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Developing a Temperature Total Maximum Daily Load for the Columbia and Snake Rivers: Simulation Methods

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Introduction

The States of Idaho, Oregon and Washington and the U. S. Environmental Protection Agency (EPA) are working in coordination with the Columbia Basin Tribes to develop Total Maximum Daily Loads (TMDL) for Temperature and Total Dissolved Gas (TDG) on the Columbia and Snake Rivers.

A TMDL for a water body is a document that identifies the amount of a pollutant that the water body can receive and still meet Water Quality Standards (WQS). A TMDL also allocates responsibility for reductions in the pollutant load that are necessary to achieve WQS. A TMDL is required by the Clean Water Act for any stream reaches included by States or Tribes on their lists of impaired waters required under Section 303(d) of the Clean Water Act. Impaired waters are those that do not attain State or Tribal Water Quality Standards (WQS).

The Snake River from its confluence with the Salmon River at RM 188 to its confluence with the Columbia River has been included on the 303(d) list of impaired waters for Temperature and TDG by Idaho, Oregon or Washington as appropriate. Oregon and Washington included all of the Columbia River on their 303(d) lists for TDG and most of the Columbia River on their lists for Temperature. The Columbia River also exceeds the WQS of the Colville Confederated Tribes for Temperature and TDG. The Spokane Tribe of Indians has WQS for the Columbia River that have been adopted by the Tribe but not yet approved by EPA. These standards are also exceeded in the Columbia River.

The states of Idaho, Oregon and Washington have assumed responsibility for developing TMDL's for total dissolved gas for their respective waters in cooperation with the dam operators within their boundaries. EPA is working with the Colville Tribe and the Spokane Tribes for the portion of the dissolved gas TMDL within reservation boundaries. Oregon DEQ and Washington DOE will collaborate on the total dissolved gas TMDL for the interstate portions of the Columbia River.

The purpose of the Columbia and Snake River main stem temperature TMDL is to understand the sources of temperature loadings and to allocate those loadings to meet state and tribal water quality standards. EPA Region 10 is the technical lead for the temperature TMDL. EPA Region 10 has chosen the mathematical model, RBM10, developed by EPA Region 10 (Yearsley et al, 2001) as the technical basis for developing a TMDL for temperature for the Snake/Columbia Main stem.

Model Description

RBM10 (Yearsley et al, 2001) is a dynamic, one-dimensional model that simulates water temperature using the energy budget method. It was originally developed to perform a temperature assessment of the Snake River from Lewiston, Idaho to its confluence with the Columbia and of the Columbia River from Grand Coulee Dam to Bonneville Dam. The model implements a mixed Eulerian-Lagrangian method for solving the dynamic energy budget equation. The model uses reverse particle tracking to locate the starting point of a water parcel at each computational time step. The water temperature at the starting point of each time step for a parcel is determined by polynomial interpolation of simulated temperatures stored on a fixed grid. The energy budget method (Wunderlich and Gras, 1967) is used to simulate the time history of temperature as the parcel moves from its starting point at time, $t-\Delta t$, to ending point at time, t. Kalman filtering is used to account for uncertainty in the water temperature data used to develop the model.

Conceptual Approach

One-dimensional models have been used to assess water temperature in the Columbia River system for a number of important environmental analyses. The Federal Water Pollution Control Administration developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study (Yearsley, 1969). The Bonneville Power Administration and others used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the Columbia River System Operation Review (BPA, 1994). Normandeau Associates (1999) used a one-dimensional model to assess temperature conditions in the Lower Snake River for the US Army Corps of Engineers. Perkins and Richmond (2001) used the one-dimensional temperature model, MASS1, to simulate both the impounded and unimpounded Snake rivers.

The water quality standards for most of the subject river reaches are written so as to limit the increase in water temperatures as a result of human activities (Washington WQS) or anthropogenic activities (Oregon WQS). This requires an estimate of temperature conditions in the absence of the human activities. The conceptual approach used in the development of the temperature TMDL is based on the notion that the effect of “human activities” can be estimated by simulating conditions in the unimpounded river segments with no point sources present. These results can then be used to determine the impacts of human activities associated with hydroelectric projects, water withdrawals and point source discharges. An important assumption in this approach is that impacts of “human activities” on water temperature outside the geographical limits of this analysis will be addressed by other TMDL’s or water quality plans; that water quality and quantity at the boundaries of this TMDL are the result of existing upstream activities.

Model Development

Much of the model development was done in the problem assessment phase of the TMDL and is described in Yearsley et al (2001). Although the basic mathematical structure of the model was not changed, the model framework was changed in a number of ways to accommodate the needs of the TMDL.

Model Domain

The Columbia River and the Snake River (Figure 1) are listed by the states of Oregon and Washington as water-quality limited under Section 303(d) of the Clean Water Act. Listed segments of these rivers in the model domain for the TMDL include the Columbia River from the International Boundary (Columbia River Mile 745.0) to the Pacific Ocean near Astoria, Oregon and the Snake River from its confluence with the Salmon River (Snake River Mile 188.2) to its confluence with the Columbia River near Pasco, Washington (Columbia River Mile 324.0). In addition, the Clearwater River from Orofino, Idaho (Clearwater River Mile 44.6) to its confluence with the Snake River near Lewiston, Idaho (Snake River Mile 139.3) was included in the model domain. The Clearwater River was included because of the influence releases from Dworshak Dam on the North Fork of the Clearwater have on water temperatures of the Snake River downstream from Lewiston. Although the Clearwater is not listed as water-quality limited under Section 303(d), it may have an important role in any implementation plans developed from the TMDL.

