WATER TEMPERATURE MODELING AND DATA COLLECTION PLAN FOR LOWER SNAKE RIVER BASIN

(BI-OP MEASURE 143)

FINAL REPORT, October 9, 2003

Prepared by
RPA 143 Workgroup

EXECUTIVE SUMMARY

1. General

The National Marine Fisheries Service (NOAA Fisheries) issued a Biological Opinion (BiOp) dated December 21, 2000, entitled "Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin." (NOAA Fisheries, 2000)

One of the measures identified within the BiOp was Reasonable and Prudent Alternative action number 143 (RPA 143). This measure states, "The Action Agencies shall develop and coordinate with NOAA Fisheries and EPA on a plan to model the water temperature effects of alternative Snake River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NOAA Fisheries and state and tribal water-quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations."

Since 1991, Dworshak Dam has been releasing cold water to help achieve two objectives: to cool the Snake River, and to increase velocities in the reservoirs to aid Chinook juveniles migrating to the ocean. Releases by the Dworshak Dam were first conducted on an experimental basis; in the last few years they have been part of the operational program. Biological goals of many agencies are to optimize the Snake River/Dworshak operations in an attempt to provide desirable temperature regimens (within existing authorities and other limitations) for both anadromous and resident fish. Sufficient information about the Snake River temperature, and how fish respond to flows and temperatures, is required in order to create a thermal environment that is as supportive of fish as possible.

Management of the Lower Snake River for fish involves more than observing and adjusting temperatures; it also involves managing discharges from all sources. This necessitates a cooperative relationship between Idaho Power Company, managers of the Hells Canyon Complex, and federal managers of the Lower Snake River projects, both for temperature and discharge.

To address this RPA measure in a cooperative manner , the Regional Water Quality team established a technical workgroup to develop the plan called for by the action item. The team is composed of numerous agencies, including the Bonneville Power Administration (BPA), Columbia River Inter-Tribal Fish Commission (CRITFC), Environmental Protection Administration (EPA), Idaho Power Company (IDPWR), Idaho Department of Environmental Quality (IDEQ), Idaho Water Resources Department (IDWRD), Nez Perce Nation, NOAA Fisheries, Oregon Department of Environmental Quality (ODEQ), Fish Passage Center, US Army Corps of Engineers (USACE) and Washington Department of Ecology (WDOE). The workgroup first met March 8, 2002. This document presents the executive summary of the plan developed by the technical workgroup.

2. Geographic Domain

The full Bi-Op language for RPA 143 actually calls for modeling more than the Snake River (also includes the lower Columbia River to Bonneville Dam) but it specifically identifies examining alternative Snake River operations as the first step.

The workgroup proposes to build an initial model domain for the minimum area needed for effective evaluation of operational effects on temperature (Phase 1) and expand the model in subsequent phases. The proposed phases are as follows:

Phase	North Fork Clearwater Boundary	Mainstem Clearwater Boundary	Upstream Snake River Boundary	Downstream Snake River Boundary
1	Mouth	Orofino	Anatone (RM 169)	Lower Granite Dam
2	Dworshak Reservoir Head	Orofino	Hells Canyon Dam Tailrace	Mouth
3	Dworshak Reservoir Head	Orofino	Brownlee Reservoir Head	Mouth

The first phase includes the minimum system components needed to develop and evaluate an operational tool for temperature management (Dworshak flow augmentation). The second phase expands the model system to include Dworshak Reservoir, Salmon/Grande Ronde Rivers, and the lower three projects on the Snake River. The third phase expands the system to include the Hells Canyon Complex on the Snake River, in cooperation with Idaho Power Company. The second and third phases extend the model to two reservoirs, Dworshak and Brownlee, both of which influence the temperature of the Snake River. While Dworshak Reservoir has not been extensively modeled to date, Idaho Power Company has developed a CE-QUAL-W2 model for Brownlee Reservoir (Idaho Power, 1999) that should provide information for Phase 3.

The proposed timeline for development and expansion of the model domain is a general estimate of the minimum time necessary to complete this work, assuming consistent and adequate resources for this project. This timeline could be delayed by a number of factors, including resource constraints, inter-agency coordination delays, and model development and evaluation challenges.

3. Biological Needs

An assessment was made of various stages of the life cycle of ESA-listed anadromous salmonids in the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River, and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River.

Spring and summer steelhead and Chinook salmon smolts, migrating mostly as yearlings, migrate sufficiently early that water temperature does not pose a direct risk to the bulk of the run. Moderately strong correlative evidence has been developed that demonstrates that flow augmentation to reduce water temperatures can increase survival of juvenile fall Chinook salmon in the lower Snake River system. Survival models demonstrate the importance of temperature either directly affecting survival or indirectly by affecting migration dates and body size, factors found to be highly associated with water temperature. Additional studies should be conducted to more fully evaluate current survival models and more fully evaluate the role in improving survival of juvenile fall Chinook salmon. At present, however, the available literature strongly supports use of flow augmentation with its attendant cooler water temperature to benefit downstream migrating fall Chinook salmon.

For adults, fall Chinook salmon and steelhead have the greatest potential exposure to warm water temperatures. However, since fall Chinook salmon are obligate migrants, and because the predominant pattern is for warm water conditions to persist later in the fall than historically occurred, fall Chinook salmon adults would appear to be at greater risk for incurring potential temperature related impacts while migrating through the lower Snake River. This conclusion is supported by analyses of telemetry data for adult fall Chinook salmon and steelhead migrating through the lower Columbia River. Although members from both runs enter tributary streams during summer, steelhead that use the cool-water refugia realized a survival advantage, while fall Chinook salmon that delay their migration to use the same refugia experience reduced escapement to spawning areas. Historically, use of cool water refugia incurred an evolutionarily derived survival advantage to both species, but under current temperature conditions, extended delays to adult fall Chinook salmon migrants represent a survival risk. Sockeye salmon pose a particular concern with respect to water temperatures. Although the bulk of the sockeye salmon pass though the lower Snake River prior to peak temperatures, their lower perceived tolerance to warm water conditions, relative to Chinook salmon and steelhead, and the remnant size of the Snake River run, place adult sockeye salmon in a precarious position. An extreme weather year, with early warming of the river in later spring, could significantly affect the reproductive success for sockeye salmon. Late summer timing of flow augmentation would benefit adult fall Chinook salmon and adult steelhead once in Lower Granite Reservoir. Effects of the releases from Dworshak Reservoir at the end of summer (late August–mid September) should be investigated to facilitate natural cooling patterns for the lower river.

4. Data Collection and Modeling Uses

The team believed that the best approach in meeting the Bi-Op requirements was to first fully understand how data collection and modeling might be used. To this end, the team identified numerous questions that an appropriate model and associated data collection activity may be called upon to answer. These questions then formed the basis for developing model selection criteria and a data collection strategy. After developing these questions, the team realized that the available Snake River environmental information was insufficient to fully resolve them. Hence, in 2002 the team began to review existing information and ongoing studies (by others) in the geographic domain of interest to better understand the river environment. As a result of this effort the team identified and coordinated with several entities to assemble data for better definition of the river's thermal environment. The ongoing studies are briefly described below:

- The Idaho Department of Environmental Quality (DEQ) was collecting continuous water temperature data at four sites in the Clearwater and Snake Rivers. Idaho DEQ also collected similar data on the Salmon River and at other points on the Snake River.

- The Idaho Power Company was collecting water temperature data at five sites in the Snake River from upstream of Brownlee Dam to downstream of Hells Canyon Dam.

- The University of Idaho was conducting a biological study and was collecting hourly water temperatures at three depths. Their data collection sites were at the interface of Lower Granite Pool in the Snake and Clearwater Rivers, at multiple points in Lower Granite Pool and at a site in each of the other pools in the Lower Snake River.

- Battelle and the United States Geological Survey (USGS), Biological Resources Division, were collecting water temperature data from several sites in the backwater from Lower Granite Dam. In addition to continuous water temperature at multiple depths, they also collected data on discharge and instantaneous water temperatures and specific conductance. These data collection efforts were part of two ongoing projects funded through BPA.

- Since 1994 the USACE has routinely operated tailwater and forebay fixed monitoring (FMS) water quality stations to address potential Lower Columbia and Lower Snake Rivers hydropower project impacts on total dissolved gas (TDG) pressures in the water. These instruments monitor TDG and water temperature hourly. Generally the forebay instrument is located well downstream and in the forebay of the receiving pool project. The forebay monitors are intended to represent a mixed cross section in the river just upstream of the dam and can be a fair approximation of aquatic habitat as defined by TDG and water temperature in that area of the pool during non-stratified times. The tailwater instruments are located nearer to the releasing project and generally in spillway releases downstream of aerated flow and prior to complete mixing with powerhouse releases. Additional sites are located on the Clearwater River and Snake River upstream of the Clearwater River. Each of these sites collects hourly data; these data are transmitted to Portland every four hours and placed on the USACE web site.

- Based on these ongoing studies during 2002, the team determined that additional data collection would be necessary to obtain a more complete picture of the river's thermal environment. To augment the data collection, the USACE, Walla Walla District funded the USACE, Engineer Research and Development Center (ERDC) to collect supplemental field temperature data in Snake River segments not being monitored by others. ERDC installed several thermistor strings in mainstem project forebays, at tailwater sites, in tributaries and near existing river gages in the Snake River and Dworshak Dam. In addition, BPA funded the United States Bureau of Reclamation (USBOR) to install weather stations (AgriMet system) along the river to collect real-time weather. Data from all entities was collected by ERDC, analyzed and presented to the team.

The forebay thermistor data demonstrate that the Lower Snake River can experience a high degree of vertical stratification. With this understood, then the multiple dimensional properties of the Lower Snake River must be taken into account when modeling is required. If the purpose is to describe or quantify habitat and potentially relate to biological communities as with RPA 143, then a 2-dimensional approach is called for to provide adequate resolution in the entire Lower Snake River. If the purpose is to forecast cross-sectional average temperatures at some point downstream, then a less rigorous 1-dimensional approach can be applied to address much of the Lower Snake River. The exception is likely in Lower Granite pool, which experiences some of the more extreme variability in thermal patterns.

Collectively, the data collection efforts of 2002 will provide a valuable dataset for future model development and testing, and a similar data collection effort is planned for 2003. A long-term monitoring strategy is discussed below.

5. Model Review and Selection

The Lower Snake River has been studied for many years. These studies have included the application of several models, which have been constructed by various agencies and organizations for various specific objectives. Selection of the model for this assessment has several criteria. The basis for the criteria is from the team's understanding of the questions that need to be addressed and a conceptual understanding of how the river functions after evaluating existing data, models and reports of the Lower Snake River. These criteria are listed below:

- The model will have at least 2-D resolution (horizontal down the length of the river plus vertical; laterally averaged);
- The model is non-proprietary and any organization or agency can obtain the code for the model and run simulations;
- The model has previously been used in similar applications including river and reservoir conditions;
- The model will take into account the release of water from Dworshak Reservoir using selective withdrawal as well as outlet structures at dams;
- The model is documented, currently maintained and is expected to be in use for the next few years;
- The computer run time should be fast enough to be usable as an operation tool;
- The model should have the capability of being expanded geographically and be able to simulate other water-quality parameters besides temperature.

It is desirable but not a selection criterion that people in the Pacific Northwest have experience with the model. There were nine different models considered for the Lower Snake River temperature modeling effort. The team recommends the two-dimensional model, CE-QUAL-W2, version 3.1, developed and maintained by USACE, be adopted for use in the Lower Snake River. It will be used to assess reservoir releases at selected depths, flow routing, simulations of water temperature and has the capability of addressing other water-quality parameters such as dissolved oxygen, algal populations and nutrients. This model meets all the criteria identified for this assessment. In addition, numerous persons in the Pacific Northwest are knowledgeable about the use of the model.

6. Model Development Framework and Issues

Successful model development requires a clear progression of thought leading from the questions that are posed, to a conceptual model of the system based on theoretical understanding and site data, to application of the most appropriate model scenarios and tools, to an uncertainty analysis, and finally to an answer to the question posed with acknowledgment of the data gaps and model limitations. Modeling tasks must also be undertaken with an acknowledgment of the intrinsic iterative nature of modeling which commonly points out the need for additional site data or model scenarios.

In the modeling work plan for this project, all data for model input parameters and boundary conditions that need to be assembled should be identified and their method of collection described. The following items should be included in the modeling work plan.

1. The goals of the modeling should be stated in a manner that allows easy comparison to modeling results so that a determination can be made as to whether goals were achieved.

2. A site-specific conceptual model of the system should be presented in graphical form (including maps and cross-sections) based on available data. The conceptual model should include the mathematical relationships that are used to describe the principal hydrogeologic processes of concern. Data gaps, assumptions, and uncertainties should be described in the conceptual model.
3. The technical requirements needed to achieve the goals should be discussed (e.g., needed spatial/temporal resolution of the model, boundary data synthesis for dynamic simulations, etc.).
4. If computer modeling is needed, the specific computer code (and version where appropriate) should be identified. The ability and limitations of the proposed computer codes to meet the conceptual model requirements should be discussed. It is critical to match the proposed code to the site conditions and the availability of data, including good justification for the input parameters.
5. Boundary and initial conditions and other input parameters should be identified, and procedures for model calibration and uncertainty analysis should be described. Parameter estimation techniques and associated uncertainties should be identified. A plan for parameter sensitivity analysis should be outlined to compare model sensitivity with variations in boundary conditions and input parameters.
6. Model documentation should incorporate the information and address the issues identified in the main report. In addition, model documentation reports should include appendices with copies of critical model input files and a CD containing all the input files used in the model.

The workgroup has begun the model development process by identifying goals, selecting a model code (CE-QUAL-W2), and providing an outline and summary of information and issues to be addressed in model development (Section 5 of this report).

7. Data Collection Strategy

The data collection strategy is designed to support the model development (calibration, verification of data sets) and will provide ongoing data for operational use and future checks on model performance. The data collection will also provide answers to some of the questions identified by the team during the plan development process. The key elements of the strategy are identified in the following paragraphs.

The USACE tailwater monitors approximate the average forebay water temperature even during periods of significant vertical gradients. This was found to be the case for all projects on the Lower Snake River as determined in the 2002 Lower Snake River Screening Study. The average profile water column temperature was very similar to the tailwater fixed monitor temperature. No change is recommended for the Lower Snake River tailwater instruments. On the other hand, the forebay monitors were very comparable to the 5 m deep profile instruments as is expected during the stratified period but not representative of the water column average. Both stations are point measures in space but the tailwater reach is generally well mixed and made up of a fairly uniform blend of the forebay waters in the case of the Lower Snake projects. The forebay instrument is positioned at one discreet depth in an area that can experience some significant vertical thermal gradients and will be a biased measure of forebay temperature during periods of stratification.

In future applications and/or studies, especially numerical model support, the potential bias associated with the forebay temperature monitoring during stratified periods should be recognized and accounted for while conducting analysis or decision-making. To eliminate sample bias during stratified periods it would be desirable to install permanent automated profiling instrument strings to describe vertical thermal patterns associated with Lower Snake River project forebays. The recommended depths are 0.5, 1.5, 3, 5, 10 meters and then at 5 meter intervals to within 1 m of bottom. Since minimal lateral bias was indicated in the screening study, then one station located at the deepest point, preferably in the thalweg, will be adequate to get representative temperature measures of the forebay waters. This station should be located an adequate distance upstream to avoid any affects from the dam on water movement such as mixing, downwelling or upwelling.. Collection of real-time data could occur on an as-needed basis, depending on how the data would be used.

The key elements of the long-term water temperature data collection strategy are to continue water quality monitoring with the following recommendations:

- Water temperature monitoring year round at all stations in pools, releases, and at upstream boundary conditions and at the mouths of all significant tributaries
- Relocate forebay monitors upstream of project to avoid near-field effects of projects
- Initiate temperature string profiling (seven to eleven depths) capable of real-time operation in project forebays. The recommended depths are 0.5, 1.5, 3, 5, 10 meters and then at 5 meter intervals to within 1 m of bottom. A single point measure monitor would be adequate during the non-stratified winter period for most projects
- Continue with no change in tailwater water quality station operation
- Continue in-project fishway thermal data collection and analysis.

In the short term to support model development and validation, we recommend to continue through 2004 with one temperature string located at mid pool (longitudinally) in each of the Lower Snake River Projects modeled after the forebay station.

The key elements of water discharge and project operation are as follows.

- Continue close interval project operations data by project, unit, and spillway on 15 minute time interval for short term support of model development and calibration
- Continue routine USACE operations data collection for the long-term
- Record all operational data for releases and reservoir volumes at hydroelectric and water storage projects. This is particularly important at projects such as Dworshak where water is released at different levels.

The meteorological data collection should be continued for the long-term to continue support of model operation from the six following sites.

- Pasco, WA (National Weather Service)
- Lewiston, ID (National Weather Service)
- Fish Hook Park, Ice Harbor Pool (Washington State University Publing Agricultural Weather System, PAWS)
- Lake Bryan-Rice Bar, WA, near little Goose Dam (AgriMet)
- Silcott Island, WA, upstream of Lower Granite pool (AgriMet)
- Dworshak pool/Dent Acres, ID (AgriMet)

It is recommended to investigate potential gaps in coverage of bathymetry and flow field/water velocity data to meet modeling effort needs. This can best be accomplished through model sensitivity analysis directed at refining or improving output errors.

Development and maintenance of the research database should continue as needed.

- ERD - Screening Study data
- Walla Walla District - routine automated water quality
- PNNL - Lower Granite Study
- IDEQ - (Clearwater and [Middle] Snake River upstream of Anatone to Hells Canyon)
- Idaho Power Company - ([Middle] Snake River)
- USGS - (Clearwater, Snake Rivers)
- Walla Walla District - (in-project fishway thermal data)
- Walla Walla District - (project operations data, both routine and close interval)
- Weather data
- Bathymetry data
- Water velocity and flow field data

The long-term continuation of the database systems should be adequate to support the future, real-time operational use of the temperature model. The database should be part of a common mainstem temperature database and accessible from the USACE Web location for the benefit of researchers and fish or river managers.

8. Summary and Recommendations

The RPA 143 technical team recommends to the regional Water Quality Team that the CE-QUAL-W2 model be adopted for development in the river reaches of interest along with the identified data collection strategy. The team recommends 3 phases. Initially, the identified limited geographical domain would be modeled to determine model usefulness in defining the thermal effects of potential river operations. Once this step has been completed satisfactorily, then consideration of expanding the model to additional river reaches should be considered.

Agency Roles and Responsibilities:

- The USACE and BPA will be responsible for implementing the model and data collection efforts.
- The inter-agency technical team participating in this plan development will be asked to continue in a technical review role. They will review potential contractor Scopes of Work, field data collection and analysis, assist in defining the period of record for use in model evaluation and review and comment on reports produced during the development. Once the model has been reviewed and accepted, the team, in conjunction with the regional Technical Management Team (TMT) and Regional Water Quality Team (WQT), will define and identify preliminary model runs required to answer questions originally posed by the team.

9. Anticipated Scheduling.

Scheduling of this work is highly dependent on available funding. At the end of FY2003, two years of detailed data will have been gathered on the river. FY2002 data collection was a screening data set used to assist in decisions concerning model selection. The FY2003 data collection has been initiated in conformance with the data collection strategy. Beginning in FY2004 (October 2004), it is anticipated that additional data collection will commence as well as initial model development. A tentative schedule for implementation is identified below:

FY2004 Tasks

- Collect additional field data
- Select periods for model evaluation
- Complete model setup including evaluation
- Technical team review calibration and verification report.

FY2005 Tasks

- System development to operate as real-time tool for use by regional interests
- Expand to Phase 2 Geographic Scope
- Revise Data Collection as needed to support Phase 2 and other model input improvements.

FY2006 and beyond

- Expand to Phase 3 Geographic Scope
- Revise data collection as needed to support Phase 3 and other model inputs and improvements

10. Reference

NMFS, 2000, Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin: NOAA Fisheries.

Table of Contents

Executive Summary.. ii

1. Introduction.. 1
1.1 Reasonable and Prudent Alternative (RPA) Action 143............................... 1
1.2 Biological Effects of Snake River Thermal Regimes on Endangered Species in the Lower Snake River……………………………......………...... 1
1.2.1 Summary……………………………………………………….…..... 1
1.2.2 Recommendations………………………………………………….... 1
1.3 Problem Statement…………………………………………...……............. 2
1.4 Goal and Objectives………………………………………………….......... 4
1.5 Geographic Scope……………………………………………………….. 5
1.6 Coordination……………………………………………………………. 6

2. Historic and Ongoing Monitoring/Modeling... 7
2.1 Past Modeling Studies……………………………………………............... 7
2.1.1 Application of 1-D Heat Budget Models....................................... 7
2.1.2 Application of 2-D Heat Budget Models....................................... 8
2.1.3 Application of 3-D Heat Budget Model... 8
2.2 Ongoing and Current Thermal Monitoring Studies……………………… 8
2.2.1 Total Dissolved Gas Fixed Station Water Quality Monitoring on Lower Snake River ……………………………………………..... 8
2.2.2 Lower Snake River Temperature/Water Quality Studies………… 9
2.2.3 In Structure/Fishway Temperature Monitoring at Lower Snake River Projects……………………………………………….…..... 9
2.2.4 Dworshak Pool Thermal Monitoring, 2001……………………..... 9
2.2.5 Clearwater and Snake Temperature Monitoring by Idaho DEQ..... 9
2.2.6 Snake River Temperature Monitoring by Idaho Power Company.. 10
2.2.7 Tri-Level Temperature Monitoring in Lower Snake River............ 10
2.2.8 Lower Granite Pool Temperature Monitoring by PNNL and USGS. 10
2.3 Biological Monitoring.. 10
2.4 Meteorological Data... 11
2.5 Dam Operations Data... 11

3. Assessment and Application of Temperature and Related Data............... 12
3.1 Role of Temperature Monitoring Data in Addressing RPA 143 Objectives/Questions.. 12
3.2 Data Management for 2002 Monitoring.. 13
3.3 Assessment of Routine Meteorological, Hydrological and Thermal Data..... 13
3.3.1 Lower Snake River Meteorological Data for 2002......................... 13
3.3.2 Summary of Hydrologic Flow Data for the Lower Snake and Clearwater Rivers during 2002.. 16
3.3.3 Summary of Hydrologic Flow Data for the Lower Snake and Tributaries Upstream of Lower Granite Headwater During 2002.. 16

3.3.4 Routine Forebay, Tailwater and selected River Fixed Monitoring Station Data………………………………………………..… 19
3.3.5 Temporal Patterns……………………………………………... 19
3.3.6 Longitudinal Patterns………………………………………….. 23
3.3.7 Temperature Screening Study on Lower Snake River for 2001 and 2002.. 25
3.3.7.1 Spatial and Temporal Patterns for Screening Study................. 25
3.3.7.1.1 Dworshak Forebay.. 25
3.3.7.1.2 Lower Granite Forebay... 27
3.3.7.1.3 Little Goose Forebay... 28
3.3.7.1.4 Lower Monumental Forebay....................................... 29
3.3.7.1.5 Ice Harbor Forebay.. 30
3.3.7.2 Lateral Bias Evaluation of Forebay Profiles.......................... 31
3.3.7.3 Boundary Conditions for Temperature................................. 33
3.3.7.3.1 Thermal Characteristics of Snake River reach from Hells Canyon to the Confluence with the Clearwater River……... 33
3.3.7.3.2 Clearwater River Thermal Characteristics................... 36
3.3.7.3.3 Dworshak Releases and North Fork Clearwater River. 36
3.3.7.3.4 Temperature Impact on the Clearwater River............. 37
3.3.7.3.5 Temperatures and Discharges at the Confluences of Snake and Clearwater Rivers and Influence on Lower Snake River Projects... 37
3.3.7.4 In-Project/Fishway Thermal Studies..................................... 40
3.4 Response to Objectives/Questions.. 41
3.4.1 Characterization of Lower Snake River Thermal Patterns............. 41
3.4.2 Evaluation and Recommendations for Fixed Water Quality Monitoring.. 43
3.4.2.1 Representativeness.. 43
3.4.3 Recommendations for Fixed Monitor Stations.............................. 44
3.4.4 Requirements to Meet Model Resolution..................................... 45

4. Model Review and Selection.. 46
4.1 Geographic Domain.. 46
4.2 Model Selection Criteria.. 46
4.3 Review of Potential Models.. 46
4.3.1 CE-QUAL-ICM.. 47
4.3.2 CE-QUAL-W2... 47
4.3.3 COLTEMP... 47
4.3.4 EFDC.. 47
4.3.5 MASS 1... 48
4.3.6 MASS 2... 48
4.3.7 MIKE 11.. 48
4.3.8 RBM 10... 49
4.3.9 WQRRS... 49
4.4 Model Recommendation.. 49

5. Model Development... 50
5.1 Management Objectives.. 50
5.2 Conceptual Model.. 50
5.2.1 System boundaries.. 50
5.2.1.1 Geographic boundaries... 50
5.2.1.2 Important time and length scales....................................... 51
5.2.1.3 Important processes... 51
5.2.2 System characteristics 52
5.2.2.1 Model Domain: Impounded/Free-Flowing Mainstem Rivers. 52
5.2.2.2 Boundary Inflows: Upstream Mainstems and Tributaries... 52
5.2.2.3 Surface Heat Exchange... 52
5.2.3 Source characteristics... 52
5.2.3.1 Outlet Structures.. 52
5.2.3.2 Spill/Power.. 52
5.2.4 Available data sources (quality and quantity)................................. 53
5.2.4.1 Bathymetry... 53
5.2.4.2 Boundary Flows.. 53
5.2.4.3 Temperature of Boundary Inflows..................................... 54
5.2.4.4 Temperature within Impoundments................................... 54
5.2.4.5 Weather (Air Temp, Wind, Wind Direction, Dew Point Temp, Cloud Cover)... 54
5.2.5 Other Data Issues.. 54
5.2.5.1 Real-Time Data System.. 54
5.3 Choice of Technical Approach.. 55
5.3.1 Rationale for approach in context of management objectives and conceptual model... 55
5.3.2 Reliability and acceptability of methodology.................................. 55
5.3.2.1 Important assumptions.. 55
5.4 Parameter Estimation.. 56
5.5 Uncertainty/Error... 56
5.5.1 Error/uncertainty in input and boundary conditions.................... 56
5.5.1.1 River temperature... 56
5.5.1.2 Meteorology... 57
5.5.1.3 Error/uncertainty in specification of environment.............. 57
5.5.1.4 Structural errors in methodology (e.g., effects of aggregation or simplification)....................................... 57

6. Recommendations for Data Collection Strategy.. 58
6.1 Long Term Data Collection Strategy... 58
6.2 Data Collection Program in 2003-2004.. 59
6.3 In-Project/Fishway Thermal Studies... 60
6.4 Relationship between Physical Conditions and Potential New Biological Monitoring... 60
6.5 Quality Assurance Program.. 60
6.5.1 Sampling Uncertainty... 60

6.5.2 Measurement Uncertainty/Instrument Validation........................... 61
6.6 Data Management.. 61

7. Summary
7.1 Recommendations.. 62
7.2 Agency Roles and Responsibilities.. 62
7.3 Anticipated Scheduling... 62

8. References.. 63

Figures

1.1 Map of geographical area (taken from Appendix C)...................................... 5
3.1 Average daily air temperatures collected at Lower Snake River weather stations, April - November 2002... 14
3.2 Average daily wind speeds collected at Lower Snake River weather stations, April - November 2002... 15
3.3 Average daily wind peaks collected at Lower Snake River weather stations, April - November 2002... 15
3.4 Average daily flows and percent total flows from selected USGS sites along the Snake and Clearwater River, April - November 2002.................... 17
3.5 Lower Snake River project average daily flows and theoretical retention time by project and the entire lower river, April - November 2002............... 17
3.6 Average daily flows and percent total flows from stations and tributaries on the Snake River above the Lower Granite headwaters and downstream of Hells Canyon Dam... 18
3.7 Tributary contribution of flow on the Lower Snake River above Lower Granite pool as a percent of the total discharge for the simmer of 2002......... 18
3.8 Ice Harbor tailwater (IDSW) and forebay (IHR) fixed monitor temperatures with total project and spillway discharges, April - November 2002.. 20
3.9 Lower Monumental tailwater (LMNW) and forebay (LMO) fixed monitor temperatures with total project and spillway discharges, April - November 2002... 21
3.10 Little Goose tailwater (LGSW) and forebay (LGS) fixed monitoring temperatures, April – September, with total project and spillway discharges, April - November 2002... 21
3.11 Lower Granite tailwater (LGNW) and forebay (LWG)) fixed monitor temperatures with total project and spillway discharges, April - November 2002.. 22
3.12 Dworshak tailwater temperatures (DWQI) with total and spillway discharges, and Clearwater River temperatures at Orofino, ID..................... 22
3.13 Fixed monitoring water temperatures for the Snake River at Anatone, WA (ANQW) and Clearwater River at Lewiston, ID (LEWI), April – September 2002... 23
3.14 Tailwater fixed monitor temperature data for the Lower Snake River Projects, plus water temperatures for the LEWI and ANQW gages, 2002.... 24

3.15 Temperature profile time histories for Dworshak forebay station DWKFB and project discharge, June – November 2002 26
3.16 Lower Snake River project and Dworshak Dam forebay daily average temperature profiles on August 30, 2002 26
3.17 Temperature profile time histories for Lower Granite forebay station LWGP2 and project discharges, June – November 2002 27
3.18 Temperature profile time histories for Little Goose forebay station LGSFBP3 and project discharges, June – November 2002 28
3.19 Temperature profile time histories for Lower Monumental forebay station LMNFBP1 and project discharges, June – November 2002 29
3.20 Temperature profile time histories for Ice Harbor forebay station IHRFBP1 and project discharges, June – November 2002 30
3.21 Paired samples mean differences for each profile temperature string of a project forebay by month 32
3.22 Snake River water temperatures, river mile 156 to 170, June – November 2002 33
3.23 Snake River average daily water temperature for river mile 156 to 229, plus Salmon River temperatures during 2002 34
3.24 Lower Snake River average warming from RM 229 (19.1°C) to RM 156 (21.5°C), July 2002 35
3.25 Selected temperature monitoring stations on Clearwater River, June – November 2002 35
3.26 Water temperatures downstream of Dworshak Dam on the north fork of the Clearwater River and project discharges, June – November 2002 36
3.27 Temperatures and discharges at DWQI on the north fork of the Clearwater River and at Orofino and Lewiston on the Clearwater River, plus a flow-weighted temperature calculated for the Clearwater River at Lewiston, June – November 2002 37
3.28 Daily average temperatures and discharges for Clearwater River (Lewiston), Snake River (Anatone) and Lower Granite releases (LGNW) plus flow weighted daily temperatures calculated for outflows from Lower Granite project (Calculated LGNW), June – November 2002 38
3.29 Twenty-four hour running average water temperatures showing a longitudinal trend from Lewiston (LEWI) and Anatone (ANQW) downstream to each project tailwater site, June – October 2002 39
3.30 Lower Granite fishway temperatures, July – September 2002 40
3.31 Temperature profile for Lower Granite forebay (LWGFBP2) with fixed monitor and column averaged data overlaid, July 2002 43
3.32 Temperature profile for Ice Harbor forebay (IHRFBP2) with fixed monitor and column averaged data overlaid, July 2002 44

Tables

1.1 Summary of Snake River water temperatures, 1973 – 81 and 1994 2002 3
3.1 Paired samples test for each profile temperature string of a project

forebay.. 31
3.2 Average water temperature at Lower Snake project tailwaters during late June to mid August 2002.. 39
3.3 Snake River average water temperature and warming during July 2002.. 42

Appendices

A. Meeting Notes.. A 1
B. Summary of Questions.. B 1
C. Biological Effects of Snake River Thermal Regimes on Endangered
Species in the Lower Snake River.. C 1
D. Data Collection Activities in Lower Snake River Basin in 2002
Table 1. Water Temperature, Other Water-Quality and Discharge Data
from the Lower Snake River and Tributaries................................. D 1
Table 2. Water Temperatures measured in Fish Ladders in 2002............. D 6
Table 3. Locations and Types of Meteorological Data Collected in 2002. D 8
Table 4. Operations Data for Lower Snake River Dams in 2002.............. D 9

E. Lower Snake Report... E 1
F. Models Considered for the Lower Snake River Temperature
Modeling Effort.. F 1
G. Measuring Uncertainty in Thermal Recording Instruments....................... G 1

1. INTRODUCTION

1.1 Reasonable and Prudent Alternative (RPA) Action 143

The National Marine Fisheries Service (NOAA Fisheries) issued a Biological Opinion (BiOp) dated December 21, 2000, entitled "Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin." (NOAA Fisheries, 2000) One of the action items identified within the BiOp Reasonable and Prudent Alternatives was Action 143 (RPA 143). This measure states, "The Action Agencies shall develop and coordinate with NOAA Fisheries and EPA on a plan to model the water temperature effects of alternative Snake River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NOAA Fisheries and state and tribal water-quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations."

1.2 Biological Effects of Snake River Thermal Regimes on Endangered Species in the Lower Snake River

The purpose of this paper on aquatic biology, included as Appendix C, is to assess the utility of flow augmentation for ESA listed fishes, examine timing of those releases and assess benefits and liabilities to the overall lower Snake River ecosystem.

1.2.1 Summary

Numerous literature surveys have been conducted on effects of temperature on the life cycle of Pacific salmon (see McCullough 1999; Brown 1976; Schuytema 1969) and a myriad of other literature not summarized (Appendix 1 of paper). Much of this information has been obtained from controlled laboratory studies which provide a structure to evaluate effects of higher temperatures in the lower Snake River. Most of these studies have examined individual life stages to regulated temperatures and observed their responses. Few field studies have been conducted and results from these were applied to thermal conditions in the lower Snake River. Often literature sources that establish a paradigm may be based on single observations or small sample sizes.

This paper examined the various stages of the life cycle of ESA listed anadromous salmonids including smolt and adult steelhead, smolt and adult spring and summer Chinook salmon, and sockeye salmon and egg, embryo, parr, smolt, and adult fall Chinook salmon in of the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including from Dworshak Dam on the North Fork Clearwater River downstream to the Clearwater River confluence with the Snake River. Spring and summer Chinook smolts migrating mostly as yearlings and steelhead migrate sufficiently early that water temperature does not pose a direct risk. Moderately strong correlative evidence has been developed that demonstrates that flow augmentation to reduce water temperatures can increase survival of juvenile fall Chinook salmon in the lower Snake River system. Survival models demonstrate the importance of temperature either directly affecting survival or indirectly by affecting migration dates and body size, factors found to be highly associated with water temperature. Additional studies should be conducted to more fully evaluate current survival models and more fully evaluate the role in improving survival of juvenile fall Chinook salmon. At present, however, the available literature strongly supports use of flow augmentation with its attendant cooler water temperature to benefit downstream migrating fall Chinook salmon.

For adults, spring and most summer Chinook salmon have the least impact from warm water conditions in the lower Snake River, while fall Chinook salmon and steelhead have the greatest potential exposure to warm water temperatures. However, since fall Chinook salmon are obligate migrants, and because the predominate pattern is for warm water conditions to persist later in the fall than historically occurred, fall Chinook salmon adults would appear to be at greater risk for incurring potential temperature related impacts while migrating through the lower Snake River. This conclusion is supported by analyses of telemetry data for adult fall Chinook salmon and steelhead migrating through the lower Columbia River by High (2002) and Goniea (2002). They found that, although members from both runs enter tributary streams during summer, steelhead that use the cool-water refugia realized a survival advantage, while fall Chinook salmon that delay their migration to use the same refugia experience reduced escapement to spawning areas. Historically use of cool water refugia incurred an evolutionarily derived survival advantage to both species, but under current temperature conditions, extended delays to adult fall Chinook salmon migrants represent a survival risk. Sockeye salmon pose a particular concern with respect to water temperatures. Although the bulk of the sockeye salmon pass though the lower Snake River prior to peak temperatures, their lower perceived tolerance to warm water conditions, relative to Chinook salmon and steelhead, and the remnant size of the Snake River run, place adult sockeye salmon in a precarious position. An extreme weather year, with early warming of the river in later spring, could significantly affect the reproductive success for sockeye salmon.

1.3 Problem Statement

The need for a review and potential optimization of current Snake River/Dworshak operations is clear from the observed temperature conditions in the Snake River. Temperatures in the Snake River have been found to be higher than considered desirable for anadromous and resident fish, and are higher than the Washington State Standard for Temperature. Data were collected from 1973 through 1981 by the U.S. Geological Survey at River Mile 8.7 downstream of Ice Harbor Dam and by the USACE from 1994 through 2002 as part of the total dissolved gas program in the tailwater of Ice Harbor Dam. A summary of these data in Table 1.1 show that there were several days each year with the temperature above 20^{o}C, the Washington State temperature standard, and 21.1^{o}C or 70^{o}F, a temperature that is considered to be lethal to fish, (Karr et al, 1998). Also these high temperatures persist for much of the summer during every summer included in the data.

Management of the Lower Snake River for fish involves more than observing and adjusting temperatures; it also involves managing discharges from all sources. While the

Snake River at Anatone makes up the majority of water entering the Lower Snake River most of the time, during times when temperatures are critical, the flow at Anatone is often nearly equal to or less than the flow from the Clearwater River that includes the release of cold water from Dworshak Dam. Thus, there is a need for the development of a cooperative relationship between Idaho Power Company, managers of the Hells Canyon Complex, and management of the Lower Snake River, both for temperature and discharge.

Table 1.1 Summary of Snake River water temperatures, 1973 – 81 and 1994 – 2002.

Year	First day above 20°C	First day above 21.1°C	Last day above 21.1°C	Last day above 20°C	Number of days above 21.1°C	Number of days above 20°C	Maximum (in °C)	Source of data
1973	11-Jul	15-Jul	12-Sep	17-Sep	60	69	24.2	USGS
1974	26-Jul	28-Jul	7-Sep	25-Sep	42	62	24.0	USGS
1975	23-Jul	27-Jul	3-Sep	18-Sep	35	56	23.1	USGS
1976	24-Jul	31-Jul	8-Sep	12-Sep	38	54	22.0	USGS
1977	26-Jun	20-Jul	13-Sep	18-Sep	49	71	23.6	USGS
1978	23-Jul	30-Jul	6-Sep	8-Sep	27	47	22.6	USGS
1979	14-Jul	19-Jul	26-Sep	2-Oct	69	81	23.7	USGS
1980	20-Jul	26-Jul	31-Aug	17-Sep	36	59	22.2	USGS
1981	19-Jul	26-Jul	20-Sep	23-Sep	55	67	23.4	USGS
1994	10-Jul	13-Jul	1-Oct	7-Oct	65	87	23.0	USACE
1995	14-Jul	21-Jul	8-Aug	19-Sep	19	47	22.2	USACE
1996	15-Jul	24-Jul	29-Aug	1-Sep	29	48	22.3	USACE
1997	19-Jul	6-Aug	16-Aug	25-Sep	9	57	21.3	USACE
1998	11-Jul	17-Jul	17-Sep	2-Oct	60	84	23.1	USACE
1999	23-Jul	28-Jul	14-Aug	2-Sep	18	42	21.7	USACE
2000	12-Jul	28-Jul	22-Aug	4-Sep	26	55	22.5	USACE
2001	13-Jul	18-Jul	8-Sep	22-Sep	31	69	22.0	USACE
2002	18-Jul	23-Jul	17-Aug	7-Sep	26	49	21.9	USACE

EPA and the states of Idaho, Washington and Oregon are currently developing a Total Maximum Daily Load (TMDL) criterion for temperature in the Columbia and Snake mainstems. A preliminary draft of the TMDL, along with a draft Problem Assessment containing an analysis of temperature in the mainstems, was released for informal public review in November 2002 (www.epa.gov/r10earth/columbiamainstemtmdl.htm).

The TMDL is expected to establish target temperatures, based on state water quality standards, along the Snake River. While the RPA 143 workgroup was formed in response to an action under the Endangered Species Act, the water quality model envisioned by the group is expected to be an important tool for TMDL implementation in the future.

Management of the Lower Snake River for fish involves more than observing and adjusting temperatures at the mainstem dams; it also involves managing discharges from all sources. While the Snake River at Anatone makes up the majority of water entering the Lower Snake River most of the time, during times when temperatures are critical, the flow at Anatone maybe equal to or less than the flow from the Clearwater River, which includes the release of cold water from Dworshak Dam. Thus, there is a need for the development of a cooperative relationship between Idaho Power Company, managers of the Hells Canyon Complex, and other agencies which manage the Lower Snake River, both for temperature and discharge.

Since 1991, Dworshak Dam has been releasing cold water to help achieve two objectives: to cool the Snake River, and to increase velocities in the reservoirs to aid Chinook juveniles migrating to the ocean. Releases at Dworshak Dam were first done on an experimental basis; in the last few years they have been part of the operational program. Biological goals of many agencies are to optimize the Snake River/Dworshak operations in an attempt to provide desirable temperature regimens (within existing authorities and other limitations) for both anadromous and resident fish. Sufficient information about the Snake River temperatures, and how fish respond to flows and temperatures, is required in order to create a thermal environment that is as supportive of fish as possible.

In summary, public agencies, private corporations and citizens in the lower Clearwater and Snake mainstem areas are concerned about the impact of dam operations on river temperature and the resulting impacts on fish. Our understanding of the thermal dynamics of this system is limited. To date, there has been no systematic and coordinated plan for improving our understanding of the Snake River conditions through data collection and predictive modeling. The process by which dam operations are planned and reviewed can be improved with a better understanding of the thermal conditions of these rivers and the impact of various dam operations on these conditions.

1.4 Goal and Objectives

The goal of this report is to document the findings and recommendations of the RPA 143 subgroup to the Water Quality Team. The objectives of this report are as follows:

- Identify all previous modeling studies of the Lower Snake River;
- Identify ongoing temperature studies and monitoring programs that have contributed to a coordinated and effective data set describing water temperature in 2002;
- Provide a list of other monitoring programs pertaining to dam operation, meteorological conditions and biological research;
- Assess temperature data collected to date and provide an updated concept of causes-and-effects associated with water temperatures in the Lower Snake River;
- Identify temperature model selection criteria and process;

- Recommend a system of numerical temperature models to address critical questions;
- Recommend a strategy for a water-quality monitoring program that will serve for calibration and verification of the model, seasonal and short-term simulation of the model and extend understanding of how to better manage the Lower Snake River for fish;
- Identify agency roles and responsibilities associated with development and use of temperature models; and
- Identify a schedule for data collection, model implementation and review of future efforts.

1.5 Geographic Scope

The geographic scope of this report is the Lower Snake River from Hell's Canyon Dam (RM 247.0) to its confluence with the Columbia River, the inflow of tributaries such as the Imnaha, Salmon, Grand Ronde and Palouse Rivers, the North Fork Clearwater River downstream from Dworshak Dam at RM 2.0, and the Clearwater River downstream of Orofino at RM 45 (Figure 1.1). The full Bi-Op language for RPA 143 addresses modeling the lower Snake River and the lower Columbia River to Bonneville Dam; also it specifically identifies examining alternative Snake River operations as the first step. In this report, the Lower Columbia River is the reach that extends from the confluence of the Snake River to Astoria, OR and the Mid-Columbia River is the reach extending from the Canadian boarder to the Snake River confluence. The Lower Snake River is the reach from Hells Canyon Dam to the Snake River mouth. While the initial domain of this plan is limited, the team recognized that it may be desirable to expand the domain in the future and so included in the model selection and data collection strategy the criterion of expandability.

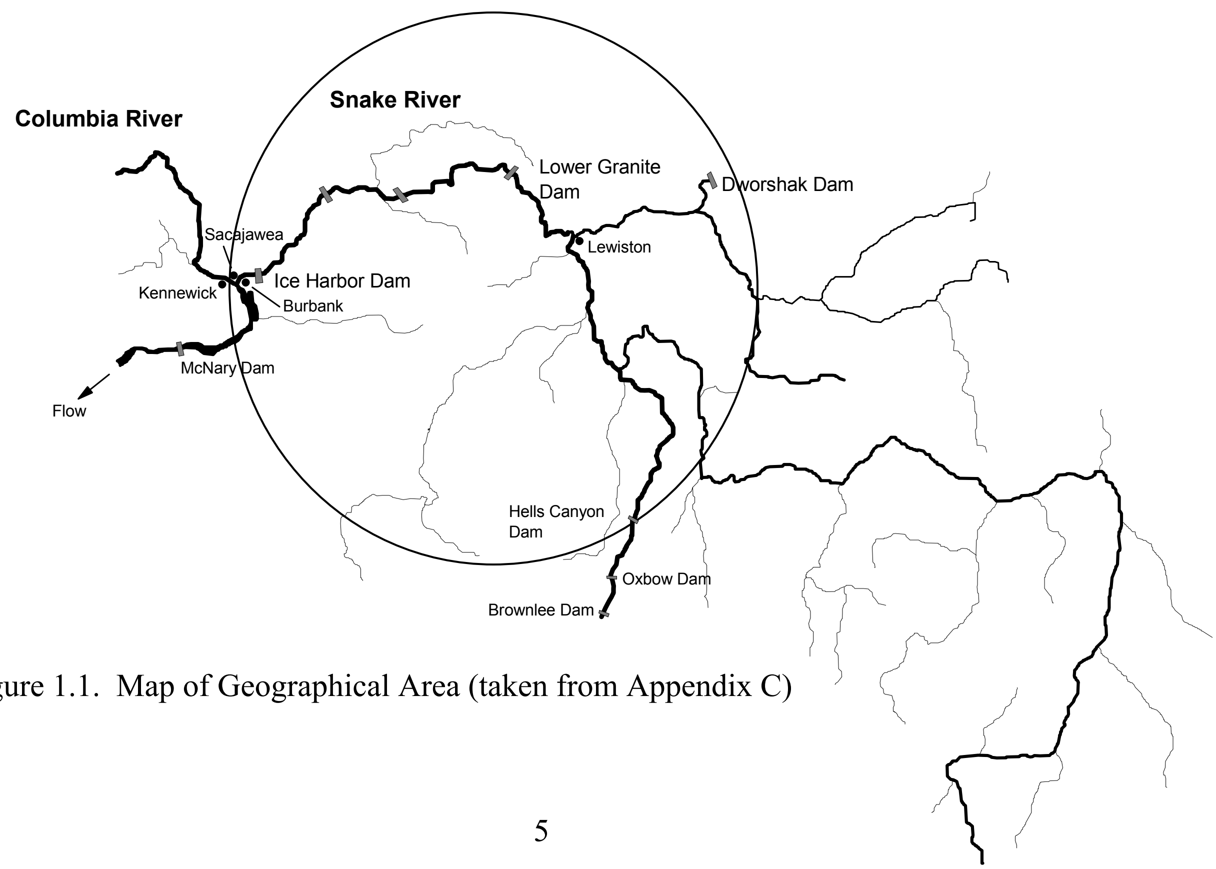


Figure 1.1. Map of Geographical Area (taken from Appendix C)

1.6 Coordination

The Water Quality Team, chaired by NOAA Fisheries, is responsible for providing technical review and advice to management groups in the salmon recovery program. The BiOp measure 143 workgroup is a subgroup of, and reports to, the Water Quality Team. Participants include representatives from Battelle, Bonneville Power Administration (BPA), Columbia River Inter-Tribal Fisheries Commission (CRITFC), Environmental Protection Agency (EPA), Idaho Power Company (IDPWR), Idaho Department of Environmental Quality (IDEQ), Idaho Water Resources Department (IDWRD), Nez Perce Nation, NOAA Fisheries, Oregon Department of Environmental Quality (ODEQ), Fish Passage Center, US Army Corps of Engineers (USACE), and Washington Department of Ecology (WDOE). The Action 143 subgroup efforts are chaired by the USACE, Walla Walla District. The workgroup first met March 8, 2002 and has been open to all who desired to participate. Meeting minutes through August 20, 2002 are located in the progress report dated September 10, 2002, Appendix 1. Minutes for meetings after September 10 can be found in Appendix A of this report.

2. HISTORIC AND ONGOING MONITORING/MODELING

2.1 Past Modeling Studies

The Lower Snake River has been studied for many years. These studies have included the calibration of several models, which have been constructed by various agencies and organizations for various specific objectives. Generally, the models can be divided into three categories: 1-dimensional (1D), 2-dimensional (2D) and 3-dimensional (3D) models. A 1D model refers to longitudinal distances in the river and ignores variability in depth and width. 2D models usually consider longitudinal and depth differences and ignore width variability. 3D models consider all three dimensions.

2.1.1 Application of 1-D Heat Budget Models

WQRRS is a model of thermal energy and constituent mass budgets. It simulates daily average temperature with gradually varied flow; hydraulic conditions are based on water routing methodology and the model has been used in the Juvenile Salmon Migration Feasibility Report/Environmental Impact Statement.

HEC5Q is a one-dimensional model designed to assess water quality conditions in the Lower Snake River as part of the Lower Snake River Feasibility study for the USACE. This work was completed by Normandeau Associates (1999).

RBM10 is a peer-reviewed model of the thermal energy budget of the Lower Snake River calibrated by EPA. It simulates daily or hourly average temperature under conditions of gradually varied flow on the Columbia and Snake mainstems. This model has been used to assess water temperature in the Snake and Columbia River systems for a number of environmental analyses, including a temperature Total Maximum Daily Loads (TMDLs). The model has been applied to reaches from Hells Canyon and Dworshak to the mouth of the Snake River. It is currently in use in annual Dworshak flow-augmentation planning and in the development of the Columbia/Snake River mainstem temperature TMDL.

MASS 1 (Modular Aquatic Simulation System 1-D) is a one-dimensional, unsteady hydrodynamic and water quality model for river systems. It was developed to be used on branched (tree-like) channel systems and has been extensively used on the Columbia and Snake Rivers. The model simulates cross-sectional average values; only single values of water surface elevation, discharge, velocity, concentration, and temperature are computed at each point in the model, at each time interval. MASS 1 has been applied by Pacific Northwest National Laboratory to the Columbia River Basin. The upper boundaries of the modeled region are the US/Canadian border on the Columbia, Dworshak Dam on the North Fork of the Clearwater River, and Hells Canyon Dam on the Snake River. The downstream boundary is near Astoria, Oregon. Within that region, simulations have included the operations of up to 15 hydropower projects. MASS1 was developed at the Pacific Northwest National Laboratory.

2.1.2 Application of 2-D Heat Budget Models

MASS 2 (Modular Aquatic Simulation System 2-D) is a two-dimensional, depth-averaged hydrodynamic and transport model for river and coastal systems. Regions modeled using MASS2 include the Lower Snake River where the model domain extends downstream from the confluence of the Clearwater and Snake Rivers to the mouth of the Snake River. On the Columbia River, the model domain extends downstream from Priest Rapids Dam to river mile 110 (about 10 miles upstream of the Willamette River confluence). MASS2 was developed at the Pacific Northwest National Laboratory.

CE-QUAL-W2 is a width averaged fully mixed lateral unsteady flow model recently revised by USACE. The model simulates velocities, water levels, travel times, temperature, nutrients, algal growth of different algal groups, pH, silica, carbonatious biochemical oxygen demand (CBOD), bacteria, suspended sediment, dissolved gas and dissolved oxygen. It uses a simplified description of wind sheltering and sediment heat exchange. It has been applied to the mid and upper Snake River. The model can be used to optimize temperatures in the Snake River with different releases from Dworshak Reservoir.

2.1.3 Application of 3-D Heat Budget Model

EFDC (Environmental Fluid Dynamics Code) solves the unsteady equations of motion for water in three-dimensions. It uses an orthogonal, curvilinear grid in the horizontal and a stretched coordinate system in the vertical to include motion of the free-surface. EFDC can also solve the coupled unsteady transport equation for various constituents including salinity, dissolved oxygen, temperature, and sediment. In the Columbia River basin, EFDC has been applied to the Lower Snake River (Perkins et al, 2002). Time periods of several months were simulated in these applications.

2.2 Ongoing and Current Thermal Monitoring Studies

There were several studies by several agencies and universities ongoing on the Lower Snake River during 2002. Each of these studies is briefly described below and a listing of site locations and data collected is available in Appendix D.

2.2.1 Total Dissolved Gas Fixed Station Water Quality Monitoring on Lower Snake River

The U.S. Army Corps of Engineers (USACE), Walla Walla District, has 12 sites where they collect data on total dissolved gas, barometric pressure and water temperature hourly from April through October. These fixed stations were established in 1984 on the forebays of each of the Snake River dam and in each of the tailraces of the dams in 1990 or 1995. Additional sites were established in the Snake River at Anatone in 1999, North Fork Clearwater River near the mouth in 1994 and Clearwater River at Peck and Lewiston in 1996. These data are automatically sent every four hours via satellite to the USACE, Pacific Northwest Division office at Portland, Oregon and entered in the CROHMS data system. These are recorded data values and as time is available, the values are reviewed and corrected or deleted as needed. These data can be seen on the USACE web site at http://www.nwd-wc.usace.army.mil/tmt/wed/tdg/months.html. Details on the data available can be seen in Table 1 of Appendix D.

2.2.2 Lower Snake River Temperature/Water Quality Studies

The Walla Walla District contracted with the USACE, Engineer Research and Development Center (ERDC) to collect data in 2002 on temperatures in the Lower Snake River, to assess the effectiveness of the total dissolved gas fixed station network, and to make recommendations for improving the existing monitoring program. Joe Carroll, with ERDC, and after consultation from the RPA 143 workgroup, installed several thermister strings in forebays, at tailwater sites, in tributaries and near existing river gages to determine if fixed station monitors were providing representative measurements. The list of sites, locations and depth of thermisters are provided in Table 1 of Appendix D. These data will be analyzed to help answer the questions identified with RPA 143.

2.2.3 In-Structure/Fishway Temperature Monitoring at Lower Snake River Projects

The BiOp 2000 (NMFS, 2000) includes RPA 114 which states: "The Corps shall examine existing fish-ladder water temperature and adult radio-telemetry data to determine whether observed temperature differences in fishways adversely affect fish passage time and holding behavior. If non-uniform temperatures are found to cause delay, means for supplying cooler water to identified areas of warmer temperatures should be developed and implemented in coordination with the annual planning process."

The Walla Walla District collected data in 2000, 2001 and 2002 to address the question, "Are fish ladder temperatures significantly different than the temperatures of the project forebays and tailwaters?" It has been determined that the temperature of water at the fish ladder exits can be significantly higher than the temperatures in the tailwaters at each dam and in particular at Lower Granite Dam. Current data collection and analysis activities are aimed at determining where in the ladder system temperature differences occur and how to minimize these temperature differences. A summary of the data collected in 2002 is located in Appendix D, Table 2.

2.2.4 Dworshak Pool Thermal Monitoring, 2001

The Walla Walla District collected water temperature data during 2001 at four points in the pool upstream of Dworshak Dam. A summary of these data can be found in Table 1 of Appendix D. These data were collected to develop an understanding of how the Dworshak Pool stratifies and how the USACE can best manage the pool for providing cool water for the Lower Snake River. An analysis of these data can be found in section 3 of this report.

2.2.5 Clearwater and Snake River Temperature Monitoring by Idaho DEQ

The Idaho Department of Environmental Quality (IDEQ) collected continuous water temperature data at four sites in the Clearwater and Snake Rivers. IDEQ also attempted to collect similar data on the Salmon River and at other points on the Snake River, but lost their equipment. A description of the data collected is included in Table 1 of Appendix D. An analysis of these data can be found in section 3 of this report.

2.2.6 Snake River Temperature Monitoring by Idaho Power Company

The Idaho Power Company (IDPWR)collects water temperature data at several points in the Snake River from upstream of Brownlee Dam to downstream of Hells Canyon Dam. Information for five sites downstream of Hells Canyon Dam, between river miles 229 and 156, is listed in Table 1, Appendix D; the information will also be included with the analysis, located in section three of this report. These data can be obtained from IDPWR by requesting in writing from the company.

2.2.7 Tri-Level Temperature Monitoring in Lower Snake River

Dr. Dave Bennett, University of Idaho, collected water temperature data at three depths. The sample sites are at the interface of Lower Granite Pool in the Snake and Clearwater Rivers, at multiple points in Lower Granite Pool and at a site in each of the other pools in the Lower Snake River. These sites also had data collected monthly at one-meter depth intervals, with two data collections in July and August. Descriptions of these data are included in Table 1 of Appendix D. The data will be analyzed in section 3 of this report.

2.2.8 Lower Granite Pool Temperature Monitoring by PNL and USGS

Battelle and USGS, Biological Resources Division, collected water temperature data from several sites in the backwater of Lower Granite Dam. In addition to continuous water temperatures at multiple depths, they also collected data on discharge and instantaneous water temperatures and specific conductance. These data are listed in Table 1 of Appendix D. These data are assessed in section 3 and will be used by Battelle to calibrate a 3-diminitial model of the Lower Granite Pool. The Battelle and USGS effort will continue into 2003.

