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Application of a 1-D Heat Budget Model to the Columbia River System

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CHAPTER 1: COLUMBIA RIVER SYSTEM AND STUDY OBJECTIVES

1.1   INTRODUCTION

The objective of the Clean Water Act (as amended by the Water Quality Act of 1987, Public Law 100-4) is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. Each state has developed standards for water quality that are used to judge how well the objectives of the Clean Water Act are being achieved. The water quality standards consist of the designated beneficial uses of the water and the water quality criteria necessary for achieving and maintaining the beneficial uses.

Under Section 303 of the Clean Water Act, states must identify waters for which effluent limitations, as required by Section 301, are not sufficient to implement established water quality standards. Oregon and Washington have identified portions of the main stem of the Columbia River from the International Border (Columbia River Mile 745.0) to the mouth at Astoria, Oregon, and the Snake River from Anatone, Washington, (Snake River Mile 168.9) to its confluence with the Columbia River as water quality limited (Figure 1-1). This designation arises from an analysis of data (Washington DOE, 1998; Oregon DEQ, 1998) showing these waters do not meet water quality standards during all or part of the year. Sources that may contribute to impairment of water quality in these segments of the Columbia and Snake rivers include the following:
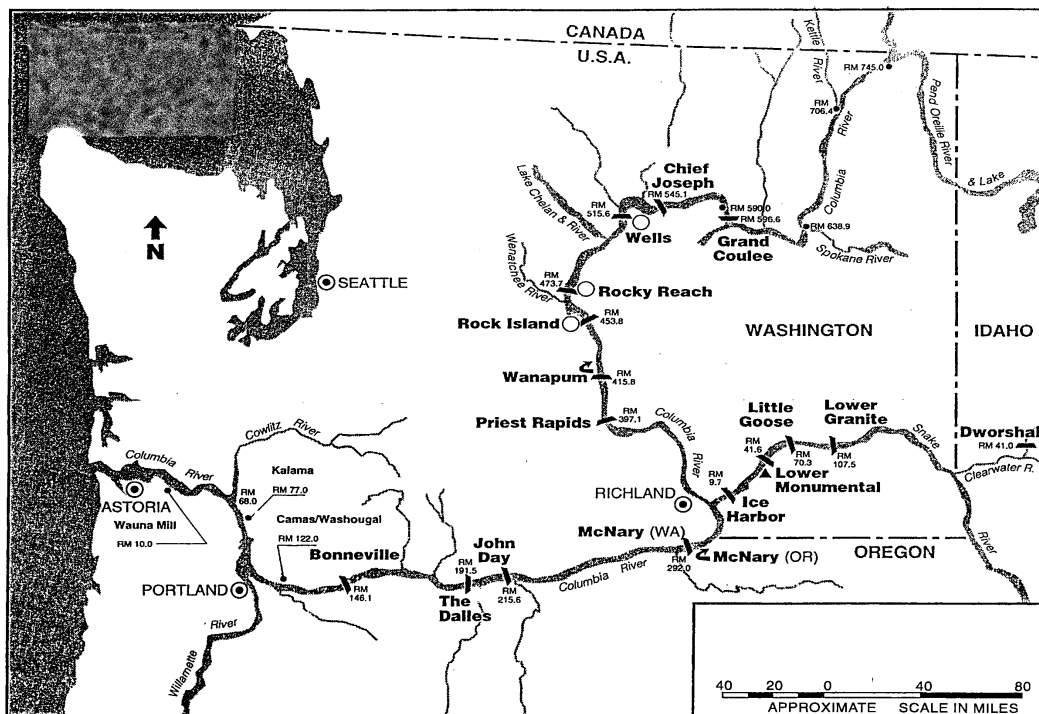
Figure 1-1.   The Columbia and Snake rivers and associated hydroelectric projects in the study area.

❑ 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 and change the system's thermal response time.

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

❑ Modifications of the watershed by agriculture and silviculture practices that reduce riparian vegetation, increase sediment loads, and change stream or river geometry.

❑ Operation of pulp and paper manufacturing facilities that discharge thermal energy and toxic substances, particularly dioxin.

After the water quality limited segments have been identified, priorities must be established for attaining water quality standards based on the severity of the pollution and the beneficial uses of the water body. Water temperature is one of the most frequently occurring constituents on Oregon's and Washington's lists of water quality limited segments on the Columbia and Snake rivers. Segments of the Columbia and Snake rivers in the study area that are water quality limited for water temperature and for which the listing criteria require a Total Maximum Daily Load (TMDL) are given in Table 1-1.

Table 1-1. Parameter list for water quality limited segments of the Columbia and Snake River in Washington

State	Water Body Name	River Mile	Parameter	Action Needed
OR	Columbia River	146.1 – 191.5	Temperature	TMDL
OR	Columbia River	191.5 – 215.6	Temperature	TMDL
OR	Columbia River	215.6 – 292.0	Temperature	TMDL
OR	Columbia River	292.0 – 309.3	Temperature	TMDL
WA	Columbia River	290.5	Temperature	TMDL
WA	Snake River	139.6-0.0	Temperature	TMDL
WA	Snake River	168.0 – 139.6	Temperature	TMDL
WA	Columbia River	515.6	Temperature	TMDL
WA	Franklin D. Roosevelt Lake	596.6	Temperature	TMDL

When setting priorities for attaining established water quality standards for temperature, the first step is to assess the importance of sources that may significantly affect the thermal energy budget. Changes in the thermal energy budget of the Snake and Columbia rivers, relative to the natural unregulated river system, are due primarily to advected thermal energy from point sources, surface water, and ground water, as well as modification of river geometry and hydraulics due to the construction and operation of hydroelectric facilities. The goal of this work is to support the priority-setting phase of the TMDL process by assessing the impacts of the principal sources of thermal energy.

1.2 GEOGRAPHY, CLIMATE, AND HYDROLOGY OF THE COLUMBIA BASIN

Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the states of Idaho, Oregon, Washington, and Wyoming. The Columbia River rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, British Columbia. The Columbia River enters the United States from the Okanogan Highland Province, a mountainous area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin—a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt—and flows south across the state of Washington. Near Pasco, Washington, and the confluence with the Snake River, the Columbia turns west, forms the border between Oregon and Washington, and flows more than 300 miles through the Casscade Mountain Range to the Pacific Ocean near Astoria, Oregon.

The headwaters of the Snake River are in Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7,000 feet above sea level. The river flows west across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western edge of Idaho, it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. Other major tributaries of the Snake in Idaho include the Bruneau, Owyhee, Boise, Payette, Weiser, and Salmon rivers.

Although the Snake River is the Columbia's largest tributary, other major tributaries include the Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes, and Willamette rivers. The Kootenai lies largely in Canada, but flows through western Montana, northern Idaho, and back into Canada before entering the Columbia below Lower Arrow Lake in British Columbia. The Clark Fork-Pend Oreille has its headwaters on the Continental Divide in Montana, flows through northern Idaho into Pend Oreille Lake and becomes the Pend Oreille River. The Pend Oreille River flows north into Canada before joining with the Columbia River. Major tributaries of the Clark Fork are the Flathead, Blackfoot, and Bitteroot rivers. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in Lake Franklin D. Roosevelt (Lake FDR). Both the Deschutes and Willamette rivers have their headwaters in Oregon; the Deschutes rises in central Oregon and flows north across lava flows of the Columbia Basalt, while the Willamette begins in the Cascade Mountains and flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely, depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while annual precipitation can exceed 100 inches per year in some of the mountainous regions of Canada.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100 °F (37.8 °C) for extended periods. Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavy snow falls in the mountains. The snowpack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snowpack is incorporated into the extensive system of glaciers in the basin; however, between the months of March and June, depending on elevation, much of the snowpack begins to melt. The resulting hydrograph is typical of a snowmelt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing, and summer air temperatures are seldom above 100 °F (37.8 °C) for long periods. Average annual precipitation west of the Cascades is more than 40 inches in most areas. Precipitation recorded at coastal stations is typically higher. Below about 5,000 feet, most of the precipitation falls as rain, with 70 percent or more falling between October and March.

Hydrology

Although the hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control, and transportation projects, the hydrograph still has the characteristics of a snowmelt regime. Streamflows are low during the winter, but increase beginning in spring and early summer as the snowpack melts. Melting of the winter snowpack generally takes place in May and June, and streamflows increase until the snowpack can no longer support high flows. Flows then recede gradually during the summer and are derived from reservoir storage and from ground water recession into the fall and winter.

Occasionally, runoff from winter storms augments the base flow and can increase river discharge rapidly. This is particularly true of the Willamette River, which does not depend on the operation of other reservoirs in the Columbia River system. Rather, it is influenced more by rain and can reach flood stage even with flood control available from reservoirs within the Willamette River system.

Mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table 1-2.

1.3   WATER RESOURCES DEVELOPMENT WITHIN THE COLUMBIA RIVER BASIN

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River above Bonneville Dam that remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the United States (Table 1-3), from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head available in this segment of the Columbia River main stem. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed, with 19 dams on the main stem and a number of impoundments on its tributaries.

Table 1-2. Mean annual discharges at selected sites on the main stem Columbia and Snake Rivers

Station Name	Gage #	Station Location		Period of Record	Average Flow (cfs)
		Latitude	Longitude		
Snake River near Anatone, Washington	13334300	46°05'50"	116° 58'36"	1958-1995	34800
Tucannon near Starbuck, Washington	13344500	46°30'20"	118° 03'55	1914-1996	176
Palouse River near Hooper, Washington	13351000	46°15'02"	118° 52'55	1898-1996	588
Snake River below Ice Harbor Dam	13353000	46°15'02"	118° 52'55"	1913-1992	53400
Columbia River at the International Boundary	12399500	49° 00'03"	117° 37'42"	1938-1996	99200
Columbia River at Grand Coulee	12436500	47° 57'56"	118° 58'54"	1923-1996	108200
Columbia River at Bridgeport, Washington	12438000	48° 00'24"	119° 39'51"	1952-1993	110200
Okanogan River at Malott, Washington	12447200	48° 16' 53"	119° 42' 12"	1965-1996	3050
Methow River near Pateros, Washington	12449950	48° 04' 39"	119° 59' 02"	1959-1996	1560
Columbia River below Wells Dam	12450700	47° 56'48"	119° 51'56"	1968-1996	109400
Columbia River at Rocky Reach Dam	12453700	47° 31' 28"	120° 18'04"	1961-1996	113200
Wenatchee River at Monitor, Washington	12462500	47° 29' 58"	120° 25' 24"	1962-1996	3250
Columbia River below Rock Island Dam	12462600	47° 19'57"	120° 04'48"	1961-1996	116300
Crab Creek near Moses Lake, Washington	12467000	47° 11' 22"	119° 15' 53"	1942-1996	63
Columbia River below Priest Rapids Dam	12472800	46° 37'44"	119° 51'49"	1918-1996	118400
Walla Walla River at Touchet, Washington	14018500	46° 01' 40"	118° 43' 43"	1951-1996	568
John Day River at McDonald Ferry, Oregon	14048000	45° 35' 16"	120° 24' 30"	1904-1996	2080
Deschutes River at Moody, near Biggs, Oregon	14103000	45° 37' 20"	120° 54' 54"	1907-1996	5800
Columbia River at the Dalles	14105700	45° 36'27"	121° 10'20"	1878-1996	191000

Table 1-3. Hydroelectric projects on the main stem Columbia and Snake rivers included in the scope of the analysis

Project	River Mile	Start of Operation	Generating Capacity (megawatts)	Storage Capacity (1000s acre-feet)
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2,069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation, and hydroelectric power generation. There are approximately 7 million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington, and 1.3 million acres in Oregon (Bonneville Power Administration et al., 1994). The system has the capacity for generating more than 20,000 megawatts of hydroelectric energy, and slack-water navigation now extends more than 460 river miles from the mouth at Astoria, Oregon, to Lewiston, Idaho.

In the United States, federal agencies, private power companies, and public utility districts own the dams in the Columbia River Basin. The Columbia Treaty between the United States and Canada governs transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

1.4 ROLE OF TEMPERATURE IN WATER QUALITY

For the Columbia and Snake rivers in Washington, Chapter 173-201A-030 (2) (b) of the Washington Administrative Code (WAC) defines characteristics uses as the following:

(i) Water supply (domestic, industrial, agricultural).

(ii) Stock watering.

(iii) Fish and shellfish:
Salmonid migration, rearing, spawning, and harvesting.
Other fish migration, rearing, spawning, and harvesting.

(iv) Wildlife habitat.

(v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).

(vi) Commerce and navigation.

The characteristic uses for the segments of the Columbia River in Oregon, as defined in the Oregon Administrative Rules (OAR) Chapter 340-041, are similar to those of Washington.

Water quality in the main stem Columbia and Snake rivers is sufficient to protect many of these beneficial uses. An important exception is that of salmonid migration, rearing, spawning, and harvesting. According to the Independent Scientific Group (1996), 200 distinct anadromous stocks returned several million adult salmon and steelhead to the Columbia River prior to development of the basin. Of these stocks, 69 have been identified as extinct and 75 others are at risk of extinction in various parts of the basin. The Independent Scientific Group concluded that the "development of the Columbia River for hydropower, irrigation, navigation and other purposes has led to a reduction in both the quantity and quality of salmon habitat, and most critical, a disruption in the continuum of that habitat."

Water temperature is an important water quality component of habitat for salmon and other cold water organisms in the Columbia and Snake rivers. The criterion for water temperature (Chapter 173-201A WAC and Chapter 340-041 OAR) in the main stem Columbia River from the mouth to Priest Rapids Dam (R.M. 397.1) and Snake River from the mouth to its confluence with the Clearwater River (R.M. 139.3) is that temperature shall not exceed 20 $^{\circ}$C (60 $^{\circ}$F) due to human activities. For the Columbia River from Priest Rapids Dam (R.M. 397.1) to Grand Coulee Dam (R.M. 596.6), the criterion for water temperature is that the temperature shall not exceed 18 $^{\circ}$C (64.4 $^{\circ}$F) due to human activities.

These criteria were developed specifically to protect cold-water aquatic life, including salmon and steelhead, in the Columbia and Snake rivers. Salmonids evolved to take advantage of the natural cold, freshwater environments of the Pacific Northwest. Temperature directly governs their metabolic rate and directly influences their life history. Natural or anthropogenic fluctuations in water temperature can induce a wide array of behavioral and physiological responses in these fish. These fluctuations may lead to impaired functioning of the individual and decreased viability at the organism, population, and species level. Feeding, growth, resistance to disease, successful reproduction, sufficient activity for competition and predator avoidance, and successful migrations are all necessary for survival.

Temperature preferences for five critical life stages of the salmonids found in the Columbia River system are listed in Table 1-4. Appendix A contains more detailed information on the preference ranges and effects of temperature on these fish. Additional information can be obtained from two recent EPA-sponsored reports: (1) *A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon* (1999) by Dale A. McCullough, and (2) *Perspectives on Temperature in the Pacific Northwest's Fresh Waters* (1999) by Charles C. Coutant.

1.5   IMPACTS OF WATERSHED DEVELOPMENT ON WATER TEMPERATURE

Once the water quality limited segments have been identified, Section 303 (d) of the Clean Water Act requires that each state establish a priority ranking determining the severity of the pollution and the uses of the water. One of the first steps is to assess the problems associated with a given water quality parameter. The purpose of an assessment is to identify the sources for the water quality parameter of concern.

Table 1-4. Summary of temperature preference ranges (°C) for five critical life stages of seven salmonid species (from Appendix A)

	Adult Migration °C	Spawning °C	Incubation °C	Rearing °C	Smoltification Out-migration °C
Spring Chinook Salmon	3.3 - 13.3	5.6 - 14.4 5.6 - 12.8	5 - 14.4 4.5 - 12.8	10 - 12.8 10 - 14.8	3.3 - 12.2
Summer Chinook Salmon	13.9 - 20	5.6 - 14.4 6.1 - 18	5 - 14.4	10 - 12.8	NA
Fall Chinook Salmon	10.6 - 19.4	10 - 12.8 10 - 16.7 5.6 - 13.9	10 - 12.8 10 - 16.7 5 - 14.4	12 - 14	4.5 - 15.5
Sockeye Salmon	7.2 - 15.6	10.6 - 12.2	4.4 - 13.5	10 - 12.8 12 - 14 11.2 - 14.6	2 - 10
Coho Salmon	7.2 - 15.6	4.4 - 9.4 7.2 - 12.8	4.4 - 13.3 4 - 6.5	11.8 - 14.6	12 - 15.5
Chum Salmon	8.3 - 15.6	7.2 - 12.8	4.4 - 13.3	10 - 12.8 11.2 - 14.6	NA
Steelhead/ Rainbow Trout	10 - 13	3.9 - 9.4 4.4 - 12.8	5.6 - 11.1	7.3 - 14.6	< 12
Cutthroat Trout	NA	6.1 - 17.2	NA	9.5 - 12.9	NA
Bull Trout	10 - 12	<9 - 10 4 - 10	2 - 4 4 - 6	4 - 4.5 fry 4 - 10 juv	NA

NA - Not available

The listing of water temperature by Oregon and Washington is based on analysis of data collected by state and federal agencies. These agencies include the Oregon Department of Environmental Quality (DEQ), the Washington State Department of Ecology (DOE) and the U.S. Army Corps of Engineers (USACE). An analysis of long-term records the USACE collected as part of the total dissolved gas monitoring study (McKenzie and Laenen, 1998) shows the frequency with which water temperatures have exceeded the water quality criterion at various locations on the Columbia and Snake rivers (Table 1-5).

Table 1-5. Frequency and average magnitude with which observed temperatures exceed Oregon's and Washington's water quality criterion at selected locations on the Columbia and Snake rivers. Observed temperatures are from the total dissolved gas monitoring program (McKenzie and Laenen, 1998)

Location	Exceeds Water Quality Criterion		Record Length
	Frequency	Magnitude	
Lower Granite Dam	0.15	2.04	5/30/88-9/17/96
Little Goose Dam	0.15	2.49	5/30/88-9/16/96
Lower Monumental Dam	0.18	2.10	5/29/88-9/17/96
Ice Harbor Dam	0.18	2.35	5/29/88-9/23/96
Wells Dam	0.10	0.87	4/18/93-9/2/97
Priest Rapids Dam	0.18	1.61	4/28/88-12/31/97
McNary Dam	0.17	1.65	4/2/85-12/31/97
John Day Dam	0.15	1.65	4/17/84-9/16/97
Bonneville Dam	0.14	1.39	4/3/86-11/2/97

Previous studies of the Columbia and Snake rivers (Davidson, 1964; Jaske and Synoground, 1970; Moore, 1969; Independent Scientific Group[1], 1996) have identified the construction and operation of hydroelectric facilities as having a major impact on the thermal regime of the Columbia and Snake rivers. Jaske and Synoground (1970) concluded that the construction of river-run reservoirs on the main stem of the Columbia River caused no significant changes in the average annual water temperature, but that the operation of Lake FDR, the reservoir behind Grand Coulee Dam, delayed the time of the peak summer temperature in the Columbia River at Rock Island Dam by about 30 days. Moore (1969) found that both Lake FDR and Brownlee Reservoir on the Snake River caused cooling in the spring and summer and warming in fall and winter. The Independent Scientific Group (1996) concluded that "mainstem reservoirs in the Snake and Columbia rivers have created shallow, slowly moving reaches of shorelines where solar heating has raised temperature of salmon rearing habitat above tolerable levels" and that changes in the thermal energy budget associated with the hydropower system in the Columbia and Snake rivers have resulted in conditions that are suboptimal or clearly detrimental for salmonids.

Surface and groundwater flows tributary to the Snake and Columbia rivers are also sources of advected thermal energy that have the potential for modifying the thermal energy budget of the main stem. Moore (1969) studied the impact of the Clearwater and Salmon rivers on the main stem Snake and the Kootenai and Pend Oreille rivers on the Columbia during 1967 and 1968. He found that the Clearwater and Salmon rivers cooled the Snake River during some of this period, but at no time did they produce a warming effect. Viewing the Snake as a tributary to the Columbia, Moore (1969) and Jaske and Synoground (1970) concluded that the advected thermal energy from the Snake River increased the temperature of Columbia River during the summer. Moore (1969) estimated that the maximum temperature increase was of the order of 1 °C during 1967 and 1968, while Jaske and Synoground (1970) estimated the annual thermal energy contribution of the Snake River to the Columbia River to be on the order of 4,000 megawatts. The Independent Scientific Group (1996) discusses temperature in the tributaries primarily as it relates to habitat in individual tributaries. The group concludes that high temperatures in the late summer and fall are detrimental to both juvenile and adult salmon in the main stem and tributaries, but does not discuss the impact of the tributaries on the thermal energy budget of the main stem.