Major tributaries to the Columbia River and Snake River (Table 1) are included in the model domain simply as point source inputs. That is the temperatures are not simulated, rather the advected energy is treated as data input. While some of these tributaries are listed as water-quality limited for temperature, any improvement in temperature that may result from TMDL's written for these segments is not considered in this analysis. There are two reasons for this. The size of these tributaries is such that their impact on the well-mixed temperature of the Columbia is small. Furthermore, any temperature improvement in the development of TMDL's on the tributaries will be included in the interpretation of the States' water quality standards as described below.

Data Requirements

Data requirements for simulating water temperatures with RBM10 include the following

- The speed of the parcel along its characteristic path and the geometric properties of the river are estimated from functional relationships between flow and geometry. A gradually varied, steady flow model (USACE-HEC 1995) is used to establish the functional relationships between flow and geometry. The basic data needed to establish these relationships are depth as a function of width at various cross-sections. For the purposes of the TMDL, data of this type were acquired from a number of sources as described in Yearsley et al (2001).

- The energy budget is developed from meteorological data. The data are wind speed, dry bulb temperature, relative humidity (or similar measure of water content), cloud cover, and station pressure as a function of time.

- Advected thermal energy is defined by the stream flow and water temperature of headwaters, tributaries and points sources.

Parameter Estimation

The basic model framework for the TMDL was developed in the problem assessment and described in Yearsley et al (2001). In the problem assessment the parameter estimation process was implemented using a smaller model domain and water temperature data from the period 1990-1994. For the TMDL, the parameter estimates were updated using the larger model domain and water temperature data from the period 1995-1999. The water temperature data are from monitoring sites below the dams and appear to be of higher quality and more representative of well-mixed river temperatures. Station descriptions for the Columbia and Snake rivers are given in Tables 2 and 3,respectively. The only parameter estimated was the coefficient, K_e, in the relationship describing the rate of heat transfer due to evaporation

$$q_{evap} = K_e \rho L(e_w - e_a)$$

where,

q_{evap} = the heat flux across the air-water interface due to evaporation,

ρ = the density of water,

L = the latent heat of vaporization,

e_w = the saturated vapor pressure at the water surface temperature,

e_a = the vapor pressure of the air above the water.

The energy budget for the model domain of the TMDL analysis is characterized by five different meteorological provinces as described above (Table 4). The coefficient, K_e, was treated as a variable for each meteorological province. The parameter estimation process was designed to select the set of coefficients, K_e , that resulted in the minimum mean squared difference, between simulated and observed for the monitoring sites shown in Table 5.

Model Acceptance

Statistics used to assess performance of the one-dimensional mathematical model, RBM10, are similar to those described as appropriate for temperature models (Bartholow, 1989) and recommended by van der Heijde and Elnawawy (1992) in EPA's guidance for selecting groundwater models. The performance measures calculated for the TMDL simulations include:

Mean Difference

$$D_{mean} = \frac{\sum_{n=1}^{N}(T_{sim} - T_{obs})}{N}$$

Absolute Mean Difference

$$D_{amd} = \frac{\sum_{n=1}^{N} | T_{sim} - T_{obs} |}{N}$$

Root-Mean-Squared Difference

$$D_{rms} = \sqrt{\frac{\sum_{n=1}^{N} (T_{sim} - T_{obs})^2}{N}}$$

where,

N = the number of matched pairs of simulated and observed temperatures,

T_{sim} = the simulated temperature at the time of the n^{th} observation

T_{obs} = the observed temperature.

The model performance statistics for the five-year (1995-1999) simulation period are given in Table 5.

TMDL Analysis

Several types of simulations were used in the development of the temperature TMDL for the Columbia and Snake rivers. Table 6 gives a summary of the simulation types. Simulation results are reported at the compliance points as described in the TMDL . The compliance points are just downstream from hydroelectric projects or, in the case of the unimpounded portion of the Columbia River below Bonneville Dam, the compliance points are generally downstream from major discharges. All the data and model source codes for developing the TMDL are on the data CD (Appendix A).
The following discussion describes the contents of the directories on the data CD. The computer programs and data files can be used to reproduce all the results used in the Final Draft Temperature TMDL for the Columbia and Snake rivers. Each of the headings below is the name of a directory on the data CD, Appendix A. File and directory names are given in **boldface**.

\Appendix_A\Forcing_Functions

The files containing thirty-year record (1970 through 1999) of energy inputs to the system are stored in this directory. Thermal energy inputs to the river system are from advected sources (main stem boundaries and tributaries) and heat transfer across the air-water interface.

Advected thermal energy from tributaries and main stem boundaries are estimated from river flow and water temperatures. Data for advected thermal energy were obtained from the sources shown in Tables 2 and 3. Missing water temperature data were filled by linear interpolation when data gaps were of the order of a week or less. For larger gaps, a lag-one Markov model was used to fill in missing data.

Heat transfer across the air-water interface is estimated from the meteorological data. Meteorological data from six weather stations are used to estimate the energy budget for the TMDL. The weather stations used in the TMDL and the segments of river are defined in Table 4. Weather data for these stations are in the directory,**\Appendix_A\Meteorology**. Only three of the weather stations, Lewiston, Portland and Yakima, are primary stations, ones where all the required meteorological variables are measured and reported.   The other three weather stations, Coulee Dam, Wenatchee and Richland, report only air temperature. The remaining meteorological data for these stations was synthesized from the the primary station as shown in Table 4. The energy budget files were created in the folder, **..\System_iv\setup**, using the programs, **build_heat.exe**, and **energy.exe**. The source code for **build_heat.exe**, and **energy.exe** has hard-wired coding that looks for weather data in specific directories. The code should be modified to ensure that the pathways specified in the coding are correct for the particular application   The output files with energy budget are named, **CityName.budget.avg**, as in, **Portland.budget.avg**.

