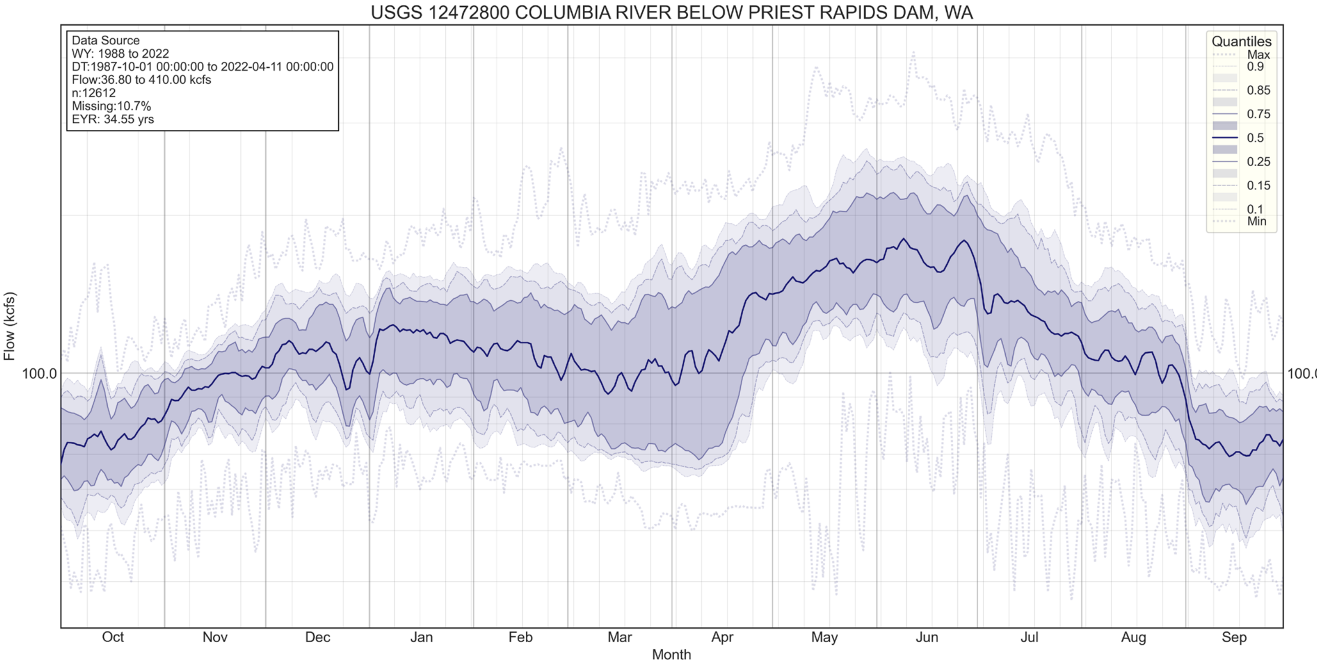


Figure 2-2. Daily quantiles for PRDW Columbia River outflows from water year 1988 to 2021.

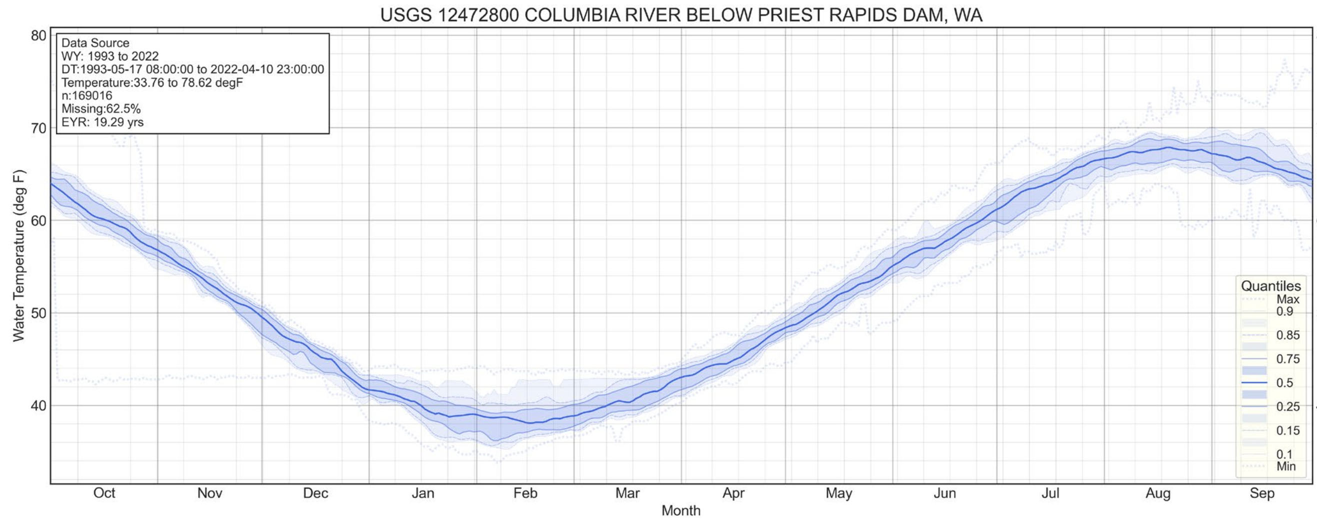


Figure 2-3. Daily quantiles for PRXW Columbia River temperatures from water year 1993 to 2021.

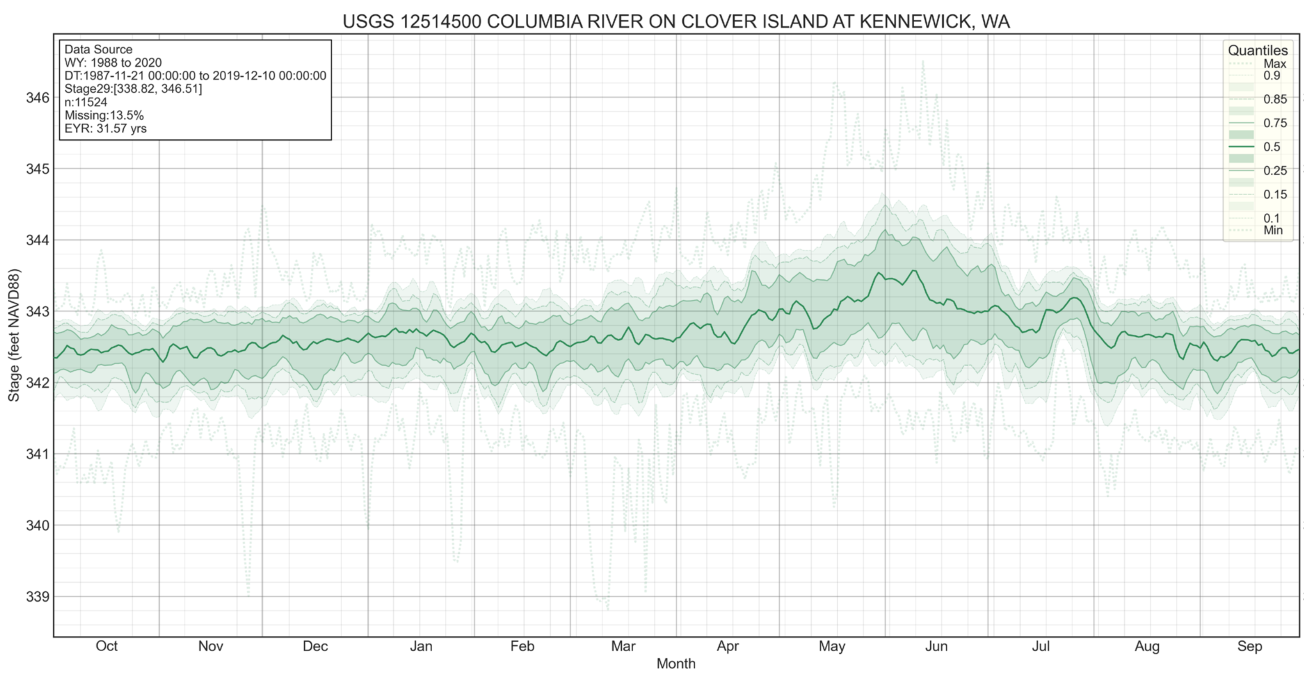


Figure 2-4. Daily quantiles for downstream stage at CCKW from water year 1988 to 2020.

2.2 Yakima River

On the Yakima River, the spring freshet is less pronounced and of shorter duration than the Columbia with a significant drop through the month of June towards a seasonal low in July (Figure 2-5). Yakima River temperatures typically maintain seasonal lows around 40°F between December and February, which steadily increase to a seasonal high of < 80°F (Figure 2-6) in July before trending back towards a median temperature around 60°F by early October.

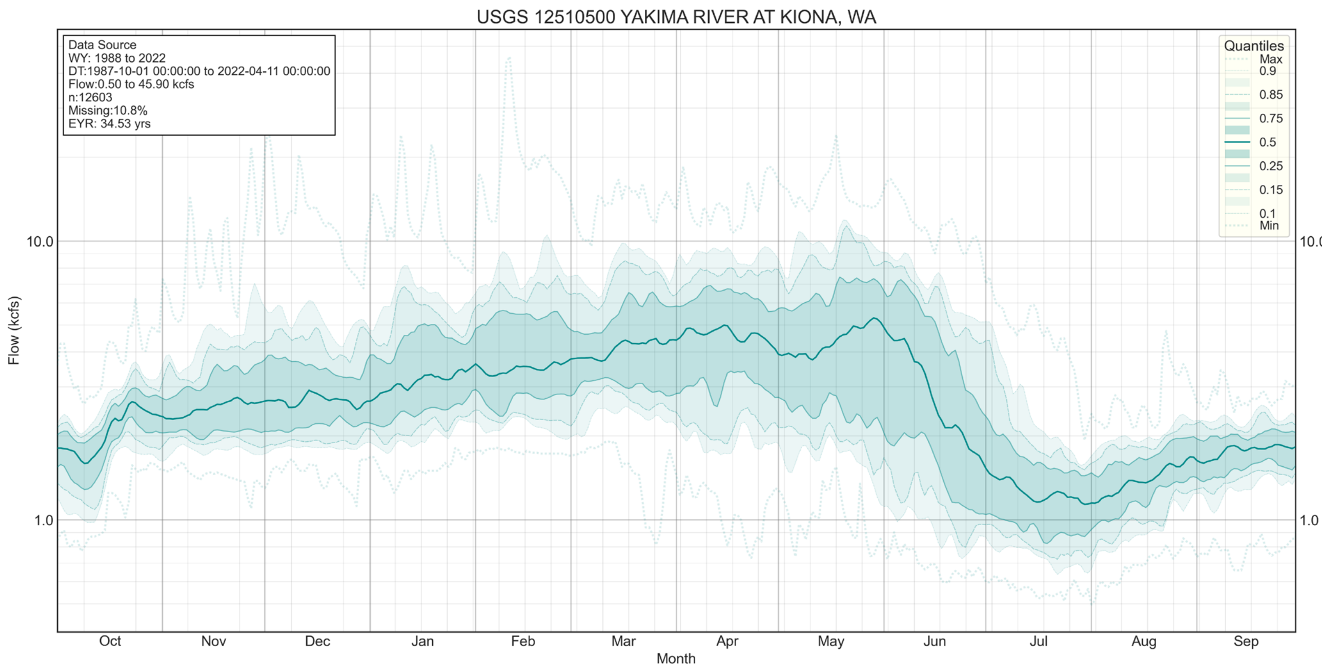


Figure 2-5. Daily quantiles for Yakima inflow and at KIOW from water year 1988 to 2021.

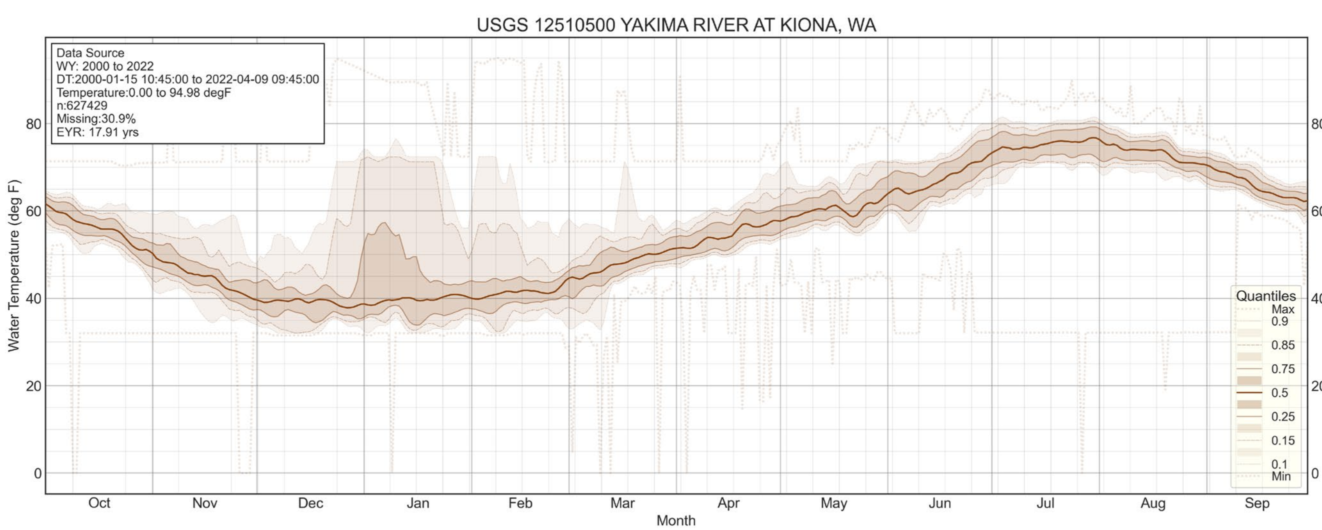


Figure 2-6. Daily quantiles for Yakima temperature at KIOW from water year 2000 to 2021.

2.3 Regional Hydraulics

To develop the flow and stage boundary conditions for the Yakima Delta study area, a one-dimensional HEC-RAS model was utilized. The regional model was adapted from the Reach 5/14 model of the 2019 CRSO study (USACE 2019) and spanned a relatively large area extending from the Priest Rapids Dam tailwater on the Columbia Upstream (~ CRM 396), to the McNary dam forebay downstream (~CRM 291). Regional Yakima River inflows at the Kiona gage (~YRM 23) were routed to the Hwy 182 crossing (~YRM 3.8) via Muskingum-Cunge at a nominal slope of 0.000755 ft/ft resulting in a variable lag time between 6 and 12 hours depending on flow rate. Downstream of the Yakima Delta study area, the regional model included a junction with the Snake River from the Ice Harbor tailwater upstream (~SRM 8.1) to the Columbia River confluence (~CRM 324.0)

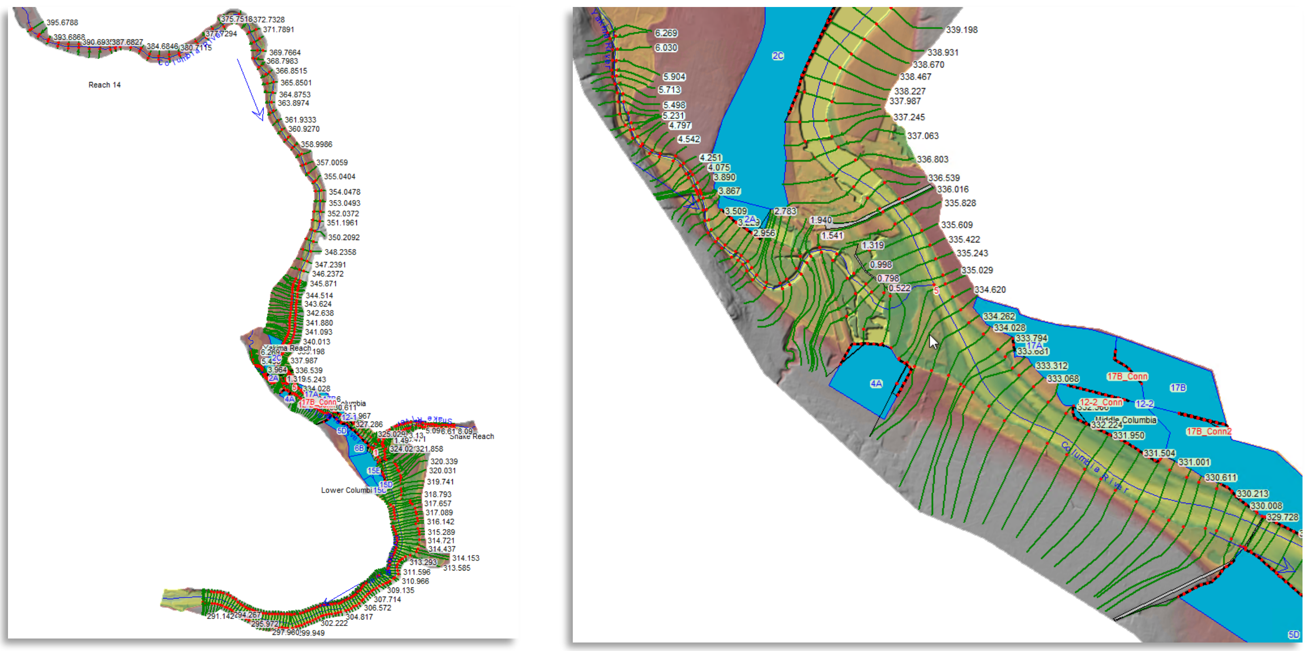


Figure 2-7. Regional HEC-RAS 1D model extents (left) and study area detail (right)

Boundary conditions for the regional 1D model were compiled as unit value timeseries for a suite of gages as listed in Table 2-1 below. The period of record used extended from 2007 to 2021, limited predominantly by stage availability at the Clover Island gage for model output and gage height comparison.

Table 2-1. Summary of regional gages used to develop study area boundary conditions.

River	Location	USGS Station	DB Query Station
Columbia	Priest Rapids Dam Outflow	12472800	PRDW & PRXW
Yakima	Kiona	12510500	KIOW
Columbia	Clover Island	12514500	CCKW
Columbia	Below Hwy395 Bridge	12514400	PAQW
Snake	Ice Harbor Dam Outflow	13353010	IHR
Columbia	McNary Dam Forebay	14019200	MCN

** USGS url: https://maps.waterdata.usgs.gov/mapper/index.html*
** DB Query url: https://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/*

To account for data gaps, calibration of the regional 1D HEC-RAS model was verified at the Clover Island Gage (CCKW Gage#12514500) for eleven discrete hydroperiod sets spanning from 2007 to 2019 with ~11.6 Equivalent Years of Record (EYR) as detailed in Table 2-2 below.

Table 2-2. Summary of regional model calibration hydroperiods.

Segment no.	Begin Date	End Date
1	10/1/2007 0:00	1/20/2008 23:45
2	1/29/2008 0:00	12/14/2008 23:45
3	12/28/2008 0:00	2/7/2009 23:45
4	2/12/2009 0:00	12/5/2009 23:45
5	12/16/2009 0:00	12/6/2013 23:45
6	12/15/2013 0:00	2/2/2014 23:45
7	2/14/2014 0:00	12/31/2014 23:45
8	1/5/2015 0:00	6/28/2015 23:45
9	9/10/2015 0:00	10/8/2015 23:45
10	10/14/2015 0:00	1/2/2016 23:45
11	1/9/2016 0:00	12/31/2019 23:45

Model stage residuals were calculated, sorted, and plotted against their percent rank (Figure 2-8). The median of the ranked residuals was 0.0002 ft and average 0.001 ft, with number of 406.4k data points. The residual distribution was confirmed to be essentially symmetrical with median = -0.0002 ft, and the inner quartile range (25th and 75th percentiles) balanced at ±0.077 feet respectively.

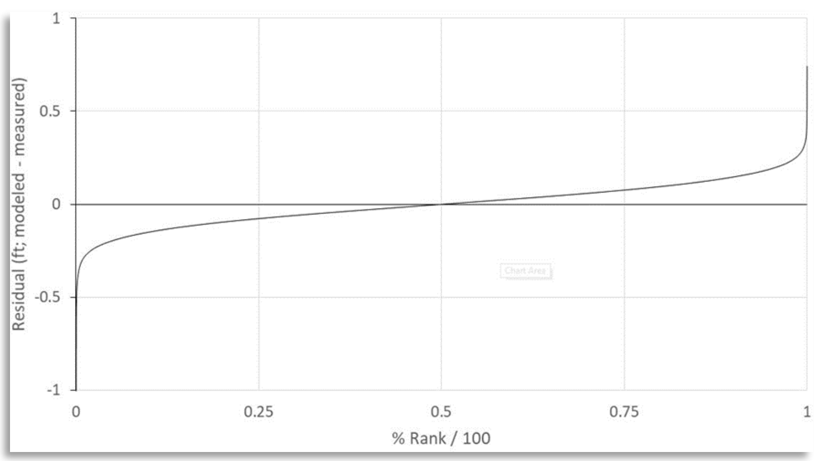


Figure 2-8. HEC-RAS 1D model residuals at Clover Island Gage (CCKW Gage#12514500)

3 Study Area Baseline

3.1 Study Area Models

An assessment of baseline hydraulic and temperature conditions in the study area was completed using three numerical models to provide a tiered framework of increasing detail. The first model, developed in HEC-RAS 2D, was used for assessing general hydraulics in the study area and selected for relatively fast compute times over long timeseries and the feature toolchain. The second model, developed in AdH 2D, was used to simulate the mixing fractions of Columbia and Yakima River flows and develop a suite of hindcast mixed flow temperature surrogates and frequency distributions at select point locations in the study area. A third provisional temperature model was developed in Flow-3D to simulate water temperature response in the study area from multiple physical phenomena including: mixing and inter-fluid heat transfer, thermal stratification and density differences, and diurnal response of external heating and cooling. This provisional model was used for initial measures screening using bookend index conditions before being descoped.