The only significant permitted point source discharge of thermal energy to the Columbia and Snake rivers in the study area (Figure 1-1) is the Potlatch Corporation discharge to the Snake River at Snake River Mile 139 near the confluence of the Snake and the Clearwater rivers. The Potlatch facilities discharge approximately 130 megawatts of thermal energy to the Snake River. The Hanford Project discharged as much as 23,000 megawatts of thermal energy and had significant impacts on the temperature of the Columbia River (Jaske and Synoground, 1970; Moore 1969; Yearsley, 1969). However, this discharge was discontinued in the 1970s.

1.6   STUDY OBJECTIVES

For the segments of the main stem Columbia and Snake rivers included in the study area (Figure 1-1), the impacts of watershed development on the thermal energy budget are associated with the operation of dams and reservoirs and advected energy from tributaries, ground water, and point sources. The objective of this study is to determine, for a given sequence of hydrology and meteorological conditions, the relative impacts of the operation of dams and reservoirs on the thermal energy budget of the main stem Columbia and Snake rivers compared to the impact of thermal input from surface and ground water inflows. The specific objectives are to do the following:

❑   Estimate the frequency with which daily average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20 °C (68 °F) under existing conditions of river management and a representative record of river hydrology and meteorology.

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[1] The Independent Scientific Group comprised nine experts in fishery sciences commissioned by the Northwest Power Planning Council to (1) perform an independent review of the science underlying salmon and steelhead recovery efforts and Columbia River Basin ecosystem health, and (2) develop a conceptual foundation that could form the basis for program measures and basinwide fish and wildlife management.

❑ Estimate the frequency with which daily average water temperatures in the Columbia and Snake rivers will exceed the benchmark of 20 ^{o}C (68 ^{o}F) with all dams on the Columbia River below Grand Coulee Dam in place and for the unimpounded condition with no dams in place below Grand Coulee on the Columbia and on the Snake below Lewiston, Idaho.

❑ Estimate the frequency with which daily average water temperatures in the Columbia and Snake Rivers will exceed the benchmark of 20 ^{o}C (68 ^{o}F) under existing conditions of river management and with major tributaries and point sources constrained to maintain temperatures less than 16 ^{o}C (60.8 ^{o}F).

❑ Characterize the uncertainty of these estimates for purposes of ultimately assessing the risks associated with potential management decisions in the Columbia and Snake rivers.

The benchmark of 20 ^{o}C (68 ^{o}F) was chosen because adult salmon are at risk when water temperatures are warmer. For example, Karr et al. (1998), used 20 ^{o}C (68 ^{o}F) as a benchmark, representing it as an upper incipient lethal water temperature for migrating salmon and steelhead. Based on a literature review, Karr et al. (1998) determined that 20 ^{o}C (68 ^{o}F) is the point where the zone of lower resistance starts for immigrating adult salmon and steelhead. Results from the Columbia River Thermal Effects study reported by Bonneville Power Administration et. al. (1994) show that 20 ^{o}C (68 ^{o}F) is the water temperature where the zone of lower resistance starts for immigrating adult salmon and steelhead. At water temperatures higher than 21.1 ^{o}C (70 ^{o}F), salmonids are in a lethal range where the time it takes to kill the fish declines rapidly. More detailed information on temperature requirements for several species of salmonids is contained in Appendix A.

Although the benchmark does represent certain aspects of the physiological requirements of salmonids, this report does not view it as a surrogate for water quality criteria or as part of an ecological risk analysis. Washington's water quality standard is based on an instantaneous value. An ecological risk analysis would have to consider both the timing and magnitude of temperature changes. Although these issues are not specifically considered in this assessment, they may be included in future analyses of water temperature in the Columbia and Snake rivers.

The constraint of 16 ^{o}C (60.8 ^{o}F) on maximum temperatures in the tributaries was based on Washington's water temperature criterion for tributaries classified as Class A (excellent). The use of the constraint, however, was not meant to imply that tributaries had attained this criterion or would do so in the future; rather, it was used to evaluate what the relative impact of the tributaries on the thermal regime of the main stems might be under very favorable conditions.

A one-dimensional mathematical model of the thermal energy budget that simulates daily average water temperature under conditions of gradually varied flow is used to address the specific objectives described above. Models of this type 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 (Yearsley, 1969) developed and applied a one-dimensional thermal energy budget model to the Columbia River as part of the Columbia River Thermal Effects Study. The Bonneville Power Administration et al. (1994) used HEC-5Q, a one-dimensional water quality model, to provide the temperature assessment for the System Operation Review, and Normandeau Associates (1999) used a one-dimensional model to assess water quality conditions in the Lower Snake River for the U.S. Army Corps of Engineers.

A one-dimensional model of daily average temperatures is appropriate for answering basic questions on how watershed development effects water temperature. Important issues associated with water temperature in the main stem Columbia and Snake Rivers for which this type of model is not appropriate include the following:

❑ Instantaneous temperatures: The water quality standards for the Columbia and Snake rivers in both Oregon and Washington are written in terms of instantaneous temperatures. The model used for this analysis does not simulate instantaneous water temperatures. Therefore, the model results cannot be

compared directly to the criteria for water temperature established by the water quality standards of Oregon and Washington.

❑ Lateral and vertical variations in water temperature: The thermal energy budget model simulates the daily, cross-sectional averaged temperature. Important spatial dimensions of the lotic ecosystem (Independent Scientific Group, 1996) are the riverine (longitudinal), riparian (lateral) and hyporheic (vertical habitat below the river channel). Development of the hydropower system has caused significant changes to the thermal regimes in all these dimensions. The one-dimensional thermal energy budget model results can be used only to characterize the water temperatures in the riverine or longitudinal dimension of habitat. The model results correspond approximately to the state variable, "thalweg temperature," used by the Independent Scientific Group (1996).

❑ Unsteady flow: The model uses the methods of gradually varied flow to characterize river hydraulics. The gradually varied flow model may not be appropriate for highly transient flow conditions such as storm or very rapid snowmelt events.

❑ Strong longitudinal temperature gradients: The model assumes that dispersion and longitudinal turbulent diffusion can be neglected. Diffusion-like processes will be important when

$$K_x/UL > 1$$

where

K_x = coefficient of longitudinal dispersion or eddy diffusivity

U = river speed in the longitudinal direction

L = a characteristic longitudinal distance

Longitudinal dispersion is generally of great importance for one-dimensional models. Experimental values of the longitudinal dispersion coefficient in rivers and estuaries, reported in Fischer et al. (1979), vary from approximately 30 feet^2/second to 15,000 feet^2/second in rivers and from 100 feet^2/second to 15,000 feet^2/second in estuaries. Assuming the largest value of the dispersion coefficient (15,000 feet^2/second) and a river velocity of 1.0 foot /second implies a characteristic length of approximately 3 miles. To analyze conditions in the Snake and Columbia rivers when strong cross-sectionally averaged longitudinal gradients were important and scales on the order of 3 to 10 miles were of interest, it would be necessary to consider including diffusion-like processes in the model. The analysis described in this report did not include any impacts with scales of less than 3 to 10 miles.

CHAPTER 2: TEMPERATURE MODEL THEORY AND FORMULATION

2.1   THERMAL ENERGY BUDGET METHOD AND FORMULATION

Base Equations

The thermal energy budget method is a useful concept for simulating temperatures in aquatic environments. Concern about the impact of reservoir operations on water temperature and aquatic ecosystems motivated early applications of the method (Burt, 1958; Delay and Seaders, 1966; Raphael, 1962; Edinger et al., 1974). Prior to the passage of the Clean Water Act, numerous studies of Electric Power Industry thermal discharges were also performed using the energy budget method (Edinger et al., 1974). Brown (1969, 1970) applied the method to simulating stream temperature increases resulting from the removal of riparian vegetation during logging operations. Recent applications of the energy budget method have focused on water quality planning issues related to reservoir operations (Cole and Buchak, 1995; Normandeau Associates, 1999), watershed management (Bonneville Power Administration et al., 1994, Foreman et al., 1997; Risley, 1997; Rishel et al., 1982; Sinokrot and Stefan, 1993) and fisheries habitat enhancement (Bartholow, 1989; Theurer et al., 1984).

Thermal energy budget models for aquatic ecosystems are developed either in an Eulerian frame of reference, in which the reference system is fixed in space and through which the water flows, or a Lagrangian frame of reference, in which the reference system moves with the fluid. The one-dimensional thermal energy model for estimating the state variable, water temperature, stated in terms of the Eulerian viewpoint and assuming there is no longitudinal dispersion is as follows:

$$\rho\, C_p A_x\, \frac{\partial T}{\partial t} + \rho\, C_p\, \frac{\partial (QT)}{\partial x} = w_x H_{net} + S_{adv} + w_T \tag{1}$$

where

ρ = the density of water, kg/meter^3

C_p = the specific heat capacity of water, kcal/deg C/kg

A_x = the cross-sectional area of the river at the distance, x, meter^2

T = the true water temperature, ^{o}C

Q = the river flow rate, meter^3/second

w_x = the width of the river at the distance, x, meters

H_{net} = the heat flux at the air-water interface, kcal/meter^2/second

S_{adv} = the heat advected from tributaries and point sources, kcal/meter/second

w_T = a random water temperature forcing function, $\sim N(0, \Sigma_Q(t))$

x = the longitudinal distance along the axis of the river, meters

t = time

In the Lagrangian frame of reference, the systems model for estimating the water temperature, using the energy budget method and assuming no longitudinal dispersion, is given by

$$\rho \, C_p A_x \, \frac{dT}{dt} \; = \; w_x H_{net} + S_{adv} + w_T \tag{2}$$

where the symbols are as previously defined.

Equations 1 and 2 are the state-space system equations for water temperature in the Eulerian and Lagrangian frames of reference, respectively. Water temperature measurements also provide an estimate of the system state. The observation model for water temperature at the kth time interval is given by (Gelb et al., 1974)

$$Z_k \quad = \quad H_k \, T_k + v_k \tag{3}$$

where

Z_k = the measured value of the water temperature, $^{\circ}C$

H_k = the measurement matrix,

v_k = the measurement error, $\sim N(0, \Sigma_R)$

Σ_R = the variance of the measurement error, v_k

Heat Exchange Across the Air-Water Interface

Heat exchange across the air-water interface is generally the major source of thermal energy for lakes, rivers, and reservoirs. As is the case for the applications described above, this study assumes the net exchange of thermal energy, H_{net}, across the air-water interface can be described by

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) +/- \; H_{evap} +/- H_{cond} - H_{back} \tag{4}$$

where

H_{net} = Net heat exchange across the air-water interface, $kcal/meter^2/second$

H_s = Shortwave solar radiation, $kcal/meter^2/second$

H_{rs} = Reflected shortwave solar radiation, $kcal/meter^2/second$

H_a = Longwave atmospheric radiation, $kcal/meter^2/second$

H_{ra} = Reflected atmospheric radiation, $kcal/meter^2/second$

H_{evap} = Evaporative heat flux, $kcal/meter^2/second$

H_{cond} = Conductive heat flux, $kcal/meter^2/second$

H_{back} = Blackbody radiation from the water surface, $kcal/meter^2/second$

The specific form for each of the terms in the heat budget formulation (Equation 4), as used in this and most other studies involving the energy budget method, is based on a compilation of heat budget studies by Wunderlich and Gras (1967). Chapra (1997) and Bowie et al. (1985) also have comprehensive discussions of each of the terms in Equation 4 adapted from Wunderlich and Gras (1967). From the work of Wunderlich and Gras (1967), individual elements of the heat budget are given by

Shortwave (Solar) Radiation

$$(H_s - H_{rs}) = F(\Phi, \delta, D_y) \tag{5}$$

where

Φ = the latitude of the site

δ = the declination of the sun at the site

D_y = the day of the year

Longwave (Atmospheric) Radiation

$$(H_a - H_{ra}) = (1-\alpha_{ar}) \, 1.23 \times 10^{-16} \, (1.0 + 0.17 \, C^2)(T_{DB} + 273.)^6 \tag{6}$$

where

α_{ar} = reflectivity of the water surface for atmospheric radiation, ~ 0.03

C = cloud cover, decimal fraction

T_{DB} = dry bulb temperature, ^{o}C

Evaporative Heat Flux

$$H_{evap} = \rho \, \lambda \, E_v \, W \, (e_o - e_a) \tag{7}$$

where

ρ = water density, kg/meter^3

λ = latent heat of vaporization , kcal/kg

E_v = empirical constant, mb^{-1}

W = wind speed, meters/second

e_o = saturation vapor pressure at the temperature of the water surface, mb

e_a = vapor pressure of the air near the water surface, mb

Conductive Heat Flux

$$H_{cond} = R_B \left[\frac{T - T_a}{e_0 - e_a} \right] \frac{p_a}{1013.3} \tag{8}$$

where

R_B = an empirical constant, 0.66

p_a = atmospheric pressure, mb

Black Body (Water Surface) Radiation

$$H_{back} = 0.97\ \sigma\ (T + 273.)^4 \tag{9}$$

where

$$\sigma = \text{Stefan-Boltzman constant, } 1.357\text{x}10^{-11}\ \text{cal/meter}^2/\text{second}/^o\text{K}$$

Advected Sources of Thermal Energy

The second method by which thermal energy is transferred to the system is through advection. This primarily relates to the discharge of waters at temperatures different from the ambient waters being simulated. These would include tributaries not simulated in the model domain that flow in, as well as point and nonpoint source discharges at temperatures different from the ambient river conditions.

The parameters utilized within the model for determination of the advected thermal energy are water temperature and flow. The heat source is then calculated as the relative difference in thermal energy between the ambient water temperature and the inflowing water temperature. These values are directly input to the model segments prescribed and are an external source (S_{adv}) in Equations 1 and 2.

2.2   STATE ESTIMATION METHODS

Mathematical models used to simulate water quality in lakes, rivers, and reservoirs have traditionally been deterministic. That is, state estimates from the model are treated as being exactly determined by preceding events in time or adjacent events in space rather than as random variables. The deterministic state estimates from process models can very seldom be reconciled precisely with state estimates obtained with standard measurement devices such as thermistors and DO probes.

Model developers have attempted to resolve this problem by invoking a process most often described in terms of two steps. The first step is labeled "calibration" and the second step either "verification" or "validation." In the calibration step, the output of the model is compared to a set of observations. If the output of the mathematical model does not agree with the measurements, the coefficients that characterize the driving forces (parameters) of the model are adjusted, or "calibrated," until there is some form of agreement between simulated and observed results. An important assumption, rarely stated in the application of this process, is that state estimates obtained with measurement devices are without error or uncertainty. While some effort has been made to formalize the calibration process (e.g., Thomann, 1982; van der Heijde, 1990), there is no consistent approach for determining when the calibration process is complete, nor quantifying the uncertainty of either the parameters or the state estimates.

The water quality simulation package QUAL2E (Brown and Barnwell, 1987) includes algorithms for estimating uncertainty using either Monte Carlo methods or propagation of uncertainty by first-order methods. The first-order methods used in QUAL2E are similar to the variance propagation methods derived for the *prediction* mode of nonlinear forms of the Kalman filter, described below. The methods used in QUAL2E do not, however, account for either systems model or measurement error. Furthermore, estimates of parameter uncertainty must be obtained in an unspecified manner, independently from the application of the simulation package. The software documentation provides a range of uncertainty estimates (Table VI-1, Brown and Barnwell, 1987) obtained from a survey of other studies, but concludes simply that "The burden of verifying and confirming input variance estimates for a particular application lies with the user." The ground water programming package MODFLOWP (Hill, 1994) provides a formal method for solving the so-called inverse problem of estimating model parameters and their confidence intervals from the data. The parameter estimation algorithms can be applied to a broad class of problems, including surface water analysis. The model is complex

and data requirements are substantial. The available literature revealed no applications of this programming package that solve the inverse problem for surface water models.

Many studies do not even attempt to quantify the adequacy of the calibration process. For example, the criteria used in the calibration process for a mathematical model of temperature and biological productivity in the Lower Snake River (Normandeau Associates, 1999) were that "the output reproduced general patterns and long term averages of observed data or knowledge."

In the second step, "validation" or "verification," output from the calibrated model is compared to observations from an independent data set. The degree to which the simulations and observations agree is subjected to some form of hypothesis testing to determine model "validity." While goodness-of-fit criteria have been proposed by some (Bartholow, 1989; van der Heijde, 1990), many studies use qualitative statements to support the conclusion that the model has been validated. The study of the Lower Snake River referenced above concludes the verification process by simply stating that "the calibrated model predicts correct seasonal warming, maximum temperatures, and fall cooling." In another example of the calibration/verification paradigm, the Bonneville Power Administration et al. (1994) relied on a water quality model, HEC5Q, of the Columbia River to evaluate complex system operations strategies and provide support for an environmental analysis required by the National Environmental Policy Act (NEPA). Although the report of the model studies invokes the terms "calibration" and "verification," no quantitative tests or results are provided. In the case of the water temperature simulations, the report simply states, "The model has been shown to adequately represent the thermal responses throughout the river system for summer months . . . . "

These examples typify the lack of rigor and consistency associated with the calibration/verification paradigm. While calibration/verification is still considered standard practice in surface water quality modeling, there has been some effort devoted to address the lack of rigor and inconsistencies in the traditional approaches. Matalas and Maddock (1976), for example, observed that

> "Calibration implies that for the parameters of the identified model, one has control over the degree of accuracy in a particular estimation. Verification implies that the identified calibrated model, tested under controlled conditions, mimics the physical system of interest and therefore the identified calibrated verified model is to be accepted.
>
> *The words identification, calibration and verification are misleading because of their connotation of greater understanding of and control over the physical processes than actually exists."* (emphasis added)

Bartholow (1989) has an excellent discussion of these issues with regard to temperature models for surface water. Oreskes et al. (1994) noted the philosophical problems associated with attempting to verify or validate deterministic earth science models.

The techniques of state estimation avoid many of the philosophical difficulties associated with traditional modeling approaches by assuming the state estimates are random variables and that there is error associated with both the systems model and the measurement model. The methods of state estimation formulate the problem in terms of a process or systems model (Equation 1 or 2) and a measurement model (Equation 3).

The systems model (Equations 1 and 2) includes both deterministic and probabilistic components. The deterministic component of the systems model is based on the known laws of physics, chemistry, and biology. In this case, the systems model is based on scientific and empirical knowledge of the thermal energy budget. The probabilistic component represents the uncertainty in the systems model. Depending on the nature of the problem, the uncertainty can be due to level of spatial or temporal aggregation, model structure, parameter estimation and input variability. The detail with which previous studies have treated systems uncertainty in water quality or quantity studies ranges from the very basic (Moore et al., 1976) to the very complex (Rajaram and Georgakakos, 1987).

The measurement model (Equation 3) reflects the fact that estimating the state of a system with some form of measuring device cannot be done without some uncertainty. This uncertainty arises from inherent error in the measurement device, sampling error and mapping of point observations to block observations. The matrix, H_k, describes which state variables or combinations of state variables are being sampled at time, k, and can also include instrument calibration factors or transformations.

State estimation methods combine the estimates from the systems model (Equation 1 or 2) and the measurement model (Equation 3), when measurements are available, to obtain an optimal estimate of the system state. As described by Gelb et al. (1974), there are three types of state estimation problems based on the time of the estimate compared to that of the last measurement of the system state. When the state estimate precedes the last measurement, it is a *smoothing* problem; when it coincides with the last measurement it is *filtering*; and when it occurs after the last measurement it is *prediction.* The Kalman filter (Gelb et al., 1974; Schweppe, 1973) gives an unbiased, minimum squared error estimate of the system state for the filtering and prediction problems when all parameters in Equation 1 or 2 and Equation 3 are known. For the filtering problem, the Kalman filter combines the state estimates from the systems model and the measurement model. The two estimates are combined using a weighting factor determined by the relative uncertainty of the systems model compared to the uncertainty of the observation model. The weighting factor, the Kalman gain matrix, K_k, is derived by constraining the error in the estimate to be unbiased and to have a minimum mean square error.