The file with thermal energy from advective sources (main stem boundary conditions and tributaries) is named, **No_Ocean.advect**. The file with elevation data is named, **No_Ocean.elev**. These files were created in the folder, **..\System_iv\setup** using the program, **start_iv.exe** in conjunction with the control file. **no_ocean.control**. These advection and elevation files were used as the forcing functions for all the scenarios simulated for the TMDL.

\Appendix_A\TMDL\Site_Potential

The framework for implementing the State of Washington’s water quality standards is constructed around the concept of “site potential.”   Site potential, in the case of the temperature TMDL, is defined as the daily-averaged, cross-sectional average temperature that would result in the absence of impoundments and discharges of thermal energy from municipal and industrial point sources as well as from various nonpoint sources. As described above, those impacts on the thermal energy budget external to the defined boundaries of the temperature TMDL are considered to be part of site potential.   These impacts include those changes in flow and temperature at the boundaries of the TMDL resulting from human activities. Non-stationary impacts on climate such as global warming from industrial carbon dioxide production may also be present in site potential as defined and realized with the inputs described below. Site-potential is not, therefore, the temperature of the river prior to human development. Rather it is the temperature that would result in the absence of major human activities in the listed river segments.

Human activities in the existing river system configuration that have altered the thermal regime of the Columbia and Snake rivers are:

1. Construction of impoundments for hydroelectric facilities and navigational locks, which increase the time waters of the Columbia and Snake are exposed to high summer temperatures, increase the surface area exposed energy transfer across the air-water interface and change the system's thermal response time.

2. Discharge of thermal energy from industrial and municipal point sources and agricultural and urban nonpoint sources

3. Hydrologic modifications to the natural river system to generate electricity, provide irrigation water for farmlands, and facilitate navigation.

4. Modifications of the watershed by urban development and agricultural and silvicultural practices that reduce riparian vegetation, increase sediment loads, and change stream or river geometry.

The TMDL focuses on those activities associated with the construction of impoundments, thermal discharges from point and nonpoint sources and, implicitly, on the effects of hydrologic modifications. The TMDL's developed for the listed tributaries of the Columbia and Snake rivers should develop water quality plans that address thermal effects of modifications of the watershed.

The impacts of impoundments on the thermal regime of the Columbia and Snake rivers are due to both the change in river geometry and to operation of the hydroelectric facilities. All of the hydroelectric projects within the model domain, with the exception of Grand Coulee Dam, are run-of-the river projects. That is, the projects are operated such that approximately all the water entering the reservoir is passed through the reservoir and released. As a result, the water level in these reservoirs fluctuates very little. This does not mean the effects of the operation do not have ecological impacts. It is well known, for example, that daily fluctuations in tailwater elevations at Priest Rapids affect spawning and rearing habitat of fall Chinook and can cause stranding of juvenile fish in the Hanford Reach of the Columbia River (Tiffan, 2003). However, the impact of these operations on the daily-averaged, cross-sectional average temperature is small. The major impact on the daily-average, cross-section water temperature is due to the increase in width and depth resulting from the construction and operation of the impoundment.

Flood control is an operational feature of Lake Roosevelt, the reservoir behind Grand Coulee Dam. As a result, the fluctuations in reservoir elevation are significant. Therefore, simulations of water temperature for the existing conditions include the effects of storage for this project.

Point source inputs for the TMDL analysis are based on permit numbers provided by the State of Oregon's Department of Environmental Quality (DEQ) and the State of Washington's Department of Ecology (DOE). The energy inputs associated with these sources are given in Table 8. Major discharges are shown individually while smaller discharges are aggregated and shown as aggregated sources at the end of certain river reaches. In addition, a 20 megawatt allowance of thermal energy is provided at each compliance point for general permits. general permit includes impacts from stormwater discharge

The model domain for simulating site potential was created with the hydraulic properties in the file **crtes.model.input.no_dams** in the directory. A 30-year period of site potential temperatures were simulated for the model domain using hydrologic data and weather data for the period 1970 through 1999 and output to the files, **Columbia.no_dams.avg** and **Snake.no_dams.avg** for the Columbia River and the Snake River, respectively.

A 30-year period of daily cross-sectionally averaged temperatures for existing conditions were simulated for the model domain using hydrologic data and weather data for the period 1970 through 1999 using the executable **rbm10_iii.exe**. The control file used for simulating existing conditions is **crtes.model.input.dams.** The simulation results were output to the files, **Columbia.dams.avg** and **Snake.dams.avg** for the Columbia River and the Snake River, respectively.

\Appendix_A\TMDL\Point_Sources

The impact of point sources at compliance points was simulated by comparing the simulated results from existing conditions, described above, with those same conditions when permitted thermal sources are removed. Environmental forcing functions and parameters were the same as those used for simulations of site potential and existing conditions. The basic source code for **RBM10** was modified to accommodate the addition of point sources. The source code is in **..\Model_iii_pnt\rbm10_iii** and is named **rbm10_pnt.f**. The executable is named **rbm10_iii_pnt.exe**.

