Technical Memorandum

To: Columbia River CWR Project Team

From: Ben Cope, Jonnel Deacon, and Peter Leinenbach

Date: June 23, 2017

Subject: CORMIX Modeling of Tributary Plumes in the Lower Columbia River

EPA is developing a Coldwater Refugia (CWR) plan to address the mainstem Columbia River from River Mile 310 (Washington-Oregon border) to the mouth. The geographic scope extends into the tributaries to this segment of the Columbia River to identify measures to deliver colder water to the mainstem. As part of this effort, EPA needs to characterize tributary confluence areas and identify areas where cold water "plumes" from tributaries may provide CWR throughout the summer adult migration period when Columbia River temperatures exceed 18°C. A Quality Assurance Project Plan (QAPP) was developed to establish the project scope and evaluate assessment approaches, and the CORMIX dilution model was identified and the most appropriate tool for this assessment (Cope 2016).

This report describes the methodology and results of the assessment of cold water in Columbia River tributary plumes.

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Problem Definition/Background

NOAA Fisheries published a biological opinion reviewing Oregon's water temperature standard, including the temperature criterion of 68 degrees Fahrenheit for the lower Willamette and Columbia rivers. It examined whether the standards adopted by the state under the Clean Water Act sufficiently protect salmon and steelhead. Research has found that when river temperatures rise, salmon and steelhead seek out cold water areas as crucial stopovers during their migrations upstream on the way to spawn. Such "cold water refugia" are often found at the confluence of the rivers with colder tributaries. In the biological opinion, NOAA Fisheries determined that the temperature standards must assure enough cold water refugia exist in the rivers for salmon and steelhead to migrate upstream safely.

NOAA Fisheries also charged EPA and others to develop plans to best assure that sufficient cold water refugia exists by identifying and mapping the cold water refuges, making clear where they need to be protected and where they should be restored. These plans are part of the "reasonable and prudent alternative" that will help avoid jeopardizing threatened and endangered salmon and steelhead. EPA is developing a Coldwater Refugia (CWR) plan for the Columbia River that is scheduled to be completed within three years. The CWR Plan will address the mainstem Columbia River from River Mile 310 (Washington-Oregon border) to the mouth. The geographic scope extends into the tributaries to this segment of the Columbia River to identify alternatives that deliver colder water to the mainstem. As part of this effort, EPA needs to characterize tributary confluence areas and identify areas where cold water "plumes" from tributaries may provide CWR throughout the summer adult migration period when Columbia River temperatures exceed 18°C. A Quality Assurance Project Plan (QAPP) was developed to establish the project scope and evaluate assessment approaches, and the CORMIX dilution model was identified and the most appropriate tool for this assessment (Cope 2016).

This report describes the methodology and results of this assessment of cold water in Columbia River tributary plumes.

Project/Task Description

There are over 190 tributaries to the Columbia River in our study reach (from river mile 0 to 310). EPA does not have the resources to characterize every temperature plume in this reach, so we focused on those tributaries with a minimum mean August discharge of 10 cfs and with water temperatures lower than the Columbia River. Of the 191 tributaries to the Columbia in the study reach, 38 have flows greater than 10 cfs and are cooler than the Columbia River. Of those 38 tributaries, we simulated the thermal plumes of 26 tributaries for mean August conditions using CORMIX model. The CORMIX model is best suited for plumes of tributaries that have simple, direct entries into the Columbia River (Figure 1). The model is less suited to estimating dilution for tributaries that have more complex hydrologic environments as they enter the mainstem Columbia River (Figure 2).

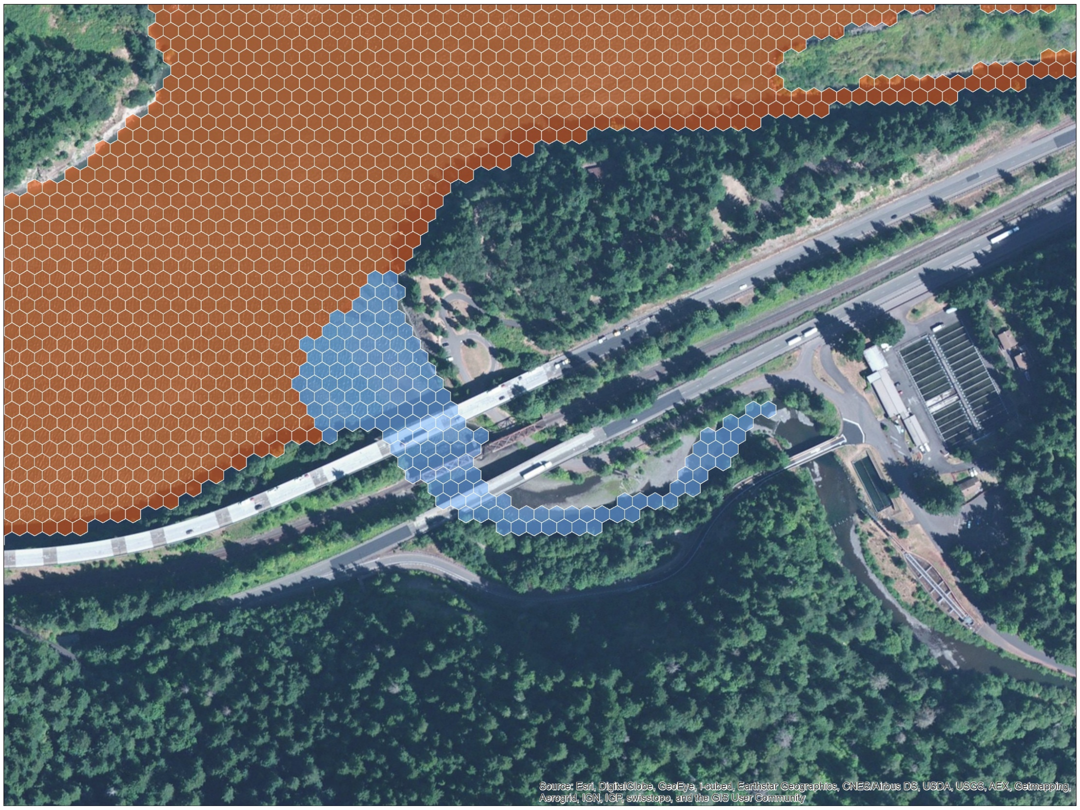
Some of the tributaries with complex confluences were the focus of a monitoring field study. To determine whether or not these complex confluences might provide CWR, EPA collected both continuous profiles and point profile measurements. This monitoring effort is covered in separate reports (Hayslip, 2016).

Figure 1. Tanner Creek, an example of the type of tributary that EPA simulated with CORMIX.