2.3 Biological Monitoring

In 2002, in-season and post-season data are summarized as follows. Early life history timing and growth of wild Snake River subyearling fall chinook salmon in 2002 was described and compared to other years. A method for increasing the accuracy and precision of passage forecasts was developed. The efficacy of summer flow augmentation during 2002 was assessed with focus on the how saving some Dworshak Reservoir water for release in September affected survival of Snake River subyearlings. In 2002, fry emergence occurred earlier in the upper reach than in the lower reach of the Snake River based on time of fry presence. Fry emergence in 2002 in the upper and lower reaches was similar to other years except emergence timing was more protracted. Shoreline rearing by parr during 2002 occurred earlier in the upper reach than in the lower reach of the Snake River. Rearing timing in the upper and lower reaches of the Snake River in 2002 was a little earlier than during other years and was more protracted. Mean growth rate was higher for parr in the upper reach than in the lower reach of the Snake River. Growth rates in 2002 were rapid and similar to years. Passage of smolts from the upper reach was earlier than for smolts in the lower reach. Overall smolt passage was slightly earlier than normal. The revised forecast method performed better than the original forecast method. Modeling results indicated that releasing Dworshak Reservoir in September exposed Snake River juveniles to lower flows and warmer temperatures than would have been the case if all the water been released in July and

August. Survival of Snake River subyearlings was reduced slightly by saving some Dworshak Reservoir water for release in September, but this reduction was not statistically significant.

2.4 Meteorological Data

Meteorological data were collected by AgriMet (Bureau of Reclamation), National Weather Service (NWS) and by cooperative stations within the NWS. Table 3 of Appendix D lists the sites within 20 miles of the Lower Snake River with 2002 data. The AgriMet sites at Dworshak and Lake Bryan were funded by BPA starting in April 2002. The AgriMet site at Silcott Island was funded by Battelle as part of their Lower Granite Pool study and started recording mid July 2002. AgriMet data can be obtained from the web site http://mac1.pn.usbr.gov/agrimet/ and includes data for air temperature, cumulative precipitation, solar radiation, dew point temperature, relative humidity, wind speed, peak wind gust speed, wind direction, cumulative wind run and barometric pressure. The data for Pasco and Lewiston, Idaho and from the COOP sites can be obtained from the NWS; these data include all of the above (except for solar radiation), plus additional data on cloud cover and height of clouds.

2.5 Dam Operations Data

Data describing the operation at each of the five USACE dams in the Lower Snake River Basin are listed in Table 4 of Appendix D. Data listing the daily mean values for flows, power generation and stages of reservoirs are available from Data Access in Real Time (DART) http://www.cbr.washington.edu/dart/dart.html. Data listing flows, power generation and stages of reservoirs is also available hourly from Columbia River Operational Hydronet and Management System (CROHMS), http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/months.html. In addition, the Walla Walla District collected 5-minute data on the discharge and gate setting of each spillway and the power generation rate and discharge associated with each turbine in each of the four Snake River Dams; also stage, total discharge, and total power generation values are available. This data set is available on compact disk from Rick Emmert at the Walla Walla District.

3. ASSESSMENT AND APPLICATION OF TEMPERATURE AND RELATED DATA

3.1 Role of Temperature Monitoring Data in Addressing RPA 143 Objectives/ Questions

Continued development and refinement of the understanding of system-wide aquatic thermal processes will greatly enhance our ability to manage project operations for the Lower Snake River projects. The relative importance of the role of good quality comprehensive thermal data in managing seasonal operational strategies for the Snake River and associated projects has long been recognized by the regional stakeholders. In order to address the objectives of RPA 143 (as described in Section 1.4 the BiOp), the measure 143 subgroup of the Water Quality Team formulated the matrix of questions described in Appendix B. The next step of the subgroup was to both prioritize the questions and then determine how to best to answer the questions. It was decided that a comprehensive temperature monitoring effort could address some of the questions either partially or entirely. In addition, any future numerical or modeling effort would require an ongoing monitoring program for development, validation, and conduct/operation.

The questions identified by the subgroup, which could be addressed completely or partially with monitoring data, are listed below and in Appendix B.

- What are the temperature patterns for Lower Granite reservoir in relation to cold-water releases from Dworshak Dam? How do these patterns change with changing flows in the Clearwater and Snake Rivers?
- What is the time delay and magnitude of effect of releases from Dworshak Dam as seen at each Snake River project downstream?
- To what degree is the Snake River stratified downstream of Lower Granite Dam?
- What is the relative contribution and how far downstream can releases from Brownlee Dam affect water temperatures in the Lower Snake River?
- How representative are the current fixed temperature stations of river conditions?

The group decision was that station representativeness could be evaluated using a special screening study designed for that purpose. The screening study was completed during 2002 to collect the summer/fall Lower Snake River temperatures. This field sampling was conducted in addition to the ongoing routine temperature data monitoring. These data, along with the data being collected by other agencies and organizations, will be used to do the following:

1) Characterize the river conditions which occurred in 2002
2) Evaluate existing water quality monitors in representativeness for both spatial and temporal patterns in temperature
3) Provide information to guide selection of locations for new permanent fixed temperature monitoring stations (FTMS)
4) Answer questions posed by the workgroup team members

5) Provide information that will help to decide on the required model resolution
6) Provide calibration and verification data for the selected model.

3.2 Data Management for 2002 Monitoring

The 2002 Lower Snake River Database is made up of five tables: the hourly temperature data table, the weather data table, the USACE routine water quality and operations (CROHMS) data table, the detailed operations data table, and the USGS flow data table. Information found in each of these tables was collected by various agencies within Washington, Oregon, and Idaho. Copies of this data base can be provided on CD-rom upon request. Detailed descriptions of the data tables and sources of data are provided in Appendix E of this document. The agencies that participated or contributed data include the USACE, Idaho Power (IDPWR), Idaho DEQ (IDEQ), U.S. Geological Survey (USGS), Battelle (BTL), Bureau of Reclamation (BOR), and the National Weather Service (NWS).

3.3 Assessment of Routine Meteorological, Hydrological, and Thermal Data

This section of the report presents an assessment of water temperature data collected on the Lower Snake and Clearwater Rivers during 2002. It will include an overview on meteorological and hydrological data as well as water temperature information. The area of interest starts with the middle Snake River above the headwaters of Lower Granite pool, and the Clearwater River including the main stem and the North Fork plus Dworshak pool. The study area ends downstream at the Lower Columbia and Lower Snake Rivers' confluence.

3.3.1 Lower Snake River Meteorological Data for 2002

The weather stations chosen to monitor conditions in the Lower Snake River area during the study consists of one National Weather Service (NWS) station at Pasco, WA, and three Bureau of Reclamation AgriMet stations located on Dworshak pool (Dent Acres, ID; Lake Bryan-Rice Bar, WA, near Little Goose Dam; and Silcott Island, WA, upstream in Lower Granite pool). As seen in the Figures 3.1-3.3, the Pasco, Washington weather station collected data throughout the entire 2002 season. The AgriMet stations located at Dworshak/Dent Acres and Lake Bryan-Rice Bar were not installed until April 20, 2002 while the Silcott Island AgriMet weather station was not installed until almost two months later on July 17, 2002. Two additional weather stations will be incorporated into future data collection and analysis. These stations are the PAWS station at Fishhook recreation area on Ice Harbor pool, WA, and the NWS station at Lewiston, ID.

The highest daily temperatures recorded at Dworshak, Lake Bryan-Rice Bar, and Pasco occurred on July 13 (Figure 3.1). Since the Silcott Island station was not recording data at this time the highest temperature at this site occurred 10 days later on July 23rd. The lowest temperatures recorded at Dworshak/Dent Acres took place on October 30th while the lowest temperature at Lake Bryan-Rice Bar, Pasco, and Silcott Island took place a day later on the 31st. From the latter part of April through the end of November, the Dworshak/Dent Acres site was generally 1-3°C cooler than that of Lake Bryan-Rice Bar, Pasco, and Silcott Island sites. Out of the three warmer sites, Lake Bryan-Rice Bar, Pasco, and Silcott Island, no one station was predominately warmer than the others throughout the season.

The weather station located at Pasco, WA measured the highest wind speeds out of the four sites seen in Figure 3.2. The three highest daily wind speeds measured at the Pasco station occurred April 14th, with an average wind speed of 17mph, July 8th, with an average wind speed of 16mph, and on November 17th, with an average wind speed of 18mph. At the other three sites, there was only one day when average wind speeds were recorded higher than 10 mph. This occurred at Silcott Island on November 16. None of the weather stations recorded daily wind speeds less than one mile per hour for the entire season.

Wind peaks measured at the weather stations shown in Figure 3.3 followed similar patterns to that of the wind speed figure mentioned above. The Pasco, WA, weather station clearly shows higher daily wind peaks than the other stations. These highest measurements occurred on May 5th and 20th with peaks of about 33 mph and on July 8 with a peak of about 38 mph. None of the weather stations during the 2002 season recorded wind peaks below approximately three miles per hour.

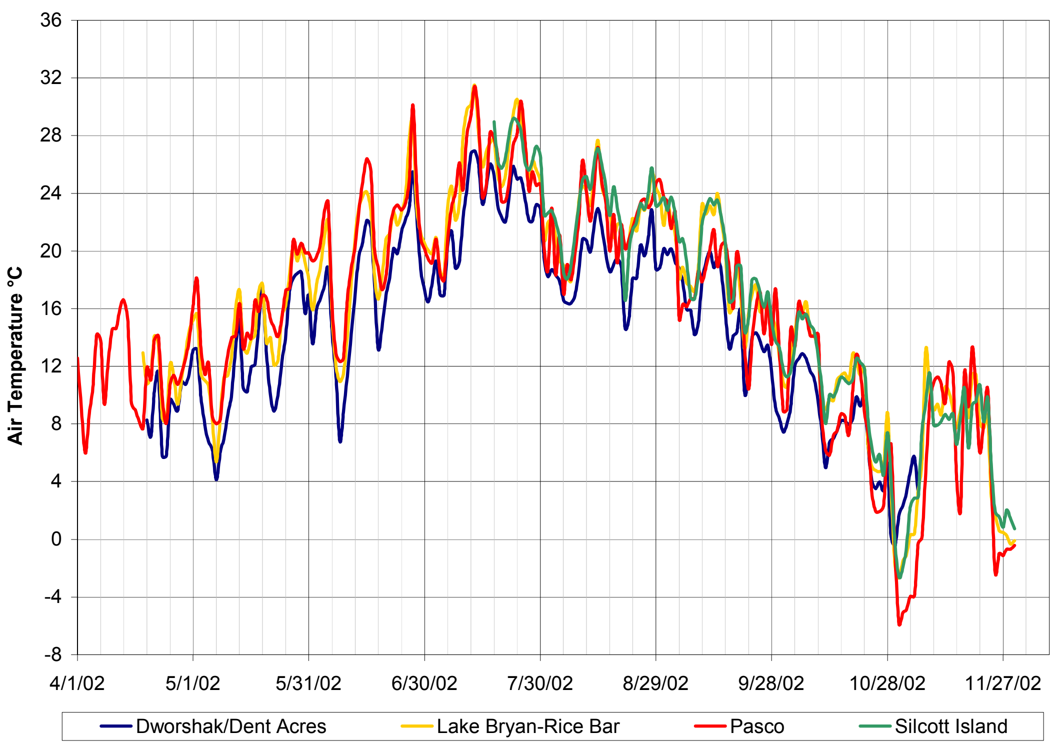


Figure 3.1. Average daily air temperatures collected at Lower Snake River weather stations, April - November 2002.

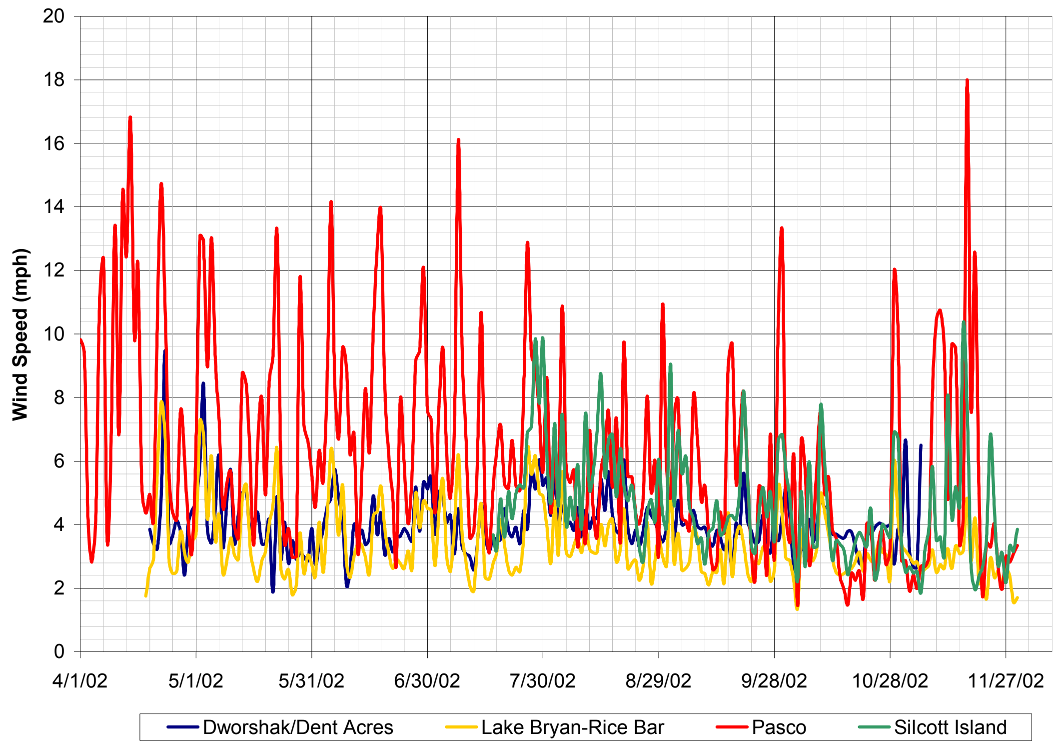


Figure 3.2. Average daily wind speeds collected at Lower Snake River weather stations, April - November 2002.

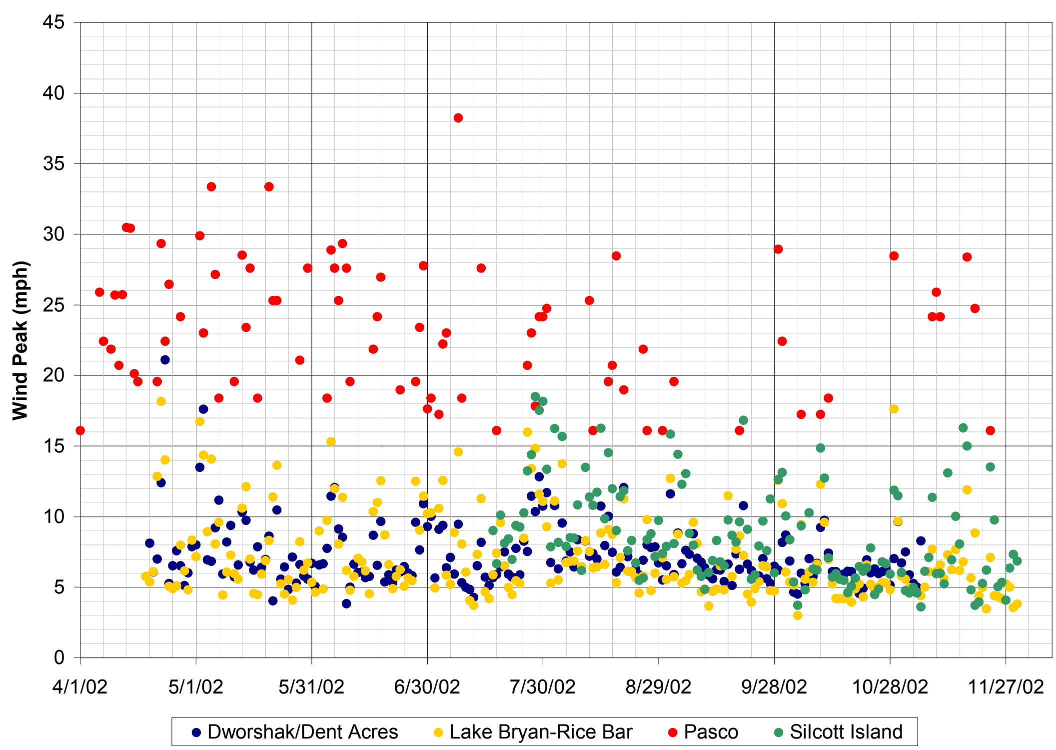


Figure 3.3. Average daily wind peaks collected at Lower Snake River weather stations, April - November 2002.

3.3.2 Summary of Hydrologic Flow Data for the Lower Snake and Clearwater Rivers during 2002

Flow data collected by USGS from the Clearwater River at Orofino, ID, the Clearwater River at Spalding, ID, the Snake River near Anatone, WA, and the fixed monitor located along the north fork of the Clearwater River (DWQI) are shown in Figure 3.4. With few exceptions, the majority of the season depicted relatively equal amounts of discharge from the Clearwater and Snake Rivers. The exception occurs from May 22nd through June 20th when Anatone flows spiked 20% higher, on average, than flows out of the Clearwater River. During the latter part of September and through the end of the season, Dworshak releases fell off and Snake River flows at Anatone rose to 60-80% of the total flow.

During 2002, Lower Snake river project flows started in the spring at 35 kcfs (average daily) and peaked at 130 kcfs in mid April and again at 140 kcfs in early June (Figure 3.5). Flows were falling off by early July on the Snake River. Low flows of 15 kcfs were typical on the Snake by late September. Theoretical retention times calculated by project using volume/surface elevation data would approximate flows through the system. The retention times varied from a low of 2 days for all projects during the April-June period to a high of 18 days for Little Goose and 12-14 days for the other projects during the fall low flows. Retention time for the Lower Snake River up through Lower Granite pool ranged from a low of 8 days for the system during May/June high flows to a high of approximately 60 days during the fall low flows.

3.3.3 Summary of Hydrologic Flow Data for the Lower Snake and Tributaries Upstream of Lower Granite Headwater During 2002

The 2002 flow data for stations upstream of the Lower Granite headwaters are depicted in Figure 3.6. The stations include Anatone, Grande Ronde River, Salmon River, Imnaha River and downstream of Hells Canyon Dam (river mile 229). The flows for this reach were dominated by releases from Hells Canyon Dam until early May and then again during mid July. The Hells Canyon flows remained fairly constant throughout the year fluctuating from 10 to 20 kcfs with few exceptions. The Salmon River was characterized by a wide range in discharges over the year. Fall and winter flows remained constant at about 3-4 kcfs. The spring and summer flows on the Salmon peaked several times with the major peak at 54 kcfs on June 2. The flow contribution from the Salmon to the Snake River exceeded 50% for much of the early summer period during 2002 whereas over 73% of the river flow came from Hells Canyon releases during August and September (Figure 3.7). The Grande Ronde and the Imnaha Rivers had minor contributions throughout the year with a minor peak for the Grande Ronde River of 19 kcfs during early April. The exception occurs from May 22nd through June 20th when Anatone flows spiked 20% higher, on average, than flows out of the Clearwater River.

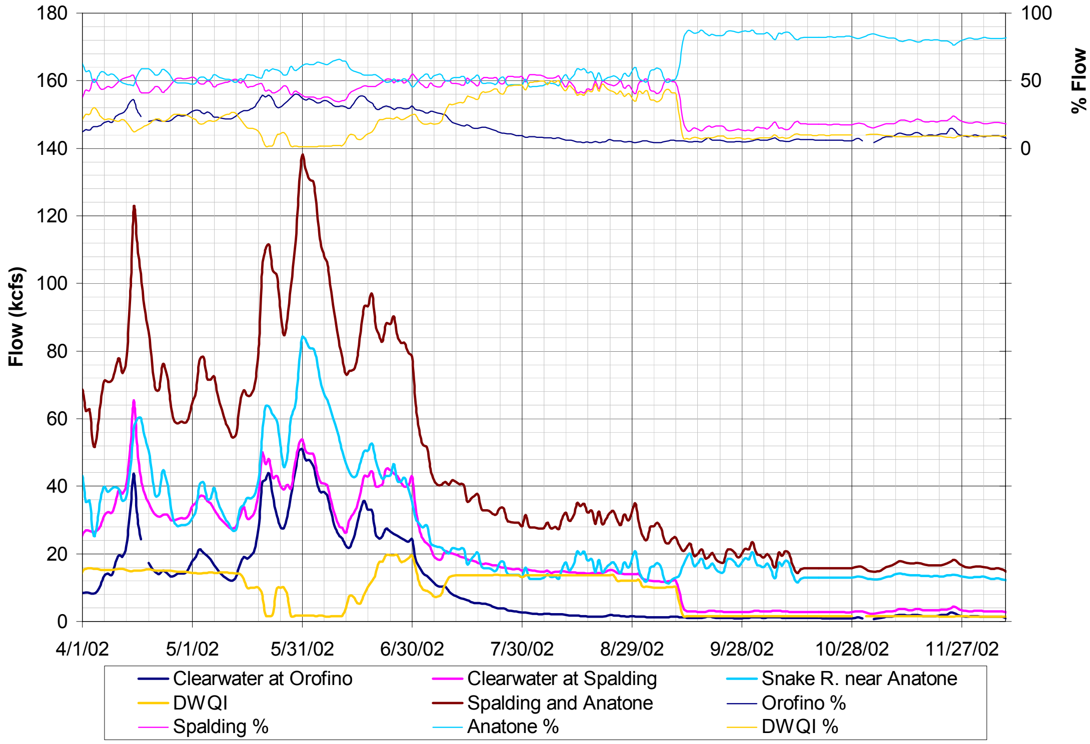


Figure 3.4. Average daily flows and percent total flows from selected USGS sites along the Snake and Clearwater Rivers, April – November 2002.

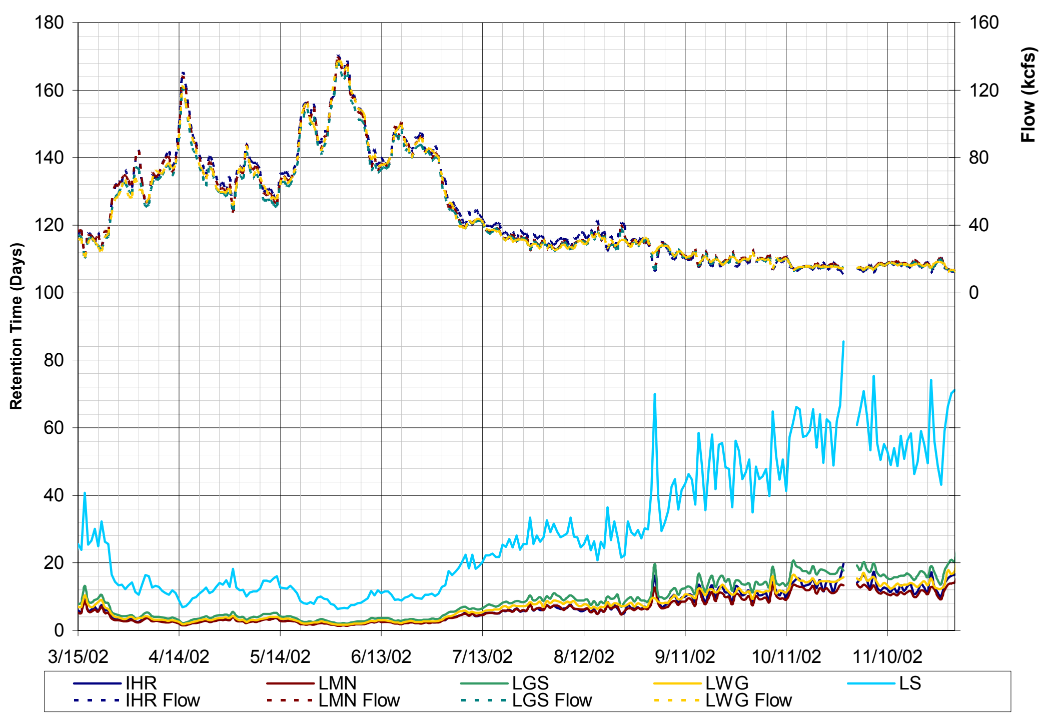


Figure 3.5. Lower Snake River average daily flow and theoretical retention time by project and the entire lower river, April – November 2002.

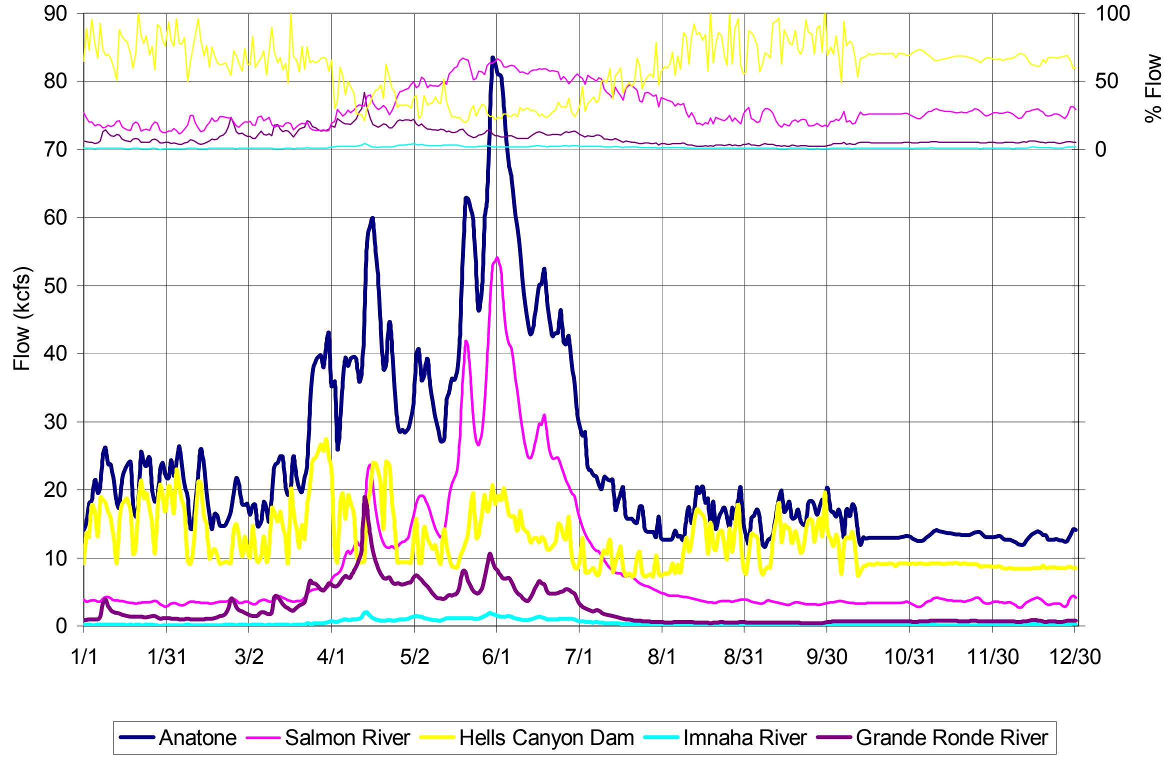


Figure 3.6. Average daily flows and percent total flows from stations and tributaries on the Snake River above the Lower Granite headwaters and downstream of Hells Canyon Dam.

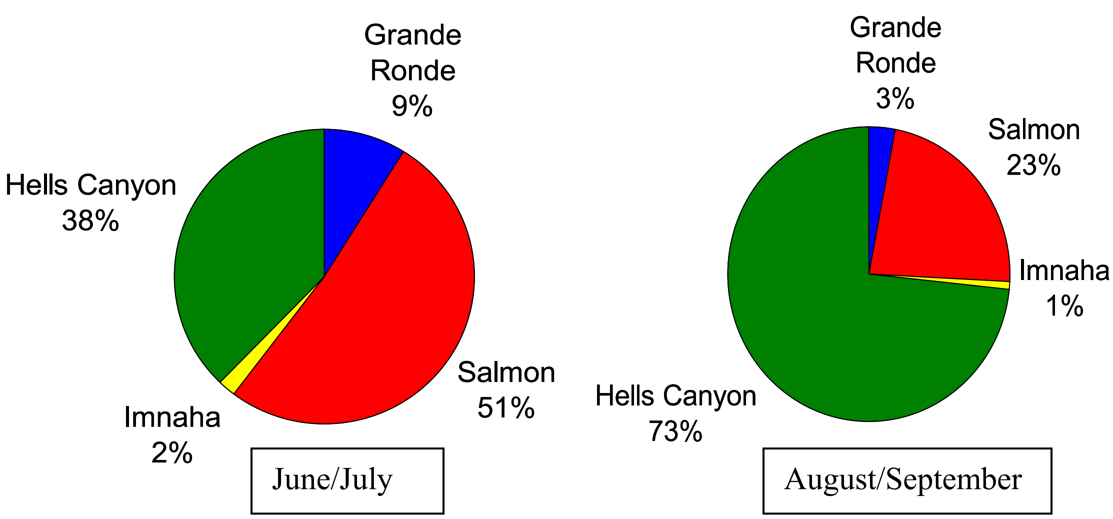


Figure 3.7. Tributary contribution of flow on the Lower Snake River above Lower Granite Pool as a percent of total discharge for the summer of 2002.

3.3.4 Routine Forebay, Tailwater, and Selected River Fixed Monitoring Station Data

The USACE has conducted routine monitoring at all Snake River projects plus selected in-river sites on both the middle Snake and Clearwater rivers for several years. The stations associated with each project are located in the forebay near or on the upstream dam face and in the tailwater just downstream of each project. Sampling is on hourly intervals at discrete depths (generally approximately 15 ft) at each location. Neither vertical nor lateral gradient patterns are captured with this sampling strategy.

These water quality stations were designed to sample total dissolved gas saturation but have been used to document water temperatures as well. The general purpose for the forebay station has been to sample or represent an average cross section of the downstream forebay waters. The purpose for monitoring in the tailwater areas has been to document spill water conditions in most cases on the river. These objectives can be met in both cases if the water is well mixed spatially at each reach of interest. Since the dams have no or little impact on water temperatures then the two stations should give comparable data throughout the sampling season for each project.

3.3.5 Temporal Patterns

The temporal patterns for water temperature collected at each of the Lower Snake River Projects fixed water quality monitoring sites (Ice Harbor, Lower Monumental, Little Goose, Lower Granite, and Dworshak on the Clearwater River) are depicted in Figures 3.8 through 3.12. The time of each plot is from April through November 2002 at each station. The Snake River water began warming from about 5°C starting in late March/early April. The Figures 3.8-3.12 also depict total project discharge and spill discharge. The warming continued at all sites until late July/early August with peak temperatures of 20-22°C on the Lower Snake River.

The warmest temperatures were noted for the forebay monitor locations. The forebay and tailwater water temperature data for the lower Snake River projects correspond well together until early July when increased warming was noted for most forebay stations. The greatest differences in forebay and tailwater temperatures were observed at Lower Granite Dam (Figure 3.11) and ranged from 2-4°C consistently during the period of July through September. Daily temperature spikes as great as 4-5°C were observed at the forebay stations until the water began cooling off in early October. The least prominent daily temperature spiking (less than 2°C) was noted for Ice Harbor forebay waters. The tailwater temperatures had minimal daily warming or spiking (generally less than 1°C) and were more characteristic of the somewhat mixed releases from each of the projects.

Dworshak releases on the North Fork of the Clearwater River remained cooler, less than 10°C until mid October (Figure 3.12). The middle fork of the Clearwater River warmed to 23°C by mid July at Orofino. Daily thermal cycles on the middle fork of the Clearwater River ranged from 2-5°C routinely during the period of July through October. The water temperature at Orofino cooled off more rapidly late in the season to less than

5°C, whereas the water temperature of the Dworshak releases was still above 8°C by late November.

Similar depictions for the river stations at Lewiston, ID, (LEWI), and Anatone, WA, (ANQW) are shown in Figure 3.13. Peak temperatures of 22-25°C occurred on the Middle Snake at Anatone by mid July. The Lewiston gage registered water temperatures around 15°C by early July and then again by mid September. Daily thermal cycles were in the order of 1-2°C with the greater daily cycles occurring on the lower Clearwater River at Lewiston.

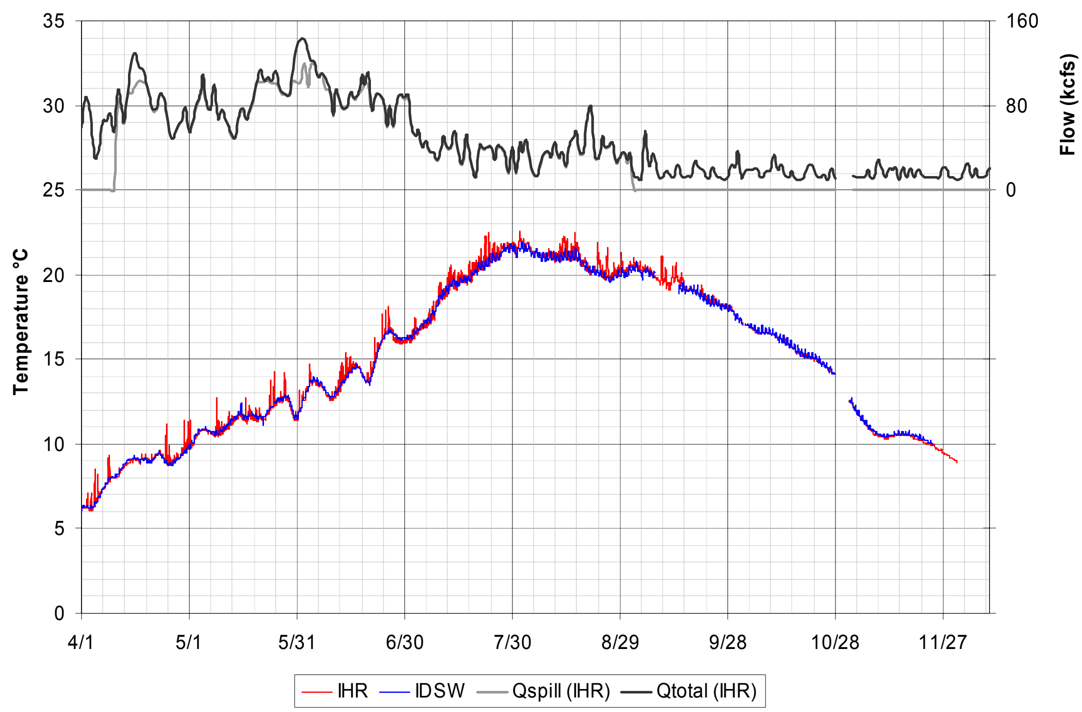


Figure 3.8. Ice Harbor tailwater (IDSW) and forebay (IHR) fixed monitor temperatures with total project and spillway discharges, April – November 2002.

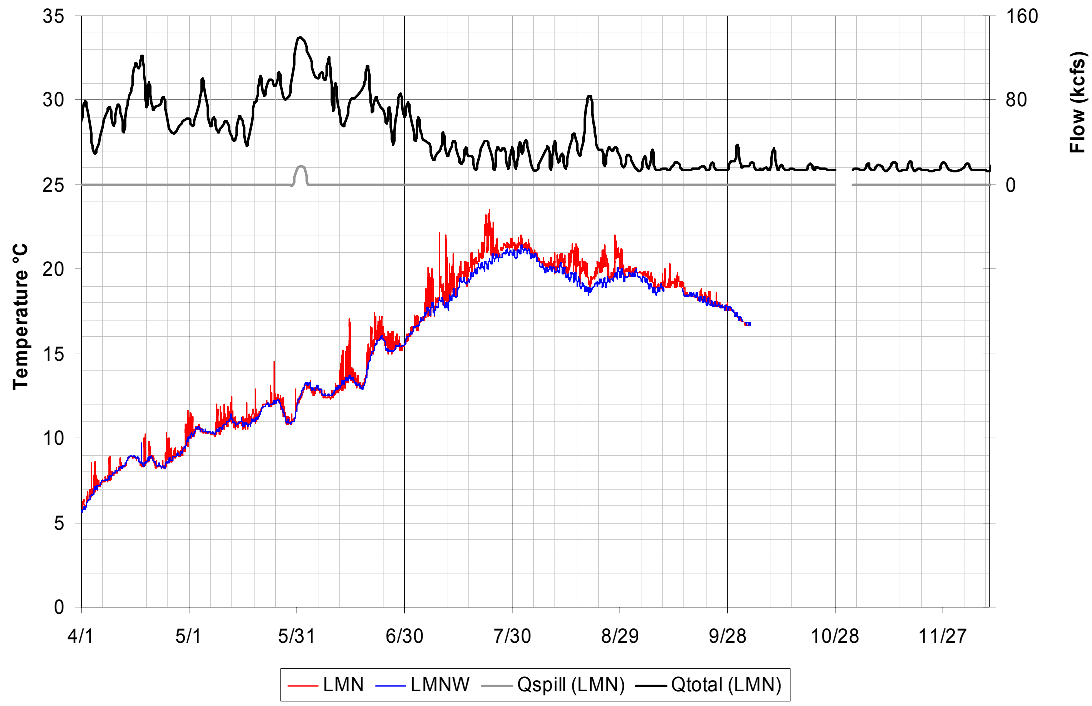


Figure 3.9. Lower Monumental tailwater (LMNW) and forebay (LMN) fixed monitor temperatures, with total project and spillway discharge, April – November 2002.

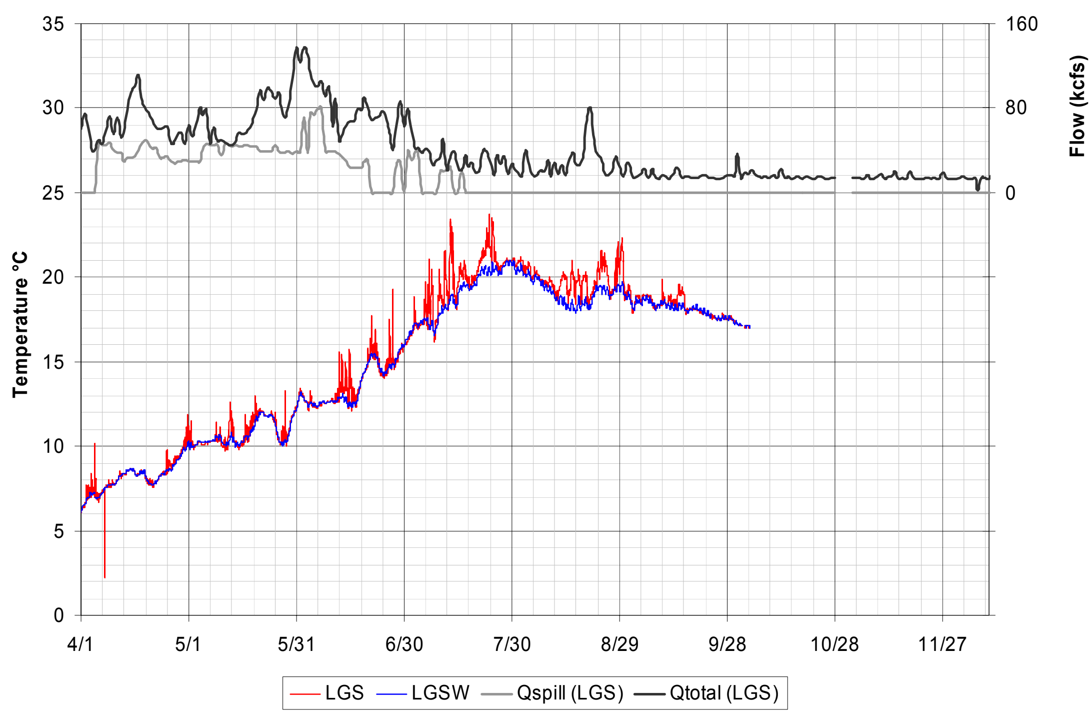


Figure 3.10. Little Goose tailwater (LGSW) and forebay (LGS) fixed monitor temperatures, with total project and spillway discharge, April – November 2002.

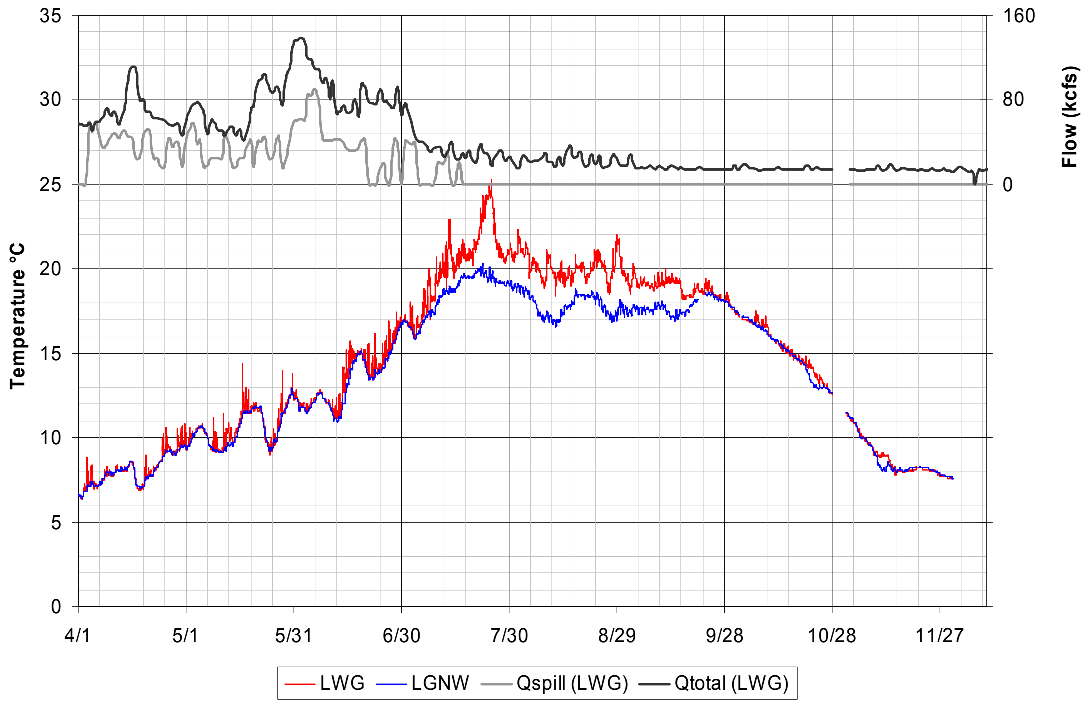


Figure 3.11. Lower Granite Tailwater (LGNW) and Forebay (LWG) fixed monitor temperatures, with total project and spillway discharges, April - November 2002.

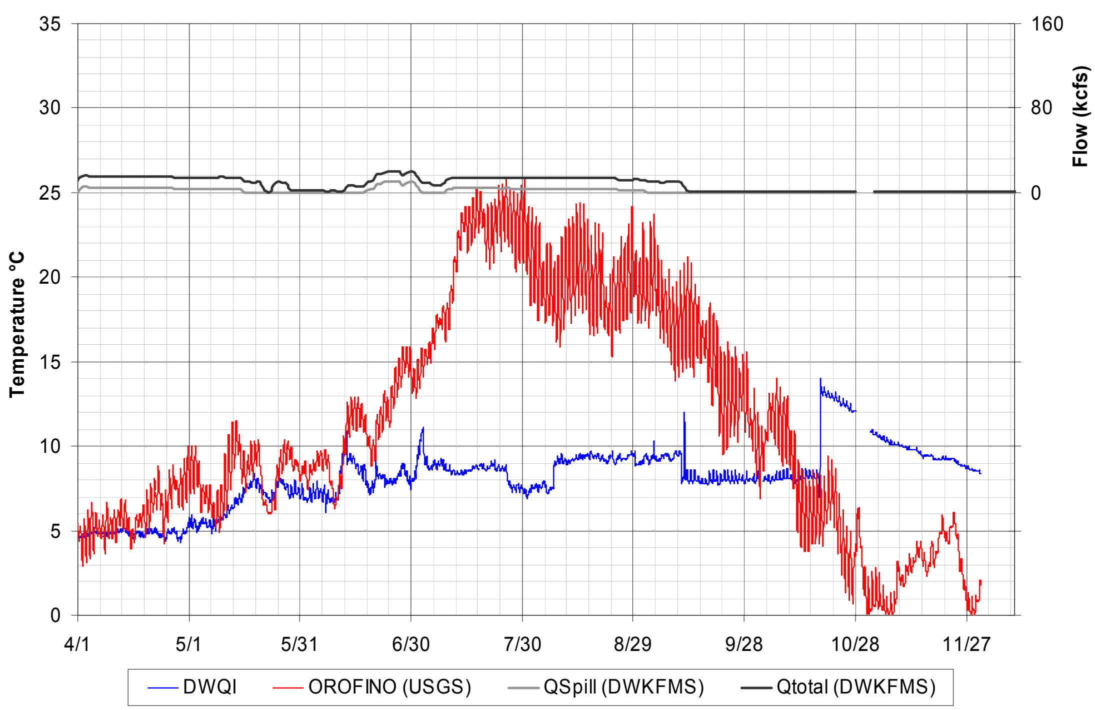


Figure 3.12. Dworshak tailwater temperature (DWQI), total discharge, spill discharge, and Clearwater River temperatures at Orofino, Idaho (OROFINO).

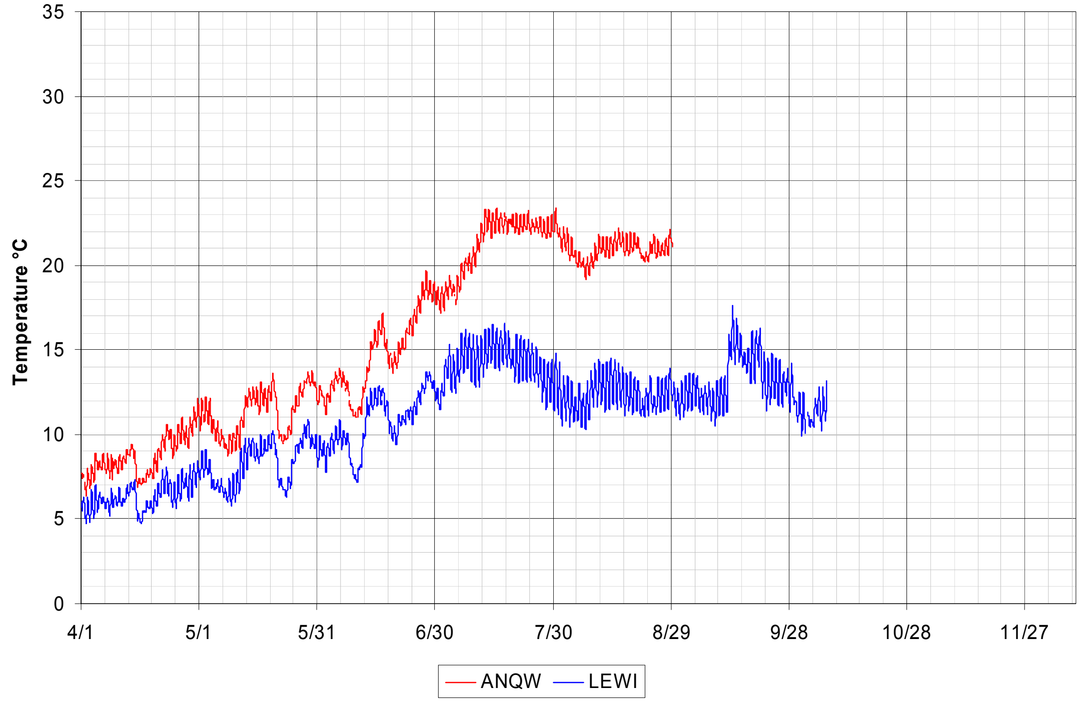


Figure 3.13. Fixed monitor water temperatures for the Snake River station at Anatone, WA, (ANQW) and the Clearwater River at Lewiston, Idaho (LEWI), April – September 2002.

3.3.6 Longitudinal Patterns

A longitudinal series of temperature data is depicted in figure 3.14. Temperature data for each tailwater fixed monitor plus the Lewiston and Anatone sites are shown. The data show a general pattern of increasing temperature in the downstream direction on the Lower Snake River indicating warming as would be expected. During the period of June through August the warming on the Lower Snake River appears to fall in the range of 1-3°C (this observation assumes some lag as we progress downstream). The water temperature at Anatone was frequently 2°C higher than that recorded further downstream at the projects. The Clearwater temperature at Lewiston remained cooler through the season due to the cold water releases from Dworshak Dam.

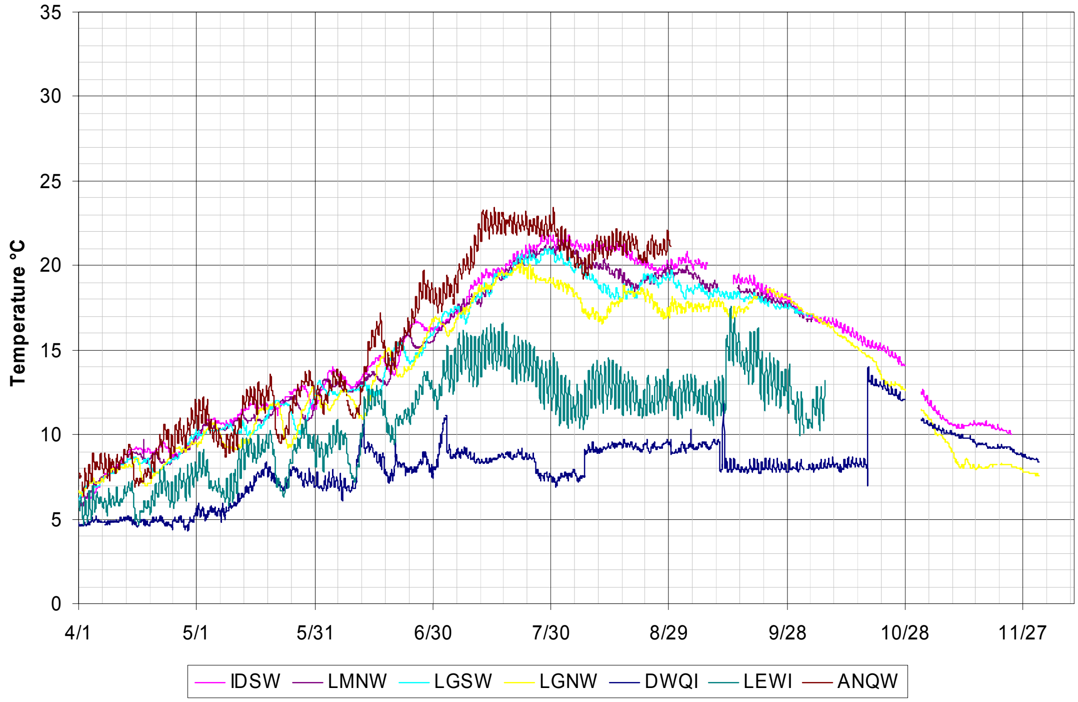


Figure 3.14. Tailwater fixed monitor temperature data for the Lower Snake River Projects plus water temperature for the LEWI and ANQW gages, 2002.

3.3.7 Temperature Screening Study on Lower Snake River for 2001 and 2002

The screening study plan and data review is presented in Appendix E of this document along with details of the purpose and study approach. The following selected data review is taken from that Appendix. Most of the temperature profile logging instruments were started in early June and retrieved in late November of 2002. Sampling depth (Z) varied from near surface to within 1 m of bottom in each case. The depth for each logging instrument is indicated in the figure legend.

3.3.7.1 Spatial and Temporal Patterns for Screening Study

A large part of the 2002 effort for the Screening Study was to collect temperature profile time histories at multiple stations in each project forebay. The following sections give overviews of temperature data for one station in each of Dworshak, Lower Granite, Little Goose, Lower Monumental, and Ice Harbor pools.

3.3.7.1.1 Dworshak Forebay

Strong vertical thermal gradients were present by mid June in the Dworshak forebay at station DWKFB as indicated in the 60 m deep profile described in Figure 3.15. Maximum temperatures of 25-29°C were achieved at the 0.5 m deep sensor by mid to late July. The surface mixed layer or the epilimnion progressed down to 5 m by late July and on down to 10 m by late September. The thermocline appeared to extend down to the 35-40 m depths with gradients up to 14°C occurring. The hypolimnion, below the 40 m depth, remained at or below 6°C for the duration of the sampling period. Figure 3.16 illustrates a daily average temperature profile of late August.

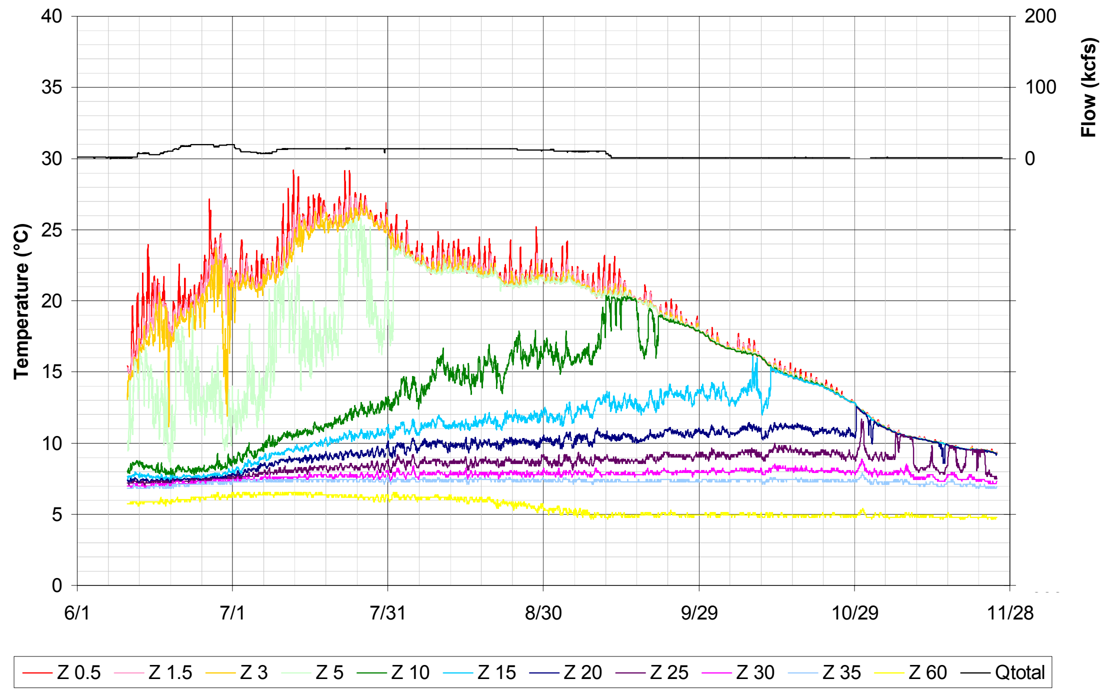


Figure 3.15. Temperature profile time histories for Dworshak forebay station DWKFB and project discharge, June - November 2002. (The sensor depths, *Z*, are in meters as indicated in the legend)

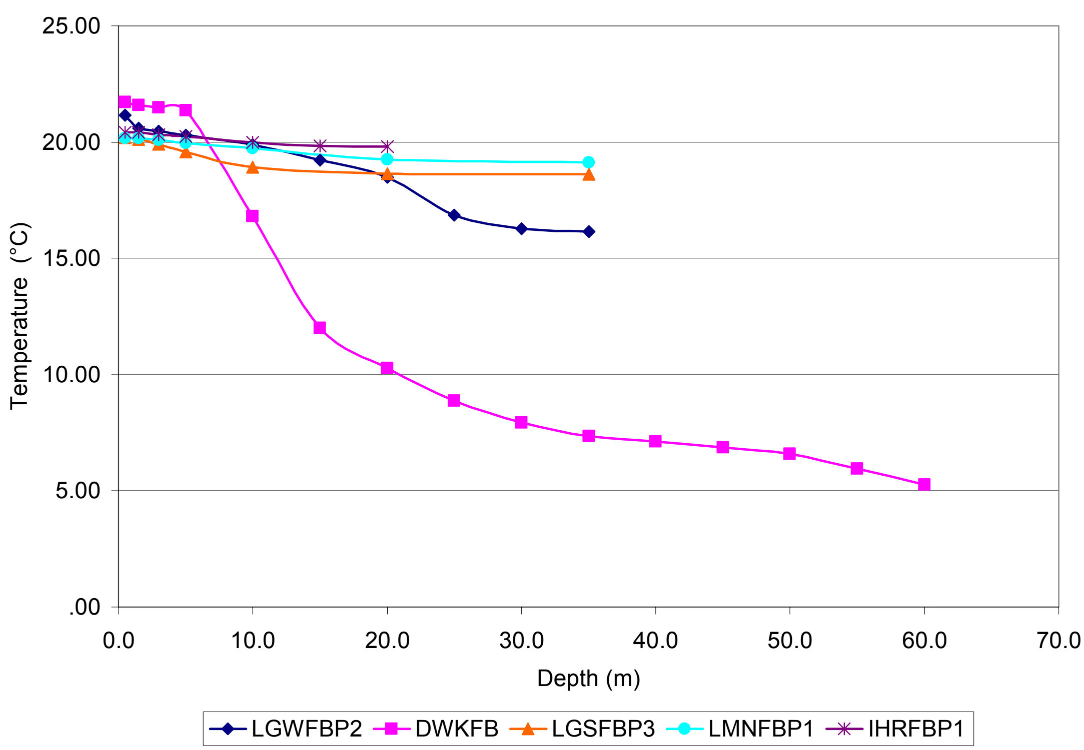


Figure 3.16. Lower Snake River project and Dworshak Dam forebay daily average temperature profiles on August 30, 2002.

3.3.7.1.2 Lower Granite Forebay

Lasting vertical thermal gradients started in early July at the Lower Granite forebay station LWGFBP2 as indicated in the profile time histories described in Figure 3.17 and continued until mid September. Maximum temperatures of 25°C were achieved at the 0.5 m deep sensor by mid to late July. The surface mixed layer never extended below 5 m with little classical development of an epilimnion. An apparent thermocline extended down to near the bottom at the 25 to 30 m depths with gradients up to 6°C occurring. The bottom temperatures remained between 16 and 19°C during the stratified period. Figure 3.16 illustrates a daily average temperature profile for late August showing no distinct thermal layers but a total gradient of 5°C.