For linear systems, the complete Kalman filter algorithm is

Systems Model:	$\underline{T}_k$	$= f_{k-1} \underline{T}_{k-1} + \underline{w}_{k-1}$	$\underline{w}_k \sim N(\underline{0}, \Sigma_Q)$	(10)
Measurement Model:	$\underline{T}_k$	$= H_k \underline{T}_k + \underline{v}_{k-1}$	$\underline{v}_k \sim N(\underline{0}, \Sigma_R)$	(11)
System Extrapolation:	$\underline{T}_k(-)$	$= f_{k-1} \underline{T}_{k-1}(+)$		(12)
Error Covariance Extrapolation:	$P_k(-)$	$= f_{k-1} P_{k-1}(+) f_{k-1} + \Sigma_Q$		(13)
State Estimate Update:	$\underline{T}_k(+)$	$= \underline{T}_k(-) + K_k[\underline{z}_k - H_k \underline{T}_k(-)]$		(14)
Error Covariance Update:	$P_k(+)$	$= [I - K_k H_k] P_k(-)$		(15)
Kalman Gain Matrix:	K_k	$= P_k(-) H_k^T [H_k P_k(-) H_k^T + \Sigma_R]^{-1}$		(16)
Innovations Sequence:	v_k	$= z_k - H_k T_k(-)$		(17)

where (-) denotes values at time, k, prior to filtering; (+) denotes values at time, k, after filtering; and f_k is the systems matrix.

The filter equations (Equations 10 to 17) are used for the prediction problem as well. However, in the prediction problem, the Kalman gain matrix, K_k, is zero because there are no observations available. In this case, only the systems model provides an estimate of the state. However, an additional feature of the Kalman filter is that it provides an estimate of the error covariance (Equation 13) for both the filter and the prediction problems.

The innovations sequence (Equation 17) provides a quantitative measure for parameter estimation. The innovations sequence is simply the difference between the system extrapolation (Equation 12) and the actual measurement, z_k. If one is thinking in terms of the traditional approach to model development, the innovations sequence is superficially similar to comparing the simulated state estimates with the measured state estimates. Formally, it is different in that the system extrapolation is a function of the previous measurements; the innovations sequence incorporates aspects of both the systems error and the measurement error. When the filter is optimal, the innovations sequence is unbiased and uncorrelated in time. That is,

$E\{v_k\} = 0$

and

$E\{v_i v_j^T\} = 0$, for i>j

where E is the expectation operator. When the innovations sequence satisfies these criteria, it means all the deterministic information has been extracted from the systems model. When the model parameters are unknown, the innovations sequence can be used as way of finding a parameter set that provides optimal estimates. That is, the model parameters can be adjusted until the criteria given above are satisfied.

Although state estimation techniques provide the basis for dealing with issues of model and measurement uncertainty in a more rational and consistent manner than do the traditional deterministic modeling methods, there have been relatively few applications of state estimation techniques in the field of surface water modeling. Lettenmaier (1975), Moore (1973), Moore et al. (1976), and Dandy and Moore (1979) used state estimation methods to evaluate strategies for designing surface water quality monitoring systems. Lettenmaier and Burges (1976) provided a tutorial on state estimation for application to measurement system design, model building and assessment, and data extension. Koivo and Phillips (1976) used state estimation techniques to show how one could obtain optimal estimates of DO, BOD, and stream parameters for a dynamic water quality model. Beck and Young (1976) studied the use of the Extended Kalman Filter (EKF) for purposes of system identification of DO-BOD model structure. Bowles and Grenney (1978) incorporated sequential EKF's into a surface water quality model to estimate nonpoint source loadings over a 36.4-mile stretch of the Jordan River in Utah.

These examples represent some of the efforts researchers made to apply or to demonstrate how to apply state estimate methods to surface water quality modeling. Their limited success in encouraging wider use of the methods could be due to a number of factors. The methods appear somewhat complex, even though the most common technique, the Kalman filter, is a close relative of linear regression using the method of least squares. The structures of models for many surface water state variables, particularly the biological constituents, cannot always be well defined; in such cases the use of state estimation techniques may not be entirely satisfactory (Beck and Young, 1976). Solving the inverse problem for surface water quality model problems can also be technically difficult. The inverse problem can carry data-gathering burdens that are not compatible with the time and capital resources available to natural resource and regulatory agencies. Water temperature, given the state of the art, is one state variable for which the techniques of state estimation are well suited. It is simple and comparatively inexpensive to gather water temperature data. In addition, there is general agreement among researchers regarding the structure of the thermal energy budget model. Algorithms for estimating rates of energy transfer for the various components of the energy budget have also been well developed. Therefore, state estimation methods were developed to make estimates of the system state and its uncertainty for water temperature in the Columbia and Snake river main stems.

To obtain an estimate of the water temperature from the systems model, it is first necessary to decide whether to implement the solution method with a Lagrangian point of view or with an Eulerian point of view. Given the spatial and temporal complexity of the natural environment, most mathematical models using the thermal energy budget method are developed in the Eulerian frame of reference. The Eulerian frame of reference is a more intuitive way of viewing changes in concentrations simply because most measuring devices are fixed at a specific location rather than moving with the water. It is also less difficult to incorporate spatial complexity into the Eulerian framework, and, therefore, easier to add more spatial dimensions as well as more complex spatial processes such as dispersion and turbulent diffusion.

Most systems models using the Eulerian framework solve Equation 1 with either finite difference (Brown and Barnwell, 1987; Cole and Buchak, 1995; Sinokrot and Stefan, 1993; Smith, 1978) or finite element methods (Baca and Arnett, 1976). These models have generally proved valuable for simulating water temperatures in a variety of aquatic environments. However, it is well known that solutions to equations of the type characterized

by Equation (1), using finite difference or finite element techniques, are subject to stability and accuracy problems (e.g., O'Neill, 1981). For water quality models, stability problems are generally not as serious as accuracy problems. When a solution becomes unstable, it is usually obvious and can generally be eliminated by reducing the time step. Accuracy problems are more pervasive and often subtle. Of particular concern to developers of finite difference and finite element methods are problems, commonly characterized as numerical dispersion, associated with the propagation of phenomena with short wavelengths. Numerical dispersion is most evident in the propagation of sharp spatial gradients when advection dominates the system. The resulting simulations can have spurious damping of high frequencies or oscillations. They are caused by differences between the rate at which the numerical scheme propagates the solution in space and the rate at which the solution would be propagated in space by the natural system.

Solution techniques based on the Lagrangian point of view (Jobson, 1981) avoid the accuracy problems associated with Eulerian methods but lack the computational convenience of a fixed grid. However, efficient accurate solution methods have been proposed which combine some of the virtues of each point of view (Cheng et al., 1984; Yeh, 1990; Zhang et al., 1993). In these hybrid Eulerian-Lagrangian methods, advective processes are treated with a Lagrangian formulation. Diffusion or dispersion processes, if present, are treated with an Eulerian formulation. With many of the hybrid methods, the need to satisfy the Courant criterion

$$U \, \Delta t / \Delta x \quad < \quad 1$$

can be relaxed. In addition, the application of state estimation techniques, as discussed below, is greatly simplified. Hybrid methods do not always eliminate numerical dispersion. However, Yeh (1990) found that the use of hybrid methods with single-step reverse particle tracking (SRPT) was definitely superior to the Eulerian method using upwind method. Zhang et al. (1993) found that hybrid methods using SRPT introduced some numerical dispersion, but that a modified form of SRPT eliminated the numerical dispersion. Cheng et al. (1984) reported that when linear interpolation was used with hybrid solution techniques, numerical dispersion was similar to that of upwind methods. Cheng et al. (1984) were able to eliminate numerical dispersion from the hybrid method by using second-order Lagrangian polynomial interpolation.

The mixed Eulerian-Lagrangian method using reverse particle tracking was chosen as the solution technique for simulating water temperature in the Columbia River system for the following reasons:

❑ It reduces the state-estimation (filtering and prediction) problem to one of a single state variable rather than one requiring a state variable for each finite difference or finite element grid point.

❑ It is relatively easy to avoid instabilities in the solution when the Courant stability criterion is exceeded.

❑ It provides the flexibility to expand the scope of model to include diffusion-like processes and/or more spatial dimensions.

❑ Although the method does not completely eliminate numerical dispersion, the results of studies described previously show that the method's ability to propagate high frequencies is generally superior to Eulerian methods. Tests of three numerical schemes showed that reverse particle tracking propagated high frequencies more accurately than both WQRRS and QUAL2E (Appendix B). These schemes are (1) reverse particle tracking, the numerical method used in this report; (2) the numerical method used by WQRRS, a water quality model commonly used by the U.S. Army Corps of Engineers (Smith, 1978; Normandeau Associates, 1999); and (3) QUAL2E (Brown and Barnwell, 1987).

The mixed Eulerian-Lagrangian method uses the concept of reverse particle tracking to implement the Lagrangian step. The river system is divided into N segments, not necessarily of the same spatial dimensions. Within each segment, however, the geometric properties of the river system are assumed to be constant during a

given time step. Water temperature values are recorded only on the boundaries between segments. As an example of the method, consider Segment J (Figure 2-1). At the end of a computational time step, $t = t_{k+1}$ a particle at the downstream end of the Segment J is flagged. The flagged particle is tracked backward in time upstream until its position at the beginning of the time step, $t = t_k$, is located. The location of a particle tracked in this manner will, in general, not be precisely on a segment boundary, where water temperatures are stored by the computational scheme. Therefore, it is necessary to determine the water temperature of the particle at the beginning of the time by interpolating between the points where water temperatures are recorded. In the solution technique used in this study, this is accomplished with a second-order polynomial using Lagrangian interpolation (Press et al., 1986). Once the location of the particle and its initial water temperature are determined for the beginning of the time step, the particle is followed back downstream to its location at the end of the time step (the downstream end of Segment J). The change in water temperature for the particle during this time step is estimated using Equation 2.
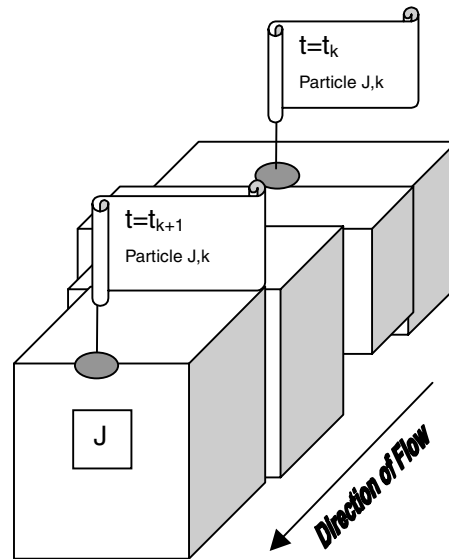
Figure 2-1. Schematic for reverse particle tracking method.

The information required for obtaining a solution to Equation 2 using reverse particle tracking includes

- ❑ River width as a function of longitudinal distance during the time step.

- ❑ Cross-sectional area as a function of longitudinal distance during the time step.

- ❑ River velocity as a function of longitudinal distance during the time step.

- ❑ Net heat exchange as a function of longitudinal distance during the time step.

The hydraulic characteristics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, area, and width (Leopold and Maddock, 1953). That is,

$$U = A_u \, Q^{Bu} \tag{18}$$

$$A_x = A_a \, Q^{Ba} \tag{19}$$

$$W_x = A_w \, Q^{Bw} \tag{20}$$

where

U = the river velocity, feet/second

A_x = the cross-sectional area, feet^2

Q = the river flow, cfs

W_x = the river width, feet

The coefficients, A_u, B_u, A_a, B_a, B_u, A_w, and B_w, are estimated by simulating river hydraulics conditions under various flow conditions using the methods of steady gradually varied flow (USACE-HEC, 1995). The gradually varied flow method gives estimates of the average longitudinal velocity, U, the average water depth, D, and the river width, W_x, as a function of river flow. The coefficients are determined by fitting Equations (18)-(20) to the resulting estimates using the method of least squares.

For the impounded reaches, the water surface elevation is assumed to remain constant, such that the depth and width remain constant at any cross-section and the velocity, U, is simply

$$U = Q/(W_x*D) \tag{21}$$

Exchange of thermal energy across the air-water interface is estimated from Equation (4) using formulations for components of the heat budget as described by Water Resources Engineers (1968).

2.3   COMPONENTS AND STRUCTURE OF MODEL SYSTEM

Based on the theoretical formulations discussed in Section 2.2, a heat budget model has been developed that projects the temperature conditions for a water body within a one-dimensional framework. The model projects the temperature under a specified set of heat flux conditions from atmospheric sources, upstream boundaries, and adjacent tributary inflows. The model projects the temperature and provides evaluation and adjustment to the model uncertainty using the Kalman filter described previously. A detailed description of the model application to the Columbia River is presented in Chapter 3.

Figure 2-2 presents a general flow chart of the model system developed. Inputs include the system geometry, the heat flux across the air-water interface, the tributary inflows, and the model hydraulic parameters.

As this is a heat budget model, the hydraulic parameters must be determined a priori to the simulation. This is done through application of another model or methodology that provides the coefficients for input to the model. These then become model input conditions rather than parts of the overall simulation. The specifics of the hydraulic parameters are presented in detail for the Columbia River application in Section 3.5.

The tributary inflows and the heat flux across the air-water interface are the other input parameters for the model. These are prescribed as time series for the period of simulation. The tributary information required is the flow rate and temperature as a function of time. The heat budget information required is the input to the six terms listed in Equation 4.

Using these inputs, the model solves the system model equation for each model segment using the mixed Eulerian-Lagrangian approach and redefines the interim system state based upon the inputs over the prescribed time period.

Model Inputs   Flow Logic
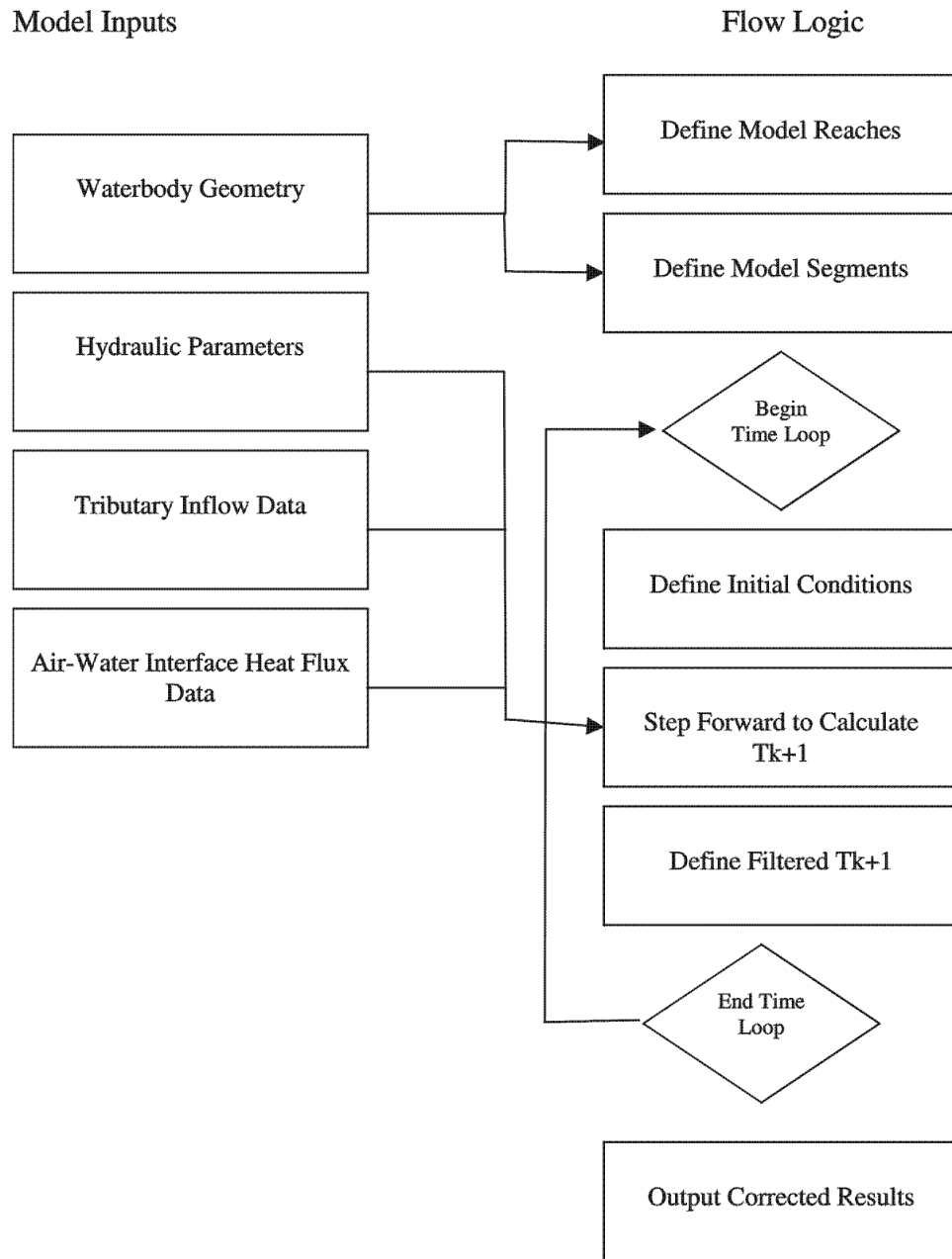
Figure 2-2. General Model Structure.

CHAPTER 3: APPLICATION OF TEMPERATURE MODEL TO COLUMBIA RIVER SYSTEM

3.1   SYSTEM HYDROLOGY BOUNDARIES AND ASSUMPTIONS

The boundaries of the Columbia River system for the assessment of water temperature include the Columbia River from the International Boundary (River Mile 745.0) to Bonneville Dam (River Mile 145.5) and the Snake River near Anatone, Washington (River Mile 168.9) to its confluence with the Columbia River near Pasco, Washington. With the exception of Grand Coulee Dam and its impounded waters, Lake Franklin D. Roosevelt (FDR), all the hydroelectric projects on these segments of the Columbia and Snake rivers have limited storage capacity and are operated as run-of-the-river reservoirs. Because of its large storage capacity (Table 1-3), Lake FDR is used for flood control as well as providing water for irrigation and generation of hydroelectric power. Typical reservoir elevations for Lake FDR show substantial annual variation (Figure 3-1).

Table 3-1. Sources of advected thermal energy in the Columbia River below Grand Coulee Dam and the Snake River below its confluence with the Grande Ronde River

Source	Location
Clearwater River	Snake R.M. 140.0
Potlatch Corporation	Snake R.M. 139.8
Tucannon River	Snake R.M. 62.2
Palouse River	Snake R.M 59.5
Lower Snake River Groundwater	Snake R.M. 168.0 – R.M. 0.0
Okanogan River	Columbia R.M. 533.5
Methow River	Columbia R.M. 523.9
Chelan River	Columbia R.M. 503.3
Crab Creek	Columbia R.M.410.8
Yakima River	Columbia R.M.335.2
Walla Walla River	Columbia R.M. 314.6
John Day River	Columbia R.M. 218.0
Deschutes River	Columbia R.M. 204.1
Upper Columbia River Groundwater	Columbia R.M. 596.0 – R.M. 292.0
Lower Columbia River Groundwater	Columbia R.M. 292.0 – R.M. 146.1

Run-of-the-river reservoirs are those for which reservoir elevation is kept more or less constant; water coming into the reservoir is passed directly through the reservoir. Typical run-of-the-river reservoirs are Lower Granite Reservoir and John Day Reservoir, the two largest run-of-the-river reservoirs on the Snake and Columbia rivers. Surface elevations for these two reservoirs during 1998 are shown in Figures 3-2 and 3-3, respectively.