Figure 2. Wind River, an example of the type of plume that EPA did not simulate with CORMIX.

After the first phase of the project, several small tributaries were added to the list of potential refuges of interest. As an alternative to running new CORMIX simulations for each of these tributaries, a regression approach was explored using the modeling results. We found a strong relationship between the "differential temperature flux" (temperature difference multiplied by tributary flow) and the CORMIX-predicted cold water volumes. A non-linear regression using these variables was used to estimate cold water refuge volume for the small, un-modeled tributaries. This regression also shed light on some of the limitations and uncertainties in the modeling analysis. Details about the regression and these insights are described later in this document.

A future component of the cold water refugia project is to develop a fish behavior and tracking model for the Columbia River using the HEXSIM model (this work will be described in a separate document). As seen in the preliminary figure below, this model represents the river fish habitat within hexagonal computational cells. There are no cells in the vertical, so a single, depth averaged temperature is assigned to each cell. The plume modeling will be a source of information for assigning estimated temperatures to the hexagons near tributary confluences. It is important to note that the HEXSIM model provides a continuous simulation over several months, and this type of model requires a time series input for temperature for each hexagon. The CORMIX modeling conducted to date, and reported here, has focused on mean August temperatures only.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 3: Example of a HEXSIM Grid (Eagle Creek)

Key Variables and Processes

The goal of the modeling assessment was to estimate the characteristics of the cold water plume as it mixes with the Columbia River. This included estimates of the width, depth, volume, and temperature of the plume with respect to distance from the confluence.

The key processes governing the size of the plume are the lateral momentum and shear forces as the two water masses collide and mix, as well as vertical buoyant mixing as the colder tributary sinks into the warmer mainstem. Because the mixing process occurs rapidly (e.g., substantial dilution in seconds to minutes), heat exchange with the atmosphere has negligible effects on the initial plume and can be neglected. It was important to include the boundary effects of the river bank adjacent to the tributary confluence, because the shoreline will limit lateral mixing on one side of the plume.

None of the simulated tributaries were located in the tidally-influenced section of the Columbia River.

Technical Approach

A variety of modeling tools are available for simulating mixing between a tributary and mainstem river. The tools range from simple steady-state Lagrangian dilution models (e.g., CORMIX) to highly complex, gridded 3D hydrodynamic models. A simple dilution model was preferred for this project, because the work involves over 20 sites, the focus is near-field mixing, corroboration data is limited or absent, and an order-of-magnitude approximation of the dimensions of the cold water plume is acceptable for this project. In any case, the project resources and schedule did not allow for the use of a 3D hydrodynamic model.

Model Framework Selection

Two established dilution (plume) models were considered, Visual Plumes (Frick et al., 2003) and CORMIX (Doneker et al., 2007). Both have been used extensively for NPDES discharge mixing zone analysis. CORMIX was preferred for several reasons.

- Visual Plumes has not been supported by EPA recently and the official version no longer runs in the current Windows operating systems.
- CORMIX handles boundary effects and open channel discharges (such as tributary discharges)
- CORMIX developer MIXZON, Inc. offers user support, which was helpful for this application

Model Development

Model Boundaries (Space and Time)

System characteristics

The tributaries that were assessed in this report are shown in Table 1, along with the estimated mean August temperature differential between the tributary and mainstem Columbia River.

Table 1. List of Tributaries Assessed in this Study

Code	Tributary Name	River Mile	Columbia Temp[3]	Tributary Temp	Temp Difference	Tributary Flow	Method Used
			°C	°C	°C	cfs	
28	Skamokawa Creek	30.9	21.3	16.2	-5.1	22.7	CORMIX
38	Mill Creek	51.3	21.3	14.5	-6.8	10.4	CORMIX
40	Abernethy Creek	51.7	21.3	15.7	-5.6	10.3	CORMIX
41	Germany Creek	53.6	21.3	15.4	-5.9	8.5	Regression
49	Cowlitz River	65.2	21.3	16.0	-5.4	3634.5	CORMIX
52	Kalama River	70.5	21.3	16.3	-5.0	314.0[2]	CORMIX
63	Lewis River	84.4	21.3	16.6	-4.8	1291.0[2]	CORMIX
77	Sandy River	117.1	21.3	18.8	-2.5	469.2	Both[1]
78	Washougal River	117.6	21.3	19.2	-2.1	106.6[2]	Both[1]
83	Bridal Veil Creek	128.9	21.3	11.7	-9.6	7.4	Regression
85	Wahkeena Creek	131.7	21.3	13.6	-7.7	15.2	CORMIX
86	Oneonta Creek	134.3	21.3	13.1	-8.2	29.2	Regression
88	Woodward Creek	137.7	21.3	16.8	-4.4	10.6	Regression
89	McCord Creek	138.8	21.3	11.7	-9.6	14.7	CORMIX
90	Moffett Creek	139.8	21.3	12.8	-8.5	8.9	Regression
91	Tanner Creek	140.9	21.3	11.7	-9.6	37.7	CORMIX
92	Eagle Creek	142.7	21.2	15.1	-6.1	72.1	CORMIX
94	Rock Creek	146.6	21.2	17.4	-3.8	47.4	Regression
96	Herman Creek	147.5	21.2	12.0	-9.2	45.5	Regression
115	White Salmon River	164.9	21.2	15.7	-5.5	714.5[2]	CORMIX
116	Hood River	165.7	21.4	15.5	-5.9	374.1	CORMIX
125	Klickitat River	176.8	21.4	16.4	-5.0	850.5[2]	CORMIX
129	Fifteenmile Creek	188.9	21.4	19.2	-2.3	36.5	Regression
135	Deschutes River	200.8	21.4	19.2	-2.2	4772.0[2]	Both[1]
176	Umatilla River	284.7	20.9	20.8	-0.1	169.0	CORMIX

[1] These tributaries were assessed using both site-specific CORMIX simulations and regression relationships. Regression was chosen as the approach likely to provide best estimates of CWR for these cases.

For each tributary assessed using CORMIX directly, we developed a unique model for each tributary that accounts for the physical characteristics of each location.