Simulations were performed in two directories, **..\Existing_Sources** and **..\Zero_Discharge** using **rbm10_iii_pnt.exe** (point source version) in conjuncton with the control file, **crtes.model.input.dams**. The Fortran source code, **rbm10_iii_pnt.f**, in the directory, **..\Existing_Sources**, differs slightly from that in the directory, **..\Zero_Discharge**. The difference is due to hardwired coding that ignores point sources in the directory, **..\Zero_Discharge**. The source code for each version is stored in the appropriate directory. This version of the control file has also been modified to accommodate the point sources. Simulated results are output at the compliance points as,
..\Existing_Sources\Columbia_Exist.RM_xxx, ..\Zero_Discharge\Columbia_Zero.RM_xxx,
..\Existing_Sources\Snake_Exist.RM_xxx, ..\Zero_Discharge\Snake_Zero.RM_xxx,
where "**xxx"** is the river mile of the compliance point. The directory labeled, **Existing_Sources**, incorporates the thermal loadings associated with the point sources, while the directory labeled, **Zero_Discharge**, simulated the impounded system with no thermal discharges from point sources.

\Appendix_A\TMDL\Dam_Impacts

The effect of adding individual hydroelectric projects to the unimpounded river was simulated by starting with the river systems in their present configuration of hydroelectric projects. Simulations of the system were then performed by changing, one hydroelectric project at a time, the hydraulic coefficients of the portion of the river upstream of the dam from freely-flowing river type to reservoir type. This assumes that the impounded section of the river associated with a specific hydroelectric project will not affect the hydraulic characteristics of the unimpounded river both upstream and downstream of the of the project being evaluated. Environmental forcing functions and parameters were the same as those used for other simulations. Results are in,**..\DamName**, where "**DamName**" is the name of the hydroelectric project.

Simulations were performed with the same forcing functions used for other scenarios and the version of the source code used for the characterization of site potential. The version of the source code is labeled, **rbm10_ iii.f**, in the directory, **..\Model_III\rbm_iii\Original_Code**. The executable associated with this source code, **rbm10_iii.exe**, was used in conjunction with control file for each each dam and labeled **crtes.model.final.nnn**, where, **nnn**, is the symbol for the specific dam as in the example, **crtes.model.final.BON**, the file containing simulated effect of adding Bonneville Dam to the unimpounded river.

\Appendix_A\TMDL\Obverse_Impacts

For purposes of the TMDL, the impact of individual dams was simulated by changing, one project at a time, the hydraulic properties of the reservoir behind the dam to hydraulic properties representing the freely-flowing river. As in the case above where individual dams were added to the natural river system, this set of scenarios assumes that the hydraulic properties of the freely-flowing river will not be affected significantly by hydroelectric projects upstream or downstream from the one being evaluated. Environmental forcing functions and parameters were the same as those used for other simulations. Results are in,**..\DamName**, where "**DamName**" is the name of the hydroelectric project.

Simulations were performed with the same forcing functions used for other scenarios and the version of the source code used for the characterization of site potential. The version of the source code is labeled, **rbm10_ iii.f**, in the directory, **..\Model_III\rbm_iii\Original_Code**. The executable associated with this source code, **rbm10_iii.exe**, was used in conjunction with control file for each each dam and labeled **DamName.Obverse**, where, **DamName**, is the symbol for the specific dam as in the example, **Bonneville**, for Bonneville Dam.

Output for the simulations in the Columbia and Snake rivers is to files named **RiverName.nnn.Obv**. **RiverName** is either **Columbia** or **Snake** and **nnn**, is the symbol for the specific dam as in the example, **Columbia.BON.Obv**, for the file with the simulated effects of removing Bonneville Dam from the impounded river.

\Appendix_A\TMDL\Work_Space

The software that implements RBM10, the time-dependent, one-dimensional energy budget model, was modified such that simulated results could be compared to the water quality standards of Washington and Oregon. The reference data sets used for making comparisons were the simulations based on site potential (**COLUMBIA.NO_DAMS.AVG** and **SNAKE.NO_DAMS.AVG**). The modified program is named **RBM10_TMDL.F** and is located in the directory **\Appendix_A\TMDL\Work_Space\RBM_TMDL**.

Several TMDL scenarios were evaluated using the RBM10 model framework. 21 of these scenarios, including the scenario used for the draft final TMDL are in the directory, **\Appendix_A\TMDL\Work_Space\TMDL_final**. All but the scenario used for the draft final TMDL, **Scenario**_21a, are archived in the compressed file, **Scenario_Archive.zip**. A brief description of the 21 scenarios is in the document, **\Appendix_A\TMDL\Work_Space\Work_Space_log.doc**.

The first step in the TMDL was to allocate loads to the permitted discharges. The simulations of point sources described above provided estimates showing that the far-field temperature effects of permitted discharges did not exceed the water quality standards of the states of Oregon and Washington. The point sources were, therefore, allocated thermal loads based on their National Pollution Discharge Elimination System (NPDES) permits. The allocations for the dams were determined from the results of the obverse impacts analysis. That is, each dam was allocated a temperature change based on the daily-averaged difference between simulated results for the existing system and the results when the particular dam was removed from the system. The file containing the allocations is named "**DELTA.TMDL**". The results were compared with the water quality standards of the states or Oregon and Washington to assure compliance.

\Appendix_A\TMDL\Hourly_Max

Hourly water temperatures in the Columbia and Snake rivers were simulated using hourly meteorological data and daily averaged temperature and flow data. Hourly simulations were performed for calendar years 1992 and 1997 and the results saved in the directory, **\Appendix_A\TMDL\Hourly_Max\Results**. The forcing functions for advection and energy transfer across the air-water interface are the advection file, **No_Ocean.advect**, and meteorological data files **CityName.199x.hourly**, where **"CityName"** is the name of the weather station **"x"** is either **"2"** or **"7"**, as in the example, **Lewiston.1992.hourly**.

The source code, **rbm10_iii.f**, is the same as that used to develop the site potential.