The differences between the run-of-the-river reservoirs and Lake FDR, with respect to both their modes of operation and storage capacity, give rise to differences in their respective thermal regimes. For the run-of-the-river reservoirs, the spatial variability of temperature within a cross section perpendicular to the direction of flow is generally less than 1 $^{\circ}$C (McKenzie and Laenen, 1998) except near the forebay of some dams. In Lake FDR, vertical variations in water temperature of up to 5 $^{\circ}$C have been observed at various locations along the longitudinal axis of the reservoir. Because of this difference in the thermal regimes, the run-of-the-river projects
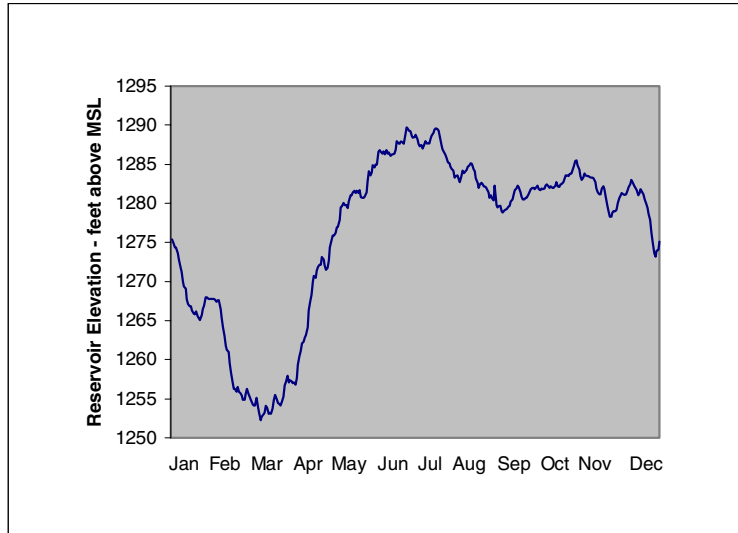
Figure 3-1. Surface elevations in Lake Franklin D. Roosevelt during 1998.

can be modeled as systems with variability in the longitudinal direction only. Lake FDR, however, is treated as a system with both vertical and longitudinal spatial variability using the water quality modeling system CEQUAL-W2 (Cole and Buchak, 1995). The assessment of water temperature in Lake FDR will be described in a later study.
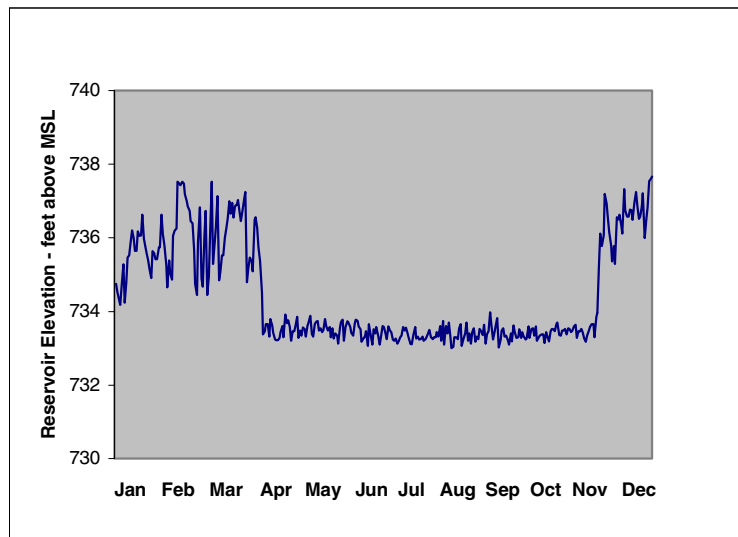
Figure 3-2. Surface elevations in Lower Granite reservoir during 1998.
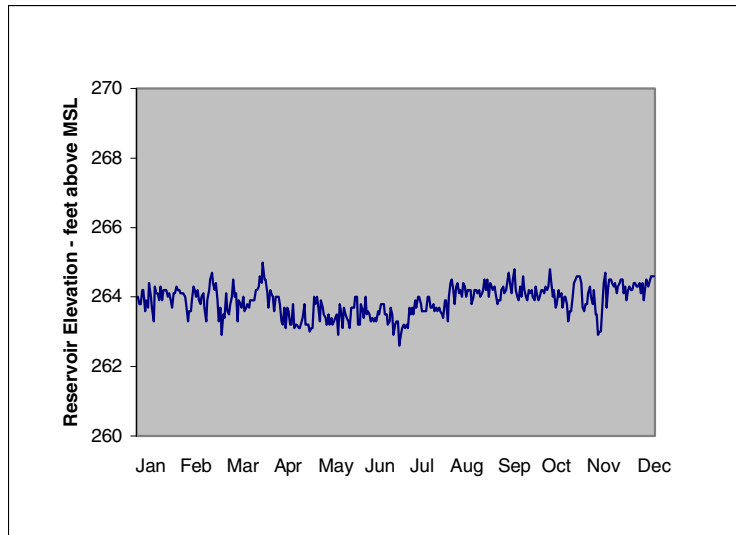
Figure 3-3. Surface elevations in John Day reservoir during 1998.

This report describes the development and application of a one-dimensional thermal energy model for the run-of-the-river reservoirs. The system boundaries for the model of the run-of-the-river segments are the main stems of the Columbia River from the tailwaters of Grand Coulee Dam (Columbia River Mile 596.6) to Bonneville Dam (Columbia River Mile 145.5) and the Snake River from its confluence with the Grande Ronde River (Snake River Mile 168.7) to its confluence with the Columbia River near Pasco, Washington (Snake River Mile 0.0). Advected thermal energy from ground water, point sources, and major tributaries (Table 3-1) to these segments are treated as inputs to the main stem rivers in this analysis.

3.2   TIME AND LENGTH SCALES

To accomplish the management objectives of the analysis, it is necessary to simulate daily average water temperatures as a function of longitudinal distance in the Columbia and Snake rivers. This establishes an approximate lower limit on system time scales and on data requirements. Stability and accuracy issues associated with solutions to Equation 2 can impose a requirement of even smaller time increments to obtain reliable solutions. However, the simulated results for time scales less than a day are valuable only in terms of their contribution to the solution accuracy. Because the time scale of the input data is equal to or greater than one day, there is no physical significance to higher-frequency output associated with the need to obtain a stable solution.

In an effort to include the environmental variability due to hydrology and meteorology, the largest time scales are on the order of two decades. The time scales are constrained by the hydrologic data available for the Columbia River system under existing management. Existing management in this case means operation of the system after the construction of the last hydroelectric project, Lower Granite Dam and Reservoir, completed in 1975. The simulation time scale, therefore, is 1975 to 1995.

The length scales for the analysis are determined by a number of factors. These factors include the availability of geometric data, spatial variability in the river geometry, and computational stability and accuracy. Data availability often provides the most severe constraint; however, there are ample data for describing river geometry in both the Columbia and Snake rivers within the boundaries of this analysis. The primary factor determining the length scale of this analysis is the need to achieve stable, accurate solutions. Length scales are such that the time it takes a parcel of water to traverse a given computational segment is always equal to or less than 1 day. For the Columbia and Snake rivers, this results in length scales on the order of 1 to 10 miles.

3.3 RATIONALE FOR APPROACH

Idealizing the largest part of the Snake and Columbia River system in terms of a one-dimensional model is based on the assumption that the primary processes affecting the thermal energy budget are advection and the transfer of thermal energy across the air-water interface. This assumption is in keeping with the management objective of providing a primary temperature assessment for the water quality planning process as required by Section 303(d) of the Clean Water Act. Based on previous work in the Columbia and Snake rivers (Raphael, 1962; Yearsley, 1969; Jaske and Synoground, 1970), a model of this type should capture the major features of water temperature impacts in this system. As described above, a number of other temperature assessments of the Columbia and Snake rivers (Bonneville Power Administration et al., 1994; Normandeau Associates, 1999) are based on one-dimensional models of the thermal energy budget. The mixed Lagrangian-Eulerian scheme for handling advection was chosen based on studies such as those done by Yeh (1990) and Zhang et al. (1993).

3.4 MODEL INPUT DATA

Water Temperature

The extensive water temperature data records for the Columbia and Snake rivers have been assembled and reviewed for quality by McKenzie and Laenen (1998). In addition, McKenzie and Laenen (1998) organized the data in electronic formats for rapid analysis. The results of their work provide a water temperature data set for the Columbia and Snake rivers, which can be used to describe uncertainty in the temperature model. The data quality analysis performed by McKenzie and Laenen (1998) provides a basis for characterizing the uncertainty associated with the measurements.

McKenzie and Laenen (1998) compiled data for the main stem Columbia and Snake rivers. Temperature data for the tributaries included in the analysis were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology (DOE) and the U.S. Geological Survey (USGS). The location of monitoring locations, period of record, and frequency of analysis are shown in Table 3-2.

River Geometry

River geometry is needed to characterize the hydraulic properties of the river as a function of flow and time. The basic information required is elevation of the river channel above mean sea level at a sufficient number of cross sections so as to adequately describe water depth, water width, and velocity as a function of river flow. A number of sources, described in Table 3-3, were used to obtain the data needed.

Hydrology

River hydrology data for the main stem Columbia and Snake rivers, as well as the major tributaries, were obtained from the records maintained by the U.S. Geological Survey. Gaging stations used in the study are shown in Table 3-4. Estimates of groundwater return flow were obtained from Hansen et al. (1994).

Table 3-2. Locations of water temperature monitoring sites for major tributaries of the Columbia and Snake Rivers in the study area

Station Name	Agency	Station Number	Station Location Latitude	Longitude	Period of Record
Clearwater River at Spalding	U.S. Geological Survey	13342500	46°26'55"	116°49'35"	1911-1996
Tucannon River at Powers	Washington DOE	35B060	46°32'18"	118°09'18"	10/17/73 – 09/02/96
Palouse River at Hooper	Washington DOE	34A070	46°45'33"	118°08'49"	07/30/59 – 09/02/96
Okanogan River at Malott	Washington DOE	49A070	48°16'53"	119°42'12"	11/17/66 – 09/10/96
Methow River at Pateros	Washington DOE	48A070	48°04'29"	119°57'20"	07/29/59 – 09/10/96
Chelan River at Chelan	Washington DOE	47A070	47°50'23"	120°01'11"	07/20/60 – 09/14/94
Crab Creek near Beverly	Washington DOE	41A070	47°11'23"	119°15'54"	10/24/61 – 09/05/94
Yakima River at Kiona	Washington DOE	37A090	46°15'13"	119°28'37"	03/20/68 – 09/09/96
John Day River at Highway 206	Oregon DEQ	404065	45°28'37"	120°28'07"	02/11/73 – 12/04/97
Deschutes River at Deschutes Park	Oregon DEQ	402081	45°37'40"	120°54'13"	07/16/62 – 12/01/97

Table 3-3. Sources of data for developing the hydraulic characteristics of the Columbia and Snake rivers

River Segment	Data Source
Columbia River: Grand Coulee Dam to Confluence with the Snake River	Columbia River Thermal Effects cross-sectional data (Yearsley, 1969)
Snake River: Lewiston, Idaho to Confluence with the Columbia River	U.S. Army Corps of Engineers (Walla Walla District) HEC-6 cross-sectional data
Columbia River: Confluence with the Snake River to Bonneville Dam	NOAA Navigation Charts

Table 3-4. U.S. Geological Survey gaging stations for the main stem Columbia and Snake Rivers and their major tributaries in the study area

Station Name	Station Number	Station Location		Period of Record	Drainage Area (mi²)	Average Annual Flow (cfs)	Gage Datum (feet above MSL)
		Latitude	Longitude				
Snake River at Anatone, WA	13334300	46°05'50"	116°58'36"	1958-1995	92960	35100	807.
Clearwater River at Spalding, ID	13342500	46°26'55"	116°49'35"	1911-1996	9570	15200	4360.
Tucannon River near Starbuck, WA	13344500	46°39'20"	118°03'55"	1915-1992	431	175	730.
Palouse River at Hooper, WA	13351000	46°45'31"	118°05'52"	1898-1994	2500	580	1041.
Columbia River at Grand Coulee, WA	12436500	47°57'56"	118°58'54"	1923-1995	74700	107200	900.
Okanogan River at Malott, WA	12447200	48°37'57"	119°42'12"	1966-1994	8080	3000	784.
Methow River at Pateros, WA	12449950	48°04'39"	119°59'02"	1959-1994	1772	1550	900.
Chelan River at Chelan, WA	12452500	47°50'05"	120°00'43"	1904-1993	924	2090	-----
Crab Creek near Beverly, WA	12472600	46°49'48"	119°49'48"	1951-1994	4840	200	500.
Yakima River at Kiona, WA	12510500	46°15'13"	119°28'37"	1906-1994	5615	3600	454.
Walla Walla River at Touchet, WA	14018500	46°01'40"	118°43'43"	1951-1996	1657	570	405.
John Day River at McDonald Ferry, OR	14048000	45°35'16"	120°24'30"	1905-1994	7580	2080	392.
Deschutes River at Moody, OR	14103000	45°37'20"	120°54'05"	1898-1994	10500	5800	168.

Meteorology

Meteorological data, including solar radiation, barometric pressure, cloud cover, wind speed, air temperature (dry-bulb), and relative humidity, are required for the thermal energy budget calculations. First order weather stations in the Columbia Basin maintained by the Weather Service and for which data are archived in the National Climatological Data Center (NCDC) include Lewiston, Idaho; Spokane, Washington; and Yakima, Washington. Data are available for these locations at 3-hour intervals from the NCDC SAMSON data sets. The period of record for each of these stations is shown in Table 3-5.

Table 3-5. First-order meteorological stations used to estimate heat budget parameters for the Columbia and Snake rivers

Station Name	WBAN #	Period of Record	Latitude	Longitude	Station Elev (feet above MSL)
Lewiston, Idaho	24149	01/01/1948- 12/31/1997	46°23'00"	117°01'00"	1436
Pendleton, Oregon	24155	01/01/1948- 12/31/1997	45°41'00"	118°51'00"	1482
Spokane, Washington	24157	01/01/1948- 12/31/1997	47°38'00"	117°32'00"	2356
Yakima, Washington	24243	01/01/1948- 12/31/1997	46°34'00"	120°23'00"	1064

Stations with maximum and minimum daily air temperatures are more numerous and are included in the NCDC Local Climatological Data Sets. The selected stations in the Columbia Basin selected are shown in Table 3-6.

Table 3-6. Weather stations from the Local Climatological Data Sets included in the parameter estimation process for heat budget calculations

Station Name	Station #	Latitude	Longitude	Station Elevation	Period of Record
Connell	1690	46°45'37"	117°10'10"	1020.	11/01/1960 – 12/31/1997
Coulee Dam	1767	47°57'00"	119°00'00"	1700.	06/01/1948 – 12/31/1997
The Dalles	8407	45°36'00"	121°12'00"	102	07/01/1948 – 12/31/1997
Pullman	6789	46°45'37"	117°10'10"	2545	10/21/1940 – 12/31/1997
Richland	7015	46°23'00"	117°01'00"	373	06/01/1948 – 12/31/1997
Wenatchee	9074	47°25'00"	120°19'00"	640	02/08/1877 – 12/31/1997

The U.S. Bureau of Reclamation maintains a network of agricultural weather stations called AgriMet stations. These stations report daily averages for all of the necessary meteorological data except cloud cover. They also report daily average solar radiation. Selected stations from the AgriMet network are shown in Table 3-7.

Table 3-7. Selected AGRIMET weather stations in the Columbia Basin maintained by the U.S. Bureau of Reclamation

Station ID	Station Name	State	Elevation	Latitude	Longitude	Install Data
GERW	George	WA	1150	47° 02' 38"	119° 38' 32"	5/14/86
GOLW	Goldendale	WA	1680	45° 48' 43"	120° 49' 28"	11/27/91
HERO	Hermiston	OR	600	45° 47' 56"	119° 31' 46"	5/17/83
LEGW	Legrow	WA	580	46° 12' 19"	118° 56' 10"	7/17/86
ODSW	Odessa	WA	1650	47° 18' 32"	118° 52' 43"	4/24/84

An analysis of a 24-year record (January 1, 1972, to December 31, 1995) for the four NCDC SAMSON weather stations showed a high degree of correlation between stations for dry bulb and dew point temperature (Table 3-8). Average annual air temperatures showed more variability among the stations than did dew point. Cloud cover was correlated, though not to the same degree as dry bulb and dew point temperature. Mean annual cloud cover in Yakima differed substantially from that of the other three SAMSON stations in the Columbia Basin. As expected, wind speed showed a much lower correlation among stations as well as more variability in the mean annual value.

Table 3-8a. Correlation coefficients and annual average for average daily air temperature collected at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.977	0.985	0.969
Pendleton		1.000	0.976	0.966
Spokane			1.000	0.975
Yakima				1.000
Annual Average	11.6 °C	11.2 °C	8.6 °C	10.1 °C

Table 3-8b. Correlation coefficients and annual average for average daily dew point at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.932	0.937	0.894
Pendleton		1.000	0.916	0.899
Spokane			1.000	0.919
Yakima				1.000
Annual Average	2.4 °C	2.0 °C	1.0 °C	1.5 °C

Table 3-8c. Correlation coefficients and annual average for average daily sky cover at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.851	0.837	0.712
Pendleton		1.000	0.790	0.830
Spokane			1.000	0.784
Yakima				1.000
Annual Average	64.1%	59.0%	61.5%	54.9%

Table 3-8d. Correlation coefficients and annual average for average daily wind speed at selected first order stations in the Columbia Basin

	Lewiston	Pendleton	Spokane	Yakima
Lewiston	1.000	0.500	0.540	0.390
Pendleton		1.000	0.560	0.0.560
Spokane			1.000	0.530
Yakima				1.000
Annual Average	2.86 m/s	3.79 m/s	3.97 m/s	3.20 m/s

3.5   PARAMETER ESTIMATION

The parameter estimation process addresses both the deterministic and probabilistic parameters in the model. The deterministic elements include the source term, f_k, and, implicitly, the travel times of parcels in the Lagrangian reference system. The components of the heat budget (Equation 4) and the advected thermal inputs from tributaries and groundwater compose the source terms. The parameters required to determine the travel times are derived from an analysis of the system hydraulics. It should be noted these parameters are not really deterministic; rather, they are random variables. For the purposes of this analysis, the composite error resulting from variability in the so-called deterministic parameters is included in the error term, $\underline{w}_{k-1}$, in Equation 10. Given this assumption, the probabilistic parameters are the means and variances of the error terms for the measurement model and the systems model.

In this study, the parameter estimation process is implemented in three steps. In the first step, the deterministic parameters are estimated, ideally, from first principles or, as is more often the case, from available research. Next, the estimated deterministic parameters are adjusted until the simulated results from the systems model are approximately unbiased. The systems model is unbiased if the mean of the innovation vector is small, where the innovation vector is the difference between time-updated simulations from the systems model and the actual measurements (Van Geer et al., 1991). Assuming the actual measurement bias and their variances are known, the final step in the parameter estimation process is to estimate the variance, Σ_Q, of the systems model.

Hydraulic Coefficients

As described previously, the hydraulic properties of each unimpounded river segment are estimated from relationships of the type given in Equations 18 to 20. Because a primary objective of the study is to assess the impact of impoundments, it was necessary to estimate these coefficients for two states of the system: one with dams in place and one without dams. For the case in which the dams were in place, the results from the USACE

HEC-5Q model of the Columbia and Snake rivers were provided by Nancy Yun of the USACE North Pacific Division Office. They are given in Tables C-1 and C-2, Appendix C. The only unimpounded reach under the present configuration is the Hanford Reach. The coefficients in Equations 18 to 20 for the Hanford Reach are given in Table C-3, Appendix C.

For the unimpounded conditions, geometric properties of the Columbia and Snake rivers, obtained from the sources given in Table 3-3, were used as input data to HEC-RAS (USACE-HEC, 1995), the steady gradually varied flow model developed by the U.S. Army Corps of Engineer's Hydrologic Engineering Center. Surface elevations of the Columbia and Snake rivers were estimated for flows of 150,000, 250,000, and 500,000 cfs in the Columbia River and 60,000, 120,000, and 240,000 cfs in the Snake River. For each of these flows, the average water depth, surface width, and velocity at selected locations were used to estimate the coefficients in Equations 18 to 20 using the methods of least squares. The coefficients obtained in this manner are given in Table C-4 and C-5, Appendix C.

Water Balance

The daily flow at any location in either river was determined from the sum of estimated ground water return flow (Hansen et al., 1994) and the daily gaged flow of the main stem headwaters and the tributaries upstream from the location. This assumes the following:

❑ Information regarding flow changes is transmitted instantaneously to locations downstream.

❑ Tributary sources other than those shown in Table 3-1 are negligible.

❑ The river gradient is sufficiently high such that the slope terms dominate (Henderson, 1966).