Available Data (Quantity and Quality)

The following datasets were used to estimate the local characteristics for each tributary plume model:

Table 2: Tributary Data

Parameter	Data Source	Specific Info
temperature	USFS (NORWEST)	Estimated average August daily mean stream temperatures for current and future stream temperature estimates (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST/ModeledStreamTemperatureScenarioMaps.shtml) "Oregon Coast" and "MidColumbia" Processing Units.
flow	4 Data Sources USGS (NWIS Stream Gauge Network) EPA/USGS (NHD Plus) USGS (Streamstats) USFS (modeled stream flow metrics)	4 Datasets USGS Stream Gauges (http://waterdata.usgs.gov/nwis) EROM (Extended Unit Runoff Method) tables (NHDOkysV21_PN_17_EROMExtension_06.7z) (http://www.horizon-systems.com/NHDPlus/NHDPlusV2_17.php) USGS StreamStats_V3 tool (http://water.usgs.gov/osw/streamstats/oregon.html) monthly average stream flow for Oregon tributaries. USFS calculated Western Stream Flow Metrics for the Pacific Northwest (PN17_Hist_flow_met_d.dbf, P17_2040_flow_met_d.dbf, and PN172080_flow_met_d.dbf) http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml
depth	Calculated from flow, width and velocity based on continuity (Q=VA)	NA
width	USACE	Columbia River bathymetry data
velocity	EPA/USGS (NHD Plus)	Downloaded the EROM (Extended Unit Runoff Method) tables (NHDOkysV21_PN_17_EROMExtension_06.7z) (http://www.horizon-systems.com/NHDPlus/NHDPlusV2_17.php)
lateral angle of entry into the Columbia	Visual estimation using Google Earth/GIS	NA
protrusion distance (if any) of the channel into the Columbia	Estimated using Google Earth/GIS scale tools	NA

Table 3: Columbia River Data

Parameter	Data Source	Specific Info
temperature flow	USACE	DART website. (http://www.cbr.washington.edu/dart/) Mean monthly temperature for a 10-year period (2005-2014) at tailrace monitoring site nearest to the tributary confluence
depth at confluence	USACE	Columbia River bathymetry data
Velocity	USGS	Gauge station velocity measurements

Data Gaps

Because the project is using several continuous regional datasets, such as NORWEST for tributary temperature and NHD Plus for river characteristics, data gaps were minimal. For flow, we used two data sources: NHD Plus and USGS gauge stations. However, most tributaries are not gauged. NHD Plus was used as the default option when data were not available from the other data sources.

For river geometry, USACE has collected continuous, fine scale bathymetry data for the Columbia River. Because this dataset does not cover all of the tributaries or extend into the tributaries, some extrapolation may be necessary in estimating the tributary cross sectional area just above the confluence with the Columbia River.

Measured temperatures at the tailraces of the lower Columbia dams, available from the Data Access in Real Time (DART) website, were used for the Columbia River temperature input for the CORMIX simulations. The average temperature for the period 2005-2014 was used. This information is only available at the four dams in the study area, so the temperatures are not site-specific to the tributary locations. This is not a major concern, because there is low variability within a particular reach (i.e., between dams) in lower Columbia River.

Important Assumptions and Limitations

The CORMIX model predicts dilution for a simplified representation of the system of interest. The following general assumptions of the CORMIX system include:

- Uniform discharge (velocity and depth) entering a uniform receiving water (velocity and depth profile)
- No heat exchange with atmosphere; physical mixing only
- Structural limitations of the CORMIX model framework (Doneker and Jirka (2007)
- Internally selected mixing modules

Final CORMIX Input Data

Table. 4: Input Data

Tributary	Trib flow cfs	Trib velocity ft/s	Trib temp deg c	Trib sigma deg	Trib width ft	Trib depth m	Col R temp deg c	Col R vel. ft/s	Col R depth m
28_skamokawa_creek	22.7	0.41	16.2	90.0	108.2	0.15	21.3	1.0	0.5
38_mill_creek	10.4	0.40	14.5	85.7	88.6	0.09	21.3	1.0	1.0
40_abernethy_creek	10.3	0.40	15.7	88.6	59.0	0.13	21.3	1.0	1.0
49_cowlitz_river	3634.5	0.87	16.0	47.5	603.5	2.11	21.3	1.0	3.3
52_kalama_river	314.0	0.54	16.3	90.0	187.0	0.94	21.3	1.0	1.5
63_lewis_river	1291.0	0.68	16.6	90.0	603.5	0.96	21.3	1.0	2.0
77_sandy_river	469.2	0.59	18.8	270.0	242.7	0.99	21.3	1.0	1.5
78_washougal_river	106.6	0.31	19.2	6.5	168.0	0.40	21.3	1.0	3.0
85_wahkeena_creek	15.2	0.61	13.6	270.0	19.7	0.39	21.3	1.0	0.6
88_woodward_creek	10.6	0.69	16.8	78.3	16.4	0.29	21.3	1.0	0.5
89_mccord_creek	14.7	0.94	11.7	329.7	16.4	0.29	21.3	1.0	0.5
91_tanner_creek	37.7	0.78	11.7	295.8	29.5	0.50	21.3	1.0	0.8
92_eagle_creek	72.1	0.51	15.1	288.2	39.4	1.09	21.2	1.0	1.7
115_white_salmon_river	714.5	0.77	15.7	81.8	239.4	1.18	21.2	1.0	3.0
116_hood_river	374.1	1.01	15.5	270.0	242.7	0.46	21.4	1.0	1.8
125_klickitat_river	850.5	1.15	16.4	90.0	170.6	1.32	21.4	1.0	2.0
135_deschutes_river	4772.0	2.00	19.2	290.8	449.4	1.63	21.4	1.0	2.5
176_umatilla_river	169.0	2.18	20.8	288.4	193.5	0.12	20.9	1.0	1.0

Note: Shaded areas are values adjusted based on CORMIX model input constraints (see Assumptions and Limitations discussion below)

Specific assumptions and limitations in this application included:

- CORMIX is one-dimensional, and its dilution estimate is a cross-sectional average. This applies initial mixing across the entire plume and leads to over-estimation of the loss of cold water near the confluence. This limitation is most impactful in situations where the tributary/mainsteam temperature difference is small (near the 2°C CWR threshold). See further discussion in the section on un-modeled tributaries below.
- Due to internal CORMIX constraints on maximum width:depth ratio, confluences could not be simulated as an open channel confluence. Instead, they were simulated using a submerged diffuser, placing one end of the diffuser on the bank of the Columbia River and the other out in the Columbia River, depending on the angle of confluence.
- Additional internal CORMIX constraints lead to the following adjustments in model inputs:
    - Velocities of certain tributaries had to be increased in order to meet model requirements (these cases are noted in the input tables).
    - Tributaries that pointed upstream into the Columbia River had to be adjusted to the maximum allowable angle of 90°.
    - Uniform depth of the Columbia River along the plume path was required. The depth at which the model switched from the near-field module 1 to module 2 was used for all simulations.
    - Depth of the Columbia River where water exits the tributary had to be adjusted for several tributaries (these cases are noted in the input tables).
- Plume width outputs are misrepresented in first module. To correct this, linear interpolation was used between confluence (width set to 0) and transition from module 1 to 2 (where plume was most narrow).
- Longitudinal extent was set to 2,000 meters downstream of confluence.
- Specified 100 output steps per module. Tributaries varies from 2 to 4 modules, but all were run to 2,000 meters, meaning that different tributaries have a different number of output steps (or resolution) depending on the number of modules.
- Columbia River velocity was set to 1 ft/sec in all runs based on measured velocity at USGS gauge stations.
- Columbia River friction factor (Manning's n) was set to a value of 0.025, representing an earth channel with some roughness due to rock and weeds on the bottom.