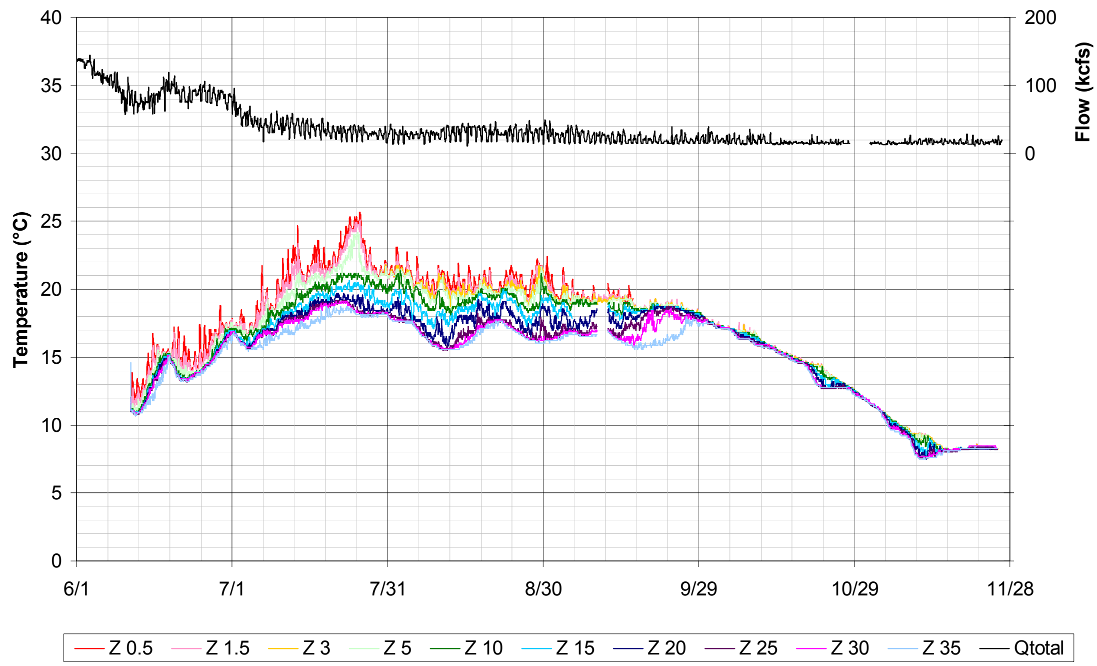


Figure 3.17. Temperature profile time histories for Lower Granite forebay station LWGP2 and project discharges, June – November 2002.

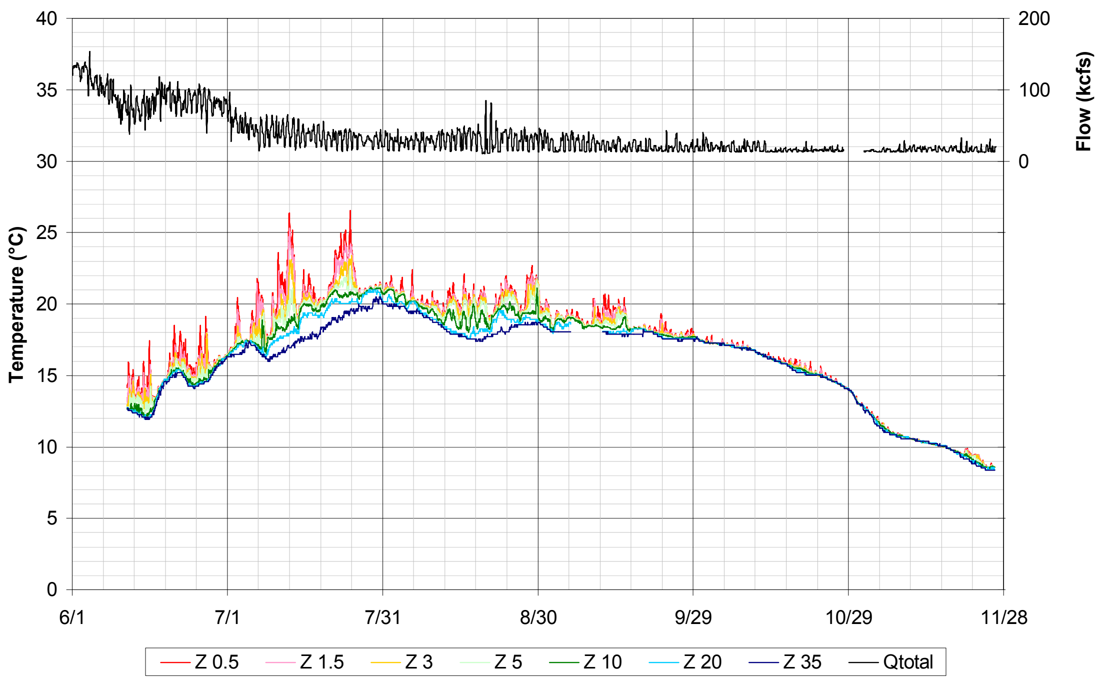


Figure 3.18. Temperature profile time histories for Little Goose forebay station LGSFBP3 and project discharges, June – November 2002.

3.3.7.1.3 Little Goose Forebay

Vertical thermal gradients started to develop for short periods (3 to 5 days) in June at the Little Goose forebay station LGSFBP3 as depicted in the profile time histories described in Figure 3.18 but would break up or mix due to surface cooling or wind mixing. Continuous but relatively weak thermal gradients of 2-4°C were apparent by July 10 and, like at Lower Granite, continued until mid September. Maximum temperatures of 25°C were achieved at the 0.5 m deep sensor by mid to late July. The thermal gradients were more gradual from surface to bottom. The bottom temperatures remained between 16 and 20°C during the stratified period. Figure 3.16 illustrates a daily average temperature profile for late August showing no distinct thermal layers but a total gradient of 2°C.

3.3.7.1.4 Lower Monumental Forebay

The time series of thermal pattern development in Lower Monumental forebay followed that of Little Goose. Short lived surface warming was observed during June and by mid July weak thermal gradients of 2-4°C were apparent at station LMNFBP1 (Figure 3.19). Maximum temperatures of 24-25°C were observed in July. The thermal gradients were gradual from surface to bottom. The bottom temperatures remained between 17 and 21°C during the stratified period. Figure 3.16 illustrates a daily average temperature profile for late August showing no distinct thermal layers but a total gradient of 1°C.

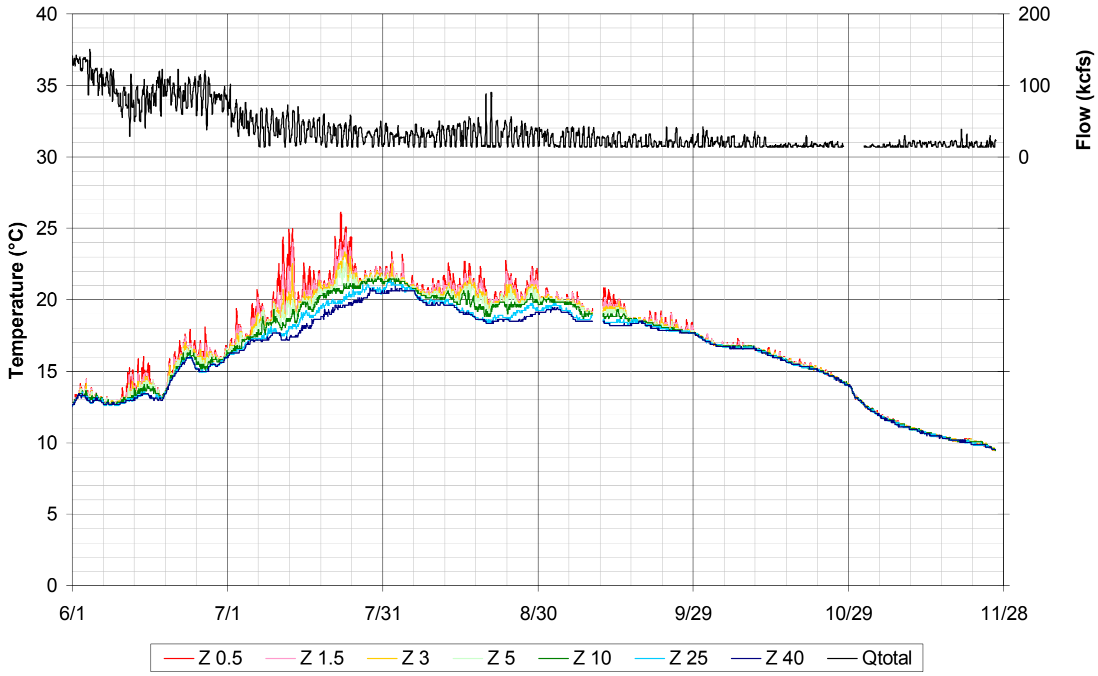


Figure 3.19. Temperature profile time histories for Lower Monumental forebay station LMNFBP1 and project discharges, June – November 2002.

3.3.7.1.5 Ice Harbor Forebay

The Ice Harbor forebay thermal profile was characterized by intermittent daily surface warming throughout the season (Figure 3.20) with a very gradual and weak vertical gradient of 1-2°C. Maximum temperatures of 24°C were observed in July. The bottom temperatures remained between 18 and 22°C during the stratified period. Figure 3.16 illustrates a daily average temperature profile for late August showing no distinct thermal layers but a total gradient of less than 1°C.

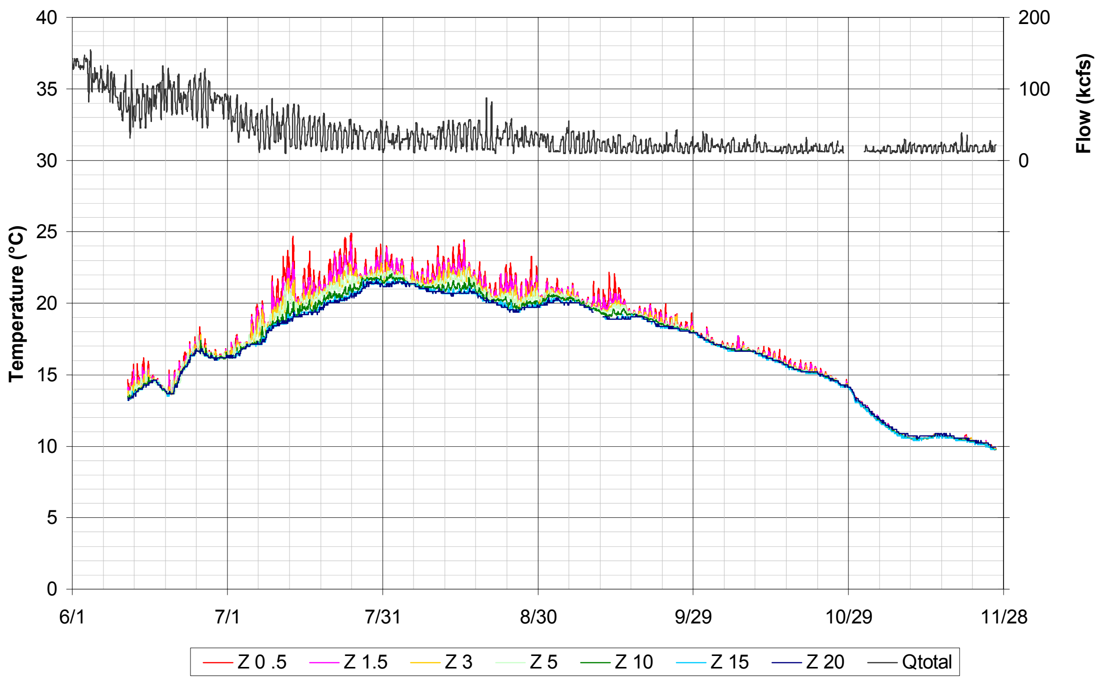


Figure 3.20. Temperature profile time histories for Ice Harbor forebay station IHRFBP1 and project discharge, June - November 2002.

3.3.7.2 Lateral Bias Evaluation of Forebay Profiles

Comparisons were made across stations for the Lower Snake River forebay profile monitoring. Paired sample statistical analyses were conducted by pairing by depth and time between two stations. This was completed in a way to compare each station in a forebay to all the other locations for that forebay. Table 3.1 shows the results of these tests across the entire sampling season of June through November. The abbreviations used in referencing the paired strings in Table 3.1 started with the project initials such as "I" for Ice Harbor followed by "F" for forebay station, and then followed with a number indicating the lateral position of the station. Lateral station numbers start on the looking downstream left bank side. The analysis was a t-test to determine if the calculated mean difference for each pair was significantly different from zero. The analyses showed each pair to be significantly different; however, the maximum mean difference for all the tests was –0.17°C for the LWF3-LWFX pair. These data indicate only minor bias (± 0.2°C) associated with the lateral positioning of stations in any of the Lower Snake River project forebays. These small differences can easily be accounted for by possible differences in instruments depths or occasional seiche action.

Table 3.1. Paired samples test for each profile temperature string of a project forebay.

Measures Paired by Time and Depth		Paired Differences Mean	Std. Dev	Srd. Error Mean	95%Confidence Interval of the Difference Lower	Upper	t	df	Sig. (2-tailed
Pair1	IF1-IF2	.0372	.24998	.00154	.0341	.0402	24.129	26344	.000
Pair2	LMF1-LMF2	.0266	.17689	.00138	.0239	.0293	19.306	16521	.000
Pair3	LMF1-LMF3	-.0088	.27889	.00192	-.0125	-.0050	-4.556	21066	.000
Pair4	LMF2-LMF3	-.0158	.22458	.00175	-.0193	-.0124	-9.029	16427	.000
Pair5	LGF1-LGF2	-.0534	.42692	.00391	.1929	.2029	77.841	19015	.000
Pair6	LGF1-LGF3	-.0816	.49092	.00449	.1512	.1623	55.312	15910	.000
Pair7	LGF1-LGFX	-.1256	.59462	.00560	.0929	.1052	31.631	15051	.000
Pair8	LGF2-LGF3	-.0213	.24101	.00149	-.0243	-.0184	-14.316	26142	.000
Pair9	LGF2-LGFX	-.1033	.39940	.00253	-.1083	-.0984	-40.860	24944	.000
Pair10	LGF3-LGFX	-.1057	.38733	.00257	-.1107	-.1007	-41.133	22715	.000
Pair11	LWF2-LWF3	.0795	.32124	.00204	.0755	.0835	39.019	24878	.000
Pair12	LWF2-LWFX	-.1021	.41403	.00277	-.1075	-.0967	-36.883	22375	.000
Pair13	LWF3-LWFX	-.1718	.42087	.00272	-.1772	-.1665	-63.079	23873	.000

These paired sample analyses were also conducted by month (Figure 3.21). The stratified periods of July and August resulted in some of the highest mean differences in paired stations of about –0.3°C. The stations located nearer the project and adjacent to the fish ladder exits (FX) were generally warmer than those stations that were further upstream of the projects.

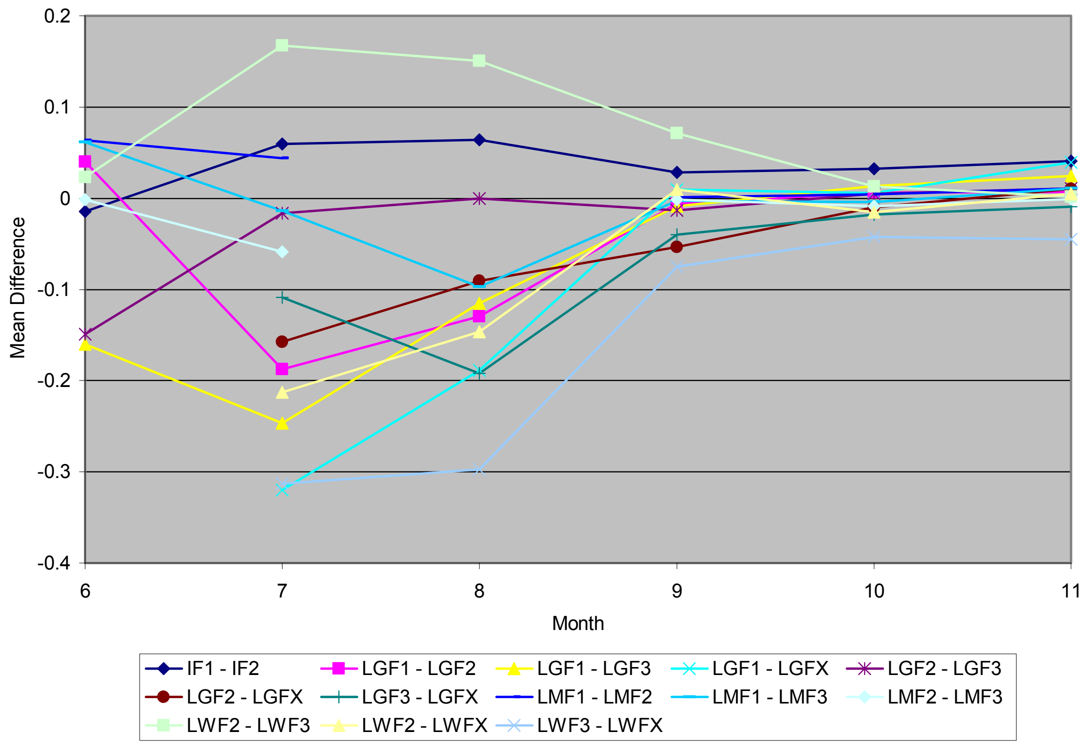


Figure 3.21. Paired samples mean differences for each profile temperature string of a forebay by month.

3.3.7.3 Boundary Conditions for Temperature

In addition to the forebay automated profiling, additional river stations were monitored including locations on the middle Snake, Grande Ronde, Clearwater, Palouse, and Toucannon Rivers, plus additional monitors were installed on each project draft tube deck. The following sections present a partial review of the individual river temperature monitor data collected in the screening study.

3.3.7.3.1 Thermal Characteristics of Snake River Reach from Hells Canyon Dam to Confluence with the Clearwater River

Water temperatures for the Snake River just upstream of Lower Granite headwaters increased to above 20°C the second week in July and remained elevated until mid September. Maximum temperature was 22-23°C for all five stations presented in Figure 3.22. Diel cycles in temperature were 1-2°C for all stations as well. Warming in the order of 0.5°C from river mile 170 downstream to river mile 156 was identified in the middle Snake River data during July and August (provided by Idaho Power Company).

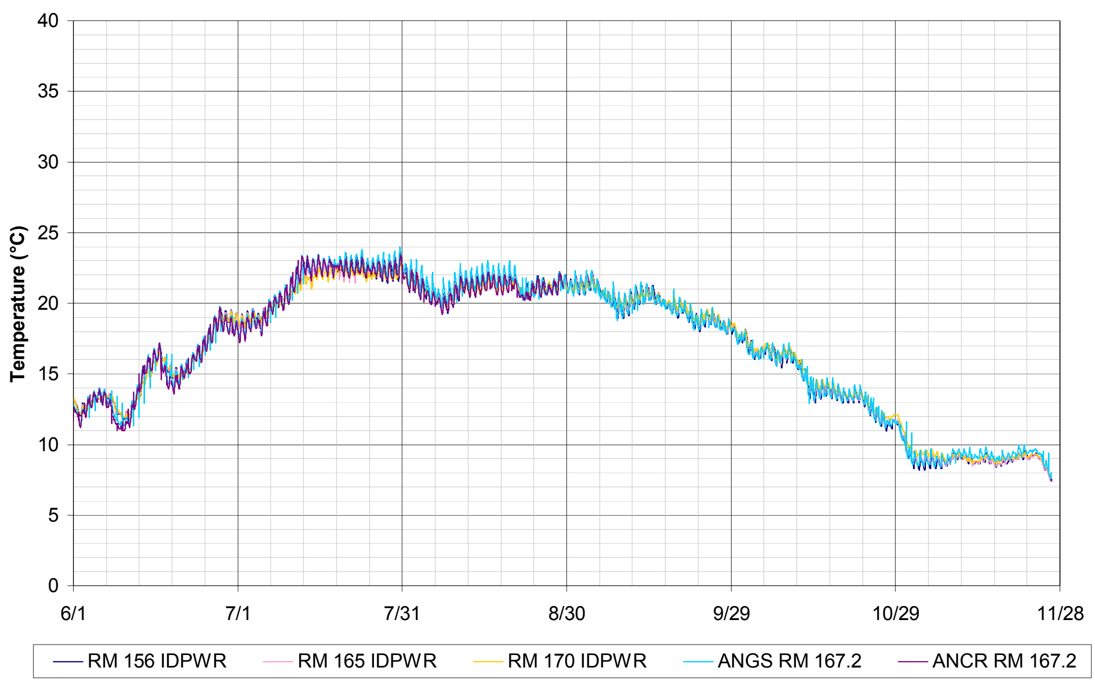


Figure 3.22. Snake River water temperatures, river mile 156 to 170. June – November 2002. (Data provided by Idaho Power, USGS, and USACE)

The average daily river temperatures depicted in Figure 3.23 indicate peak temperatures of 24°C occurring during mid July in the Salmon River. By early August the Salmon River water begins to cool more rapidly than the Snake. This trend continues through out the fall and into the winter. The Snake River waters warmed to 22°C by late August and is then characterized by a somewhat slower cooling trend into the winter.

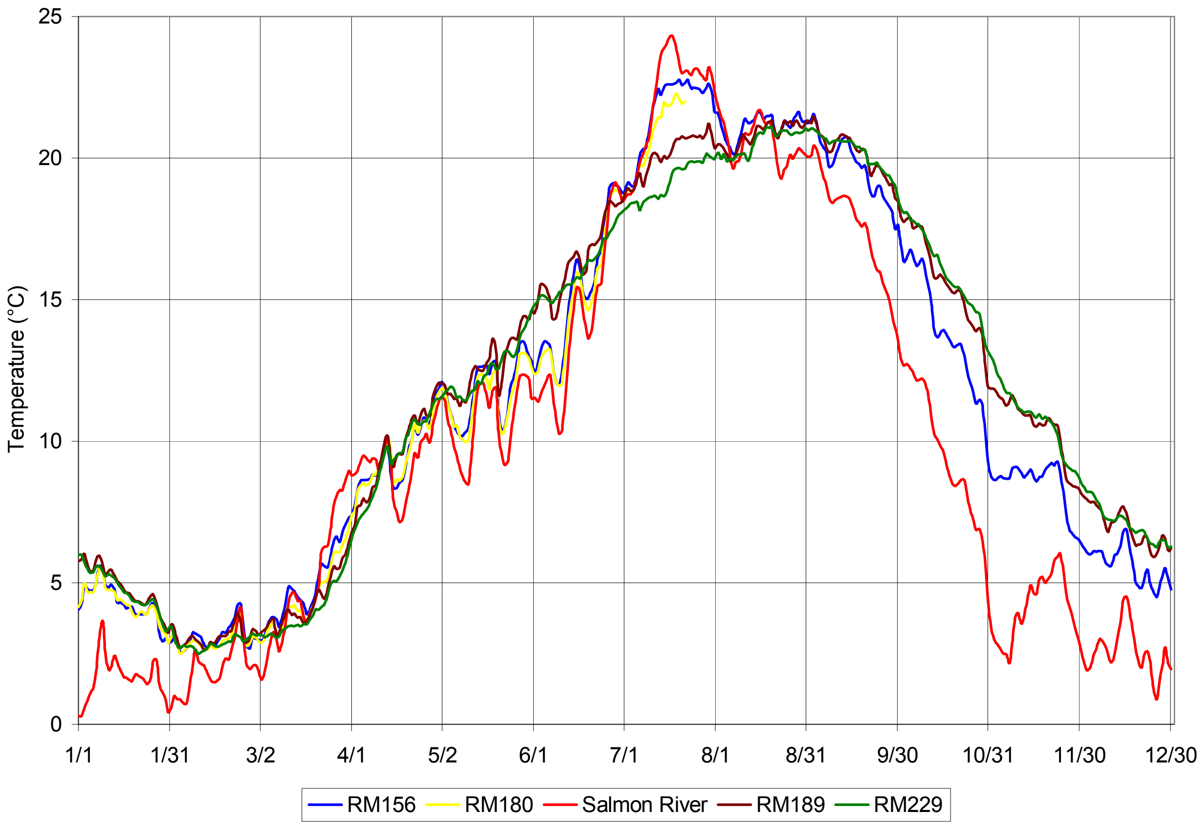


Figure 3.23. Snake River average daily water temperature for river mile 156 to 229, plus Salmon River temperature during 2002 (Data provided by Idaho Power).

Figure 3.24. Depicts warming at selected stations in the Snake River reach above Lower Granite pool in July of 2002. The major heat contributor is the Salmon River with an average increase of 0.89°C flowing in at about river mile 188 on the Snake. The other reaches show similar warming trends of about 0.02°C per river mile.

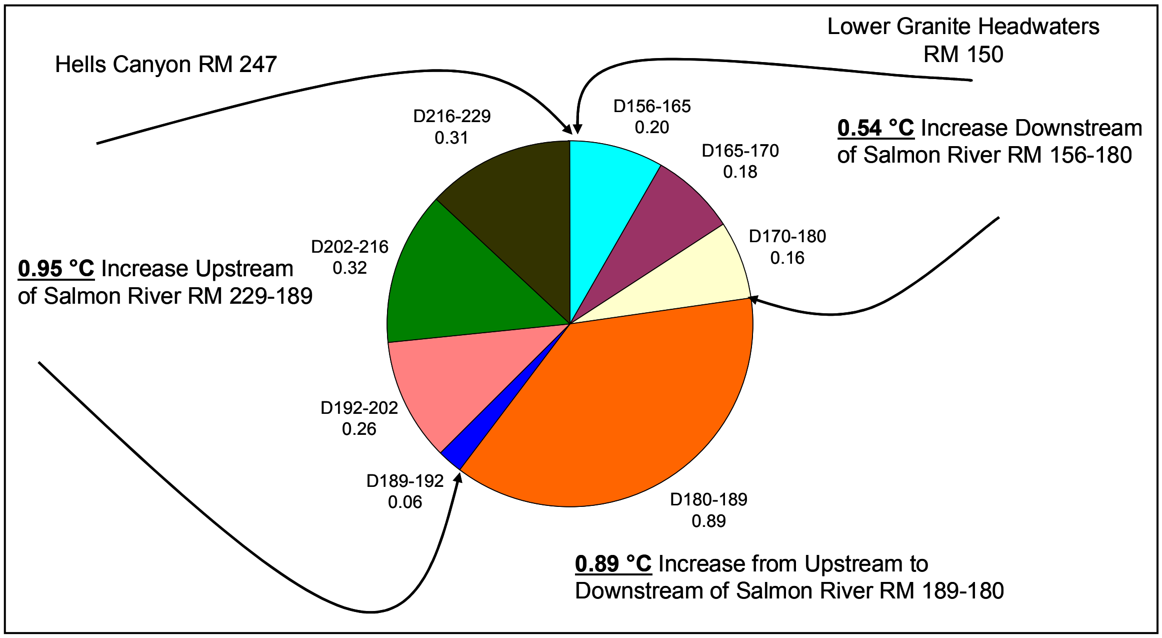


Figure 3.24. Lower Snake River average warming from RM 229 (19.1°C) to RM 156 (21.5°C), July 2002.

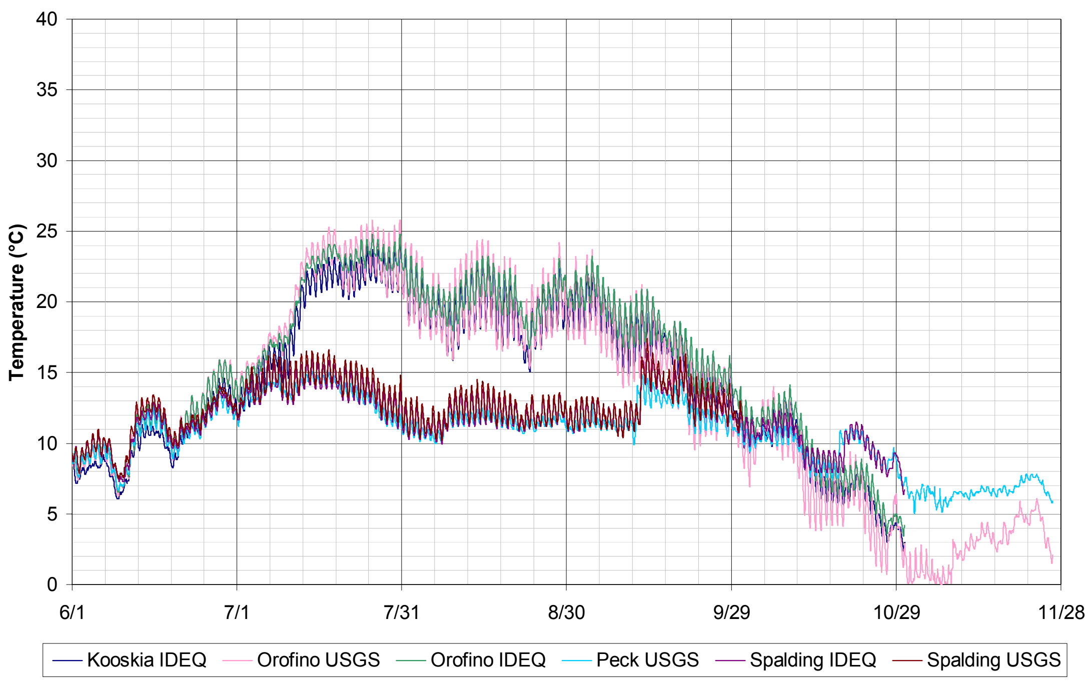


Figure 3.25. Selected temperature monitoring stations on Clearwater River, June – November 2002. (Data provided by Idaho DEQ and USGS)

3.3.7.3.2 Clearwater River Thermal Characteristics

Figure 3.25 depicts Clearwater temperatures for the upstream main fork at Orofino, ID, and Kooskia, ID, plus lower river stations at Peck, ID, and Spalding, ID. The sources of data for these stations include both USGS and Idaho DEQ. As on the middle Snake River, the upstream Clearwater temperatures for the Kooskia and Orofino stations went above 20°C by the second week in July and peaked at 22-25°C during late July. Diel temperature cycles for these stations ranged from 2 to 5°C. The downstream stations at Peck and Spalding peaked at around 15°C with daily fluctuations of only 1-2°C.

3.3.7.3.3 Dworshak Releases and North Fork of Clearwater River

Figure 3.26 depicts water temperatures for the north fork of the Clearwater River in the releases from Dworshak Dam and 1 mile downstream at the USACE fixed monitoring station (DWQI). In general these temperatures fluctuated significantly in relation to operation of Dworshak dam. Intake elevation for the powerhouse, powerhouse discharge, and discharge of the spillway affected the average release temperatures as recorded 1 mile downstream at the USACE fixed monitor DWQI. Station DWQIP5 located directly across the river from station DWQI remained 0.5°C warmer than the fixed monitor (DWQI) temperature log during the period of spill. These two stations would consist of a mix of the releases from the powerhouse and spillway at Dworshak.

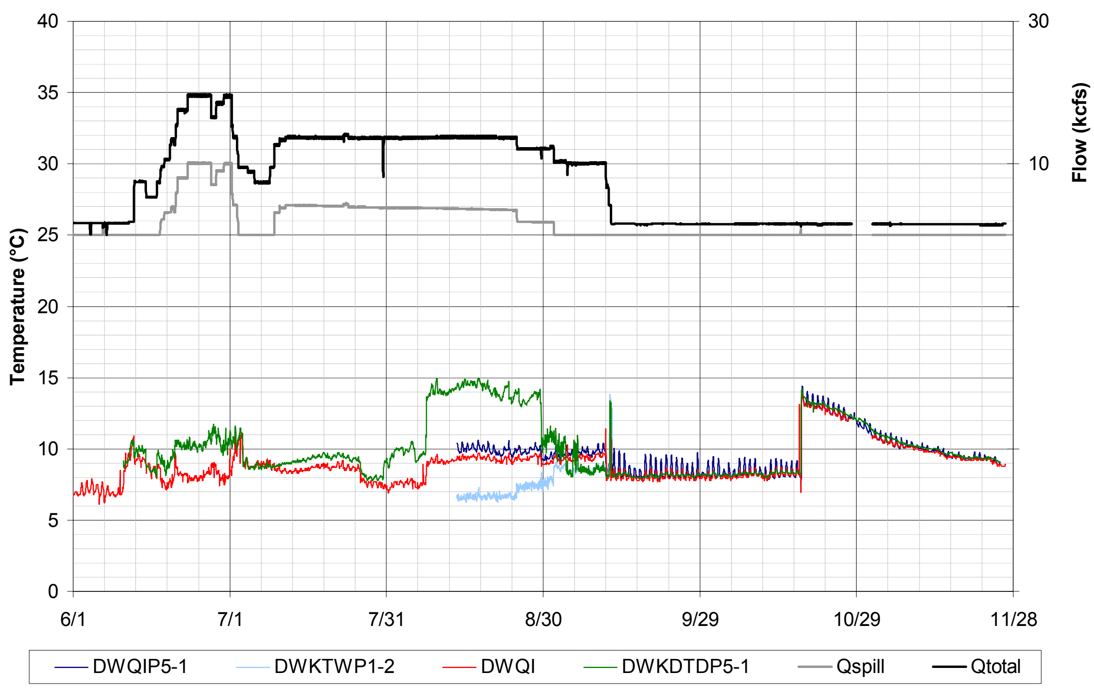


Figure 3.26. Water temperatures downstream of Dworshak Dam on the north fork of the Clearwater River and project discharges, June – November 2002.

3.3.7.3.4 Temperature Impact on the Clearwater River

Figure 3.27 depicts a flow weighted average temperature calculation for the lower Clearwater River at Lewiston using discharge and temperatures for Orofino on the Clearwater River and DWQI on the North Fork of the Clearwater River. During the July 14 through September 11 period the average water temperature at Lewiston was 12.9°C. The average calculated temperature was 2.2°C cooler at 10.7°C for the same period. The average temperature at PEKI on the Clearwater was 11.6°C for the same period. The difference of 2.2°C at Lewiston and 0.9°C at PEKI are due to the solar warming of the river. The water at Lewiston also experienced wider daily swings in temperature than shown in the flow weighted calculated average. Decreases in Dworshak cold water releases on September 12th resulted in quick increases in water temperatures for both the measurements and calculated values for the Peck station.

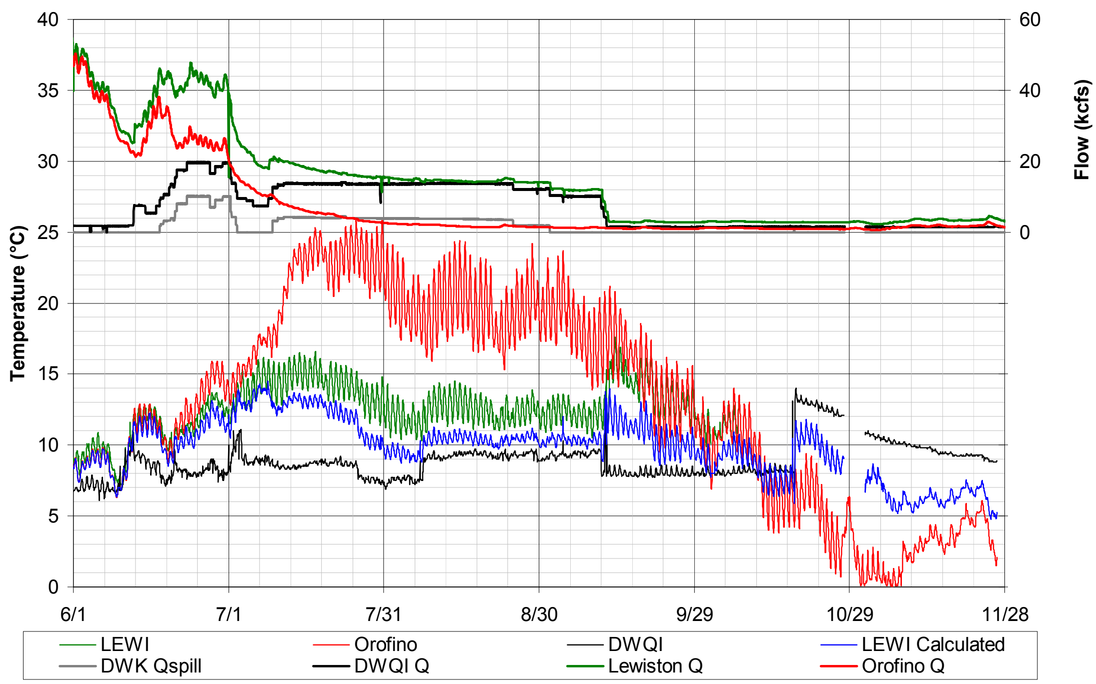


Figure 3.27. Temperatures and discharges at DWQI on the north fork of the Clearwater River and at Orofino and Lewiston on the Clearwater River, plus a flow-weighted temperatures calculated for the Clearwater River at Lewiston, June – November 2002.

3.3.7.3.5 Temperatures and Discharges at the Confluence of Snake and Clearwater Rivers and Influence on Lower Snake River Projects

Figure 3.28 presents a similar calculation for the waters at the confluence of the Clearwater and Snake Rivers using river temperature and discharge for the lower Clearwater (Lewiston) and middle Snake River (Anatone) to calculate the flow weighted average temperature of waters flowing into the Lower Granite pool. The calculated inflow temperature was compared to LGNW values by first adding the time of travel to time stamp for the calculated values. The calculated inflow values averaged 17.5°C for the period of July 14 to September 12 while the releases from Lower Granite for the same period average 18.2°C or 0.7°C warmer. The difference was determined first by calculating a time of travel from the headwaters to the dam using the theoretical retentions presented in Figure 3.5. The average retention time for Lower Granite changed from 5 days to 7 days during the period of comparison. The 0.7°C warming in Lower Granite pool would be primarily attributed to solar warming since there are only minimal tributary and other sources of heat present in the system.

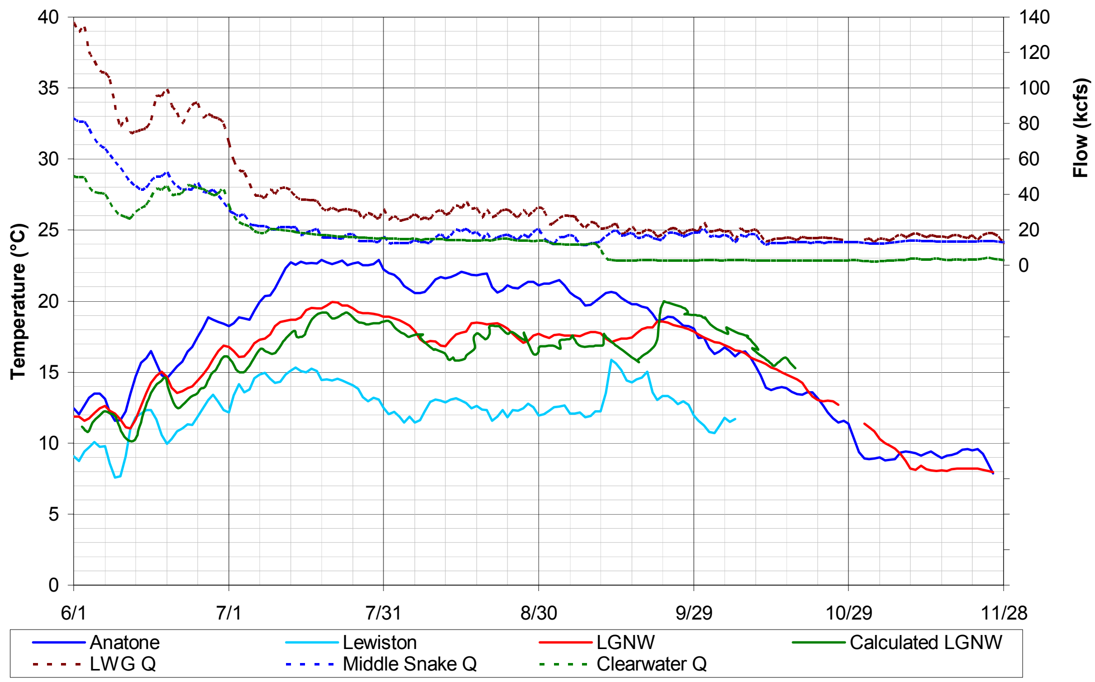


Figure 3.28. Daily average temperatures and discharges for Clearwater River (Lewiston), Snake River (Anatone), and Lower Granite releases (LGNW), plus flow-weighted daily temperatures calculated for outflows from Lower Granite project (Calculated LGNW), June – November 2002.

Clearwater River temperature at Lewiston increased 4°C on September 12, 2002 (Figure 3.28). This increase was immediately following the decreased cold water releases from Dworshak. Over the next twelve days, there was a gradual increase by 2°C in Snake River water at LGNW. Other responses in Snake River temperatures further down river were likely overshadowed by complicated heated and cooling cycles responding to changing weather conditions. Figure 3.29 depicts the longitudinal trend in warming on down the Lower Snake River to the Ice Harbor tailwater monitor. Indications from this data are for coincidental responses downstream as significant water temperature changes occur at Lower Granite Dam, but it is difficult to determine whether the cause was due to coincidental weather changes in the system or release changes at Dworshak Dam.

When considering time of travel, the warming by project is presented in Table 3.2 for the period starting in the last week of June and ending in mid August with waters at the confluence of the Snake and Clearwater Rivers. Average warming for the entire 140 miles for the Lower Snake River during this period was 3.2°C, which is only 1°C higher than the 2.2°C reported above for the 40 miles of the Lower Clearwater River.

Table 3.2. Average water temperature at Lower Snake project tailwaters during late June to mid August 2002			
Station	River Mile	Average Temperature	Average Warming
FWCLWG*	140	17.4 °C	
LWGN	107	18.3 °C	0.9 °C
LGSW	70	19.2 °C	0.9 °C
LMNW	42	19.7 °C	0.5 °C
IDSW	6	20.6 °C	0.9 °C

*FWCLWG = Flow weighted calculated inflow to Lower Granite Pool

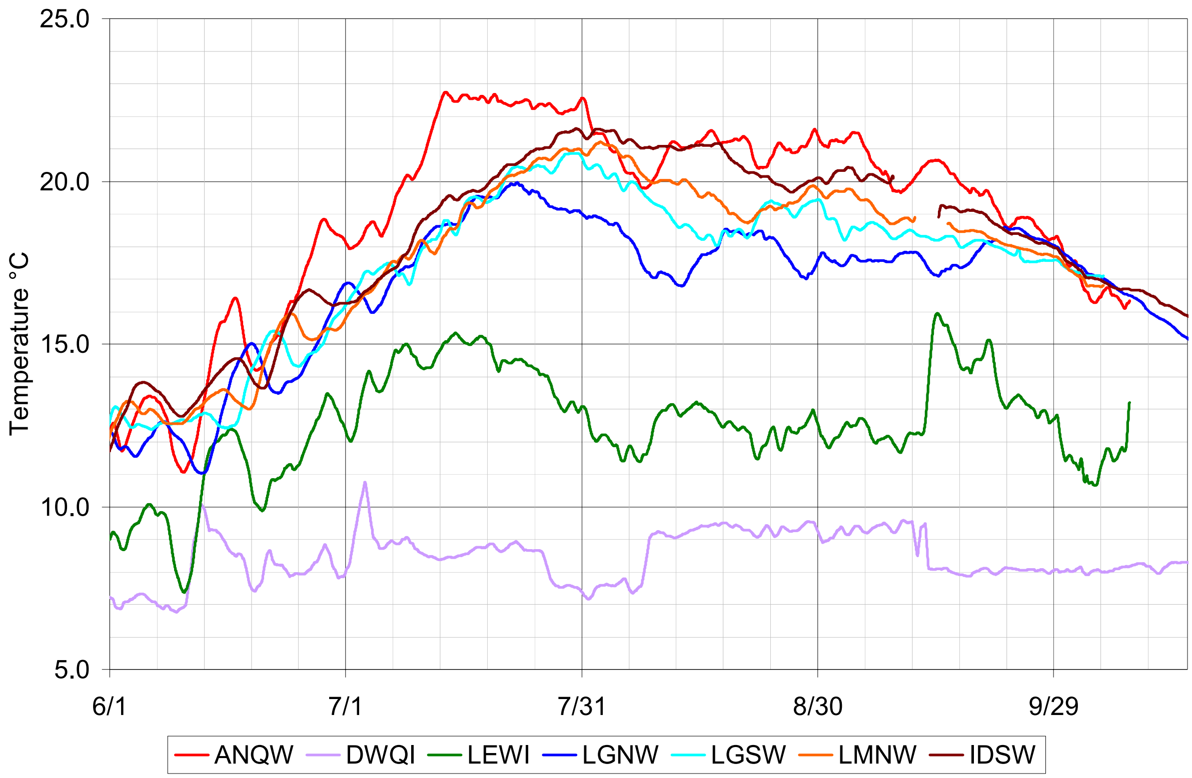


Figure 3.29. Twenty-four hour running average water temperatures showing a longitudinal trend from Lewiston (LEWI) and Anatone (ANQW) downstream to each project tailwater site, June – October 2002.

3.3.7.4 In-Project/Fishway Thermal Studies

The Walla Walla District has been conducting lower Snake River project fishway temperature studies since August 1999. This work has focused on thermal gradients in the fishways from the upstream exit pools to the downstream entrances. Generally 5 to 7 thermal logging devices were dispersed throughout the length of each fishway, logging data hourly from April to October each year. During the 2001 season temperature differences from 5 to 8°C were recorded for both the Lower Granite and Little Goose fishways. An example of those temperature time histories for the Lower Granite fishway is presented in Figure 3.30 for the 2002 monitoring season (data provided by Rex Baxter, Walla Walls District). Daily temperature spikes became apparent in the exit pool during June and by July the exit pool waters stayed consistently warmer than the downstream fish entrance until early September. The daily spiking which is evident in the surface waters for Lower Granite and the other Lower Snake River pools continued in the exit pool throughout the summer period. The fishway temperature gradients are more severe in the Lower Granite and Little Goose fishways than in the downstream projects of Lower Monumental and Ice Harbor Dams. This coincides with the larger vertical thermal gradients present in Lower Granite pool and, to a lesser extent, Little Goose pool.

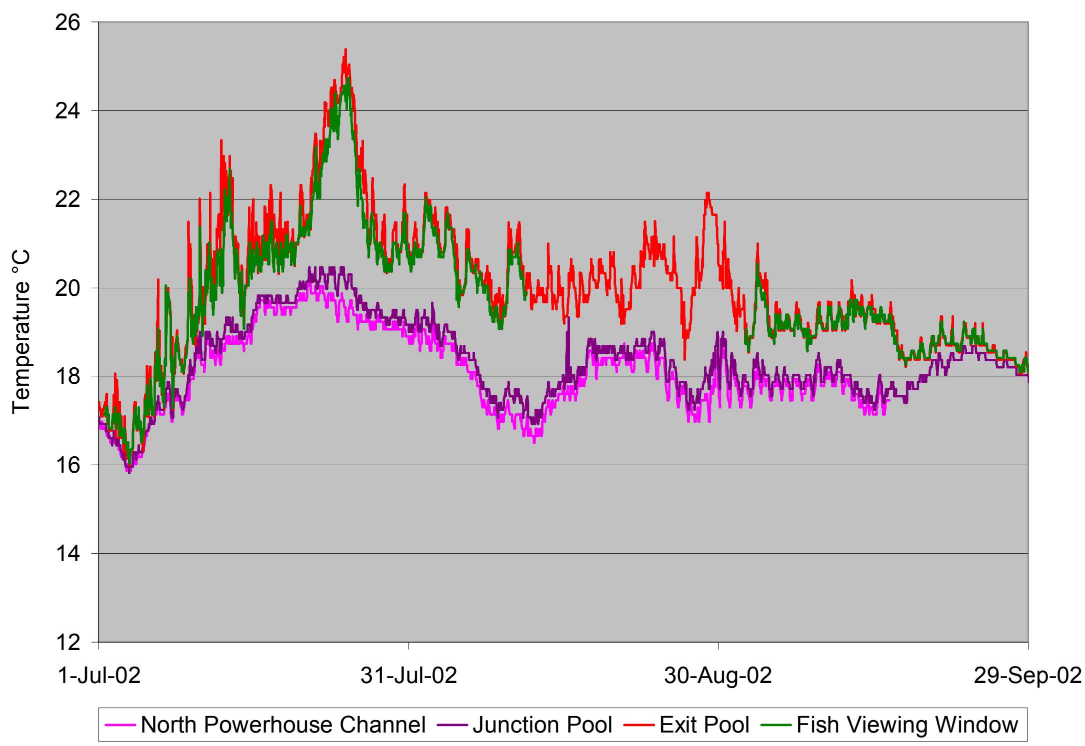


Figure 3.30. Lower Granite fishway temperatures, July – September 2002 (data provided by Rex Baxter, Walla Walla District).

3.4 Response to Objectives/Questions

3.4.1 Characterization of Lower Snake River Thermal Patterns

Thermal and hydrologic processes result in significant thermal, spatial, and temporal temperature gradients in the Lower Snake River. One of the more important features is the extreme vertical density and temperature gradients resulting in Dworshak reservoir. The annually occurring 12-14°C change in water from the surface down to 60 m results in 4-6°C stored in the lower depths, some of which can be released through the selective withdrawal system on the dam.

Release of the cold waters into the North Fork of the Clearwater River can result in rapid and significant changes in the lower Clearwater River temperatures depending on the ratio of the warmer upper Clearwater River to that from the North Fork. The resulting change in Lower Granite forebay water temperature is more subtle/dampened and highly dependent on the ratios of the Snake and Clearwater River water, total discharge (travel time), and weather conditions.

Annual thermal cycles are consistent at all of the study area sampling stations as would be expected. Spring warming trends start in March with most station's temperatures (both in-pool and in-river) peaking in late July, followed by fall cooling. Maximum temperatures were observed a few weeks earlier in Dworshak pool. Daily solar warming results in significant diel temperature cycles as well as lasting general warming on most of the riverine reaches. This is true for both the middle Snake as well as the Clearwater Rivers.

Based on the screening study data, in conjunction with data from NPL (Cook et al, 2003) collected upstream on the Lower Granite pool, a density under flow of the Clearwater River water results when mixing in with the Snake River waters. This incomplete mixing and forced thermal stratification persists throughout the length of Lower Granite pool with the colder Clearwater River water flowing underneath the warmer Snake River waters. There appears to be slight warming of the surface waters but once the Clearwater has at least partially mixed in there only slight change in the bottom water temperatures by the time they reach the Lower Granite Dam. The resulting forebay temperature profiles may have as much as a 6°C gradient from surface to bottom. This condition of a thermally induced density gradient exists from early July until mid September.

Data for the stations farther downstream of Lower Granite dam indicated much weaker and often shorter lived vertical thermal gradients. Data for Ice Harbor forebay indicated surface warming but a very small temperature gradient from there to the bottom.

Longitudinal thermal gradients due to warming as the river flowed down the Lower Snake were indicated by the mixed river measures such as the tailwater fixed monitor data collected by the USACE. The change was gradual from project to project with a total change of 2°C from Lower Granite Dam down to Ice Harbor Dam during the

July-August period. In addition, a longitudinal increase of approximately 1°C occurred in the Lower Granite pool from the head waters down to the dam. Changes of approximately 1°C were indicated in the downstream reaches of the Clearwater River as well. Occasional warming by 0.5°C was detected on the middle Snake River from river mile 170 down to river mile 156 during the July-August period.

Table 3.3 presents a summary of average river water temperature and warming during July 2002, for the Lower Snake and Clearwater Rivers. The data indicate the possibility of significant warming from each of the three major river segments.

Table 3.3. Snake River average water temperature and warming during July 2002.

River Reach	Station	River Mile	Average Temperature	Average Warming	Warming by reach
Snake above Salmon R.	Hells Canyon Release	229	19.1 °C		
Snake above Salmon R.	RM 189	189	19.7 °C	0.6 °C	
Snake Salmon River	RM 180	180	20.6 °C	0.9 °C	
Snake below Salmon R.	Lower Granite Headwater	156	21.5 °C	0.9 °C	2.4 °C
Clearwater/North Fork	Calculated	40	12.3 °C		
Clearwater	PEKI	33	13.0 °C	0.7 °C	
Clearwater	LEWI	2	14.2 °C	1.2 °C	1.9 °C
Lower Snake/Clearwater	Calculated	140	17.4 °C		
Lower Granite	LWGN	107	18.3 °C	0.9 °C	
Little Goose	LGSW	70	19.2 °C	0.9 °C	
Lower Monumental	LMNW	40	19.7 °C	0.5 °C	
Ice Harbor	IDSW	6	20.6 °C	0.9 °C	3.2 °C

Lateral thermal gradients were not found to be a major component of the spatial patterns. Some minor differences were determined between stations and depths for any one forebay. However, these differences were minimal in relation to the vertical and even some of the longitudinal gradients. The average differences recorded were generally in the order of 0.2°C and comparable to instrument/measurement uncertainty. Greater differences were observed for specific times but likely can be explained by water movement (wave or seiche action) and/or minor differences in the recorded depths of the instruments.

3.4.2 Evaluation and Recommendations for Fixed Water Quality Monitors

3.4.2.1 Representativeness

In general the tailwater monitor was a good measure of average forebay water temperature even during periods of significant vertical gradation. This is illustrated in Figures 3.31 and 3.32 for Lower Granite and Ice Harbor projects which contrast the fixed monitor (tailwater and forebay) to profile time histories during 10 days of July for each. In both cases the profile column average data was no different from the tailwater fixed monitor data. On the other hand the forebay monitors, LWG and IHR, were both very comparable to the 5 m profile instruments as would be expected during the stratified period. Both are point measures in space but the tailwater reach is generally well mixed and made up of a fairly uniform blend of the forebay water in the case of the Lower Snake projects. The forebay instrument is positioned at one discreet depth in an area that can experience some significant vertical thermal gradients and will be a biased measure of forebay temperature. These relationships were found to be the same for two other projects, Lower Monumental and Little Goose.

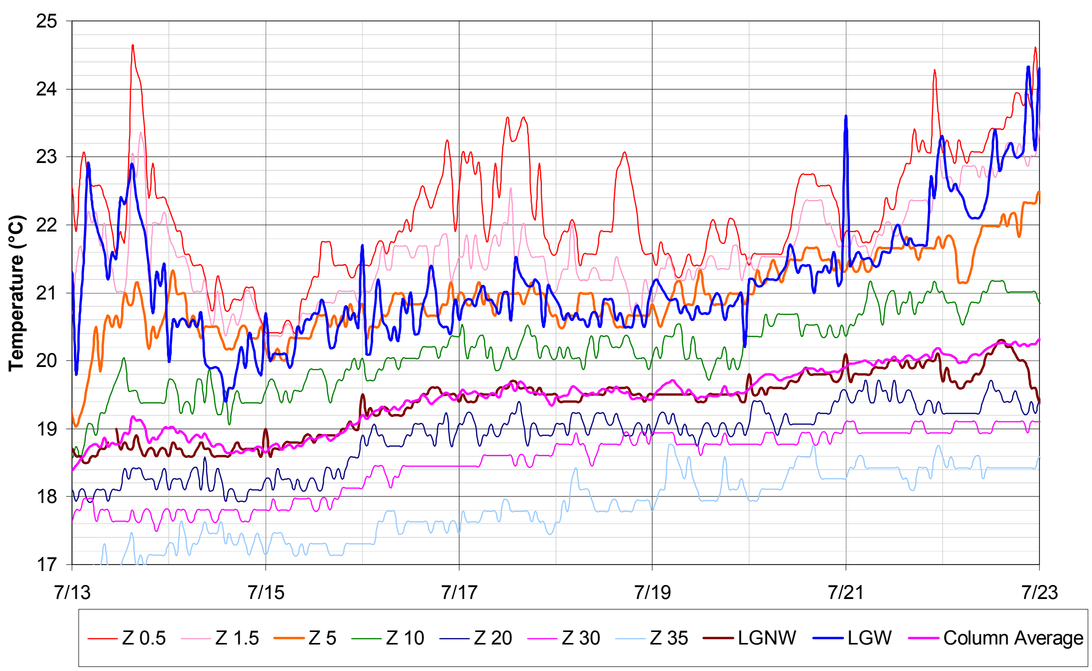


Figure 3.31. Temperature profile for Lower Granite forebay (LWGFBP2) with fixed monitor and column averaged data overlaid, July 2002.