3.1.1 2D Hydraulic Models

Hydraulic mixing patterns in the Yakima Delta study area are predominately influenced by the flow magnitude and ratio between the incoming Columbia and Yakima Rivers, as well as the downstream stage regulated by MCN. To characterize these interactions, depth averaged hydraulics for the Yakima Delta study area were developed using a depth averaged HEC-RAS 2D diffusion wave model that extended from the Hwy 240 and Hwy 182 bridge crossings on the Yakima and Columbia Rivers upstream, to the Clover Island Gage near the Hwy 397 Bridge crossing downstream. A nominal 25-foot grid resolution was selected for the overall HEC-RAS 2D model domain with breaklines and select refinement regions resulting in a total cell count of ~350k.

A second depth averaged 2D model was developed in AdH (CHL Adaptive Hydraulics) to evaluate flow mixing patterns around Bateman Island. The AdH 2D model used the same domain extents with a depth variable mesh size resulting in a total element count of ~160k. Boundary conditions & water surface calibration profiles for both study area 2D models were based on routed flows and stages from the regional HEC-RAS 1D model discussed in Section 2.3 above.

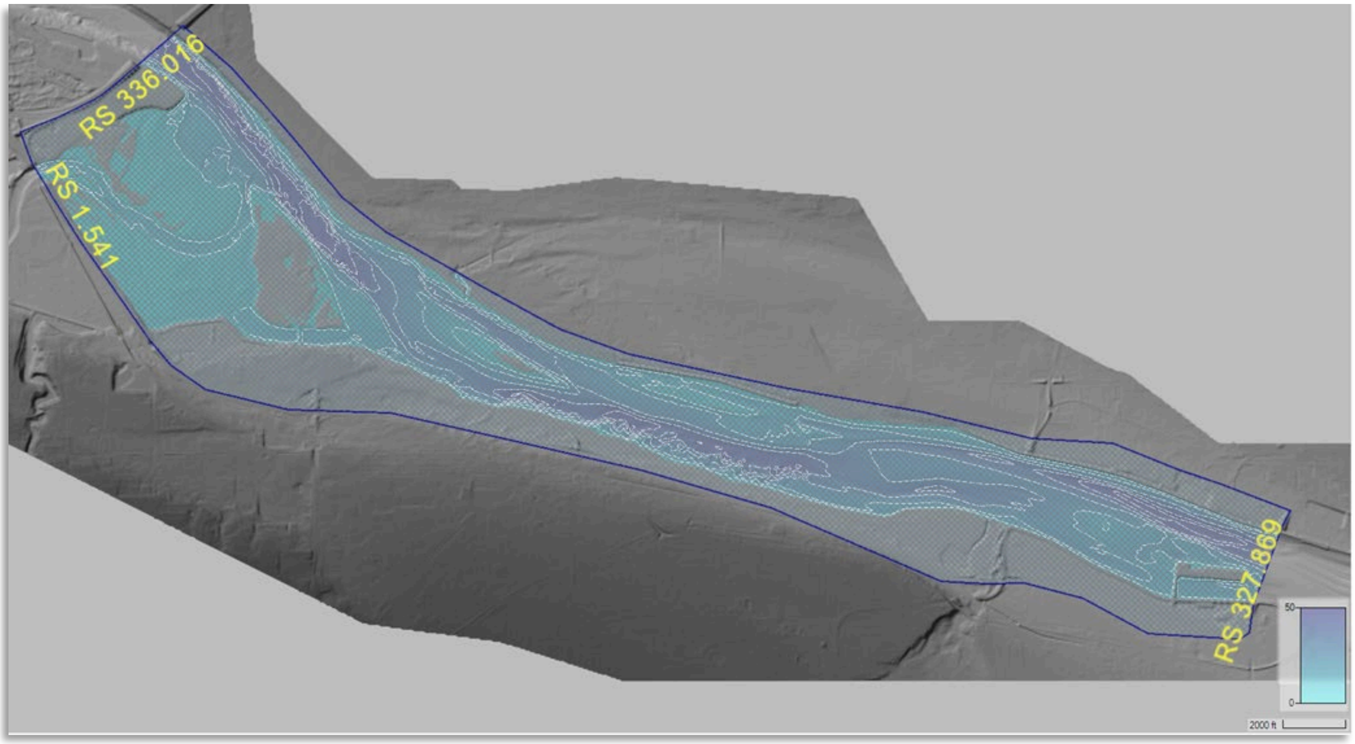


Figure 3-1. Yakima Delta Study Area 2D Model Extents with bathymetric depth in feet.

3.1.2 Temperature Model

Considering the relatively large area where the cooler Columbia River and warmer Yakima River flows mix and thermally stratify, a temperature model was requested that could handle a large a geographic footprint, density differences, heat transfer within the fluid as well as external thermal loading. In lieu of using the depth averaged AdH model for temperature simulations, the CFD model Flow-3D was initially selected for the additional capability to simulate vertical temperature stratification.

The temperature modeling plan was to start with Flow-3D steady-state index simulations (see Section 3.2.1) of depth-averaged mixing temperature, and then to incrementally add vertical mixing followed by external thermal loading. Following the steady-state index simulations, the temperature modeling plan was to simulate unsteady timeseries of select events to capture transient effects such as diurnal heating and cooling during time-critical periods such as fish migration for comparisons with select measures. This approach would provide refinement of the model parameterization for a final evaluation of the TSP. However, after initial development of the Flow-3D model and provisional simulation of two steady-state index conditions used for measures screening, the temperature model was descoped. As such, neither the remaining index-sets for measures screening nor the event-based temperature simulations with external thermal loading were refined further for this study.

The Flow-3D mesh resolution and model parameters were tuned to balance compute time with fidelity. Ultimately a uniform orthogonal mesh size of 30 x 30 x 5 feet with a timestep of <0.5 second was found to provide sufficient resolution for informative model output while producing relative stable model runs with tractable computation times up to parity. While 5 feet can be deeper than some of the slow/shallow backwater areas west of Bateman Island at low conditions, this vertical mesh resolution was selected with the intent that it could provide coarse or slightly better resolution in the water column to represent thermal stratification while not being overly dense for the 60 ft deep Columbia River channel.

At the time of the Flow-3D temperature simulation task, measured water temperature data from 2009 was available at two locations in the Yakima Delta as depicted in Figure 3-2. For an initial calibration check of the provisional Flow-3D steady-state index temperature model, a high temperature with low flow condition from August 2009 was run with external thermal loading and a heat transfer to void coefficient of 0.01 slugs/s^3/°F and a unitless emissivity to void coefficient of 0.01.

The provisional simulated temperature from flow-mixing was compared against the 2009 measured data as shown in Figure 3-2 below. After a 24-hour spin-up period, the model prototype was found to over-estimate water temperature at the Delta site by up to ~2°F, while the response from the Causeway West site did not deviate from the initial condition of 86°F due to limited flow mixing. This response reinforced the need to extend the duration of the steady-state index model spin-up period to enable complete mixing throughout the model domain, refine the coefficients responsible for heat transfer across the air-water interface and quantify the model sensitivity to these parameters.

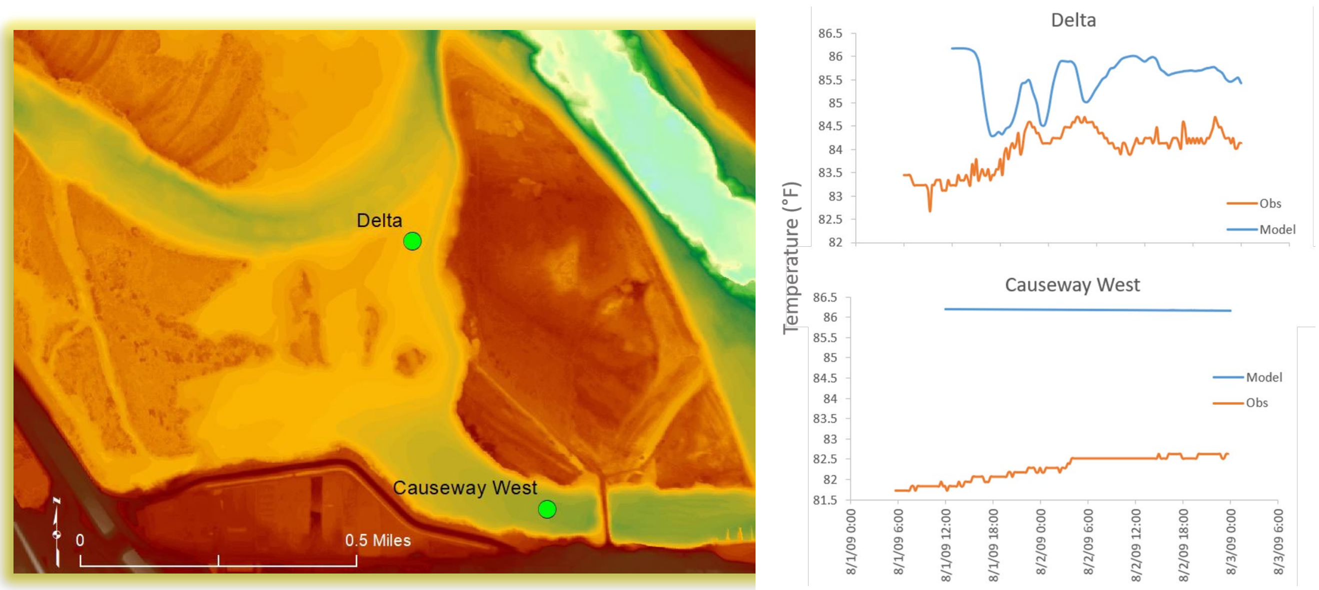


Figure 3-2. Historical Temperature Measurement Locations and initial Flow-3D model response.

Despite the un-converged temperature calibration of the provisional Flow-3D mixing models without external thermal loading, the modeled temperature bias was deemed acceptable by the PDT biologist for use in developing limiting factor habitat indices to quantify feasibility benefits for measures screening (Appendix A) as they were still effective at representing hydraulic mixing patterns and relative mixing temperature response between measures.

3.1.3 Model Terrain

Terrain for the study area models was derived as a composite of the latest available bathymetric and lidar datasets as summarized in Table 3-1 below. The composite terrain was developed by merging representative pieces of the source terrain in GIS and used the FIPS 4602 NAD 1983 State Plane Washington South horizontal and NAVD88 vertical datums respectively.

Table 3-1. Summary of terrain datasets used for study area hydraulic models.

Year	Type	Dataset	Notes
2015	Composite	NHC2015_BathyCompositeSet3_WA83SF88	Best available data for Yakima West of Bateman Island & superseded for Columbia.
2017	Multibeam	CRSO2017_Reach05_GoatIsland_RD3_Infill4_WA83SF	Latest Columbia River bathymetry.
2017	Interpolated Single Beam	CRSO2017_Reach05_RM325_SingleBeamInterp_WA83SF	In downstream reaches of study area 2d model.
2017	Multibeam	CRSO2017_Reach05_Confluence_IceHarbor_RD3_Infill4_WA83SF	Latest Lower Snake River bathymetry below ice harbor.
2010	Lidar	crt2010_r5t3 & crt2010_r5t4	For non-bathymetric overbanks

3.2 Boundary Conditions

Two general categories of flow and thermal boundary conditions were used for this feasibility assessment. The first category is index conditions that are intended to represent quasi-steady loading for representative and extreme events over a daily (or greater) period and the second boundary condition category considered are timeseries of unit values (typically 15min to hourly) that represent a measured or synthetic event of sufficient duration to represent temporal variability.

3.2.1 Index Boundary Conditions

Index condition sets considered include both thermal index conditions and extreme hydrologic loading conditions. Simulation of select monthly index and exceedance conditions were also planned for measures evaluation but were descoped. Four sets of thermal index boundary conditions were identified to represent the seasonal range of hydraulic and thermal conditions expected for the study area to be used for measures screening. The first two index sets were selected to frame the anticipated range of temperature response in the study area, while the second two index sets were selected to assess sensitivity to flow and temperature loading during the late summer.

- Low flow, high temperature scenario (1 Aug 2009)
- High flow typical early season freshet, typical temperature (16 Jun 2012)
- Typical temperature, typical flow for August (8 Aug 2014) – descoped.
- High temperature, typical flow for Sept / Oct (1 Sep 2014) – descoped.

To establish hydraulically and thermally equilibrated base index conditions for the measures screening conditions, quasi-steady representative boundary conditions were applied to various model configurations for a quasi-steady equilibrium state at 24 hours of elapsed time without external heating. Boundary condition values for the four thermal index condition sets are enumerated in Table 3-2. Ultimately, only the first two indices (worst case and best case) were utilized in this study for measures screening.

Table 3-2. Summary of bounding index conditions for measures screening simulation.

Date	Condition	Notes	Index T* (°F)		Index Q* (kcfs)		Index WSEL* (feet)
			Yakima R	Columbia R	Yakima R	Columbia R	
01 Aug 2009	High T Low Q	Nominal worst case	86.2	69.1	1.130	101.103	343.05
16 Jun 2012	High T, Typical May/June freshet Q	Nominal best case	65.7	58.7	7.649	248.867	344.57
08 Aug 2014	*Avg T Avg Q*	*Typical Aug flow*	*76.1*	*68.9*	*1.177*	*128.515*	*343.24*
01 Sep 2014	*High T, Avg Q for Sept/Oct*	*Typical Sept/Oct flow, High T*	*76.2*	*69.8*	*2.236*	*90.306*	*342.77*

**The term "index" refers to the average or maximum temperature in the week surrounding the date selected as representative for that condition.*

Four sets of extreme loading index boundary conditions were identified to represent a nominal range of duration and annual exceedance probability based on period of record data from 1960 to 2021. These boundary conditions were applied for the HEC-RAS 2D velocity modeling simulations at the Columbia Park Marina (see section 4.2.1) and are enumerated in Table 3-3 below.

Table 3-3. Summary of nominal exceedance flows for period of record from water year 1960 to 2021.

Set Id	Set Label	CR Flow @ PRDW	YAK Flow @ KIOW	CR Stage @ CCKW	Approach Stage	Levee @355' Overtopped
AEP001	Nom 1% Annual Exceedance Prob	556 kcfs	41.8 kcfs	Min of 340 ft NAVD88	361	Yes
DV001	Nom 1% DV Exceedance Duration	323 kcfs	14.1 kcfs		352	No
DV005	Nom 5% DV Exceedance Duration	228 kcfs	9.13 kcfs		348	No
DV010	Nom 10% DV Exceedance Duration	198 kcfs	6.97 kcfs		346	No

{AEP = Annual Exceedance Probability, DV = mean daily value, CR = Columbia River, YAK = Yakima River}

3.2.2 Timeseries Boundary Conditions

As noted in Section 3.1, the second task of the temperature modeling plan was to simulate unsteady timeseries of select events to capture transient effects such as diurnal heating and cooling during time-critical periods such as fish migration for evaluating measures and alternatives. However, as previously noted, the temperature modeling of representative timeseries was descoped, and instead only a single timeseries for the water year 2021 freshet was carried forward as a nominally representative spring and summer set for use in the HEC-RAS 2D and AdH 2D models. Baseline hydraulic response for a seasonal freshet was evaluated by modeling the March through September 2021 hydroperiod with routed unit value inflows for the Yakima and Columbia Rivers, and downstream stage routed from the MCN forebay elevation to the downstream extents of the 2D models (Figure 3-3).

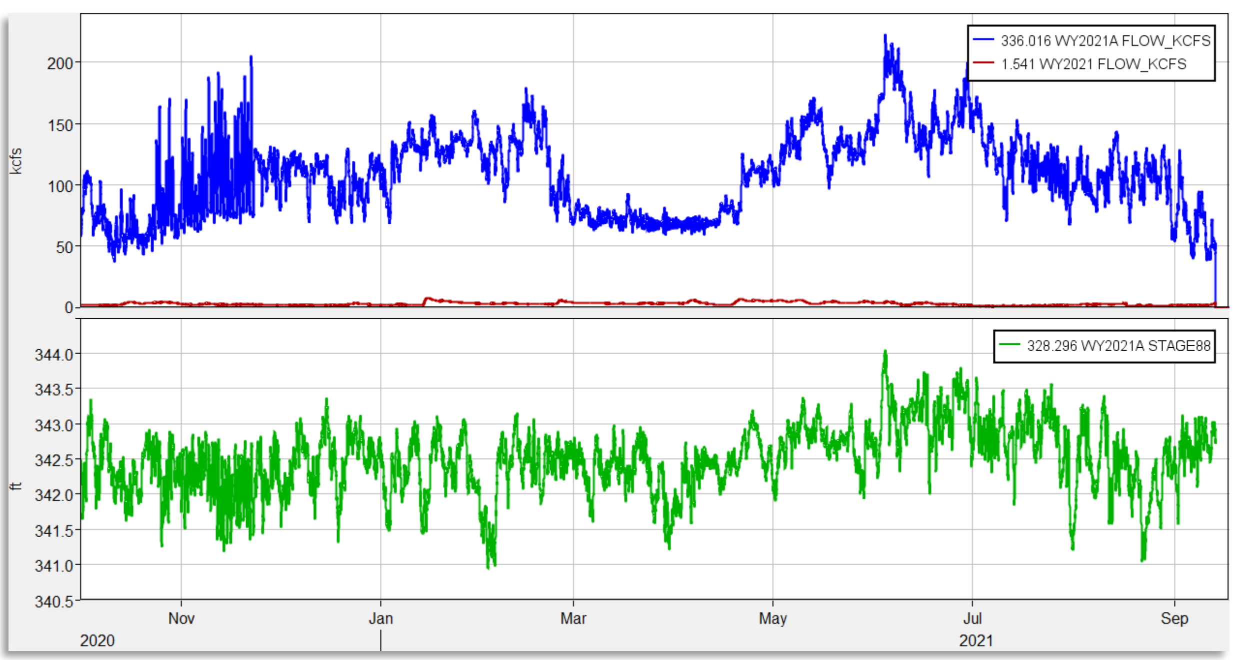


Figure 3-3. Summary of water year 2021 boundary conditions simulated. Top: Columbia River and Yakima River inflows in blue and red respectively. Bottom: Downstream stage near Clover Island in green.

3.3 Point Locations

Timeseries from various model simulation results were sampled at sixteen discrete point locations within the study area that coincide with the WY 2021 field locations monitored for temperature and water quality under the USACE Sustainable Rivers Program as depicted in Figure 3-4 below. The point location identifiers used through the remainder of this appendix utilize a letter prefix (D=Delta, Y=Yakima, W=West, E=East) and an incremental number.

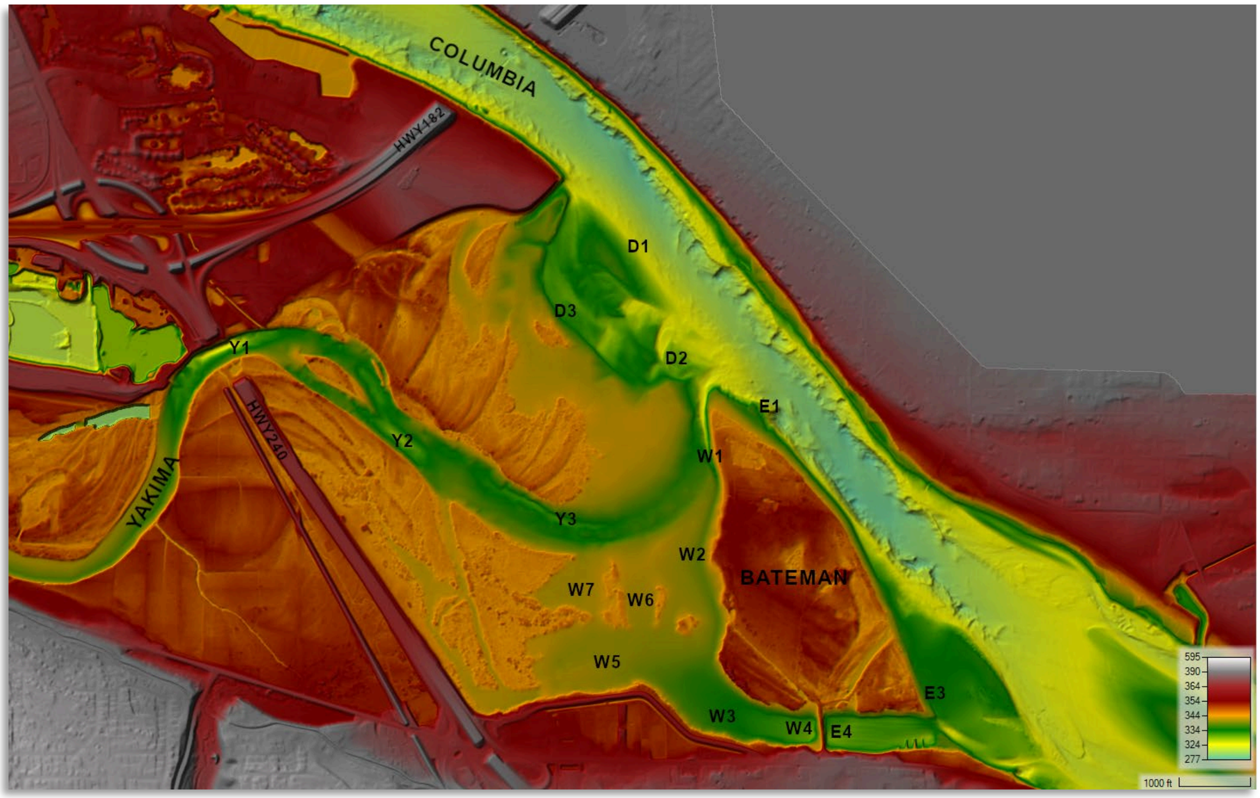


Figure 3-4. Yakima Delta study area monitoring locations from 2021 SRP used to query model results.