Model Calibration

Models are often calibrated against observations of the simulated parameter. However, this project assessed areas with limited or no temperature observations within tributary plumes. The project team was only able to obtain summary plots of within-plume temperatures for two tributaries included in this modeling study (Klickitat and Deschutes Rivers). This information was produced by the University of Idaho, but it is unpublished. The raw data was not available and the sampling procedures used to assure that samples occurred within the cold water plume were not known. Due to the high uncertainty in the representativeness of the data in capturing the actual within-plume temperatures, it was decided not to use this information to evaluate the representativeness of the model simulations.

Another potential source of corroboration information was infrared images of the thermal signatures at the confluences. However, these images only provide surface temperatures and the plumes are predicted in CORMIX to sink below the surface due to negative buoyancy. The images are also snapshots of plumes under specific flow and weather conditions, whereas this project is simulating a mean August condition. Based on these limitations, remote sensing information was not included as a calibration check. However, this information was considered in the assessment of model results for the Deschutes River plume (discussed below).

Sensitivity Testing

CORMIX is used to estimate mixing based on physical characteristics of each confluence, and it has been extensively tested and documented (Doneker and Jirka, 2007). All of the model inputs except one (Manning's n) are physical parameters that are measured or mapped, and the CORMIX methodology assumes spatial uniformity in the characteristics of the receiving water. To assess the uncertainties related to the assumption of uniformity, sensitivity tests were run on a range of values for Columbia River characteristics of Manning’s n, depth and velocity, as follows:

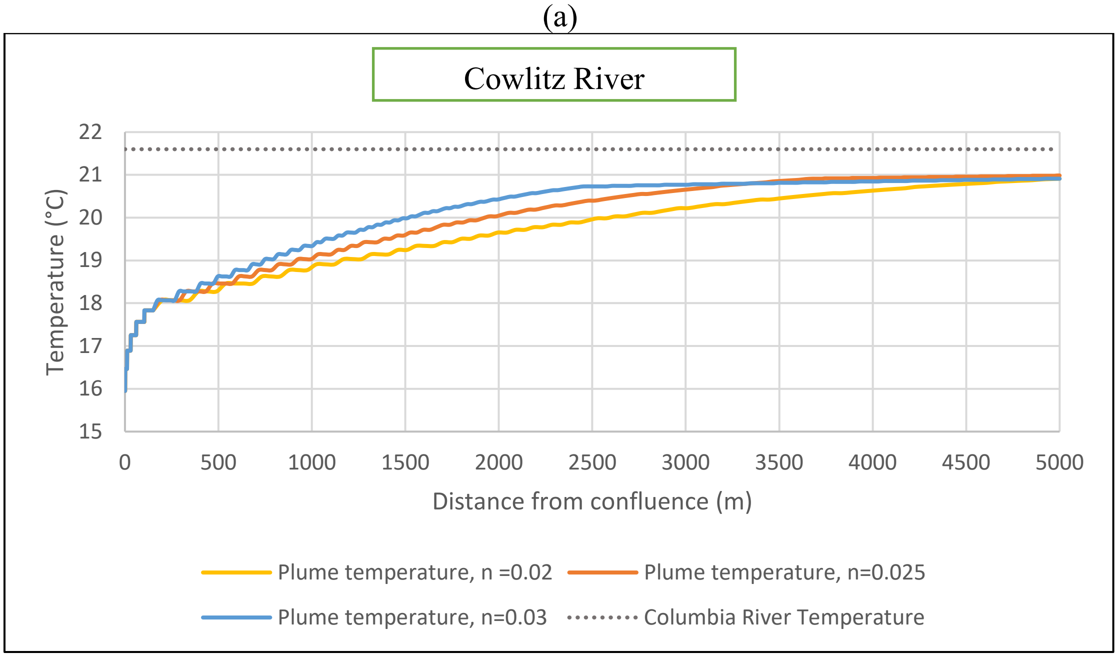
- Mannings n effect was tested using values of 0.02, 0.025, and 0.03. Three tributaries were used as examples: Cowlitz, Klickitat, and Deschutes rivers. The values represent the following: 0.02 (gravel bottom with concrete sides, no weeds), 0.025 (earth channel, some stones and weeds), and 0.03=clean and straight natural rivers).

- Columbia River depth effects were tested using a near-confluence depth (3 m) and far-field depth (16 m) for the Cowlitz River.

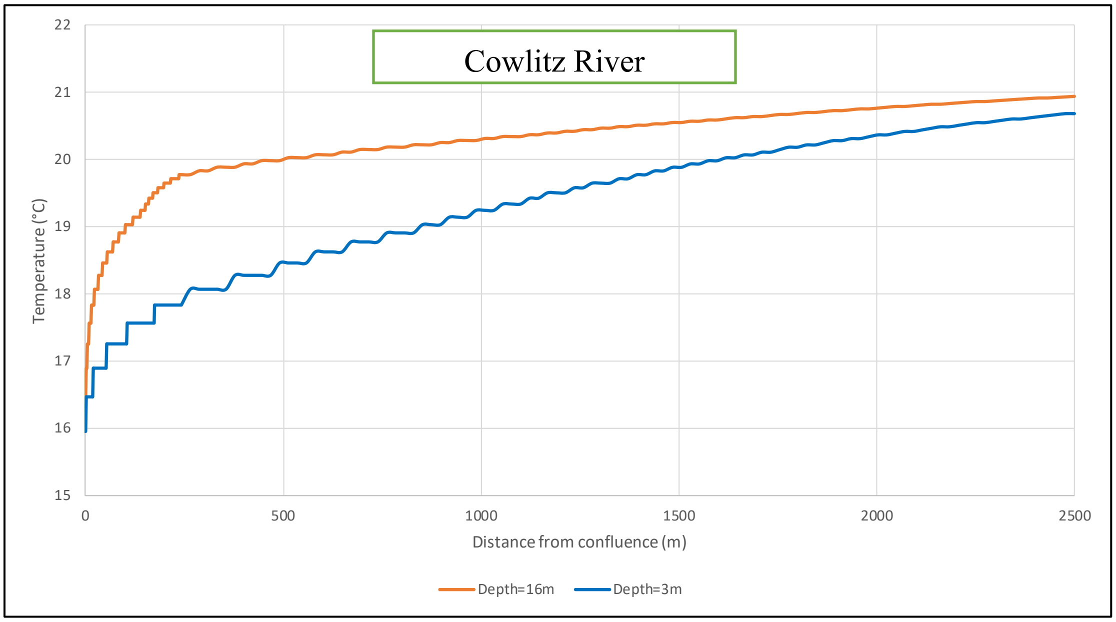
- Columbia River velocity effect was tested using values of 0.5, 1.0, and 1.5 ft/s. Two tributaries were used as examples: Lewis and Klickitat rivers.