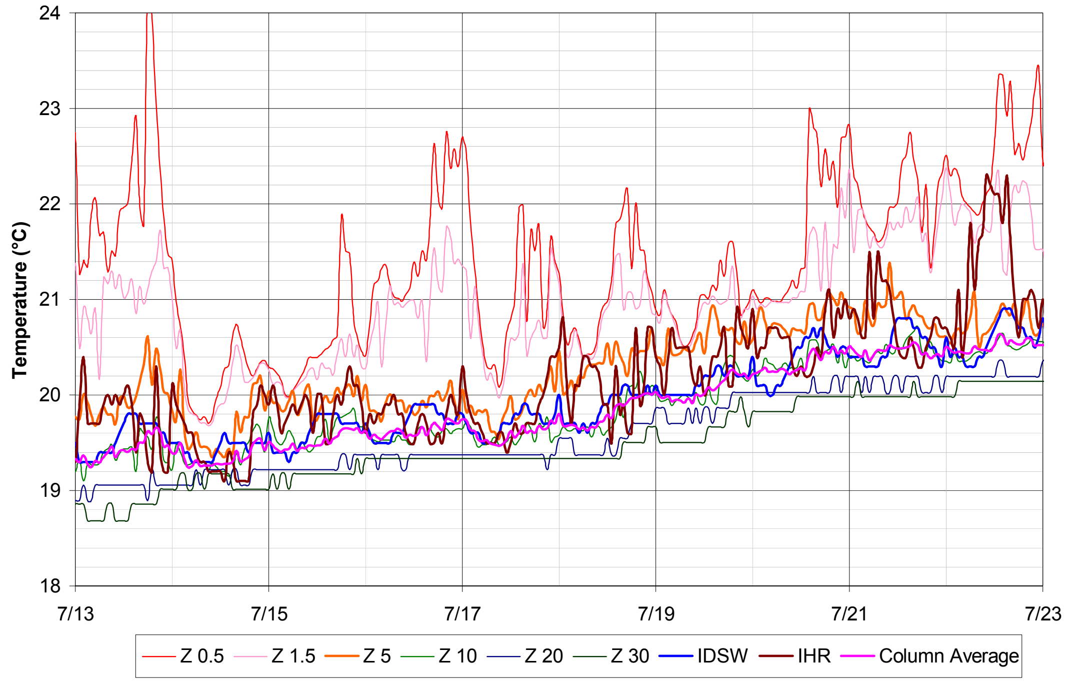


Figure 3.32. Temperature profile for Ice Harbor forebay (IHRFBP2) with fixed monitor and column averaged data overlaid, July 2002.

3.4.3 Recommendations for Fixed Monitoring Stations

In future applications and/or studies, the potential bias associated with the forebay temperature monitoring during stratified periods should be recognized and accounted for while doing analysis or decision making. It would be desirable to install permanent automated profiling instrument strings to describe vertical thermal patterns associated with Lower Snake River project forebays. The recommended depths are 0.5, 1.5, 3, 5, 10 meters and then at 5 meter intervals to within 1 m of bottom. Since minimal lateral bias was indicated in the screening study, one station located at the deepest point, preferably in the thalweg, will be adequate to get representative temperature measures of the forebay waters. This station should be located an adequate distance upstream to avoid any effects from the dam on water movement such as mixing, down welling or upwelling. Collection of real-time data could occur on an as-needed basis, depending on how the data would be used.

The tailwater fixed monitors were determined to be representative of the well mixed project releases which is generally a good indicator of average column conditions in the project forebay. No change is recommended for the Lower Snake River tailwater instruments.

3.4.4 Requirements to Meet Model Resolution

The Lower Snake River can experience a high degree of stratification which supports vertical density gradients. This results from incomplete inflow mixing of waters of different temperatures such as the Snake and Clearwater Rivers. The other factors heavily influencing the vertical and longitudinal gradients in temperature is solar warming and wind mixing. With this understood, the multiple dimensional properties of the Lower Snake River must be taken into account when modeling is required. If the purpose is to describe or quantify habitat then a 2-dimensional approach is called for to provide adequate resolution in the entire Lower Snake River. If the purpose is to forecast average temperatures at some point downstream then a 1-dimensional approach will address most of the Lower Snake River. The exception is likely in Lower Granite pool, which experiences some of the more extreme variability in the thermal patterns.

4. MODEL REVIEW AND SELECTION

The RPA 143 subgroup of the Water Quality Team (WQT) identified several questions that needed to be addressed by a thermal energy budget model of the Lower Snake River. The subgroup then identified those questions that met two criteria: they were of high priority, and they required the use of a model of river temperatures, along with monitoring data, to help quantify the operational options. These questions, which were both important and needed a model, are listed in Appendix B.

4.1 Geographic Domain

The geographic extent of the selected model will be downstream from the Hells Canyon Complex on the mainstem Snake River and include tributary contributions from the Salmon, Grande Ronde, Clearwater, Palouse and Tucannon Rivers. The model will also include the discharge and temperature conditions resulting from the selective withdrawal system at Dworshak Dam on the North Fork Clearwater River to the mouth of the Clearwater River.

4.2 Model Selection Criteria

Selection of the model for this assessment has several criteria. The basis for the criteria is from RPA 143's understanding of the questions that need to be addressed and a conceptual understanding of how the river functions after evaluating existing data, models and reports of the Lower Snake River. These criteria are listed below:

1. The model will have at least 2-D resolution (horizontal down the length of the river plus vertical);
2. The model is non-proprietary and any organization or agency can obtain the code for the model and run simulations;
3. The model has previously been applied to similar applications including river and reservoir conditions;
4. The model will allow for release of water from Dworshak Reservoir using selective withdrawal as well as outlet structures at dams;
5. The model is documented, currently maintained and is expected to be in use for the next few years;
6. The computer run time should be fast enough to be usable as an operation tool;
7. The model should have the capability of simulating other water-quality parameters besides temperature.

It is desirable, but not a criterion, that people in the Pacific Northwest have experience with the model.

4.3 Review of Potential Models

There were nine different models considered for the Lower Snake River temperature modeling effort. Information gathered about each of the models relative to the criteria is listed below. Additional information on each model is in Appendix F and in some cases in section 2.1.

4.3.1 CE-QUAL-ICM

Dimensions……………………	1, 2, or 3-D
Proprietary…………………….	Public
Previous application…………..	Estuaries on East and West coast
Outlet structure options……….	None
Documented and maintained….	Yes http://www.wes.army.mil/el/elmodels/index.html
Run time for 1 yr simulation….	Dependent on grid resolution and number and type of constituents
Other WQ parameters available	Nutrients, eutrophication, sediment oxygen demand

4.3.2 CE-QUAL-W2

Dimensions…………………..	1, 2-D (quasi 3D)
Proprietary……………………	Public
Previous application………….	Several rivers and reservoirs in US and Western US
Outlet structure options………	Point, line, distributed source
Documented and maintained…	Yes http://www.ce.pdx.edu/w2/Applications.html
Run time for 1 yr simulation…	Depends on grid resolution (hours generally)
Other WQ parameters available	Dissolved oxygen, nutrient, algal dynamics, sediment

4.3.3 Coltemp

Dimensions……………………	1-D
Proprietary…………………….	Public
Previous application…………..	Columbia River Basin, Dworshak/Snake River
Temperature Management	
Outlet structure options……….	Empirical selective withdrawal approximations
Documented and maintained….	Subset of HEC 5Q
Run time for 1 yr simulation….	Depends on system size (minutes)
Other WQ parameters available	?

4.3.4 EFDC (Environmental Fluid Dynamics Code)

Dimensions……………………	1, 2 or 3-D
Proprietary…………………….	Non-proprietary
Previous application…………..	Lower Granite Pool, Lower Snake River and McNary Reservoirs and Wanapum and Priest Rapids Reservoirs
Outlet structure options……….	Specify forebay stage
Documented and maintained….	Yes – Jin, K.R., J.H. Hamrick and T. Tisdale, 2000
Run time for 1 yr simulation….	Lower Granite Pool, Intel P4 (1.7 GHz) 20 CPU days to perform a 1-year simulation
Other WQ parameters available	Sediment transport, sediment-contaminant interaction, wetting/drying of cells

4.3.5 MASS 1 (Modular Aquatic Simulation System 1 D)

Dimensions……………………	1-D
Proprietary……………………..	Non-proprietary
Previous application…………...	Lower Snake River, Dworshak, Hanford reach Columbia River, Wanapum and Priest Rapids
Outlet structure options………..	Specified forebay stage, project discharge, stage target and discharge target are boundary conditions types
Documented and maintained…..	Yes – Richmond, M.C., W.A. Perkins and Y. Chien, 2000
Run time for 1 yr simulation…..	Mid-Columbia Application on a 1.7 GHz P4 (460 river miles, 1094 cross sections, hydro time step = 30 min, temperature time step = 3 min) = 90 min/year
Other WQ parameters available	Total dissolved gas and dissolved oxygen

4.3.6 MASS 2 (Modular Aquatic Simulation System 2 D)

Dimensions……………………	2-D depth averaged
Proprietary……………………..	Non-proprietary
Previous application…………...	Lower Snake River, Columbia River, Hanford reach
Outlet structure options………..	Can simulate a point withdrawal in 2D, specified and project discharge – boundary condition types
Documented and maintained…..	Yes – Richmond, M.C., W.A. Perkins and Y. Chien, 2000
Run time for 1 yr simulation…..	Bonneville Pool on a Intel P4 (1.7 GHz) system = 10 CPU days to simulate 1-year
Other WQ parameters available	Total dissolved gas, dissolved oxygen, sediment transport, sediment contaminant interactions and wetting/drying of cells

4.3.7 MIKE 11

Dimensions……………………	1-D river flow
Proprietary……………………	Proprietary
Previous application…………..	Numerous worldwide; Snake River Hells Canyon Complex; Clearwater/Lower Snake Reservoirs; South Fork Clearwater; Pudding Rive, Oregon; Napa River and Klamath Lake
Outlet structure options………..	Weirs, culverts, regulating structures, control structures, dam-break, user-defined and tabulated
Documented and maintained…..	Yes. www.dhigroup.com
Run time for 1 yr simulation…..	Depends on numerous factors
Other WQ parameters available	Many add on modules are available including sediment transport and total dissolved gas

4.3.8 RBM 10

Dimensions…………………….	1-D
Proprietary……………………..	Non-proprietary
Previous application…………...	Columbia River, Lower Snake River, Dworshak Dam, Box Canyon Dam
Outlet structure options………..	None
Documented and maintained…..	Yes – EPA, 2001
Run time for 1 yr simulation…..	Less than 1 minute for Snake/Clearwater Rivers
Other WQ parameters available	?

4.3.9 WQRRS

Dimensions…………………….	1 D
Proprietary……………………..	Public
Previous application…………...	?
Outlet structure options………..	Empirical selective withdrawal approximations
Documented and maintained…..	Yes – http://www.hec.usace.army.mil/
Run time for 1 yr simulation…..	Minutes
Other WQ parameters available	Ecological cycle conditions in river and reservoir Systems

4.4 Model Recommendation

The RPA 143 workgroup recommends the two-dimensional model, CE-QUAL-W2, version 3.1, developed and maintained by USACE, be adopted for use in the Lower Snake River. This model will be used on the Lower Snake River, North Fork Clearwater and Clearwater Rivers, Dworshak Reservoir and the four reservoirs on the Lower Snake River. It will be used to assess reservoir releases at selected depths, flow routing, simulations of water temperature and has the capability of addressing other water-quality parameters such as total dissolved gas, dissolved oxygen, algal populations and nutrients. This model meets all the criteria identified for this assessment. In addition, several persons in the Pacific Northwest are knowledgeable about the use of the model.

5. MODEL DEVELOPMENT

The following is a framework for evaluating and documenting the development of a temperature model for the Snake and Clearwater Rivers. The discussions below are intended to communicate workgroup expectations and baseline information for model developers and interested parties. This information should be considered in the development of future workplans.

5.1 Management Objectives

RPA 143 calls for development of a temperature model and data collection strategy for the lower Snake River. The workgroup envisions that the model will be used in two ways. First, the model will be used, in a manner similar to past modeling evaluations, to improve our understanding of the system, such as the spatial/temporal patterns of temperature in the pools and the impacts of alternative hydropower operations on river temperatures. Second, the workgroup believes the model should be used as a real-time, predictive tool to assist in the operation of Dworshak Dam releases to meet target temperatures in the Clearwater and Snake Rivers. This kind of tool could lead to a more optimal use of limited cold water releases to improve downstream fish habitat. Since there are currently no target temperatures established for the system, additional policy work to establish target temperature conditions will need to proceed in parallel with real-time model development.

Because of the interest in vertical stratification within the impoundments, the workgroup selected a model framework (CE-QUAL-W2) that provides 2-dimensional, laterally-averaged estimates of temperature.

5.2 Conceptual Model

5.2.1 System Boundaries

5.2.1.1 Geographic Boundaries

A map of the study area is included in Figure 1.1. The workgroup proposes to build an initial model domain for the minimum area needed for effective evaluation of operational effects on temperature (Phase 1) and expand the model in subsequent phases. The proposed phases are as follows:

Phase	North Fork Clearwater Boundary	Mainstem Clearwater Boundary	Upstream Snake River Boundary	Downstream Snake River Boundary
1	Mouth	Orofino	Anatone (RM 169)	Lower Granite Dam
2	Dworshak Reservoir Head	Orofino	Hells Canyon Dam Tailrace	Mouth
3	Dworshak Reservoir Head	Orofino	Brownlee Reservoir Head	Mouth

The first phase includes the minimum system components needed to develop and evaluate an operational tool for temperature management (Dworshak flow augmentation). The specific sites are locations where long-term river flow and temperature monitoring has been conducted. The second phase expands the model system to include Dworshak Reservoir, the lower three projects on the Snake River and upstream on the Snake River to Hells Canyon Dam tailrace, in cooperation with Idaho Power Company. The third phase extends the model to Brownlee Reservoir, which influences discharges and temperatures of the Snake River. While Dworshak Reservoir has not been extensively modeled to date, Idaho Power Company has developed a CE-QUAL-W2 model for Brownlee Reservoir (Idaho Power, 1999) that should provide information for Phase 3.

5.2.1.2 Important Time and Length Scales

It is anticipated that the model will support multiple purposes. In terms of time scales of analysis, simulations of hourly temperatures may be desired for special studies on diurnal variation. For support of operations, daily average temperatures will probably be the metric of interest. The time span of interest is expected to range from a few days (operational decisions) to years (special studies).

In terms of length scales, previous efforts have indicated that the model domain for this system can be sub-divided into approximately mile-long segments for model calculations and outputs. In the vertical dimension, the length scales of interest should be on the order of one to two meters.

5.2.1.3 Important Processes

The temperature modeling conducted to date has indicated that advective heat inflows (tributaries, boundary inflows) and surface heat exchange represent the primary drivers of the mainstem Snake River and lower Clearwater River heat budgets. The elements of the surface heat exchange include short wave radiation, long wave radiation, black body radiation, evaporation, and conduction. Reasonable temperature estimates have been obtained without inclusion of other potential influences on the heat budget such as groundwater, shade, and point source discharges. The largest point source, Potlatch Corporation, should be included as an advective heat input. In the future, the effects of topographic shade on river temperatures warrants evaluation and possible inclusion in the model.

Vertical thermal stratification, which occurs in the impoundments, is an important process influencing fish habitat. Because water density is a function of temperature, stratification is also an important variable in the mixing and transport within the pools. Mixing at the confluence of the Snake and Clearwater Rivers is also influenced by the differences in the temperatures of the two rivers, particularly during flow augmentation periods. The model configuration and parameters should account for the expected mixing characteristics downstream of this confluence.

Hydroelectric facility operations have a significant effect on conditions in the Clearwater and Snake mainstems. Dworshak Dam, which has a selective withdrawal structure, determines both the flow and temperature of the North Fork Clearwater River.

Brownlee Dam (the upstream dam of the Hells Canyon Complex), does not have a selective withdrawal capability, but it determines the flow of the mainstem Snake River and hence plays a major role in downstream water temperatures. The two smaller downstream projects, Hells Canyon Dam and Oxbow Dam, are run-of-the-river dams with little influence on downstream flows.

5.2.2 System Characteristics

5.2.2.1 Model Domain: Impounded/Free-Flowing Mainstem Rivers

The model domain will consist of the mainstem Clearwater and Snake Rivers. The upstream segments of the Snake and Clearwater Rivers in the Phase 1 study area are free-flowing. Downstream of the confluence of the Snake and Clearwater, in the vicinity of Lewiston, the Snake River becomes a series of four impoundments with the surface elevation held relatively constant by the downstream dam structures. Free-flowing and impounded segments within the study area must be distinguished so the model captures the hydrodynamics properly. The W2 model package includes pre-processor programs to check the volume-elevation relationships and the water balances within the impoundments. The pre-processors should also be used to check the simulated water surface elevations, depths, and velocities in free-flowing segments.

5.2.2.2 Boundary Inflows: Upstream Mainstems and Tributaries

The flow and temperature of the upstream model boundaries and significant tributaries inputs will be included as boundary inputs of advected heat.

5.2.2.3 Surface Heat Exchange

In addition to tributary inputs of heat, the model will include surface heat exchange. The net heat exchange is calculated based on short wave radiation, long wave radiation, black body radiation, evaporation, and conduction. Based on the size of the rivers, shading of the water surface due to vegetation and/or topographic features may be negligible. However, topographic shading of the river surface will be considered as a possible future model improvement.

5.2.3 Source Characteristics

5.2.3.1 Outlet Structures

There are multiple structures that transport water through the dams. The primary structures are the intake structures to the powerhouse and the spillway. The configuration of these structures, including the depth from which water is drawn from the forebay, varies among the dams. Except for the Dworshak selective withdrawal system (which would be part of Phase 1), the structures and withdrawal depths are fixed.

5.2.3.2 Spill/Power

Since the powerhouse and spillway draw water from different depths, the flow through the dam should be distinguished as either powerhouse flow or spill flow in the model. The two flow contributions are monitored on an hourly basis.

5.2.4 Available Data Sources (Quality and Quantity)

Data quality is discussed at length under Data Collection Strategy. It is important to develop a common understanding of the different types of information needed for the model. The following is a general discussion of the kinds of data needed for the model and the available information at the present time:

5.2.4.1 Bathymetry

The geometry of a waterbody is critical for simulation of hydrodynamics and heat budgets. As a two-dimensional, laterally-averaged model, W2 requires the user to provide the cross-sectional width of the channel at each vertical layer of the model. This information is generated from profiles of the bottom of the waterbody. Because of the value of understanding the elevation/volume relationships and sedimentation patterns within the impoundments, there is generally ample bathymetry information for the Snake River below Lewiston. The limitations of the bathymetry information for Dworshak Reservoir and the Hells Canyon Complex may warrant additional data collection.

There is generally less bathymetry data for free-flowing stretches. For example, it is currently necessary to piece together bathymetry information from poorly archived studies and gauging stations to simulate the Clearwater River between Dworshak Dam and the confluence with the Snake River.

Because bathymetry information is collected by various agencies for a variety of purposes, it can be difficult to locate all the available data. As part of development of the W2 model, the model developers should collect and document the available bathymetry data sources. In data-rich locations, high resolution bathymetry information may require aggregation to datasets with one profile per mile (i.e., for each model segment), while in data-poor locations, a single profile may need to be used to represent river lengths of more than one mile.

5.2.4.2 Boundary Flows

Boundary inflows are critical to the water and heat balances of the system. Two of the three significant tributary and boundary flows to the Phase 1 model domain are monitored on an hourly basis by USGS with data available online (Snake River at Anatone and Clearwater River at Orofino). The third flow, the North Fork Clearwater, is monitored hourly by the USACE. Outflows at each of the Lower Snake dams are monitored as well.

There is a question as to the adequacy of inflow data to Dworshak Reservoir. The main inflow (north fork of the Clearwater River near Canyon Ranger Station) is monitored hourly, but a significant fraction of the inflows is not monitored (on the order of 60%). The phase 2 expansion to include Dworshak Reservoir would require estimation and/or additional data collection to improve the model inputs for this reservoir.

Phases 2 and 3 will require the addition of flow data for a number of significant tributaries. As with the Phase 1 tributaries, real-time data for these tributaries is available from USGS. Expansion to cover Dworshak Reservoir in Phase 2 will necessitate monitoring of the vertical elevation from which flow is released from the selective withdrawal inlets.

5.2.4.3 Temperature of Boundary Inflows

There has been no long-term, systematic data collection program for river temperature in this study area. The data collection strategy in this plan should significantly improve both the coverage and quality assurance of this monitoring. Generally, the temperature of the mainstem Snake River and hydroelectric project releases has been monitored consistently, while tributary temperatures (e.g., Clearwater River at Orofino) have been monitored only sporadically. In order to run dynamic simulations, EPA and other agencies have employed a variety of methods (or models) to fill data gaps and synthesize continuous temperature estimates for sporadically monitored tributaries. The basis for selection of a particular model to accomplish each synthesis, and the uncertainties associated with its use, should be documented during model development.

5.2.4.4 Temperature within Impoundments

To date, there has been very limited monitoring of temperature within the impoundments. Models have typically been evaluated using fixed point measurements in the forebays and tailraces of the dams. EPA has tested models using vertical, in-pool measurements collected by CRITFC in 1992. In the summer of 2002, vertical thermister strings were placed in the reservoir forebays by the USACE, and Battelle placed strings in the vicinity of Lower Granite Dam. The data collection strategy calls for long-term, vertical monitoring in the forebays and at locations within the pools.

5.2.4.5 Weather (Air Temp, Wind, Wind Direction, Dew Point Temp, Cloud Cover)

Historically, measurements of the five parameters of the heat budget calculation have been taken only at regional weather stations. In this study area, the three nearest stations are in Lewiston, Spokane, and Yakima. As a result, some model evaluations have assumed that conditions at the Lewiston airport are representative of conditions throughout the study area. There are a number of new AgriMet weather stations in this study area which monitor all the parameters of the heat budget except cloud cover, and monitoring has increased along with the interest in temperature assessment (see discussion of recent monitoring in Section 6., Data Collection Strategy). The use of Lewiston meteorology may be sufficient for initial model development and evaluation. Model developers should also examine the sensitivity of the temperature estimates to alternative weather datasets.

5.2.5 Other Data Issues

5.2.5.1 Real-Time Data System

To use the model as an operational tool, it will be necessary to devise a data management system to obtain and store the measured flow, water temperature, and weather data for each day leading up to the day of the predictive simulations. In addition, forecast information looking ahead approximately 2 to 5 days (approximate range of travel times from Dworshak to Lower Granite Dam) will need to be obtained on a daily basis.

One possible source of forecast information is the MM5 numerical weather prediction model. A regional MM5 forecasting effort is supported by the Northwest Regional Modeling Consortium, a group of local, state, and federal agencies and cooperating private companies. The model provides 72- hour forecasts of Pacific Northwest weather, and forecasts are produced twice daily by the University of Washington.

A forecasting system for river flows has been used by the project managers for the Columbia/Snake River hydropower system for a number of years. The workgroup expects that this forecasting information can be used for the real-time model.

5.3 Choice of Technical Approach

5.3.1 Rationale for Approach in Context of Management Objectives and Conceptual Model

A two-dimensional model of the system, beginning with the Phase 1 geographic coverage, should meet the most pressing needs identified by the RPA 143 workgroup. Future expansion of the geographic scope to include the key upstream control points of Dworshak Reservoir and Brownlee Reservoir will improve our understanding of the constraints on system operations to manage temperature in the mainstems.

The W2 model framework selected by the workgroup includes the necessary heat budget methodology, and the conceptual model proposed for evaluation of the system has been used in previous temperature studies.

5.3.2 Reliability and Acceptability of Methodology

The reliability of the heat budget method has been proven through many temperature studies throughout the United States. While there are alternative formulations available for estimation of specific elements of the heat budget (e.g., evaporation), the general method is a common part of dynamic water quality model frameworks such as W2.

The W2 model framework has already been employed to simulate temperature in the summer of 1992 in Lower Granite Pool (EPA, 2002). The model generally captured the observed temperature patterns in the pool, and the simulated outlet temperature was consistent with the timing and trajectory of the measured temperatures during periods of flow augmentation. The model tended to under-predict observed temperatures in the tailrace, with a mean difference between simulated and measured temperatures (measured - simulated) for the 29 sample days of 0.7°C with a standard deviation of 0.6°C. The root mean square difference was 0.2°C.

5.3.2.1 Important Assumptions

A number of simplifying assumptions will be necessary in the development of the model. Some of the likely assumptions include the following:

1) Lateral temperature variations in the mainstems are negligible.
2) Local meteorology at the water surface is represented by regional weather station data.
3) The Snake and Clearwater confluence is either completely mixed or stratifies based on the relative density of the two flows.
4) Groundwater, vegetation, topography, and point-source influences on river temperatures are negligible.
5) Assumptions about outlet withdrawal zones near the dams.
6) Assumptions necessary to complete water balances (e.g., handling of flow/elevation errors).

5.4 Parameter Estimation

Generally, parameters are estimated by comparing observed and simulated temperatures for a given period of analysis. Observations of vertical temperature profiles are needed for model evaluation and parameter estimation for a 2-D model. This kind of data is only available for the years 1992 (CRITFC) and 2002 (USACE and Battelle). The 1992 data were obtained from grab samples spaced from one to several days apart, while in-situ thermisters were used for the 2002 monitoring. The fixed tailrace temperature data is also available for these years. Additional data should be available for the summer of 2003.

The model includes a variety of parameters related to hydrodynamics and the heat budget that can be adjusted by the model user. For the hydrodynamic calculations, the parameters include roughness coefficients, eddy diffusivity, and eddy viscosity. Heat budget parameters include wind speed coefficients, wind sheltering coefficient, shade coefficients, and solar radiation absorption fraction. Generally, it is expected that a combination of W2 defaults and/or literature values will be used for most of these parameters.

In past work, the parameters associated with evaporation in the heat budget calculations have been adjusted from default values found in the literature to reduce the difference between simulated and observed temperatures. This is because (1) evaporation has a significant affect on the simulated temperatures, and (2) there is relatively high uncertainty in the actual wind speed at the river surface.

5.5 Uncertainty/Error

5.5.1 Error/Uncertainty in Input and Boundary Conditions

River flows drive both the advective heat inputs and hydrodynamics within the system. USGS reports that errors in river flow are generally less than 5% at good quality stations. Errors in flow estimates may also be compounded due to the necessary balancing of flows and elevations of the impoundments.

5.5.1.1 River Temperature

For simulations of 2002 conditions, hourly/daily temperature observations should be available for significant tributaries and mainstem boundaries. The error in measurements using continuous thermisters is generally ±0.2^{o}C (see further discussion in Section 6.5). Apart from measurement errors, river temperature data must be reviewed to minimize recording errors, and data gaps are filled using a variety of estimation techniques which include uncertainty as well.

5.5.1.2 Meteorology

While there are measurement errors in the meteorology data, a more significant source of error is the use of regional data to represent conditions at the river water surface. The long-term regional data collection at Lewiston has been augmented by new AgriMet stations in this study area. The error associated with local meteorological variability can be examined by testing the sensitivity of the model to these new weather datasets.

5.5.1.3 Error/Uncertainty in Specification of Environment

As discussed above, there are a number of specifications that establish the basic structure of the Snake/Clearwater system, including river geometry, physical mixing of tributary inflows, mixing characteristics within the system, types of outlet structures, friction coefficients, and flow balances. Some of the errors associated with these specifications, such as flow balance errors and volume/elevation relationships, can be quantified. Others could be evaluated through model testing and sensitivity analysis.

5.5.1.4 Structural Errors in Methodology (e.g., Effects of Aggregation or Simplification)

The model grid resolution and time series inputs should provide adequate spatial and temporal resolution for appropriate comparisons of simulated outputs to observed data. They should also address the management needs identified by the workgroup.

6. RECOMMENDATIONS FOR DATA COLLECTION STRATEGY

In order to continue management and enhancement of Lower Snake River project operation for thermal conditions in relation to biological habitat and anadromous fish migration through the use of real-time models and other related tools, it will be necessary to continue with good quality comprehensive data collection and management strategies. In addition to management support, this strategy will provide ongoing detailed characterization of the Lower Snake River spatial and temporal thermal patterns. The data collection strategy will also be instrumental in continued compliance monitoring as well as implementation and evaluation of Total Maximum Daily Load (TMDL) management for river temperatures. TMDL's for additional parameters could be addressed with additional sampling emphasis for the parameter or concern.

Data collection strategies recommended for numerical model implementation and continued operation or river temperature management fall into two categories, a long-term continued effort and the near-term or the 2003-2004 period. The primary types of data identified by the RPA 143 subgroup effort include water quantity, water quality, project operations (discharge and elevations), and meteorological conditions. Some of the more important criteria of the data collection strategy is that the information be of known acceptable quality and that it be available either real time or near real time (within hours). These data coupled with a user friendly accessible data management system are high priority items to support future regional efforts in water quality management on the river system. Lower priority data types would include added bathymetry and flow field data as needed to fill in gaps for support of model calibration and validation.

6.1 Long Term Data Collection Strategy

Data required to support future model calibration and seasonal simulation, as mentioned above, fall into three primary data types: water quality, water quantity and meteorological. The data availability should be real time to conduct short term forecasts of river conditions for management purposes. To address routine water quality or temperature sampling needs, the USACE should continue water quality monitoring at each project tailwater and forebay with the following recommendations:

- Water temperature monitoring should be conducted year round at all tailwater stations instead of sampling only during the spill season (April through September) as is the current standard for some stations.
- The sample interval should remain at 1 hour.
- The forebay monitor should be relocated an adequate distance upstream of projects to avoid down welling/upwelling associated with project vertical walls. The monitor station should be in or near the deepest part of the forebay cross section. This can be accomplished either by the use of water quality station floats or placement on upstream floating navigation lock guidance walls. The station locations should be selected on a project-specific basis.
- The point monitoring at one depth in the project forebay should be replaced with a profiling approach using a string of instruments. Forebay monitoring can be discontinued during the non-stratified winter period. The

instrumentation should be capable of real-time operation with sensors at as many as 8-12 depths, distributed from surface to bottom. The recommended sample depths are 0.5, 1.5, 3, 5, 10, and then 5 m intervals to the bottom.

- It is recommended to continue sampling at selected project tailwater/powerhouse release station locations, tributaries such as the Palouse, Tucannon, Grande Ronde, and the Salmon rivers, and other routine water quality stations located on both the Clearwater and Snake Rivers sites downstream of the Hells Canyon Complex.

Future long-term water discharge information requirements include continued routine USACE project operations data as well as a continuation of all current USGS gauging stations on the mainstem rivers and tributaries. This will address critical requirements to the model simulations including boundary conditions (flows from upstream and secondary tributaries) plus the individual project water management information such as pool elevation, storage, and discharge. The data collection interval should be hourly or shorter.

The meteorological data collection strategy requires continued operation of the following stations to support the model simulations.

- Pasco, WA, airport (NWS)
- Lake Sacagawea-Fishhook Recreation Area, WA, near Ice Harbor Dam (PAWS)
- Lake Bryan-Rice Bar, WA, near Little Goose Dam (AgriMet)
- Silcott Island, WA, mid-pool on Lower Granite pool (AgriMet)
- Lewiston, ID, airport (NWS)
- Dworshak pool/Dent Acres, ID (AgriMet)

A potential additional station should be considered for the Snake River reach below Hells Canyon Dam possibly at Cache Bar. The parameters to be monitored include air temperature, barometric pressure, wind speed, wind direction, solar radiation, and precipitation, dew point, and relative humidity.

6.2 Data Collection Program in 2003-2004

The water temperature data collection strategy for the short-term model calibration and validation is similar to the proposed long-term strategy with additional in-pool sampling on each Lower Snake River Project. An automated temperature profile monitor should be maintained in the deepest part of the river cross section approximately halfway upstream in Ice Harbor, Lower Monumental, and Little Goose pools. PNNL plans to continue adequate spatial sampling in Lower Granite pool for the same period. This will add the ability to validate model runs at various depths for more than one longitudinal location in each pool. The same sampling specifications (time intervals and depths) as used for the forebay stations should be applied.

Additional short-term requirements include single temperature monitors located at 5m deep on each draft-tube deck plus lateral stations located across river from PEKI and DWQI stations.

To better understand localized effects on wind, short-term deployments of multiple portable weather stations should be conducted for 2-week periods in selected river reaches for each of the Lower Snake River projects. This should provide information to better understand micro-meteorological variability in areas characterized by significant changes in river basin direction and morphometry.

6.3 In-Project/Fishway Thermal Studies

The Walla Walla District studies directed at evaluating fishway effects on fish passage will continue the phase one physical descriptions of fishway conditions. Thermal monitoring studies will continue at all Lower Snake River projects. Phase two of this effort is scheduled to begin in 2004 which will focus on relating fish passage characteristics or parameters to in-fishway water temperatures and gradients.

6.4 Relationship between Physical Conditions and Potential New Biological Monitoring

Future water quality monitoring should be flexible and adaptive to accommodate investigations of relationships between physical and biological parameters. It will be important to adapt as needed to support any new biological monitoring efforts.

6.5 Quality Assurance Program

The goal of any field data collection program is to collect data that best represents conditions at the study site and to compile that data as accurately as possible in data sets for later use in regulatory or scientific applications. This goal is achieved by minimizing data inaccuracies and by understanding variations in the actual sample water temperature and instrument measures of that water temperature. There are essentially three sources of errors: instrument error (theoretical limits due to design), sampling error (study design and technique of measuring water temperature), and database management error.

6.5.1 Sampling Uncertainty

There are two types of variations in water temperature, spatial (differences in water quality laterally, longitudinally, or vertically) and temporal (changes in water temperature over time). Point measures or samples from river/reservoir systems will have some degree of sampling and/or measurement uncertainty. Routine temperature monitoring, usually automated and typically conducted on the Snake River at a forebay monitor, can be reflective of the temporal or time series of events for a point of measure. However, this same instrument or measure may be impacted significantly on a spatial basis due to potential vertical or horizontal thermal gradients. Obviously any uncertainty in actual depth placement of a sampling instrument can add to the overall sampling error when vertical thermal stratification is present.

If there is a vertical component to the thermal characteristics of the river/reservoir, then an instrument placed at some discrete depth below the surface will likely not be representative of the water column (all depths) during any stratified period. Surface warming or colder underflows may be missed by the monitoring system. In addition, any lateral or longitudinal gradients in thermal patterns will be poorly represented by a single point measure. An additional source of sample uncertainty can be introduced by intermittent hydrologic events. An example of this is presented when localized withdrawal zones near the upstream dam face set up. Surface waters may be drawn down the dam face in the area of the fixed forebay monitor. The forebay temperature data presented in Figures 3.6-3.10 (Section 3) all indicate some degree of variation (warming) that could be attributed to the above-described sources of error.

Future sampling strategies should incorporate design characteristics conducive to minimizing sampling error. These would include adequate sample distribution in time and space plus, appropriate sample and/or measurement replication. Sample location is an important consideration for specific studies dealing with specific structural components (fishways) or project-related phenomenon such as releases or withdrawal processes at dams.

6.5.2 Measurement Uncertainty/Instrument Validation

The error attributable to the instrumentation is more fully discussed in Appendix G. However measurement requirements (accuracies and precision) for much of the ongoing temperature research in the region routinely falls into the range of ± 0.2°C; with repeated measures, depending on sampling variability, mean estimates should be within 0.1-0.2°C of the true mean of the water temperatures. This level of accuracy is generally required to address issues concerning impacts on the biology of the system such as water quality standards or compliance issues. This agrees with the data quality criteria established by the USACE developed for fixed monitoring stations on the Columbia River (USACE, 2003). For temperature calibrations the USACE requires that an instrument must agree within ± 0.2°C with a primary National Institute of Standards and Technology (NIST) standard mercury thermometer.

In general, there is little available information regarding the validation of temperature instrumentation used either for routine monitoring or in special research studies on the river system. It is customary to accept manufacturer's specifications when reporting instrument uncertainty. This may not be the case, especially with equipment, which has been used for several years following purchase. In addition, uncertainties calculated from bench-top studies, as conducted by most manufacturers, may not be applicable in field-use situations. Appendix G describes the method used in validating instrumentation applied in the Lower Snake River Temperature Screening Study.

6.6 Data Management

Data management, including both warehousing and accessibility will continue to be needed to support model development and seasonal simulations. In the short term a research database will be maintained as necessary to support storage and retrieval requirements. Over the long term, a system should be developed with the capability to support real-time model operations as needed for management strategies. This effort should be closely coordinated with ongoing regional efforts to develop a consolidated water quality database.

7. SUMMARY

7.1 Recommendations

The RPA 143 technical team recommends to the regional Water Quality Team that the CE-QUAL-W2 model be adopted for development in the river reaches of interest along with the identified data collection strategy. The team recommends 3 phases and that the identified limited geographical domain be initially modeled to determine model usefulness in defining the thermal effects of potential river operations. Once this step has been completed satisfactorily, then consideration of expanding the model to other river reaches should be considered.

7.2 Agency Roles and Responsibilities

The USACE and BPA will be responsible for implementing the model and data collection efforts. The inter-agency technical team participating in this plan development will be asked to continue in a technical review role. They will 1) review potential contractor scopes of work, 2) review field data collection and analysis, 3) assist in defining the period of record for use in model evaluation and review and 4) comment on reports produced during the development. Once the model has been reviewed and accepted, the team, in conjunction with the regional Technical Management Team (TMT) and Regional Water Quality Team (WQT), will define and identify preliminary model runs required to answer questions originally posed by the team.

7.3 Anticipated Scheduling

Scheduling of this work is highly dependent on available funding. At the end of FY2003, two years of detailed data will have been gathered on the river. FY2002 data collection was a screening data set used to assist in decisions concerning model selection. The FY2003 data collection has been initiated in conformance with the data collection strategy. Additional field data collection will be conducted during the 2004 and 2005 seasons as needed to support validation of the Phase 2 and 3 modeling efforts. A tentative schedule for implementation is identified below.

FY2004 Tasks:

- Collect additional field data,
- Select periods for model evaluation,
- Complete model setup including evaluation, and
- Technical team review calibration and verification report.

FY2005 Tasks:

- Collect additional field data,
- System development to operate as real-time tool for use by regional interests,
- Expand to Phase 2 Geographic Scope, and
- Revise Data Collection as needed to support Phase 2 and other model input improvements.

FY2006 and beyond:

- Expand to Phase 3 Geographic Scope, and
- Revise data collection as needed to support Phase 3 and other model inputs and improvements.

8. REFERENCES

Brown, H.W., 1976, Handbook of the effects of temperature on some North American Fishes: American Electric Power Service Corporation, Canton, Ohio.

Cook, C.B., Richmond, M.C., Coleman, A.M., Rakowski, C.L., Titzler, S.P., and Bleich, M.D. 2003. Numerically Simulating the Hydrodynamic and Water Quality Environment for Migrating Salmon in the Lower Snake River. PNNL-14297, Pacific Northwest National Laboratory, Richland, WA.

EPA, 2002, Temperature Simulation of the Snake River above Lower Granite Dam Using Transect Measurements and the CE-QUAL-W2 Model: U.S. Environmental Protection Agency, Region X, Seattle, WA. EPA 910-R-02-008.

Goniea, T.M, 2002, Temperature influenced migratory behavior and use of thermal refuges by upriver bright fall Chinook salmon: Master thesis, University of Idaho, Moscow, Idaho.

High, B., 2002, Effect of water temperature on adult steelhead migration behavior and survival in the Columbia River basin: Master thesis, University of Idaho, Moscow.

Idaho Power Company, 1999, Status Report on Brownlee Reservoir Water Quality And Model Development: Draft Technical Report and Appendices.

Jin, K.R., Hamrick, J.H., and Tisdale, T., 2000, Application of Three-Dimensional Hydrodynamic Model for Lake Okeechobee: Journal of Hydraulic Engineering, 126(10):758–771.

Karr, M.H., Frye, J.K., and Mundy, P.R., 1998, Snake River Water Temperature Control Project Phase II: Evaluate the Effects of Cold Water Releases and Flows on the Thermal Characteristics and Adult Fish Migration in the Lower Snake River Reservoirs: Columbia River Inter-Tribal Fish Commission, Portland, Oregon.

McCullough, D.A., 1999, 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: Report of Columbia River Inter-tribal Fish Commission, Portland, Oregon, for U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

NOAA, 2000, Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin: NOAA Fisheries.

Normandeau Associates, 1999, Lower Snake River Water Quality and Post -Drawdown Temperature and Biological Productivity Modeling Study: Vols. 1 and 2, R-16031.011, Bedford, New Hampshire, May 1999.

Schuytema, G., 1969, Literature review, effects of temperature on Pacific salmon: Pages A-1-A-62 in (Parker, F.L. and P.A. Krenkel, eds.). Thermal pollution: status of the art, Department of Environmental and Water Resources Engineering, Vanderbilt University, Nashville, Tennessee.

USACE, 2003 (Report in progress), "2003 Dissolved Gas and Water Temperature Monitoring Report". Water Quality Unit, Reservoir Control Center, Water Management Division, U. S. Army Corps of Engineers North Pacific Division, Portland, Oregon.

Appendix A

Meeting Minutes

RPA 143 Workgroup on Snake River Temperatures

Final Minutes -- November 7, 2002

Discussion Points

1. Meeting was held on Thursday November 7th at NMFS in Portland. The following people were either in attendance or on conference phone: Chris Cook PNNL; Marshall Richmond, PNNL; Gene Spangrude, COE; Garth Newton, IDWR; Terry Sobecki, ERDC; Ben Cope, EPA; Jim Irish, BPA; Paul Pickett, WDOE; Mark Gunter, CBE; Ralph Myers, IPC; Don Essig, IDEQ; Phil Groves IPC; Eric Brandstetter, MWH; Mark Schneider, NMFS; Mike Schneider, ERDC; Joe Carroll, OA Systems; Rick Emmert, COE.

2. Monitoring update. Joe Carroll presented update on temperature monitoring and some initial analysis completed to date**.**

3. Review of composite question matrix. The team did a quick review of the question matrix. The main purpose was to make a team judgment as to the spatial dimensionality required of a numerical model to answer the stated question. The results are shown below.

Composite Question Matrix Number	Spatial Dimensionality
1	2d
1a	2d
1b	2d
2	2d
2a	2d
2b	2d
2c	1d
2d	2d
2e	2d
2f	1d
2g	Not applicable
3	2d
3a	2d
3b	2d
3c	2d
3d	1d/2d
4	2d
4a	1d
4b	1d
4c	1d
4e	1d

4f	1d
5	2d
7	Most likely answered by monitoring
7a	Most likely answered by monitoring
7c	Most likely answered by monitoring
7e	Most likely answered by monitoring
8	1d

In general, the team judged that 14 of the questions would require a minimum spatial resolution of a 2-dimensional model to answer the stated question, while 9 of the questions could be answered using a minimum spatial resolution of a 1-dimensional model.

4. Define model selection criteria. Ben Cope presented summary slides of the information gathered prior to the meeting. Much team discussion resulted in a proposal to use CEQUAL-W2 which is a 2-dimensional code, not proprietary, is continuously supported/updated by ERDC, has long history of use and can be run in either 1-dimensional or 2-dimensional modes. Team requested to think more about this proposal. Further discussion will be held at the next team meeting.

5. Next meeting agenda items. The next meeting was tentatively scheduled for either Dec 5 or 12 at the NMFS office in Portland. Team members to check on availability and email Rick Emmert and Mark Schneider.

   Agenda items discussed as possibilities for the next meeting are as follows:

   a) Ask Chris Cook to present monitoring update of his work on the Lower Granite Pool.
   b) Invite one or more folks from the TMT to the meeting to describe how they envision the use of model output.
   c) Ask Tom Cole (ERDC) or Scott Wells (Portland State University??) to discuss strengths and weaknesses of CEQUAL-W2 model.

Ask Garth Newton IDWR to share his experiences in use of CEQUAL-W2.

RPA 143 - Snake River Temperatures
Final minutes – December 5, 2002

Discussion points

- Meeting started at 10:07 with Rick Emmert welcoming everyone to the meeting at NOAA fisheries, Portland. Rick asked everyone to introduce themselves, reviewed results of the last meeting, and received acceptance of the agenda for this meeting.
- Chris Cook, Battelle, presented preliminary data that was collected in 2002 in Lower Granite Reservoir. These data will be used to calibrate a 3D model of this reach, including the confluence of the Clearwater to the Snake River.
- Bathymetric data collected in July 2002 includes RTK GPS data from Silcott Island to Potlatch, Idaho; this data is accurate to within 1 ft. Downstream of Silcott Island to the forebay of Lower Granite Dam, DGPS data were collected with an accuracy of about 2 to 3 ft. This data will be used to help configure the 3D model with 12 layers.
- 11 sites in the area were equipped with thermister strings, with over 70 thermisters. The temperature measuring equipment was in place from June 26 through September 25; four sites still have the equipment in and will be pulled in December. At bridge sites, the thermister strings were located upstream of bridge piers with sufficient weight to keep the strings straight. Depths in the water were adjusted for reservoir water level fluctuations.
- Velocity data in the reservoir and near the confluence were collected during two trips two weeks apart. These data were collected at 4 to 5 stations and at 13 sections laterally. These data will be used with a transient model to route flows.
- Profiles of temperature and electrical conductivity were collected at two week intervals.
- Meteorological data were collected by AgriMet at Silcott Island, River Mile 130.
- Joe Carroll had a CD with the temperature and meteorological data on it.
- Chris Cook showed a movie portraying the topography along the river, bathymetry of the river and location of temperature strings.
- Chris Cook has the data from temperature strings collected by USGS-BRD.
- All thermisters used for temperature measurements and hydrolabs used for profiles were calibrated before use and after use.
- The data showed there to be little variability in the cross section downstream of Silcott Island. It was noted that there was a large amount of variability in the wind longitudinally; next year Battelle is considering placing several wind gages at key points along the reservoir to record the wind patterns.
- The Clearwater River appears to be mixed vertically with measurable diel variability.
- The Southway Bridge on the Snake River is mixed vertically. The Interstate Bridge sees cold water from the Clearwater at lower depths as it moves to a deep hole between the two bridges. Temperature data showed cold water moving into the deep hole and back out at a latter date.

- An Infrared photo of the Clearwater River confluence shows warm temperatures on the surface of the Snake River, a sharp line of cold water in the Clearwater River at the confluence where the Clearwater plunges beneath the Snake River. Downstream of the Clearwater River, the cross sectional variability in the Snake River is up to 5°C. This cross-sectional variability decreases to between 0 and 2 °C at Red Roof Bridge and is not distinguishable in the noise upstream of Silcott Island. Downstream of Silcott Island in the thalweg of the reservoir, the temperature data shows evidence of heating at the surface and greater differences in the vertical direction.
- Analysis of the temperature data shows a lag time of 1.8 to 3.0 days and a heating of 3.2 to 4.6 °C between the Clearwater River confluence and the Lower Granite Dam forebay.
- Summary of observations:
  - Clearwater River is mixed in the cross section;
  - Snake River is mixed two miles upstream of Clearwater River confluence;
  - Clearwater River plunges to bottom of Snake River;
  - Cold water moves 1 mile upstream of confluence in Snake River;
  - Up to 5°C variability in Snake River cross section downstream of Clearwater River confluence, 2°C at Red Roof bridge and immeasurable at Silcott Island; and
  - Vertical variation persists downstream of confluence with the magnitude increasing due to heating at the surface.

  Slides of what Chris Cook showed the group can be seen at
  ftp://ftp.nww.usace.army.mil/Outgoing/RPA143%20120502/
- The meeting took a 10 minute break at 1135.
- Mark Schneider introduced Paul Wagner, NOAA Fisheries and member of the TMT.
- Paul explained what fisheries data was available for the TMT to decide when and how much water to release from Dworshak Reservoir. It is desirable to use the reservoir for both juveniles and adult salmon; however the benefit for juveniles is better defined. Correlations between water temperature at the Lower Granite forebay and survival and between Snake River flows and survival have R^2 values in the 80 percentiles. As temperatures go down and as flows go up, survival improves. An average 1°C lowering of daily mean temperatures in Lower Granite Tailwater over the period of passage of four distinct groups of fall Chinook increases survival 7 percent. The same regression model predicts survival improves 3 percent when temperatures are held constant and with an average increase of 100 m3/s of Lower Granite discharge for four distinct groups of fall Chinook.
- The TMT has managed a similar volume of water from Dworshak Reservoir and the upper Snake River from year to year and assumes this volume will continue in planning flows for each year.
- It is thought that the forebay temperatures relate to exposure for the juvenile Fall Salmon in the upper 5 meters in the pool. Information on the temperature at various depths within Lower Granite Reservoir would be of help to the fishery

agencies and would help fisheries determine the degree that juvenile fish seek out cool waters.

- Passage for sub-yearling Fall Chinook is from early June through mid September. Fish from the main stem Snake River (upstream of the Salmon River) move out first, from the Salmon River second, and the Clearwater River last. Since the dams have gone in on the Snake River, the migration of juveniles has been slowed to a later date; before the dams, juvenile fish were out of the Snake River system by the end of June because of cooler temperatures in the fall and warmer temperatures in the spring.
- In 1999, the TMT looked at 29 scenarios of when and how to use Dworshak water. What appeared to be best was use of the water starting in July. CRITFC would prefer that some of the cold water was available for September. The review considered early release of water from Brownlee Reservoir; then Dworshak could be used from late July to mid September. Paul reminded the meeting that the State of Idaho prefers to keep water at a maximum level until after July 4 for recreational purposes.
- Paul indicated that use of a 2D model would be of interest for the TMT.
- The meeting took a 5 minute break to start lunches.
- In the Lower Snake River reach, Lower Granite Reservoir is considered the critical reach. This past year, RBM10 was used to look at effects of releasing Dworshak water at alternate times. This resulted in continuing to release Dworshak water in 2002 into the first three weeks of September. At this time, there is minimal data to support releasing Dworshak water in September.
- When the juvenile fish start to migrate, it is thought they see the slow velocities in the reservoirs, think they have arrived at the ocean. It now takes many of the fish 30 days to pass though Lower Granite Reservoir; now the juvenile fish have an unnatural delayed migration to the ocean relative to before dams were in the rivers.
- It is thought that a 2D model would help manage Dworshak releases, determining when and how much to release. TMT does not know at this time what depth to regulate temperatures to maximize fish passage. It is hoped that by managing the release of Dworshak water better, the season of release could be extended into September. It is known that adults do utilize cool water. Fall Chinook are usually in the Snake River from late October to Early November.
- Another concern is the hatchery on the Clearwater River. The redesign of the hatchery may help some, however if Dworshak is drafted too low, only very cold warm water may be available.
- Some results on juvenile fall Chinook survival to lower Granite Dam include the following:

  1993 – 8 percent survival
  1999 – 50 percent survival
  2001 – 21 percent survival
  2002 – 40 percent survival
- Dworshak Reservoir usually fills with water, even on dry years. 98 percent of the time, Dworshak Reservoir has filled by July 1.

- The debate at TMT is usually when to start release, how much do we release, and do we hold water for September release.
- A worse case scenario is when the Snake River flow is low, discharge from Dworshak is higher, but the total discharge and downstream velocities in Lower Granite Reservoir are so low there is poor movement through the reservoir and loss in the reservoir is high.
- There is still a lot of information that needs to be collected on how fish respond to cool water at depth. If the fishery researchers had a better understanding of the thermal conditions, this may help them in their research. TMT would like to know the cross sectional temperatures for all the lower Snake River. The understanding that this group is obtaining needs to be explained to the TMT and what a 2D model could provide after calibration.
- It was determined that the proposed 2D model would likely be used to look at several season long events and during the season to fine tune for extended release. Outputs would be needed at several specific points in different reservoirs. TMT would manage first for Lower Granite Reservoir and second for the three lower reservoirs. It is thought at this time that TMT would be willing to vary release of Dworshak water relative to meteorological forecasts.
- Mark Schneider agreed to make copies of Paul's slides and send them to attendees.
- Tom Cole, USACE, ERDC, Waterways Experimental Station presented a summary of CE-QUAL-W2, version 3.1. This is a 2D model, longitudinally and vertically, hydrodynamic model for streams and reservoirs. It will simulate temperature, nutrients, algal growth, pH and dissolved oxygen. It requires 128 MB of memory and 1 GB or more of disc space.
- The model will handle multiple algal groups, silica, carbonatious biochemical oxygen demand, bacteria, suspended sediment, dissolved gas and other water-quality characteristics. This model has been used in the Pacific Northwest on the Willamette, Columbia and Spokane Rivers and on the Columbia Slough.
- The model can be as accurate as 0.5 oC for temperature. Run times are about 24 hours for one year of record with 10 to 30 second time steps for 100 miles of reach using a 2 GB computer. It was estimated to take less than 30 minutes to do a 5 day simulation. There is no post processor with the model, but commercial processors are available.
- The model is more numerically difficult to initially calibrate (make stable) than reservoirs. It uses a simplified description of wind sheltering and sediment heat exchange. The model can be used to optimize of temperatures in the Snake River with different releases from Dworshak Reservoir.
- It was suggested that early use of the model on the lower Snake River could identify the most sensitive parameters and use this information to finally design the data collection program.
- Bathymetry of the Lower Granite Reservoir is currently good; some additional work would need to be done on the other reservoirs to have bathymetric data of similar quality. However, previous models have shown a low sensitivity to bathymetry. The model allows one to vary the grid size for bathymetry; it was suggested to start with a fine grid and make coarser over time.

- Rick Emmert has made Tom's slides available on the web at ftp://ftp.nww.usace.army.mil/Outgoing/RPA143%201205021
- The meeting took a 10 minute break at 1444.
- Those in attendance and on the phone had a general discussion about whether we were ready to decide about the model. The group did not see why the CEQUAL-W2 model would not work. The group also concluded that we need to inform TMT of what we know about the lower Snake River, we need to evaluate historic monitoring data relative to data collected in 2002 and what should be collected in the future and we should expect to learn more about how fish respond to cool water at depths in Lower Granite Reservoir.
- One of the next tasks for this group will be to develop a report on model selection, data needs to support calibration of the model and key data to monitor the system and data to support short term model runs to optimize management of temperatures.
- Next meeting is unscheduled at this time, but will be held in Portland and NOAA Fisheries office; let Rick know which date is best for you. Agenda items include:
  - Review report outline and timeline for completion,
  - Determine how to link middle Snake River with lower Snake River
  - Determine what input data is now available to calibrate and run the model,
  - Determine what data should be collected to support model simulations in the future, and
  - Determine is we need more real-time data collection to allow short-term model runs.

Attendance:

Jim Irish	BPA	
John Piccininni	BPA	
Mike Schneider	USACE- The Dalles	
Rick Emmert	USACE-Walla Walla District	
Gene Spangrude	USACE-Walla Walla District	
Stu McKenzie	USACE Contractor	
Joe Carroll	USACE Contractor	
Tom Cole	USACE- ERDC	
Paul Pickering	Washington Dept. of Ecology	
Jim Britton	USACE-Portland District	
Ben Cope	EPA	
Chris Cook	Battelle	
Marshal Richman	Battelle	
Mark Schneider	NOAA Fisheries	
Dick Cassidy	USACE – Division	
Wendy Briner	USACE –Portland District	
Paul Wagner	NOAA Fisheries	
Garth Newton	Idaho Water Resources	On phone
Jamie Davis	Nez Perce Nation	On phone

RPA 143 Workgroup on Snake River Temperatures
Final minutes – April 29, 2003 at Portland District COE office

Discussion points

- Rick Emmert, USACE, called the meeting to order at 0950. All members introduced themselves (See list of workgroup present at end of minutes).
- Ben Cope, EPA, indicated that the report needed more detail about the planned modeling effort. There are elements of the CEQUALW2 model that can be spelled out now and because they will be needed by the model, would make the modeling effort more efficient. Areas of concern include a) detailing available and needed bathymetry coverage, b) use of meteorological data from one site (CEQUALW2 currently uses one set of data) or dividing the Lower Snake River into multiple reaches with different sources of meteorological data, c) establish relationships between water elevation and flow, and d) representing the outlet structures for Dworshak Dam. It was agreed that this workgroup can and should provide these details for the modeling team.
- John Piccininni, BPA, stated that Chris Cook was currently calibrating CEQUALW2 for the lower three pools of the Lower Snake River. Chris Cook will be asked to report on his progress and recommendations for improving the model accuracy.
- Mark Schneider, NOAA Fisheries, and Rick Emmert agreed that this workgroup needed to seek input from the Action Agencies, (USACE, USBOR and BPA) as well as EPA, States and Tribes, when defining specifics of the modeling effort and how the modeling effort will be accomplished; examples include using BPA contracting service, using the contracting service of some other agency, or one of the Action Agencies doing the effort in house. It was agreed that the decision was not needed at this time and would not be part of this report. When this report and its recommendations are completed, it will be presented to the Water Quality Team for review and then presented to the TMT (Technical Management Team) for implementation. When TMT receives the report, we need to be prepared to identify the questions that TMT will be asking, showing how the model and associated monitoring effort will provide answers to these questions.
- Jim Irish, BPA, reminded the group that as hydrologic conditions outside of current monitoring conditions occur, data will be needed to define the resulting conditions and to determine if the model is adequately accurate for these future conditions.
- Rick Emmert indicated that a contract was in preparation to have someone summarize from the literature what is known about biota in the Lower Snake Rive and how water temperature is related to the behavior of fishes. Currently Battelle and Normandeau Associates are interested in the contract; it is expected to be awarded in about one week and the first draft would be expected in 40 days with the final due within 15 days of receiving review comments. This effort will be included as one of the appendices in the report.
- Jim Irish asked if the report and all the appendices would be published or would only the plan or strategy be published and the rest of the report placed on a web site. It was decided that the executive summary would be replaced with the plan

and strategy and that it would be 5 to 10 pages long; the complete report would likely have a limited number of copies printed and listed on a web site. Consideration would be given to having the appendices available on a web site.