3.4 Baseline Hydraulics

Under baseline conditions with the existing causeway in place, hydraulics in the study area are characterized by a general pattern of isolation between the Columbia and Yakima River flows, with limited localized mixing in the delta shelf area north of Bateman Island. In the delta area to the west of Bateman Island, hydraulic patterns are essentially stagnant and unable to mix with cooler Columbia River water under both low and high flow conditions. During the spring freshet, Yakima River flows inundate multiple shallow swales, recharging the west side of Bateman Island with relatively warm water which slowly transitions to stagnant stratified conditions over extended durations through the summer.

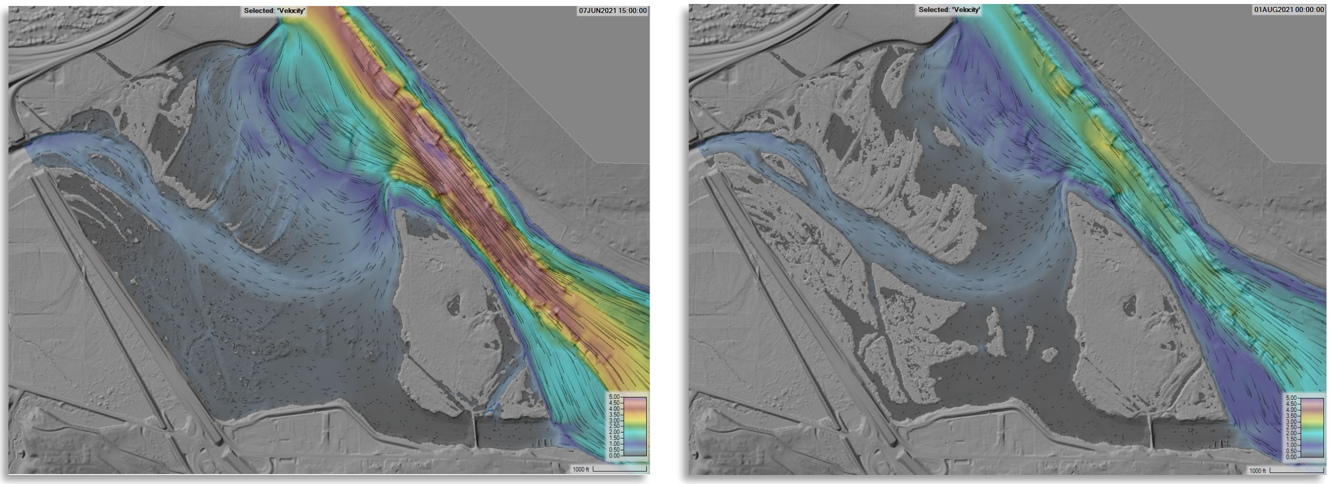


Figure 3-5. 2D model simulation depicting baseline velocity on 07June2021 (left) and 01Aug2021 (right). Note the relatively low baseline velocities southwest of Bateman Island.

As discussed in Section 2, seasonality of regional conditions does influence localized hydraulics in the Yakima Delta study area. The rise of spring flows typically starts first with the Yakima freshet in March/April and extends through May. Figure 3-6 depicts timeseries for May through September 2021. During this period, Yakima River flows into the study area at velocities up to 2.5 feet/sec very slowly mixed into the area west of Bateman Island with lower velocities (< 0.5 feet/sec) and shallow overbank inundation. The Yakima spring freshet recedes quickly through June, where the velocity in the main Yakima channel drops to < 0.5 feet/sec and velocities to the west of Bateman Island remain near-zero over extended durations for the remaining of the summer. The Columbia River freshet is generally a month later than the Yakima, starting in May and extending into July. During this period, velocities at the eastern edge of the delta shelf near the main Columbia River channel exceed 2.5 feet/sec and taper to around 1.0 foot/sec to the west. The Columbia spring freshet recedes gradually through July and August, where baseline velocity in the north delta slows to ~0.5 feet/sec. Cumulative ranked distributions for baseline velocity exceedance at select locations within the study area are presented in Figure 3-7 below. Note the near-zero velocities west of Bateman Island at locations W3 through W7.

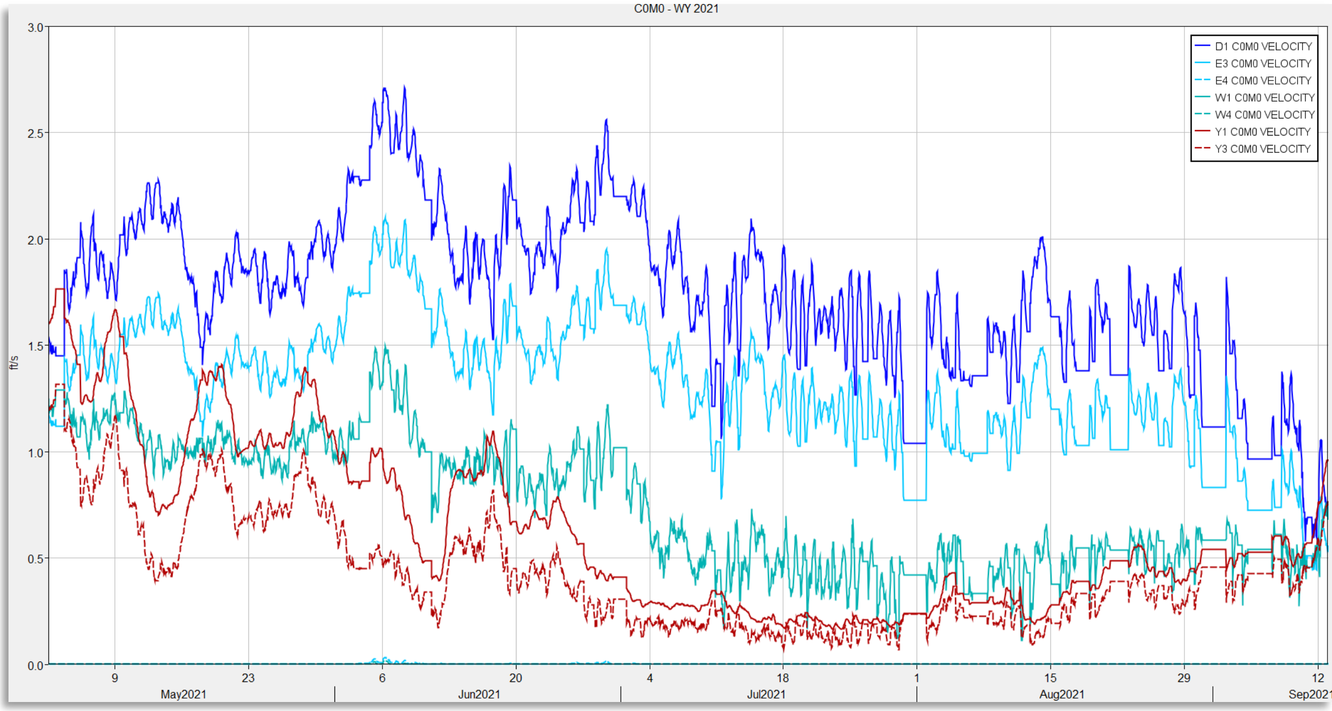


Figure 3-6. Timeseries of modeled baseline velocity for May through September 2021 at select monitoring locations. *Note near-zero baseline velocities at W4 & E4.*

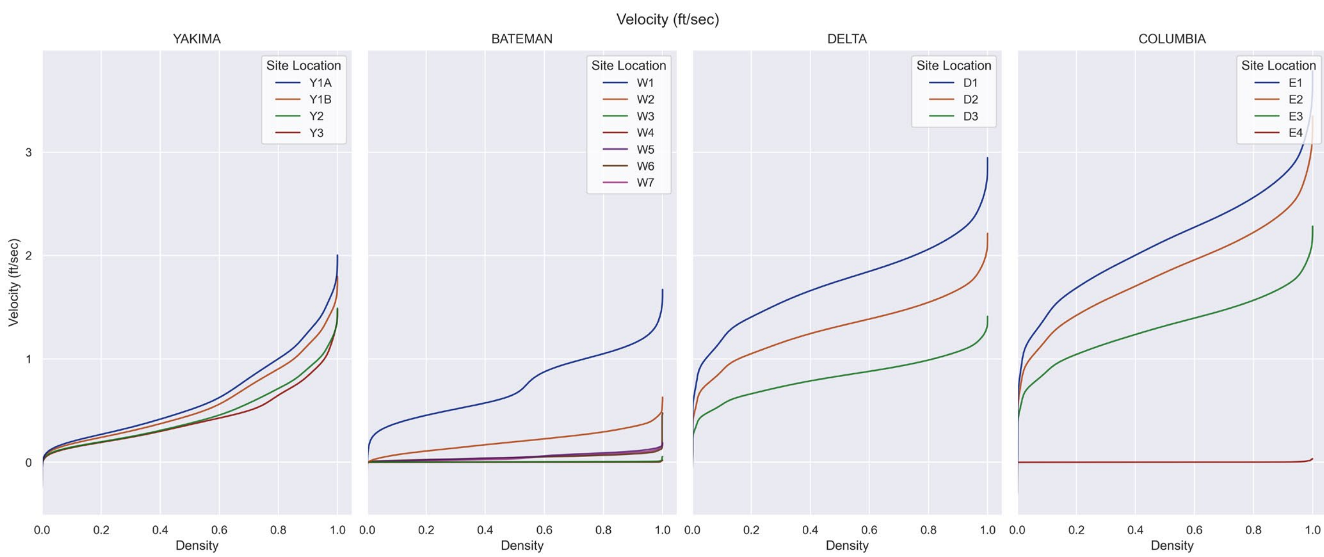


Figure 3-7. Cumulative distributions of modeled baseline velocity for May through September 2021 at select monitoring locations by sub-reach.

3.5 Baseline Water Temperature

The Yakima River and delta has historically been plagued by high temperatures and degraded water quality (Holroyd 1998). Thermal imaging collected by USBR in 1997 (Holroyd 1998) found that the warmest waters in the lower Yakima River were located within the area west of Bateman Island. Previous sampling by the Benton Conservation District measured Yakima flows entering the delta area at temperatures >80°F, which exceeds the Washington state standard of 70°F. Further, water temperatures were found to rapidly warm to as much as 90°F in the delta area (Appel et al. 2011, Wassell et al., 2014). Flow from the Columbia River is relatively cooler with average summer temperatures of 67°F, but can exceed 70 °F at times. Improved temporal and spatial water quality data for the Yakima delta was identified as a data gap in the characterization of baseline conditions and simulation of mitigation alternatives. To support this feasibility assessment and subsequent mitigation design efforts, additional measurements of temperature and water quality were collected between May and September of 2021 by NWW under the USACE Sustainable Rivers Program (Figure 3-8).

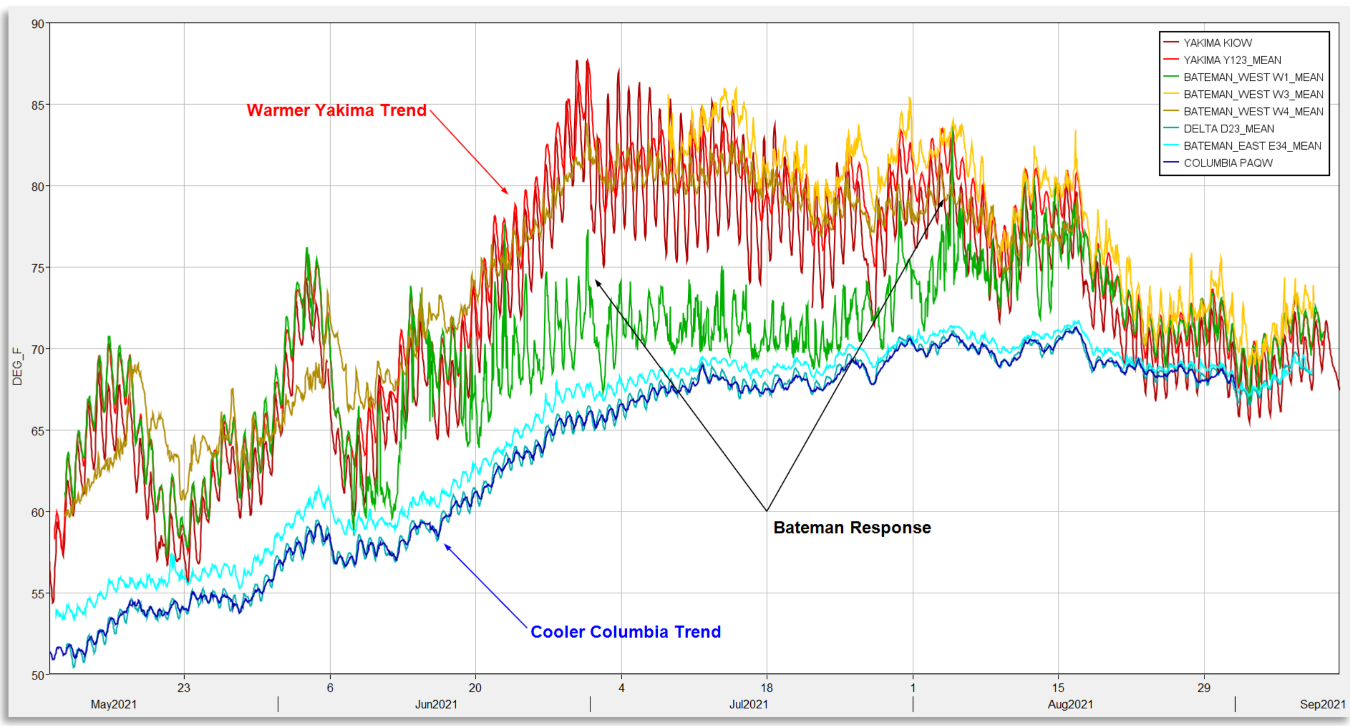


Figure 3-8. Timeseries of depth-averaged temperature string data measured between May and September 2021

Bivariate distributions of water year 2021 measured water temperature paired with various exogenous conditions were plotted to provide insight into baseline seasonal and depth trends (Figures 3-9 to 3-11). The plots are presented as smoothed kernel density estimates for paired timeseries. In addition, the Spearman correlation coefficient was computed as a rank-order nonparametric measure of strength and direction of the monotonic relationship between water temperature and various exogenous variables. The strongest correlations at all sites were to the baseline water temperatures of either the Yakima or Columbia River inflows, or both for sites with some baseline mixing. Additional hydraulic and meteorological drivers were found to have a minor correlation (relative to source flow) resulting in observed deviations from the baseline trend depending on location and depth.

3.5.1.1 Baseline Water Temperature Trends

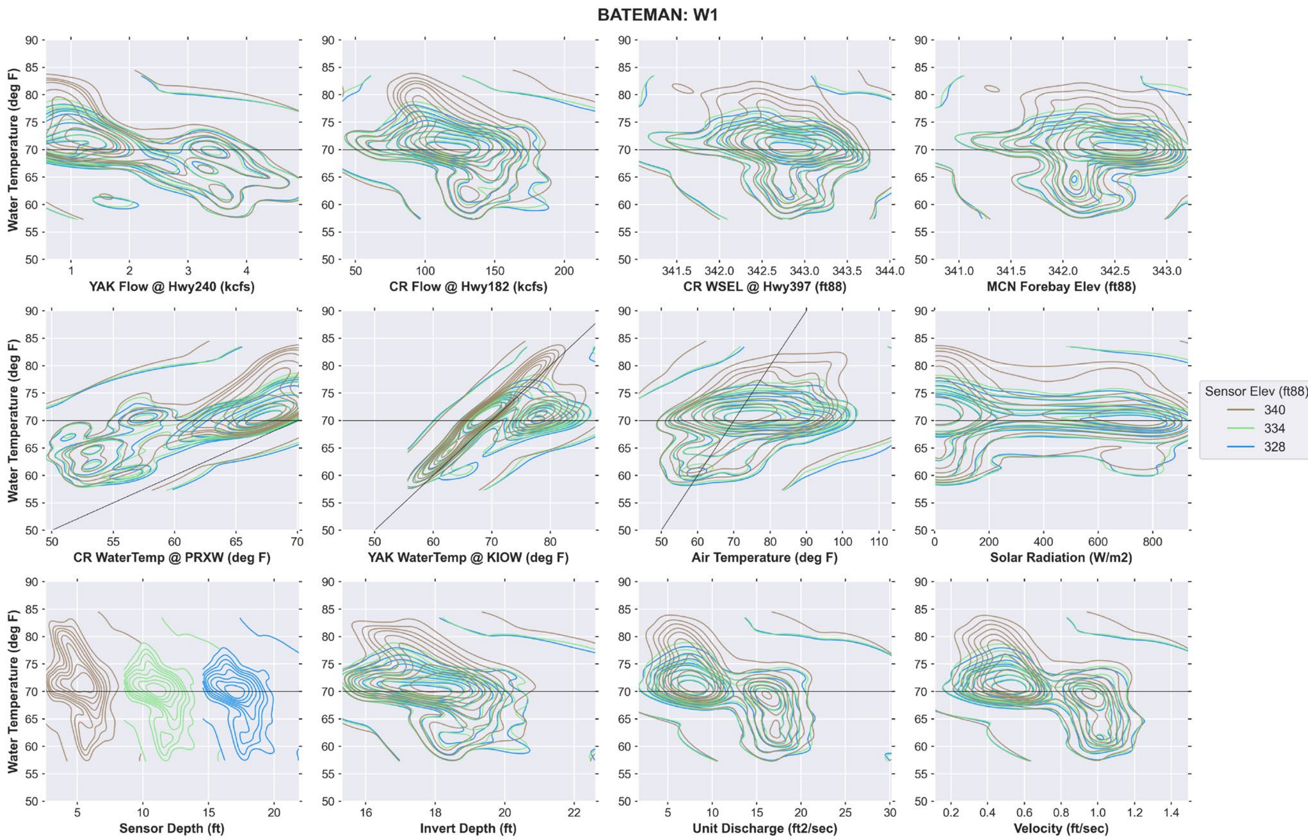


Figure 3-9. Kernel Density Estimate plots of measured summer 2021 water temperatures versus various exogenous parameters at site W1 on the Northwest Side of Bateman Island.

Table 3-4. Spearman Rank Correlation Coefficients for Water Temperature at Site W1 versus various parameters by Sensor @ Elevation.