Figure 4: Example Sensitivity Plots for (a) Mannings n, (b) depth, and (c) velocity of Columbia River

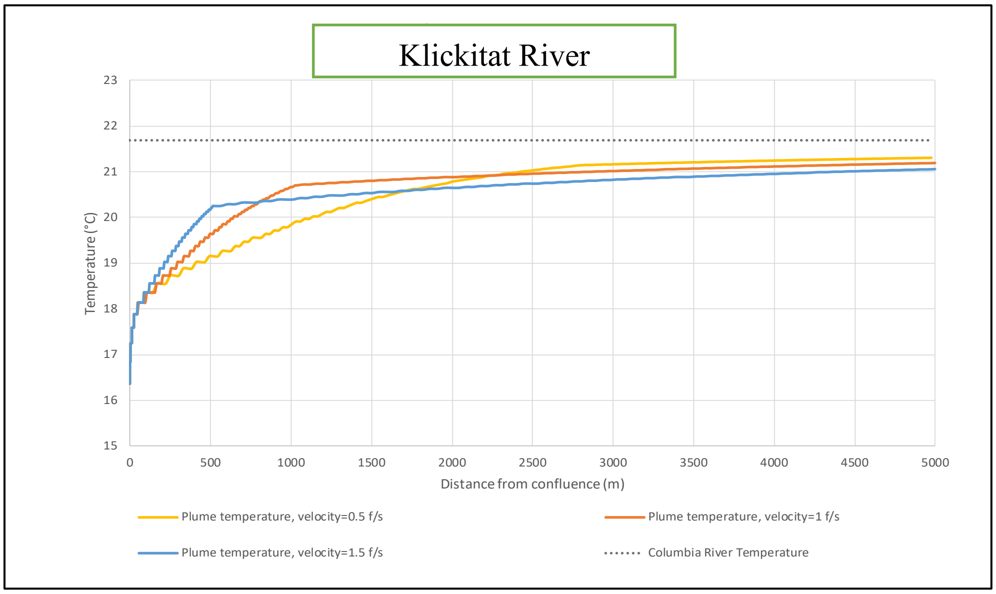
(a)



(b)



(c)



The sensitivity plots (examples in Figure 4) indicate that the model results vary substantially across the range of variation/uncertainty in the model inputs. The depth variation was particularly influential for large, cold tributaries such as the Cowlitz River (Fig. 4A), because the plume traverses a long distance and the depth of the Columbia River increases substantially over this distance (we would expect less sensitivity for the typical tributary). Overall, the results suggest an uncertainty range for predicted plume temperature of approximately ± 0.5-1.0 °C at a given location. This difference can translate into significant differences in cold water volumes. This is one reason that the volume estimates should be considered in terms of order-of-magnitude estimates.

Other factors in the characteristics of the tributaries (particularly the temperature difference compared to the mainstem) and simplifications in the CORMIX calculations lead to uncertainties/errors in plume volumes beyond those illustrated in the sensitivity tests. These factors are discussed below in the regression analysis for un-modeled tributaries.

Peer Review and Model Acceptance

In addition to internal reviews of this work, the team communicated multiple times with CORMIX experts Dr. Robert Doneker and Adi Ramachandran of MIXZON, Inc. and shared an example model setup for their review before running the simulations. The process to reach model acceptance involved this upfront expert review, troubleshooting and sensitivity testing, and review of assumptions, results, and limitations by the EPA interdisciplinary project team. As discussed below, the site-specific CORMIX estimates for tributaries (e.g., Deschutes) with a small tributary/mainstem temperature differential (< 3 deg C) were set aside in favor of a regression approach, because the regression estimates for CWR volume were deemed to be more reasonable for those tributaries.

Estimation of Plume Volumes for Un-Modeled Tributaries

As noted earlier, after the first phase of the project, several small tributaries were added to the list of potential refuges of interest. As an alternative to building and running site-specific CORMIX simulations for each of these small tributaries, the team explored a statistical approach for estimating CWR volumes based on the CORMIX results in hand. We found a strong correlation between differential temperature flux (temperature difference times tributary flow) and CORMIX-predicted cold water volume for the tributaries. A power function was selected for this regression (see figure below). The equations for the regression lines were used in conjunction with the flow and temperature differential for each un-modeled tributary to estimate its refugia volume.

In the process of building the regressions, the patterns in the data raised questions about the validity of CWR estimates from CORMIX when the difference in temperature between the tributary and mainstem is small (less than 3°C). The final regression excluded the three tributaries with a temperature difference less than 3°C (Deschutes, Washougal, and Sandy). The two plots show the outlier values for the Deschutes (plot of all regression data) and Washougal/Sandy (plot of lower flow tributaries). These plots strongly suggest that CORMIX under-predicts the refugia volumes when the tributary/mainstem temperature difference is small. This is plausible outcome, given that the model is one-dimensional and each dilution estimate is an average across the entire plume. In reality, the plume is not uniformly, instantaneously mixed as assumed in the one-dimensional representation in CORMIX. The over-simplification of modeled mixing in the immediate vicinity of the confluence is particularly important when the temperature differential is small, because the CWR volume is completely mixed and lost in the near-field in the model representation. In reality, some fraction of the CWR volume should be preserved into the far-field, where dilution is much slower with distance.

The CWR volume for the Deschutes based on its site-specific CORMIX simulation is only 91 m^3, whereas the regression value is approximately 300,000 m^3. To evaluate whether the larger, regression-based estimate is reasonable, we analyzed a summer FLIR image for the confluence of the Deschutes (see figure below). This image shows a substantial plume with CWR temperatures (2°C colder than the mainstem) in August. A rough delineation of the area of the CWR plume in the image (68,000 m^2), combined with the estimated depth near the confluence (2.5 m), results in a volume estimate of approaching 200,000 m^3. This indicates that the Deschutes CWR volume is the same order-of-magnitude as the regression estimate, and the site-specific CORMIX result for this tributary should be considered invalid due to the model limitations and river characteristics.