- Joe Carroll, USACE contractor (OA Systems, Inc.) presented his analysis of data collected in 2002 on the Lower Snake River. His power point presentation included the questions that could be addressed by data collected in 2002, the objectives used to analyze the 2002 data, and the monitoring design used for 2002. The area studied included Dworshak Reservoir on the North Fork Clearwater River, lower 74 miles of the Clearwater River, and from River Mile 229 on the Snake River to its mouth. Joe reviewed where stations were located in this area.
- Meteorological data included the National Weather Service site at Pasco and AgriMet sites (collected by the U.S. Bureau of Reclamation) on Dworshak pool (Dent Acres, ID), in Lower Granite pool (Silcott Island, WA), and near Little Goose Dam (Lake Bryan-Rice Bar, WA). Silcott Island started collecting data on July 17, 2002 and the other AgriMet sites started April 20, 2002. Comparison of the average temperature data showed Dent Acres, ID to be cooler than the other three sites; the lower three sites all had similar temperatures. Pasco had higher daily wind speeds and higher peak wind speeds. Ben Cope suggested that the NWS site at Lewiston ID should be looked at.
- Analysis of discharge showed the Snake River dominating flows previous to June 20 and from early July through mid September, the Clearwater and Snake River contributed about equal flows. Dworshak releases decreased in late September making Snake River the dominant source of water in the four pools. During the high flows in May and June, time of travel estimated for each of the pools was as low as 2 days but during July through mid September, travel times approached 18 days for Little Goose and 12-14 days for the other three pools. During the fall low flows, travel time through the four pools was approximately 60 days using volume/surface elevation data and assuming plug flow transport.
- A review of precision and accuracy associated with instruments used in 2002 by the USACE indicated errors of less than plus or minus 0.2 ^{o}C. Appendix G explains the methods and analyses used to determine this error.
- Temperature in the South Fork Clearwater River at Kooskia and Clearwater River at Orofino had maximum values of 22 to 25 ^{o}C. Diel temperature cycles ranged from 2 to 5 ^{o}C. Sites downstream of the North Fork Clearwater River at Clearwater River at Peck and at Spalding peaked at around 15 ^{o}C with diel cycles of 1 to 2 ^{o}C. A flow weighted average temperature using discharge and temperature from the Clearwater River at Orofino and DWQI site on the North Fork Clearwater River was 1.07 ^{o}C higher than the Clearwater River temperature at Peck. This difference is probably caused by solar heating and from the low biased temperature measured at DWQI.
- A review of the thermister string upstream of Dworshak Dam shows a thermocline extending to the 35 to 40 meter depth with gradients of up to 14 ^{o}C occurring and depths below 40 m remaining at 6 ^{o}C.
- Analysis of data in the North Fork Clearwater River downstream of Dworshak Dam showed that site DWQI may be biased low by a small amount because the

river is not mixed at this point. It is recommended that the thermister at his site be moved further into the stream; action has already been taken to follow this recommendation.

- Water temperatures upstream of Lower Granite pool were above 20 °C the second week in July and remained elevated until mid September. The Snake River at Anatone had peak temperatures of 22 to 25 °C with diel cycles of 1 to 2 °C. There was a recorded 2 °C increase in temperature from RM 229 to RM 156 by Idaho Power Company recorders.
- Lower Granite temperatures upstream of the forebay were a maximum of 25 °C at 0.5 meter depth and surface heating never extended below a 5 meter depth. Differences between surface temperatures and 25 to 30 meter depths were up to 6 °C with bottom temperatures remaining between 16 and 19 °C.
- Little Goose temperatures upstream of the forebay showed some temperature gradients for 3 to 5 day periods starting in June and would break up or mix due to surface cooling or wind mixing. Gradients from July though September of 2 to 4 °C were present. A maximum temperature of 25 °C was achieved at the 0.5 meter depth with bottom temperatures remaining between 16 and 20 °C.
- Lower Monumental temperatures upstream of the forebay indicated weak thermal gradients of 2 to 4 °C during June and mid July and 1 °C in late August. Maximum temperatures near the surface were 24 to 25 °C and bottom temperatures were 17 to 21 °C.
- Ice Harbor temperatures upstream of the forebay were as high as 24 °C near the surface and between 18 and 22 °C near the bottom. Thermal gradients over the depth of the pool were 1 to 2 °C for the summer season.
- Comparison of FMSD (fixed monitoring station Data) for each project showed temporal pattern for the season that was very similar for all four projects. Another similar pattern was the higher temperatures at each of the forebay sites relative to the tailwater sites. This pattern of high temperatures was shown to be influenced by wind conditions; when winds were high, the differences were less and when there was no wind, differences were greater. Differences between forebay and tailwater sites were 2 to 4°C at Lower Granite and decreased at the downstream dams. Diel variability ranged from 4 to 5°C at Lower Granite forebay to less than 2°C at Ice Harbor forebay and less than 1°C at the Ice Harbor tailwater site. Review of the 2002 data shows the tailwater temperature measurements are representative of river conditions at these sites for each of the projects. It was observed that a thermister about 1000 feet upstream of the forebay at 5 meter depth was often approximately equal to the tailwater temperature; it was also observed that an average of the temperatures over all recorded depths was about the same at the tailwater temperature, suggesting that the dam was pulling water from all depths as it passed through the dam. It is recommended that the current fixed monitoring station forebay temperature site be replaced with a string of thermisters to be located sufficiently upstream of the dam face to accurately determine the incoming temperatures. Recommended depths are 0.5, 1.5, 3, 5, 10 meters and then at 5 meter intervals to within 1 meter of bottom. It is also recommended that forebay and tailwater temperatures be recorded year around.

- There were three strings of thermisters upstream of the forebay in the cross section of each project. One of the strings was near the exit of the fish ladders at three of the projects. Other strings were located laterally across the river about 1000 feet upstream of the forebays. Joe calculated the average difference between thermister records at the same depth for two strings of the 2002 record; he then averaged the results for all depths where there were paired thermisters. These averaged differences between strings were less than 0.18^{o}C. These data indicate only minor bias associated with lateral positioning of stations. It is interesting to note that all the strings near the fish ladder exits were warmer than the strings 1000 feet upstream of the dam face.
- Viewing the temperatures measured in 2002 longitudinally from June through August for the reach Lewiston to the mouth of the Snake River shows a 1 to 3 ^{o}C warming trend. Maximum temperatures in the Snake River at Anatone were frequently 2 ^{o}C higher than that recorded downstream at the projects; it has not been determined how much of this increase is due to tributary inflow.
- The incomplete inflow mixing of waters from the Clearwater and Snake Rivers at Lewiston as well as the solar heating and mixing resulting from winds result in vertical gradients for the Lower Snake River that can best be represented by a 2-dimensional habitat modeling. If the purpose is to forecast average temperatures at some point downstream, then a 1-dimensional approach will work; a potential exception is Lower Granite pool which experiences some of the more extreme variability in thermal patters.
- Joe concluded his presentation by listing all the hydrologic data he has assembled and its source, and indicated that he would make it available upon request on a CD.
- The workgroup took a lunch break from 12:10 to 1:20 pm.
- Joe Carroll presented his recommendations for data collection 2003 and 2004. He felt that two years of data were needed to meet the objectives of RPA 143 and to measure hydrologic changes that occur from year to year. There is a need to continue to manage a data base of all hydrologic data being collected in this reach; Joe indicated that he will be doing this effort over the next two years, but some long-term solution for managing the data base is needed beyond 2004.
- Joe identified as a low priority the collection of additional bathymetric cross section data until it can be shown that additional data would help the modeling effort. The relation between elevation of water surface and water velocities is fairly well known at this time. There are currently some thermal imagery results available from Battelle and the decision to collect more should wait until the needs has been identified.
- Monitoring that is high priority and should be continued includes the following:
    a. The COE should continue fixed station monitoring, with tailwater sites remaining as is; forebay sites should be moved about 1000 feet upstream of the dam face with a thermister string and with real time data available.
    b. Battelle will continue its data collection program in the Lower Granite pool.
    c. The COE should establish thermister strings at a mid point longitudinally in the lower three pools. Dave Bennett will not be collecting these data in 2003 or 2004 because he is retiring from the University of Idaho.

d. A thermister should be located at the draft tube deck and used to measure mixed temperature conditions from the turbines.
e. COE will continue to use thermisters to measure temperatures of tributaries inflows to the Lower Snake River.
f. COE, Walla Walla District, should continue to collect operational data at each of the projects at 15 minute intervals, rather than the 5 minute data collected in 2002.
g. COE, Walla Walla District, should review historic and current data on inflow to Dworshak Reservoir with the possibility of gauging additional inflows.
h. BPA should continue funding meteorological data collection, with the possibility of adding a long wave sensor or some other method of measuring cloud cover. COE, Walla Walla District should consider setting up some wind speed and direction sensors at points along the Lower Snake River. It is believed that there are now anemometers at each of the dams and dam operators record values at some unknown time interval.
i. Joe will continue to collect and manage the data base for 2003 and 2004. USACE has decided to store sample data for single points in time in STORET. Continuous data is now stored in CROHMs; CROHMs will be replaced with SWMS.
j. Idaho DEQ will continue to place thermisters in tributaries and the Snake River. Idaho DEQ currently has identified 8 sites.
k. Idaho Power Company will continue to measure water temperature at multiple sites between Hells Canyon Dam and Asotin.

- It was agreed that when the strategy is forwarded to the TMT, this workgroup needs to identify a road map for supporting real time data collection and how the data and modeling results will be used to manage the Lower Snake River.
- The report needs to reflect the change in geographic boundaries of RPA 143 from Hells Canyon Complex on the Snake River to Bonneville Dam on the Columbia River. The workgroup changed the downstream boundary to the mouth of the Snake River. The upstream boundary (Hells Canyon Dam or Snake River at Anatone) will be discussed later by the workgroup.
- The following suggestions were provided on the existing draft:
  a. Increase table 1 showing the existence of high water temperatures in the Lower Snake River
  b. Summarize flow conditions for the Lower Snake River Basin during the 2002 season;
  c. Washington State Water Temperature Standard is 20 ^{o}C;
  d. Section 2.2.1 – add information about ongoing monitoring, including when data collection began and where are the sites located;
  e. Section 2.2.2 – Add when monitoring of meteorological data began and what parameters are being collected;
  f. Section 2.1 – Summarize material to emphasize what was done with post modeling studies;
  g. Describe Dworshak operation conditions during the 2002 season relative to other years;
  h. Add information about fish ladder information and what it means;

i. Consider organizing section 3 by reaches;
j. Document the change in geographic scope for RPA 143;
k. Add reference to TMDL that is ongoing in the Lower Snake River; This strategy will need to incorporate the points of compliance listed in the TMDL and the ongoing monitoring plan will need to be compatible with the TMDL implementation plan.
l. Change title to "Water Temperature Modeling and Data Collection Plan for Lower Snake River Basin";
m. Ben Cope will provide some material describing model development recommendations; and
n. A Plan and Strategy section will replace the Executive Summary in the report.

Reviewers were asked to provide specific changes within one week to Rick, Joe and Stu.

- The workgroup agreed to meet June 12. Rick Emmert will send agenda to workgroup members. Potential items on the agenda for the next meeting are as follows:
  a. How agencies will participate when developing the model;
  b. How agencies will implement model development;
  c. Review white paper summarizing biology of the Lower Snake River (40+ days away);
  d. Review revisions to the final RPA 143 report;
  e. Develop an outline for the Plan and Strategy to be presented to TMT;
  f. Ben to present material describing model development recommendations;
  g. Chris Cook to report on progress in understanding Lower Granite flows and temperatures and modeling of the lower three pools;
  h. Discuss upper boundary to the Plan and Strategy on the Snake River; and
  i. Review information about adding long-wave radiation to meteorological sites.
- Meeting adjourned at 3:50 pm.

Attendance at April 29, 2003 RPA 143 meeting

Name	Agency	Telephone	Email
Steve Juul	Walla Walla COE District	509-527-7281	Steve.T.Juul@usace.army.mil
Rick Emmert	Walla Walla COE District	509-527-7536	Rick.L.Emmert@usace.army.mil
Joe Carroll	OA Systems	541-980-5584	JCarroll@Gorge.Net
Mark Schneider	NOAA Fisheries	503-231-2306	mark.schneider@noaa.gov
Ben Cope	EPA	206-553-1442	cope.ben@epa.gov
Mike Schneider	CE-ERDC-CHC	541-298-6872	Michael.I.Schneider@nwp01.usace.army.mil
Jim Britton	Portland COE District	503-808-4888	James.L.Britton@nwp01.army.mil
Nick Beer	U. of Washington	206-221-3708	nickbeer@u.washington.edu
Jim Irish	BPA	503-230-5914	jtirish@bpa.gov
Carolyn Schneider	CE-ERDC-EL	541-298-6885	Carolyn.b.schneider@nwp01.usace.army.mil
John Piccininni	BPA	503-230-7641	jppiccininni@bpa.gov
Arthur Armour	Portland COE District	503-808-4833	arthur.armour@nwp01.usace.army.mil
Stu McKenzie	OA Systems	503-658-6824	stumckenzie@msn.com

RPA 143 Workgroup on Snake River Temperatures
Minutes – June 12, 2003 at The Dalles

Discussion points

- Joe Carroll started the meeting at10:15 since Rick Emmert was held up because of an accident ahead of him on the road from Walla Walla to The Dalles.
- Joe asked each attendee to introduce themselves and indicate who they represented.
- Joe reviewed the agenda with the workgroup.
- There were no changes to the minutes for the April 29th meeting.
- Chris Cook reviewed the sampling program and data results of the Battelle (PNNL) study. This study includes the Lower Granite pool, where the Clearwater River water flows upstream along the bottom of the Snake River, and backwater from the Lower Granite into the Clearwater River. Chris handed out a copy of the results from the first year's study. The study is planned to continue for the next two years for a total of three years with BPA funding.
- The data program has included data collected by Joe Carroll and the USGS (Biological Division). Bathymetry data collected included a reach from River Mile (RM) 4 on the Clearwater River, head of Lower Granite pool in the Snake River, and downstream on the Snake River to RM 143; this reach had an accuracy of plus or minus 2 feet. The rest of the Lower Granite pool was completed with a second method and had an accuracy of plus or minus 5 feet. Eleven temperature logging sites were used by PNNL and USGS where cross section temperatures were also taken; 14 foot subsurface buoys or bridges and anchors were used to keep the thermister springs in place. Upstream sites on the Snake and Clearwater Rivers had uniform temperatures over depth. Water velocities were measured using an acoustic velocity meter providing 52 velocity values in the cross section for each of the 13 transects. Plans for 2003 are to collect more information on how water moves at the plunge point (confluence of Coldwater River).
- Chris presented results of the data and indicated their progress and problems associated with a 3-D model of Lower Granite Pool and a 2-D model from Anatone to the Snake River mouth. Several workgroup members had questions and suggestions. On April 14, 2002, the Clearwater River was 1.5 ^{o}C cooler than the Snake River and the two rivers were moving as two parallel streams in the Snake River downstream of the confluence of the Clearwater River. On July 21, the Clearwater River was 10 ^{o}C cooler and the cool Clearwater River water was plunging to the bottom of the Snake River. There is a small stream, estimated 25 cfs on April 4, from the Potlach plant at the Clearwater River mouth that can be quite warm. Modeling results with the 3-D model show a need to improve on the balance between upstream and downstream discharge values.
- Use of the CE Qual-W2 model takes about 15 minutes. This model is using the bathymetry data from MASS1 model used previously on this reach. Cells are 1 mi long and 1 meter deep.
  1. In Lower Granite pool, the mass balance of water is 5 to 9 percent off between the model and control manual. Hourly discharge and temperatures from tributaries were used. Meteorological data was taken from Rice Bar

AgriMet station. The model seemed to be under-predicting the water temperatures. It was not known if the total flows on the Corps web site included fish ladders, locks, juvenile by-passes and evaporation. There are plans to conduct sensitivity tests. The differences in mass balance are thought to not affect the simulated temperature results.

2. Little Goose pool had comparable simulated and measured temperatures. It was suggested that PNNL look at the amount of heating that occurs in the pool. Data from Joe Carroll was used to test the results of this reach. Lower Monumental and Ice Harbor pools had similar results. At this time, each pool is run separately; it was suggested that the four pools need to be connected so that the simulated output of one pool becomes the input for the downstream pool.

- For 2003, similar temperature data will be collected, starting the week of April 26. On May 14-16 and August 11 and 25, 15 cross sections will have velocity measurements in triplicate. This will include additional cross sections at the Clearwater River confluence and plunge area. There will be additional work done using CE-QUAL-W2 and the 3-D model. Chris handed out a report on their 2002 work. Plans are to place the report on the Fish and Wildlife web site. Basic data are on the streamnet web site.
- At 12:05 pm, the workgroup took a lunch break.
- Chris finished his presentation by saying the 2nd year would emphasize data collection and calibration of the models. The 3rd year would try at placing biology into the 3-D model using fish tracking data. Billy Connor and Ken Tiffan want to see if the model can help explain the holdback associated with fish. BPA indicated that the third year of funding is in some level of question for this province of the Columbia River Basin.
- Ben Cope reviewed Section five of the report on model development that he had prepared. The approach and method that Ben showed was well received with some corrections suggested by workgroup members. Ben was asked to change from 4 phases of development to three phases. Phase 3 would be needed if Brownlee Dam were able to change its operation. It was suggested that modelers should first do a sensitivity analysis before completing the last phase. The model would be able to use hourly data, but daily values may answer many of the questions. Scales were suggested to be 1 or 0.5 miles longitudinally and 1 to 2 meters vertically. In areas of special study, such as dam forebays, other scales may be needed. Ben reviewed other issues, likely assumptions and calibration questions concerning the model.
- Joe Carroll presented some material on discharges of the Snake River at Hells Canyon Dam and tributaries that made up the Lower Snake River for 2002. This analysis showed the Snake River discharge upstream of the Clearwater River being dominated by Snake River at Hells Canyon and Salmon River in June and July and by Hells Canyon in August and September. Joe also showed water temperatures for 2002 for the Snake River reach from Hells Canyon Dam to RM 156 plus the Salmon River. Results for July 2002 showed an average 0.6 ^{o}C warming from Hells Canyon to upstream of Salmon River, 0.9 ^{o}C warming from upstream of Salmon River to RM 180, and 0.9 ^{o}C warming from RM 180 to RM

150 (headwater of Lower Granite pool). Heating in the Clearwater River from Dworshak to PEKI site was calculated to be 0.7 ^{o}C, and to LEWI at Lewiston to be 1.2^{o}C. Heating in Lower Granite pool was calculated to be 0.9 ^{o}C and 0.9, 0.5 and 0.9^{o}C in the next three pools downstream. Joe cautioned that the travel time for RM 229 to RM 150 on the Snake River is 1 to 2 days, 12 hours on the Clearwater River and up to 20 days on the Lower Snake River. Joe will be adding some of this material to section three of the report.

- Rick Emmert led the workgroup in reviewing the executive summary. It was decided to prepare a draft of the executive summary for the Water Quality Team to review in August. Joe Carroll is to add information of monitoring. Ben Cope will prepare information on the three phases of model development.
- Rick then asked for comments on the main report. The workgroup asked for table 1.1 to be expanded to include Ice Harbor tailwater data, add a section explaining the TMDL activity and add the source of data in the table. Stu McKenzie is to obtain a summary of biological monitoring in 2002. Mark Schneider is to research the geographic boundaries of Lower and Middle Snake River that most agencies are using; this will be added to the report. Stu McKenzie is to write section 7 on the summary, using information from the executive summary.
- Rick Emmert is to determine when the paper summarizing what is known about the biology in the Lower Snake River will be available for review. This paper will be sent to all workgroup members, who will have 10 days to provide review comments to Rick. The authors will then provide a final report. Stu McKenzie will place the report in the appendix, place a summary of the biological paper in the body of the RPA 143 report and review the main report to make sure the two reports are compatible.
- Ben Cope will provide an updated version of Section 5 on Modeling. Ben and Chris Cook will provide information on references. Chris Cook will provide information on temperature data collected in 2002. Stu McKenzie is to make sure the reference to Battelle uses the acronym PNNL. Joe Carroll is to look into finding someone that can provide an editorial review of the report.
- The meeting adjourned at 3:45 pm.

The following list of items was identified at the June 12 meeting to complete the RPA 143 report on Snake River Temperatures. Please send requested material to Rick Emmert, Joe Carroll and Stu McKenzie.

- Joe Carroll – Furnish material for executive summary on data collection
- Joe Carroll – Add to section 3 on presentations made at June 12 meeting
- Joe Carroll – Look into providing an editor to review the report
- Mark Schneider – Determine correct terminology for Snake River from Brownlee Reservoir to Anatone
- Stu McKenzie – Get material on biological monitoring from Billy Connor (Section 2.3)
- Stu McKenzie -- Place summary of biological paper in text (section 1.2)
- Stu McKenzie – Add source of temperature data in section 1.3

- Stu McKenzie – Add temperature data for Ice Harbor tailwater site for period of record to section 1.3
- Stu McKenzie – Write section 7 (Summary) from executive summary, add info on funding limitations drive schedule
- Stu McKenzie – See that RPA 143 report is compatible with bio paper
- Stu McKenzie – Do search in RPA 143 report and change Battelle to PNNL (Pacific Northwest National Laboratory)
- Ben Cope – Provide update on section 4, Model Development from meeting discussion
- Ben Cope – Provide information on TMDL for section 1.3
- Ben Cope – Provide information on three phases for executive summary
- Ben Cope – Provide information for References
- Chris Cook – Provide information for References
- Chris Cook – Provide information for temperature table
- Rick Emmert – Determine when biological paper will be available for review. Paper should be out for review after June 20
- Marvin Shutters – Send out biological paper for review to workgroup members soon after June 20
- All workgroup members – Provide review comments on biological paper to Marvin Shutters within 10 days after receiving for review
- Meeting was adjourned at 3:45 pm.

Attendance at April 29, 2003 RPA 143 meeting

Name	Agency	Email
Rick Emmert	Walla Walla COE District	Rick.L.Emmert@usace.army.mil
Joe Carroll	OA Systems	JCarroll@Gorge.Net
Mark Schneider	NOAA Fisheries	mark.schneider@noaa.gov
Ben Cope	EPA	cope.ben@epa.gov
Mike Schneider	CE-ERDC-CHC	Michael.I.Schneider@nwp01.usace.army.mil
Jim Irish	BPA	jtirish@bpa.gov
Carolyn Schneider	CE-ERDC-EL	Carolyn.b.schneider@nwp01.usace.army.mil
John Piccininni	BPA	jppiccininni@bpa.gov
Dave Soballe	CE-CERDC-EL	david.m.soballe@erdc.usace.army.mil
Chris Cook	PNNL	Chris.Cook@pnl.gov
Mark Gunter	OA Systems	mgunter@gorge.net
Kathryn Barko	DYNCORP	Kathryn.L.Barko@nwp01.usace.army.mil
Erich Brandstetter	Montgomery-Watson-Harza	erich.r.brandstetter@mwhglobal.com
Paul Pickett	Wash DOE	ppic461@ecy.wa.gov
Stu McKenzie	OA Systems	stumckenzie@msn.com

On the telephone:

Marvin Shutters	Walla Walla COE District	Marvin.K.Shutters@nw01.usace.army.mil

Appendix B

Summary of Water-Quality Questions

The following is a summary of water-quality questions that were identified by the RPA workgroup that were of high priority and should be addressed with a model and data collection program.

1. What is the temperature pattern for Lower Granite reservoir when stratified with release of cold water from Dworshak Dam? How does this stratification change with different temperatures and flows in the Clearwater and Snake Rivers? What are the temperature and velocity profiles in the reservoir when stratified? How do these profiles change in time?
2. What is the time delay and magnitude of effects when Dworshak Reservoir releases cool water? During seasons and flow conditions of interest? For different lake stages and temperature releases of interest? At each Snake River fixed monitoring station?
3. Can a "smarter" release scheme for Dworshak be developed that optimizes cold water usage and achieves more desirable downstream temperatures in the Snake River?
4. What are the limiting factors controlling the amount of water and temperature of water from Dworshak Reservoir after the initial release and after cool water releases are discontinued? Is the amount of water for the amount of cold water more limiting? Could day-to-day changes in flows and temperatures extend the effects of Dworshak Reservoir on the Snake River?
5. How can management a) meet maximum temperature criteria in the Snake River, b) meet minimum temperature guidelines in the Clearwater River, and c) minimize differences upstream and downstream of the North Fork Clearwater River in the Clearwater River?
6. What are the potential benefits of using real-time ambient conditions (e.g., meteorology, water temperatures, river flow) to manage daily operations at Dworshak?
7. How do the cooled waters from Lower Granite Dam pass through the three lower Reservoirs? Is there a management alternative to influence the temperature in downstream reaches?
8. Can release of water from Brownlee Dam affect water temperatures in the Lower Granite Dam to Snake River to mouth reach? For all seasons, flows and temperatures of interest? How far downstream? What is the magnitude of the temperature change? What is the optimum balance between Brownlee and Dworshak augmentation for the fish? How do operational options affect water temperatures in the Snake River?

9. What are the meteorological effect (wind, solar radiation, and humidity) on stratification, temperatures and velocities in the Snake River reservoirs?
10. How representative are the current fixed temperature stations of river conditions? During augmentation from Dworshak Reservoir? For the Snake River from Brownlee Reservoir to Snake River mouth? At tributaries when used as boundaries for numerical models?
11. How are operational decisions complying with the implementation plan from the Snake River TMDL?

APPENDIX C

Biological Effects of Snake River Thermal Regimes on Endangered Species in the Lower Snake River

BIOLOGICAL EFFECTS OF SNAKE RIVER THERMAL REGIMES ON ENDANGERED SPECIES IN THE LOWER SNAKE RIVER

Prepared for

US ARMY CORPS OF ENGINEERS
WALLA WALLA DISTRICT
Walla Walla, Washington 99362

Prepared by

NORMANDEAU ASSOCIATES, INC.
25 Nashua Road
Bedford, NH 03110

Dr. David Bennett
Dr. Christopher Peery
College of Natural Resources
Department of Fish and Wildlife Resources
University of Idaho
Moscow, Idaho

P-18880.007

September 2003

Executive Summary

Threats to anadromous Pacific salmonid (*Oncorhynchus* spp.) stocks in the Columbia Basin from human development activities began over a century ago. Intense fishing, irrigation dams and water diversions, land management activities such as mining, logging, and cattle grazing, and hydoelectrical power development all have adversely affected Pacific salmonids (Lichatowich 1999). Numerous salmonid stocks went extinct as a result of stream blockage and degraded habitat (Nehlsen et al. 1991) whereas others continue to slowly decline. Snake River stocks, the largest contributing tributary to the Columbia River (Hassemer et al.1997), declined seriously in the mid 1970s. In 1992, the National Marine Fisheries Service (NOAA Fisheries) listed under the Endangered Species Act of 1972 the Snake River sockeye salmon (*O. nerka*-1991) followed by listing (1992) of spring and summer Chinook salmon (*O. tshawytscha*) and fall Chinook salmon (NMFS 1992). Most recently, steelhead (*O. mykiss*) was listed in 1998 (NMFS 1998).

In response to the listing, NOAA Fisheries, the federal agency responsible for enforcement of the Endangered Species Act of 1972 for anadromous Pacific salmonids, issued the Biological Opinion (BIOP) for operations of the Federal Hydroelectric Power System on the Columbia River (NMFS 2000). In the BIOP, the Reasonable and Prudent Alternative section contained measure No.143 that directed "The Action Agencies shall develop and coordinate with NOAA Fisheries and the Environmental Protection Agency (EPA) on a plan to model the water temperature effects of alternative Snake River operations. The geographic area currently encompassed by measure No. 143 is from Dworshak Dam on the North Fork Clearwater River and on the Snake River from Hells Canyon Dam downstream to Bonneville Dam on the lower Columbia River although the current implementation efforts of measure No. 143 are focused on the lower Snake River.

Concern over elevated temperatures impacting the upstream migration of fall Chinook salmon and steelhead in August 1990 was directed from the Fish Passage Center, acting on behalf of the fishery agencies, and Indian tribes, who requested flow augmentation through the lower Snake River. The US Army Corps of Engineers through their Reservoir Control Center responded by increasing flow to full powerhouse capacity from Dworshak Reservoir, beginning September 4, 1990 (Karr et al. 1992). Water was released for 17 days and a total volume of 320 Kacre-feet reduced water temperatures in the Clearwater River and moved downstream to Lower Granite Dam as a density current under the warmer water. Promising results of decreasing water temperatures at Lower Granite Dam led to monitoring studies of the dynamics of higher flows and colder water in the lower Snake River. Since then, timed cold water releases from Dworshak Reservoir and increased flows from the middle Snake River reservoirs have been used earlier in the summer to benefit juvenile fall Chinook salmon (Connor et al. 1998; 2000). Questions continue however, as to which stocks and life history stages are the most at risk from high water temperatures. Consequently, the purpose of this white paper is to assess the utility of flow augmentation through cool water releases for river temperature management and ESA listed fishes, examine timing of those releases and assess benefits and liabilities to the overall lower Snake River ecosystem.

Specific objectives were:

1. To conduct and compile a literature review on effects of water temperature on life history stages of Chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss*;

2. To identify the most sensitive ESA listed salmonid stocks and life stages to water temperature patterns and extremes characteristic of the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River;
3. To identify the life stages of the affected ESA listed species and examine the critical months and seasons or timing for operational actions to alter or control water temperatures to maximize biological benefit; and,
4. To identify the three dimensional distribution of adult and juvenile anadromous salmonids passing through the Snake River corridor with emphasis on Lower Granite Reservoir and if possible, correlate fish locations with water temperature.

Numerous literature surveys have been conducted on effects of temperature on the life cycle of Pacific salmon (see McCullough 1999; Brown 1976; Schuytema 1969) and a myriad of other literature not summarized in these literature surveys (Appendix 1). Much of this information has been obtained from controlled laboratory studies although few field studies have been conducted and results have generally not been applied to thermal conditions in the lower Snake River. Often literature sources that have established a paradigm may be based on small sample sizes.

We examined the various stages of the life cycle (smolt and adult steelhead, smolt and adult spring and summer Chinook salmon, and sockeye salmon and egg, embryo, parr, smolt, and adult fall Chinook salmon) of ESA listed anadromous salmonids in the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River.

Spring and summer Chinook salmon smolts, migrating mostly as yearlings and steelhead migrate sufficiently early that water temperature does not pose a direct risk to the bulk of the run. Published survival models corroborate this interpretation. However, the middle 80% of the listed juvenile sockeye salmon in 1997 extended to early September which exposed 6.7% of the run to waters >20°C. These water temperatures are >5°C higher than those identified to affect juvenile sockeye salmon migrations (Brett et al. 1958). The smolt index data suggest that fall Chinook salmon juveniles are the latest migrators and potentially the most affected stock of ESA listed salmonid fishes to potentially deleterious existing thermal conditions in the lower Snake River. Altered life history patterns have been reported as a result of environmental changes in their rearing environment. The altered life history patterns have placed the juvenile fall Chinook salmon in a condition of migrating later in the year at a time when water temperatures are warmer. During the 4 years examined, representing recent high and low flow years, mean scrollcase water temperatures were at or exceeded 18°C - 20°C, for three of those years. Also, the proportion of the total run of wild fall Chinook salmon juveniles exposed to water temperatures >20°C was higher than 28%. Temperatures near 23°C (± 1.08°C; Baker et al. (1995) have been reportedly lethal to 50% of marked hatchery released fish in the Sacramento River, California. In addition, moderately strong correlative evidence has been developed that demonstrates flow augmentation to reduce water temperatures can increase survival of juvenile fall Chinook salmon in the lower Snake River system (Connor et al. 1998, 2003b). Survival models demonstrate the importance of temperature either directly affecting survival or indirectly by affecting migration dates and body size, factors found to be highly associated with water temperature. Additional studies should be conducted to more fully evaluate current survival models and more fully evaluate the role of cooler water temperatures in improving survival of juvenile fall Chinook salmon. At present, however, the available literature strongly supports use of flow augmentation with its attendant cooler water temperature to benefit downstream migrating fall Chinook salmon.

For adults, spring and most summer Chinook salmon have the least impact from warm water conditions in the lower Snake River, while fall Chinook salmon and steelhead have the greatest potential exposure to warm water temperatures. However, since fall Chinook salmon are obligate migrants, and because the predominate pattern is for warm water conditions to persist later in the fall than historically occurred, fall Chinook salmon adults would appear to be at greater risk for incurring potential temperature related impacts while migrating through the lower Snake River. This conclusion is supported by analyses of telemetry data for adult fall Chinook salmon and steelhead migrating through the lower Columbia River by High (2002) and Goniea (2002). They found that, although members from both runs enter tributary streams during summer, steelhead that use the cool-water refugia realized a survival advantage, while fall Chinook salmon that increasingly delay their migration to use the same refugia experience reduced escapement to spawning areas. Historically, use of cool water refugia incurred an evolutionarily derived survival advantage to both species, but under current temperature conditions, extended delays to adult fall Chinook salmon migrants represent a survival risk. Sockeye salmon pose a particular concern with respect to elevated water temperatures. Although the bulk of the sockeye salmon pass though the lower Snake River prior to peak temperatures, their lower perceived tolerance to warm water conditions, relative to Chinook salmon and steelhead, and the remnant size of the Snake River run, place adult sockeye salmon in a precarious position. An extreme weather year, with early warming of the river in later spring, could significantly affect the reproductive success for sockeye salmon.

The following recommendations were developed:

1. The literature suggests that flow augmentation to decrease water temperatures would afford limited benefit to ESA listed spring and summer Chinook salmon and steelhead.

2. Flow augmentation to decrease water temperatures in the lower Snake River have the potential to enhance survival of out-migrating subyearling Chinook salmon. Field data combined with modeling provide the strongest scientific evidence for use of flow augmentation to decrease water temperatures to enhance survival of subyearling Chinook salmon. Flow augmentation to enhance the thermal environment for juvenile fall Chinook salmon might benefit late out-migrating sockeye salmon and probably upstream migrating adult summer Chinook and sockeye salmon.

3. Because of limited volume in upstream sources, flow augmentation to decrease water temperatures in August and early September have limited potential to significantly reduce temperatures in lower Snake River reservoirs. One study showed a 1°C decrease in summer water temperature (1991) at Ice Harbor Dam. Consequently, most benefits accrue to adults that would be mostly migrating through Lower Granite Reservoir. Late summer timing of flow augmentation to reduce water temperatures would benefit adult fall Chinook salmon and adult steelhead once in Lower Granite Reservoir. Effects of the releases from Dworshak Reservoir at the end of summer (late August–mid September)

should be investigated to facilitate natural cooling patterns for the lower river. Such investigations should focus on effects of temperature exposures on survival to spawning areas and reproductive success. Specifically, what are delayed effects of exposure to warm water temperatures on spawning success and gamete quality?

4. Although results are not conclusive, the best scientific information suggests that properly timed flow augmentation with its attendant cooler water temperatures can improve juvenile survival. Current models developed to predict fall Chinook salmon survival could be improved with larger data sets and greater variation among years.

TABLE OF CONTENTS

PAGE

Executive Summary ii

1.0 Introduction 1

2.0 Study Area 2

3.0 Objective 1 3

3.1 Methods 3
3.2 Results 4

4.0 Objective 2 5

5.0 Objective 3 18

5.1 Timing of Releases 18
5.2 Predation Effects 21
5.3 Resident Fishes 21

6.0 Objective 4 22

7.0 Summary 23

8.0 Recommendations 24

9.0 References 25

LIST OF FIGURES

Page

Figure 1. Map of lower Snake River area of concern. 33

Figure 2. Water temperatures recorded at mouth of the Snake River during 1955-58, and mean water temperatures for the four years. Taken from Eldidge (1963) and Peery ey al. (2003). 34

Figure 3. Mean decadal water temperatures recorded at Ice Harbor Dam from 1962 to 2002. 35

Figure 4. Mean number of adult Chinook salmon and steelhead counted and mean water temperatures at Ice Harbor Dam during 1963-72 (top) and during 1993-2002 (bottom). Dashed horizontal line represents reference temperature of 20°C. 36

Figure 5. Spring Chinook salmon temperature requirements (From: McCullough 1999). 37

Figure 6. Cumulative percent of wild yearling Chinook salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu). 38

Figure 7. Mean sockeye salmon counts and water temperatures at Ice Harbor Dam during 1963-72 (top) and 1993-2002 (bottom). Dashed horizontal line represents reference temperature of 20°C. 39

Figure 8. Cumulative percent of wild juvenile sockeye salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu). 40

Figure 9. Run timing and water temperatures for adult Chinook salmon and steelhead at Ice Harbor Dam during 1998. 41

Figure 10. Lower Granite Reservoir showing temperature monitoring sites in 2001 (Reischel et al. In press). 42

Figure 11. Mean Snake River water temperatures in Hells Canyon Reach (Anatone, WA) during 1993-2002. 43

Figure 12. Cumulative percent of wild subyearling Chinook salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu). 44

Figure 13. Travel times for steelhead between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1996 and 1997. Shown are relationships between travel times and temperature at Ice Harbor Dam in 1996, and between travel times and temperature at McNary Dam in 1997 (insets). Dashed lines represent median travel times (Peery et al. 2003). 45

Figure 14. Date that 25% of the fall Chinook salmon and steelhead runs were counted at Ice Harbor Dam versus mean water temperature measured in the forebay of the dam

during the period from 1 August through 15 September for each year 1962-2000. Fall Chinook salmon counts from 12 August until 31 October. Steelhead counts were from 1 June until 31 October (Peery et al. 2003). 46

Figure 15. Cumulative percent of wild juvenile steelhead migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu). 48

Figure 16. Weekly mean outflows (Kcfs) from Dworshak Reservoir, North Fork Clearwater River, starting 1 March for 1997, 2001, and 2002 (http://www.cbr.washington.edu). 49

LIST OF TABLES

Page

Table 1. Comparison of timing of the middle 80% of the run of ESA listed yearling Chinook salmon (spring and summer), sockeye salmon, subyearling Chinook salmon, and steelhead at Lower Granite Dam, Snake River for selected representative low (1992, 1994) and high (1993, 1997) flow years (from http://www.cbr.washington.edu/perform). Also shown is the percent of the total run exposed to water temperatures > 20°C (based on scrollcase temperatures). 50

Table 2. Comparison of timing of the middle 80% of the run of ESA listed sockeye salmon and subyearling Chinook salmon at Lower Granite Dam, Snake River for years 1998 to 2002 (from http://www.cbr.washington.edu/perform). Also shown is the percent of the total run exposed to water temperatures > 20°C (based on scrollcase temperatures). 51

Table 3. Mean fish body temperatures for adult Chinook and steelhead tracked in the Lower Reach of Lower Granite reservoir compared to tri-level temperature recordings at Wawawai landing (RKM 699.8) July-October, 2001. From Reischel et al. (in press). 52

Table 4. Mean fish body temperatures for adult Chinook and steelhead tracked in the in the middle reach compared to tri-level temperature recordings at Steptoe Creek (RKM 727.9) July-October, 2001. From Reischel et al. (in press). 52

Table 5. Mean fish body temperatures for adult Chinook and steelhead tracked in the the upper reach compared to temperature recordings near Red Wolf Crossing Bridge (RKM 742.8), near Potlatch Mill on the Clearwater River (RKM 747.8), and near Asotin on the Snake River (RKM 754.7) July-October, 2001. From Reischel et al. (in press). 53

Table 6. Percent of time for body temperatures (ºC) of summer/fall Chinook salmon and steelhead tracked in the Lower Granite Reservoir by reservoir reach (Figure 10) and month. From Reischel et al. (in press). Blank cells represent zero time spent at a particular temperature. 53

Table 7. Monthly mean body temperatures (ºC) of adult Chinook salmon and steelhead migrating through the tailraces (TR) and reservoirs (Res) of Ice Harbor (IH), Lower Monumental (LM), Little Goose (LGo), and Lower Granite (LGr, tailrace only) dams, lower Snake River dam during 2000, with standard deviations (sd) and number of fish (n). 54

Table 8. Monthly mean depths (m) of adult Chinook salmon and steelhead migrating through the tailraces (TR) and reservoirs (Res) of Ice Harbor (IH), Lower Monumental (LM), Little Goose (LGo), and Lower Granite (LGr, tailrace only) dams, lower Snake River dam during 2000, with standard deviations (sd) and number of fish (n). 55

Table 9. Percent of time adult Chinook salmon and steelhead spent at different depths as they migrated trough Ice Harbor, Lower Monumental and Little Goose reservoirs during 2000. 56

Table 10. Percent of time spent at different depths (m) by summer/fall Chinook salmon and steelhead tracked in the Lower Granite Reservoir by reservoir reach (Figure 10) and month. Blank cells represent zero time spent at a particular depth. 57

APPENDICES

Appendix 1.	Literature Review. Effects of Water Temperature on Chimode salmon and Steelhead.
Appendix Table 2.	Relationship between date and temperature for yearling and subyearling Chinook salmon, sockeye, and steelhead migrants passed Lower Granite Dam during two low flow years (1992, 1994) and two high flow years (1993, 1997). Numbers below each of the flow years refer to proportion of run passed Lower Granite Dam (e.g., 25-25% of run).

1.0 Introduction

Threats to anadromous Pacific salmonid (*Oncorhynchus* spp.) stocks in the Columbia Basin from human development activities began over a century ago. Intense fishing, irrigation dams and water diversions, land management activities such as mining, logging, and cattle grazing, and hydoelectrical power development all have adversely affected Pacific salmonids (Lichatowich 1999). Numerous salmonid stocks went extinct as a result of stream blockage and degraded habitat (Nehlsen et al. 1991) whereas others continue to slowly decline. Snake River stocks, the largest contributing tributary to the Columbia River (Hassemer et al.1997), declined seriously in the mid 1970s. In 1992, the National Marine Fisheries Service (NOAA Fisheries) listed under the Endangered Species Act of 1972 the Snake River sockeye salmon (*O. nerka*-1991) followed by listing (1992) of spring and summer Chinook salmon (*O. tshawytscha*) and fall Chinook salmon (NMFS 1992). Most recently, steelhead (*O. mykiss)* was listed in 1998 (NMFS 1998).

In response to the listing, NOAA Fisheries, the federal agency responsible for enforcement of the Endangered Species Act of 1972 for anadromous Pacific salmonids, issued the Biological Opinion (BIOP) for operations of the Federal Hydroelectric Power System on the Columbia River (NMFS 2000). The BIOP covers numerous areas to enhance salmonid fish recovery. One goal of the BIOP is to optimize water temperatures for anadromous salmonid and resident fishes. In the BIOP, the Reasonable and Prudent Alternative section contained measure No.143 that directed "The Action Agencies shall develop and coordinate with NOAA Fisheries and the Environmental Protection Agency (EPA) on a plan to model the water temperature effects of alternative Snake River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NOAA Fisheries and state and Tribal water quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations." The geographic area currently encompassed by measure No. 143 is from Dworshak Dam on the North Fork Clearwater River and on the Snake River from Hells Canyon Dam downstream to Bonneville Dam on the lower Columbia River. The current implementation efforts of measure 143, however, are focused on the lower Snake River (Figure 1). The concern for this measure has been stated for many years as water temperatures in the Snake River have often exceeded temperatures considered stressful for salmonids.

Widespread concern over elevated temperatures impacting the upstream migration of fall Chinook salmon and steelhead in August 1990 was directed from the Fish Passage Center, acting on behalf of the fishery agencies, and Indian tribes, who requested flow augmentation through the lower Snake River. The US Army Corps of Engineers through their Reservoir Control Center responded by increasing flow to full powerhouse capacity from Dworshak Reservoir, beginning September 4, 1990 (Karr et al. 1992). Water was released for 17 days and a total volume of 320 Kacrefeet reduced water temperatures in the Clearwater River and moved downstream to Lower Granite Dam as a density current under the warmer water. These releases "show considerable promise in achieving meaningful habitat improvements for the river's vital fish runs…" (Karr et al. 1992). Flow augmentation was continued in 1991 when water temperature and velocity characteristics of experimental releases were evaluated. Data showed a combination of higher flows and colder water, if started sooner and sustained longer, resulted in more complete mixing of the colder water through most of the lower Snake River (Karr et al. 1992). Since then, timed cold water releases from Dworshak Reservoir and increased flows from the middle Snake River reservoirs, have been used earlier in the summer to benefit juvenile fall Chinook salmon (Connor et al. 1998, 2000). Questions continue however, as to which stocks and life history stages are the most at risk from high water temperatures. Consequently, the purpose of this white paper is to assess the utility of flow augmentation through cool water releases for river temperature management and ESA listed fishes, examine timing of those releases and assess benefits and liabilities to the overall lower Snake River ecosystem.

Specific objectives were:

1. To conduct and compile a literature review on effects of water temperature on life history stages of Chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss*;
2. To identify the most sensitive ESA listed salmonid stocks and life stages to water temperature patterns and extremes characteristic of the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River;
3. To identify the life stages of the affected ESA listed species and examine the critical months and seasons or timing for operational actions to alter or control water temperatures to maximize biological benefit; and,
4. To identify the three dimensional distribution of adult and juvenile anadromous salmonids passing through the Snake River corridor with emphasis on Lower Granite Reservoir and if possible, correlate fish locations with water temperature.

2.0 Study Area

The area of concern for this white paper is the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River (Figure 1). The section of the Snake River from Hells Canyon downstream to Lower Granite Dam and upstream in the Clearwater River to the confluence with the North Fork Clearwater River has been described by Connor et al. (2003a; 2003b). Muir et al. (2001) provided a description of the structural, fish collection and bypass systems from Lower Granite Dam downstream to the confluence with the Columbia River. Temperatures have been monitored throughout the lower Snake River annually during the warmer months generally from 1991 through 2002 (Karr et al. 1992; Bennett et al. 1997a, 1997b, 1997c, unpublished data). Peak water temperatures following impoundment of the lower Snake River are about 25°C (Funk et al. 1985).

2.1. SNAKE RIVER TEMPERATURES

The lower Snake River, draining high desert regions from southern Idaho, eastern Oregon and traversing southeastern Washington before joining with the Columbia River, has probably always been warm during summer. One researcher noted the Snake River near its mouth routinely reached temperatures in excess of 72°F (22.2°C) during August, and during late July of 1956, water temperature were recorded above 77°F (25°C) (Sylvester 1958). Impoundment of the lower Snake River by Ice Harbor (1962), Lower Monumental (1969), Little Goose (1970) and Lower Granite

(1975) dams created a series of slack-water reservoirs extending 220 km from Ice Harbor Dam upstream to the confluence with the Clearwater River. Flows through the lower Snake River are influenced by operation of Dworshak Dam on the North Fork of the Clearwater River and by the Hells Canyon complex (Hells Canyon, Oxbow and Brownlee dams) in the mid-Snake River. Impoundment and flow manipulations have significantly altered thermal conditions in the lower Snake River however, there is little information on water temperatures in the Snake River prior to impoundment to provide a point of comparison. Peery et al. (2003) described some information collected at the mouth of the Snake River during a 4 year period 1954-58, which indicated water temperatures could exceed 20°C from early July until mid-September (Figure 2). However, without comparable data during the intervening period, little can be inferred on the degree of change to thermal regime of the river with development of the hydropower system.

The most reliable temperature information has been collected at Ice Harbor Dam starting in 1962. Quinn et al. (1997) analyzed scrollcase temperatures for the period 1962 through 1994 and concluded that the fall cooling (down to 15.5ºC) occurred 11 days later at the end of that period. Looking at the mean scrollcase temperatures by decade (Data from DART website; Figure 3) we see that in the 1960s there were 63 days, on average, when water temperatures were 20°C or warmer, spanning the period from 14 July until 14 September and peaking with mean temperatures around 23°C (range 22.2 to 24.4°C). The 1970s were relatively cooler, with temperatures of 20°C or warmer occurring for 52 days on average, spanning the period 25 July through 14 September, and peaking at about 22°C (range 21.7 to 23.3°C). During the 1980s and 1990s, temperatures warmer than 20ºC occurred for 58 d (1980s) and 73 d (1990s). Peak temperatures were 23.1°C (21.7 to 24.8°C) in the 1980s and 23.0°C (21.4 to 25.1°C) in the 1990s. However later cooling in the fall was evident as the average period for temperatures of 20°C or warmer spanned from 22 July until 18 September during the 1980s and from 15 July until 25 September during the 1990s. The first 3 years of the current decade have experienced noticeably cooler summers than average, with mean water temperatures warmer than 20°C spanning 14 July until 5 September (54 d) and peaking around 21.5°C (21.1 to 22.7°C) through 2002. All these values were summarized from scrollcase readings which measure water temperatures from about mid-depth in reservoirs and are recorded once or twice daily and averaged however, we know that water temperatures near the surface (top 5 m) can be 1 to 2°C warmer than water at depths at Ice Harbor Dam (Peery et al. 2003).

3.0 Objective 1

To conduct and compile a literature review on effects of water temperature on life history stages of Chinook salmon Oncorhynchus tshawytscha and steelhead O. mykiss.

3.1 Methods

A plethora of information exists on effects of temperature on the life cycle of Pacific salmon. Early studies were summarized by Brown (1976) and Schuytema (1969) and more recent summaries were completed by McCullough (1999), EPA (2003) and Berman (1998). Much of this information has been obtained from controlled laboratory studies and provides a basis to evaluate effects of higher temperatures on anadromous salmonid fishes in the lower Snake River. Some authors have reported similarities between field and laboratory findings (Baker et al. 1995) although extrapolation of laboratory results can be misleading because of the dynamic nature of the "natural" habitat. We therefore, have placed greater emphasis on more recent studies and those based on field research under "natural" habitat conditions than on those from laboratory results. We conducted electronic searches to compile literature on effects of water temperature on the life history of steelhead and Chinook salmon. The following search engines were used:

- Fish and Fisheries Worldwide
- ABSEARCH (Includes all American Fisheries Society publications, Canadian Journal of Fisheries and Aquatic Sciences, Ecological Society of America and Copeia)
- Aquatic Sciences and Fisheries Abstracts (Biological Sciences & Living Resources)
- Aquatic Sciences and Fisheries Abstracts (Aquatic Pollution & Environ Quality)
- Aquatic Sciences and Fisheries Abstracts (Aquaculture Abstracts)
- Aquatic Sciences and Fisheries Abstracts (Marine Biotech Abstracts)
- Aquatic Sciences and Fisheries Abstracts (Web Resources)
- Aquatic Sciences and Fisheries Abstracts (Recent References)
- Biological and Agricultural Index
- Cambridge Scientific Abstracts (Biological Sciences)
- Cambridge Scientific Abstracts (Biology Digest)
- Cambridge Scientific Abstracts (Conference Papers Index)
- Cambridge Scientific Abstracts (Environ Science & Pollution Mgt)
- Cambridge Scientific Abstracts (MEDLINE)
- Cambridge Scientific Abstracts (Plant Science)
- Cambridge Scientific Abstracts (TOXLINE)
- Cambridge Scientific Abstracts (Recent References)
- Cambridge Scientific Abstracts (Web Resources)
- Elsevier Science Direct
- Thermal Ecology Workshops
- Wildlife and Ecology Studies Worldwide

Results from these searches were downloaded and the appropriate information was copied and pasted into word processing software. They were then sorted by author and redundancy removed.

3.2 Results

The located citations are shown in Appendix 1.

4.0 Objective 2

To identify the most sensitive ESA listed salmonid stocks and life stages to water temperature patterns and extremes characteristic of the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River.

4.1 METHODS

To obtain the information required to satisfy this objective and the following objective, we used a variety of published and unpublished reports and web data ((http://www.cbr.washington.edu). Smolt index numbers and water temperatures from the scrollcase at Lower Granite Dam were used in these analyses. In addition, comparisons were made using available data query tools on the web (http://www.cbr.washington.edu/perform).

Temperature exposure was evaluated using a maximum water temperature of 20°C for two major reasons. Hokanson (1977) in his review of temperature requirements of freshwater fishes identified water temperatures <20°C as the maximum optimum temperature for salmonid fishes. Also, the State of Washington has used 20°C as a maximum water temperature standard to protect salmonids based on the Clean Water Act (Washington Administrative Code 1992; cited in Tiffan et al. 2003)

4.2 FINDINGS

Water temperatures >20°C for 1 to 3 months n the Snake River have the potential to adversely affect nearly all life history stages of several ESA listed fishes. For example, the egg and parr stages of fall Chinook salmon and smolt stages for steelhead, sockeye salmon, spring, summer and fall Chinook salmon are all potentially affected by elevated water temperatures in the area of concern. Adult salmonids are exposed to a variety of temperature conditions during their tenure in freshwater. The best examples are Chinook salmon that migrate through the lower Columbia and Snake rivers from March into November and are categorized into spring, summer, and fall runs primarily based on the time they enter freshwater and pass Bonneville Dam. Steelhead also migrate in large numbers through both the lower Columbia and lower Snake rivers. The main group of steelhead, the summer run, pass Bonneville from mid-July to mid October and pass Ice Harbor Dam from July through October. Adult sockeye salmon historically returned to the Snake River in larger numbers from mid-June through October, but currently are only a remnant group sustained by intensive artificial production, including a captive broodstock program. Each of these species and stages will be examined relative to their timing and existing temperatures in the Snake River.

Salmonids are poikilotherms, vertebrates whose body temperatures are similar or slightly warmer than the surrounding water. In addition, Pacific salmon are considered cold-water species, that is, fishes whose optimal water temperatures are less than 20°C (Hokanson 1977). As such, water temperatures outside their thermally optimal levels will constitute stressors and elicit a stress response (Fagerlund et al. 1995). The response can be either behavioral (seeking of, and movement to, cooler water) or physiological (e.g., release of stress hormones, increase metabolic rate, etc.), or a combination of both. Salmonids have some ability to adapt to or acclimate to new temperature conditions, up to a point, after which sub-lethal and then lethal effects will occur.

4.2.1 Spring Chinook Salmon

Timing of life history patterns of spring Chinook salmon probably make them the least affected by elevated temperatures in the Snake River of all of the ESA listed salmonids

4.2.1.1 Adults

Adults typically migrate upstream through the area of concern from April through June when temperatures are generally less than 15°C (Figure 4). Even under the lowest flow years and warmest temperatures, water temperatures are generally less than 13.3°C, the temperature identified by McCullough (1999) to cause stress. McCullough (1999) indicated that adult migration blockage would occur at 21°C (Figure 5) but adult spring Chinook salmon typically migrate through the area of concern before these temperatures occur. Keefer et al. (submitted) demonstrate how spring Chinook salmon intra-annual migration rates increase through the season, both at dams and through reservoirs, and the effects were correlated with temperatures while inter-annual migration rates through the hydrosystem were correlated with flow levels. Spawning occurs outside of the area of concern, as does most of the rearing in the parr stage. However, some subyearling migrations of spring Chinook salmon occur that generally coincide with the downstream migration of fall Chinook salmon (Connor et al. 2000). No known information exists about overall survival of these subyearling spring Chinook salmon and their possible contribution to the adult population.

4.2.1.2 Smolt

Several investigators have examined travel time of yearling Chinook salmon in the Columbia River basin. Giorgi et al. (1997) found that release date was the most important variable (r^2=0.21) in a bivariate analysis describing migration rate from Rock Island Dam to McNary Dam. Water temperature and flow explained <20% of the variation in migration rates of yearling Chinook salmon. Berggren and Filardo (1993) reported that flow, time of release before reaching Lower Granite Dam, and delta flow (max.-min.) collectively accounted for 74% of the variation in travel time in their multiple regression model. Travel time and survival are reportedly correlates (Raymond 1979).

The importance of flow and temperature on yearling Chinook salmon survival in the lower Snake River was recently examined. Smith et al. (2002) reported that the association of estimated survival and flow was weak and not consistently positive or negative. The relationship between travel time and flow was strong and consistent among years and that flow augmentation could decrease travel time. However, Smith et al. (2002) concluded that "with the survival rates observed under the flow conditions that existed recently for spring-migrating smolts in the lower Snake River, it would seem that little room exists for increased flow to improve overall survival in that stretch of the river." They believed that higher flows could possibly benefit other stages of the life cycle further downstream in the estuary. However, correlations of survival and water temperature were not significant.

Spring Chinook salmon typically enter the area of concern during the period from March through June (http://www.cbr.washington.edu). As can be seen in Figure 6, the majority of the downstream migrants of listed yearling Chinook salmon passed Lower Granite Dam about 60 d following 1 April of 1992, 1993, and 1994 but was later in 1997. During low flow years (1992, 1994 used throughout this report as examples), the middle 80% of the smolt downstream migration passed Lower Granite Dam by early June (Table 1). During high flow years (1993, 1997 used throughout this report as examples), the middle 80% of the smolt downstream migration passed Lower Granite Dam by about early June in 1993 and the end of June in 1997. Approximately 1% and 0% of the juvenile wild spring and summer Chinook salmon were exposed to water temperatures of 20°C and higher in 1992 and 1994, respectively (Table 1). In comparison, less than 0.1% of the juvenile wild spring and summer Chinook salmon were exposed to water temperatures of 20°C and higher in 1993 and 0% in 1997. Water temperatures averaged about 12°C during 1993 (range 10.3-14.2°C) and 1997 (range 8.9-16.7°C) during the middle 80% of the ESA listed yearlings compared to about 13°C during both 1992 (range 9.4-16.8°C) and 1994 (range 10.8-16.5°C). For all yearling smolts, 90% passed Lower Granite Dam at temperatures <15°C during both representative low flow and high flow years (Appendix Table 1).

4.2.2 Sockeye Salmon

The life cycle of the Snake River sockeye salmon places them in the area of concern during the adult and smolt stages. Rearing occurs upstream in lakes in the Sawtooth Mountains (Beauchamp et al. 1997) although their downstream access to the Columbia River and Pacific Ocean make them potentially affected by high water temperatures in the lower Snake River. Also as returning adults, they encounter the area of concern when they ascend to their natal waters for spawning.