Parameter	W1A_328 (deepest)	W1A_334 (middle)	W1A_340 (shallowest)
Yakima Flow @ Hwy 240 (kcfs)	-0.336	-0.349	-0.399
CR Flow @ Hwy182 (kcfs)	-0.440	-0.424	-0.443
CR WSEL @ Hwy397 (feet)	-0.304	-0.286	-0.218
MCN Forebay (feet)	-0.066	-0.049	0.038
CR Water Temp @ PRXW (deg F)	0.769	0.757	0.772
Yakima Water Temperature @ KIOW	0.581	0.607	0.747
Air Temperature (deg F)	0.335	0.362	0.490
Solar Radiation (deg F)	-0.179	-0.153	-0.094
Sensor Depth	-0.468	-0.452	-0.446
Invert Depth	-0.468	-0.511	-0.446
Unit Discharge	-0.503	-0.516	-0.586
Velocity	-0.503	-0.516	-0.607

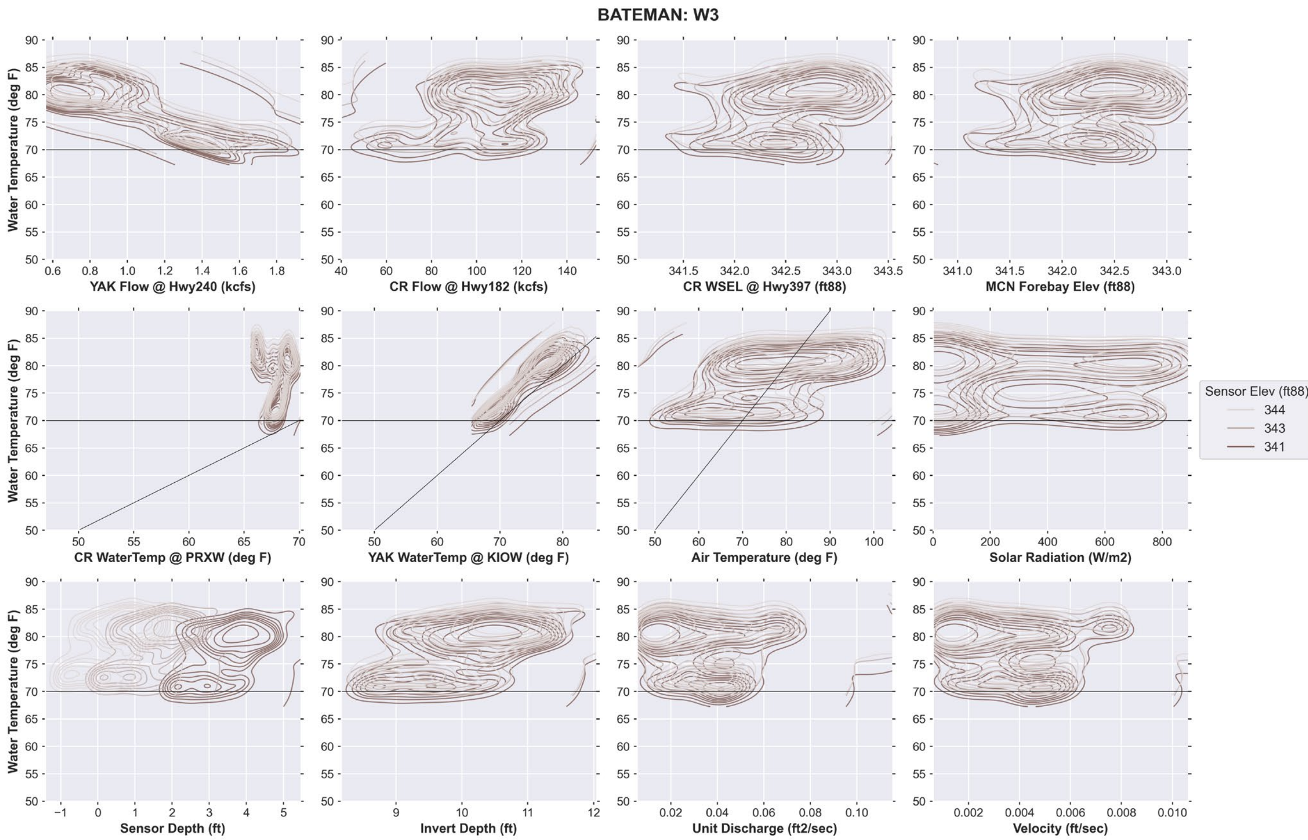


Figure 3-10. Kernel Density Estimate plots of measured summer 2021 water temperatures versus various exogenous parameters at site W3 on the West Side of Bateman Island.

Table 3-5. Spearman Rank Correlation Coefficients for Water Temperature at Site W3 versus various parameters by Sensor @ Elevation.

Parameter	**W3B_341 (deepest)**	**W3B_343 (middle)**	**W3B_344 (shallowest)**
Yakima Flow @ Hwy 240 (kcfs)	-0.074	-0.029	-0.024
CR Flow @ Hwy182 (kcfs)	0.327	0.318	0.319
CR WSEL @ Hwy397 (feet)	0.280	0.297	0.305
MCN Forebay (feet)	0.193	0.212	0.220
CR Water Temp @ PRXW (deg F)	-0.054	-0.019	-0.015
Yakima Water Temperature @ KIOW	**0.854**	**0.898**	**0.932**
Air Temperature (deg F)	0.440	0.482	0.504
Solar Radiation (deg F)	0.012	-0.015	-0.044
Sensor Depth	0.394	0.390	0.391
Invert Depth	0.394	0.390	0.391
Unit Discharge	-0.055	-0.008	-0.007
Velocity	-0.114	-0.067	-0.234

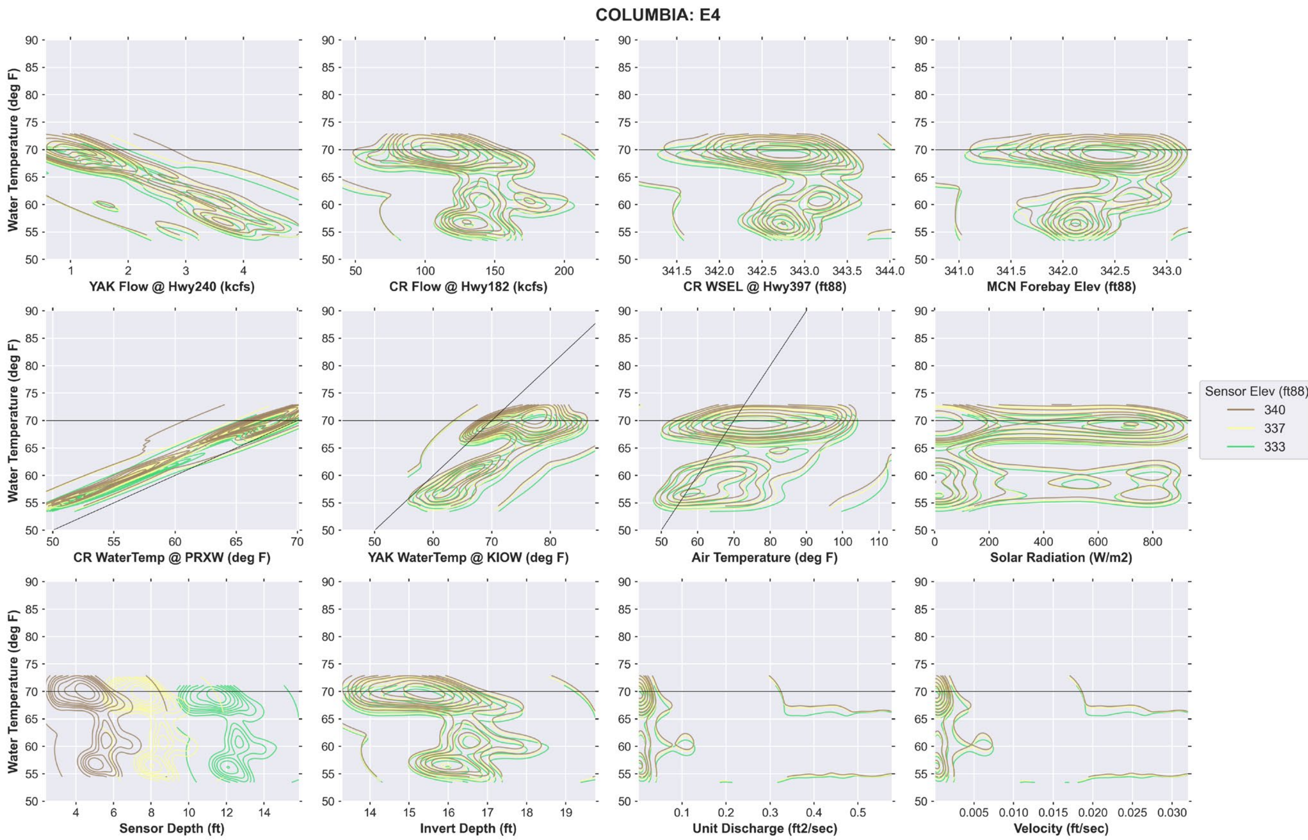


Figure 3-11. Kernel Density Estimate plots of measured summer 2021 water temperatures versus various exogenous parameters at site E4 on the East Side of the Bateman Island causeway.

Table 3-6. Spearman Rank Correlation Coefficients for Water Temperature at Site E4 versus various parameters by Sensor @ Elevation.

Parameter	**E4_333 (deepest)**	**E4_337 (middle)**	**E4_340 (shallowest)**
Yakima Flow @ Hwy 240 (kcfs)	-0.585	-0.579	-0.569
CR Flow @ Hwy182 (kcfs)	-0.593	-0.589	-0.605
CR WSEL @ Hwy397 (feet)	-0.291	-0.287	-0.305
MCN Forebay (feet)	0.052	0.057	0.039
CR Water Temp @ PRXW (deg F)	**0.942**	**0.942**	**0.949**
Yakima Water Temperature @ KIOW	**0.715**	**0.736**	**0.742**
Air Temperature (deg F)	0.347	0.361	0.394
Solar Radiation (deg F)	-0.061	-0.084	-0.097
Sensor Depth (feet)	-0.589	-0.585	-0.604
Invert Depth (feet)	-0.589	-0.585	-0.604
Unit Discharge	-0.452	-0.442	-0.440
Velocity	-0.425	-0.414	-0.408

3.5.1.2 Baseline Water Temperature Index simulation

Provisional Flow-3D baseline index temperature simulations indicates substantial mixing of warmer Yakima River flows into the west Bateman area during the spring, transitioning to near zero mixing in the summer (Figure 3-12). Under baseline conditions, Columbia River flows do not mix in the west Bateman area regardless of index season. In the north delta area, Columbia River flows frequently mix in the deeper low shelf area what extends about a quarter mile west of the main Columbia River channel edge. Further west of this low shelf flows from the Yakima River appear to mix more frequently than those from the Columbia.

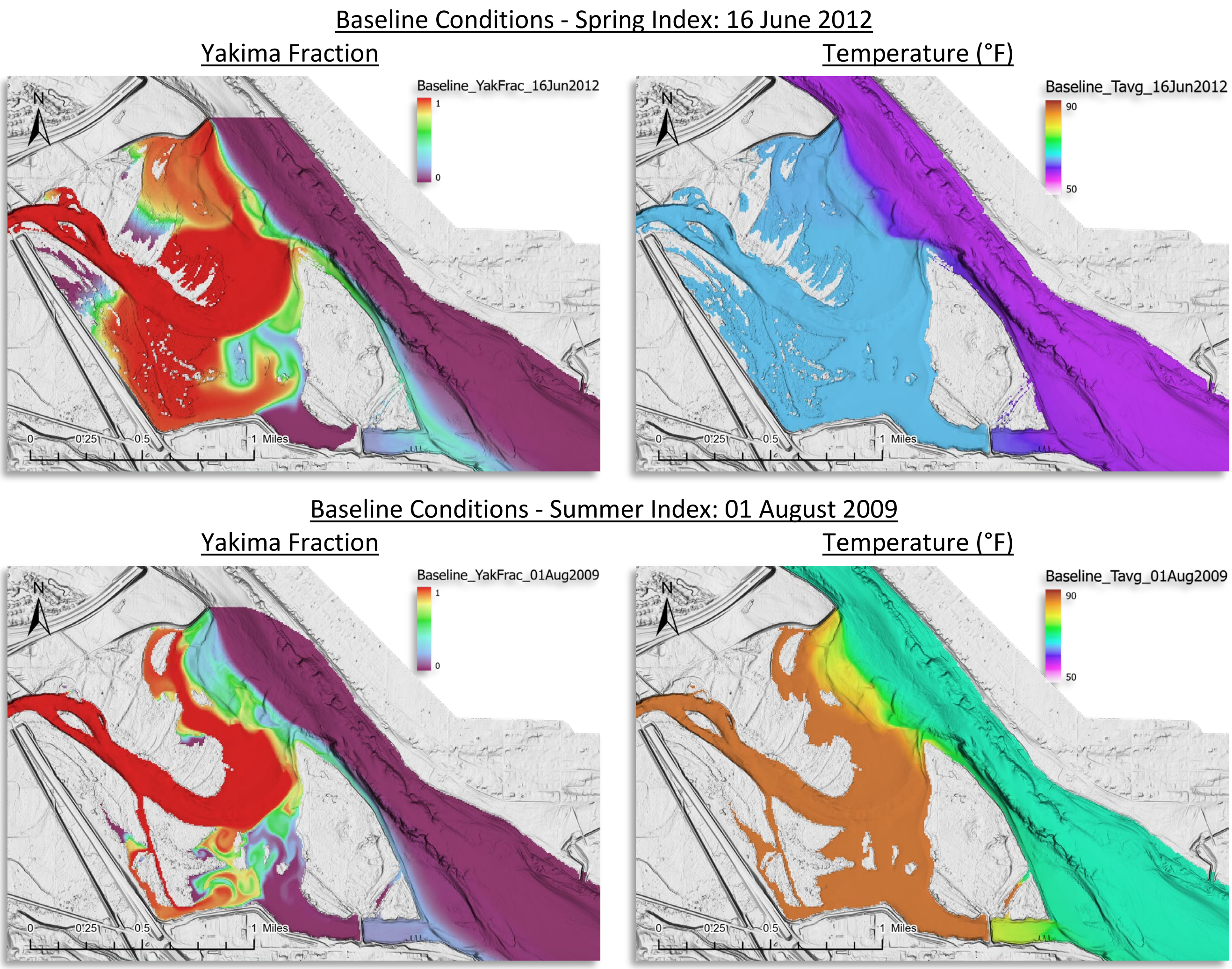


Figure 3-12. Baseline temperature simulation for late summer index conditions. (01Aug2009- High T, Low Q)

4 Measures Evaluation

Hydraulic and thermal evaluation of two select measures (Measures 5 and 7) was completed for this feasibility study. Measure 5 would be the installation of flow control structures intended to concentrate Yakima River flows to the main channel and increase vertical mixing (to reduce thermal stratification) while seasonally isolating the backwater west of Bateman Island. Measure 7 would be the complete or partial removal of the causeway intended to reduce temperatures in the areas west and south of Bateman Island by increasing the conveyance and mixing fraction of cooler Columbia River water.

4.1 Measure 5

The intent of Measure 5 would be to concentrate Yakima River flows to the main channel to increase velocities and provide/sustain deeper water and a cooler path for migrating adult salmon in the lower half-mile of the river delta. Concentration of Yakima River flows could be accomplished using a suite of submerged flow-control structures in various configurations constructed of rock or wood. The flow-control structures would be intended to promote a deeper thalweg and vertical mixing for the Yakima River to address thermal stratification.

A typical configuration could be a series of 4-6 structures installed along the right side of the Yakima River channel in the meander bend immediately upstream of the confluence at Bateman Island. The structures would tie into a constructed low bench (previously Measure#10) that would be set at a threshold elevation and project approximately 250-300 feet out into the Yakima River thalweg. The top of structure elevations were graded to transition from the low-bench tie-in down to the thalweg and maintain at 2/3 residual depth for recreational boat access. For the provisional configuration, the low bench tie-in elevation was set to be overtopped during the spring freshet, and would then serve to keep Yakima River flows separate from the West Bateman backwater as incoming flows drop over the summer. Other configurations for the low bench tie in would be different or variable tie-in elevations over the vertical profile or low-flow notches or swales to control the degree of seasonal connection and fish passage for Yakima River flows to the west Bateman area.

Measure 5A Grading Measure 5B Grading

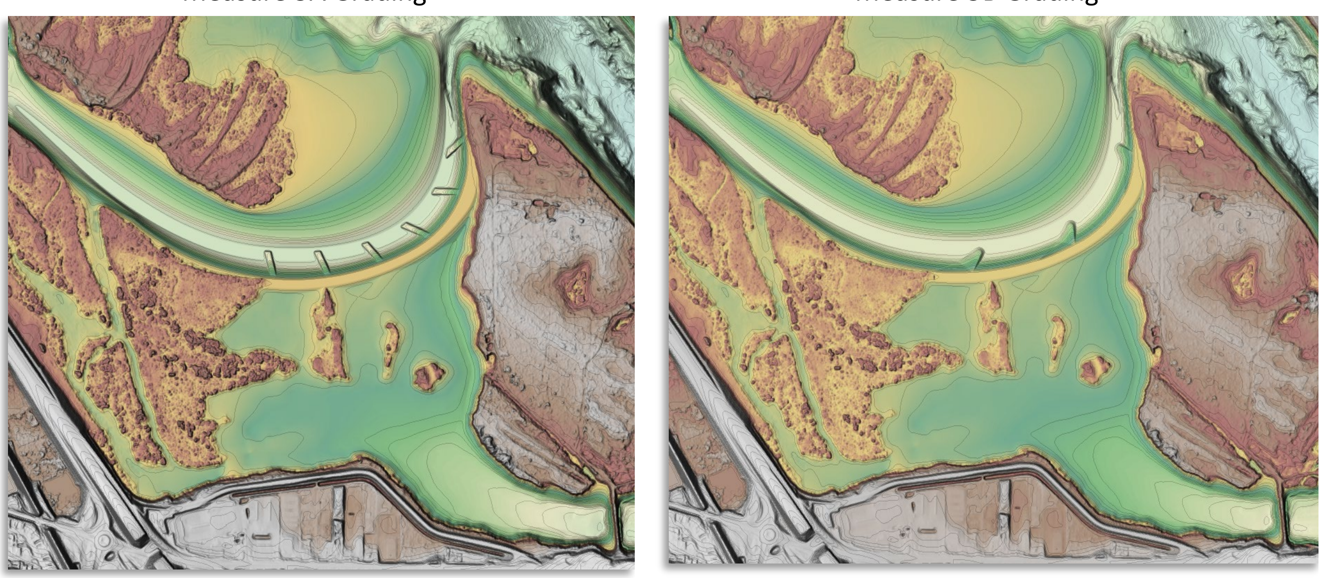
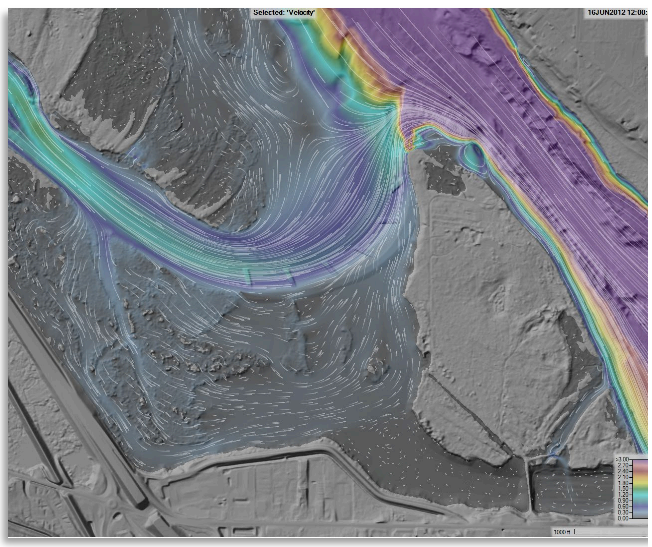


Figure 4-1. Overview of Measure 5 configuration geometries evaluated. Left: bendway weirs (M5a); Right: river barbs (M5b). Simulated velocity for spring freshet index condition 16Jun2012.

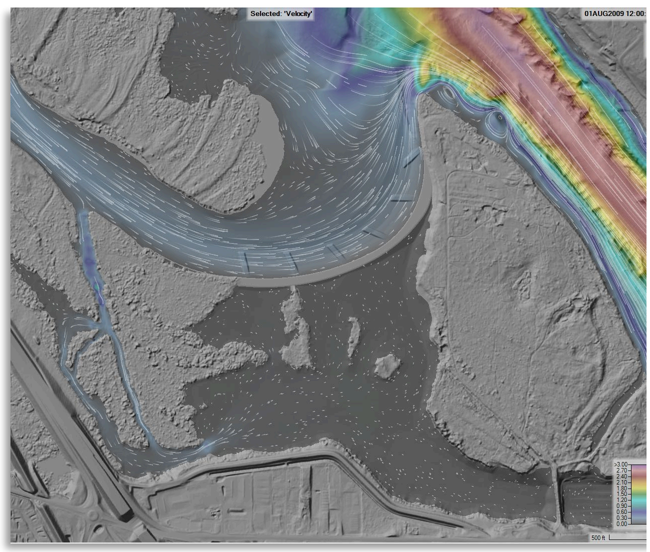
4.1.1 Measure 5 Hydraulic Trends

Hydraulic and thermal modeling of Measure 5 was limited to the two index conditions noted in Section 3.2.1 above. For spring index conditions (16June2012), Yakima River flows overtop the right overbank as well as the Measure 5 constructed low bench to allow for spring recharge and mixing. For summer index conditions (01 August 2009), the Yakima River flows remain concentrated to the main channel while the backwater west of Bateman Island is isolated from the main channel with the exception of a small backwater swale ~150+ feet wide that provides limited but consistent inflow to the west Bateman area. As would be expected, under Measure 5, Columbia River water does not mix in the lower Yakima channel or the west Bateman Area.

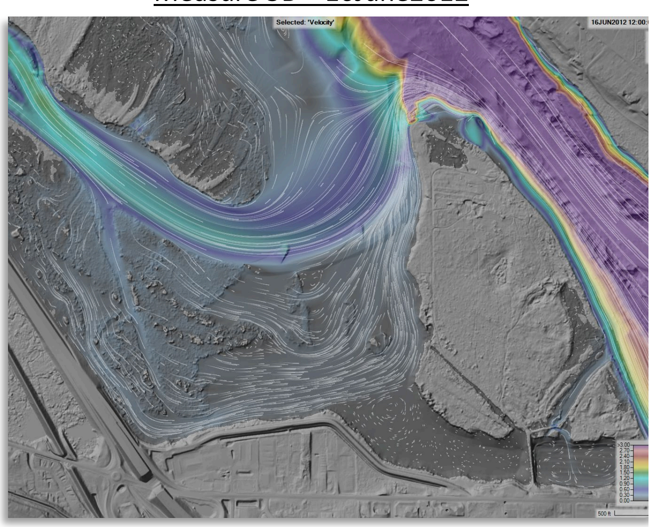
Measure 5A – 16June2012



Measure 5A – 01August2009



Measure 5B – 16June2012



Measure 5B – 01August2009

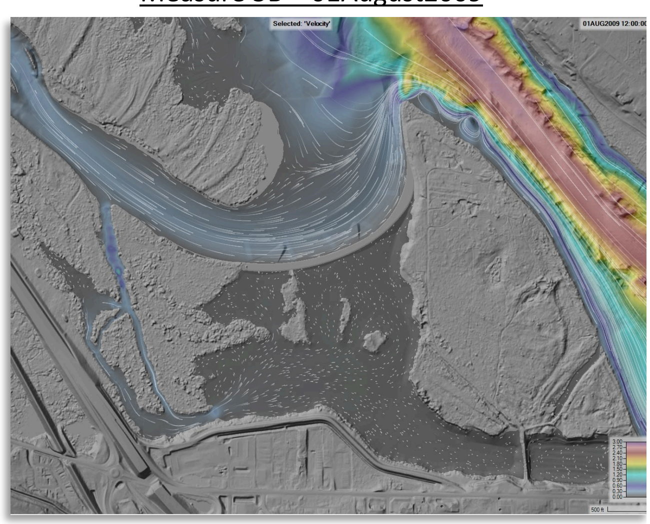


Figure 4-2. Overview of Measure 5 index velocity. Top: 5A, Bottom: 5B. Left: Spring Index - 16June2012, Right: Summer Index - 1Aug2009.