Figure 5: Infrared image of Deschutes River confluence (source: Watershed Sciences LLC)

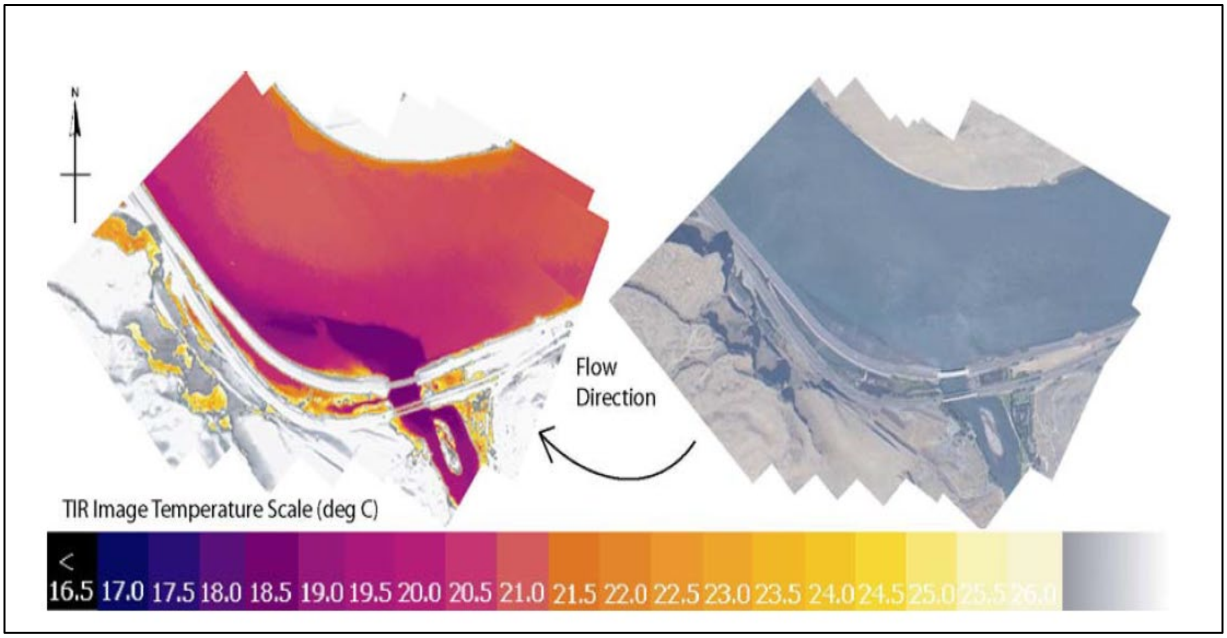


Figure 6: Regression plot for all CORMIX-modeled tributaries

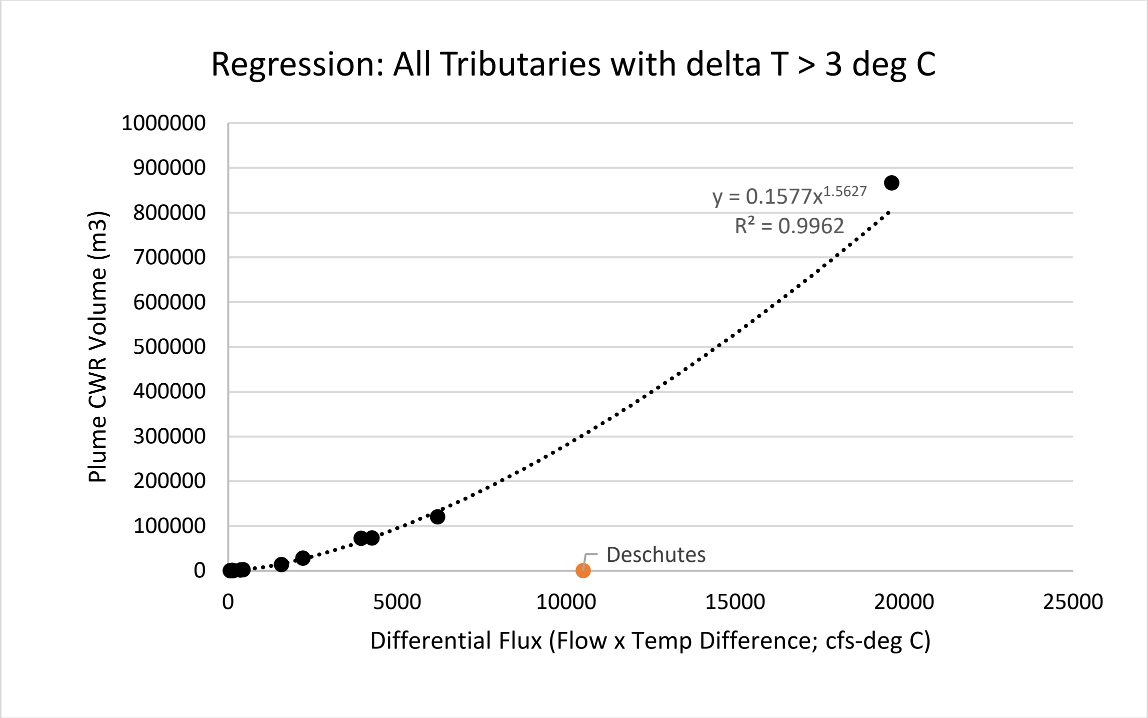
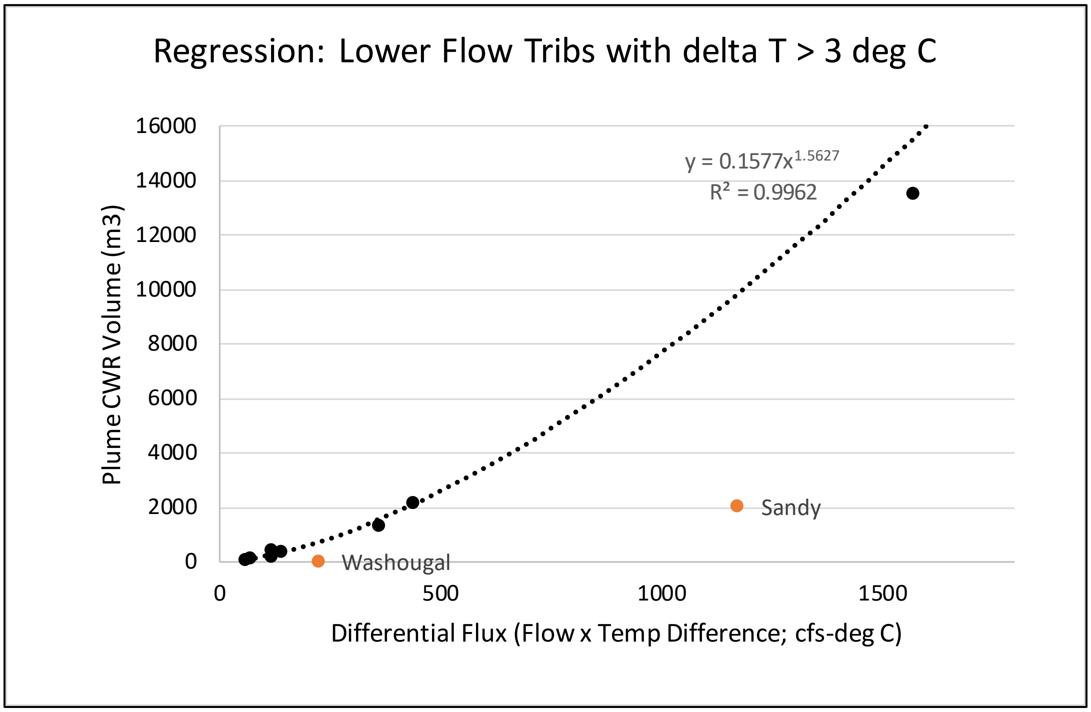
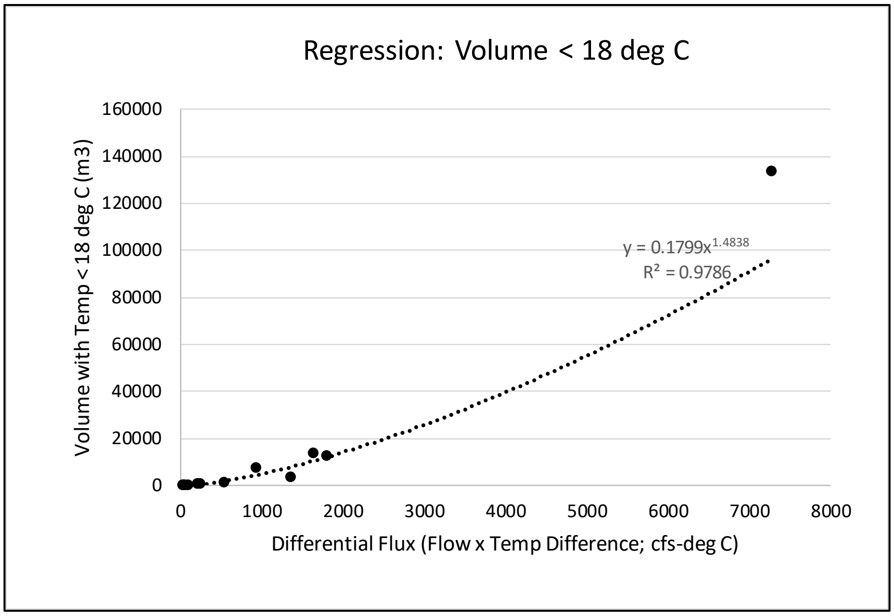