4.2.2.1 Adult

Bell (1986 cited by Bjornn and Reiser 1991) stated that sockeye salmon are known to migrate in waters at temperatures from 7.2 to 15.6°C. Optimal migrating temperatures for adult sockeye salmon are thought to be 15 to 17°C, based on laboratory evaluations (Brett and Glass 1973; McDonald et al. 2000). The preferred temperature for adult migrating sockeye salmon is unknown. Historically, Quinn et al. (1997) reported the migration period of adult Snake River sockeye salmon over Ice Harbor Dam was from June 14 – October 26, which included the period of highest water temperatures in the lower Snake River (Figure 7). During this time, water temperatures can exceed 25°C (Funk et al. 1985; Peery at al. 2003).

The primary behavioral trait reported for adult anadromous salmonids with respect to warm water temperatures was that fish will tend to delay or halt migrations when water temperatures reach 21°C or warmer (e.g., ODEQ 1995; McCullough 1999; Sauter et al. 2001). This observation is based on early tagging studies such as one by Major and Mighel (1967) in which they correlated movements of sockeye salmon to water temperatures in the Okanogan River, as determined from fish counts and movements of tagged fish between Rocky Reach and Zosel dams. They concluded that sockeye salmon were delayed reaching Zosel Dam during periods when water temperatures in the Okanogan River were 21.1°C (70°F) or warmer, although they failed to consider the influence the relative differences between the Okanogan and Columbia rivers temperatures may have contributed to delays. Likewise, Hatch (1999 cited in McCullough 1999) found that the adult sockeye migration into the Okanogan River was curtailed until temperatures decreased to < 22.8°C. As Quinn et al. (1997) pointed out, the general sockeye salmon run pattern at Ice Harbor Dam was bimodal, with the nadir between modes coinciding with the period when water temperatures exceeded 20 to 21°C (Figure 7). In the last few years (1999-2002), returning adult progeny from the Redfish Lake broodstock program have passed Ice Harbor Dam during late June and early July, just prior to peak water temperatures, with only a few individuals observed during August and September (Figure 7).

Potential sub-lethal effects from exposure to warm water conditions include increased susceptibility to disease, higher metabolic rates, and inhibited gonadal development (McCullough et al. 1999, 2001). For example, adult male sockeye salmon held at 16.5°C developed smaller gonads than males held at 10°C over a 44 d period (Bouck et al. 1975). An area of increasing research is the relation between energy use and migration and reproductive success for sockeye salmon in the Fraser River, Canada (e.g., Hinch and Rand 1998; Hinch and Rand 2000). Although those studies did not directly address temperature effects, they point out the potential of energy exhaustion affecting adult migrating sockeye salmon. Since metabolic costs increase exponentially with temperature (Brett 1995), the potential for Columbia and Snake River sockeye salmon to exhaust energy reserves prior to spawning increases during warmer water conditions (as speculated by McDonald et al. 2000). Studies of this nature have not been undertaken for Columbia River sockeye salmon, although similar research has been initiated with Chinook salmon (Brown et al. 2002).

Lethal levels for adult sockeye salmon have not been critically determined but it is generally believed that adult temperature tolerances are lower than those for juveniles (e.g., McCullough et al. 2001). The upper incipient lethal temperature for juvenile sockeye salmon is about 24 to 25°C (Brett 1952). At 26°C, mean survival time was 100 min for adult sockeye salmon (Servizi and Jensen 1977). Survival for Columbia River sockeye salmon averaged 3.2 d when held in tanks at 22°C and 11.7 d when held at 20°C (Bouck et al. 1975). In the Fraser River during 1998, one of the warmest years on record, in-river mortality of adult sockeye salmon was estimated to be 65% of the run (McDonald et al. 2000). McDonald et al. (2000) concluded that the excess mortality for the adult Fraser River sockeye salmon occurs when system water conditions exceed 17 to 18°C for prolonged periods of time. They also reported low fertilization and hatching success, and depressed sexual hormone levels in females for various Fraser River sockeye salmon stocks during 1998. Water temperatures routinely exceed 18°C during the period adult sockeye salmon are migrating through the lower Snake River. We do not have accurate travel times for sockeye salmon through the lower Snake River, but adults migrated between McNary and Rocky Reach dams (293 km and four dams/reservoir reaches) in a median of 12.6 d during 1997 (Naughton et al. 2003).

4.2.2.2 Smolt

Giorgi et al. (1997) presented regression models to explain travel time of juvenile sockeye salmon from Rock Island Dam to McNary Dam. They reported that flow in their bivariate models accounted for the largest amount of variation (r^2=0.423) while temperature explained less of the variation (r^2=0.248). Their multiple regression model included flow release date and body length. Thus, water temperature has limited effect on sockeye salmon smolt travel time.

Sockeye salmon smolts are first collected at Lower Granite Dam in late March to mid-April (http://www.cbr.washington.edu/). As can be seen in Figure 8, over 80% of the downstream migration during both low flow and high flow years generally occurred before 75 days following 1 April. Dates of the middle 80% of the ESA listed run were generally from early to late May although in 1997 the run extended into September (Table 1). Unfortunately, no data were available for higher flow year 1993. Examination of run timing for additional years (1998-2002) indicated a similar trend in the downstream migration of wild sockeye salmon (Table 2). Highest mean scrollcase water temperatures at the Lower Granite Dam during the middle 80% of the ESA listed sockeye smolt run during high and low flow years ranged from 13.4 ºC (1994; low flow year) to 17.4 ºC (1997; high flow year). In comparison, the mean scrollcase water temperature during the middle 80% of the run from 1998-2002 was 17.8°C and ranged from a low of 9.4°C (2001) to a high of 20.6°C (Table 2). During the selected high and low flow years, 0% of the listed sockeye salmon run generally was exposed to water temperatures >20°C except in 1997 (6.7%). In the years 1998-2002, exposure to waters >20°C ranged from 0.3% to 6.8% for the total run of wild juvenile sockeye salmon. Sockeye smolt numbers during 1992 and 1994 were low (<40 fish), whereas numbers of wild fish in 1998-2002 ranged from about 1,500 to >76,000. For the overall downstream migrations of sockeye salmon from the representative low and high flow years, between 10% and 25% passed Lower Granite Dam at temperatures that ranged from 12.8°C (1994) to 18.9°C (1997; Appendix Table 1). Brett et al. (1958) reported that sockeye salmon smolts curtail their migration at water temperatures of 12°C to14°C although collections made in Lower Granite Reservoir during some of the representative years did not demonstrate sockeye were residualizing in the reservoir (unpublished data, D.H. Bennett, University of Idaho).

4.2.3 Summer Chinook Salmon

Summer run Chinook salmon in the Snake River are potentially affected by warm water conditions in the adult and smolt stages. Like sockeye salmon and spring run Chinook salmon, their spawning and rearing is upstream of the area of concern.

4.2.3.1 Adult

Adult summer Chinook salmon are generally believed to pass through the lower Snake River from mid June through mid August. Typically this time period coincides with increasing water temperatures but generally prior to the peak annual water temperatures in the lower Snake River (Figure 4). However, during warm years the latter portion of the summer run can occur when water temperatures are 20°C or warmer (e.g., Figure 9). Summer Chinook salmon migration rates were consistently higher than those for spring Chinook salmon, and this effect again appeared related to river temperature (Keefer et al. submitted). Based on thermal limits for adult spring Chinook salmon, McCullough (1999) suggests an optimum temperature for migration to 13.3°C with adult migration blockages at 21.0°C (Figure 5). Although these data were collected for spring Chinook salmon, McCullough (1999) reported “little justification for assuming large genetic adaptation on a regional basis to temperature regimes” for family and stock level designations. Peery et al. (2003) considered exposure to water temperatures of 20°C or warmer would cause non-lethal temperature effects. Region 10 EPA concluded water quality criteria for adult migrating salmon should be 20°C (7 day average of the daily maximums) although reductions in migration fitness (swimming ability, disease susceptibility) may occur with prolonged exposures to water temperatures of 17 to 18°C or warmer (US EPA 2003). Consequently, thermal maxima in the Snake River create a possible risk for adult summer Chinook salmon upon entering the Snake River, upstream to the confluence with the Salmon River. Further discussion on effects of temperatures on Chinook salmon are provided below in the section for fall Chinook salmon.

4.2.3.2 Smolt

Timing of the downstream spring and summer Chinook salmon smolt migration is identical in the Snake River and consequently, the same influence of temperature on spring Chinook salmon smolts applies to summer Chinook smolts. Summer Chinook salmon smolts, migrating as yearlings, typically enter the area of concern during the period from March through June (http://www.cbr.washington.edu). As indicated earlier, McCullough (1999) reported that lethal /loading stress temperatures to smolts were at 18.3°C (Figure 5). As mentioned under spring Chinook salmon smolts, water temperatures during the warmest and driest years can range from 9.4°C to 16.8°C during the middle 80% of the ESA listed yearling out-migration (Table 1), several degrees below the lethal loading temperature identified by McCullough (1999). As indicated for spring Chinook salmon, approximately 1.2% of the run of ESA listed yearling Chinook salmon were exposed to water temperatures >20°C in 1992 (Table 1). Exposure of yearling Chinook salmon to similar temperatures was 0.1% or less in the remaining representative years. Water temperatures were about 13°C when 75% of the indexed run passed Lower Granite Dam (Appendix Table 2-1).Timing of the latter 10% of all yearling Chinook out-migration by Lower Granite Dam occurred consistently by about mid-May. Because juvenile summer Chinook salmon migrate as yearlings, results of various models presented earlier under spring Chinook salmon would apply to juvenile summer Chinook salmon migration characteristics.

4.2.4 Fall Chinook Salmon

Certain life history stages of fall Chinook salmon are reportedly the stock of Chinook salmon at highest possible risk associated with the warm water temperatures occurring in the area of concern (Connor et al. 1998; Connor et al. 2000; Connor et al. 2003a; Connor et al. 2003b). Timing of adults into the Snake River historically occurred after peak water temperatures, but currently warm water temperatures persist later into the fall in the lower Snake River (Peery et al. 2003; Quinn et al. 1997) increasing temperature exposure levels for adult fall Chinook salmon. Juvenile fall Chinook salmon migrations downstream generally coincides with the highest water temperatures in the study area. As a result, timing of various aspects of the life cycle of fall Chinook salmon has been shifted to later in the year, coinciding with higher water temperatures (Connor et al. 2002).

4.2.4.1 Adult

The upstream migration of adult fall Chinook salmon runs from mid-August to December in the Snake River (Figure 4) during which water temperatures can range from highs of 24 to 25°C to lows later in the fall below 10°C (Peery et al. 2003). Bell (1986 as cited by Bjornn and Reiser 1991) stated that fall Chinook salmon will migrate in waters at temperatures from about 10 to 19°C. Spigarelli and Smith (1975) suggested that adult Chinook salmon prefer to migrate in waters around 17°C. As with sockeye salmon, it is believed that water temperatures of 21°C will inhibit adult Chinook salmon migrations. For example, Stabler (1981) found that some radio-tagged Clearwater River Chinook salmon would stray into the cooler North Fork Clearwater River (14 to 16°C) when the mainstem water temperatures were 21°C or warmer. At that time, the North Fork was being cooled from water released from Dworshak Reservoir. The relevance of this discussion is that fish may delay or halt their migrations when water temperatures reach 21°C, potentially creating a bottleneck to passage for fish entering the Snake River during summer when water temperatures in the Snake River reach 21°C and Columbia River water temperatures are < 21°C, and for fish passing Snake River dams when water temperatures in fishways exceed this level.

Evidence that a migration block occurred at the mouth of the Snake River was presented from an early telemetry study conducted in 1967 (Stuehrenberg et al. 1978). In that report Stuehrenberg et al. (1978) reported that summer Chinook salmon and steelhead began to congregate in the Columbia River outside the mouth of the Snake River during July when Snake River water temperatures reached 21°C while the Columbia River water temperature was 17°C. The delay of fish appeared to dissipate by the first week of September when water temperatures in both rivers decreased to 21°C. Peery et al. (2003) reported results from telemetry studies that some adult Chinook salmon would delay entering the Snake River during warm water temperatures, based on travel times between McNary and Ice Harbor dams, although overall relationships were weak (r^2 values < 0.1). They summarized 2 years of data, 1997 and 1998, for Chinook salmon, but since relatively few fall Chinook salmon enter the Snake River, sample sizes were small (69 summer and 2 fall Chinook salmon in 1997, 66 summer and 25 fall Chinook salmon during 1998). Peery et al. (2003) also concluded from analyses of count data that fall Chinook salmon runs arrived later at Ice Harbor and Lower Granite dams during years with warmer summer-time water temperatures. Thus, water temperatures will affect the timing when salmon and steelhead enter and move through the Snake River, and that some, but not all fish may delay entering the mouth of the Snake River when water temperatures reach 21°C (Figure 9). Goniea (2002) also found a general trend where run timing for fall Chinook salmon in the lower Columbia River (based on dam counts) was later with warmer water temperatures and the relationship became stronger as the run progressed upstream from Bonneville to McNary dams. Timing to Ice Harbor Dam was not included in the analysis since a relatively small proportion of fall Chinook salmon enter the Snake River.

Subsequent analyses of 2 years (1998 and 2000) of telemetry data for fall Chinook salmon (Goniea 2002) revealed that significant numbers of fish destined for upriver sites (upstream from John Day Dam) temporarily strayed into cooler water tributaries of the lower Columbia River before continuing their migration to upstream locations, and that the proportion that strayed into tributary rivers was higher during the warmer of the 2 years evaluated. During 1998, when Columbia River water temperatures at Bonneville Dam averaged 22.2°C during August and September, 30.2% of the 464 radio-tagged fall Chinook salmon known to have later passed John Day Dam temporarily strayed into cool-water tributaries in the Bonneville and The Dalles reservoirs, as compared to 14.5% of 540 radio-tagged salmon that strayed into the lower river tributaries in 2000 when water temperatures averaged 20.3°C (Goniea 2002).

Keefer et al. (submitted) used radio telemetry to evaluate migration rates of adult Chinook salmon and steelhead in the Columbia and Snake rivers over a 5 year period. They found that passage rate differences between years for spring and summer Chinook salmon were most strongly and inversely related to river discharge and within-year migration rates were highly correlated with water temperatures. Migration patterns for fall Chinook salmon were more correlated to water temperatures, with slower migration rates through the lower Columbia River during warmer temperature conditions.

Peery et al. (2003) found little relationship between times to pass Ice Harbor and Lower Granite dams by radio-tagged adult Chinook salmon and water temperatures even though temperatures in fishways were often in excess of 20°C. This may be used to infer that water temperatures have little effect on salmon passage at dams, however this may be misleading. Relatively few fish migrate through the lower Snake River during periods of warmest water temperatures and this was evident in the low number of radio-tagged salmon, originally tagged at Bonneville Dam that attempted to pass the two Snake River dams during the warmest periods of the study. So, some (30% and 15% during 1998 an 2000) upriver fall Chinook salmon may first delay their migration seeking cold water refuge in the lower Columbia River tributary streams, and a portion of the run may later delay entering the Snake River during warm water conditions, although the number of fish that may delay and the amount of delay at the Snake River mouth is presently unknown.

Passage by Chinook salmon at hydroelectric dams may also be related to water temperatures. Keefer et al. (2003) investigated salmon and steelhead passage at John Day Dam with respect to temperatures because adult migrants exhibit longer passage times at that project relative to other dams in the system. Keefer et al. (2003) found that more fish tended to turn around in the transition pools and subsequently exit fishways at John Day Dam than at other dams, leading to the longer passage times. They also found that proportions of steelhead, sockeye, and fall Chinook salmon that exited the fishways increased as water temperatures increased. This suggests that, in some situations, temperature may contribute to delayed passage at dams.

Little is known about preferred or optimal water temperatures for migrating adult Chinook salmon in freshwater. Some insights may be available from a 2001 study in which adult Chinook salmon and steelhead were outfitted with sonic tags that transmitted depth and temperatures of the fish as they migrated in the Snake River between Lower Granite Dam and the confluence with the Clearwater River to evaluate use of cool water releases from Dworshak Reservoir (Reischel et al. in press). By tracking individual fish using a boat outfitted with hydrophones and sonic receiver, depths and temperatures were collected and stored in a portable computer. Concurrent with the study, water temperatures were being collected through the reservoir (D. Bennett, University of Idaho, unpublished data) so that fish behavior and body temperature could be related to prevailing water temperatures (Figure 10). Reischel et al.(in press) found that the Chinook salmon body temperatures were usually similar to the coolest water available in the segments of Lower Granite Reservoir monitored (Tables 3-5), but fish temperatures could also vary over a relatively wide range of water temperatures available to choose from (Table 6). It appears fish selected for water temperatures between 15°C and 19°C while migrating through the lower Snake River and moved to water as cool as 12°C to 14°C, when available, inside the mouth of the Clearwater River.

Fish temperatures (and depths, see Objective 4) have also been collected using archival transmitters for adult Chinook salmon migrating through the lower Snake River up to Lower Granite Dam (C. Peery and T. Reischel, University of Idaho, unpublished data). Although sample sizes are small, we see from a preliminary summary of the data that temperatures were warmest during August, especially at Ice Harbor Dam and Reservoir where mean fish body temperatures were > 20°C (Table 7). Coutant (1970) concluded that the incipient lethal temperature for adult ('jack') Chinook salmon was 21°C to 22°C. Using this as a standard, fish in the tailrace at Ice Harbor Dam and in the Ice Harbor Reservoir were at near lethal temperature levels during August 2000. Fish body temperatures were cooler upstream from Lower Monumental Dam during August, possibly related to the release of cool water from Dworshak Reservoir.

As noted above, lethal temperature levels for adult Chinook salmon are thought to be around 21 to 22°C (Coutant 1970). However, sub-lethal effects from temperatures can occur at temperatures below this level. For example, Berman (1990) found that spring Chinook salmon females held at 19°C for about 3 weeks prior to spawning produced smaller eggs and alevins with more pre-hatch and developmental abnormalities than females held at 14°C. A total of 33 females from Roza Dam on the Yakima River were used for that study. It is believed optimal holding temperatures for adult salmon prior to spawning are < 14°C (Piper et al. 1982), but it is not known how early in the migration that warm water temperature exposures will adversely affect gamete development. If, as McDonald et al. (2000) found with sockeye salmon in the Fraser River, reproductive hormone production is affected in females that migrate during warm water conditions, fall Chinook salmon passing through the lower Snake River from late July until early September could be adversely affected.

Fall Chinook salmon spawn in the un-impounded section of Snake River between Asotin, Washington, and Hells Canyon Dam (162 km), typically between late October and early December (Groves and Chandler 1999). Groves and Chandler (1999) reported that fall Chinook salmon spawning in the Hells Canyon reach during 1993 to 1995 began at 16°C, with a daily mean temperature of 10.5°C. On average, water temperatures in the Snake River decrease below 15 to 16°C by mid-October (Figure 11), however during a warmer than average year (e.g., Figure 9), the onset of spawning could be delayed, or fish may be forced to spawn at elevated water temperatures.

4.2.4.2 Egg and Alevin

Effects of high temperature exposure within the female on egg viability has not been quantified in the study area. However, published literature strongly suggests adverse effects of exposure of ripe Chinook salmon females to temperatures exceeding 14°C (Rice 1960; Leitritz and Lewis 1976, both cited by McCullough 1999). Exposure to temperatures > 14°C reportedly can result in egg mortality and delayed alevin development.

Thermal conditions in the area of concern during incubation are probably suitable and not have adverse effects on alevin survival and emergence. Bjornn and Reiser (1991) reported that optimum incubation temperatures range from 5.0°C to 14.4°C although some researchers have reported an upper limit not to affect embryo incubation of 12.8°C (McCullough 1999). At higher incubation temperatures, incubation success is reduced by about 50%. At the timing of fall Chinook salmon spawning in the Snake River water temperatures are within this recommended range. Conversely, low water temperatures are not a factor in the Clearwater River as a result of warmer water releases (≥4.0°C) from Dworshak Reservoir. Historically, low water temperatures probably precluded fall Chinook spawning in the Clearwater River downstream of the North Fork Clearwater River and probably currently do upstream of that tributary (Don Chapman, Boise, Idaho, Personal Communication).

4.2.4.3 Parr and Smolt

Present water temperatures in the area of concern affect growth of parr and have resulted in different life history strategies of fall Chinook salmon among the Clearwater River, Snake River downstream of the Salmon River and Snake River upstream of the Salmon River (Connor et al. 2002). These thermal conditions have affected growth and ultimately changed the life history to a “river-type” for fall Chinook salmon in the Clearwater River and later migrate in the Snake River, although maintaining the historic “ocean-type” of life history, with parr attaining parr size (>45 mm) earlier upstream of the Salmon River. Size of juveniles initiating their downstream migration is critical as length has been implicated in survival (Connor et al. 2003a) and rate of movement (Connor et al. 2003b). Rate of movement and size both have significant implications in predator avoidance (Anglea 1997; Poe et al. 1991) and successfully reaching the cooler Columbia River.

The “river-type” of life history described by Connor et al. (2002) for fall Chinook salmon from the Clearwater River is a by-product of the lowered water temperatures in the Clearwater River. Fry emerge later, rear for the summer and probably over-winter in the lower Snake River reservoirs and migrate seaward in the spring. Captures of juvenile Chinook salmon in Lower Granite Reservoir in the fall of 2002 corroborate Connor et al.’s hypothesis (Normandeau and Bennett 2003).

Currently, fall Chinook salmon in the Snake River, emerge later, grow more slowly than historic fish and rear for about 2-3 months, and migrate later than historic fish (Connor et al. 2002). As a result of this “shift” in their life cycle, temperature regimes are considerably higher than historic conditions that place these fish in potentially thermally stressful situations until they migrate to the Columbia River.

Giorgi et al. (1997) found that a combination of length and mean daily flow from Rock Island Dam to McNary Dam explained more of the variation in subyearling Chinook salmon migration rates than any other combination of variables. Although temperature was a significant variable, it contributed little to the model.

Currently, subyearling Chinook salmon migrate the latest of all the ESA listed anadromous salmonids in the area of concern (http://www.cbr.washington.edu/).Figure 12 shows that the migration of subyearling Chinook salmon passed Lower Granite Dam considerably earlier in 1992 than 1993, 1994, and 1997. The earliest date when the middle 80% of the out migrating subyearling Chinook salmon passed Lower Granite Dam during the high and low flow years was 30 June in 1992 and the latest was 22 August 1993 and 21 August 1997 (Table 1). However, the 1992 out-migration of listed fall Chinook salmon juveniles was small (n=42) which may have affected the early June date. Migrants during more recent years passed Lower Granite Dam in mid-June with the exception of 1999 (20 April) and the latter part of the middle 80% of the run was generally similar to the low and high flow years (Table 2). Mean water temperatures at the scrollcase when the middle 80% of the ESA listed run passed Lower Granite Dam ranged from 16.8°C (1997) to 21.1°C (1994), slightly higher than those from 1998 to 2002 (Table 1). The proportion of the total listed downstream run of fall chinook salmon exposed to waters >20°C ranged from 1.6% (1997) to 73.7% (1994;Table 1), a little higher than found in 1998-2000 (0.0%-1999to 42.2%-1998; Table 2) The water temperatures that were measured at Lower Granite Dam when 90% of all indexed subyearlings passed Lower Granite Dam consistently exceeded 20°C during both low flow and high flow years (Appendix Table 1). In both 1992 and 1994, the highest water temperatures recorded during the middle 80% of the downstream migration was about 24°C (Table 1). Water temperatures at this level are especially critical as Baker et al. (1995) demonstrated that the upper incipient lethal level for fall Chinook (50% survival) was 23.01°C ± 1.08°C based on field collections of marked hatchery released fish in the Sacramento River, California. Laboratory studies by Brett (1952) demonstrated that the upper incipient lethal temperatures were about 2°C higher for fish acclimated at 15°C than lower acclimations and about 2°C higher than the Baker et al. (1995) model predictions. However, field studies consider the indirect effects of temperature on fish (e.g., disease, predation) rather than the direct effects determined in the laboratory by Brett (1952) and others.

4.2.5 Steelhead

Steelhead are in the area of concern as smolts and adults. Their life cycle is different from that of spring and summer Chinook salmon in that naturally spawned steelhead rear for 2 years in tributaries prior to their downstream migration to the Pacific Ocean in the early spring. Their return as adults during the late summer to early fall place them at risk to elevated temperatures in the lower Snake River. Adult steelhead are not obligate summer migrants as fall Chinook salmon are, as steelhead typically spawn from March to June of the year following their freshwater entry.

4.2.5.1 Adult

Adult steelhead migrate into the Snake River from the end of July and into November (Figure 4) during which time water temperatures can range from highs at 22°C to 23°C to lows below 15°C (Peery et al. 2003). Early migrating adults would be at risk for exposure to relatively high water temperatures in the Snake River. The preferred migration temperature for adult steelhead is unknown, but we speculate it would most likely be in the range for Chinook salmon, between 15°C and 20°C (see above). As with sockeye and Chinook salmon, it is believed that water temperatures of 21°C will inhibit adult migrations (McCullough 1999; Figure 5), which could delay fish entering the Snake River during summer and early fall. Evidence for a migration block occurring at the mouth of the Snake River was presented from an early telemetry study conducted in 1967 (Stuehrenberg et al. 1978). In that study, summer Chinook salmon and steelhead were reported to have congregated in the Columbia River outside the mouth of the Snake River during July when Snake River water temperatures reached 21°C as compared to the Columbia River that was 17°C. The delay of fish appeared to dissipate by the first week of September when water temperatures in both rivers decreased to 21°C.

Peery et al. (2003) reported results from telemetry studies that some adult steelhead would delay entering the Snake River during warm water temperatures, based on travel times between McNary and Ice Harbor dams, although the overall relationships were weak (r^2 values < 0.1). They summarized 2 years of data, 1996 and 1997, for steelhead with relatively good sample sizes (n = 178 for 1996, 345 for 1997). A trend existed where some steelhead took longer to migrate between McNary and Ice Harbor dams, while many fish continued to migrate between the two dams at close to the median travel time of about 2 d even though water temperatures in the Snake River were 20°C or higher (Figure 13). Peery et al. (2003) also concluded from analyses of count data that steelhead runs arrived later at Ice Harbor and Lower Granite dams during years with warmer summertime water temperatures (Figure 14). Thus, it appears water temperatures will affect the timing when steelhead enter and move through the Snake River, and that some fish may delay entering the mouth of the Snake River when water temperatures reach 21°C. There is also evidence that the timing of steelhead runs through the lower Columbia River is affected by water temperatures, which will determine when fish first reach the Snake River (High 2002). During warm years (mean water temperatures at Bonneville Dam >22°C), analysis of count data indicates the steelhead run is delayed passing through Bonneville Reservoir. During cooler years (mean temperatures 20°C or cooler), steelhead progress through the lower Columbia River but then delay between McNary Dam and Ice Harbor Dam (see High 2002, Figures 4 and 9). There is also a trend that steelhead are arriving later at the Snake River as compared to historical run timing (Figure 14; Peery et al. 2003: Robards and Quinn 2002), which correlates with trends in flows (decreasing) and temperatures (increasing) over time. An explanation for this pattern is indicated from analysis of 3 years of telemetry data for adult steelhead outfitted with radio transmitters at Bonneville Dam (High 2002). High (2002) reported that over half (57 to 66%) of radio-tagged steelhead monitored during 3 years (765, 975 and 1,160 radio-tagged fish released) of a basin-wide telemetry study temporarily strayed into cool-water tributaries in the lower Columbia

River between Bonneville and John Day dams. Use of these tributaries was greatest during periods with highest mainstem Columbia River temperatures that resulted in delayed timing of fish migrating through the lower Columbia River during warm water conditions. As the system has warmed over time (Quinn et al. 1997), more steelhead may be delaying in the lower river seeking cool water refugia.

Fish temperatures (and depths, see Objective 4) have also been collected for steelhead migrating through the lower Snake River up to Lower Granite Dam using archival transmitters. Although sample sizes are low and summaries presented here are preliminary, we see that adult steelhead migrating through the lower Snake River experience warmest temperature exposures during July and August when mean body temperatures were > 20°C (Table 7; C. Peery and T. Reischel, University of Idaho, unpublished data). Coutant (1970) suggested that the incipient lethal temperature for adult steelhead was near 21°C, which could mean that adult steelhead were migrating through the lower Snake River near lethal temperature levels during July and August of 2000. Fish body temperatures were slightly cooler as they approached Lower Granite Dam, probably related to the release of cool water from Dworshak Reservoir.

Keefer et al. (submitted) used radio telemetry to evaluate migration rates of adult steelhead in the Columbia and Snake rivers over a 5 year period. They found that passage rate differences among years were best explained by temperature conditions. Specifically, median times for steelhead to migrate between Bonneville and McNary dams were about 10 d during June and early July, increased rapidly with water temperatures to between 30 d and 60 d in August, then decreased through September until times were near 10 d again in late October. Passage through McNary Reservoir was slower during summer than during cooler periods, but the effect was less than that seen in Bonneville and The Dalles reservoirs, which was attributed to adult steelhead delaying migration while seeking cooler water refuge in lower tributaries. Once steelhead reached the Snake River they generally moved quickly between Ice Harbor and Lower Granite dams (8 to 15 d medians) with relatively little variation among years. Migration patterns for steelhead were more variable than those reported for fall Chinook salmon, indicating a greater flexibility in their ability to alter migration timing with respect to environmental conditions (Keefer et al. submitted).

Peery et al. (2003) found little relationship between times to pass Ice Harbor and Lower Granite dams by radio-tagged steelhead and water temperatures, even though temperatures in fishways were often in excess of 20°C, possibly because few fish attempted to pass dams during the warmest periods of the study. However, Keefer et al. (2003) investigated salmon and steelhead passage at John Day Dam with respect to temperatures because adult migrants exhibit longer passage times at that project relative to other dams in the system. Keefer et al. (2003) found that more fish tended to turn around in the transition pools and subsequently exit fishways at John Day Dam than at other dams, leading to the longer passage times. They also found that proportion of steelhead, sockeye, and fall Chinook salmon that exited the fishways increased as water temperatures increased. This suggests that, in some situations, temperature may contribute to delayed passage at dams.

As mentioned previously, little is known on the preferred or optimal migration temperatures for migrating adult steelhead. However, Reischel et al. (in press) found that adult steelhead outfitted with temperature-sensitive transmitters had body temperatures similar to the coolest water available in the segments of Lower Granite Reservoir monitored (Tables 3-5), but fish temperatures varied over a relatively wide range of water temperatures available to choose from (Table 6). Fish selected for water temperatures between 15°C and 19°C while migrating through the lower Snake River and moved to water as cool as 12°C to 14°C when available inside the mouth of the Clearwater River. This study was conducted as an evaluation of cool water releases from Dworshak Reservoir.

There is little information on sub-lethal effects of elevated water temperatures on adult steelhead. As with sockeye and Chinook salmon, it is conceivable that sub-lethal effects of warm water temperatures for steelhead could be excessive energy use, elevated susceptibility to disease, and reduced reproductive potential through altered hormone production and reduced gamete development (e.g., McCullough 1999).

4.2.5.2 Smolts

Some reports suggest that juvenile steelhead might be more tolerant of higher water temperatures than juvenile Chinook salmon. For example, Reese and Harvey (2002) reported the Eel River, California, supporting "high" densities of juvenile steelhead when water temperatures averaged 20°C -23°C. Also, Roper et al. (1994) reported relatively high densities of juvenile steelhead in a tributary of the South Umpqua River, Oregon, when maximum daily water temperatures were 20°C-22°C. In contrast, McCullough (1999) reported stressful temperatures at >18.3°C (Figure 5).

A number of researchers have developed models to predict survival and migration rates of juvenile steelhead through the Snake and Columbia rivers reservoirs. Giorgi et al. (1997) reported that flow was the single most important variable ($r^2 = 0.32$) affecting juvenile steelhead (hatchery and wild) migration in the mid-Columbia River from Rock Island Dam to McNary Dam. Temperature was significant but explained <1% of the variation in migration rates of juvenile steelhead. Berggren and Filardo (1993) found that flow alone explained 90% of the variation in migration rates of juvenile steelhead from Lower Granite Dam to McNary Dam. In this model temperature was not a significant variable affecting juvenile steelhead migration rates. Interestingly, water temperature was a significant variable in their steelhead migration model for the Middle Columbia River reach to predict smolt travel time; temperature contributed equally to the model as flow. In these models with flow fixed, increasing water temperature decreased travel time for juvenile steelhead.

The downstream migration of juvenile steelhead over Lower Granite Dam generally peaks in early May (http://www.cbr.washington.edu). Approximately 50 days following 1 April, nearly 80% of the wild run passed Lower Granite Dam (Figure 15). By mid-May in each of the 4 years, regardless of low or higher flows, the middle 80% of the steelhead had passed Lower Granite Dam (Table 1). During this time, water temperatures are typically below optimum (14°C) as mean temperatures during the middle 80% of the downstream migration were below 13°C. Highest water temperatures during the middle 80% of the out-migration were 13.7°C (1992) and 14.9°C (1994). During both 1993 and 1997, the high flow years, water temperatures for 90% of the out-migrants were < 13°C (Appendix Table 1). During the low flow years, water temperatures in 1994 were below 14°C when 90% of the run had passed Lower Granite Dam but not in 1992 (17.2°C). During low flow years, a small proportion of the total run (<0.5%) was exposed to water temperatures at or higher than 20°C (Table 1). Although these data indicate exposure of juvenile steelhead to water temperatures >20°C is low, huge numbers of steelhead are confined to Lower Granite Reservoir during low flow years which ultimately result in high mortality (Bennett et al. 1995; Bennett unpublished data, University of

Idaho, Moscow). Observed mortality in the reservoir from summer to the following spring is high although surviving juveniles "remold" and migrate the following spring based on presence/absence sampling (Bennett Unpublished data, University of Idaho, Moscow). Flow, as reported earlier by Giorgi et al. (1997) and Berggren and Filardo (1993), is a more important habitat variable in juvenile steelhead migration than water temperature.

5.0 Objective 3

To identify the life stages of the affected ESA listed species and examine the critical months and seasons or timing for operational actions to alter or control water temperatures to maximize biological benefit.

5.1 Timing of Releases

Flow augmentation to enhance the thermal environment in the lower Snake River could benefit the ESA listed fishes as follows: early in the spring migration season, coinciding with the juvenile steelhead and spring and summer Chinook salmon downstream movement; releases coinciding with the downstream migration of juvenile fall Chinook salmon and the latter portion of the sockeye salmon outmigration; and releases coinciding with the timing of adult summer and fall Chinook salmon and the latter part of the juvenile fall Chinook salmon migration.

5.1.1 Brief Overview of Flow Augmentation for Temperature Enhancement

Water sources for flow augmentation for the lower Snake River are limited to Dworshak Reservoir on the North Fork Clearwater River and reservoirs upstream of Brownlee Dam on the Snake River. Supply and competing water uses limit the volume potentially available from the Snake River. In addition, cooler waters are not available from Brownlee Reservoir because of the lack of selector gates and thus, waters released are relatively warm (17.5°C-20.3°C; Connor et al. 1998). Therefore, Dworshak Reservoir provides the only source of water for flow augmentation for temperature control. However, supply and competing demands also limit the volume. Dworshak Reservoir can be drafted to near-minimum operating level but further drafting limits the refill potential.

First reported attempts for downstream temperature reductions using waters from Dworshak Reservoir occurred in 1990 to increase survival of adult fall Chinook salmon and steelhead (Karr et al. 1992). This was followed by experimental releases and monitoring in 1991 to quantify temperature reductions. These efforts demonstrated that the largest temperature reductions were in Lower Granite Reservoir followed downstream sequentially to Ice Harbor Reservoir. More recently, the BIOP has called for use of Dworshak Reservoir waters to decrease high temperatures and help satisfy flow targets for ESA listed stocks. Generally, outflows from Dworshak Reservoir in April through June are related to refill (Figure 16). Higher inflows increase the probability of refill and therefore can result in higher outflows in the spring. In July and August, the reservoir has been drafted to near-minimum operating levels to decrease reservoir temperatures and outflows have increased to near maximum for hydroelectrical power generation (~25 Kcfs) followed by a reduction in flows to inflow levels for the remainder of the calendar year. Figure 16 shows these general patterns in flow from operational changes.

5.1.2 Enhance the Thermal Environment for spring and summer Chinook salmon, sockeye salmon, and steelhead

Examination of thermal characteristics of representative low flow (1992, 1994) and high flow (1993, 1997) years revealed that water temperatures in the lower Snake River are generally less than 16°C during most of the downstream runs of juvenile steelhead and yearling Chinook salmon. Water temperatures are generally at or near optimum for these stocks, except for a small proportion of the latter downstream migration during some years. These stocks might benefit from increased flows as some authors (Giorgi et al. 1997; Berggren and Filardo 1993) have indicated the significance of flow especially for juvenile steelhead. However, enhancing the thermal environment for these stocks during the early and middle part of the run is not warranted. We know of no predictable benefit to adult salmon and steelhead at the time of the majority of the yearling Chinook salmon and steelhead downstream migration and consequently, do not see any advantage to these ESA listed Pacific salmonids to release water for temperature improvement.

5.1.3 Enhance the Thermal Environment for Subyearling Chinook salmon and Late Migrating Sockeye Salmon

Flow augmentation to decrease water temperatures in the lower Snake River has been shown to be highly effective at increasing detection rates (Connor et al. 1998) and survival of juvenile fall Chinook salmon (Connor et al. 2003b). The importance of Snake River flow and water temperatures were demonstrated by Connor et al. (2003b) in their final survival model (Survival = 140.82753 + 0.2648 x (flow) – 7.14437 x (temperature)). Both flow and water temperature explained 92% of the variation in survival of subyearling Chinook salmon from the unimpounded Snake River downstream to the tailrace of Lower Granite Dam. Maintaining the main effect of flow constant in their model resulted in about 7% decrease in survival for each 1°C increase in water temperature. Although survival was predicted to increase by about 3% with each change in 100 m^3/s in flow (temperature held constant), effects of water temperature were more significant. Their results supported decreasing water temperatures through flow augmentation as an interim recovery step for fall Chinook salmon.

In addition, water releases from Dworshak Reservoir might benefit water temperatures in the latter part of the sockeye salmon downstream migration. As indicated earlier, approximately 6.7% of the listed juvenile sockeye salmon migration (n=166) occurred in 1997 when water temperatures exceeded 20°C. Also from 1998-2002, exposure of the total run of wild sockeye salmon to water temperatures at or above 20°C ranged from about 0.5% to 6.8%. Brett et al. (1958) reported that sockeye salmon smolts curtail their migration at water temperatures of 12°C to14°C, which were similar to mean water temperatures in 1992, 1994, 1998, 2000, 2001, and 2001 when the middle 80% of the run passed Lower Granite Dam. Consequently, flow augmentation to decrease water temperatures at this time could also benefit juvenile sockeye salmon.

For adult sockeye salmon, current run timing through the lower Snake River is prior to peak water temperatures. However, because sockeye salmon appear to be less tolerant of warm water temperatures than other species, during a warmer than average spring and early summer, releases of water from Dworshak could benefit sockeye salmon by reducing the potential for passage delays or other sub-lethal effects on adult sockeye salmon migrating through the lower Snake River.

5.1.4 Enhance the Thermal Environment for Adult Fall Chinook salmon and Steelhead

Flow augmentation for reduced water temperatures timed to benefit adult fall Chinook salmon and steelhead, is the third possible temperature enhancement in the lower Snake River. Water releases from Dworshak and the middle Snake River reservoirs was timed in 1990 and 1991 to benefit fall Chinook salmon. In 1990, those releases were not monitored and no known assessment was made. In 1991, those releases brought about minor water temperature decreases throughout the entire lower Snake River reservoirs with approximately a 1°C decrease at Ice Harbor Dam (Karr et al. 1992). No known quantification of benefits of cooler waters to adult fall Chinook salmon was made in either year. In general, however, water temperatures in the forebay and fishways at Lower Granite Dam were estimated to be reduced by 1 to 3°C when Dworshak Reservoir releases reached 50 to 60% of summer-time Snake River flow (Peery et al. 2003). They determined that adult fall Chinook salmon and steelhead would select the coolest water available while migrating through the Lower Granite reservoir (Reischel et al. in press), thereby lowering their thermal exposure in that segment of the river. Cool water available in the Lower Granite Reservoir during that study was the result of Dworshak Reservoir releases.

The correlation of increased temperatures and flow declines with delay for adult steelhead during the late summer in the Columbia River basin was identified recently by Robards and Quinn (2002). They reported that the timing of the "early part" of the run has been delayed 21 days relative to 1950 prior to construction of many dams in the basin, in spite of strong evidence of hatchery selection for earlier migrants (Leider et al. 1984). In contrast, the later portion of the run, largely B-run fish migrating to the Snake River in Idaho, have been arriving later at Ice Harbor Dam but not at Bonneville Dam, on the Columbia River (Busby et al. 1996). High (2002) reported an interesting finding that the apparent delay in the adult steelhead migration between McNary and Ice Harbor dams was more obvious during cooler (August mean <20.5°C) years when the temperature differential in August between the Snake and Columbia rivers averaged 1.3°C compared to the warmer (August mean >22°C) years when the differential averaged 0.4°C. The average passage time for 40% of the run between dams was 13.3 and 7 days for cooler and warmer years, respectively.

Few studies have addressed this issue at the mouth of the Snake River. Although adult steelhead are not "obligate" migrators like fall Chinook salmon, exposure to higher temperatures may adversely affect the over-winter survival, and egg and alevin viability. Nakamoto (1994) found that adult steelhead held in pools in the New River, California, at a temperature range of 16.8°C to 24.6°C while pools about 1°C warmer did not support adult steelhead. Although other factors could have affected the suitability of uninhabited pools, temperatures near 26°C are near the ultimate upper incipient lethal limit (Hokanson 1977) and can ultimately affect their survival. McCullough (1999) reported a maximum temperature of 24°C for short-term exposure. Therefore, temperatures in late July, August and into September at the mouth of the Snake River could exceed this temperature limit for short-term exposure. Thus it appears that Dworshak releases sufficient to cool Snake River water temperatures between Ice Harbor and Lower Granite dams so as to replicate pre-impoundment fall cooling and to provide a cool-water migration corridor through Lower Granite reservoir would directly benefit adult fall Chinook salmon and steelhead migrants.

5.2 Predation Effects

Water temperature directly affects metabolic activities in fishes and increases food consumption. Vigg et al. (1991) reported that temperature is probably the most important single variable regulating consumption rates in fishes. Petersen and Kitchell (2001) reported that a 2°C increase in temperature associated with climate shifts could increase predation on salmonids by as much as 26-31% in the Columbia River. In fact, studies conducted on the Columbia River demonstrated that highest predation coincided with higher temperatures and higher salmonid abundance (Vigg et al. 1991). Predation on subyearling Chinook salmon by smallmouth bass (*Micropterus dolomieu*) was highest in August when water temperatures were the highest in John Day Reservoir, Columbia River (Poe et al. 1991). Anglea (1997) demonstrated that increased predation was associated with higher temperatures in Lower Granite Reservoir for May and June with reduced predation occurring later in the year, presumably a reflection of reduced salmonid abundance. However, estimated smallmouth bass predation was highest on juvenile salmonids in 1994 and 1995 (Anglea 1997) compared to years of higher flows in 1996 and 1997 (Naughton 1998). Predation losses can be substantial as Rieman et al. (1991) reported that predation losses amounted to about 14% of all juvenile salmon and steelhead that entered John Day Reservoir. In Lower Granite Reservoir, Anglea (1997) speculated that smallmouth bass predation on subyearling Chinook salmon may have accounted for a loss of 7% of the juvenile run during 1995. Connor et al. (1998) reported that pit tag detection rates of fall Chinook salmon were considerably lower in 1994 and 1995 compared to 1996 and 1997, coinciding with the higher estimated predation rates of Anglea (1997) in 1994 and 1995 compared to those in 1996 and 1997 (Naughton 1998). Although the higher losses of subyearling Chinook salmon occurred during the lower flow years, predation may be only one factor affecting detection rates and ultimately survival in the lower Snake River. In addition, higher survival in the latter years may have been related to increased success of the predator removal program that began in 1990 (Parker et al. 1995).

5.3 Resident Fishes

The significance of elevated water temperatures on resident fishes varies among species. White sturgeon (*Acipenser transmontanus*) a Species of Concern in Idaho and Washington is one species that could be impacted by higher water temperatures. Other fishes, such as smallmouth bass and other centrarchid fishes (pumpkinseed [*Lepomis gibbosus*], crappies [*Pomoxis* spp.], warmouth [*L. gulosus*], and channel catfish [*Ictalurus punctatus*]) are introduced and below their optimum temperatures of >29°C (Scott and Crossman 1990). Therefore, elevated temperatures during the warmer months could ultimately enhance populations of these warmer water species in the lower Snake River reservoirs and can increase dietary overlap and increase predation on species known to prey on juvenile salmonid fishes (Bennett 1999; Poe et al. 1991; Anglea 1997; Naughton 1998).

The significance of elevated temperatures on "native" resident fishes in the lower Snake River reservoirs remains largely unknown. In general, warmer water temperatures would generally benefit survival of fishes until temperatures exceed optimal levels (Kroll et al. 1992; Brett 1979). Increased survival with larger body size has generally been reported for fishes (Rice et al. 1993). Of interest though is that water temperatures >20°C may inhibit growth of juvenile northern pikeminnow as Cichosz (1996) reported negative correlations of growth with duration of temperatures > 20°C in Lower Granite Reservoir. However, Vigg et al. (1991) reported that predation on juvenile salmonid fishes by all predatory fishes, including northern pikeminnow, increased with higher water temperatures in John Day Reservoir.

Effects of elevated water temperatures on white sturgeon are largely unknown. Natural spawning of white sturgeon in the Snake River, downstream of Hells Canyon Dam, occurs (Tim Cochnauer, Personal Communication, IDF&G) in the area of concern. Spawning habitat in the Columbia River consists of high velocity waters (0.8-2.8 m/s), 4-24 m deep, and mostly over cobble to boulder substrates (Parsley et al. 1993). Most spawning occurred from April through July at water temperatures of 14°C although limited spawning was reported at 18°C -20°C. However, Wang et al. (1985) reported high mortality of embryos >18°C. Temperature tolerance increases with age as Cech et al. (1984 cited in US EPA 2003) reported that growth increased from 15°C - 20°C but was not significantly different between 20°C -25°C.

Studies of white sturgeon in Lower Granite Reservoir suggested a young population; most fish were between ages 0 to 8 (Lepla 1994). Lepla (1994) speculated that juvenile white sturgeon recruited to the reservoir, reared for varying times, and then possibly migrated upstream as adults to the unimpounded waters of the Snake River. No known evidence exists that suggests that spawning occurs in the reservoir. Distribution data of the various life history stages in comparison to temperature data suggests white sturgeon are not at risk from elevated temperatures. Although the literature suggests that the embryo stage in the life history of white sturgeon is the most sensitive to high temperature, comparing the water temperatures that occur in the area of concern with the spring timing of spawning and incubation, suggests that temperature should probably be less of a concern than for some of the stocks of salmonids.

6.0 Objective 4

To identify the three dimensional distribution of adult and juvenile anadromous salmonids passing through the Snake River corridor with emphasis on Lower Granite Reservoir and if possible, correlate fish locations with water temperature.

Limited data are available on the distribution of juvenile anadromous salmonids passing through the lower Snake River corridor. Recently, Tiffan et al. (2003) examined the thermal exposure of juvenile fall Chinook salmon migrating through Little Goose Reservoir. Using a combination of bathythermograph measurements with temperature-sensing, gastrically implanted radio tags, they found that mean body temperatures were similar to mean water column temperatures from early August to early September. Differences between water temperatures and body temperatures were <0.3°C and less than the sensitivity of the tags. Fish temperatures were highest in 1998 and ranged from 20.4°C to 20.9°C as compared to 18.2°C to 19.8°C in 1999. Thermal exposures were related to water temperatures and fish residence times.

Depth used by adult Chinook salmon and steelhead migrating through the lower Snake River from Ice Harbor Dam to Lower Granite Dam, as determined from archival tags retrieved at Lower Granite Dam during 2000, are shown in Tables 8 and 9. Monthly mean migration depths generally ranged from 3 to 5 m and 50% of time was spent at depths of 4 m or shallower while migrating through the three lower reservoirs during 2000. Seasonal differences in migration depths were more obvious for adult Chinook salmon and steelhead migrating through the Lower Granite reservoir, as determined from tracking fish with acoustic transmitters during 2001 (Table 10). The depth distribution of adult fish appeared related to the layering of cool Dworshak and warmer Snake River water sources (see Table 5) in Lower Granite Reservoir, prior to the mixing of the two water masses as flow passed Lower Granite and downstream dams.

7.0 Summary

Numerous literature surveys have been conducted on effects of temperature on the life cycle of Pacific salmon (see McCullough 1999; Brown 1976; Schuytema 1969) and a myriad of other literature not summarized by these authors (Appendix 1). Much of this information has been obtained from controlled laboratory studies that provide a basis to evaluate effects of higher temperatures in the lower Snake River. Most of these studies have examined individual life stages to regulated temperatures and observed their responses. Few field studies have been conducted and results from these were applied to thermal conditions in the lower Snake River. Often literature sources that have established a paradigm may be based on small sample sizes.

We examined the various stages of the life cycle (smolt and adult steelhead, smolt and adult spring and summer Chinook salmon, and sockeye salmon and egg, embryo, parr, smolt, and adult fall Chinook salmon) of ESA listed anadromous salmonids in the Snake River, from Hells Canyon Dam downstream to the confluence with the Columbia River and including the Clearwater River from Dworshak Dam downstream to its confluence with the Snake River. Spring and summer Chinook salmon smolts, migrating mostly as yearlings, and steelhead migrate sufficiently early that water temperature does not pose a direct risk to the bulk of the run. Published survival models corroborate this interpretation. However, the middle 80% of the listed juvenile sockeye salmon in 1997 extended to early September which exposed 6.7% of the run to waters >20°C. These water temperatures are >5°C higher than those identified to affect juvenile sockeye salmon migrations (Brett et al. 1958). The smolt index data suggest that fall Chinook salmon juveniles are the latest migrators and potentially the most affected stock of ESA listed salmonid fishes to potentially deleterious existing thermal conditions in the lower Snake River. Altered life history patterns have been reported as a result of environmental changes in their rearing environment. The altered life history patterns have placed the juvenile fall Chinook salmon in a condition of migrating later in the year at a time when water temperatures are warmer. During the 4 years examined, representing recent high and low flow years, mean scrollcase water temperatures were at or exceeded 18°C - 20°C, for three of those years. Also, the proportion of the total run of wild fall Chinook salmon juveniles exposed to water temperatures >20°C was higher than 28%. Temperatures near 23°C (± 1.08°C; Baker et al. (1995) have been reportedly lethal to 50% of marked hatchery released fish in the Sacramento River, California. In addition, moderately strong correlative evidence has been developed that demonstrates that flow augmentation to reduce water temperatures can increase survival of juvenile fall Chinook salmon in the lower Snake River system (Connor et al. 1998, 2003b). Survival models demonstrate the importance of temperature either directly affecting survival or indirectly by affecting migration dates and body size, factors found to be highly associated with water temperature. Additional studies should be conducted to more fully evaluate current survival models and more fully evaluate the role in improving survival of juvenile fall Chinook salmon. At present, however, the available literature strongly supports use of flow augmentation with its attendant cooler water temperature to benefit downstream migrating fall Chinook salmon.

For adults, spring and most summer Chinook salmon have the least impact from warm water conditions in the lower Snake River, while fall Chinook salmon and steelhead have the greatest potential exposure to warm water temperatures. However, since fall Chinook salmon are obligate migrants, and because the predominate pattern is for warm water conditions to persist later in the fall than historically occurred, fall Chinook salmon adults would appear to be at greater risk for incurring potential temperature related impacts while migrating through the lower Snake River. This conclusion is supported by analyses of telemetry data for adult fall Chinook salmon and steelhead migrating through the lower Columbia River by High (2002) and Goniea (2002). They found that, although members from both runs enter tributary streams during summer, steelhead that use the cool-water refugia realized a survival advantage, while fall Chinook salmon that delay their migration to use the same refugia experience reduced escapement to spawning areas. Historically, use of cool water refugia incurred an evolutionarily derived survival advantage to both species, but under current temperature conditions, extended delays to adult fall Chinook salmon migrants represent a survival risk. Sockeye salmon pose a particular concern with respect to elevated water temperatures. Although the bulk of the adult sockeye salmon pass though the lower Snake River prior to peak temperatures, their lower perceived tolerance to warm water conditions, relative to Chinook salmon and steelhead, and the remnant size of the Snake River run, place adult sockeye salmon in a precarious position. An extreme weather year, with early warming of the river in later spring, could significantly affect the reproductive success for sockeye salmon.

8.0 Recommendations

1. The literature suggests that flow augmentation to decrease water temperatures would afford limited benefit to ESA listed spring and summer Chinook salmon and steelhead.

2. Flow augmentation to decrease water temperatures in the lower Snake River have the potential to enhance survival of out-migrating subyearling Chinook salmon. Field data combined with modeling provide the strongest scientific evidence for use of flow augmentation to decrease water temperatures to enhance survival of subyearling Chinook salmon. Flow augmentation to enhance the thermal environment for juvenile fall Chinook salmon might benefit late out-migrating sockeye salmon and probably upstream migrating adult summer Chinook and sockeye salmon.

3. Because of limited volume in upstream sources, flow augmentation to decrease water temperatures in August and early September have limited potential to significantly reduce temperatures in lower Snake River reservoirs. One study showed a 1°C decrease in summer water temperature (1991) at Ice Harbor Dam. Consequently, most benefits accrue to adults that would be mostly migrating through Lower Granite Reservoir. Late summer timing of flow augmentation to reduce water temperatures would benefit adult fall Chinook salmon and adult steelhead once in Lower Granite Reservoir. Effects of the releases from Dworshak Reservoir at the end of summer (late August–mid September) should be investigated to facilitate natural cooling patterns for the lower river. Such investigations should focus on effects of temperature exposures on survival to spawning areas and reproductive success. Specifically, what are delayed effects of exposure to warm water temperatures on spawning success and gamete quality.

4. Although results are not conclusive, the best scientific information suggests that properly timed flow augmentation with its attendant cooler water temperatures can improve juvenile survival. Current models developed to predict fall Chinook salmon survival could be improved with larger data sets and greater variation among years.

9.0 References

Anglea, S.M. 1997. Abundance, food habits, and salmonid fish consumption of smallmouth bass and distribution of crayfish in Lower Granite Reservoir, Idaho-Washington. Master's thesis. University of Idaho, Moscow.

Baker, P.F., T.P. Speed, and F.K. Ligon. 1995. Estimating the influence of temperature on the survival of Chinook salmon smolts (*Oncorhynchus tshawytscha*) migrating through the Sacramento-San Joaquin River Delta of California.

Beauchamp, D.A., C. Luecke, W.A. Wurtsbaugh, H.G. Gross, P.E. Budy, S. Spaulding, R. Dillenger, and C.P. Gubala. 1997. Hydroacoustic assessment of abundance and diel distribution of sockeye salmon and kokanee in the Sawtooth Valley lakes, Idaho. North American Journal of Fisheries Management. 17:253-267.

Bell, M.C. 1986. Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Bennett, D.H. 1999. So many predatory resident fishes-What needs to be done? In ODFW and NMFS. 1999. Management Implications of Co-occurring Native and Introduced Fishes. Proceedings of the Workshop. October 27-28, 1998, Portland, Oregon.

Bennett, D.H., M.A. Madsen, and M.H. Karr. 1997a. Water temperature characteristics of the Clearwater River, Idaho and Lower Granite, Little Goose, Lower Monumental, and Ice Harbor reservoirs, Lower Snake River, Washington, during 1991-1992 with emphasis on upstream water releases Data Volume I. Completion Report. Project 14-16-0009-1579). US Army Corps of Engineers, Walla Walla, Washington.

Bennett, D.H., M.H. Karr, and M.A. Madsen. 1997b. Thermal and velocity characteristics in the lower Snake River, Washington, as a result of regulated upstream water releases. Completion Report. Project 14-16-0009-1579). US Army Corps of Engineers, Walla Walla, Washington.

Bennett, D.H., M.A. Madsen, and M.H. Karr. 1997c. Water velocity characteristics in the Clearwater River, Idaho and Lower Granite, Little Goose, Lower Monumental, and Ice Harbor reservoirs, Lower Snake River, Washington, during 1991-1992 with emphasis on upstream water releases Data Volume II. Completion Report. Project 14-16-0009-1579). US Army Corps of Engineers, Walla Walla, Washington.

Bennett, D.H., M.A. Madsen, T.J. Dresser, Jr., and T.S. Curet. 1995. Monitoring fish community activity at disposal and reference sites in Lower Granite Reservoir, Idaho-Washington Year 5 (1992). Completion Report to US Army Corps of Engineers, Walla Walla, Washington.

Berggren, T.J., and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North American Journal of Fisheries Management 13: 48-63.

Berman C. 1998. Summary of temperature preference ranges and effects for life stages of seven species of salmon and trout. Appendix A. Review of the State of Oregon standard for water temperature. US Environmental Protection Agency, Region 10, Seattle, Washington.

Berman, C.H. 1990. The effect of elevated holding temperatures on adult spring Chinook salmon reproductive success. Masters thesis. University of Washington, Seattle.