4.1.2 Measure 5 Temperature Trends

Provisional Flow-3D temperature simulations of Measures 5A (bendway weirs) and 5B (barbs) indicates a large degree of flow mixing between the Yakima River channel and the north delta area (Figure 4-3 and Figure 4-4). Although not quantified, this appears to diminish the degree of Columbia River flow mixing in the north delta area. In addition, due to the Measure 5 configuration, the west Bateman area tracked with the Yakima River inflow temperatures as expected.

Measure 5A: Bendway Weirs

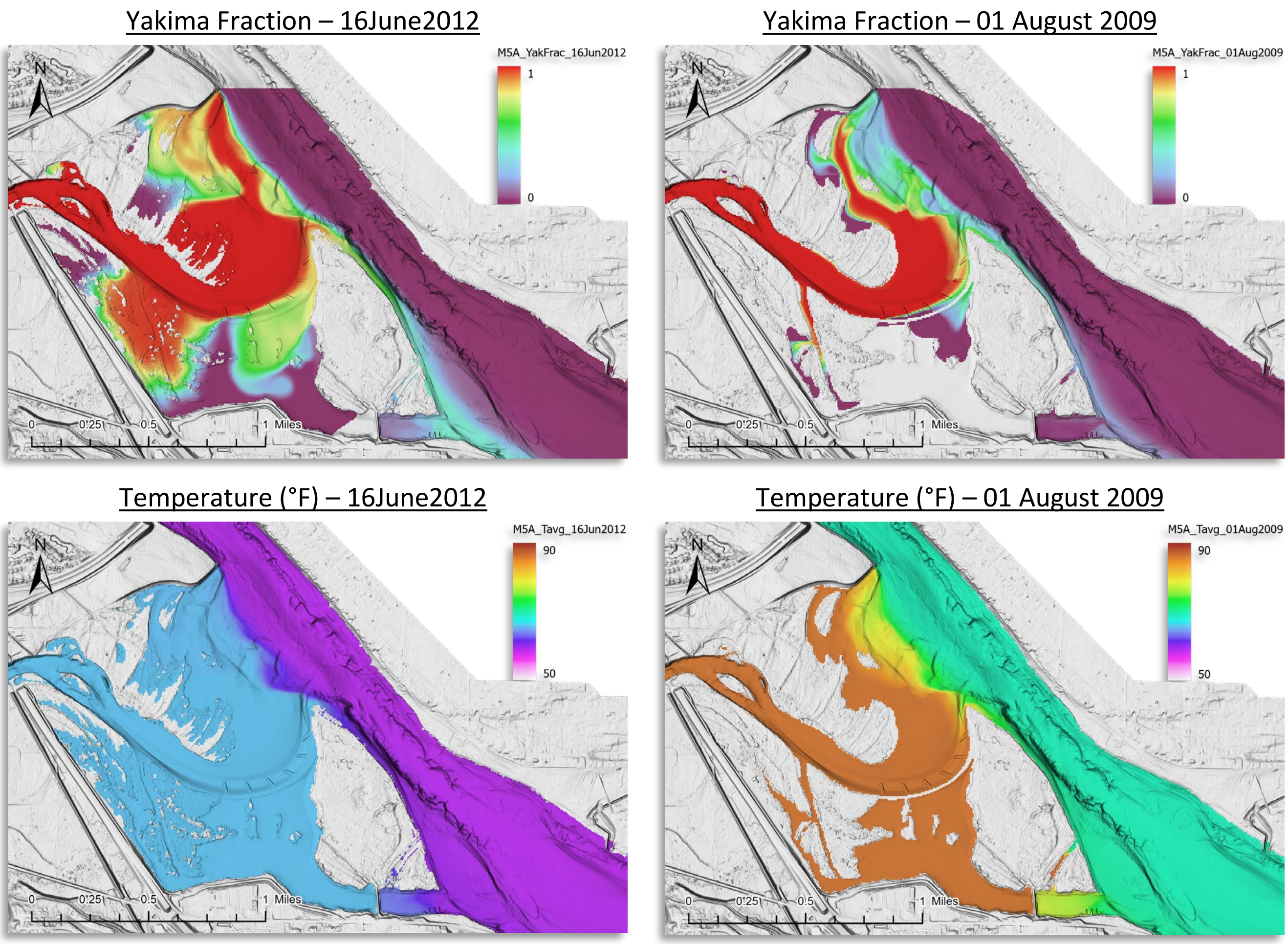


Figure 4-3. Overview of Measure 5A simulated index mixing fraction and temperature. Left: Spring Index - 16June2012. Right: Summer Index - 1Aug2009.

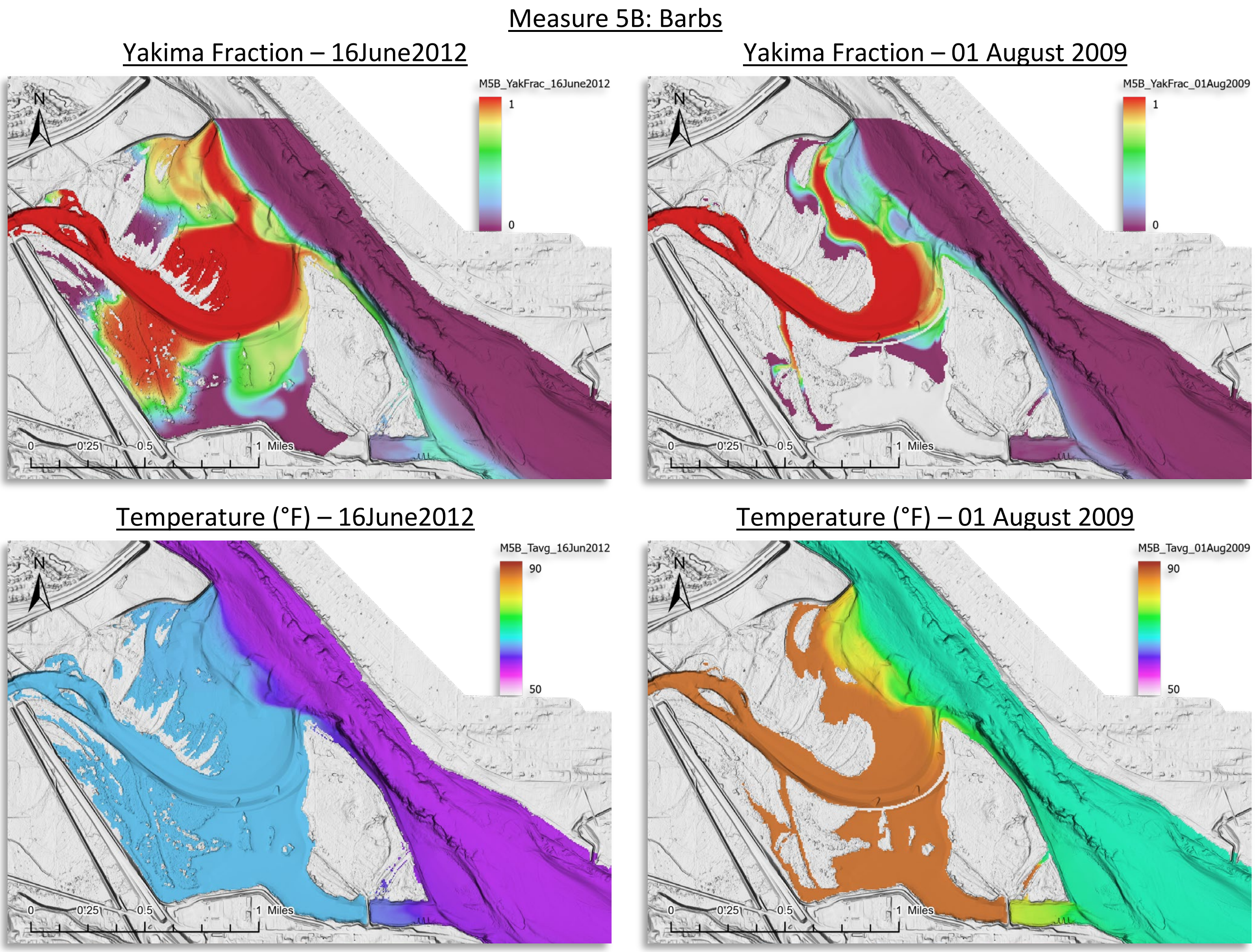


Figure 4-4. Overview of Measure 5B simulated index mixing fraction and temperature. Left: Spring Index - 16June2012. Right: Summer Index - 1Aug2009.

4.2 Measure 7

Measure 7 would include the partial or complete removal of the 560-foot-long Bateman Island causeway with the intent of improving the mixing of Columbia River flows with Yakima River flows to reduce temperatures in the area west of Bateman Island. Two scaling configurations for measure 7 were evaluated: C1 (full causeway removal) and, C2 (partial causeway removal of the North half). Grading for the full removal (C1) option blended adjacent grades and would transition to adjacent banklines by flattening with limited fill (versus excavation) and revegetation. In addition, the construction of a barrier levee (M1) to protect the Columbia Park Marina from increased velocity was also evaluated. The four Measure 7 configurations evaluated are depicted in Figure 4-5 below.

The evaluation for Measure 7 configuration included the simulation of hydraulic and flow mixing patterns around Bateman Island and how they may be affected by modifications to the existing causeway. Due to descoping, estimates of Measure 7 temperature response was limited to a scalar calculation of mixing temperature using the AdH 2D simulated fractions of Columbia and Yakima River flows respectively.

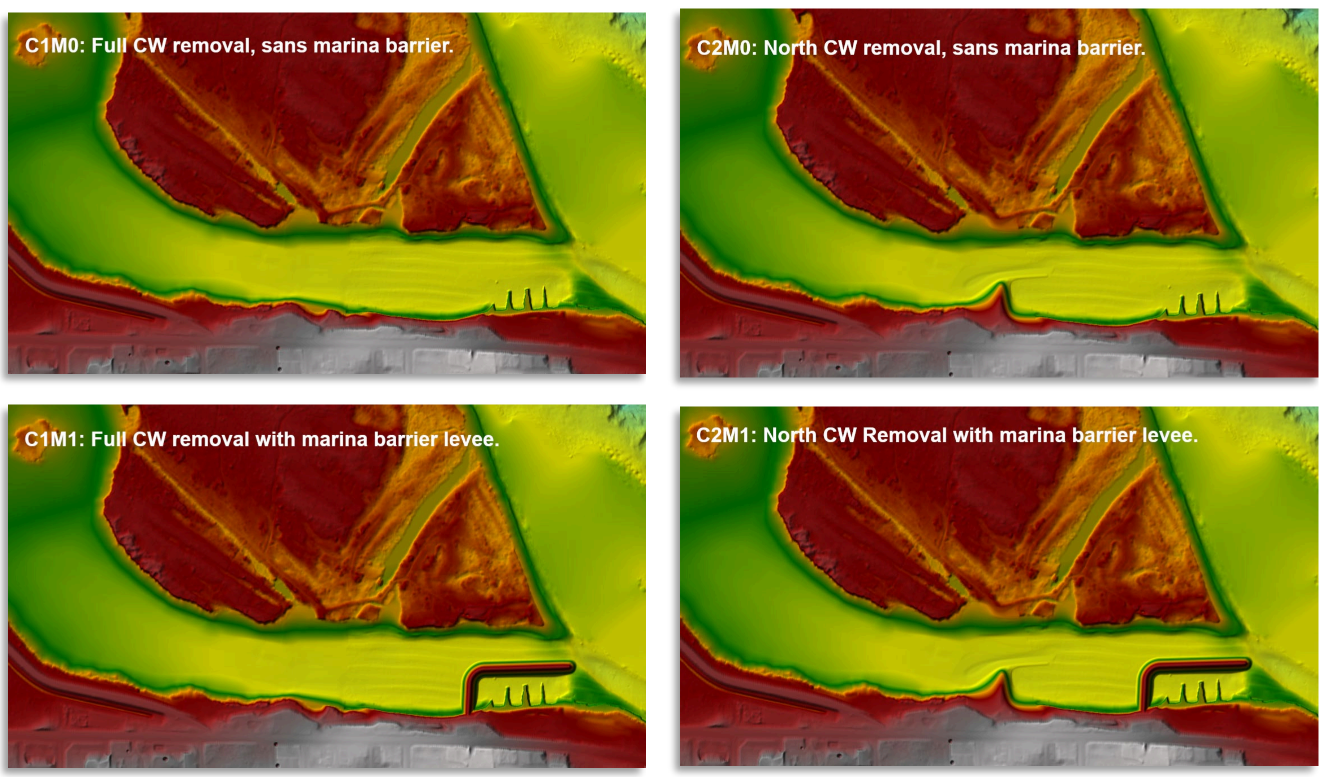


Figure 4-5. Overview of Measure 7 configuration geometries evaluated. Left: Full removal (C1); Right: Partial removal (C2); Bottom: with marina barrier levee (M1).

4.2.1 Measure 7 Hydraulic Trends

Relative to the near-zero baseline conditions west of Bateman Island, Measure 7 would significantly increase velocity and volumetric flow mixing of both Yakima and Columbia River water. Figure 4-6 below depicting net unit flow rates (in cfs/foot) illustrates a similar pattern of magnitude and extent for both the full (C1) and partial north (C2) causeway openings measures. One notable difference is that the partial north measure (C2), was characterized by a pattern of concentrated volume flux through the north opening associated with increased localized velocities. Despite increased flow through the causeway corridor, the mixing fraction and duration of Columbia River water varies depending on boundary conditions and is transient. See Section 4.2.2 below.

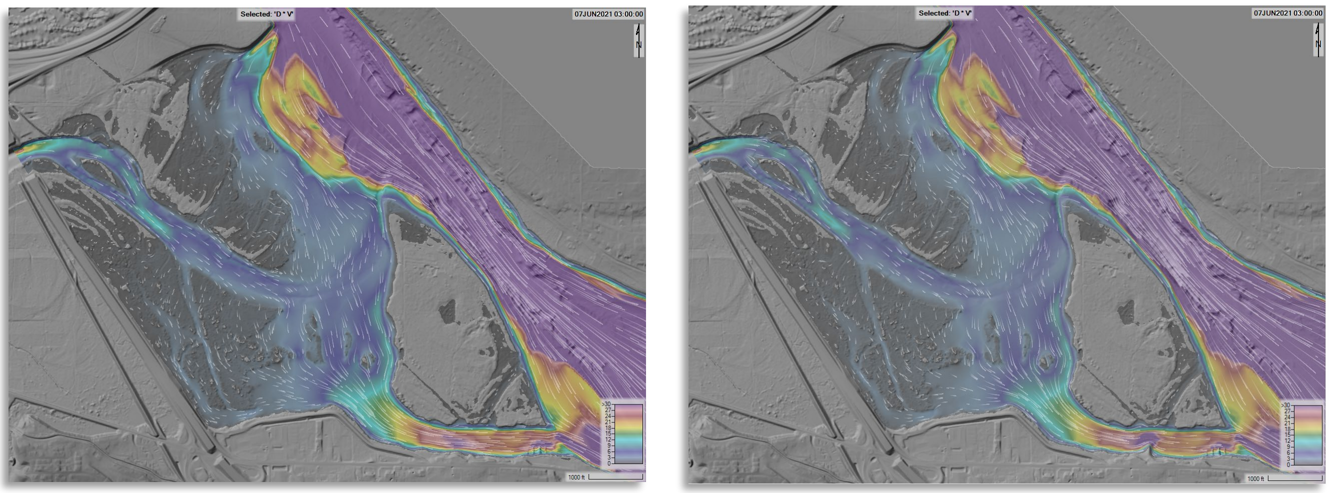


Figure 4-6. Measure 7 model simulation depicting unit discharge on 7June2021 from 0 to >30 cfs/ft. Left: full causeway removal (C1); Right: partial north causeway removal (C2).

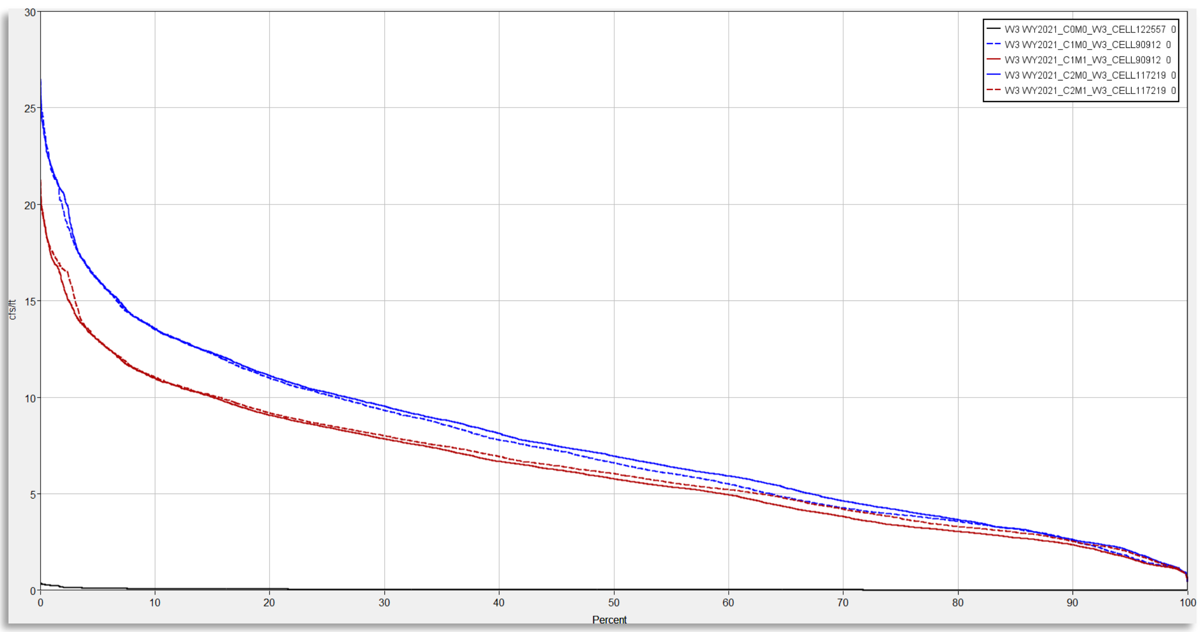


Figure 4-7. Exceedance duration of simulated unit discharge (cfs/foot) at site W3 for 15Apr through 15Nov - Water Year 2021. *Note the C0 baseline of near-zero conveyance at the bottom of the plot.*

Measure 7 – Water Surface Elevations and Depths

As discussed in Section 2, water surface elevations and corresponding depths in the Yakima Delta study area are notably influenced by Lake Wallula pool levels upstream of MCN. As depicted in Figure 2-4, the Lake Wallula stage on the Columbia River downstream of the Yakima Delta study area (USGS 12514500, Clover Island gage), is operated over a typical range of 3 to 5 feet to regulate inflows from the Columbia, Snake, and Yakima Rivers and manage hydropower demands of the greater FCRPS. Despite the sub-daily forebay operations of MCN, the median daily stage and the inner quartile range of Lake Wallula stage at Clover Island fall within a one-foot elevation band (342 – 343 feet NAVD88) year-round, except during the spring freshet in May and June when the IQR upper band (75% percentile) can increase an additional foot and daily maximum stage can be three feet higher than median conditions.

As observed in the field, hydraulic simulations of the study area confirm that water surface elevations around Bateman Island are predominately in equilibrium with the downstream stage of Lake Wallula. With the existing causeway in place, localized stage to the west of Bateman Island can exhibit minor increases on the order of <0.5 feet associated with Yakima River inflows in the spring which decreases as Yakima inflows drop in the summer. As illustrated in Figure 4-8 below, small increases in baseline water surface elevations of <0.2 feet to the west of Bateman Island were predicted to shift downstream with the causeway removed during the spring and diminish to near-zero change east of the causeway as summer progresses. These transient changes in localized stage are expected to be negligible, especially when considering the much larger sub-daily variability in MCN operations and corresponding Lake Wallula stage.