Heat Flux Across Air-Water Interface

The variables in the meteorological input file (*.HOT) were either directly measured or calculated from daily averaged data. These variables were then used to quantify the heat flux terms used in the energy budget method. The variables in the meteorological input file were determined as follows:

❑ Net Solar Radiation – calculated using equation (5)

❑ Net Atmospheric Radiation – calculated using Equation 6

❑ Dry-Bulb Temperature – directly measured

❑ Wind Speed – directly measured

❑ Factor for Bowen Ratio (psychrometric constant) – calculated using the following equation:

$$R_B \quad = \quad (c_a\, P) / (0.622\, \lambda) \tag{22}$$

where

c_a = heat capacity of air, cal/g/C, 0.24;

P = pressure at sea level, mb, 1013.3;

λ = latent heat of vaporization, cal/g;

$$\lambda \quad = \quad 597.3 - (0.564\, T_d); \text{ and} \tag{23}$$

T_d = dry-bulb temperature, degrees Celsius

❑ Vapor Pressure – was calculated using the following equation

$$e_a = 6.11 \text{ EXP } (17.27 \, T_{dew}) \, / \, (237.3 + T_{dew}) \tag{24}$$

where,

T_{dew} = dew-point temperature, degrees Celsius

Photo Period – this variable is not used in this model.

Initial Water Temperatures

Daily water temperatures are not always available for the locations used as initial conditions on the tributaries (Table 3-1) of the Columbia and Snake. For most stations, long-term sampling with a period of two to four weeks provides sufficient data to synthesize stream temperatures using air temperature. In their study of 584 USGS stream gaging stations within the contiguous United States, Mohseni et al. (1998) used a nonlinear model of the following type to synthesize water temperatures:

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \tag{25}$$

where

T_s = the weekly stream temperature

T_a = the weekly air temperature from a nearby weather station and

α, β, γ, and μ are determined by regressing the observed water temperature data on the air temperature data by minimizing the squared error with the downhill simplex method (Nelder and Mead, 1965).

Separate functions of the type defined in Equation 25 are used to describe the rising limbs and the falling limbs of the annual water temperature cycle in each of the tributaries. Mohseni et al. (1998) concluded that the method was accurate and reliable at 89 percent of the streams. Mohseni et al. (1998) also found that the method gave good results even when the air temperature measurements were not in proximity to the stream gaging locations.

The parameters obtained for the tributaries following the method of Mohseni et al. (1998), for both rising and falling limbs, at each of the input locations, are given in Table 3-9.

For the initial water temperatures on the main stem Columbia River, scroll case and total dissolved gas data from Chief Joseph Dam were combined to provide a long-term record. On the Snake River, the USGS data from the monitoring site at Anatone, Washington, was combined with data collected by Idaho Power Company and the Columbia River Intertribal Fish Commission to form a long-term record.

Measurement Bias and Error

The analysis of water temperature in the Columbia and Snake rivers by McKenzie and Laenen (1998) provides the basis for an initial estimate of the probabilistic parameters of the measurement model (Equation (3)). The data reviewed by McKenzie and Laenen (1998) were obtained from scroll case measurements and

Table 3-9. Parameters for estimating input temperatures of main stem and tributaries using nonlinear regression methods described by Mohseni et al. (1998)

River	Weather Station	Week for Rising Limb / Week for Falling Limb	T_{max}	β	γ	μ
Methow River	Wenatchee	1	22	14.4976	0.2007	0.5576
		30	22	12.9058	0.1787	0.4964
Walla Walla River	Yakima	1	29	12.7334	0.1763	0.4897
		30	29	11.6612	0.1615	0.4485
Clearwater River	Lewiston	1	24	16.2527	0.2250	0.6251
		30	24	13.00	0.1800	0.500
Chelan River	Wenatchee	1	26	13.0000	0.1800	0.500
		30	26	8.3590	0.1157	0.3215
Crab Creek	Wenatchee	1	26	11.2747	0.1561	0.4336
		30	26	11.4084	0.1580	0.4388
Deschutes River	Yakima	1	24	10.5902	0.1466	0.4073
		30	24	8.0669	0.1117	0.3103
John Day River	Lewiston	1	29	13	0.1800	0.5000
		32	29	12.3896	0.1715	0.4765
Okanogan River	Wenatchee	1	26	15.4810	0.2144	0.5954
		30	26	13.3483	0.1848	0.5134
Palouse River	Yakima	1	28	14.2740	0.1976	0.5490
		30	28	14.7654	0.2044	0.5679
Tucannon River	Lewiston	1	22	12.2640	0.1698	0.4717
		32	22	11.3405	0.1570	0.4362
Wenatchee River	Wenatchee	1	23	16.5413	0.2290	0.6362
		30	23	12.5088	0.1732	0.4811
Yakima River	Yakima	1	28	12.7321	0.1763	0.4897
		30	28	11.9158	0.165	0.4583

measurements made in conjunction with total dissolved gas monitoring. The scroll case measurement reflects the temperature of the water as it enters the generating turbine and is measured by reading the level of a mercury thermometer. The total dissolved gas monitoring program uses a temperature probe located in the forebay of each of the dams usually at a depth of 15 feet or more.

The quality, bias, and variability of these data vary considerably from site to site. For the scroll case data, McKenzie and Laenen (1998) report frequent "stepping" of the data. Stepping is characterized by periods of several days when the reported temperature is constant. Scroll case temperatures are measured by visual observations from mercury thermometers and recorded manually, usually on a daily basis. McKenzie and Laenen (1998) suggest that the measurement method might have contributed to the "stepping" and that the stepping might have been due to the frequency with which scroll case temperatures were measured and reported in the past.

The variation in data quality makes the task of quantifying measurement bias and error a difficult one. McKenzie and Laenen (1998) report bias in the measurements as high as 2.0 °C and variability as high as 2.0 °C

at certain sites and during certain periods of the year. However, at most sites and for recent data (post–1990), bias is in the range of 0.0-1.5 $^{\circ}$C and variability is generally less than 1.0 $^{\circ}$C.

Systems Model Bias and Error

The approach to estimating the probabilistic parameters for the systems model (Equation 2) follows that of Van Geer et al. (1991). Initial estimates of deterministic parameters are obtained from some combination of first principles and existing research. These parameters include the heat transfer across the air-water interface, advected thermal energy from tributaries and point sources and hydraulic properties of the river system. Adjustments are made to certain parameters until the mean of the innovations vector (Equation 17) is small.

The parameters selected for adjustment are constrained by assuming that any error in the basic heat transfer components (Equations 5 to 9), the advected energy from tributaries, and the hydraulic computations can be aggregated into the systems model error, $\Sigma_Q(t)$. Given these constraints, what remains to be adjusted is the choice of meteorological stations used to estimate the basic heat transfer components and the evaporation rate. This formulation of the evaporation was obtained from the comprehensive energy budget of Lake Hefner in Oklahoma (Marciano and Harbeck, 1952) and has been shown to perform satisfactorily for other water bodies (Bowie et al., 1985). However, there is uncertainty in the empirical constant, E_v (Kohler, 1954; Bowie et al., 1985). There is also uncertainty and variability associated with the meteorological variables, wind speed, W, and vapor pressure, e_a. The uncertainty in the meteorological variables, as discussed below, is primarily a result of the assumption in this study that wind speed and vapor pressure can be treated as regional phenomena. The approach used in this report has been to assume the meteorological variables can be obtained from the NCDC SAMSON data sets and treat the empirical constant, E_v, as a parameter that can be estimated during the process described above.

The choice of appropriate meteorological stations for estimating the heat budget at the spatial scale of this analysis must take into account regional variations in weather under the constraint of a limited number of stations with complete data. The problem is not unique to this study. The analysis of systems operations in the Columbia Basin (Bonneville Power Administration et al., 1994) used the data from three weather stations (Boise, Idaho; Lewiston, Idaho; and Spokane, Washington) to develop the heat budget for the Columbia, Snake, and Clearwater rivers. These data were used to describe surface heat exchange from and including Brownlee Reservoir on the Snake to the confluence with the Columbia; the Clearwater River from and including Dworshak Reservoir and the Columbia River from the International Border to Bonneville Dam. A study of thermal energy in the Hells Canyon complex by Idaho Power Company (Harrison et al., 1999) used the combined meteorological data from Parma, Idaho, and Prairie City, Oregon, to predict water temperatures in Brownlee Reservoir from approximately Snake River Mile 335 to Snake River Mile 285. Parma is approximately 50 miles from Brownlee Reservoir, while Prairie City is approximately 100 miles from Brownlee Reservoir.

As shown in Table 3-8, there are strong regional correlations among certain meteorological variables in the Columbia Basin, particularly air temperature, dew point, and cloud cover. Regional correlations for wind speed are not as strong because of the influence of topography. There is some regional variation in the climate as reflected in the annual average values (Table 3-8). Data from two classes of meteorological stations are available to estimate these components, as described previously. Some Surface Airways (SAMSON) stations report the complete suite of meteorological variables. There is extensive coverage of daily maximum and minimum air temperatures from the Local Climatological Data (LCD). Data from the SAMSON stations were used to expand the spatial coverage for heat budget analysis. This was accomplished by assuming that wind speed, cloud cover, relative humidity, and barometric pressure are large-scale phenomena and that air temperature is more of a local phenomenon. Several LCD stations were augmented with SAMSON data in this way to provide more spatial coverage of the surface heat transfer. Meteorological data were assigned to river segments based on a qualitative assessment of local meteorology. A number of combinations of stations were evaluated in an effort to achieve unbiased simulations. The final configuration of stations and the values of the empirical constant, E_v, for each river segment are given in Table 3-10.

Table 3-10. Final configuration of weather stations used to estimate the heat budget terms for the mathematical model of water temperature in the Columbia and Snake Rivers.

Weather Station	Station Type	Evaporation Coefficient (mb^{-1})	River Segments
Lewiston, Idaho	SAMSON	1.45x10^{-9}	Snake River from Lewiston, Idaho to the Confluence with the Columbia
Wenatchee, Washington	LCD	1.55x10^{-9}	Columbia River from Grand Coulee Dam to Rock Island Dam
Yakima, Washington	SAMSON	1.40x10^{-9}	Columbia River from Rock Island Dam to the Confluence with the Snake
Richland, Washington	LCD	1.10x10^{-9}	Columbia River from the confluence with the Snake to Bonneville Dam

Using the parameters estimated above, estimates of the system model error variance, $\Sigma_Q(t)$, are obtained by adjusting the estimated variance until the theoretical variance for the innovations vector is approximately equal to the sample variance (Mehra, 1972). The theoretical variance is given by (Kailath, 1968)

$$E\{v_k v_k^T\} = H P_k(-) H^T + \Sigma_R \tag{26}$$

and the sample variance, S, by

$$S = \frac{1}{m} \sum_{k=1}^{m} v_k v_k^T \tag{27}$$

This is an iterative process because the innovations vector is a function of the deterministic parameters and the probabilistic parameters. In addition, there are bias and error in the observations (McKenzie and Laenen, 1998), as described previously. The systems model error estimate was obtained by first finding a set of meteorological stations, which provided good (in a qualitative sense) agreement. This was followed by an adjustment of measurement bias and error for the total dissolved gas temperature data, within the range estimated by McKenzie and Laenen (1998). The final values for systems model variance, Σ_Q, and measurement error and bias are given in Table 3-11.

After completing the parameter estimation process for both the deterministic and probabilistic parameters, the systems model was run in the predictive mode. That is, the measurements were not used to update the state estimate. Running the model in the predictive mode provides a way of comparing state estimates from the systems model with the state estimates from the measurement model in a manner similar to the traditional approaches using the calibration and verification paradigm. The output from these simulations is shown in Figures 3-4 through 3-12. Various statistics that can be used to assess model performance are given in Appendix D.

Table 3-11. Measurement bias, measurement error variance and systems dynamic error variance at locations of scroll case temperature measurements on the Columbia and Snake Rivers

Location of Measurement	Measurement Bias (^{o}c)	Error Variance	
		Measurement $^\circ c^2$	Systems Dynamics $^\circ c^2$
Lower Granite Dam	0.0	0.50	0.008
Little Goose Dam	0.0	0.50	0.008
Lower Monumental Dam	0.0	0.50	0.008
Ice Harbor Dam	0.0	0.5	0.008
Rock Island Dam	0.5	0.50	0.008
Priest Rapids Dam	0.0	0.50	0.008
McNary Dam	1.0	0.50	0.008
The Dalles Dam	1.0	0.50	0.008
Bonneville Dam	1.5	0.50	0.008

Figure 3-4. Simulated and observed water temperatures at Wells Dam for the period 1990–1994.

Figure 3-5. Simulated and observed water temperatures at Priest Rapids Dam for the period 1990–1994.

Figure 3-6. Simulated and observed water temperatures at McNary Dam for the period 1990–1994.

Figure 3-7. Simulated and observed water temperatures at John Day Dam for the period 1990–1994.

Figure 3-8. Simulated and observed water temperatures at Bonneville Dam for the period 1990–1994.

Figure 3-9. Simulated and observed water temperatures at Lower Granite Dam for the period 1990–1994.
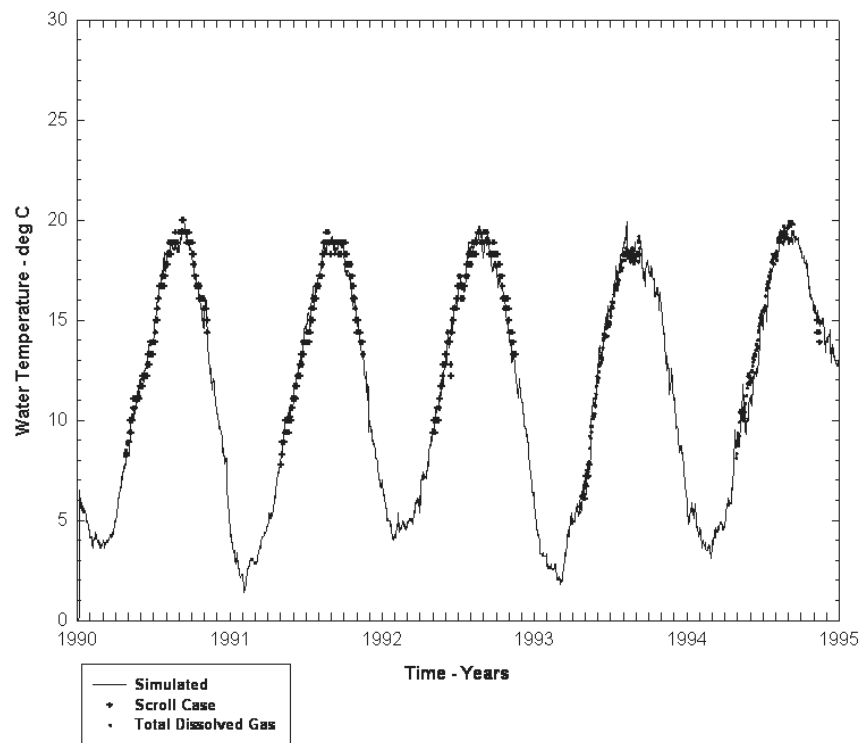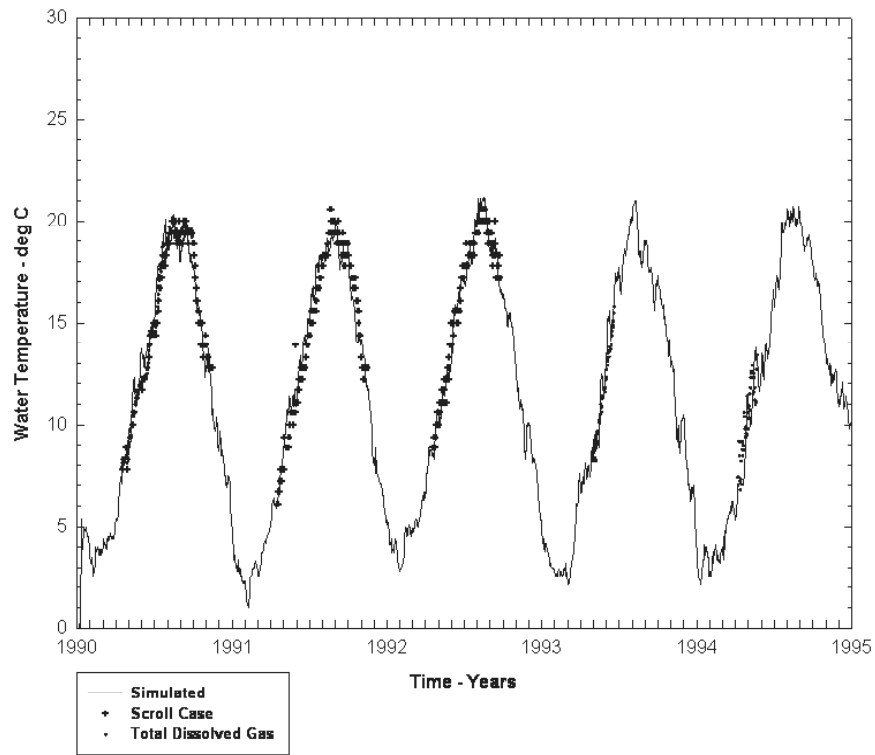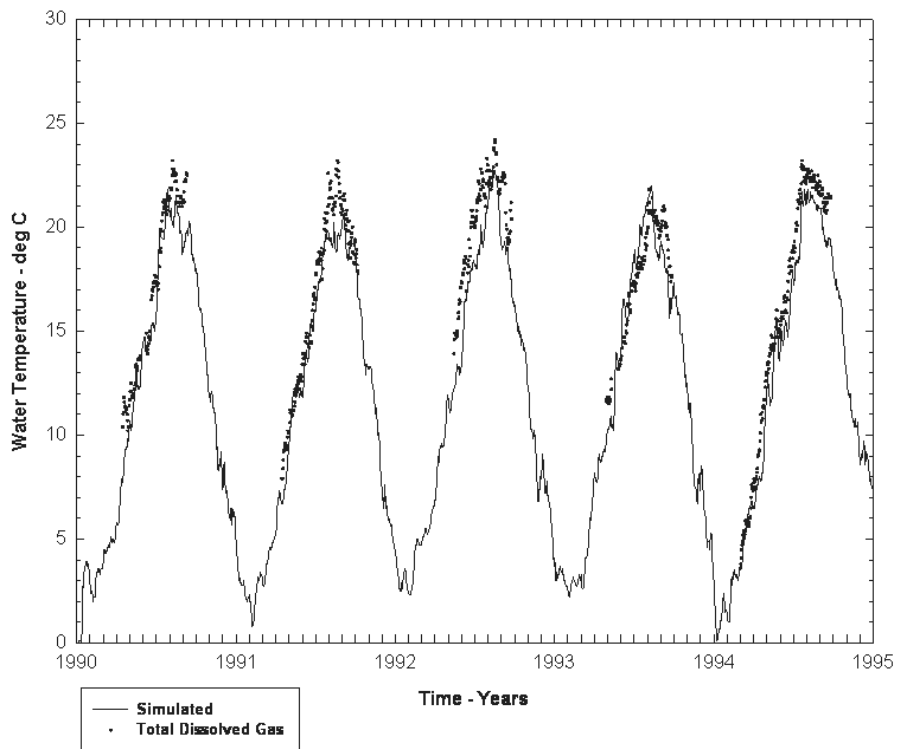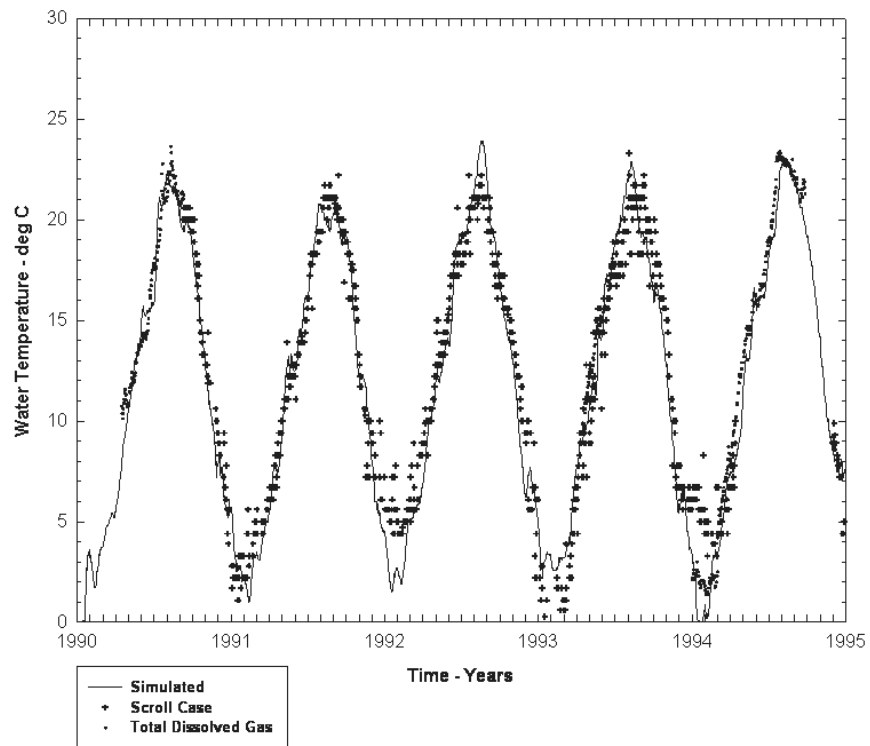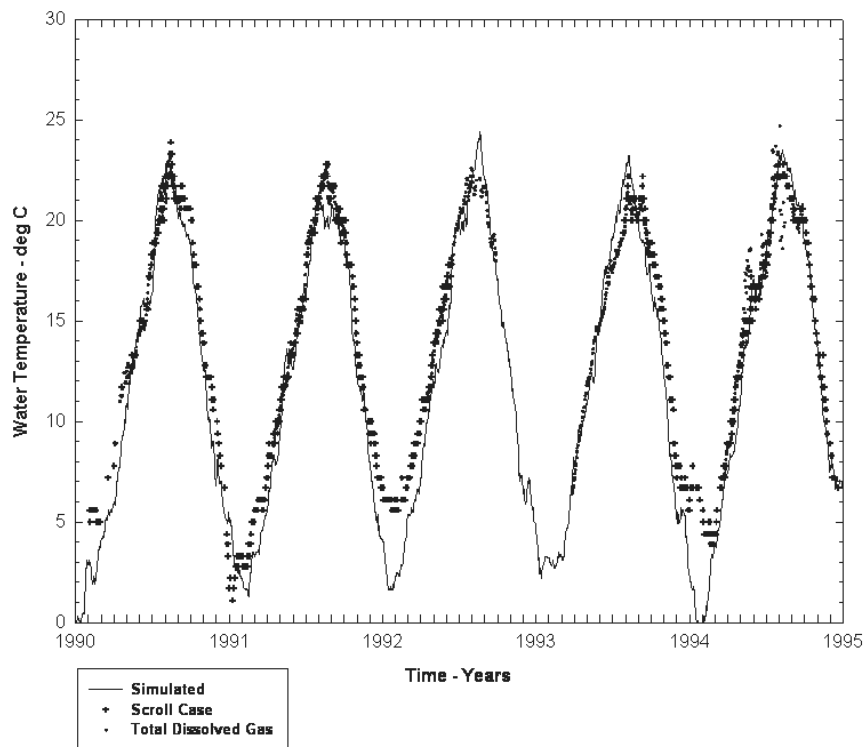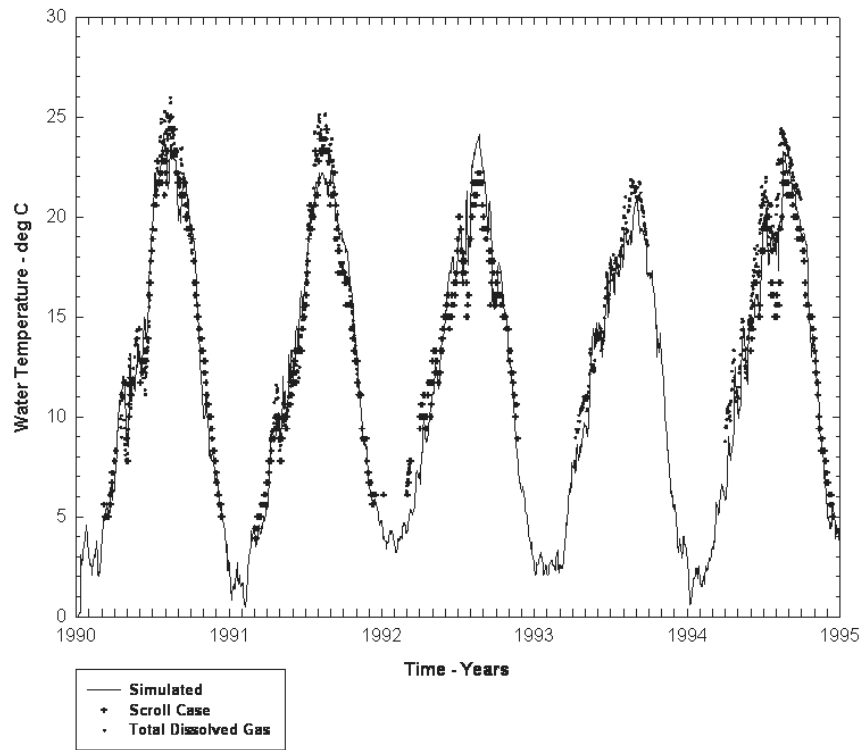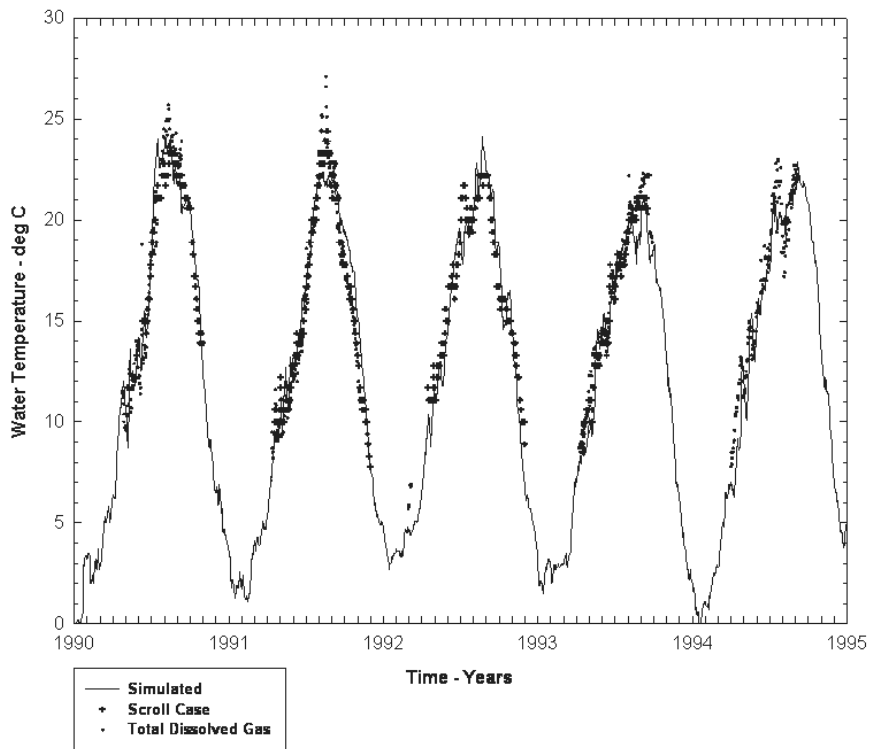