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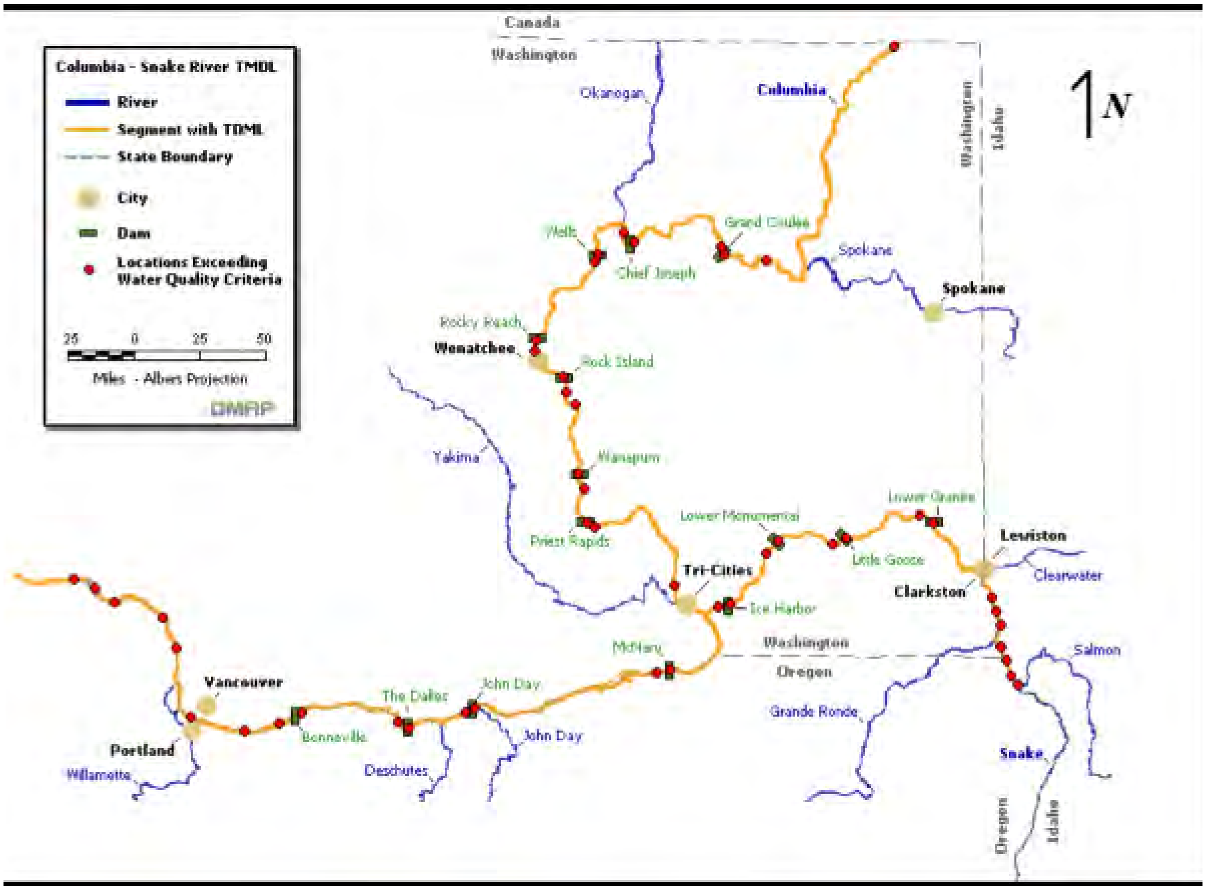

Figure 1. Location map for Columbia TMDL

Table 1. Data sources for advected energy in the Columbia and Snake rivers

	Data Sources	
	Flow	**Temperature**
Salmon River at White Bird, Idaho	USGS 13317000	USGS 13317000
Grande Ronde River at Troy, Oregon	USGS 13333000	Washington DOE 35C070
Snake River near Anatone, Washington	USGS 13334300	USGS 13334300; DART Site ANQW
Clearwater River at Orofino, Idaho	USGS 13340000	USGS 13340000
North Fork Clearwater at Dworshak Dam	DART Site DWR	DART Site DWR
Tucannon near Starbuck, Washington	USGS 13344500	Washington DOE 35B060
Palouse River near Hooper, Washington	USGS 13351000	Washington DOE 34A070
Columbia River at the International Boundary	USGS 12399500	DART Site CIBW
Kettle River near Laurier, Washington	USGS 12404500	Washington DOE 59A070
Colville River at Kettle Falls, Washington	USGS 12409000	Washington DOE 60A070
Spokane River at Long Lake	USGS 12433000	USGS 12433000
Feeder Canal at Grand Coulee, Washington	USGS 12435500	-----
Okanogan River at Malott, Washington	USGS 12447200	Washington DOE 49A070
Methow River near Pateros, Washington	USGS 12449950	Washington DOE 48A070
Wenatchee River at Monitor, Washington	USGS 12462500	Washington DOE 45A070
Crab Creek near Moses Lake, Washington	USGS 12467000	Washington DOE 41A070
Yakima River at Kiona, Washington	USGS 12510500	Washington DOE 37A090
Walla Walla River at Touchet, Washington	USGS 14018500	USGS 14018500
Umatilla River near Umatilla, Oregon	USGS 14033500	USGS 14033500
John Day River at McDonald Ferry, Oregon	USGS 14048000	Oregon DEQ 404065

Table 1 (continued). Data sources for advected energy on the main stem Columbia and Snake Rivers

Deschutes River at Moody, near Biggs, Oregon	USGS 14103000	Oregon DEQ 402081
Klickitat River	USGS 14105700	USGS 14113000
Hood River	USGS 14120000	Oregon DEQ 402081
Sandy below Bull Run Reservoir, Oregon	USGS 14142500	Oregon DEQ 402349
Willamette River at Portland, Oregon	USGS 14211720	Constrained to Columbia River
Lewis River at Ariel, Washington	USGS 14220500	Oregon DEQ 402081
Cowlitz River at Castle Rock, Oregon	USGS 14243000	Oregon DEQ402081