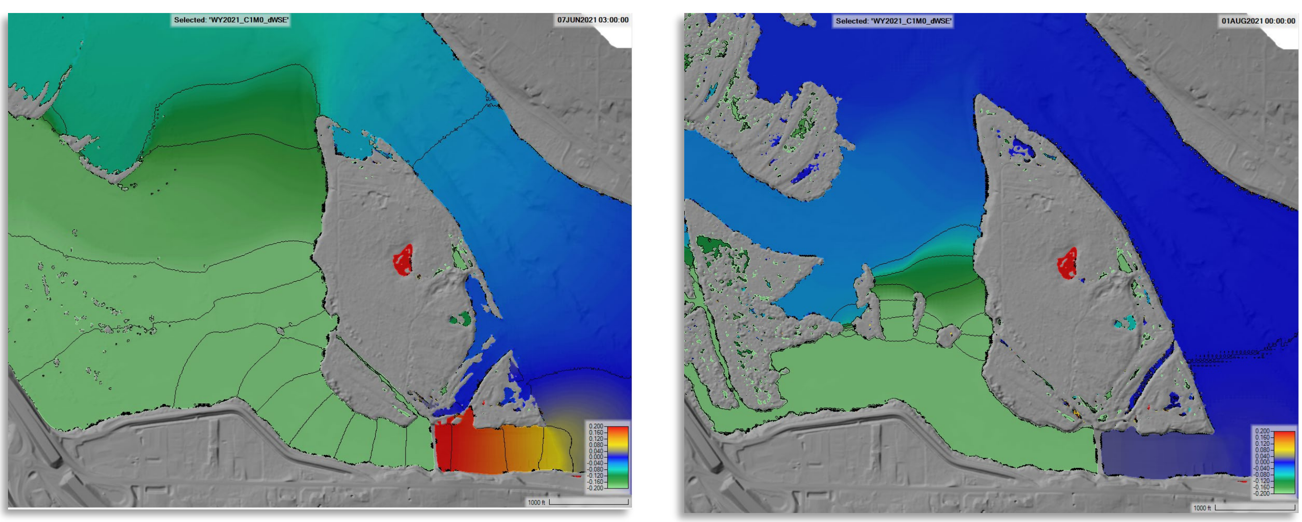


Figure 4-8. Comparison of simulated water surface elevations for full causeway removal (C1) minus baseline conditions (C0). *Legend range spans from -0.2 feet (green) to 0.0 feet (blue) and +0.2 feet (red) with a 0.05 foot contour interval. Left: 07June2021. Right: 01August2021.*

Measure 7 - Causeway Velocities & Marina Protection

The Columbia Park Marina is located within an existing hydraulic shadow on the east side of the Bateman Island causeway. Project stakeholders raised concerns that complete or partial removal of the causeway under Measure 7 could increase velocities at the marina and impact operations.

One approach to protecting the marina with all or part of the causeway removed would be the installation of a levee or equivalent structural measure to isolate the marina from flows along the south side of Bateman Island. A conceptual barrier levee alignment was developed that tied into the south bank just upstream of the marina, projecting ~275 lf out into the channel and then turning east for another ~650 lf to catch the existing channel bed elevation at the right edge of the main Columbia River channel. The projection length was set with consideration for providing a 50'W offset distance between the end of the existing marina docks and levee toe. The top of the barrier levee was set at a nominal elevation of 355 feet NAVD88 (to match the adjacent parking lot grade) with a 12-foot top width and 3H:1V side slopes. With the barrier levee in place, the effective hydraulic top width for the Bateman Island south channel would be reduced from ~550' to ~250', a ~55% reduction.

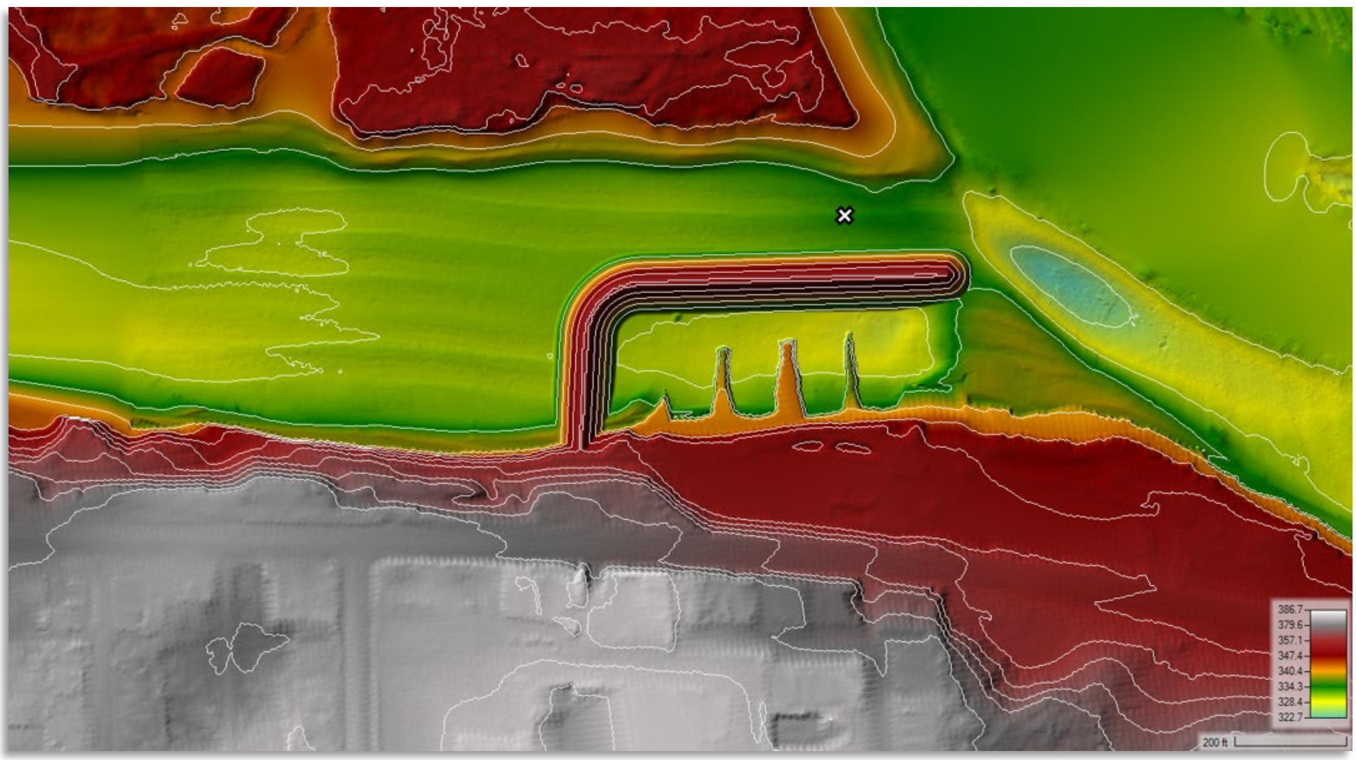


Figure 4-9. Layout for conceptual marina protection barrier levee M1 with velocity sampling location depicted.

As depicted in Figure 4-9 above, one possible barrier levee configuration was evaluated for both the full causeway removal (C1M1) and the partial causeway removal (C1M2). With the causeway either partially or fully removed, for water year 2021, the median baseline velocity of ~0.25 ft/sec was predicted to increase to ~0.75 ft/sec. The addition of the conceptual marina barrier would increase the median velocity further to ~2.0 ft/sec. Hydraulic simulation results predicted nearly equivalent velocity distributions at the marina, for both the full and partial north causeway removal measures.

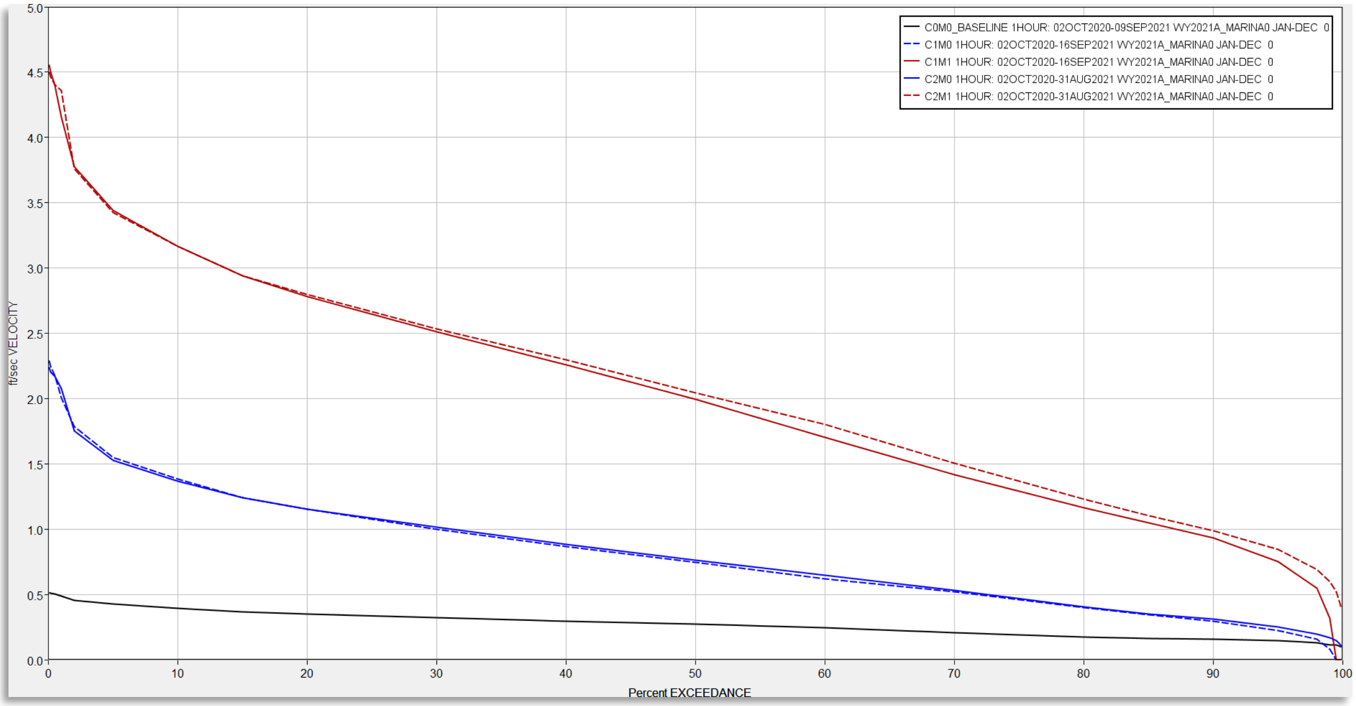


Figure 4-10. Exceedance duration of simulated velocity at the Marina causeway for Water Year 2021.

Four sets of extreme loading index boundary conditions were simulated to represent a nominal range of velocity duration and annual exceedance probability (Section 3.2.1, Table 3-2). These boundary conditions were applied for the velocity modeling simulations at the Columbia Park Marina as presented in Figures 4-11 and 4-12. In addition, a cursory evaluation of hydraulic forces on the M1 barrier levee was conducted by sampling shear stress at various model locations in the causeway as depicted in Figures 4-13 through 4-15.
Although the magnitude of estimated velocity and shear stress in the causeway corridor are larger than baseline conditions, they are not prohibitive to constructing a stable barrier levee for the marina with revetment along the North bank-line of Bateman Island to mitigate for localized erosion potential.

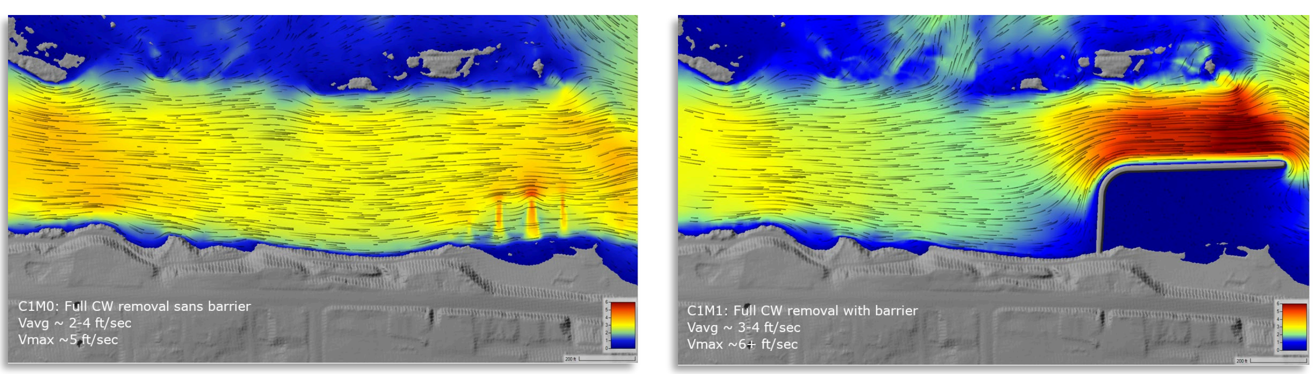


Figure 4-11. Simulated velocity for full causeway removal without (left) and with (right) marina barrier measure.

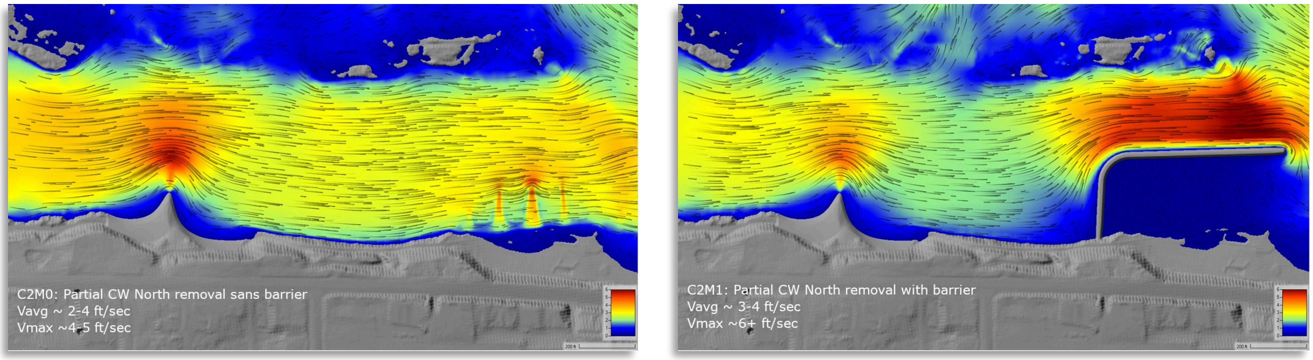


Figure 4-12. Simulated velocity for partial north causeway removal without (left) and with (right) marina levee barrier measure.

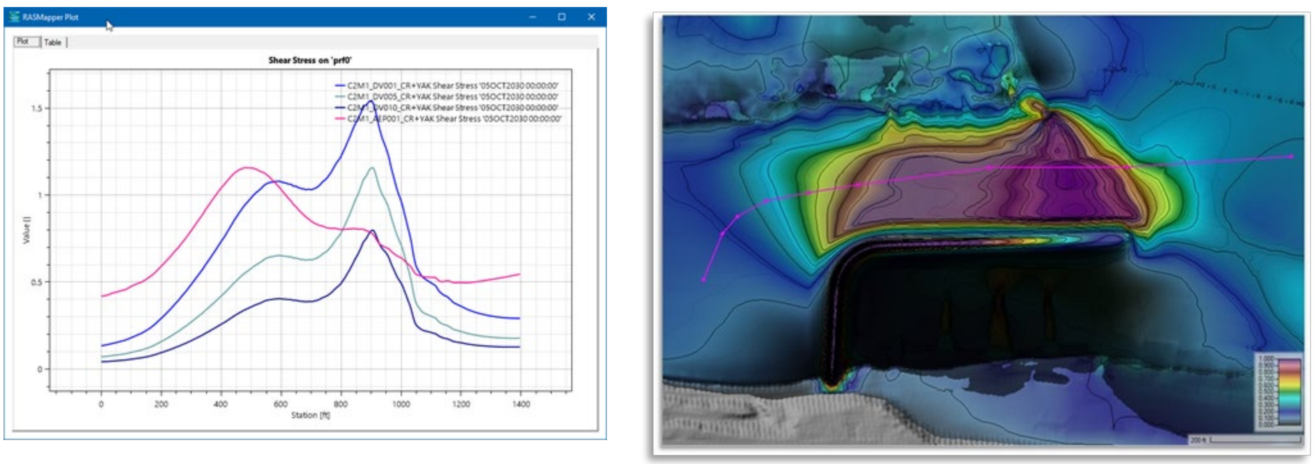


Figure 4-13. Shear Stress Profile along open causeway on North side of M1: Levee Marina Barrier

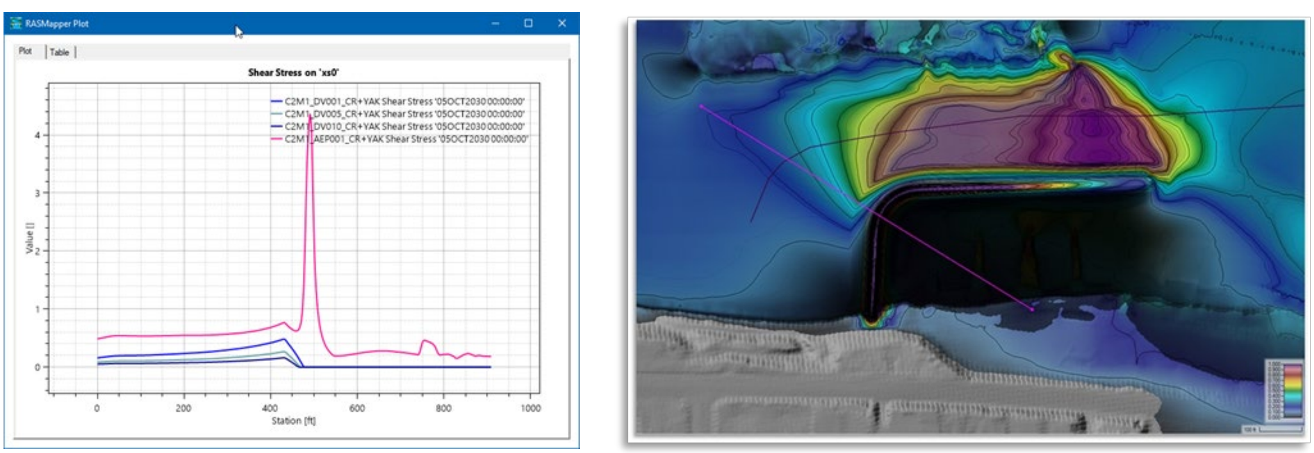


Figure 4-14. Shear Stress Cross-Section across upstream side of M1: Levee Marina Barrier

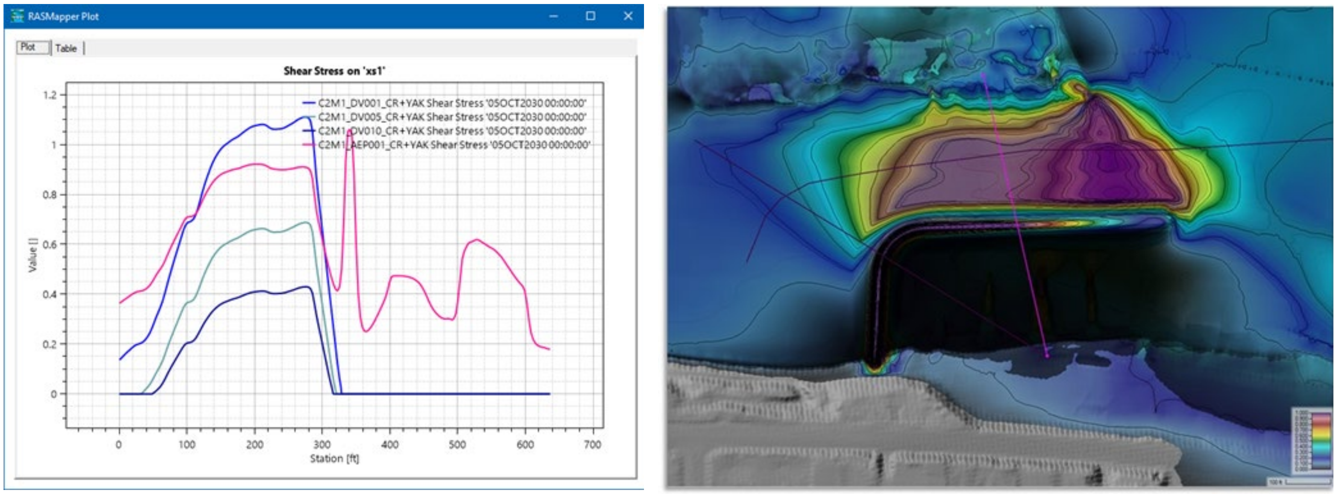


Figure 4-15. Shear Stress Cross-Section across M1: Levee Marina Barrier

4.2.2 Measure 7 Flow Mixing Trends

As noted above, while opening the causeway in Measure 7 increases flow through the corridor, the magnitude and duration of Columbia River water mixing fraction varies depending on boundary conditions and is transient at the sub-daily scale. Simulations of the spatial extent of Columbia River water mixing west of Bateman Island using the depth averaged AdH 2D model (Figure 4-16) indicates that these pulses of cooler flow are concentrated primarily to a relic thalweg conveyance that links deeper pools from sites W1 through E4. Despite the reduced resolution and age of the bathymetric data west of Bateman Island (see Section 3.1), the spatial extent and relative depth of this relic thalweg was verified during WY 2021 field visits. While not considered for this assessment, there may be potential for additional relic channels further west of Bateman to reactivate with increased flow and flushing of fine sediment which could help expand the diffusion and mixing patterns of cooler Columbia River water under Measure 7. Note that even with reduced mixing, the opening of the Causeway will allow for ongoing flux of Yakima River flows which despite being warmer could still help to diminish impacts from meteorological loading, thermal stratification, and water quality.