Figure 3-10. Simulated and observed water temperatures at Little Goose Dam for the period 1990–1994.
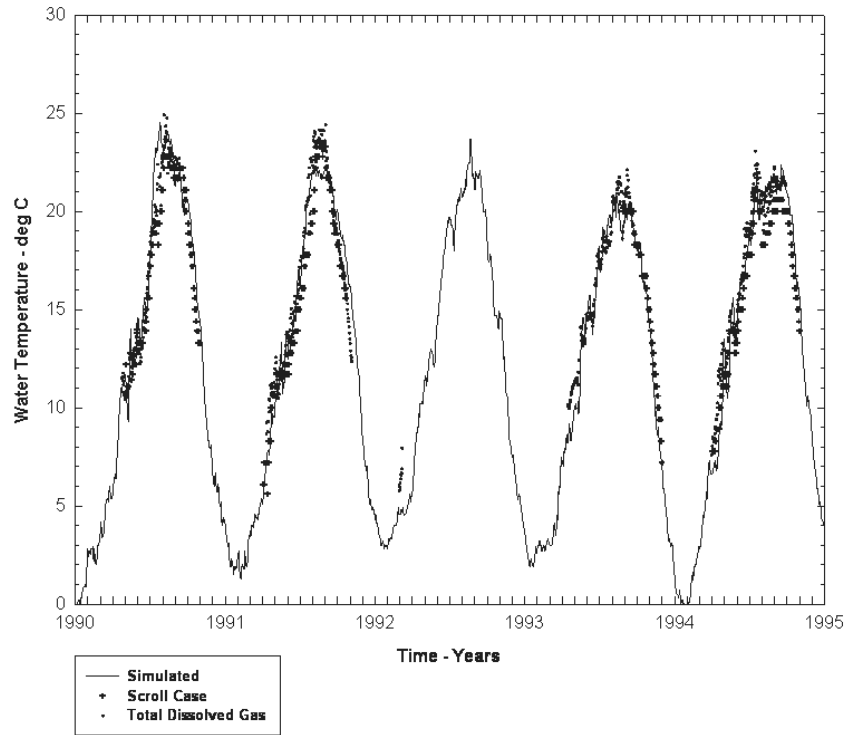
Figure 3-11. Simulated and observed water temperatures at Lower Monumental Dam for the period 1990–1994.
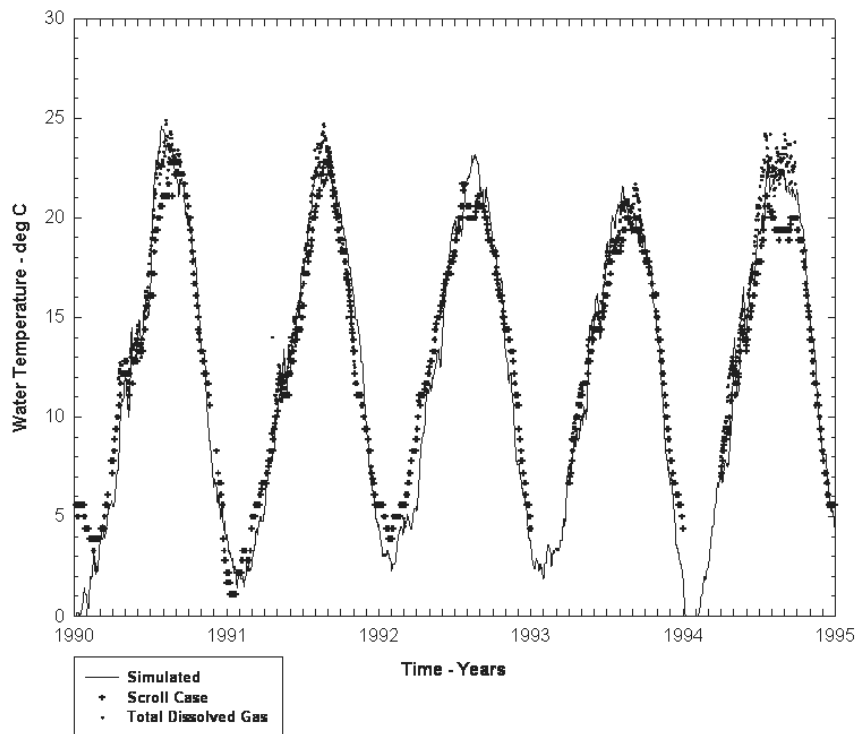
Figure 3-12. Simulated and observed water temperatures at Ice Harbor Dam for the period 1990–1994.

3.6   MODEL APPLICATION

Scenarios

The objectives of this study are to assess the relative contribution of impoundments and tributary inputs to changes in the thermal regime of the Columbia and Snake rivers. To capture the environmental variability in hydrology and meteorology, the 21-year record of stream flows and weather data from 1975 to 1995 is used to characterize river hydraulics and surface heat transfer rates. Most tributary temperatures are developed from local air temperatures using the relationship given by Equation 25 and air temperature data for the same 21-year period. The period from 1975 to 1995 was chosen to represent a period of relatively consistent management of the hydroelectric system. This assumption was based on the fact that it includes the period for which all the dams that are presently installed have been in operation. However, the assumption is confounded to a degree by the change in operation of Dworshak Dam beginning in the summer of 1992. Selective withdrawal of cold water at Dworshak Dam, beginning in 1992, has led to modifications in the temperature regime of the Snake River (Karr et al., 1998). For the period 1992-1995, measured temperatures at Dworshak Dam and at Orofino, Idaho, were used to account for the effects of selective withdrawal at Dworshak Dam.

The assessment of impacts to the thermal regime of the Columbia and Snake River is based on the following three scenarios:

Scenario 1   This scenario includes the existing configuration of dams, hydrology, and meteorology from 1975 to 1995 and tributary temperatures estimated from the 21-year meteorologic record using Equation 25.

Scenario 2   This scenario assumes the Columbia River downstream from Grand Coulee and the Snake River downstream from Lewiston, Idaho, are unimpounded and that hydrology, meteorology, and tributary temperatures are the same as Scenario 1.

Scenario 3   This scenario assumes the existing configuration of dams, with hydrology and meteorology for the period 1975 to 1995. Tributary input temperatures are estimated from the 21-year meteorologic record using Equation 25, but are not allowed to exceed 16 $^{\circ}$C (60.8 $^{\circ}$F).

For each of these scenarios, daily average water temperatures are simulated and the mean, mean plus one standard deviation, and the mean minus one standard deviation of the simulated water temperatures are compared to the benchmark, 20 $^{\circ}$C (68 $^{\circ}$F). Temperature excursions are defined for the three conditions as follows:

$$T_{ex}^{i}   =   T_{sim}^{i} - 20 \text{ for } T_{sim}^{i} > 20$$

$$=   0 \text{ for } T_{sim}^{i} < 20$$

where

T_{sim}^{1} = the simulated daily average water temperature – one standard deviation

T_{sim}^{2} = the simulated daily average water temperature

T_{sim}^{3} = the simulated daily average water temperature + one standard deviation

The average annual duration, or frequency, f_{ex}^{i}, of temperature excursions is estimated as the number of days in excess of the benchmark compared to the total number of days in the simulation. That is,

$$f_{ex}^i = \frac{\sum \delta_{ex}^i}{N}$$

where

$$\delta_{ex}^i = 1 \quad \text{for} \quad T_{ex}^i > 20$$

$$= 0 \quad \text{for} \quad T_{ex}^i < 20.$$

$$N = \text{total number of days simulated}$$

The standard deviation for these simulations is computed with the Kalman filter (Equations 10 to 17) in the prediction mode. In the prediction mode, the measurement matrix, H, is set to zero. This means the Kalman gain, K, is always zero and the variance propagation is a result of updating by the systems model only:

$$\Sigma_k = f_{k-1} P_{k-1} f_{k-1}^T + \Sigma_Q$$

where the (+) and (-) convention has been dropped since there is no updating based on the observations.