Figure 7: Regression plot for lower flow tributaries (same as Plot 6 but closer to origin)



The same regression approach was used for estimating the volume of water less than 18°C, with the temperature difference defined as the difference between the tributary temperature and 18°C. Several tributaries (e.g., Deschutes, Washougal, Sandy) are excluded from this estimation step, because they are warmer than 18°C on average in August.

Figure 8: Regression plot for estimation of volume in plume less than 18°



Results and Discussion

This project included CORMIX model setup and simulation of 26 tributaries for mean August conditions. Model outputs were transferred from the CORMIX model environment to spreadsheets to convert the dilution estimates from the model to average plume temperatures with distance from the confluence. This enabled the calculation of volumes of water at different temperatures within the plume.

Figure 16 shows an example set of model output plots for the Cowlitz River. CORMIX rounds dilution to the nearest tenth, and this results in the stepped plot lines for plume temperature.

Table 1 shows the CORMIX-derived estimates for total plume volume that fits the definition of cold water refugia (>2°C colder than mainstem Columbia temperature) and total volume in the plume with water temperature less than 18°C.

It is evident from the results that the estimated cold water refugia volumes in the assessed tributaries vary by several orders of magnitude. The primary factors are the temperature difference and flow of the tributary, as seen in the strong correlation in the regressions using these two variables. This correlation breaks down for tributaries (Deschutes, Washougal, Sandy) with a temperature difference close to the 2°C CWR threshold. The CWR volumes for these tributaries appear to be substantially under-predicted, and other methods and lines of evidence should be considered in these cases.

Despite the relatively high uncertainty in the predicted CWR volumes using the CORMIX model, the model algorithms are well-established and the regressions indicate consistency in the results for tributaries with a substantially colder temperature than the Columbia mainstem. Overall, the model provides a reasonable set of order-of-magnitude estimates to identify the most significant CWR plumes along the lower Columbia River for additional analysis and protection.