Figure 4-16 depicts mixing for three AdH 2D simulated conditions on 28-June-2021. Under baseline (C0) conditions, all water west of Bateman is sourced from the Yakima River, and Columbia River water does not flow south of Bateman Island. Under both Measure 7 configurations, the simulation estimates notable mixing west of Bateman Island. While the presence of the south causeway for Measure 7 C2 does create a localized mixing effect in the causeway corridor, the effect was not observed extending substantially upriver or downriver. This was further evaluated by accumulating the unit discharge (cfs/foot) for discrete Columbia and Yakima River flow fractions over a six-month freshet simulation period of Mar-1 to Sept-1, 2021. As illustrated in Figure 4-17, under Measure 7, the cumulative unit volume through the causeway corridor peaked at approximately 800 acre-feet/foot regardless of the full (C1) or partial north (C2) removal. The effect on Measure 7 volumetric throughput between full and partial north removal is illustrated as a difference plot (Figure 4-18) which depicts a localized symmetric offset of ~350 acre-feet/foot coincident with the velocity increases previously noted in Section 4.2.1 above. Thus, the net conveyance volume through the full (C1) and partial (C2) causeway removal scenarios is effectively equal.

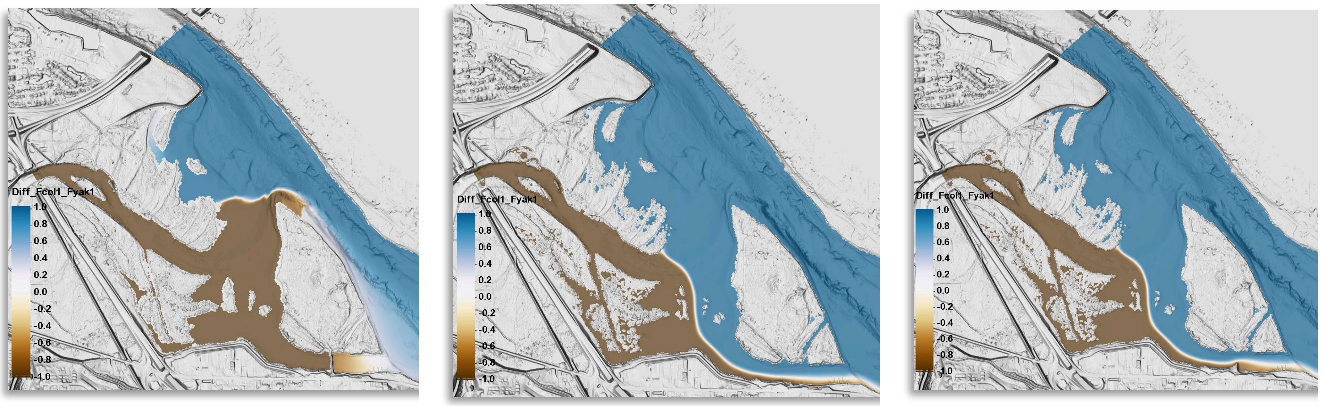


Figure 4-16. Simulations depicting mixing fractions of Columbia and Yakima River flows around Bateman Island on 28-June-2021. Left: Baseline (C0M0), Center: Full Causeway Removal (C1M0), Right: Partial North Causeway Removal (C2M0).

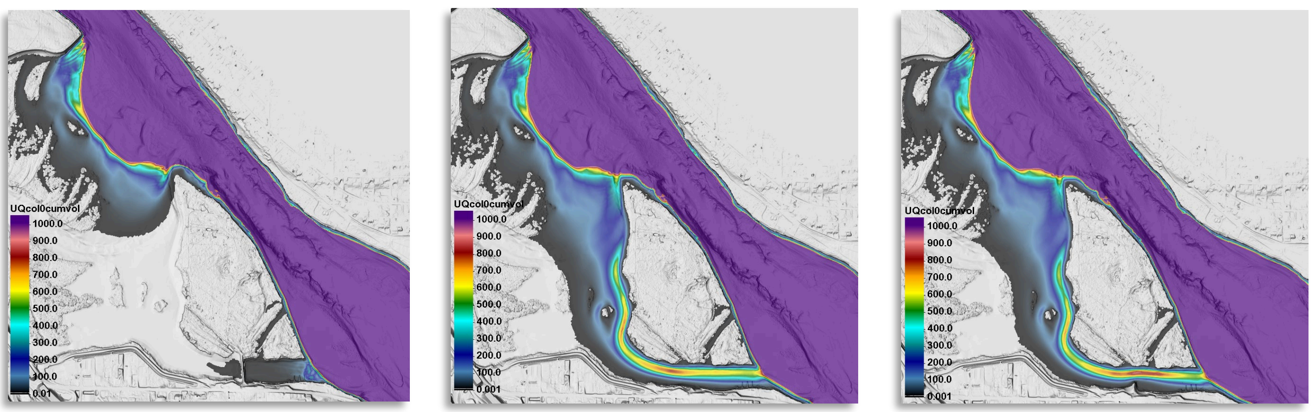


Figure 4-17. Simulated cumulative unit volume (acre-feet per foot) of Columbia River Water for March to September, 2021. Left: Baseline (C0M0), Center: Full Causeway Removal (C1M0), Right: Partial North Causeway Removal (C2M0). Note upper scale clipped to ≥1kaf/ft to highlight Yakima delta patterns.

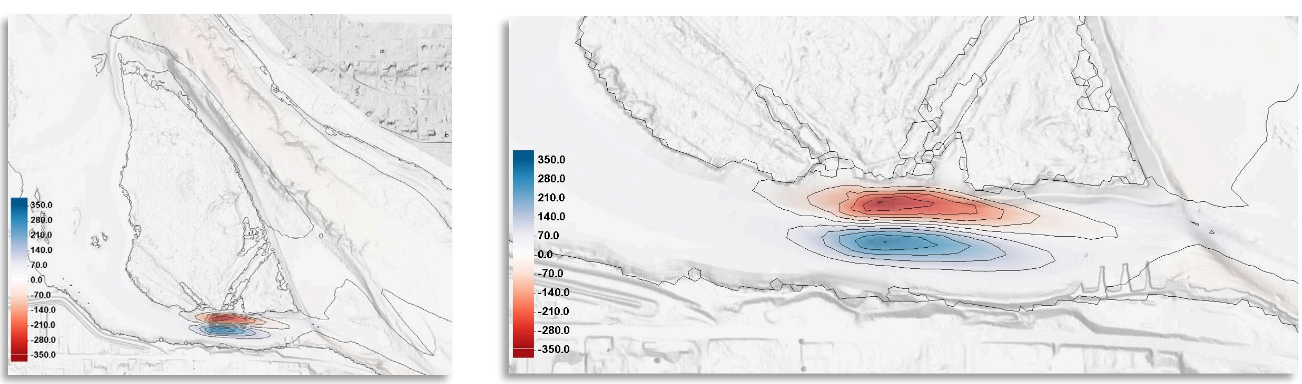


Figure 4-18. Difference in simulated cumulative unit volume (acre-feet per foot) between Full Causeway Removal (C1) and partial North Causeway Removal (C2) sans marina barrier over the March to September 2021 duration. *Left: study area. Right: zoom to causeway corridor.*

4.2.3 Measure 7 Mixing Ratings

Mixing fractions of Columbia and Yakima River flow volumes at select points were extracted from WY 2021 simulation results for both Measure 7 configurations. As depicted in Figure 4-19 below, the flow mixing fraction West of Bateman under Measure 7 would vary with the magnitude and ratio of the Columbia and Yakima River flow sources. One interesting pattern is the large degree of mixing predicted to occur in July and August at W3 when Yakima River flows drop below 1kcfs and Columbia River flows are above 100kcfs.

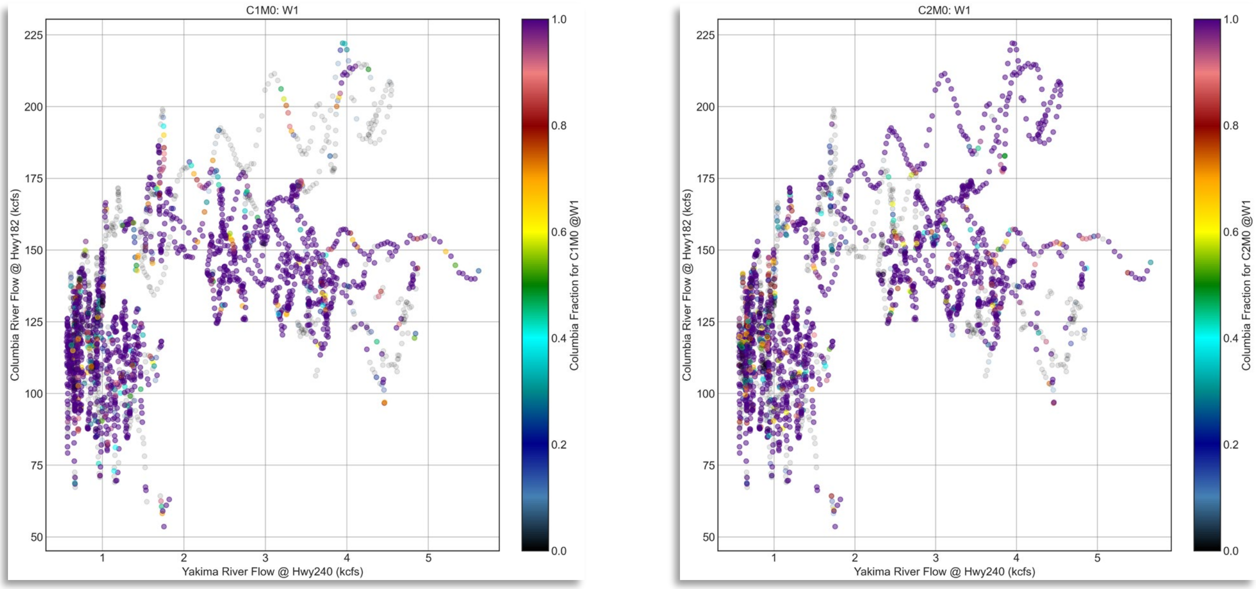


Figure 4-19. Simulated Columbia River flow fraction at Site W1 for WY2021. Left: Full causeway removal (C1M0), Right: Partial north causeway removal (C2M0)

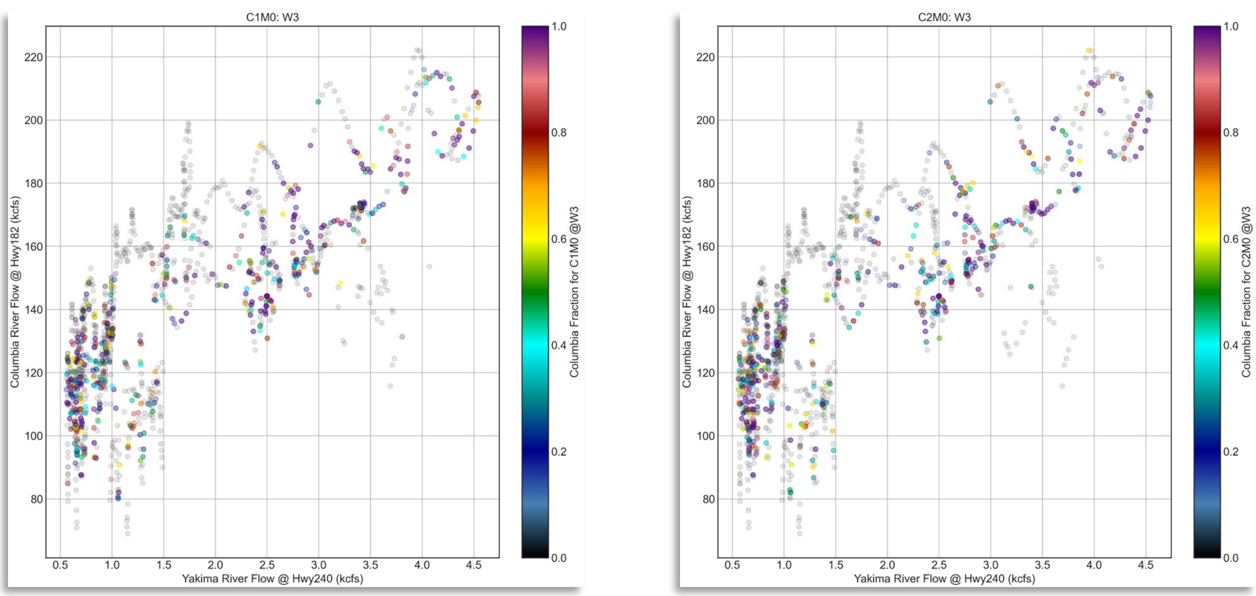


Figure 4-20. Simulated Columbia River flow fraction at Site W3 for WY2021. Left: Full causeway removal (C1M0), Right: Partial north causeway removal (C2M0)

Flow fractions were used to develop provisional mixing ratings at select sites as a linear function of the Columbia and Yakima River inflows using weighted least squares (WLS) regression with a convolving gaussian kernel. As a linear response, the ratings are an over-simplified representation intended to develop a provisional flow mixing hindcast over an extended duration for quantifying relative departure in duration. The addition of downstream stage as a third WLS predictor was considered but not found to improve the WLS response for the WY 2021 input simulation data available. The provisional mixing ratings currently under-predict peak Columbia fractions, topping out around 0.7, despite simulation estimates indicating that peak mixing can reach unity in select locations. This underprediction results in conservative (i.e. warmer) estimates of mixing temperature response which was deemed acceptable for this feasibility level assessment. Nonetheless, the ratings would benefit from a more robust cluster regression or ML method with improved training data to capture hysteresis and other transient mixing effects.

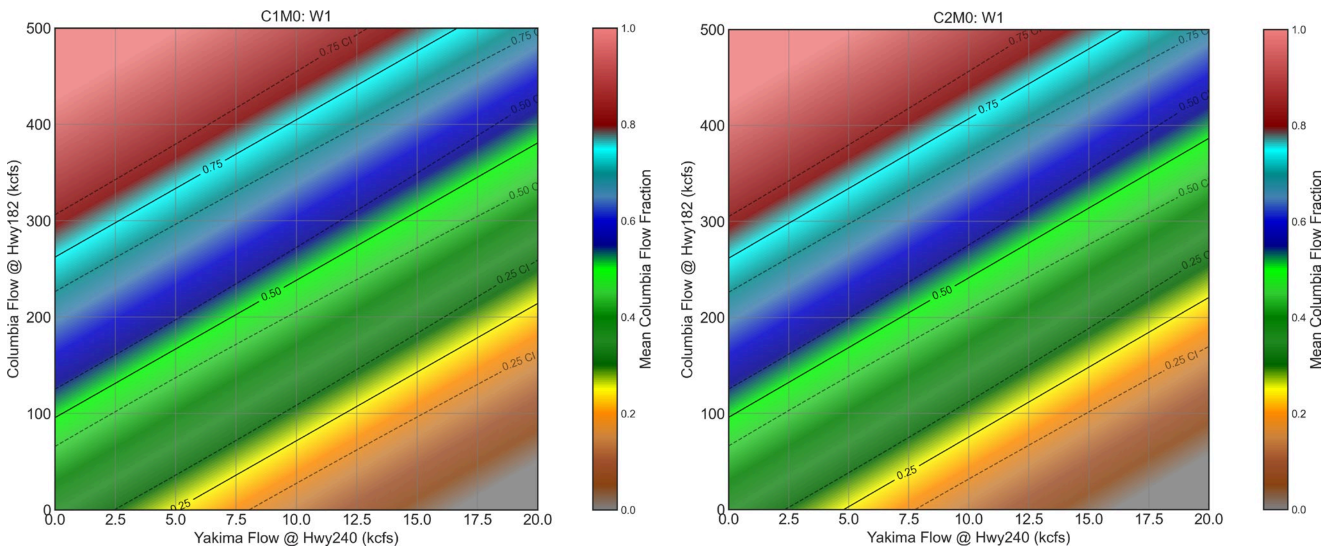


Figure 4-21. Provisional ratings with α=0.05 for Columbia River flow fraction at Site W1 near the north end of Bateman Island. Left: Full causeway removal (C1M0), Right: Partial north causeway removal (C2M0).

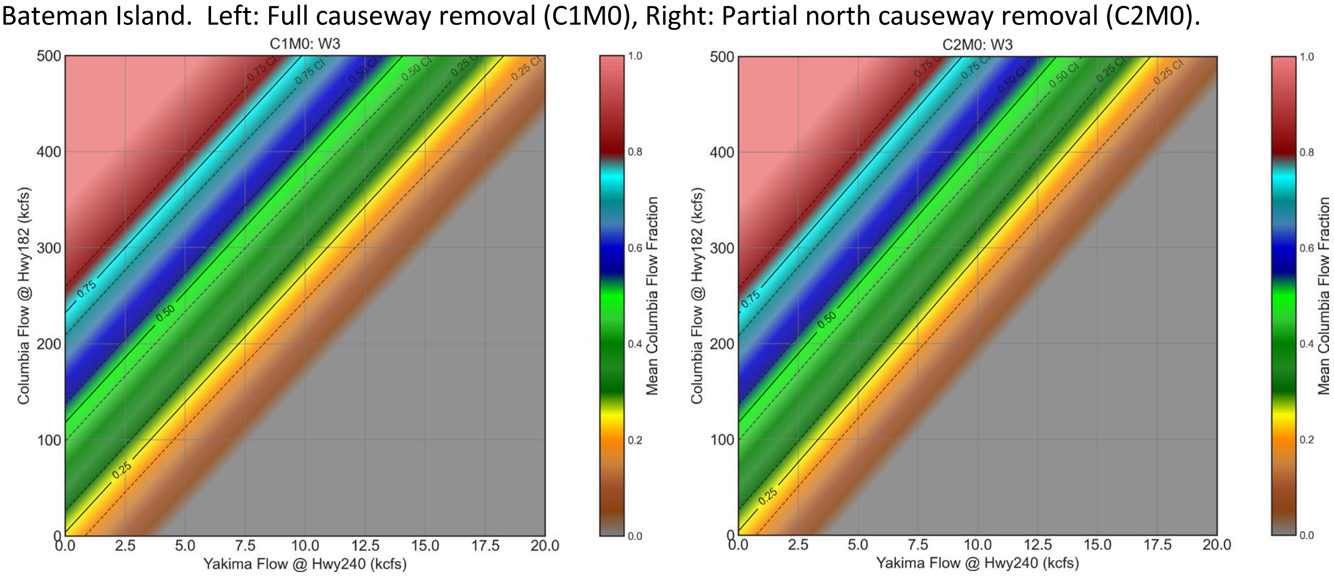


Figure 4-22. Provisional ratings with α=0.05 for Columbia River flow fraction at Site W3. Left: Full causeway removal (C1M0), Right: Partial north causeway removal (C2M0).

The provisional mixing ratings were then applied to develop daily hindcast estimates for the available period of record between water year 1988 and 2020 (Figures 4-23 and 4-24). At site W3, the hindcast mixing response was very similar for the two Measure 7 configurations: C1 and C2. Conversely at Sites W4 and E4, both located in the hydraulic shadow of the partial north causeway removal (Measure 7, C2), the localized mixing difference is more pronounced between the two configurations (Figure 4-24). As previously illustrated in Figure 4-18, this is due to the symmetric offset in unit discharge between the C1 and C2 configurations.

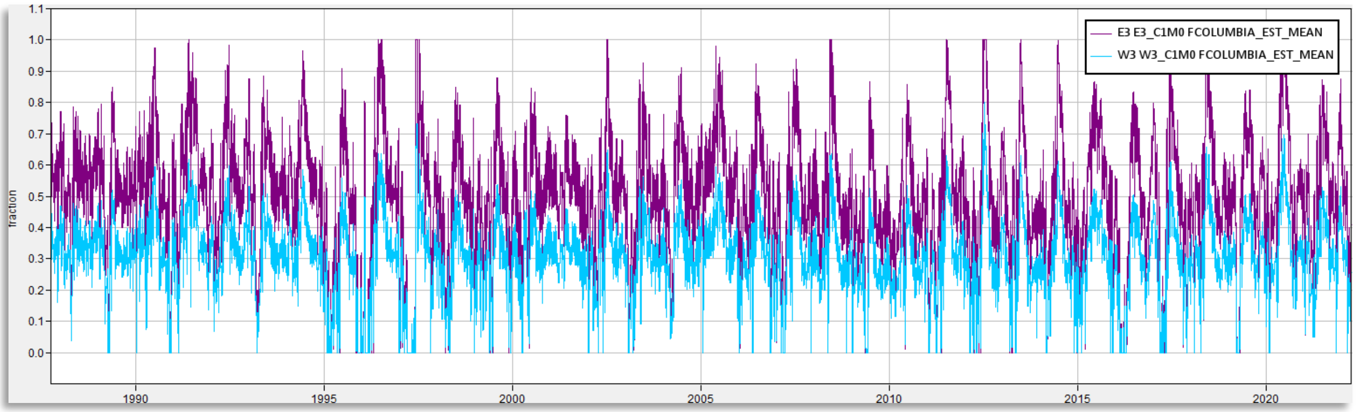


Figure 4-23. Timeseries of provisional hindcast for Columbia River flow fraction at site W3 for WY 1988 to 2020.