Bjornn, T.C., and D.W. Reiser. 1991. Habitat requirements of anadromous salmonids. Influences of forest and rangeland management and salmonid fishes and their habitats. American Fisheries Society Special Publication 19:83-138.

Bouck, G.R., G.A. Chapman, P.W. Schneider Jr., and D.G. Stevens. 1975. Effects of holding temperatures on reproductive development in adult sockeye salmon (*Oncorhynchus nerka*). In, Donaldson, J.R., ed. 26th annual Northwest Fish Culture Conference, Otter Creek, OR pp. 24-40.

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus Oncorhynchus. Journal Fisheries Research Board of Canada 9:265-323.

Brett, J.R., M. Hollands, and D.F. Alderdice. 1958. The effect of temperature on the cruising speed of young sockeye and coho salmon. Journal Fisheries Research Board of Canada 15:587-605.

Brett, J.R. 1979. Environmental factors and growth. Pages 599-675 in W.S. Hoar, D.J. Randall, and J.R. Brett, editors. Fish physiology, Volume VIII. Academic Press, Inc., New York.

Brett, J.R. 1995. Energetics. Pages 1 to 68. in C. Groot, L. Margolis and W.C. Clarke, editors. Physiological Ecology of Pacific Salmon. UBC Press, Vancouver, British Columbia, Canada.

Brett, J.R., and N.R. Glass. 1973. Metabolic rates and critical swimming speeds of sockeye salmon (*Oncorhynchus nerka*) in relation to size and temperature. Journal of the Fisheries Research Board of Canada 30:379-387.

Brown, H.W. 1976. Handbook of the effects of temperature on some North American fishes. American Electric Power Service Corporation. Canton, Ohio.

Brown, R.S., D.R. Geist, and M.G. Mesa. 2002. The Use of Electromyogram (EMG) Telemetry to Assess Swimming Activity and Energy Use of Adult Spring Chinook Salmon Migrating through the Tailraces, Fishways, and Forebays of Bonneville Dam, 2000 and 2001. Prepared for the U.S. Army Corps of Engineers. Portland, Oregon under Contract DE- AC06 76RLO1830 CENWP MIPR No. W66QK10432368 PNNL-14080 by Pacific Northwest National Laboratory, Richland, Washington and U.S. Geological Survey Biological Resources Discipline Western Fisheries Research Center Columbia River Research Laboratory, Cook, Washington.

Busby, P.J., T.C. Wainwright, E.J. Bryant, L.J. Lierheimer, R.S. Waples, F.W. Waknitz, and I.A.Lagomarsino. 1996. Status review of West Coast steelhead from Washington, Idaho, Oregon, and California. US. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-27.

Cichosz, T.A. 1996. Factors limiting the abundance of northern squawfish in Lower Granite Reservoir. Master's thesis. University of Idaho, Moscow.

Connor, W.P., H.L. Burge, and D.H. Bennett. 1998. Detection of pit-tagged subyearling Chinook salmon at a Snake River Dam: Implications of summer flow augmentation. North American Journal of Fisheries Management 18(3): 530-536.

Connor, W. P., R.K. Steinhost, and H. L. Burge. 2000. Forecasting survival and passage of migratory juvenile salmonids. North American Journal of Fisheries Management 20:651-660.

Connor, William P., H.L.Burge, R.Waitt, and, T. C. Bjornn. 2002. Juvenile life history of wild fall Chinook salmon in the Snake and Clearwater rivers. North American Journal of Fisheries Management. 22(3):703-712.

Connor, W. P., R.K. Steinhorst, and H. L. Burge. 2003a. Migrational behavior and seaward movement of wild subyearling fall Chinook salmon in the Snake. North American Journal of Fisheries Management 23:413-430.

Connor, W.P., H. L. Burge, J. R. Yearsley, and T. C Bjornn. 2003b. Influence of flow and temperature on survival of wild subyearling fall Chinook salmon in the Snake. North American Journal of Fisheries Management 23:362-375.

Coutant, C.C. 1970. Thermal resistance of adult coho (*Oncorhynchus kisutch*) and jack Chinook (*O. tshawytscha*) salmon, and adult steelhead trout (*Salmo gairdneri*) from the Columbia River. AEC Research and Development Report. Battelle Memorial Institute, Pacific Northwest Laboratories. BNWL-1508.

Eldridge, E. F. 1963. Proceedings of the twelfth Pacific Northwest Symposium on water pollution research: Water temperature, influences, effects, and control. U.S. Department of Health, Education, and Welfare, Public Health Service, Pacific Northwest Water Laboratory, Corvallis, Oregon, November 7, 1963.

Fagerlund, U.H.M., J.R. McBride, and I.V. Williams. 1995. Stress and Tolerance. Pages 459 to 504. in C. Groot, L. Margolis and W.C. Clarke, editors. Physiological Ecology of Pacific Salmon. UBC Press, Vancouver, British Columbia, Canada.

Funk, W.H., C.M. Falter, and A.J. Lingg. 1985. Limnology of an impounded series in the lower Snake River. Final report. U.S. Army Corps of Engineers, Walla Walla, Washington.

Giorgi, A.E., T.W. Hillman, S.R. Stevenson, S.G. Hays, and C.M. Peven. 1997. Factors that influence the downstream migration rates of juvenile Chinook salmon and steelhead through the hydroelectric system in the mid-Columbia River basin. North American Journal of Fisheries Management 17:268-282.

Goniea, T.M. 2002. Temperature influenced migratory behavior and use of thermal refuges by upriver bright fall Chinook salmon. Master thesis. University of Idaho, Moscow, Idaho.

Groves, P.A., and J.A. Chandler. 1999. Spawning habitat used by fall Chinook salmon in the Snake River. North American Journal of Fisheries Management 19:912-922.

Hassemer, P.F., S.W. Kiefer, C.E. Petrosky. 1997. Idaho's salmon: can we count every last one? Pages 113-125 in D.G. Stouder, P.A. Bisson, and R.J. Naiman, editors. Pacific salmon and their ecosystems: status and future options. Chapman and Hall, London.

High, B. 2002. Effect of water temperature on adult steelhead migration behavior and survival in the Columbia River basin. Master thesis. University of Idaho, Moscow.

Hinch, S.G., and P.S. Rand. 1998. Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): role of local environment and fish characteristics. Canadian Journal of Fisheries and Aquatic Sciences 55: 1821-1831.

Hinch, S.G., and P.S. Rand. 2000. Optimal swimming speeds and forward-assisted propulsion: energy-conserving behaviors of upriver-migrating adult salmon. Canadian Journal of Fisheries and Aquatic Sciences 57:2470-2478.

Hokanson, K.E.F. 1977. Temperature requirements of some percids and adaptations to the seasonal temperature cycle. Journal of the Fisheries Research Board of Canada 34:1524-1550.

Karr, M.K., B. Tanovan, R. Turner, and D.H. Bennett. 1992. Water temperature control project, Snake River Interim report: Model studies and 1991 operations. Columbia River Inter-Tribal Fish Commission, U.S. Army Corps of Engineers, and University of Idaho, Moscow.

Keefer, M.L., C.A. Peery, B. Burke. 2003. Passage of radio-tagged adult salmon and steelhead at John Day Dam with emphasis on fishway temperatures: 1997-1998. Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho for U.S. Army Corps of Engineers, Portland and Walla Walla Districts. Technical Report 2003-1.

Keefer, M.L., C.A. Peery, T.C. Bjornn, M.J. Jepson, and L.C. Stuehrenberg. Migration rates of radio-tagged adult Chinook salmon and steelhead past dams, through reservoirs and in unimpounded rivers of the Columbia Basin. Submitted to Canadian Journal of fisheries and Aquatic Sciences.

Kroll, K.J., K.P. Van Eenennaam, S.I. Doroshov, J.E. Hamilton, and T.R. Russels. 1992. Effect of water temperature and formulated diets on growth and survival of larval paddlefish. Transactions of the American Fisheries Society 121: 538-543.

Leider, S.A., M.W. Chilcote, and J.J. Loch. 1984. Spawning characteristics of sympatric populations of steelhead trout (*Salmo gairdneri*): evidence for partial reproductive isolation. Canadian Journal of Fisheries and Aquatic Sciences 41:1454-1462.

Lepla, KB. 1994. White sturgeon abundance and associated habitat in Lower Granite Reservoir, Washington. Master's thesis. University of Idaho, Moscow.

Lichatowich, J. 1999. Salmon without rivers: A history of the Pacific Salmon Crisis. Island Press, Washington, D.C.

Major, R. L., and J. L. Mighell. 1967. Influence of Rocky Reach Dam and the temperature of the Okanogan River on the upstream migration of sockeye salmon. Fishery Bulletin 66: 131-147.

McCullough, D.A. 1999. 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. Report of Columbia River Inter-tribal Fish Commission, Portland, Oregon, for U.S. Environmental Protection Agency, Region 10, Seattle, Washington.

McCullough, D.A., S. Spalding, D. Sturdevant, M. Hicks. 2001. Issue Paper 5: Summary of Technical Literature Examining the Physiological Effects of Temperature. Prepared for, Region 10 Temperature Water Quality Criteria Guidance Development Project. Seattle, Washington.

McDonald, J.S. and 11 co-authors. 2000. The influence of extreme water temperatures on migrating Fraser River sockeye salmon (*Oncorhynchus nerka*) during the 1998 spawning season. Canadian Technical Report of Fisheries and Aquatic Sciences 2326.

Muir, W.D., S.G. Smith, J.G. Williams, E.F. Hockersmith, and J.R. Skalski. 2001. Survival estimates for migrant yearling Chinook salmon and steelhead tagged with passive integrated transponders in the lower Snake and Columbia rivers, 1993-1998. North American Journal of Fisheries Management 21:269-282.

Nakamoto, R.J. 1994. Characteristics of pools used by adult summer steelhead oversummering in the New River, California. Transactions of the American Fisheries Society 131: 523-536.

Naughton, G.P. 1998. Predator abundance and salmonid prey consumption in the tailrace and forebay of Lower Granite Dam and upper arms of Lower Granite Reservoir. Master's thesis. University of Idaho, Moscow.

Naughton, G.P., M.L. Keefer, T.C. Bjornn, C.A. Peery, K.R. Tolotti, R.R. Ringe, P/J. Keniry, and L.C. Stuehrenberg. 2003. Migration of adult sockeye salmon past Columbia River dams, through reservoirs and distribution into tributaries, 1997. . Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho for U.S. Army Corps of Engineers, Portland and Walla Walla Districts. Technical Report 2003-3.

Nehlsen, W., J.E. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon and Washington. Fisheries 16:4-21.

NMFS (National Marine Fisheries Service). 1992. Threatened status for Snake River spring/summer Chinook salmon, threatened status for Snake River fall Chinook salmon. Final Rule. Federal Register 57:78 (April 22, 1992):14563-14663.

NMFS (National Marine Fisheries Service). 1998. Endangered and threatened species: threatened status for two ESUs of steelhead in Washington, Oregon, and California. Federal Register 68:13347-13371.

NMFS (National Marine Fisheries Service). 2000. Biological opinion of the Federal Columbia River power system including the juvenile fish transportation program and the US Bureau of Reclamation's 31 dams, including the entire Columbia Basin project. Seattle, Washington.

Normandeau Associates and D.H. Bennett. 2003. Monitoring and evaluation of potential sites for the Lower Snake River dredged material management plan and the woody riparian development program. Completion Report. Army Corps of Engineers, Walla Walla, Washington.

ODEQ (Oregon Department of Environmental Quality). 1995. 1992-1994 water quality standards review for temperature. Final Issue Paper. Portland, OR 77 pp.

Parker, R.M., M.P. Zimmerman, and D.L. Ward. 1995. Variability in biological characteristics of northern squawfish in the lower Columbia and Snake rivers. Transactions of the American Fisheries Society 124: 335-346.

Parsley, M.J., L.G. Beckman, and G.T. McCabe, Jr. 1993. Spawning and rearing habitat use by white sturgeon in the Columbia River downstream of McNary Dam. Transactions of the American Fisheries Society 122: 217-227.

Peery, C. A., T. C. Bjornn, and L. C. Stuehrenberg. 2003. Water temperatures and the passage of adult salmon and steelhead in the lower Snake River. Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, for the U. S. Army Corps of Engineers, Walla Walla, Washington. Technical Report 2003-2.

Petersen, J.H., and J.F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Canadian Journal of Fisheries and Aquatic Sciences 58:1831-1841.

Piper, R.G., I.B. McElwain, L.E. Orme, J.P. McCraren, L.G. Fowler, and J.R. Leonard. 1982. Fish Hatchery Management. U.S. Department of the Interior, Fish and Wildlife Service, Washington D.C.

Poe, T., H.C. Hansel, S. Vigg, D.E. Palmer, and L.A. Prendergast. 1991. Feeding of predaceous fishes on out-migrating juvenile salmonids in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120: 405-420.

Quinn, T.P., S. Hodgson, and C. Peven. 1997. Temperature, flow, and the migration of adult sockeye salmon (*Oncorhynchus nerka*) in the Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 54:1349-1360).

Rand, P.S., and S.G. Hinch. 1998. Swim speeds and energy use of upriver-migrating sockeye salmon (*Oncorhynchus nerka*): simulating metabolic power and assessing risk of energy depletion. Canadian Journal of Fisheries and Aquatic Sciences 55:1832-1841.

Raymond, H.L. 1979. Effects of dams and impoundments on migrations of juvenile Chinook salmon and steelhead from the Snake River, 1966-1975. Transactions of the American Fisheries Society 105: 505-529.

Reese, C.D. and B.C. Harvey. 2002. Temperature-dependent interactions between juvenile steelhead and Sacramento pikeminnow in laboratory streams. Transactions of the American Fisheries Society 131: 599-606.

Reischel, T., C.A. Peery, T.C. Bjornn, and D.H. Bennett. In press. Temperature of Lower Granite Reservoir and response of adult salmon and steelhead to cold water releases from Dworshak reservoir, 2001. Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, for the U. S. Army Corps of Engineers, Walla Walla, Washington. Technical Report 2003-6.

Rice, J.A., and six co-authors. 1993. Growth rate variation and larval survival: Inferences from an individual-based size-dependent predation model. Canadian Journal of Fisheries and Aquatic Sciences 50:133-142.

Rieman, B.E., R.C. Beamesderfer, S.Vigg, and T.P. Poe. 1991. Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120: 448-458.

Robards, M.D. and T.P. Quinn. 2002. The migratory timing of adult summer-run steelhead in the Columbia River over six decades of environmental change. Transactions of the American Fisheries Society 131: 523-536.

Roper, B.B., D.L. Scarnecchia, and T.J. LaMarr. 1994. Summer distribution and habitat use by Chinook salmon and steelhead within a major basin of the South Umpqua River, Oregon. Transactions of the American Fisheries Society 123: 298-308.

Sauter, S.T., J. McMillan, J. Dunham. 2001. Issue Paper 1: Salmonid behavior and water temperature. Prepared for, Region 10 Temperature Water Quality Criteria Guidance Development Project.

Schuytema, G. 1969. Literature review, effects of temperature on Pacific salmon. Pages A-1-A-62 in (Parker, F.L. and P.A. Krenkel, eds.). Thermal pollution: status of the art. Department of Environmental and Water Resources Engineering. Vanderbilt University, Nashville, Tennessee.

Scott, W.B., and E.J. Crossman. 1990. Freshwater fishes of Canada. Fisheries Research Board of Canada, Bulletin 184. Ottawa.

Servizi, J.A. and J.O.T. Jensen. 1977. Resistance of adult sockeye salmon to acute thermal shock. Progress report no. 34. International Pacific Salmon Fisheries Commission, British Columbia, Canada. 51 p.

Smith, S.G., W.D. Muir, J.G. Williams, and J.R. Skalski. 2002. Factors associated with travel time and survival of migrant yearling Chinook salmon and steelhead in the lower Snake River. North American Journal of Fisheries Management 22:385-405.

Spigarelli, S.A. and D.W. Smith. 1975. Growth of Plume Resident Fishes in Lake Michigan. Argonne National Lab., Radiological and Environmental Research Div. In: Radiological and Environmental Research Division Annual Report - Ecology, pp 173-179.

Stabler, D.F. 1981. Effects of altered flow regimes, temperatures and river impoundment on adult steelhead trout and Chinook salmon. Masters thesis. University of Idaho, Moscow.

Stuehrenberg, L.C., K.L. Liscom, and G.E. Monan. 1978. A study of apparent losses of Chinook salmon and steelhead based on count discrepancies between dams on the Columbia and Snake rivers, 1967-1968. A report for the U.S. Army Corps of Engineers, Portland, Oregon.

Sylvester, R. O. 1958. Water quality studies in the Columbia River basin. U.S. Fish and Wildlife Service, Special Scientific Report-Fisheries No. 239.

Tiffan, K.F., C.A. Haskell, and D.W. Rondorf. 2003. Thermal exposure of juvenile fall Chinook salmon migrating through a lower Snake River reservoir. Northwest Science 77:100-109.

U.S. Environmental Protection Agency. 2003. EPA Region 10 guidance for Pacific Northwest State and Tribal temperature water quality standards. EPA 910-B-03-002. Region 10 Office of Water, Seattle, Washington.

Vigg, S., T.P. Poe, L.A. Prendergast, and H.C. Hansel. 1991. Rates of consumption of juvenile salmonids and alternative prey fish by northern squawfish, walleyes, smallmouth bass, and channel catfish in John Day Reservoir, Columbia River. Transactions of the American Fisheries Society 120: 421-438.

Wang, Y.L., F.P. Binkowski, and S.I. Doroshov. 1985. Effect of temperature on early development of white and lake sturgeon, *Acipenser transmontanus* and *A. flavescens*. Environmental Biology of Fishes 14:43-50.

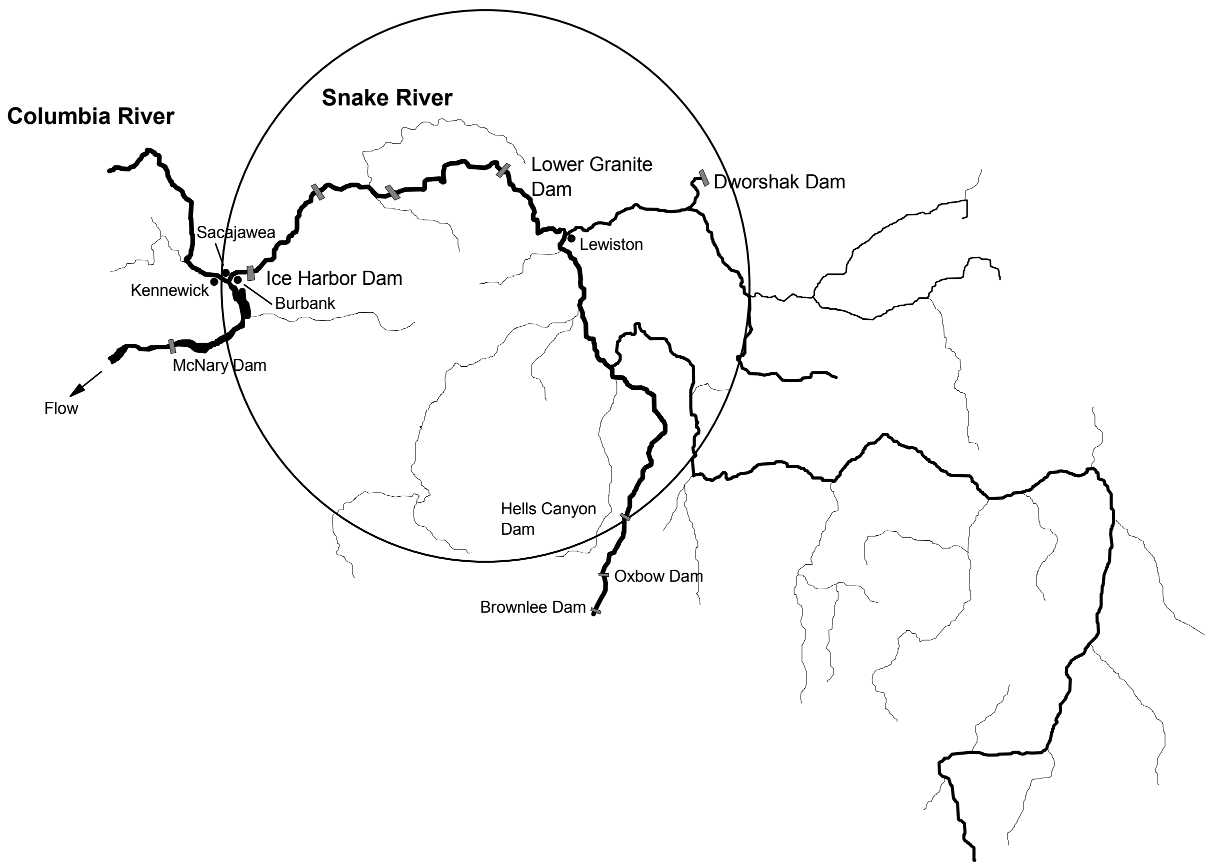


Figure 1. Map of lower Snake River area of concern.

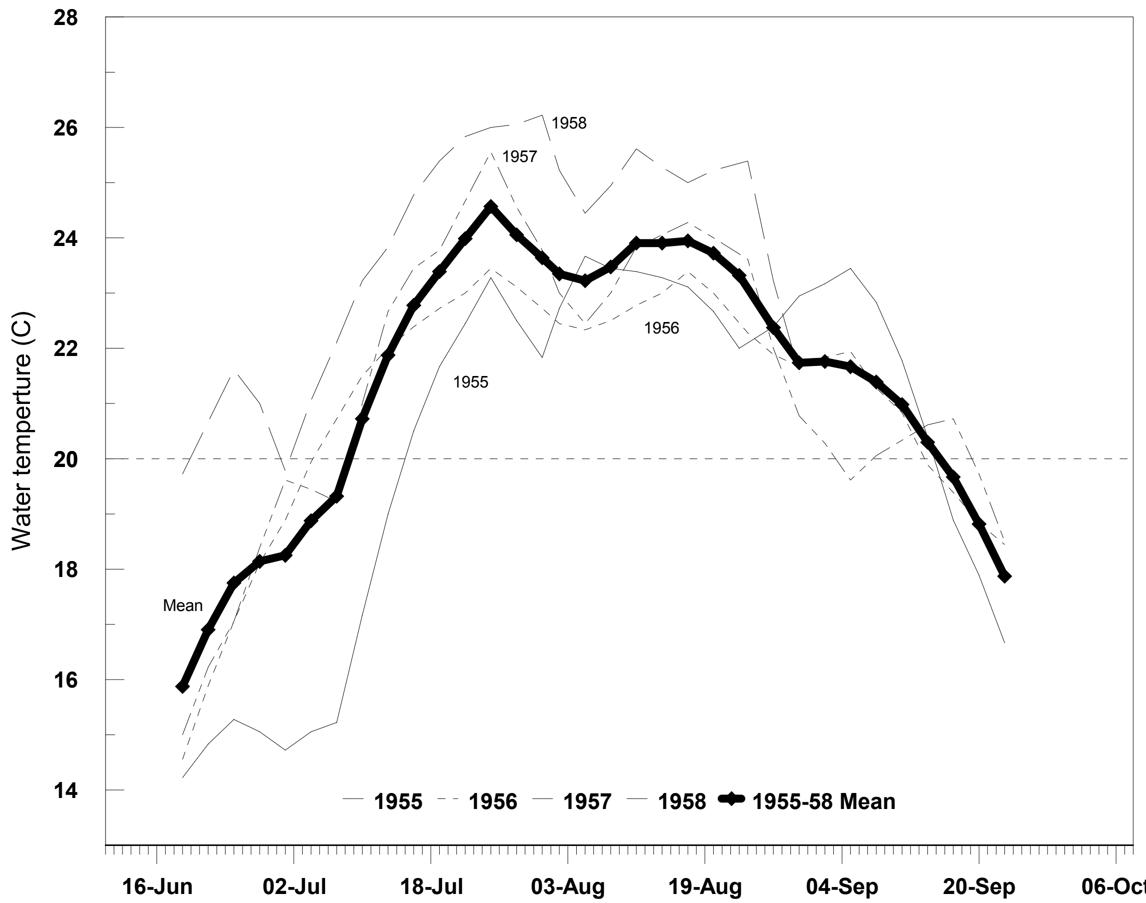


Figure 2. Water temperatures recorded at mouth of the Snake River during 1955-58, and mean water temperatures for the four years. Taken from Eldidge (1963) and Peery ey al. (2003).

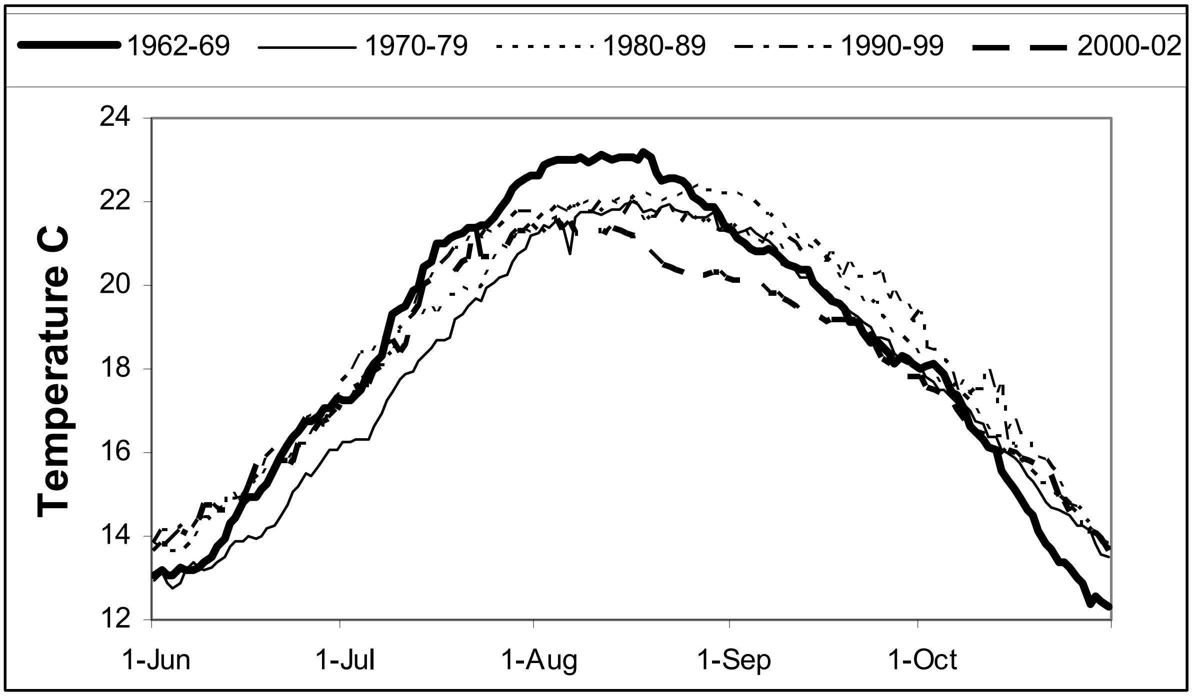
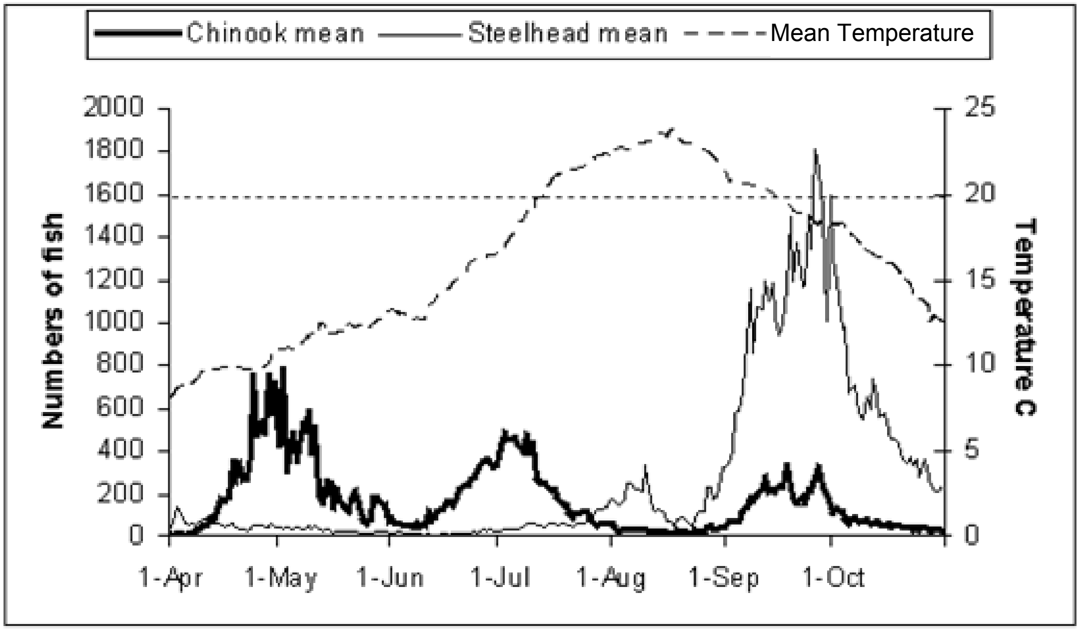


Figure 3. Mean decadal water temperatures recorded at Ice Harbor Dam from 1962 to 2002.



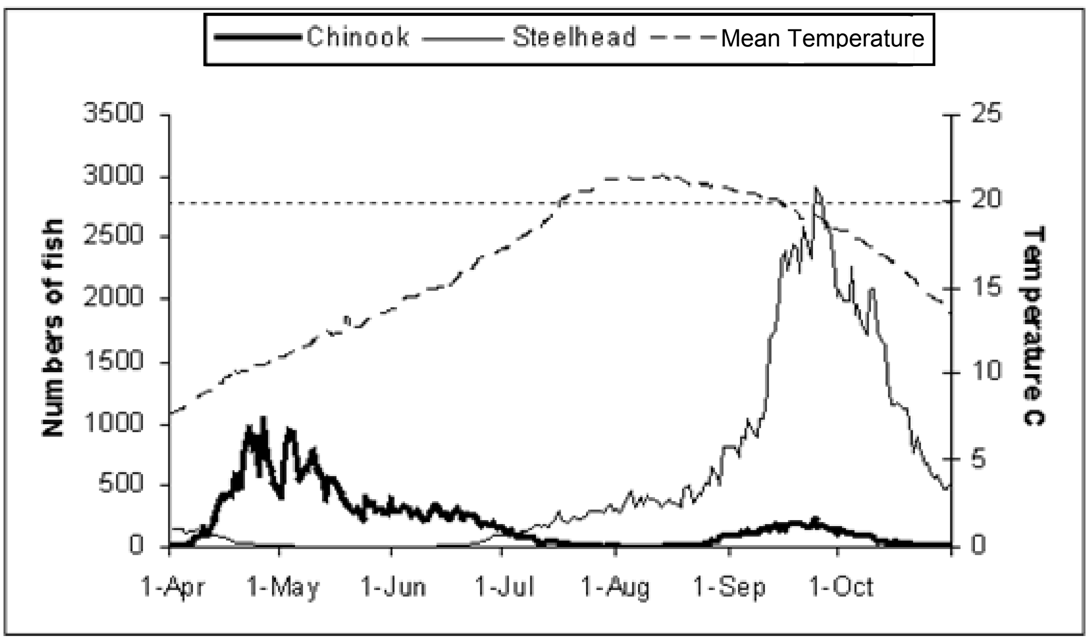


Figure 4. Mean number of adult Chinook salmon and steelhead counted and mean water temperatures at Ice Harbor Dam during 1963-72 (top) and during 1993-2002 (bottom). Dashed horizontal line represents reference temperature of 20°C.

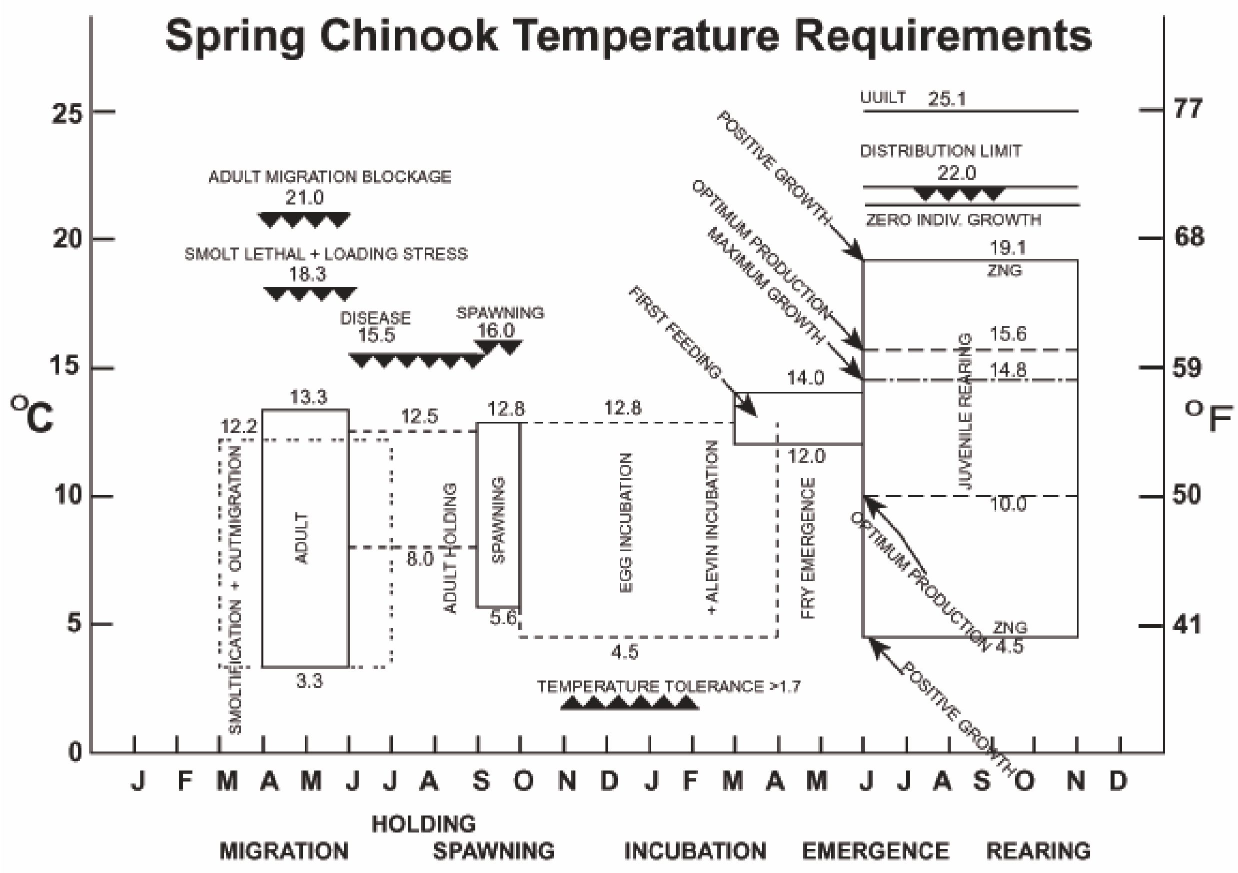


Figure 5. Spring Chinook salmon temperature requirements (From: McCullough 1999).

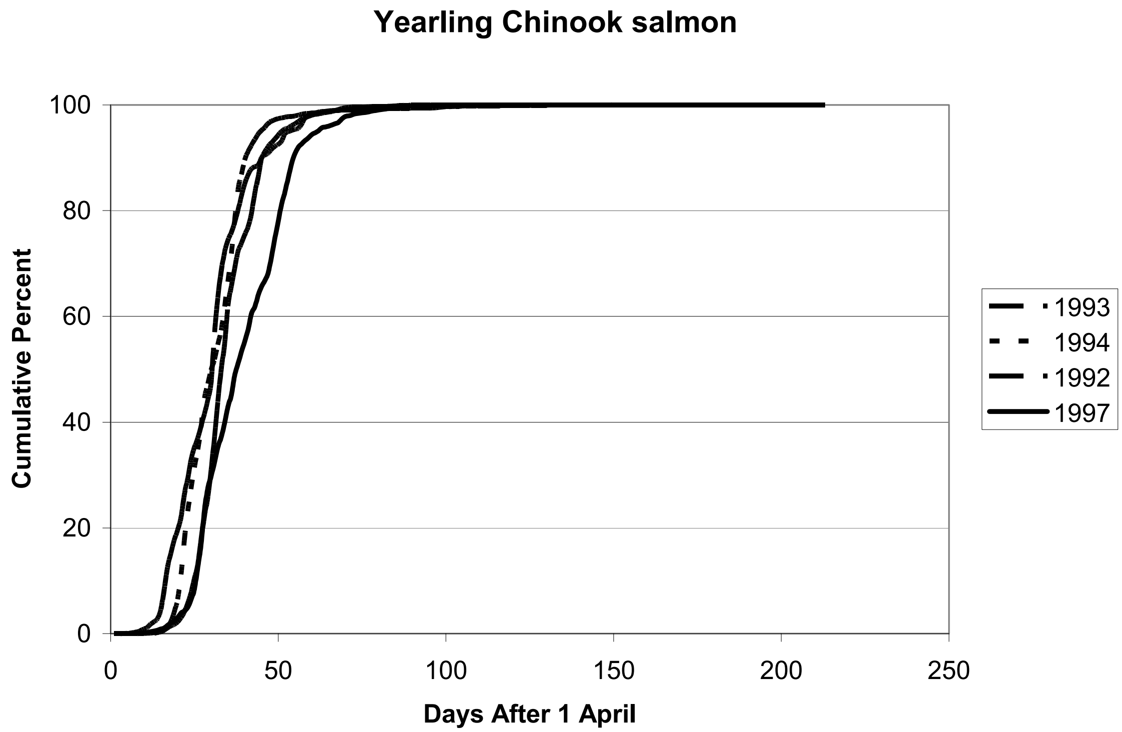


Figure 6. Cumulative percent of wild yearling Chinook salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu).

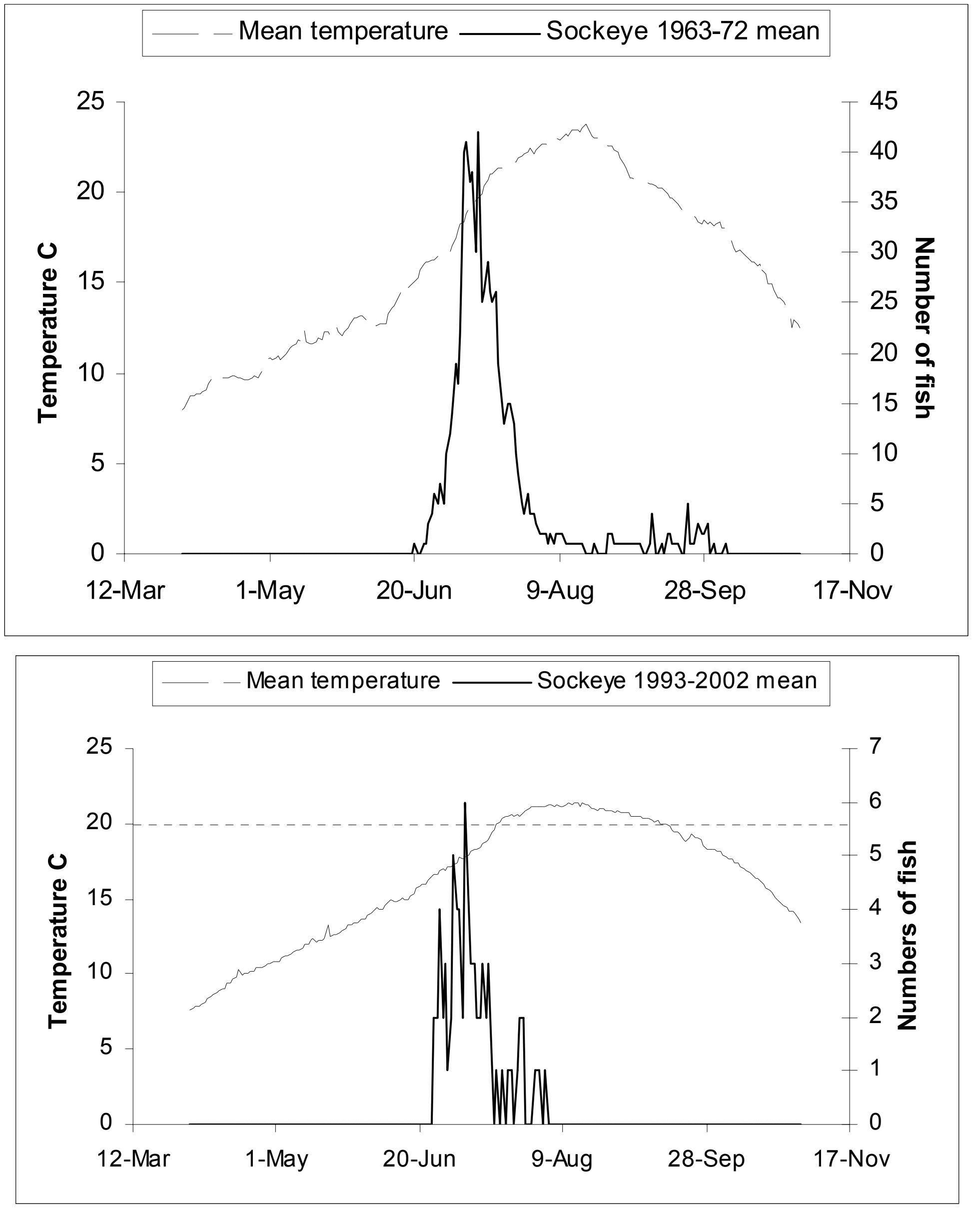


Figure 7. Mean sockeye salmon counts and water temperatures at Ice Harbor Dam during 1963-72 (top) and 1993-2002 (bottom). Dashed horizontal line represents reference temperature of 20°C.

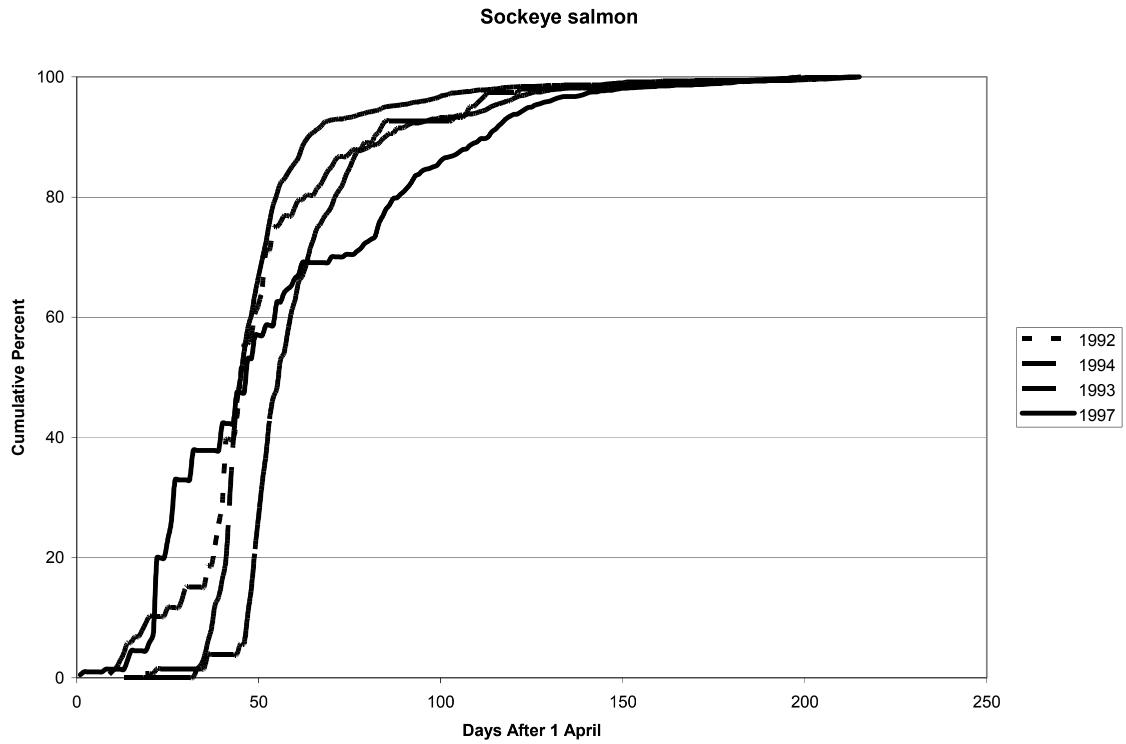


Figure 8. Cumulative percent of wild juvenile sockeye salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu).

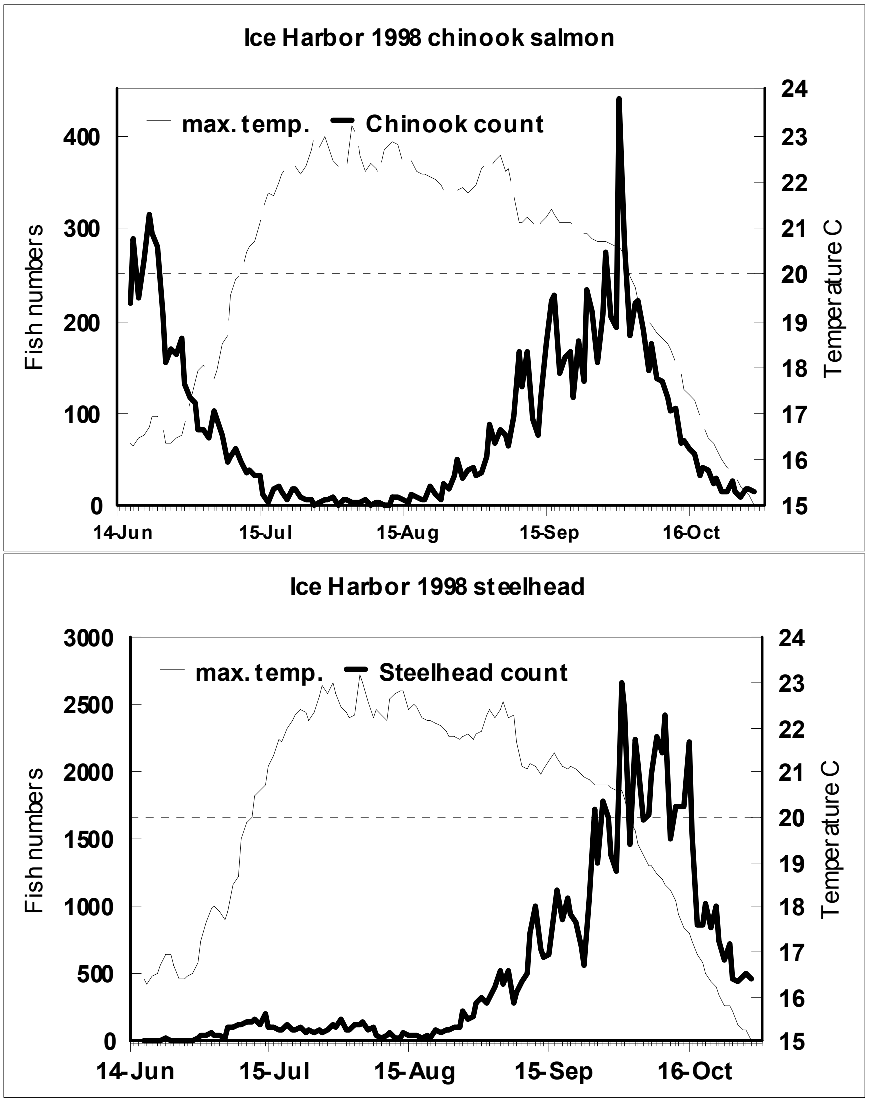


Figure 9. Run timing and water temperatures for adult Chinook salmon and steelhead at Ice Harbor Dam during 1998.

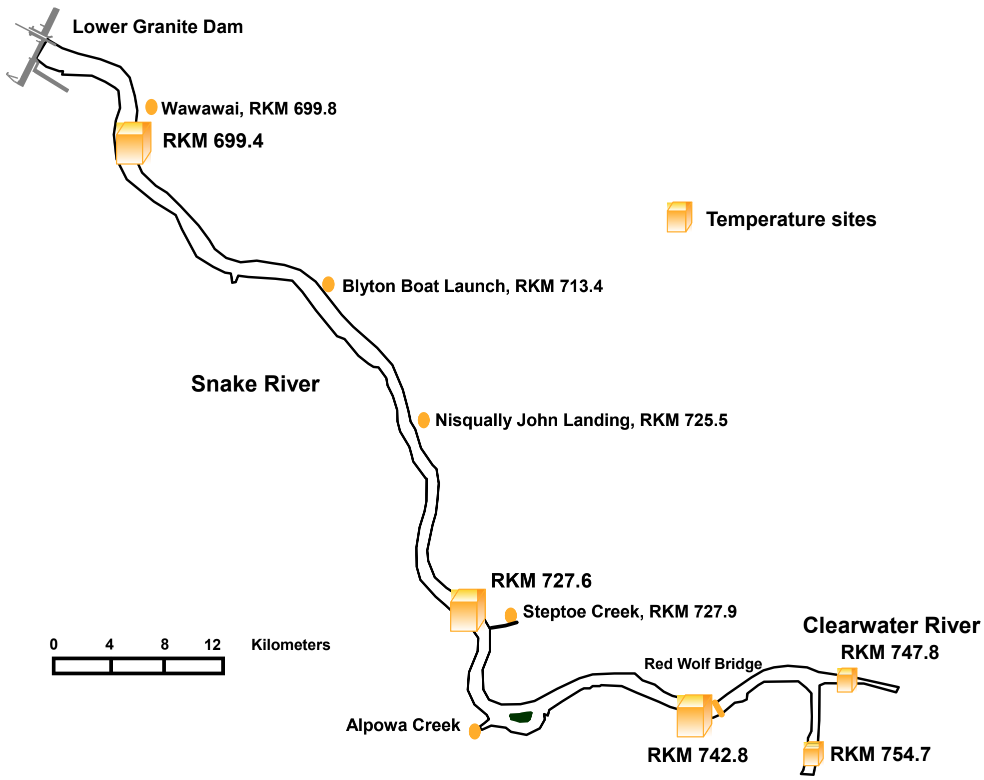


Figure 10. Lower Granite Reservoir showing temperature monitoring sites in 2001 (Reischel et al. In press).

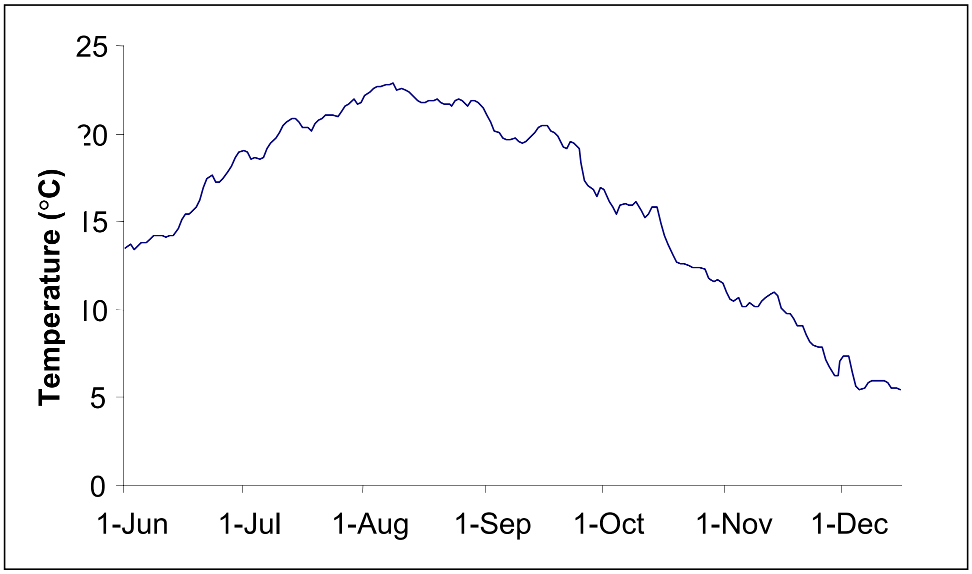


Figure 11. Mean Snake River water temperatures in Hells Canyon Reach (Anatone, WA) during 1993-2002.

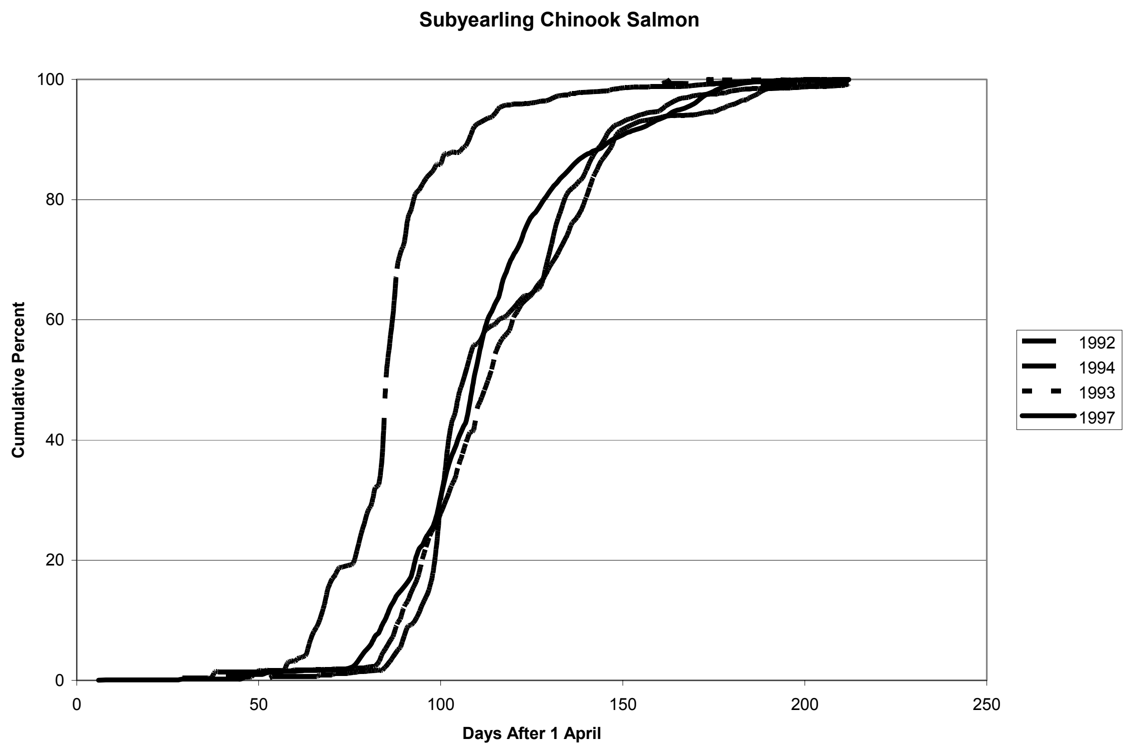


Figure 12. Cumulative percent of wild subyearling Chinook salmon migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu).

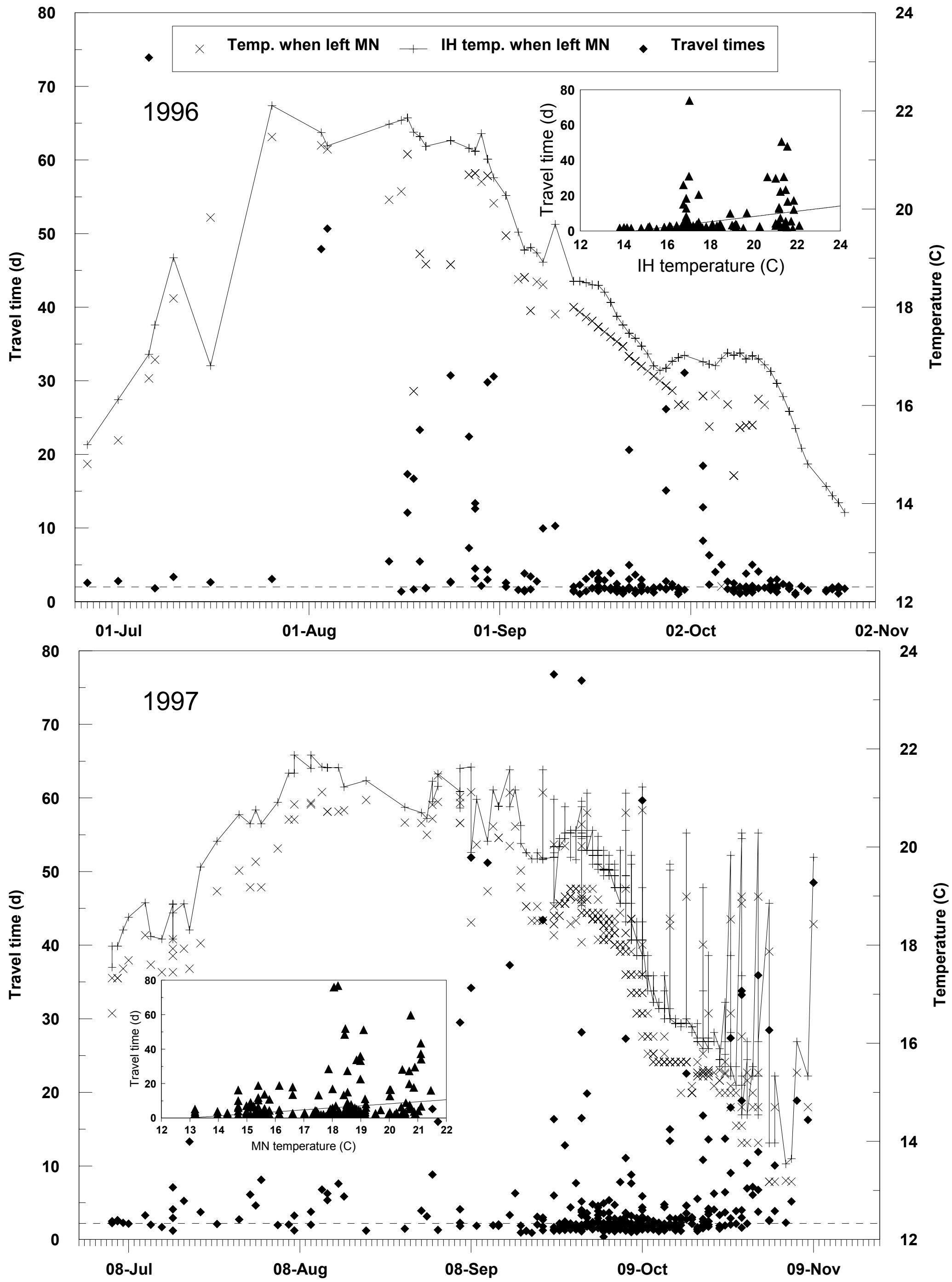


Figure 13. Travel times for steelhead between McNary (MN) and Ice Harbor (IH) dams and mean water temperatures at McNary and Ice Harbor dams on the day fish left McNary Dam in 1996 and 1997. Shown are relationships between travel times and temperature at Ice Harbor Dam in 1996, and between travel times and temperature at McNary Dam in 1997 (insets). Dashed lines represent median travel times (Peery et al. 2003).