Table 2. Temperatures monitoring sites in the Columbia River

Station	Station Identifier	Station Description
Bonneville Dam tailwater	**BON**	Columbia RM 146: Right end of spillway near center of dam
The Dalles Dam tailwater	**TDDO**	Columbia RM 190: Left bank one mile d/s of dam
John Day Dam tailwater	**JHAW**	Columbia RM 215: Dam tailwater Right bank of river
McNary Dam tailwater-Washington	**MCPW**	Columbia RM 291: Dam Tailwater Right bank of river
Priest Rapids tailwater	**PRXW**	Columbia RM 396: Tailwater D/s of dam
Wanapum Dam tailwater	**WANW**	Columbia RM 415: Tailwater D/s of dam
Rock Island Dam tailwater	**RIGW**	Columbia RM 452: Tailwater D/s of dam
Rocky Reach Dam tailwater	**RRDW**	Columbia RM 472 Tailwater D/s of dam
Wells Dam tailwater	**WELW**	Columbia RM 514: Tailwater D/s of dam
Chief Joseph Dam tailwater	**CHQW**	Columbia RM 545: Tailwater D/s of dam
Grand Coulee Dam tailwater	**GCGW**	Columbia RM 590: Six miles D/s of dam

Table 3. Temperatures monitoring sites in the Columbia River

Station	Station Identifier	Station Description
Ice Harbor Dam tailwater	**IDSW**	Snake RM 6.8: Right bank 15,400 feet d/s of dam
Lower Monumental Dam tailwater	**LMNW**	Snake RM 40.8:Left bank 4,300 feet d/s of dam
Little Goose Dam tailwater	**LGSW**	Snake RM 69.5:Right bank 3,900 feet d/s of dam
Lower Granite Dan tailwater	**LGNW**	Snake RM 106.8: Right bank 3,500 feet d/s of dam

Table 4. Meteorological station used to estimate heat budget

Station Name	Station #	Station Type	Station Used to Synthesize	River Segments
Lewiston, Idaho	WBAN 24149	Surface Airways	---	Snake RM 0.0 – 188.0 Clearwater RM 0 – 42.0
Portland, Oregon	WBAN 24229	Surface Airways	---	Columbia RM 0.0 – 1245.5
Spokane, Washington	WBAN 24157	Surface Airways	---	---
Yakima, Washington	WBAN 24243	Surface Airways	---	Columbia RM 292.0 – 453.4
Coulee Dam	NCDC 451767	Local Climatological Data	Spokane	Columbia RM 738.0 – 596.5
Richland	NCDC 457015	Local Climatological Data	Yakima	Columbia RM 292.0 – 145.5
Wenatchee	NCDC 459074	Local Climatological Data	Spokane	Columbia RM 596.5 – 453.4

Table 5. Model performance statistics for RBM10

Columbia River	# of Samples	Absolute Mean Difference	Average Difference	RMS Difference	Standard Deviation
Grand Coulee	1150	0.73	-0.08	0.97	0.94
Chief Joseph	678	1.05	0.81	1.46	1.46
Wells	348	0.52	0.40	0.70	0.32
Rocky Reach	512	0.67	0.57	0.86	0.42
Rock Island	534	0.64	0.53	0.85	0.43
Wanapum	889	0.81	0.05	1.25	1.56
Priest Rapids	773	0.78	-0.09	1.03	1.06
McNary	1222	0.56	-0.34	0.72	0.40
John Day	666	0.46	0.02	0.59	0.35
The Dalles	703	0.43	0.06	0.54	0.29
Bonneville	493	1.07	-0.59	1.36	1.49
Snake River					
Lower Granite	1144	0.83	-0.64	1.03	0.65
Little Goose	746	0.77	-0.29	1.13	1.19
Lower Monumental	819	0.73	-0.19	0.93	0.82
Ice Harbor	1222	0.78	-0.30	0.93	0.78

Table 6. Model applications in TMDL

RBM10 Application	Model Setup	Output Files	Findings
1. Site Potential Temperature	Daily Time Step Un-impounded River Existing tributary/boundary inflows No point sources	**Columbia.no_dams.avg** **Snake.no_dams.avg**	Temperatures exceed numeric criteria (e.g., 20 deg C in lower Columbia) in absence of human activity on mainstems
2. Actual Temperature	Daily Time Step Impounded River Existing tributary/boundary inflows All point sources	**Columbia.dams.avg** **Snake.dams.avg**	Actual temperatures are higher than site potential temperatures in late summer/fall (e.g., 3.5 deg C warmer at John Day dam)
3. Point Source Cumulative Impacts	Daily Time Step Impounded River Existing tributary/boundary inflows Point Sources - 2 scenarios Scenario 1: No point sources Scenario 2: All point sources	**..\Zero_Discharge** **Columbia_Zero.RM_xxx** **Snake_Zero.RM_xxx** **..\Existing_Sources** **Columbia_Exist.RM_xxx** **Snake_Exist.RM_xxx**	Maximum, cumulative point source impact less than 0.14 deg C.
4. Individual Dam Impacts	Daily Time Step Impounded River Existing tributary/boundary inflows All point sources Dams - 16 scenarios - Scenario 1: all dams included Scenarios 2-16: one dam removed and effects evaluated	**..\Obverse_Impacts** **Columbia.nnn.Obv** **Snake.nn.Obv**	Maximum temperature increases due to dams range from 0.1 deg C (Rock Island) to 6.2 deg C (Grand Coulee)