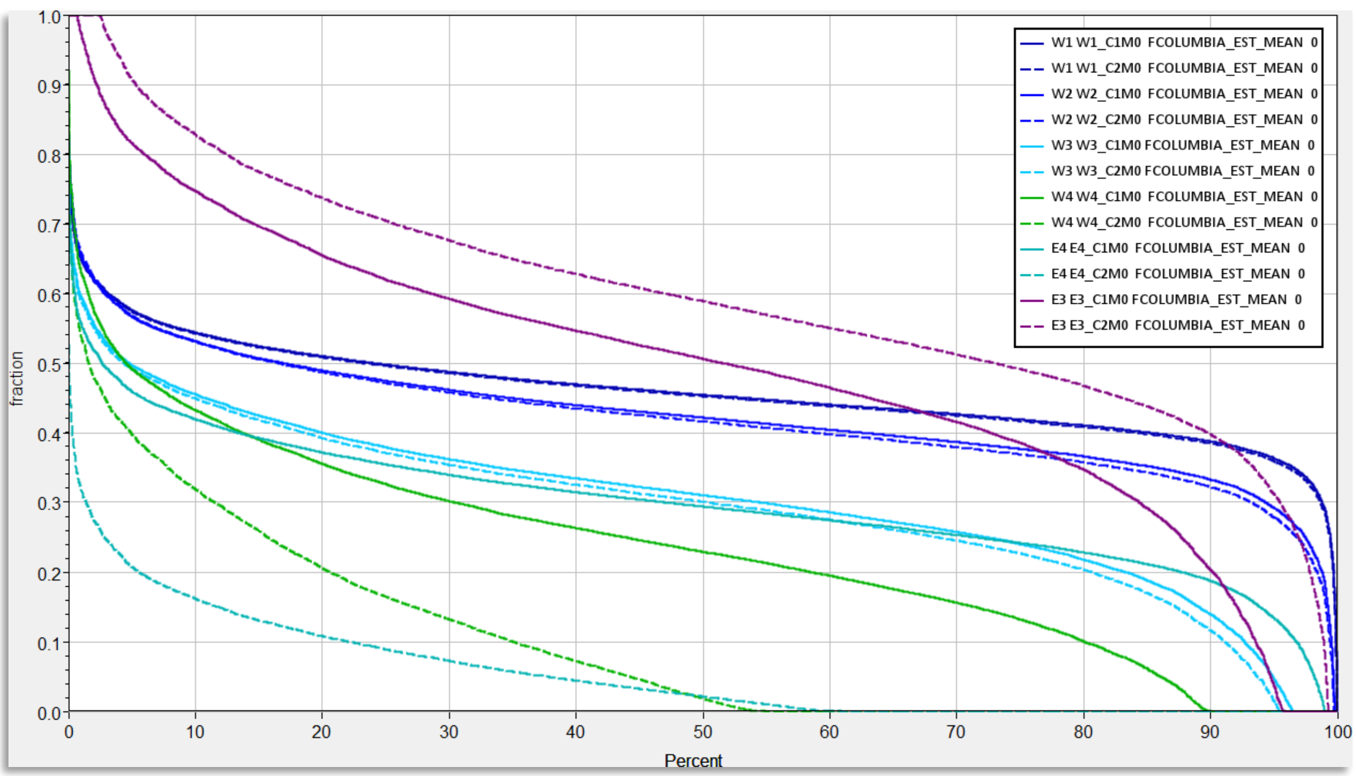


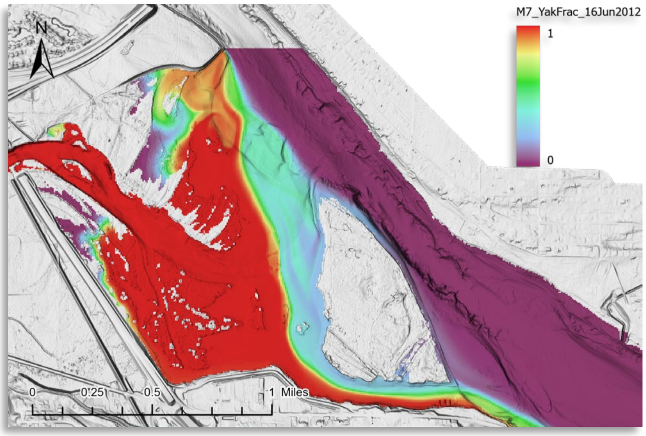
Figure 4-24. Exceedance duration of provisional hindcast Columbia River flow fraction for Measure 7 at select sites for WY 1988 to 2020.

4.2.4 Measure 7 Temperature Trends

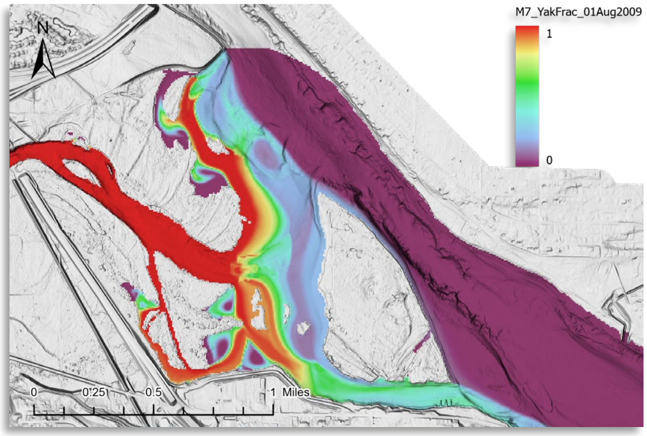
Provisional Flow-3D temperature simulations of Measure 7 indicates improved mixing and decreased temperatures in the both the north delta and west Bateman Island areas both the spring and summer index conditions as illustrated in Figure 4-25 below.

Measure 7(C1): Full Causeway Removal

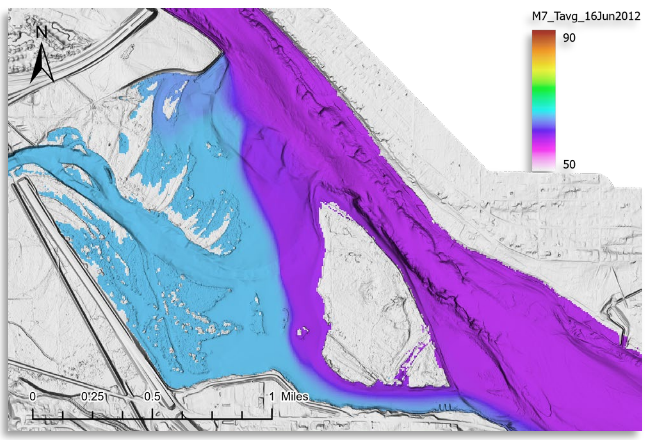
Yakima Fraction – 16June2012



Yakima Fraction – 01 August 2009



Temperature (°F) – 16June2012



Temperature (°F) – 01 August 2009

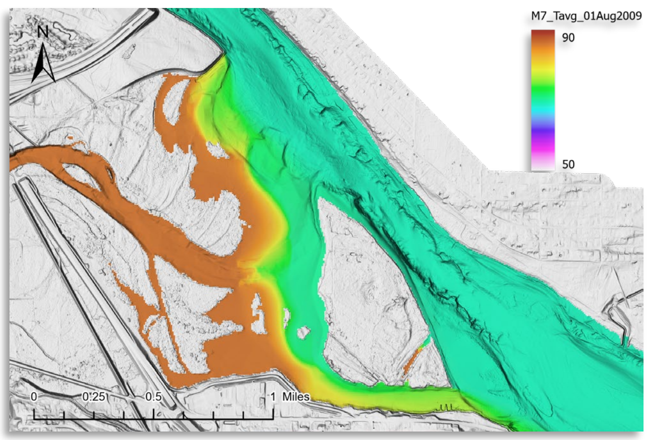


Figure 4-25. Measure7 (C1 – full causeway removal) simulation for late summer index conditions. (01Aug2009-High T, Low Q)

To further evaluate Measure 7 mixing temperature trends over an extended duration, the rating estimates of hindcast unit discharge fractions were used to weight mean daily temperature values from the representative Columbia and Yakima River source fractions to compute a hindcast daily surrogate of mean mixing temperature in the delta. While this approach is rudimentary at best, it does capture the predominant drivers of water temperature in the study area (see Section 3.5.1.1), that being the source flow temperatures and mixing fractions respectively. Drawbacks of this simplistic approach is that it neither accounts for secondary thermal loading and diurnal effects, nor other physical phenomenon such as density differences and thermal stratification.

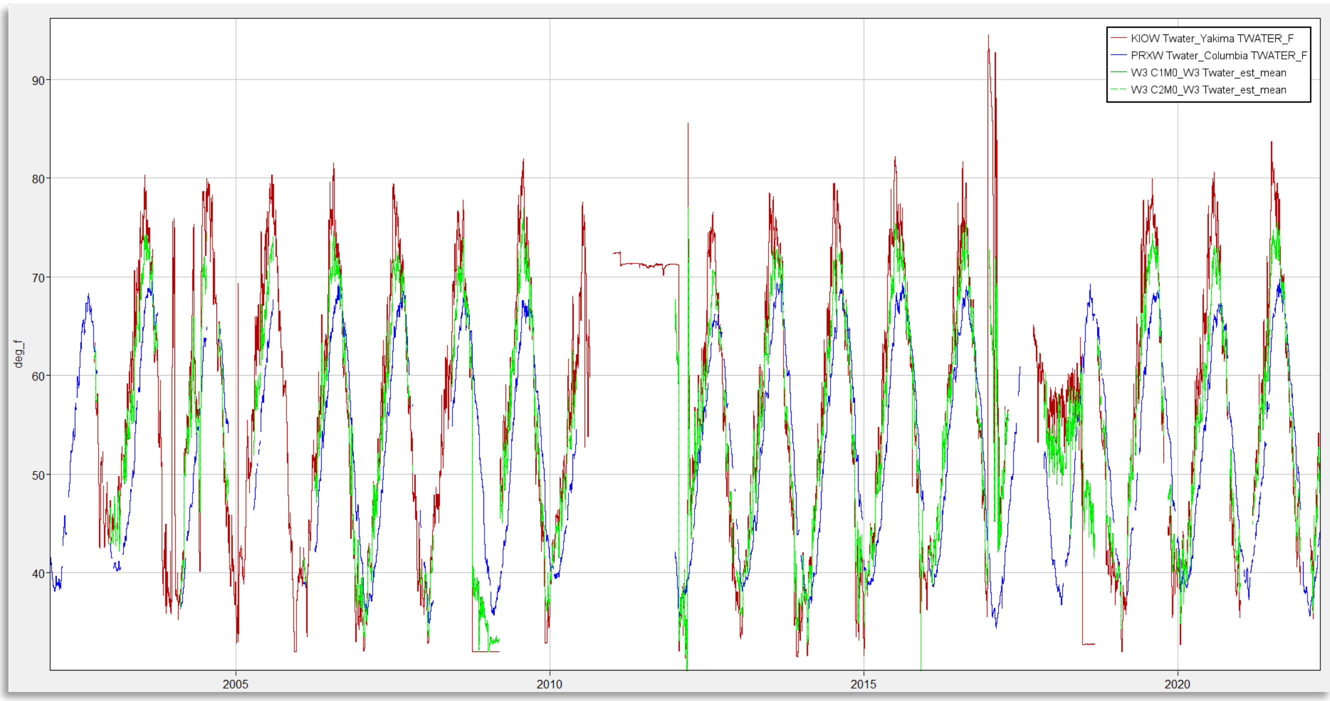


Figure 4-26. Timeseries of provisional hindcast estimates for mixing temperature at site W3 for WY 2004 to 2020.

As illustrated in Figures 4-27 through 4-29 below, exceedance duration estimates of temperature in the west Bateman area indicate various degrees of realized benefit depending on the threshold temperature of interest. For example, at the Washington State threshold temperature of 70°F, baseline conditions west of Bateman would track with the Yakima temperatures with a 15-April through 15-November exceedance duration of ~35%. The temperature reduction from Columbia River flow mixing would shift the exceedance curve to the left (depending on location) to ~20% for the same hydroperiod, a 15% relative temperature benefit at a 70°F threshold. Similar estimates of mixing temperature relative benefits can be computed for various threshold temperatures and hydroperiods as needed.

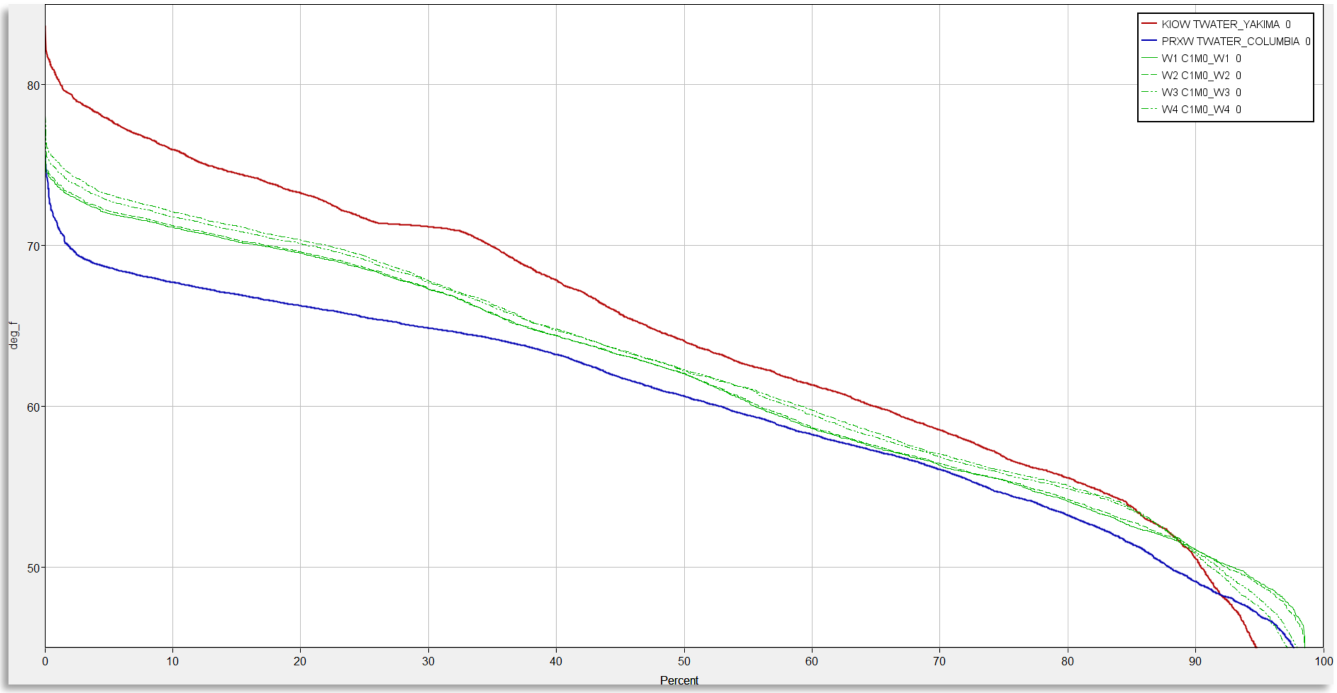


Figure 4-27. 15-April through 15-November Exceedance durations of provisional hindcast estimates for mixing temperature at sites W1 through W4 for Measure 7 with full causeway removal (C1M0).

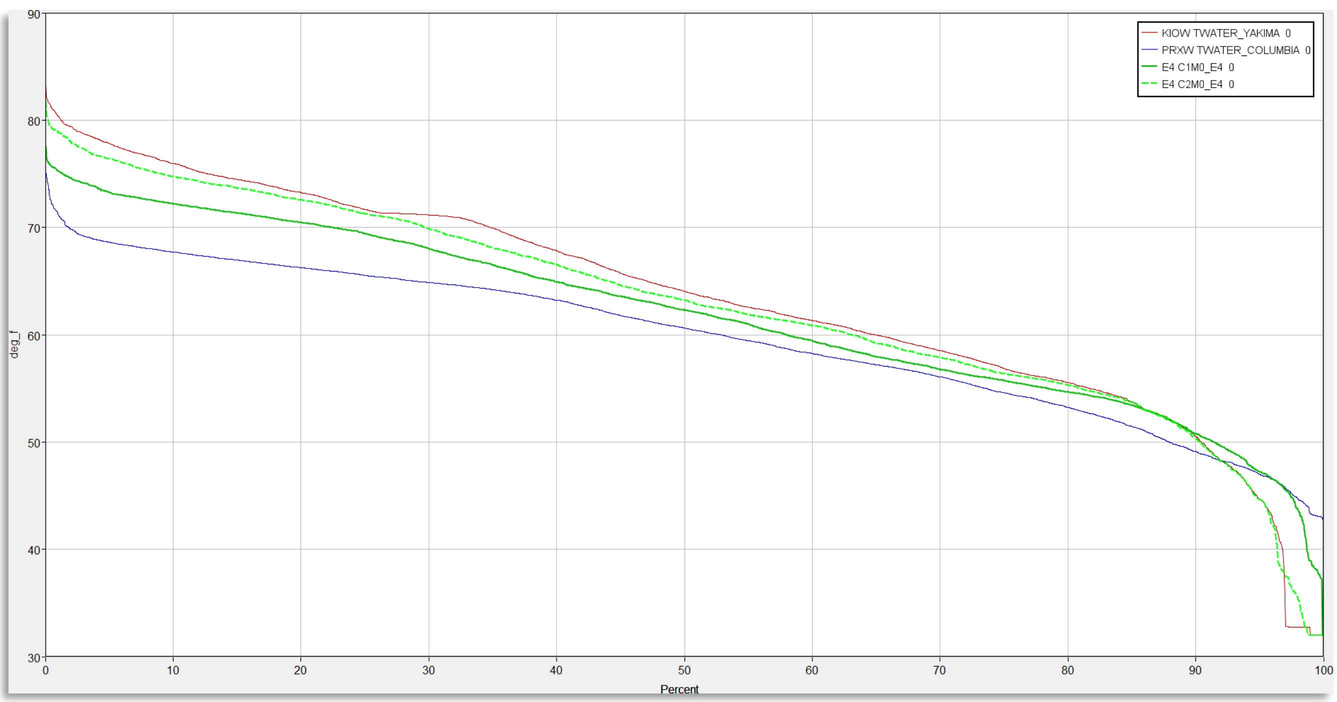


Figure 4-28. 15-April through 15-November Exceedance durations of provisional hindcast estimates for mixing temperature at site E4 for Measure 7.

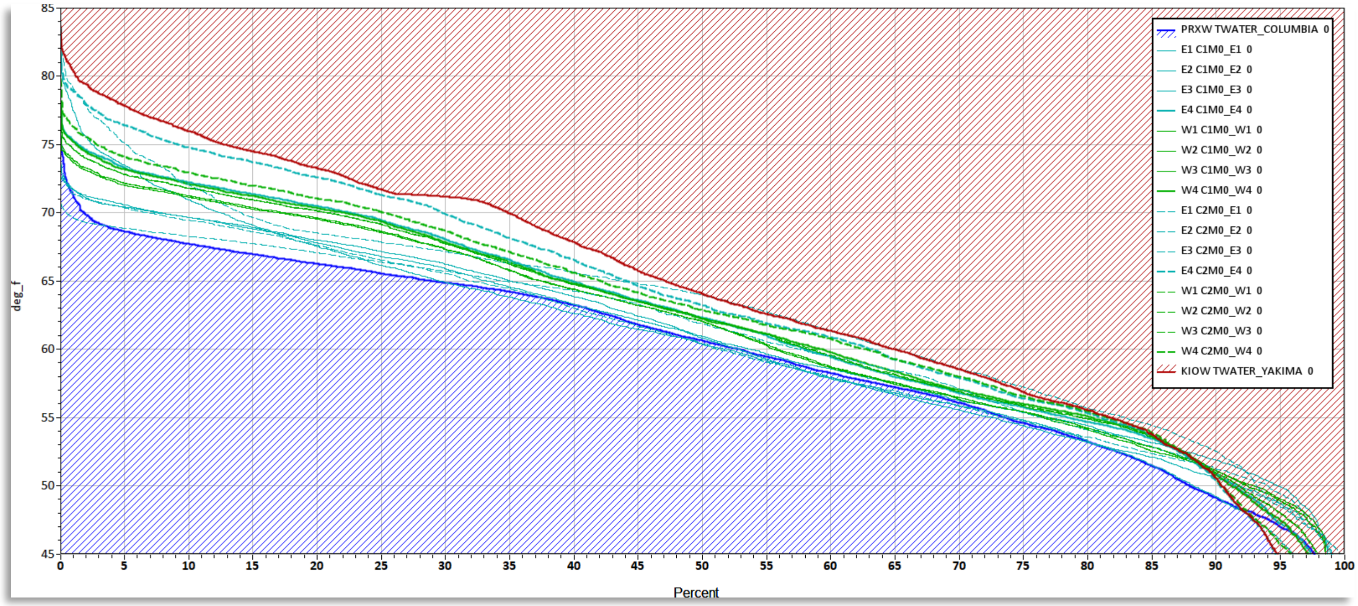


Figure 4-29. 15-April through 15-November Exceedance durations of provisional hindcast estimates for mixing temperature across sites W1-W4 and E1-E4 for Measure 7. *Potential for realized temperature benefits in the Yakima Delta fall within the unshaded plot area and varies by location.*

5 References

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