The frequencies of temperature excursions for each scenario as a function of Columbia and Snake River Mile are shown in Figures 3-13 to 3-18. The error bars in each of the plots represent the frequencies estimated with the simulated means plus one standard deviation and the simulated means minus one standard deviation.
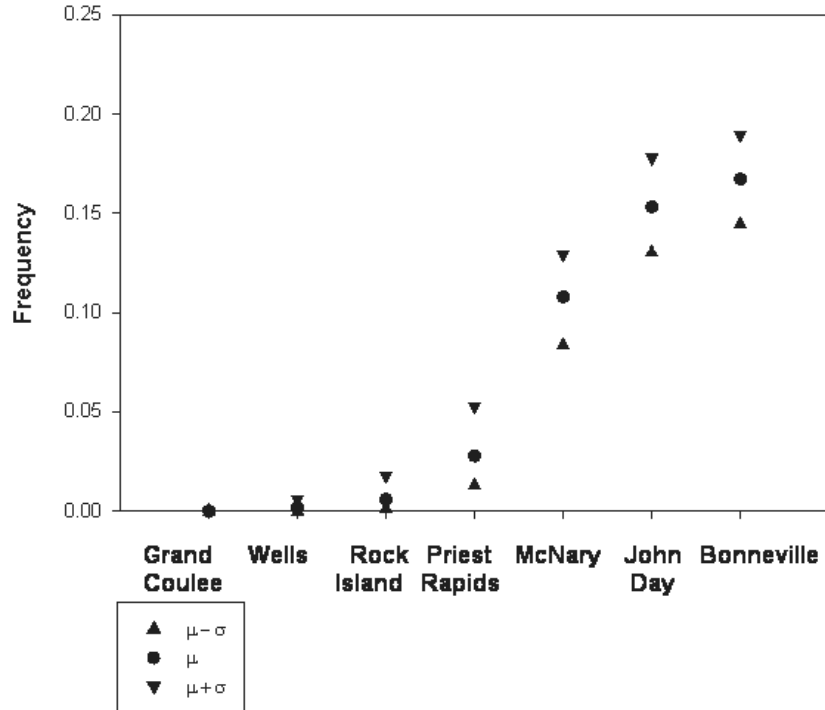
Figure 3-13. Frequency of predicted water temperature excursions in the Columbia River with dams in place.
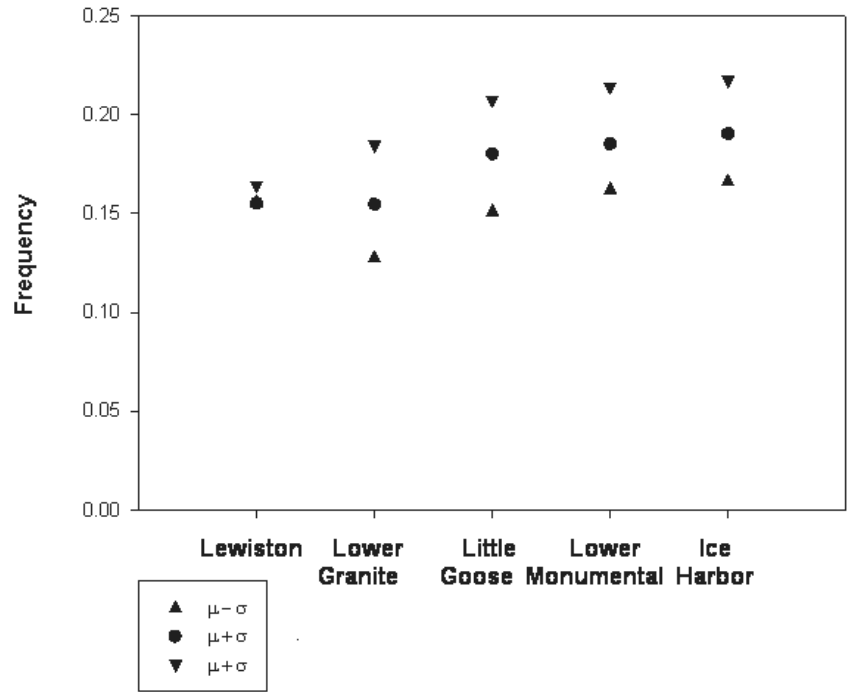
Figure 3-14. Frequency of predicted water temperature excursions in the Snake River with dams in place.
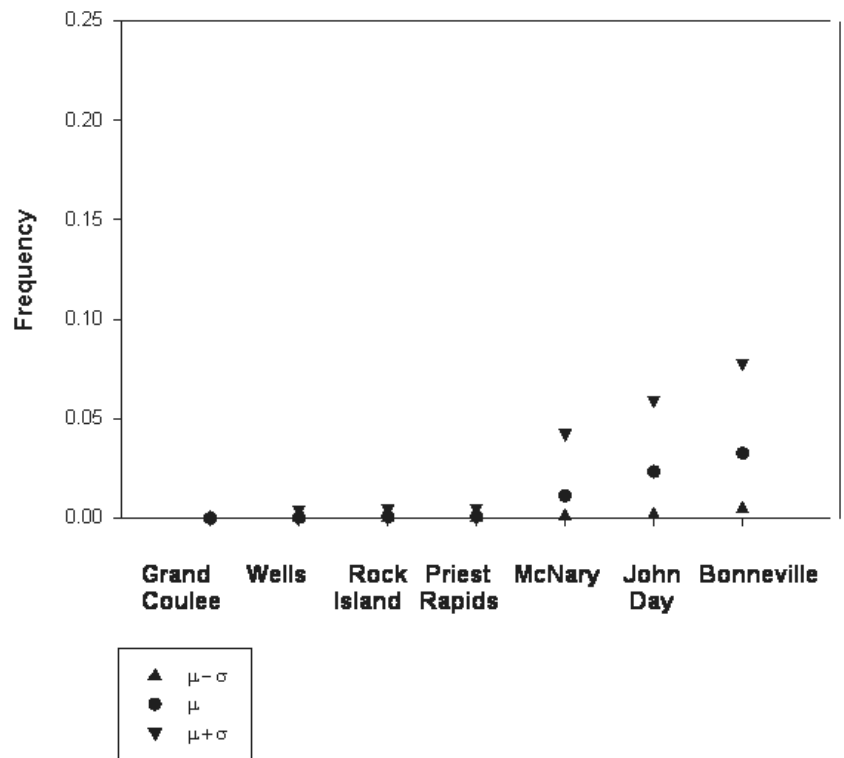
Figure 3-15. Frequency of predicted water temperature excursions in the Columbia River for the unimpounded river.
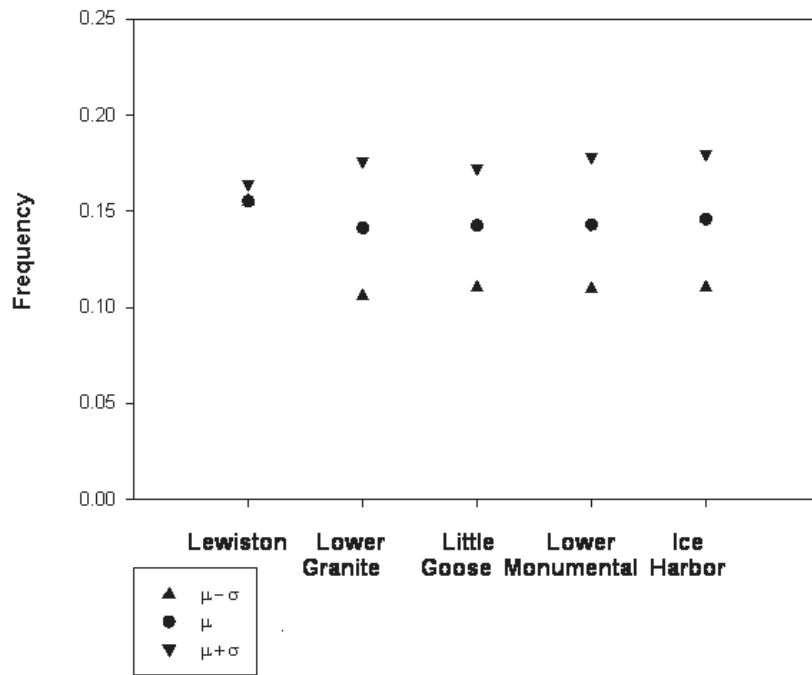
Figure 3-16. Frequency of predicted water temperature excursions in the Snake River for the unimpounded river.
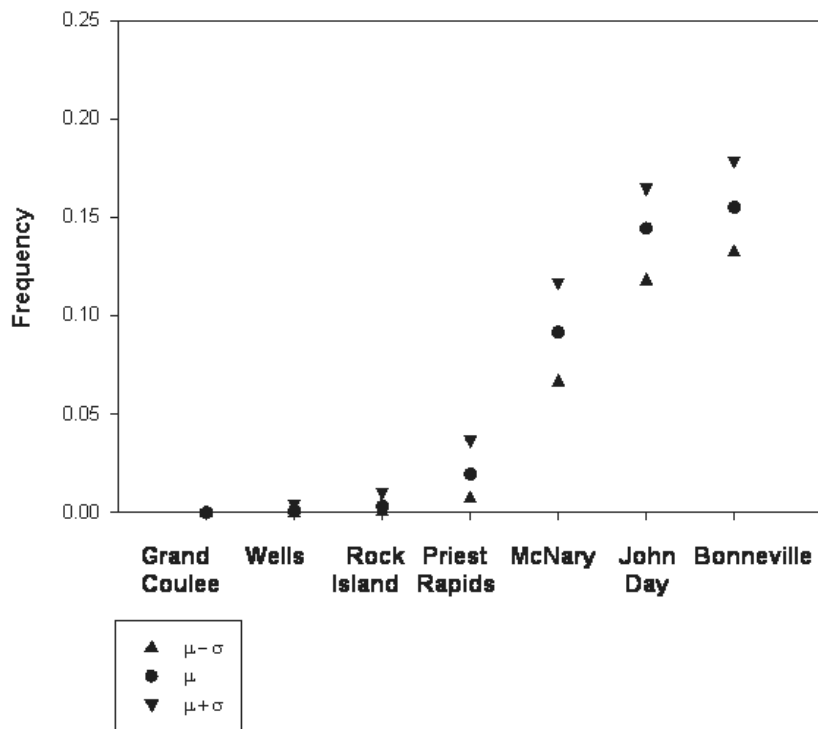
Figure 3-17. Frequency of predicted water temperature excursions in the Columbia River with dams in place and tributaries equal to or less than 16 °C.
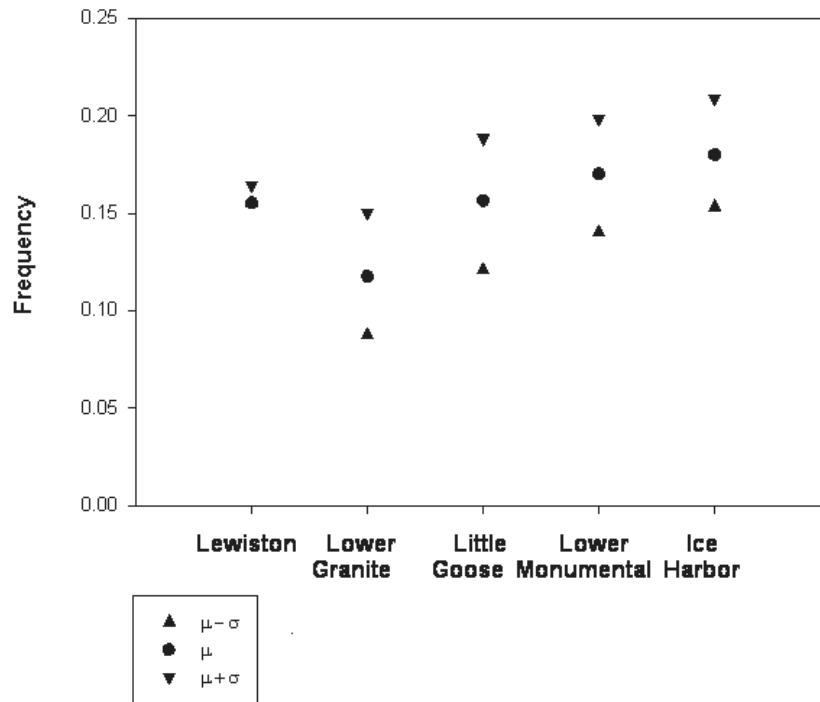
Figure 3-18. Frequency of predicted water temperature excursions in the Snake River with dams in place and tributaries equal to or less than 16 °C.

Results

The frequency of temperature excursions, calculated from the mean state estimates, establish a basis for assessing the relative impact of dams and tributary inflow on the thermal regime of the Columbia and Snake rivers. The frequency of temperature excursions, calculated from the mean plus and minus one standard deviation of the state estimates, provide the basis for assessing the significance of differences between scenarios. In this report, the significance of differences is discussed in a qualitative way only. A quantitative discussion of significance is usually done in the context of hypothesis testing or decisionmaking under uncertainty. Although one might argue that this temperature assessment is a form of decisionmaking under uncertainty, it has been treated in this report as part of the problem formulation for watershed planning under Section 303 (d) of the Clean Water Act. Implicit in this view of the temperature assessment is the notion that use of this methodology as a decisionmaking tool may require additional efforts to reduce uncertainty, as well as the development of formal statements or protocols regarding acceptable levels of risk.

For the Columbia River in Scenario 1, the existing conditions with dams in place, the mean annual frequency of temperature excursions increases from near zero at Grand Coulee Dam to somewhat greater than 0.03 at Priest Rapids. The influence of the warmer Snake River leads to an increase of the average frequency of excursions between Priest Rapids and McNary Dam from 0.03 to 0.11. Downstream from McNary Dam, the mean frequency of temperature excursions continues to increase to 0.17 at Bonneville Dam. The range of the frequency of excursions for the simulated average plus one standard deviation and the simulated average minus one standard deviation is of the order of ±0.03.

For the unimpounded case (Scenario 2), the mean annual frequency of excursions is approximately 0.03 at Bonneville Dam. The estimated uncertainty of the frequency increases slightly compared to the results of

Scenario 1, so that the frequencies of temperature excursion associated with the mean simulation plus one standard deviation are approximately 0.04 greater than that of the simulation. The increase in the uncertainty of the estimate for the river in the unimpounded scenario is due to the change in system dynamics associated with shallower depths and higher velocities. In spite of the increase in uncertainty, the difference in Scenarios 1 and 2 at those sites downstream from the confluence of the Snake River are clearly outside the bands defined by one standard deviation of the state estimates. In a qualitative sense, these differences are significant; that is, the unimpounded Columbia River has significantly fewer temperature excursions than does the impounded river. For the purposes of this assessment, however, no attempt has been made to evaluate the significance in terms of impact on the ecosystem.

The frequency properties of Scenario 3, for which tributary temperatures are constrained to be always less than 16 $^{\circ}$C, are similar to Scenario 1 on the Columbia River upstream of its confluence with the Snake. The combined average annual flows of advected sources in this segment (Table 3-1) are less than 10 percent of average annual flow of the Columbia River at Grand Coulee Dam. The impact of these sources on the thermal energy budget of the main stem Columbia is, therefore, small. The 16 $^{\circ}$C constraint was not applied to the Snake River and the warming effect of the Snake River on the Columbia is evident in the increase in the frequency of excursions between Priest Rapids Dam and McNary Dam. The net result being that frequency of excursions is not significantly different between Scenarios 1 and 3.

In the Snake River, with dams in place (Figure 3-14), the mean frequency of temperature excursions is relatively high (0.15) at the starting point (Snake River Miles 168.0), drops slightly due to the influence of the Clearwater River, then increases to 0.19 between there and Ice Harbor Dam (Snake River Miles 9.0). Because the Snake is a smaller river, it responds more rapidly to changes in systems dynamics. This, in turn, leads to larger uncertainty in the estimates as reflected in increased ranges of both frequency and magnitude of excursions. For the unimpounded case (Figure 3-16), the analysis predicts that the mean frequency of temperature excursions at Ice Harbor is approximately the same as the initial point near Anatone, Washington. The Clearwater River has a noticeable impact on water temperatures of the Snake River as shown by the reduction in the mean frequencies of temperature excursions for Scenarios 2 and 3 at Lower Granite Dam compared to the initial conditions for the Snake River at Anatone, Washington.

The wider bands of uncertainty reduce the significance of the results for the Snake River scenarios in the estimated frequency and magnitude of temperature excursions. At Lower Granite Dam, the differences in the three scenarios are small and within the uncertainty bands defined by one standard deviation of the state estimates. The qualitative level of significance in differences between Scenarios 1 and 2 increases downstream. At Ice Harbor Dam, the mean values of the frequency estimates for Scenario 2 are outside the uncertainty bands defined by one standard deviation of the state estimates of Scenario 1. Differences between Scenarios 1 and 3 are significant only at Lower Granite, where the impact of lower temperatures in the Clearwater River is still important.

Changes in cross-sectional daily average water temperature between initial conditions and some downstream point in rivers are due to (1) meteorology (wind speed, air temperature, cloud cover, air moisture content), (2) river depth, and (3) travel time between the two points. The meteorology determines the maximum temperature the water body can achieve; the depth and certain components of meteorology determine the rate at which the water body exchanges heat with the atmosphere; and the travel time determines the importance of initial conditions.

Some limits on the cross-sectional daily average water temperature in rivers can be estimated by defining the equilibrium temperature as the temperature a body of water would reach after very long exposure to a specific set of meteorological conditions. For a river moving with an infinitely high speed, the cross-sectional daily average water temperature at some downstream point will be exactly the same as the initial conditions. The meteorology would have no effect on cross-sectional daily average water temperature for this case. A water body at rest (no velocity) under constant meteorological conditions would eventually reach the equilibrium temperature

determined by wind speed, air temperature, cloud cover, and air moisture content. The water depth and certain components of the meteorology would determine the time it takes to reach the equilibrium temperature.

The impact of structural changes on the cross-sectional daily average water temperature river system, such as the construction and operation of dams and reservoirs, is determined by the relative importance of the three factors described above. The results for Scenarios 1 and 2 imply that the structural changes associated with construction and operation of hydroelectric facilities on the Columbia and Snake rivers have led to changes in the travel times that are sufficient to modify the temperature regimes of these rivers.

The impact of advected sources such as tributaries and point discharges on the cross-sectional daily average water temperature of the main stem Columbia and Snake rivers is determined by the ratio of advected energy from the source ($\rho C_p Q_{adv} T_{adv}$) to the advected energy of the main stem ($\rho C_p Q_{main} T_{main}$). Contribution of thermal energy of most of the advected sources (Table 9) is small due to the magnitude of their flow compared to the main stems. The Clearwater River does have a significant cooling effect on the cross-sectional daily average water temperature of the Snake River. In addition, the Snake River has a significant warming effect on the cross-sectional daily average water temperature of the Columbia River.

CHAPTER 4: MODEL INPUT AND OUTPUT FILES

4.1   INPUT FILES

The Columbia River Temperature model requires three types of input files: the control file, advected source file, and meteorological file. The main input file, or control file, contains general model and reach information and lists which weather station files the model will use. The advected source file contains daily flow and temperature values for the main reaches as well as all the tributary inputs. The meteorological file contains data about each weather station that is used in the model.

The input files are divided into sections. Each section pertains to a general group of data. The sections are as follows:

> **Control File**
> Section 1 – General Model Information
> Section 2 – Reach Information
> Section 3 – Weather Station (Meteorological) File Names
>
> **Advected Source File**
> Section 4 – Input File Information for Advected Source File
>
> **Meteorological File**
> Section 5 – Input File Information for Meteorological File

Each section is made up of one or more records. A record contains data for a specific portion of that section. Each record is then defined by one or more lines of data. A detailed description of the input data structure for the input files follows.

Control File

An example of a control file is shown in Figure 4-1.

Section 1 (General Model Information)

Record 10 (General Model Information)

Line 1   advected source file name (i.e., crtass.adv)
> *Name of file that contains advected thermal energy data (flow and temperature) for main river stems and tributaries. In this model, there are three main river stems (Clearwater River, Snake River, and Columbia River) and 12 tributaries.*

Line 2   model description
> *Description of Temperature Model*

Line 3   model title
> *Temperature Model Title*

Line 4   model start date, model end date
> *Date that model will begin and end computations. Format for each date is YYYYMMDD.*

```
*************** INPUT FILE - CRTES.INP - FOR RBM10 ***************
*************** SECTION 1 - GENERAL MODEL INFORMATION ***************
R10.L1 crtass.adv
R10.L2 Reverse Particle Tracking Model-Existing Conditions-add Clearwater R
R10.L3 Columbia River Temperature Assessment Project - EPA Region 10
R10.L4   19750101 19951231        2
R10.L5 Number of reaches
R10.L6         3
*************** SECTION 2 - REACH INFORMATION ***************
*************** REACH 1 - CLEARWATER RIVER ***************
R20.L1 Clearwater River           4         5
R20.L2  40.0 30.0 20.0 10.0  5.0

R21.L1 Abv NF Confluence       RIVER          42.0 40.6 980.0000.
R21.L2    2    3    0    0    0
R21.L3    4.1693    0.693    56.765    0.233
R21.L4 End of Segment #A

R22.L1 Blw NF Confluence 1     RIVER          40.6 11.9 900.
R22.L2    30    3    0    1    0
R22.L3    4.053    0.693    56.234    0.233
R22.L4 Tributary Inflows
R22.L5 NF Clearwater R    1NFclr    40.1    9640.0
R22.L6 End of Segment #B
*************** REACH 2 - SNAKE RIVER ***************
R20.L1 Snake River               49         5
R20.L2  168. 107. 70.5 41.7 10.1

R21.L1 Hells Canyon Reach       RIVER          168.7150.0 812.0000.
R21.L2    9    3    0    0    0
R21.L3    4.222    0.693    57.005    0.233
R21.L4 End of Segment #A

R22.L1 Hells Canyon Reach       RIVER          144.0140.0 760.
R22.L2    2    3    0    1    1
R22.L3    4.169    0.693    56.764    0.233
R22.L4 Tributary Inflows
R22.L5 Clearwater R.    2clear    140.1    9640.0
R22.L6 End of Segment #C

R24.L1 Lower Granite Resrvr     RSRVR          140.0137.3 746.
R24.L2    2    3    0    1    0
R24.L3    20825.    597.4      2.7   Volume (acre-feet) and Area (acres) in Seg 1
R24.L4 Tributary Inflows
R24.L5 Potlatch Corp    3potlt    139.5
R24.L6 End of Segment #1
*************** REACH 3 - COLUMBIA RIVER ***************
R20.L1 Columbia River              56         7
R20.L2  516. 474. 397. 292. 216. 192. 146.

R21.L1 Head of Chief Joseph     RIVER          596.1593.31000.
R21.L2    1    1    0    0    0
R21.L3    2.6338    0.7352    18.0219    0.3374
R21.L4 End of Segment #1

R24.L1 Wells Reservoir    #1     RSRVR          539.2533.3 803.
R24.L2    1    1    0    1    0
R24.L3    33809.6    1571.       5.9   Volume (acre-feet) and Area (acres) in Seg 1
R24.L4 Tributary Inflow
R24.L5 Okanogan River    6okngn    533.3    8340.0
R24.L6 End of Segment #13

R22.L1 Hanford Reach #13        RIVER          329.4324.0 450.  0.0  0.0
R22.L2    1    2    0    1    2
R22.L3    94.4921    0.5597 1585.1760    0.1194
R22.L4 Tributary Inflow
R22.L5 Snake River      12  sna    324.0   109000.
R22.L6 End of Segment #41

R23.L1 Bonneville Reservoir     RSRVR          165.7145.5  82.  0.0  0.0
R23.L2    7    4    0    0    0
R23.L3    285538.    9072.      20.2   Volume (acre-feet) and Area (acres) in Seg 2
R23.L4 End of Segment #56
*************** SECTION 3 - WEATHER STATION FILES AND EVAPORATION COEFFICIENTS ***************
R30.L1 wnatchee.hot                   1.55e-9
R30.L1 yakima.hot                     1.40e-9
R30.L1 lewiston.hot                   1.45e-9
R30.L1 richland.hot                   1.10e-9
```

Figure 4-1. Example control file.

Line 5   comment line

Line 6   number of reaches
> *This is the number of river reaches that are being modeled. In this model there are three river reaches (Clearwater River, Snake River, and Columbia River).*

Section 2 (Reach Information)

Record 20 (Reach Description)

Line 1   reach name, number of segments in reach, number of plots to be sent to output file

Line 2   location of plots with respect to River Mile

Record 21 (River Segment with no tributary inflow)

Line 1   segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2   number of computational elements per segmentation, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated
> *There can be a maximum of 600 computational elements per reach. The reach number of the tributary in this case (no tributary inflow) should be zero.*

Line 3   a area, b area, a width, b width
> *These are the hydraulic coefficients determined for each reach.*

Line 4   end of record

Record 22 (River Segment with tributary inflow)

Line 1   segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation

Line 2   number of computational elements per segment, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated
> *There can be a maximum of 600 computational elements per reach. The tributary numbering system is tricky, particularly if the tributary is one that is being simulated. The number appearing on this line is the REACH NUMBER of the tributary, while the number appearing on line 5 below is the ORDINAL NUMBER for the tributary. As an example, the Snake River (REACH 2) is a tributary to the Columbia and is the 12th tributary in the order of tributaries. Therefore, to specify the Snake as a tributary, one would enter a "2" on line 2, and a "12" on line 5, below. The order in which simulated tributaries occur is also important. The main requirement is that tributaries must be simulated before the reach to which they are tributary is simulated.*

Line 3   a area, b area, a width, b width
> *These are the hydraulic coefficients determined for each reach.*

Line 4   comment line

| Line 5 | tributary name, designated tributary number (ordinal number), abbreviated tributary name, river mile at which tributary connects to main segment, square miles of the watershed associated with the tributary |
| | *The square miles of the watershed associated with the tributary is not used in the program at this point.* |

| Line 6 | end of record |

Record 23 (Reservoir Segment with no tributary inflow)

| Line 1 | segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation |

| Line 2 | number of computational elements per segmentation, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated |
| | *There can be a maximum of 600 computational elements per reach. The reach number of the tributary in this case (no tributary inflow) should be zero.* |

| Line 3 | reservoir volume, reservoir area, delta x |

| Line 4 | end of record |

Record 24 (Reservoir Segment with tributary inflow)

| Line 1 | segment name, segment type, beginning mile location of segment, ending mile location of segment, elevation |

| Line 2 | number of computational elements per segment, weather file to be used, headwaters number, number of entering tributaries, reach number if the tributary is one for which temperatures are simulated |
| | *There can be a maximum of 600 computational elements per reach. The tributary numbering system is tricky, particularly if the tributary is one that is being simulated. The number appearing on this line is the REACH NUMBER of the tributary, while the number appearing on line 5 below is the ORDINAL NUMBER for the tributary. As an example, the Snake River (REACH 2) is a tributary to the Columbia and is the 12th tributary in the order of tributaries. Therefore, to specify the Snake as a tributary, one would enter a "2" on line 2, and a "12" on line 5, below. The order in which simulated tributaries occur is also important. The main requirement is that tributaries must be simulated before the reach to which they are tributary is simulated.* |

| Line 3 | reservoir volume, reservoir area, delta x |

| Line 4 | comment line |

| Line 5 | tributary name, designated tributary number (ordinal number), abbreviated tributary name, river mile at which tributary connects to main segment, square miles of the watershed associated with the tributary |
| | *The square mileage of the watershed associated with the tributary is not used in the program at this point.* |

| Line 6 | end of record |

Section 3 (Weather Station (Meteorological) File Names)

Record 30 (Weather Station File Name Information)

Line 1   weather station file name, evaporation coefficient

Advected Source File

An example of an advected source file is shown in Figure 4-2.