Table 6 (continued). Model Applications Used in Development of TMDL

RBM10 Application	Model Setup	Outputs	Findings
5. TMDL Target Temperatures	Daily Time Step Un-impounded River Existing tributary/boundary inflows All point sources Dams - 2 seasons: Aug-Oct Mean daily effect from 5 dams (Wells, Rocky Reach, Rock Island, Priest Rapids, and The Dalles), zero effect from remaining dams Nov-Feb Mean daily effect from 5 dams (Wells, Rocky Reach, Rock Island, Priest Rapids, and The Dalles), 0.12 deg C effect from remaining dams	**..\TMDL_Final\Scenario_21a** **Columbia_TMDL.RM_xxx** **Snake_TMDL.RM_xxx**	This model setup represents a fully allocated temperature increment, based on compliance with standards at RM42
6. Diurnal Fluctuation	Hourly time step Impounded and Un-impounded Existing tributary/boundary inflows	**..\Hourly_max\Results** **Columbia.no_dams.yyyy.hourly** **Columbia.dams.yyyy.hourly** **Snake.no_dams.yyyy.hourly** **Snake.dams.yyyy.hourly**	Greater diurnal fluctuations in un-impounded river than impounded river

Table 7. Point sources of thermal energy in the Columbia River

Facility	River Mile	Thermal Load (MW)	Allocation	Flow, Q (cfs)	Temperature (deg C)
Avista – Kettle Falls	702.4	1.374	Bubble	0.360	32.2
Grand Coulee - Chief Joseph				0.360	32.2
Grand Coulee Dam	596.6	0.906	Bubble	0.279	27.5
Grand Coulee	596.6	2.518	Bubble	1.063	20.0
City of Coulee Dam	596.0	1.099	Bubble	0.464	20.0
Chief Joseph - Wells			Total	1.806	21.2
Chief Joseph Dam	545.1	0.030	Bubble	0.009	27.5
Bridgeport STP	543.7	1.510	Bubble	0.464	22.0
Brewster	529.8	1.832	Bubble	0.563	23.0
Patteros STP	524.1	0.414	Bubble	0.127	23.0
Wells - Rocky Reach			Total	1.164	22.6
Wells Dam	515.8	0.004	Bubble	0.002	20.0
Wells Hydro Project	515.0	0.015	Bubble	0.006	20.0
Chelan STP	503.5	7.399	Bubble	2.274	25.0
Entiat STP	485.0	0.604	Bubble	0.186	23.0
Rocky Reach - Rock Island			Total	2.468	24.8
Rocky Reach Dam	474.9	0.020	Bubble	0.006	27.5
Tree Top	470.8	0.331	Bubble	0.127	22.0
Naumes Processing	470.5	10.543	Bubble	2.674	33.3
Columbia Cold Storage	466.3	5.990	Bubble	0.928	23.9
E Wenatchee STP	465.7	19.126	Bubble	5.879	23.5
KB Alloys	458.5	1.484	Bubble	0.464	27.0
Specialty Chemical	456.3	15.464	Bubble	6.189	21.1
Alcoa Wenatchee	455.2	17.847	Bubble	6.962	21.6
Rock Island - Wanapum			Total	23.230	23.5
Rock Island	453.4	0.008	Bubble	0.002	27.5
Rock Island West Powerhouse	453.4	0.008	Bubble	0.002	27.5
Vantage STP	420.6	0.438	Bubble	0.135	26.0
Wanapum - Priest Rapids			Total	0.139	26.0
Priest Rapids - McNary					
Columbia Generating Sta	351.8	53.697	Bubble	15.114	30.0
Fluor Daniel Hanford, Inc	347.0	27.902	Bubble	8.475	27.8
Richland STP	337.1	57.378	Bubble	17.638	23.5
Baker Produce	329.2	0.040	Bubble	0.012	27.5
Twin City Foods	328.3	0.041	Bubble	0.012	28.3
Kennewick	328.0	61.405	Bubble	18.876	23.0
Pasco	327.6	22.752	Bubble	6.993	27.5

Total	67.121	25.8

Table 7(continued). Point sources of thermal energy in the Columbia River

Facility	River Mile	Thermal Load (MW)	Allocation	Flow, Q (cfs)	Temperature (deg C)
Agrium Bowles Road	322.6	405.821	Individual	62.150	28.1
				62.150	28.1
Agrium Game Farm Road	321.0	484.694	Individual	102.410	31.7
				102.410	31.7
Sanvik Metals	321.0	0.920	Individual	0.388	20.0
				0.388	20.0
Boise Cascade Walulla	316.0	234.905	Individual	51.200	47.0
McNary to John Day				51.200	47.0
Umatilla STP	289.0		Individual	0.780	23.0
Goldendale	216.7	39.813	Individual	12.888	26.1
John Day - The Dalles				12.888	26.1
Biggs OR	208.8	0.236	Bubble	0.084	23.9
Wishram STP	200.8	0.488	Bubble	0.234	25.2
The Dalles - Bonneville			Total	0.234	25.2
Dalles/Oregon Cherry OR	189.5	7.877	Bubble	2.784	23.9
Northwest Aluminum OR	188.9	8.793	Bubble	2.228	33.3
Cascade Fruit OR	188.3	0.875	Bubble	0.309	23.9
Lyle	183.2	0.008	Bubble	0.930	28.0
Mosier OR	174.6	0.131	Bubble	0.046	23.9
			Total	6.298	27.8
SDS Lumber	170.2	160.323	Individual	16.240	28.3
				16.240	28.3
Bingen STP	170.2	4.027	Bubble	1.238	23.0
Hood River OR	168.4	0.438	Bubble	0.155	23.9
Cascade Locks OR	151.0	0.381	Bubble	0.135	23.9
Stevenson STP	150.0	1.830	Bubble	0.696	22.2
Bonneville - Coast			Total	2.223	22.9
Tanner OR	144.2	1.113	Bubble	0.392	24.0
North Bonneville STP	144.0	0.508	Bubble	0.193	22.2
Multnomah Falls OR	134.2	0.186	Bubble	0.059	26.7
BBA Nonwovens Washougal	124.0	0.336	Bubble	0.155	18.3
Exterior Wood, Inc.	123.8	0.295	Bubble	0.077	32.2
Washougal STP	123.5	9.111	Bubble	3.466	22.2
Camas STP	121.2	24.812	Bubble	9.438	22.2
			Total	13.780	22.3
Georgia Pacific	120.0	313.206	Individual	93.230	30.6