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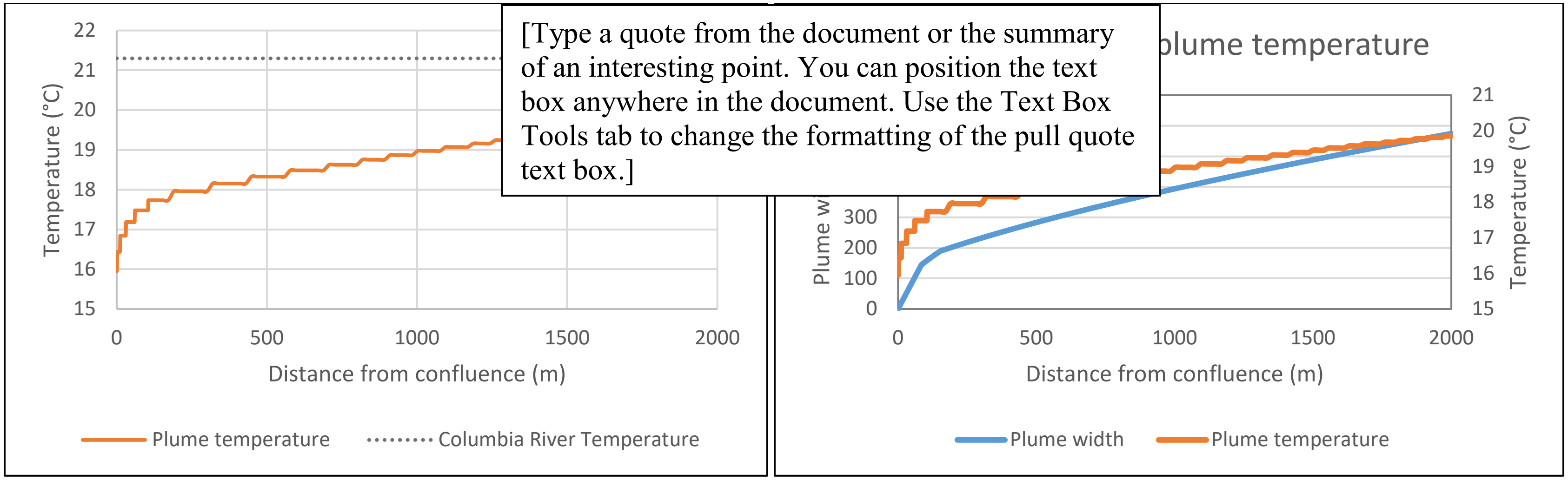
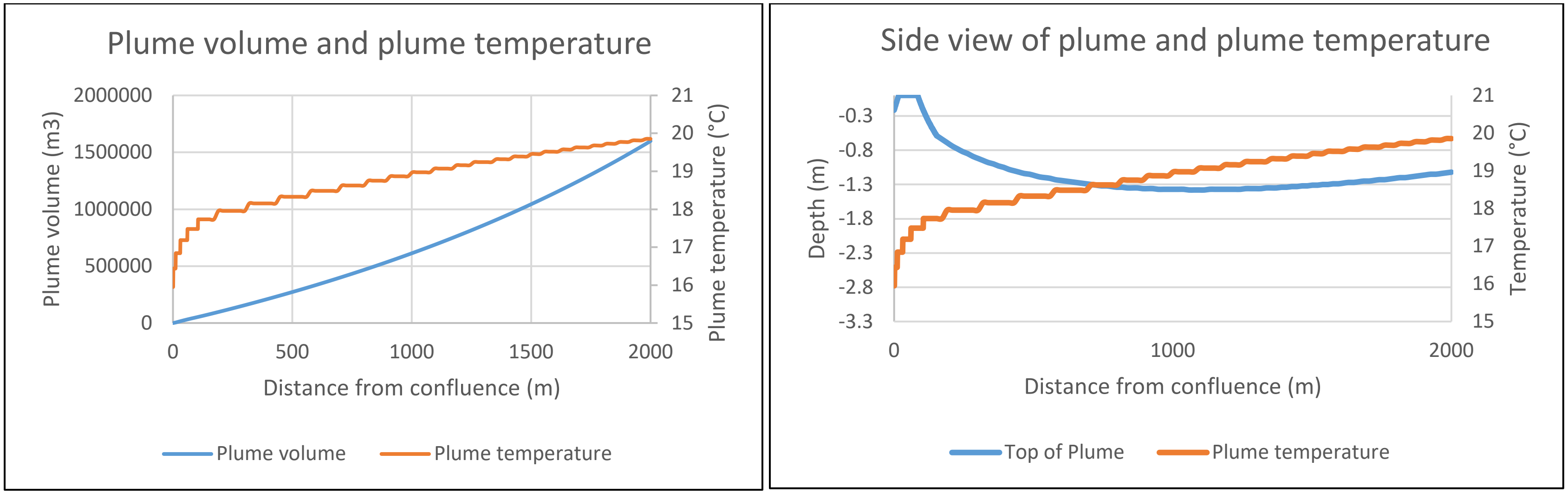


a. Plume temperature and distance downstream from confluence

b. Plume temperature and width downstream



c. Plume temperature and volume downstream.

d. Plume temperature and upper boundary of plume.

Figure 9: Sample CORMIX model results for the Cowlitz River for mean August conditions.

Table 5. CORMIX-based plume volume estimates for mean August conditions (all volumes rounded to 2 significant figures).

Code	Tributary Name	River Mile	Columbia Temp[3]	Tributary Temp	Temp Difference	Tributary Flow	Plume CWR Volume (> 2°C Δ)	Plume CWR Volume (< 18°C)
			°C	°C	°C	cfs	m3	m3
28	Skamokawa Creek	30.9	21.3	16.2	-5.1	23	450	48
38	Mill Creek	51.3	21.3	14.5	-6.8	10	110	41
40	Abernethy Creek	51.7	21.3	15.7	-5.6	10	81	17
41	Germany Creek	53.6	21.3	15.4	-5.9	9	72[1]	18[1]
49	Cowlitz River	65.2	21.3	16.0	-5.4	3635	870,000	130,000
52	Kalama River	70.5	21.3	16.3	-5.0	314[2]	14,000	980
63	Lewis River	84.4	21.3	16.6	-4.8	1291[2]	120,000	13,000
77	Sandy River	117.1	21.3	18.8	-2.5	469	9,900[4]	0
78	Washougal River	117.6	21.3	19.2	-2.1	107[2]	740[4]	0
83	Bridal Veil Creek	128.9	21.3	11.7	-9.6	7	120[1]	54[1]
85	Wahkeena Creek	131.7	21.3	13.6	-7.7	15	220	92
86	Oneonta Creek	134.3	21.3	13.1	-8.2	29	820[1]	280[1]
88	Woodward Creek	137.7	21.3	16.8	-4.4	11	64[1]	8[1]
89	McCord Creek	138.8	21.3	11.7	-9.6	15	380	190
90	Moffett Creek	139.8	21.3	12.8	-8.5	9	140[1]	53[1]
91	Tanner Creek	140.9	21.3	11.7	-9.6	38	1,300	630
92	Eagle Creek	142.7	21.2	15.1	-6.1	72	2,100	610
94	Rock Creek	146.6	21.2	17.4	-3.8	47	530[1]	26[1]
96	Herman Creek	147.5	21.2	12.0	-9.2	46	2,000[1]	740[1]
115	White Salmon River	164.9	21.2	15.7	-5.5	715[2]	72,000	14,000
116	Hood River	165.7	21.4	15.5	-5.9	374	28,000	7,500
125	Klickitat River	176.8	21.4	16.4	-5.0	851[2]	73,000	3,300
129	Fifteenmile Creek	188.9	21.4	19.2	-2.2	37	160[1]	0
135	Deschutes River	200.8	21.4	19.2	-2.2	4772[2]	300,000[4]	0
176	Umatilla River	284.7	20.9	20.8	-0.1	169	0	0

Notes:

[1] Un-modeled tributary - estimate from regression using CORMIX results for other tributaries

[2] August mean flow from USGS gauge record

[3] August mean Columbia River temperatures from DART website (nearest tailrace monitoring location to confluence; 10 year mean for 2005-2014)

[4] Tributary/mainstem temperature difference near 2C threshold. Regression-based estimate. See discussion in section on un-modeled tributaries.

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