Section 4 (Input File Information for Advected Source File)

Record 40 (Input File Information for Advected Source File)

Line 1   model start date, model end date

Record 41 (Advected Source Data for Each Julian Day)

Line 1   year, Julian day, flow for Clearwater River (cfs), water temperature for Clearwater River (deg-C), flow for Snake River (cfs), water temperature for Snake River (deg-C), flow for Columbia River (cfs), water temperature for Columbia River (deg-C)

Line 2   NF of Clearwater River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 3   Potlatch Corp: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 4   Tucannon River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 5   Palouse River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 6   Okanogan River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 7   Methow River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 8   Chelan River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 9   Wenatchee River: Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

```
*************** INPUT FILE - CRTASS.ADV - FOR RBM10 ************
*** SECTION 4 – INPUT FILE INFORMATION FOR ADVECTED SOURCE DATA ***
  19750101  19951231
 1975    1    1150.     6.6    24000.     3.9    95300.     6.2
    1   2890.0  6.6
    3     62.2 33.0
    4    138.0  3.4
    5    174.0  4.2
    6    894.0  2.0
    7    320.0  2.5
    8   2190.0  2.6
    9   1250.0  6.4
   10     30.0  3.2
   11   2860.0  4.1
   13    494.0  4.3
   14    451.0  4.8
   15   6560.0  4.6
 1975    2    1140.     5.6    23000.     3.6    94700.     5.7
    1   4990.0  5.6
    3     62.2 33.0
    4    136.0  3.5
    5    167.0  3.9
    6    866.0  1.9
    7    330.0  2.3
    8   2180.0  2.6
    9   1180.0  5.3
   10     29.0  3.3
   11   2750.0  3.9
   13    482.0  4.1
   14    416.0  4.6
   15   6560.0  4.6
 1975    3    1430.     4.8    25000.     3.3    93000.     5.3
    1   7090.0  4.8
    3     62.2 33.0
    4    136.0  3.5
    5    172.0  3.7
    6    793.0  1.8
    7    330.0  2.1
    8   2180.0  2.6
    9   1160.0  4.5
   10     28.0  3.4
   11   2700.0  3.7
   13    462.0  3.9
   14    451.0  4.5
   15   6490.0  4.5
 1975    4    1500.     4.2    26800.     3.3   104000.     5.5
    1   7070.0  4.2
    3     62.2 33.0
    4    167.0  3.6
    5    282.0  3.5
    6    932.0  1.7
    7    340.0  2.0
    8   2180.0  2.6
    9   1160.0  3.8
   10     30.0  3.5
   11   2730.0  3.6
   13    482.0  3.7
   14    375.0  4.4
   15   6560.0  4.5
```

Figure 4-2. Example advected source file.

Line 10	Crab Creek:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 11	Yakima River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 12	Walla Walla:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)
Line 13	John Day River:	Ordinal number of tributary, flow (cfs), water temperature (degrees Celsius)

Line 14   Deschutes River: Ordinal number of tributary, flow (cfs),
water temperature (degrees Celsius)

Meteorological File

An example of a meteorological file is shown in Figure 4-3.

```
********** YAKIMA WEATHER DATA FROM HOURLY MEAN WDM DATA **********
***** SECTION 5 – INPUT FILE INFORMATION FOR METEOROLOGICAL FILE *****
YAKIMA AIR TERMINAL
        1      2000.       47.      121.  19750101  19951231
    1   0.01556   0.05185   1.16667   2.90580   0.65531   4.62069   0.05000
    2   0.00917   0.04683  -3.38889   2.14582   0.65250   3.87065   0.05000
    3   0.01056   0.05717   1.38889   2.32464   0.65545   5.06278   0.05000
    4   0.01472   0.05598   1.11111   4.20223   0.65527   4.89787   0.05000
    5   0.01500   0.05373   1.38889   3.48695   0.65545   5.77268   0.05000
    6   0.01444   0.05612   1.11111   2.63757   0.65527   4.85739   0.05000
    7   0.01000   0.05278  -2.83333   2.19052   0.65284   4.23095   0.05000
    8   0.01194   0.05350   1.27778   5.72218   0.65538   4.50621   0.05000
    9   0.01000   0.05152  -3.33333   3.21873   0.65253   3.47740   0.05000
   10   0.01833   0.04228  -7.94444   2.59286   0.64971   2.80806   0.05000
   11   0.00972   0.04945  -7.00000   2.54816   0.65029   2.74667   0.05000
   12   0.01194   0.04960  -6.61111   2.14582   0.65052   2.82048   0.05000
   13   0.01000   0.05516  -2.11111   1.29643   0.65328   4.41275   0.05000
   14   0.00972   0.05800   0.16667   0.89409   0.65469   5.54193   0.05000
   15   0.01278   0.06001   1.72222   2.10111   0.65565   5.29756   0.05000
   16   0.01194   0.05885   0.83333   0.75998   0.65510   5.34127   0.05000
   17   0.01222   0.05940   1.38889   2.32464   0.65545   5.89121   0.05000
   18   0.01944   0.05614   5.77778   3.48695   0.65818   7.05872   0.05000
   19   0.01306   0.05137  -0.33333   2.14582   0.65438   5.04190   0.05000
   20   0.01889   0.05849   6.66667   3.53166   0.65873   5.04190   0.05000
   21   0.01917   0.04951  -1.11111   2.27993   0.65390   4.05583   0.05000
   22   0.01000   0.05606  -0.11111   2.01170   0.65452   4.97972   0.05000
   23   0.01111   0.05710   1.44444   1.78818   0.65548   5.61028   0.05000
   24   0.00944   0.05991   2.55556   1.87759   0.65617   6.23463   0.05000
   25   0.01167   0.05907   1.00000   1.34114   0.65520   6.18451   0.05000
   26   0.02111   0.05234   0.11111   1.92230   0.65465   4.54409   0.05000
   27   0.02306   0.04568  -4.16667   3.08461   0.65202   3.17492   0.05000
   28   0.01528   0.05235  -3.94444   1.56466   0.65216   3.61468   0.05000
   29   0.01500   0.04988  -4.77778   2.19052   0.65165   3.38847   0.05000
   30   0.01306   0.05191  -4.83333   3.17402   0.65161   3.40315   0.05000
   31   0.01444   0.05375  -3.27778   2.95050   0.65257   3.53783   0.05000
   32   0.01389   0.05646  -1.05556   2.59286   0.65393   4.64001   0.05000
   33   0.01389   0.05536  -1.94444   1.92230   0.65339   4.23095   0.05000
   34   0.01389   0.05835   0.44444   1.87759   0.65486   5.14707   0.05000
   35   0.01500   0.05561  -0.72222   4.78339   0.65414   4.28478   0.05000
   36   0.01528   0.05304  -2.61111   4.96220   0.65298   3.16112   0.05000
   37   0.01639   0.05381  -3.22222   3.08461   0.65260   3.49242   0.05000
   38   0.02222   0.05130  -4.11111   1.56466   0.65205   3.56839   0.05000
   39   0.01639   0.05296  -3.94444   2.72698   0.65216   2.69842   0.05000
   40   0.02389   0.04909  -5.61111   2.50345   0.65114   3.16112   0.05000
   41   0.02833   0.04934  -1.72222   2.86109   0.65352   3.55308   0.05000
   42   0.01944   0.06050   4.22222   3.79989   0.65721   5.40743   0.05000
   43   0.01556   0.06309   6.16667   5.81159   0.65842   7.31533   0.05000
   44   0.02250   0.05747   4.22222   3.08461   0.65721   5.79621   0.05000
   45   0.02944   0.05142   1.61111   4.24693   0.65558   3.98760   0.05000
   46   0.01556   0.05005  -3.22222   2.50345   0.65260   3.70885   0.05000
   47   0.03194   0.04922  -0.72222   2.59286   0.65414   3.92039   0.05000
   48   0.02750   0.05098   0.27778   2.63757   0.65476   4.19540   0.05000
   49   0.01472   0.05966   1.72222   1.38584   0.65565   5.12588   0.05000
   50   0.01472   0.05984   3.00000   3.17402   0.65645   6.46463   0.05000
   51   0.02694   0.05153   1.33333   6.39275   0.65541   3.72475   0.05000
   52   0.03306   0.05173   1.16667   3.57636   0.65531   3.25886   0.05000
   53   0.02472   0.05581   2.22222   2.41405   0.65596   4.64001   0.05000
   54   0.02861   0.05922   3.00000   2.63757   0.65645   5.27583   0.05000
   55   0.03639   0.05435   4.27778   2.81639   0.65724   5.21110   0.05000
```

Figure 4-3. Example Meteorological File.

Section 5 (Input File Information for Meteorological File)

Record 50 (Input File Information for Meteorological File)

Line 1   weather station name

Line 2   nwpd, elevation of weather station, latitude of weather station, longitude of weather station, start date of weather station data, end date of weather station data

Record 51 (Weather Data for Each Day)

Line 1   Julian day, net solar radiation, Net atmospheric radiation, dry bulb temperature, wind speed, factor for Bowen ratio, vapor pressure at given air temperature, photo period
                         Photo period is not used in this model.

4.2   OUTPUT FILES

An output file will be generated for each reach in the model. The number of output files is therefore specified in Record 10, Line 6. Data in the output file consist of daily average temperature and the standard deviation at each specified location. The number of sections within a reach to output data is located in Record 20, Line 1. The location of the output data, in river mile, is indicated in Record 20, Line 2. All output files contain the same format. An example of an output file is shown in Figure 4-4.

Column 1 of the output file is the decimal date out to three digits. The output from each station is then listed as three columns with the first column being the segment number, the second column being the standard deviation of the temperature in Deg C, and the third column being the absolute temperature in Deg C.

```
********** SAMPLE OUTPUT DATA FILE **********
1975.004     3      0    0.007    14      0    0.007    24      0    0.007
1975.006     3    5.3    0.031    14    5.1     0.13    24    4.9    0.227
1975.009     3    4.6    0.028    14    4.5    0.092    24    4.3    0.147
1975.012     3    4.2    0.028    14    4.1    0.095    24      4    0.154
1975.015     3    3.8    0.031    14    3.8    0.103    24    3.7    0.174
1975.017     3    3.4    0.084    14    3.3    0.132    24    3.3    0.229
1975.020     3    2.9    0.083    14    2.8    0.129    24    2.8    0.225
1975.023     3    2.7    0.028    14    2.6    0.098    24    2.6    0.161
1975.026     3      2    0.069    14    1.8    0.113    24    1.7    0.193
1975.028     3    1.8    0.125    14    1.7    0.136    24    1.6    0.239
1975.031     3    1.6    0.147    14    1.3    0.142    24      1    0.252
1975.034     3    1.5    0.166    14    1.2    0.096    24      1    0.136
1975.037     3    1.7    0.028    14    1.7    0.096    24    1.7    0.159
1975.039     3    1.6    0.182    14    1.7    0.162    24    1.7    0.295
1975.042     3    1.5     0.34    14    1.5     0.23    24    1.5    0.425
1975.045     3    1.5    0.301    14    1.5     0.19    24    1.5    0.339
1975.048     3    2.4    0.222    14    2.5    0.151    24    2.6    0.264
1975.050     3    3.9      0.1    14      4    0.112    24    4.1    0.186
1975.053     3    2.3    0.468    14    2.2    0.226    24    2.2    0.388
1975.056     3    2.8    0.313    14    2.8    0.162    24    2.8     0.27
1975.059     3    1.5    0.335    14    1.5    0.182    24    1.5    0.309
1975.061     3    2.1    0.133    14    2.1    0.113    24    2.1    0.184
1975.064     3      3    0.156    14      3    0.125    24      3    0.205
1975.067     3    2.1    0.372    14    2.1    0.222    24    2.2    0.386
1975.069     3    1.7    0.482    14    1.7    0.329    24    1.7    0.576
1975.072     3    0.6    0.144    14    0.6    0.116    24    0.7    0.188
1975.075     3    1.2    0.428    14    1.2     0.24    24    1.2    0.417
1975.078     3    1.3    0.425    14    1.3    0.247    24    1.2    0.446
1975.080     3    1.2    0.323    14    1.2     0.18    24    1.2    0.319
1975.083     3      1    0.152    14    0.7    0.128    24    0.5     0.22
1975.086     3      1    0.124    14    0.7     0.12    24    0.5    0.206
1975.089     3    1.4    0.104    14    1.4     0.12    24    1.4    0.207
1975.091     3    1.3     0.28    14    1.3    0.188    24    1.3     0.34
1975.094     3    1.2    0.372    14    1.2    0.205    24    1.2    0.371
1975.097     3      1    0.229    14      1    0.154    24      1    0.271
 1975.1      3    0.9     0.22    14    0.8     0.16    24    0.8    0.284
1975.102     3    0.9    0.207    14    0.7     0.16    24    0.6    0.285
1975.105     3    0.9    0.133    14    0.7    0.136    24    0.6    0.238
1975.108     3    0.9    0.302    14    0.8    0.199    24    0.8    0.363
1975.111     3    0.9    0.199    14    0.7    0.154    24    0.6    0.273
1975.113     3    1.1    0.192    14    1.1    0.164    24    1.1    0.294
1975.116     3    1.4    0.043    14    1.5    0.105    24    1.5    0.177
1975.119     3    1.6    0.169    14    1.7    0.145    24    1.8    0.255
1975.121     3    1.7    0.183    14    1.8    0.148    24    1.9    0.262
1975.124     3    1.6    0.189    14    1.6    0.157    24    1.7    0.278
1975.127     3    1.4    0.161    14    1.4    0.147    24    1.4    0.259
1975.130     3    1.4    0.167    14    1.4     0.15    24    1.4    0.264
1975.132     3    1.5    0.252    14    1.5    0.216    24    1.5    0.393
1975.135     3    1.5    0.144    14    1.5    0.145    24    1.5    0.256
1975.138     3    1.7      0.1    14    1.8    0.125    24    1.8    0.217
1975.141     3    1.4    0.027    14    1.4    0.099    24    1.3    0.164
1975.143     3    1.7    0.175    14    1.7    0.151    24    1.7    0.268
1975.146     3    1.7    0.097    14    1.7    0.125    24    1.7    0.218
1975.149     3      2    0.036    14    2.1    0.105    24    2.2    0.177
1975.152     3    2.4    0.133    14    2.5    0.128    24    2.6    0.223
1975.154     3    2.2    0.209    14    2.2    0.175    24    2.3    0.315
1975.157     3      2    0.157    14      2    0.152    24      2    0.268
1975.160     3    2.4    0.124    14    2.5    0.132    24    2.5    0.231
```

Figure 4-4. Example output file.

CHAPTER 5: STUDY SUMMARY AND CONCLUSIONS

The results of the analysis lead to the following conclusions:

- Structural changes in Columbia River downstream from Grand Coulee Dam and in the Snake River from its confluence with the Grande Ronde River to its confluence with the Columbia River near Pasco, Washington, cause an increase in mean frequency of water temperature excursions above a daily average water temperature of 20 $^{\circ}$C. The structural changes are a result of the construction and operation of hydroelectric facilities on the Columbia and Snake rivers in the study area. This conclusion is based on a comparison of the mean frequency of temperature excursions for the system as presently configured and for the same system in the unimpounded condition. The unimpounded condition assumes there are no dams on the Columbia River below Grand Coulee and no dams on the Snake River below Lewiston, Idaho. The uncertainty in these estimates is approximately of the order of the estimated differences in the results, however. Improving both the systems and measurements models could reduce uncertainty. Actions could include improving the quality of water temperature observations, increasing the spatial coverage of required meteorological data, and studying the seasonal variations in certain terms of the heat budget, particularly the evaporation rate. The reduction in uncertainty would not affect the basic result that structural differences in the system due to the construction and operation of hydroelectric facilities have a greater impact on the temperature regime than does the thermal input from all of the major tributaries other than the Clearwater River.

- Most advected sources, including tributaries, groundwater and point sources, contribute a relatively small amount of advected thermal energy to of the main stem Columbia and Snake rivers in the study area. Their impact on the cross-sectional daily average water temperature is limited. The exceptions are the impact of the Clearwater River on the cross-sectional daily average water temperature of the Snake River and that of the Snake River on the cross-sectional daily average water temperature of the Columbia River.

- The objective of the analysis was to assess the relative impact of dams and tributaries on the temperature regime of the Columbia and Snake rivers. The impact of upstream inputs was limited to the characterization of initial temperature conditions at Grand Coulee Dam on the Columbia River and River Mile 168 on the Snake River. However, upstream inputs have an important role in the temperature regime of both rivers. In the Columbia River, construction of Canadian impoundments and the operation of Grand Coulee Dam affect the temperature of the Columbia River at Grand Coulee Dam, although the frequency of excursions are small at this location. For the Snake River, initial conditions near Anatone, Washington, are such that the mean frequency of temperature excursions is approximately 0.15. This is due to structural changes to the natural river upstream from Anatone, and to the river's exposure to high temperatures as it crosses the Snake River Plain. A larger geographical scope is needed to assess the impacts of water management in both the Columbia and Snake rivers.

Topics for Further Study

The results of this assessment lead to the conclusion that the construction and operation of dams on the Columbia River downstream from Grand Coulee Dam and on the Snake River downstream from Lewiston, Idaho, have a greater impact on the thermal regime of these rivers than do the thermal inputs form most of the tributaries. However, in the case of the Snake River, the significance of this conclusion is reduced by uncertainty in the mathematical model. Use of the model as a decision-making tool would require additional efforts to reduce this uncertainty. Elements of the model where reduction in uncertainty would be of benefit include the following:

- Heat budget – The choice of meteorological stations to characterize the energy budget was done subjectively, to achieve good (in a qualitative sense) agreement between simulated values and observations. The analysis would benefit from additional studies of the effect of local climatology, particularly wind speed.

- River hydraulics – Particle displacement speeds and system geometry were based on the assumption that gradually varied, steady-state flow methods were appropriate. This assumption is reasonable for the scenarios for which the dams are in place and less so for the river without dams. The uncertainties associated with rapidly changing flows are likely to be greatest during the spring and early summer snowmelt periods. It is less likely they will be important during the critical late summer and early fall periods when flows are low and reasonably steady.

- Initial water temperatures – Initial conditions for water temperature of both main stem and tributaries were estimated by synthesizing a record with data from various sources. The error introduced as a result is greatest for the main stem temperatures, since the results of the analysis show that the tributaries have little impact on the average temperatures of the Columbia and Snake rivers. The error introduced in the main strem estimates will decrease in the downstream direction.

- Filter – The estimation of the systems model error is based on the assumption the filter is optimal. The filter is optimal if the innovations sequence is a zero mean, Gaussian white noise process. Tests for optimality of the filter have been described by Mehra (1970). These tests were not performed on the water temperature innovations sequence due to the number of missing data points, but a visual inspection of the 30-day averages of the innovations sequence suggest the results are autocorrelated. This correction could be a result of structural errors in the model, as described above, or could be related to observation bias and error reported by McKenzie and Laenen (1998).

- Water temperature data – The water temperature monitoring program on the Columbia and Snake rivers has produced a large volume of data; however, the quality of the data is sometimes questionable. The analysis of water temperature issues on the Columbia and Snake rivers would benefit greatly from a comprehensive plan for measuring water temperatures.

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