Table 7 (continued). Point sources of thermal energy in the Columbia River

Facility	River Mile	Thermal Load (MW)	Allocation	Flow, Q (cfs)	Temperature (deg C)
Toyo Tanso USA OR	118.1	0.196	Bubble	0.071	23.4
Gresham OR	117.4	106.708	Bubble	39.176	23.0
Marine Park	109.5	64.431	Bubble	24.755	22.0
Vancouver Ice & Fuel Oil	106.0	0.005	Bubble	0.002	20.0
Graphic Packaging OR	105.6	31.503	Bubble	9.852	27.0
Northwest Packing Co.	105.2	0.348	Bubble	0.077	30.0
Portland STP OR	105.0	521.939	Bubble	195.881	22.5
Great Western Malting	105.0	36.278	Bubble	15.317	20.0
Vancouver Westside STP	105.0	183.024	Bubble	71.093	21.7
Support Terminal Services	104.8	0.008	Bubble	0.002	16.0
Clark County PUD	103.2	5.198	Bubble	1.099	40.0
Van Alco	103.0	25.321	Bubble	7.705	27.8
Salmon Creek STP	95.5	38.236	Bubble	14.544	22.2
			Total	379.574	22.5
Boise/St Helens OR	85.8	219.555	Individual	52.970	35.0
Columbia River Carbonates	83.5	5.898	Individual	1.547	32.2
Coastal St Helens OR	82.6	365.094	Individual	77.266	39.9
Clariant Corp	76.0	5.894	Bubble	1.547	32.2
Kalama STP	75.0	1.627	Bubble	0.619	22.2
Noveon Kalama, Inc	74.0	7.450	Bubble	1.547	40.7
Steelscape, Inc.	73.5	1.885	Bubble	0.278	57.2
			Total	3.992	35.7
PGE Trojan OR	72.7	511.152	Individual	0.035	22.0
Port of Kalama	72.2	0.081	Bubble	0.031	22.2
Riverwood OR	70.2	0.072	Bubble	0.025	24.0
Cowlitz STP	68.0	109.027	Bubble	41.766	22.0
Longview Fiber	67.4	540.993	Bubble	116.530	33.0
Rainier OR	67.1	2.436	Bubble	0.979	21.0
Cytec Industries	67.0	3.232	Bubble	1.516	22.0
Houghton International	67.0	0.008	Bubble	0.016	27.0
			Total	160.864	30.0
Longview STP	66.0	10.983	Individual	4.177	22.2
Weyerhauser Longview	64.0	398.626		73.610	38.9

			Individual		
				73.610	38.9
Reynolds	63.0	58.208	Bubble	24.600	20.0
Stella STP	56.4	0.014	Bubble	0.005	22.2
PGE Beaver OR	53.4	7.026	Bubble	1.695	35.0
New Source OR	52.8	24.841	Bubble	6.992	30.0
			Total	33.293	20.0
GP Wauna OR	42.3	301.706	Individual	76.277	33.4
				76.277	33.4
Cathlamet STP	32.0	0.549	Bubble	0.209	22.2
Astoria OR	11.8	23.383	Bubble	8.227	24.0
Ft. Columbia State Park	7.2	0.020	Bubble	0.008	22.2
Bell Buoy Crab Co.	6.0	0.329	Bubble	0.139	20.0
Warrenton OR	5.0	2.505	Bubble	0.881	24.0
Ilwaco STP	2.0	3.523	Bubble	1.083	20.0
Jessies Ilwaco Fish Co.	2.0	2.748	Bubble	1.160	16.0
Coast Guard Sta.	1.0	0.010	Bubble	0.003	27.5
			Total	11.711	22.8

Table 8. Point sources of thermal energy in the Snake River

Facility	River Mile	Thermal Load (MW)	Allocation	Flow, Q (cfs)	Temperature (deg C)
Salmon R - Lower Granite					
Asotin STP	145.0	4.016E	Bubble	1.5626438	21.7
Clarkston STP	138.0	6.265E	Bubble	2.0267955	26.1
			Total	3.5894393	24.2
Potlatch	139.3	298.8	Individual	75.697228	33.3
Lower Granite to Little Goose					
Lower Granite Dam	107.5	0.0194	Individual	0.0077689	21.1
				0.0077689	21.1
Little Goose - Lower Monumental					
Little Goose Dam	70.3	0.0116	Bubble	0.0045907	21.3
Lyon's Ferry	59.1	1.381	Bubble	0.4484799	26.0
			Total	0.4530706	26.0
Lower Monumental - Ice Harbor					
Lower Monumental Dam	44.6	0.00392	Individual	0.0015472	21.4
Ice Harbor - Columbia R.					
Ice Harbor Dam	9.7	0.00395	Individual	0.0015472	21.5