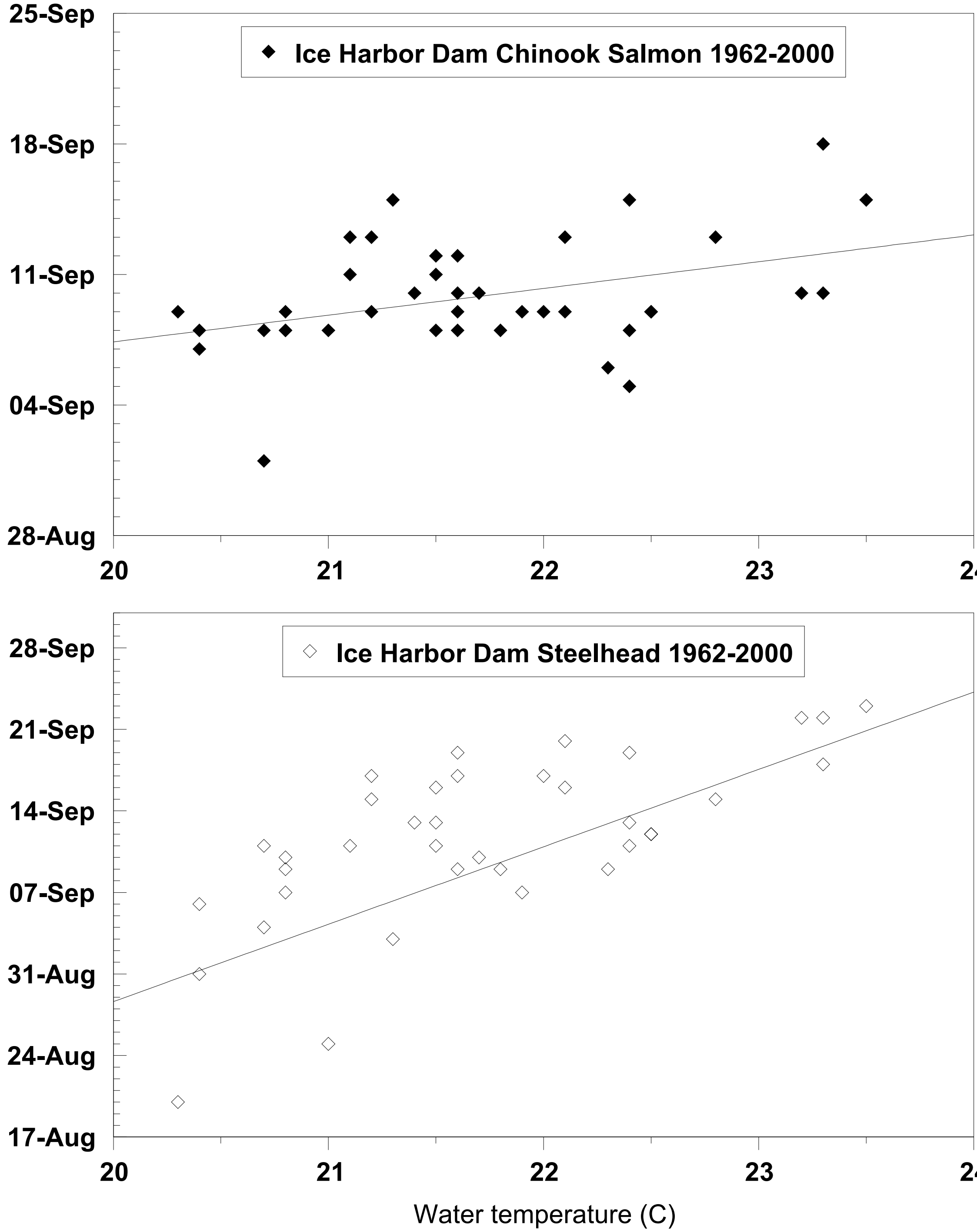


Figure 14. Date that 25% of the fall Chinook salmon and steelhead runs were counted at Ice Harbor Dam versus mean water temperature measured in the forebay of the dam during the period from 1 August through 15 September for each year 1962-2000. Fall Chinook salmon counts

from 12 August until 31 October. Steelhead counts were from 1 June until 31 October (Peery et al. 2003).

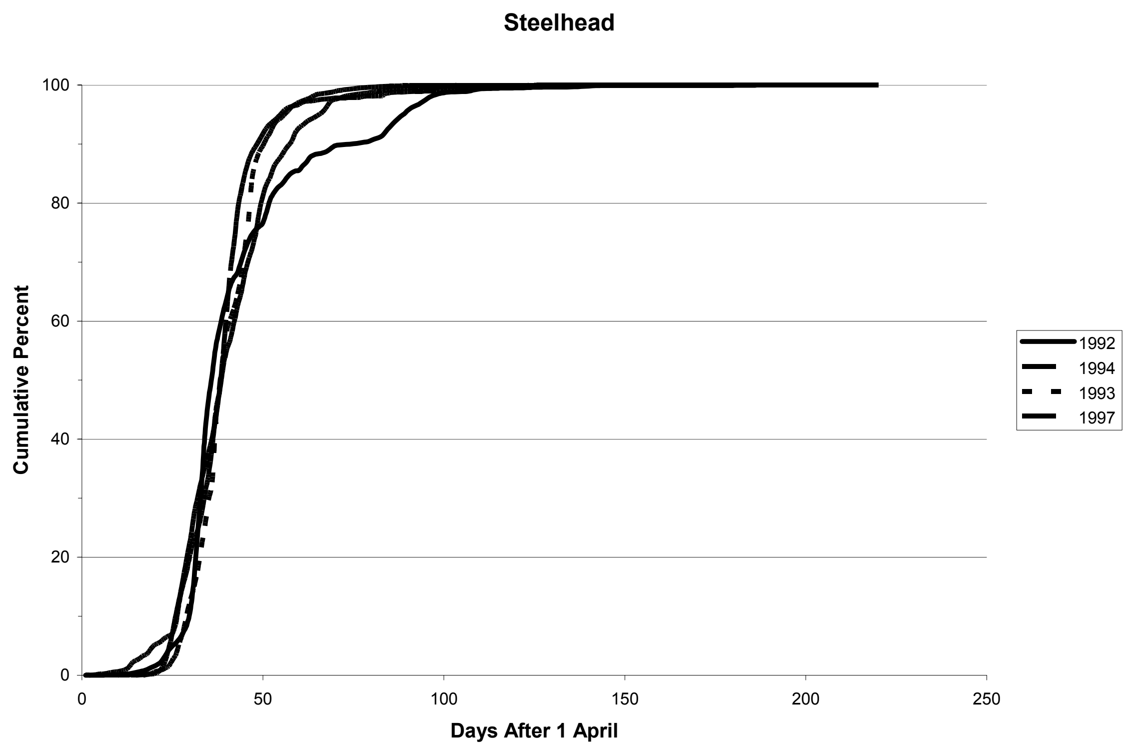


Figure 15. Cumulative percent of wild juvenile steelhead migrating downstream passed Lower Granite Dam, Snake River, during 1992 and 1994 and 1993 and 1997 representing low and high flow years, respectively (http://www.cbr.washington.edu).

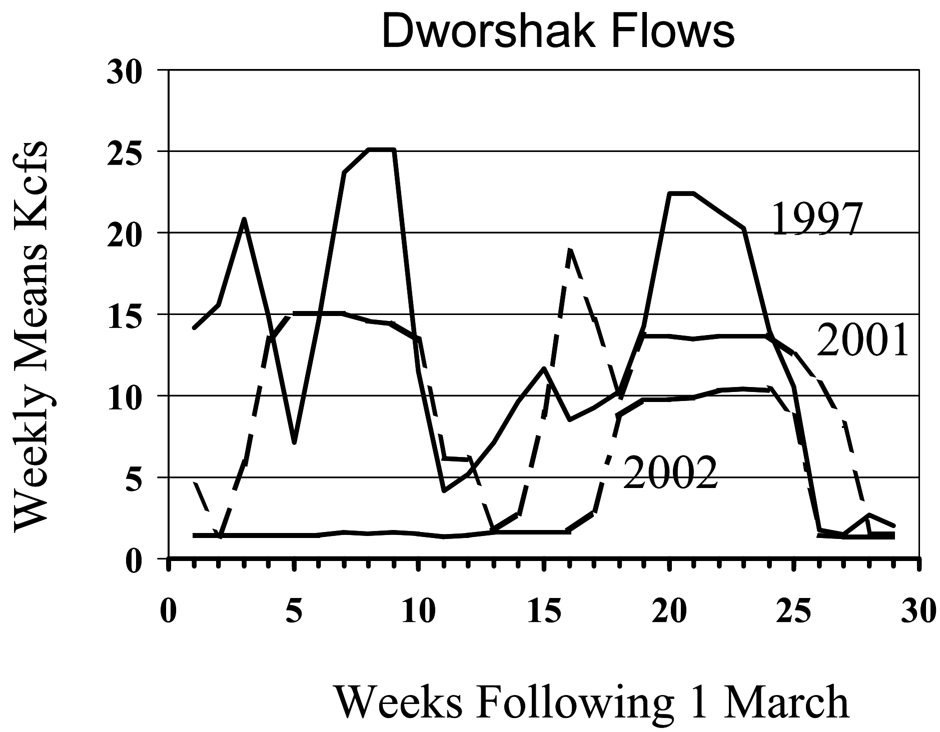


Figure 16. Weekly mean outflows (Kcfs) from Dworshak Reservoir, North Fork Clearwater River, starting 1 March for 1997, 2001, and 2002 (http://www.cbr.washington.edu).

Table 1. Comparison of timing of the middle 80% of the run of ESA listed yearling Chinook salmon (spring and summer), sockeye salmon, subyearling Chinook salmon, and steelhead at Lower Granite Dam, Snake River for selected representative low (1992, 1994) and high (1993, 1997) flow years (from http://www.cbr.washington.edu/perform). Also shown is the percent of the total run exposed to water temperatures > 20°C (based on scrollcase temperatures).

Water Flow Year	Stock	Year	N	Date of Middle 80%	% Exposed >20°C	Mean[a] Temp (°C)	Range[b]
Low	yearling	1992	1224	4/15-6/3	1.2	13.4	9.4-16.8
Low	yearling	1994	7374	4/22-6/6	0.0	13.3	10.8-16.5
High	yearling	1993	3522	4/26-6/6	0.1	12.4	10.3-14.2
High	yearling	1997	1316	4/12-6/28	0.0	12.1	8.9-16.7
Low	Sockeye	1992	11	5/9-5/30	0.0	14.5	12.6-16.6
Low	Sockeye	1994	39	5/9-5/29	0.0	13.4	11.9-14.8
High	Sockeye	1993	N O	D A T A			
High	Sockeye	1997	166	5/19-9/3	6.7	17.4	11.7-21.7
Low	subyearling	1992	42	6/6-6/30	28.5	18.0	15.7-23.6
Low	subyearling	1994	194	7/2-8/21	73.7	21.1	16.7-24.4
High	subyearling	1993	162	7/1-8/22	33.9	18.9	17.1-21.8
High	subyearling	1997	3822	6/20-8/8	1.6	16.8	12.8-19.4
Low	Steelhead	1992	3638	4/19-5/15	0.2	12.6	10.8-13.7
Low	Steelhead	1994	4558	4/23-5/18	0.4	12.6	10.8-14.9
High	Steelhead	1993	3832	4/30-5/16	0.0	11.6	10.3-13.4
High	Steelhead	1997	2435	4/20-5/14	0.0	10.6	9.4-12.2

[a]Mean scrollcase temperature at Lower Granite Dam during the middle 80% of the run.
[b]Range of scrollcase temperatures at Lower Granite Dam during the middle 80% of the run.

Table 2. Comparison of timing of the middle 80% of the run of ESA listed sockeye salmon and subyearling Chinook salmon at Lower Granite Dam, Snake River for years 1998 to 2002 (from http://www.cbr.washington.edu/perform). Also shown is the percent of the total run exposed to water temperatures > 20°C (based on scrollcase temperatures).

Stock	Year	N	Date of Middle 80%	% Exposed>20°C	Mean[1] Temp (°C)	Range[2]
subyearling	1998	88,325	6/12-8/25	42.2	18.8	15.0-21.1
subyearling	1999	2,793	4/20-6/3	0.0	11.3	10.0-13.3
subyearling	2000	747,839	6/14-8/20	15.0	18.8	14.4-21.7
subyearling	2001	740,554	6/11-8/10	18.5	17.9	13.9-21.1
subyearling	2002	753,596	6/18-8/2	32.1	17.6	11.7-20.6
Sockeye	1998	1,382	5/11-5/26	0.4	13.2	12.2-13.9
Sockeye	1999	11,951	4/2-5/5	0.3	9.7	7.8-11.1
Sockeye	2000	8,889	4/29-8/2	6.8	15.5	11.1-20.0
Sockeye	2001	4851	4/21-6/16	2.0	12.0	9.4-15.6
Sockeye	2002	76,701	4/26-6/2	0.8	17.8	13.9-20.6

[1]Mean scrollcase temperature at Lower Granite Dam during the middle 80% of the run.
[2]Range of scrollcase temperatures at Lower Granite Dam during the middle 80% of the run

Table 3. Mean fish body temperatures for adult Chinook and steelhead tracked in the Lower Reach of Lower Granite reservoir compared to tri-level temperature recordings at Wawawai landing (RKM 699.8) July-October, 2001. From Reischel et al. (in press).

Mean Temperature (ºC)	July	August	September	October
Fish (sd)[a] n[b] =	17.3 (0.9) 5	18.4 (1.3) 21	18.9 (0.8) 7	15.8 (1.5) 14
Surface (6 m)	22.3 (1.4)	21.0 (0.8)	20.2 (0.6)	15.7 (2.4)
Middle (21 m)	19.2 (0.8)	17.4 (0.7)	19.5 (0.6)	15.3 (1.0)
Bottom (37 m)	17.9 (0.7)	16.7 (0.7)	17.8 (1.3)	15.2 (2.4)

[a] standard deviation [b] n=number of fish

Table 4. Mean fish body temperatures for adult Chinook and steelhead tracked in the in the middle reach compared to tri-level temperature recordings at Steptoe Creek (RKM 727.9) July-October, 2001. From Reischel et al. (in press).

Mean Temperature (ºC)	July	August	September	October
Fish (sd)[a] n[b] =	16.2 (1.0) 4	15.1 (1.0) 4	18.0 (1.4) 15	14.7 (2.0) 12
Surface (6 m)	18.5 (1.3)	17.9 (1.3)	19.8 (0.8)	15.0 (1.9)
Middle (16 m)	17.7 (1.5)	15.9 (0.9)	19.2 (0.7)	15.0 (1.8)
Bottom (27 m)	17.3 (1.4)	15.3 (0.8)	18.0 (1.1)	14.6 (1.8)

[a] standard deviation [b] n=number of fish

Table 5. Mean fish body temperatures for adult Chinook and steelhead tracked in the the upper reach compared to temperature recordings near Red Wolf Crossing Bridge (RKM 742.8), near Potlatch Mill on the Clearwater River (RKM 747.8), and near Asotin on the Snake River (RKM 754.7) July-October, 2001. From Reischel et al. (in press).

Mean Temperature (ºC)	July	August	September	October
Fish (sd)[a] n[b] =	13.7 (1.2) 7	12.7 (1.6) 26	15.6 (1.6) 37	13.8 (2.2) 10
Red Wolf Bridge (12 m)	19.2 (1.8)	17.4 (1.1)	19.5 (0.9)	15.3 (2.1)
Clearwater River (4 m)	14.5 (2.1)	12.3 (1.1)	14.3 (1.1)	9.6 (1.1)
Snake River (5 m)	20.9 (0.6)	21.9 (0.6)	20.4 (0.9)	14.6 (2.1)

[a] standard deviation [b] n=number of fish

Table 6. Percent of time for body temperatures (ºC) of summer/fall Chinook salmon and steelhead tracked in the Lower Granite Reservoir by reservoir reach (Figure 10) and month. From Reischel et al. (in press). Blank cells represent zero time spent at a particular temperature.

	Lower Reach				Middle Reach				Upper Reach			
Temp. (ºC)	Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct
8.0 – 8.9												8.1
9.0 – 9.9												
10.0 – 10.9										19.0		
11.0 – 11.9										10.2		6.0
12.0 – 12.9				7.0		5.9		12.5	38.0	28.5	3.9	15.9
13.0 – 13.9				2.0	0.5	4.8		54.7	39.4	15.8	11.6	19.7
14.0 – 14.9				20.3	14.5	18.1	1.0		7.1	12.7	24.9	29.1
15.0 – 15.9		1.0		15.0	18.9	38.0	0.5		5.2	12.7	12.9	1.9
16.0 – 16.9	61.4	16.4	6.9	42.8	56.8	33.1	7.6	12.1	10.3	0.9	28.4	11.3
17.0 – 17.9	23.4	28.4	4.9	7.6	9.3		13.6	16.4			12.3	6.0
18.0 – 18.9	2.6	18.9	8.8	1.5			25.0				1.5	2.0
19.0 – 19.9	10.5	24.8	71.4	2.7			9.9	4.0			4.2	
20.0 – 20.9	2.1	3.8	8.6	0.7			42.1					
21.0 – 21.9		6.6										

Table 7. Monthly mean body temperatures (°C) of adult Chinook salmon and steelhead migrating through the tailraces (TR) and reservoirs (Res) of Ice Harbor (IH), Lower Monumental (LM), Little Goose (LGo), and Lower Granite (LGr, tailrace only) dams, lower Snake River dam during 2000, with standard deviations (sd) and number of fish (n).

	IH TR			IH Res			LM TR			LM Res			LGo TR			LGo Res			LGr TR		
Mon.	**Mean (°C)**	**sd[a]**	**n[b]**	**Mean (°C)**	**sd**	**n**	**Mean (°C)**	**sd**	**n**	**Mean (°C)**	**sd**	**n**	**Mean (°C)**	**sd**	**n**	**Mean (°C)**	**sd**	**n**	**Mean (°C)**	**sd**	**n**
Chinook salmon																					
Apr.	11.6	0.3	7	11.5	0.3	7	11.6	0.4	5	11.1	0.3	3	10.8	0.2	2	11.8	0.4	2	12.1	0.1	2
May	13.8	1.2	33	13.4	1.2	31	13.6	1.1	30	13.2	1.4	29	13.1	1.3	25	12.8	1.3	30	13.2	0.9	29
Jun.	15.0	0.8	39	15.4	1.0	40	15.4	1.3	35	15.4	1.3	43	15.8	1.6	34	15.5	1.6	41	14.9	1.7	36
Jul.																			19.3	0.4	2
Aug.	21.4	0.2	3	20.4	0.4	3	20.1	0.2	2	17.5	2.6	2	18.0	1.6	4	17.9	0.5	1			
Sep.	19.1	0.6	4	18.1	0.6	6	18.1	0.5	2	13.1	2.8	6	18.4	0.1	4	18.4	0.4	6	18.4	0.2	3
Oct.	16.7	0.0	1	16.4	0.1	1				15.9	1.9	4	15.3	0.0	2	17.2	0.5	3	17.1	0.1	3
Nov.	12.0	0.0	1	11.1	0.3	1				10.2	0.1	1	10.1	0.0	1	9.0	0.1	1	8.9	0.0	1
Steelhead																					
Jun	17.5	0.2	2	18.4	0.2	2	18.3	0.1	2	15.6	3.1	1									
Jul	21.0	0.1	2	21.0	0.3	2	20.7	0.2	2	14.8	3.2	3	20.3	0.1	1	18.9	0.7	3	19.5	0.0	2
Aug	21.6	0.0	2	21.0	0.4	2	20.3	0.1	2	14.2	2.5	3				19.2	0.4	2			
Sep	17.6	0.5	13	18.2	0.5	13	19.0	0.5	8	17.7	2.1	13	18.7	0.2	3	19.1	0.6	11	18.5	0.9	6
Oct	15.0	1.1	18	15.9	1.2	21	15.4	0.9	12	15.0	1.6	23	15.1	0.9	11	14.2	1.7	21	13.8	1.0	11
Nov	14.0	0.0	4	13.0	0.1	6				12.4	0.4	7	12.6	0.1	4	11.2	0.5	10	10.3	0.3	8

[a] standard deviation [b] n=number of fish

Table 8. Monthly mean depths (m) of adult Chinook salmon and steelhead migrating through the tailraces (TR) and reservoirs (Res) of Ice Harbor (IH), Lower Monumental (LM), Little Goose (LGo), and Lower Granite (LGr, tailrace only) dams, lower Snake River dam during 2000, with standard deviations (sd) and number of fish (n).

Mon.	IH TR			IH Res			LM TR			LM Res			LGo TR			LGo Res			LGr TR		
	Mean (m)	sd[a]	n[b]	Mean (m)	sd	n	Mean (m)	sd	n	Mean (m)	sd	n	Mean (m)	sd	n	Mean (m)	sd	n	Mean (m)	sd	n
Chinook salmon																					
Apr.	2.8	1.4	7	5.4	4.1	7	4.7	1.9	5	6.9	6.7	3	5.2	3.3	2	5.1	4.2	2	3.9	2.1	2
May	3.2	2.5	33	5.3	4.8	31	3.6	2.1	30	5.2	5.0	29	4.4	3.2	25	5.9	5.1	30	4.0	2.9	29
Jun.	3.3	2.7	39	4.6	3.7	40	4.7	2.0	35	5.1	4.7	43	2.9	3.0	34	6.4	4.9	41	4.5	3.3	36
Jul.																			5.3	2.3	2
Aug.	4.5	2.0	3	6.2	3.4	3	5.2	2.8	2	5.7	4.4	2	5.3	3.7	4	9.1	6.1	1			
Sep.	4.4	2.8	4	5.8	3.5	6	3.6	2.2	5	1.7	2.4	6	3.7	2.0	4	6.2	5.2	6	3.7	3.2	3
Oct.	3.2	1.9	1	4.5	3.1	1				2.8	2.9	4	1.7	0.6	2	2.9	2.5	3	4.5	2.7	3
Nov.	6.6	2.5	1	3.9	2.6	1				7.4	2.8	1	4.8	3.0	1	7.0	3.4	1	6.9	3.4	1
Steelhead																					
Jun	3.6	1.9	2	5.2	3.2	2	4.6	2.0	2	4.7	5.6	1									
Jul	4.5	2.4	2	5.3	4.9	2	3.9	2.2	2	2.9	2.8	3	3.7	1.5	1	4.1	4.5	3	4.4	2.0	2
Aug	4.2	1.1	2	3.9	3.5	2	3.5	1.9	2	3.3	2.9	3				3.6	5.8	2			
Sep	3.3	3.0	13	4.2	3.0	13	5.1	1.4	8	4.0	3.2	13	6.4	3.1	3	4.0	2.5	11	4.7	3.6	6
Oct	4.4	2.8	18	2.8	1.9	21	4.2	2.6	12	2.9	2.3	23	3.1	1.8	11	4.2	2.2	21	2.7	2.0	11
Nov	4.9	1.9	4	2.3	1.4	6				3.1	1.9	7	3.0	1.7	4	4.3	2.4	10	4.1	2.3	8

[a] standard deviation [b] n=number of fish

Table 9. Percent of time adult Chinook salmon and steelhead spent at different depths as they migrated trough Ice Harbor, Lower Monumental and Little Goose reservoirs during 2000.

Depth (m)	Ice Harbor	Lower Monumental	Little Goose
0 and 0.9	8.4	6.0	6.3
1 and 1.9	17.9	18.8	15.7
2 and 2.9	13.5	17.1	15.1
3 and 3.9	10.2	12.6	11.5
4 and 4.9	11.0	9.6	8.6
5 and 5.9	11.0	7.6	7.6
6 and 6.9	7.8	5.4	6.3
7 and 7.9	4.5	4.1	5.1
8 and 8.9	3.3	3.4	4.1
9 and 9.9	2.8	2.6	3.3
10 and 10.9	2.5	2.1	2.7
11 and 11.9	1.5	1.6	2.1
12 and 12.9	1.0	1.4	1.9
13 and 13.9	0.8	1.2	1.7
14 and 14.9	0.7	1.0	1.4
15 and 15.9	0.6	0.9	1.6
>=16	2.5	4.6	5.2

Table 10. Percent of time spent at different depths (m) by summer/fall Chinook salmon and steelhead tracked in the Lower Granite Reservoir by reservoir reach (Figure 10) and month. Blank cells represent zero time spent at a particular depth.

	Lower Reach				Middle Reach				Upper Reach			
Depth (m)	Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct	Jul	Aug	Sep	Oct
0 – 2.9	0.9	6.7	20.9	**49.0**	2.3	2.4	**24.3**	**63.0**	29.1	14.9	5.8	**48.3**
3.0 – 5.9	2.2	5.7	**23.1**	20.9	2.2	8.2	16.0	19.8	21.3	**40.0**	25.2	8.3
6.0 – 8.9	3.9	7.8	16.0	10.4	**35.6**	21.4	20.3	6.3	**33.9**	37.1	**53.3**	16.6
9.0 – 11.9	4.9	9.3	8.7	7.6	23.7	**36.1**	20.5	3.8	15.4	7.9	14.2	25.9
12.0 – 14.9	6.9	10.9	4.5	4.0	17.6	17.3	7.8	1.6	0.1		0.7	0.9
15.0 – 17.9	15.7	15.9	6.7	2.6	17.0	14.6	10.6	0.2	0.3	0.1	0.9	
18.0 – 20.9	18.7	**17.9**	10.0	2.2	1.7		0.4	0.6				
21.0 – 23.9	**20.1**	11.5	7.4	2.3				4.6				
24.0 – 26.9	16.8	6.2	1.5	0.4								
27.0 – 29.9	9.4	4.5	0.7	0.3								
30.0 – 32.9	0.5	3.5	0.5	0.3								

APPENDICES

Appendix 1
Literature Review
Effects of Water Temperature on Chinook Salmon and Steelhead

Aadland, L.P.E. 1987. Food Habits, Distribution, Age and Growth of Chinook Salmon, and Predation on Newly Stocked Chinook Smolts in Lake Sakakawea, North Dakota. Ph.D. Dissertation. North Dakota Game and Fish Dept.; 133 pp.

Abbad, F.N. 1980. The Influence of the Quality of Spawners and of Conditions of Rearing on Variability of Underyearling of the Steelhead Trout, *Salmo gairdneri*. Journal of Ichthyology 20(2):144-148.

Adams, B.L., W.S. Zaugg, and L.R. McLain. 1975. Inhibition of Salt Water Survival and NA-K-ATPASE Elevation in Steelhead Trout (*Salmo gairdneri*) by Moderate Water Temperatures. American Fisheries Society Transactions 104(4):766-769.

Adams, B.L., W.S. Zaugg, and L.R. McLain. 1973. Temperature effect on parr-smolt transformation in steelhead trout (*Salmo gairdneri*) as measured by gill sodium-potassium stimulated adenosine triphosphatase. Comparative Biochemistry and Physiology, Part A: Physiology 44(4):1333-1339.

Adams, R.M., P.C. Klingeman, and H.W. Li. 1990. A Bioeconomic Analysis of Water Allocations and Fish Habitat Enhancements, John Day Basin, Oregon. Final Report, August 1990. 168pp.

Adeniyi, R. 1997. Effect of temperature on the feeding rate of young steelhead trout (*Oncorhynchus mykiss*). 127th Annual Meeting of the American Fisheries Society, Monterey, CA, 24-28 Aug 1997. American Fisheries Society, Bethesda, MD.

Alderdice, D.F. and F.P.J. Velsen. 1978. Relation between temperature and incubation time for eggs of Chinook salmon *Oncorhynchus tshawytscha*. J. Fish. Res. Board Can., 35(1):69-75.

Allen, G.H., J. Hedgepeth, J. Pandozzi, and M. Jennings. 1980. Rearing Pacific Salmon in Saltwater Ponds Fertilized with Domestic Wastewater, Data Report, June 1979 - May 1980. 73 pp.

Allen, G.H. 1959. Behavior of Chinook and Silver Salmon. Ecology 40(1):108-113.

Allin, R.W. 1958. Game Fish Investigations of Alaska: Environmental Studies of the Steelhead of Alaska as Related to Their Spawning Habits, Age, Growth, Fecundity, Migrations, and Movements. Alaska Dept of Fish and Game; 28 pp.

Amend, D.F. 1972. Efficacy, Toxicity, and Residues of Nifurpirinol in Salmonids. U.S. Bur. Sport Fish. Wildl. Tech. Pap. No. 62: 13 pp.

Anderson, D.G. 1993. Status of Summer Steelhead Trout in Redwood Creek, Redwood National Park, CA. U.S. Natl. Park Serv. Trans. Proc. Ser. 9:1-8.

Anderson, J.D., D.W. Huston, C.J. Loeb, G.T. Orlob, and I.P. King. 1998. Assessing aquatic ecosystem response to stress. Proc. ASCE Wetlands Eng. River Restor. Conf. 6 pp.

Anderson, S.S. and B.A. Bravender. 1996. Catch, length, and weight data for juvenile salmonids sampled from the Campbell River estuary and Discovery Passage, B.C., during 1994 and 1995. Can. Data Rep. Fish. Aquat. Sci./Rapp. Stat. Can. Sci. Halieut. Aquat. 1037:187 pp.

Anonymous. 1984. Pacific salmon aquatic habitat. Report of engineering and biological literature pertaining to the aquatic environment: With special emphasis on dissolved oxygen and sediment effects on salmonid habitat; pp. 3-37.

Anonymous. 1970. Water Quality Criteria for European Freshwater Fish: Report on Ammonia and Inland Fisheries. Food and Agriculture Organization of the United Nations. European Inland Fisheries Advisory Commission. Technical Papers Issue No.11:1-13.

Antonio, D. B., and R. P. Hedrick. 1995. Effect of Water Temperature on Infections with the Microsporidian Enterocytozoon Salmonis in Chinook Salmon. Diseases of Aquatic Organisms 22(3):233-236.

Appleby, A., and T. Anderson. 1993. Effects of acclimation of the survival of spring Chinook salmon. Annual report, 1992. Progress report. Bonneville Power Administration, Portland, OR Div. of Fish and Wildlife. Rept. No.: DOEBP004671, 21 pp.

Armour, C.L. 1991. Guidance for Evaluating and Recommending Temperature Regimes to Protect Fish. U.S. Fish and Wildlife Service. Biological Report 90(22):13p.

Arvey, W.D., M.J. Kramer, J.E. Hallberg, J.F. Parker, and A.L. DeCicco. 1991. Annual Management Report for Sport Fisheries in the Arctic-Yukon- Kuskokwim Region, 1987. Alaska Department of Fish and Game. Fishery Management Report 91-1: 150 pp.

Arvey, W.D., and J.F. Parker. 1991. Annual Management Report for Sport Fisheries in the Arctic-Yukon- Kuskokwim Region, 1988. Alaska Department of Fish and Game. Fishery Management Report 91-2; 130 pp.

Auerbach, S.I., D.J. Nelson, S.V. Kaye, D.E. Reichle, and C.C. Coutant. 1971. Ecological Considerations in Reactor Power Plant Siting. Environmental Aspects of Nuclear Power Stations Symposium, New York, Aug. 10-14, 1970, International Atomic Energy Agency, Vienna, 19 pp.

Aultman, D.C., and J.M. Haynes. 1993. Spring thermal fronts and salmonine sport catches in Lake Ontario. North American Journal of Fisheries Management 13(3):502-510.

Axler, R., C. Tikkanen, M. McDonald, C. Larsen, and G. Host. 1993. Fish bioenergetics modeling to estimate waste loads from a net-pen aquaculture operation. Techniques for Modern Aquaculture, American Society of Agricultural Engineers, St. Joseph, MI, pp. 596-604.

Baada, R.T. 1957. Game Fish Investigations of Alaska: Environmental Studies of the Cutthroat Trout, Southeastern Alaska. Quart. Prog. Rep. Alaska Dept. of Fish and Game; pp. 62-67.

Baigun, C.R., J. Sedell, and G. Reeves. 2000. Influence of water temperature in use of deep pools by summer steelhead in Steamboat Creek, Oregon (USA). Journal of Freshwater Ecology 15(2):269-279

Baker, P.F., T.P. Speed and F.K. Ligon. 1995. Estimating the influence of temperature on the survival of Chinook salmon smolts (*Oncorhynchus tshawytscha*) migrating through the Sacramento-San Joaquin River delta of California. Canadian Journal of Fisheries and Aquatic Sciences/Journal Canadian des Sciences Halieutiques et Aquatiques. Ottawa. 52(4):855-863.

Banks, J.L., and L.G. Fowler. 1988. Effect of Accelerated Fingerling Rearing on Adult Survival of Spring Chinook Salmon. U.S. Fish and Wildlife Service, Abernathy Salmon Cult. Dev. Cent. Technol. Transfer Ser. No. 87-1: 12 pp.

Banks, J.L., and L.G. Fowler. 1982. Transportation, Storage, and Handling Studies of Fall Chinook Salmon Gametes and Newly Fertilized Eggs. U.S. Fish and Wildlife Service, Abernathy Salmon Cult. Dev. Cent. Technol. Transfer Ser. No. 82-4. 18p.

Banks, J.L., L.G. Fowler, and J.W. Elliot. Effects of rearing temperature on growth, body form, and hematology of fall Chinook fingerlings. Prog. Fish Cult. 33(1):20-26.

Banks, J.W. 1969. A review of the literature on the upstream migration of adult salmonids. Journal of Fish Biology 1(2):85-136.

Bardach, J.E., J.H. Ryther, and W.O. McLarney. 1972. Culture of the Pacific Salmons (Oncorhynchus spp.). Aquaculture, The Farming and Husbandry of Freshwater and Marine Organisms. Wiley-Interscience, New York; 450-502.

Barnhart, R.A. 1986. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Southwest) Steelhead. U.S. Fish and Wildlife Service Biological Report 82(11.60): vi+21 pp.

Bartholow, J.M., reviewer. 2001. 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 (book review). Transactions of the American Fisheries Society 130(2):350.

Bartholow, J.M., J.L. Laake, C.B. Stalnaker, and S.C. Williamson. 1993. A salmonid population model with emphasis on habitat limitations. Rivers 4(4):265-279.

Barton, B.A., and C.B. Schreck. 1987. Metabolic cost of acute physical stress in juvenile steelhead. Transactions of the American Fisheries Society 116(2):257-263.

Barton, B.A., and C.B. Schreck. 1987. Influence of acclimation temperature on interrenal and carbohydrate stress responses in juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Aquaculture 62(3-4):299-310.

Basov, Yu.S. Experimental use of geothermal water in rearing young salmons. In: Fishery oceanography, hydrobiology and fish parasitology of the Pacific Ocean/Promyslovaya okeanografiya, gidrobiologiya i parazitologiya ryb Tikhogo okeana. Publ.by: T. Izv. Tinro, v.101.

Beacham, T. D., and R. E. Withler. 1991. Genetic Variation in Mortality of Chinook Salmon, *Oncorhynchus tshawytscha* (Walbaum), Challenged with High Water Temperatures. Aquaculture and Fisheries Management 22(2):125-133.

Beacham, T.D. and C.B. Murray. 1989. Variation in Developmental Biology of Sockeye Salmon (*Oncorhynchus nerka*) and Chinook Salmon (*O.tshawytscha*) in British Columbia. Canadian Journal of Zoology 67(9):2081-2089.

Beamish, R.J., B.E. Riddell, C-E.M. Neville, B.L. Thomson, and Z. Zhang. 1995. Declines in Chinook salmon catches in the Strait of Georgia in relation to shifts in the marine environment. Fisheries Oceanography 4(3):243-256.

Beauchamp, D.A. 1995. Riverine predation on sockeye salmon fry migrating to Lake Washington. North American Journal of Fisheries Management 15(2):358-365.

Becjnab, B.R., D.A. Larsen, C. Sharpe, B. Lee-Pawlak, C.B. Schreck, and W.W. Dickhoff. 2000. Physiological status of naturally reared juvenile spring Chinook salmon in the Yakima River: Seasonal dynamics and changes associated with smolting. American Fisheries Society. Transactions 129(3):727-753.

Becker, D.C. 1969. The Food and Feeding of Juvenile Chinook Salmon in the Columbia River at Hanford. Biological Effects of Thermal Discharges: Annual Progress Report, 1968, pp. 27-31.

Becker, C.D. 1970. Temperature, Timing, and Seaward Migration of Juvenile Chinook Salmon from the Central Columbia River. Battelle Northwest Laboratories Report BNWL-1472, 21 pp.

Becker, C.D. 1971. Food and Feeding of Juvenile Chinook Salmon in the Central Columbia River in Relation to Thermal Discharges and Other Environmental Features. BNWL-1528, UC-48, 68 pp.

Becker, C.D. 1973a. Columbia River Thermal Effects Study: Reactor Effluent Problems. J. Water Pollution Control Federation 45(5):850-869.

Becker, C.D. 1973b. Food and Growth Parameters of Juvenile Chinook Salmon, *Oncorhynchus tshawytscha*, in Central Columbia River. U.S. National Marine Fisheries Service Fish Bulletin 71(2):387-400.

Becker, C.D., C.C. Coutant, and E.F. Prentice. 1971. Experimental Drifts of Juvenile Salmonids Through Effluent Discharges at Hanford, PART II, 1969; Drifts and Conclusions. Atomic Energy Commission Research and Development Report BNWL-1527, UC-48, 61 pp.

Becker, C.D., D.A. Neitzel, and D.H. Fickeisen. 1982. Effects of Dewatering on Chinook Salmon Redds: Tolerance of Four Developmental Phases To Daily Dewaterings. American Fisheries Society. Transactions 111(5):624-637.

Beckman B.R., D.A. Larsen, S. Moriyama S, B. Lee-Pawlak, and W.W. Dickhoff. 1998. Insulin-like growth factor-I and environmental modulation of growth during smoltification of spring Chinook salmon (*Oncorhynchus tshawytscha*). General and comparative endocrinology 109(3):325-35.

Beckman, B.R., D.A. Larsen, B. Lee-Pawlak, and W.W. Dickhoff. 1998. Relation of Fish Size and Growth Rate to Migration of Spring Chinook Salmon Smolts. North American Journal of Fisheries Management 18(3):537-546.

Beeman, J.W., P.V. Haner, and A.G. Maule. 1998. Evaluation of a new miniature pressure-sensitive radio transmitter. North American Journal of Fisheries Management 18(2):458-464.

Beer, W.N. and J.J. Anderson. 2001. Effect of spawning day and temperature on salmon emergence: interpretations of a growth model for Methow River chinook. Canadian Journal of Fisheries and Aquatic Sciences 58(5):943-949.

Beer, W.N. 1999. Comparison of Mechanistic and Empirical Methods for Modeling Embryo and Alevin Development in Chinook Salmon. North American Journal of Aquaculture 61(2):126-134.

Beer, W.N. and J.J. Anderson. 1997. Modeling the Growth of Salmonid Embryos. Journal of Theoretical Biology 189(3):297-306.

Bencic, D.C., R.L. Ingermann, and J.G. Cloud. 2001. Does CO_2 enhance short-term storage success of Chinook salmon (*Oncorhynchus tshawytscha*) milt? Theriogenology 56(1):157-166.

Berggren, T.J. and M.J. Filardo. 1993. An analysis of variables influencing the migration of juvenile salmonids in the Columbia River basin. North American Journal of Fisheries Management 13(1):48-63.

Berman, C.H. and T.P. Quinn. 1991. Behavioural thermoregulation and homing by spring Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. Journal of Fish Biology 39(3):301-312.

Berst, A.H. and G.R. Spangler. 1973. Lake Huron: The ecology of the fish community and man's effects on it. Great Lakes Fishery Commission [United States and Canada] Technical Report Series 21:1-41.

Birtwell, I.K. and G.M. Kruzynski. 1989. In situ and laboratory studies on the behaviour and survival of Pacific salmon (genus *Oncorhynchus*). Environmental Bioassay Techniques and Their Application, Hydrobiologia 188-189:543-560..

Bisson, P.A. and G.E. Davis. 1976. Production of Juvenile Chinook Salmon, Oncorhynchus Tshawytscha, in a Heated Model Stream. Fishery Bulletin 74(4):763-774.

Bisson, P.A. 1975. Elevated Temperature and the Production of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in a Model Stream. Ph.D. Dissertation, Oregon State Univ.; 86p.

Bjornn, T.C., T.W. Reischel, R.R. Ringle, K.R. Tolotti, and L.S. Stuehrenberg. 1999. Radio Telemetry Assessments of Migration Patterns and Fallbacks of Adult Salmon and Steelhead in the Forebay of Bonneville Dam, 1996-1997. Florida Coop. Fish and Wildlife Research Unit. Tech. Report 99-1, 38 pp.

Bjornn, T.C. 1971. Trout and Salmon Movements in Two Idaho Streams as Related to Temperature, Food, Stream Flow, Cover, and Population Density. American Fisheries Society. Transactions 100(3):423-438.

Bjornn, T.C. 1969. Salmon and Steelhead Investigations: Spawning and Emergence of Chinook Salmon as Related to Temperature. Idaho Fish and Game Dept.; 6 pp.

Bjornn, T.C. 1966. Salmon and Steelhead Investigations: Steelhead Trout Production Studies, Lemhi Big Springs Creek: Fish Populations in Big Springs Creek. Idaho Fish and Game Dept.; pp. 36-41.

Blachut, S.P. 1988. The winter hydrologic regime of the Nechako River, British Columbia. Can. Manuscr. Rep. Fish. Aquat. Sci., 1964: 154 pp.

Blahm, T.H., R.J. McConnell, and G.R. Snyder. 1973. Final Report - Part I, Effect of Gas Supersaturated Columbia River Water on the Survival of Juvenile Salmonids. 61 pp.

Blanco, O. and T. Meade. 1980. Effect of Dietary Ascorbic Acid on the Susceptibility of Steelhead Trout (*Salmo gairdneri*) to Nitrite Toxicity. Revista de biologia tropical 28(1):91-107.

Bonneville Power Administration, Div. of Fish and Wildlife, Portland, OR. 1984. Natural Propagation and Habitat Improvement - Washington, Volume IIB, Similkameen River Habitat Inventory. DOE Report No. DOE/BP--247-Vol.2B, 73 pp.

Borstad, G.A., R.M. Brown, D. Truax, T.R. Mulligan, and J.F.R. Gower. 1982. Remote sensing techniques for fisheries oceanography: Examples from British Columbia. NAFO Sci. Counc. Stud. 4:69-76.

Botsford, L.W. and C.A. Lawrence. 2002. Patterns of co-variability among California Current, Chinook salmon, coho salmon, Dungeness crab, and physical oceanographic conditions. Progress in Oceanography 53(2-4):283-305.

Bottom, D.L. 1981. The carrying capacity of Sixes Estuary for fall Chinook salmon. Estuaries 4(3):247.

Bouck, G.R. 1977. The Importance of Water Quality to Columbia River Salmon and Steelhead. Proceedings of a Symposium, Vancouver, Washington, March 5-6, 1976. American Fisheries Society, pp 149-154.

Bouck, G.R., A.V. Nebeker, and D.G. Stevens. 1976. Mortality, Saltwater Adaptation and Reproduction of Fish During Gas Supersaturation. Ecological Research Series, EPA-600/3-76-050, 55 pp.

Bower, S.M. 1995. Differences in acquired and innate resistance among Pacific salmon (Oncorhynchus spp.) against the haemoflagellate *Cryptobia salmositica* and numbers delivered by the leech vector *Piscicola salmositica*. Canadian Journal of Fisheries and Aquatic Sciences 52(1):1-6.

Boyce, R.R. 1985. Effects of Feeding Level, Temperature, and Photoperiod on Growth and Selected Scale Characteristics of Juvenile Steelhead Trout. M.S. Thesis. Oregon State University, 81 pp.

Bradford, M.J., J.A. Grout, and S. Moodie. 2001. Ecology of juvenile Chinook salmon in a small non-natal stream of the Yukon River drainage and the role of ice conditions on their distribution and survival. Canadian Journal of Zoology 79(11):2043-2054.

Bradford, M.J. and P.S. Higgins. 2001. Habitat-, season-, and size-specific variation in diel activity patterns of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*). Canadian Journal of Fisheries and Aquatic Sciences 58(2):365-374.

Bradford, M.J. 1994. Trends in the abundance of Chinook salmon (*Oncorhynchus tshawytscha*) of the Nechako River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 51(4):965-973.

Bradford, M.J. and G.H. Geen. 1992. Growth estimates from otolith increment widths of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) reared in changing environments. Journal of Fish Biology 41(5):825-832.

Bramblett, R.G., M.D. Bryant, B.E. Wright, and R.G. White. 2002. Seasonal use of small tributary and main-stem habitats by juvenile steelhead, coho salmon, and Dolly Varden in a southeastern Alaska drainage basin. North American Journal of Aquaculture 131(3):498-506.

Brandt, S.B., D.M. Mason, and M.J. McCormick. 2001. Climate change: implications for food production, habitat quality and quantity, and fish growth performance. American Fisheries Society Annual Meeting 131:49-50.

Brandt, S.B. 1993. The Effect of Thermal Fronts on Fish Growth: A Bioenergetics Evaluation of Food and Temperature. Estuarine Fronts: Hydrodynamics, Sediment Dynamics and Ecology. Estuaries 16(1):142-159.

Bravender, B.A., S.S. Anderson, and J. Van Tine. 1997. Juvenile salmon survey, 1996, Discovery Harbour Marina and surrounding nearshore area, Campbell River, B.C. Can. Data Rep. Fish. Aquat. Sci./Rapp. Stat. Can. Sci. Halieut. Aquat. 50 pp.

Bravender, B.A., C. Annand, A. Hillaby, and J. Naylor. 1997. Fish species, juvenile Chinook diets and epibenthos in the Englishman River estuary, 1993. Can. Data Rep. Fish. Aquat. Sci./Rapp. Stat. Can. Sci. Halieut. Aquat. 46 pp.

Breton, B., F. Le Gac, and E. Sambroni. 1986. Gonadotropin hormone (GtH) receptors in the ovary of the brown trout *Salmo trutta L*. in vitro studies. General and Comparative Endocrinology 64(2):163-171.

Brett, J.R., W.C. Charke, and J.E. Shelbourn. 1982. Experiments on thermal requirements for growth and food conversion efficiency of juvenile Chinook salmon, *Oncorhynchus tshawytscha*. Can. Tech. Rep. Fish. Aquat. Sci., 1127:33 pp.

Brown, E.E. 1977. World Fish Farming: Cultivation and Economics. 1. United States of America. World Fish Farming: Cultivation and Economics. The AVI Publishing Company, Inc., pp. 4-71.

Burck, W.A. 1993. Life History of Spring Chinook Salmon in Lookingglass Creek, Oregon. Oregon Department of Fish and Wildlife. Information Report Number 94-1: 158 pp.

Burck, W.A. 1971. Growth of Juvenile Spring Chinook Salmon in Lookingglass Creek. Research Report, Fish Commission of Oregon 3:37-43.

Burger, C.V. 1987. Thermal adaptations in Alaskan Chinook and sockeye salmon. Common Strategies of Anadromous and Catadromous Fishes. American Fisheries Society. Symposium 1:553.

Burger, C.V. 1985. Thermal Adaptations in Alaskan Chinook and Sockeye Salmon. American Fisheries Society Annual Meeting No. 115. p. 59.

Cai, G., I.I. Solar, and E.M. Donaldson. 1989. Comparison of heat and hydrostatic pressure shocks to induce triploidy in steelhead trout (*Oncorhynchus mykiss*). Can. Tech. Rep. Fish. Aquat. Sci. 1718: 15 pp.

Campbell, S.G., R.B. Hanna, M. Flug, and J.F. Scott. 2001. Modeling Klamath River system operations for quantity and quality. Journal of Water Resources Planning and Management 127(5):284-294.

Capuzzo, J.M. 1979. The Effect of Temperature on the Toxicity of Chlorinated Cooling Waters to Marine Animals-A Preliminary Review. Marine Pollution Bulletin 10:45-47.

Carl, G.C. 1971. Handbook No.21: Guide to marine life of British Columbia. British Columbia Provincial Museum: Department of Recreation and Conservation; Issue 21:1-135.

Cech, J.J. 1999. Steelhead and Chinook salmon bioenergetics: Temperature, ration, and genetic effects. University of California Water Resources Center, Report No.96, pp. 41-43.

Chadwick, H.K. 1971. Thermal Effects of Power Plant Discharges on Fishery Resources in the Sacramento-San Joaquin Estuary, California. Proc. 51st. Ann. Conf. Western Assoc. of State Game and Fish Commissioners. CA Dept. of Fish and Game; pp. 117-131.

Chatters, J.C., D.A. Neitzel, M.J. Scott, and S.A. Shankle. 1991. Potential impacts of global climate change on Pacific Northwest spring Chinook salmon (*Oncorhynchus tshawytscha*): An exploratory case study. Northwest Environ. J. 7(1):71-92.

Chebanov, N.A. and B.E. Riddell. 1998. The spawning behavior, selection of mates, and reproductive success of Chinook salmon (*Oncorhynchus tshawytscha*) spawners of natural and hatchery origins under conditions of joint spawning. Journal of Ichthyology 38(7):517-526.

Chechun, T.Y. and N.B. Markevich. 1984. The Dynamics of Growth of Two Generations of Steelhead (*Salmo Gairdneri Gairdneri* Rich.) With Reference to the Thermal Regime at the Experimental Mullet Hatchery. Marine Fish Farming, Collected Papers. All-Union Res. Inst. Mar. Fish. Oceanogr. (Moscow); p. 122-138.

Chivers, C. J. 1999. Why is this dam here? Wildlife Conservation 102(1)22-29.

Clarke, W.C. 1997. Physiological ecology of Pacific salmon migration. Memoirs of the Faculty of Fisheries Hokkaido University (Hakodate) Vol. 44(1), Special Edition 1:10-14.

Clarke, W.C. and J. E. Shelbourn. 1985. Growth and Development of Seawater Adaptability by Juvenile Fall Chinook Salmon (*Oncorhynchus tshawytscha*) in Relation to Temperature. Aquaculture 45(1-4):21-31.

Clarke, W.C., J.E. Shelbourn, and J.R. Brett. 1981. Effect of artificial photoperiod cycles, temperature, and salinity on growth and smolting in underyearling coho (*Oncorhynchus kisutch*), Chinook (*O. tshawytscha*), and sockeye (*O. nerka*) salmon. Aquaculture, 22(1-2):105-116.

Close, T.L. and C.S. Anderson. 1992. Dispersal, density-dependent growth, and survival of stocked steelhead fry in Lake Superior tributaries. North American Journal of Fisheries Management 12(4):728-735.

Coche, A.G. 1967. Production of Juvenile Steelhead Trout in a Freshwater Impoundment. Ecological Monographs 37(3):201-228.

Collings, M.R. and G.W. Hill. 1973. The Hydrology of Ten Streams in Western Washington as Related to the Propagation of Several Pacific Salmon Species. Water-Resources Investigations 11-73, 149 pp.

Collings, M.R., R.W. Smith, and G.T. Higgins. 1970. The Hydrology of Four Streams in Western Washington as Related to Several Pacific Salmon Species. US Geological Survey Open-File Report, 158 pp.

Collins, G.B. 1976. Effects of Dams on Pacific Salmon and Steelhead Trout. Marine Fisheries Review 38(11):39-46.

Combs, B.D. 1965. Effect of temperature on the development of salmon eggs. Progressive Fish-Culturist 27(3):134-137.

Connolly, P.J. and J.H. Petersen. 2001. Is bigger always better? Winter severity and overwintering of young-of-the-year steelhead. American Fisheries Society Annual Meeting 131, p. 33.

Connor, W.P. 2002. Juvenile life history, downstream migration rate, and survival of wild Snake River fall Chinook salmon (*Oncorhynchus tshawytscha*). PhD Dissertation, University of Idaho. Dissertation Abstracts International Part B: Science and Engineering 62(10):4288.

Connor, W.P., H.L. Burge, R. Waitt, and T.C. Bjornn. 2002. Juvenile Life History of Wild Fall Chinook Salmon in the Snake and Clearwater Rivers. North American Journal of Fisheries Management 22(3):703-712.

Connor, W.P., H.L. Burge, and D.H. Bennett. 1998. Detection of PIT-Tagged Subyearling Chinook Salmon at a Snake River Dam: Implications for Summer Flow Augmentation. North American Journal of Fisheries Management 18(3):530-536.

Conner, W.P., B.D. Amsberg, E. Connor, and C.M. Prewitt. 1990. Mainstem Clearwater River study: Assessment for salmonid spawning, incubation, and rearing. Annual report, 1989. Rep. U.S. Dept. Energy, 155 pp.

Conrad, J.F., R.A. Holt, and T.D. Kreps. 1975. Ozone Disinfection of Flowing Water. Progressive Fish-Culturist 37(3):134-136.

Cousins, K.L. and J.O.T. Jensen. 1994. The effects of temperature on external egg membranes in coho salmon (*Oncorhynchus kisutch*) and the occurrence of soft-shell disease. Canadian Journal of Zoology/Revue Canadian de Zoologie 72(10):1854-1857.

Coutant, C.C. 2001. Water flow management for juvenile salmon outmigration in the Lower Snake River: What guidance does science offer? American Fisheries Society Annual Meeting 131:159.

Coutant, C.C. 1973. Behavior of Ultrasonic Tagged Chinook Salmon and Steelhead Trout Migrating Past Hanford Thermal Discharges (1967). Report BNWL-1530, Prepared for the US Atomic Energy Commission, 15 pp.

Coutant, C.C. 1973. Effect of thermal stock on Vulnerability of juvenile salmonids to predation. J. Fish. Res. Board Can. 30(7):965-973.

Coutant, C.C. 1972. Effect of Thermal Shock on Vulnerability to Predation in Juvenile Salmonids. II. A Dose Response by Rainbow Trout to Three Shock Temperatures. Battelle Memorial Inst., Pacific Northwest Labs. BNWL-1519, 12 pp.

Coutant, C.C. 1971. Effect on Organisms of Entrainment in Cooling Water: Steps Toward Predictability. Nuclear Safety 12(6):600-607.

Coutant, C.C. 1970. Exploratory Studies of the Interactions of Gas Supersaturation and Temperature on Mortality of Juvenile Salmonids. Battelle-Pacific Northwest Labs., Richland, WA. 23 pp.

Coutant, C.C. 1969. Responses of Salmonid Fishes to Acute Thermal Shock. Battelle-Northwest, Richland, WA. In: Biological Effects of Thermal Discharges Annual Progress Report for 1968, pp. 1-8.

Coutant, C.C., C.D. Becker, and E.F. Prentice. 1969. Passage of Downstream Migrants. Biological Effects of Thermal Discharges: Annual Progress Report for 1968, pp. 9-12.

Coutant, C.C. 1969. Temperature, Reproduction and Behavior. Chesapeake Science 10(3-4):261-274.

Coutant, C.C. and R.G. Genoway. 1968. Final Report on an Exploratory Study of Interaction of Increased Temperature and Nitrogen Supersaturation of Adult Salmonids. For the U.S. Bureau of Commercial Fisheries, Seattle, Washington, 28 pp.

Coutant, C.C. 1968. Behavior of adult salmon and steelhead trout migrating past Hanford thermal discharges. BNWL-714, U.S. Atomic Energy Commission. pp 9.10-19+.

Coutant, C.C. Behavior of Sonic-Tagged Chinook Salmon and Steelhead Trout Migrating past Hanford Thermal Discharges. Biological Effects of Thermal Discharges: Annual Progress Report for 1968, pp. 21-26.

Coxson, D.S. and K.A. Kershaw. 1983. Nitrogenase activity during Chinook snowmelt sequences by Nostoc commune in Stipa-Bouteloa grassland. Second International Symposium on Nitrogen Fixation with Nonlegumes, 1983. Can. J. Microbiol. 29(8):938-944.

Craig, J.L. 1992. Klamath River Fisheries Assessment Program: Juvenile Salmonid Trapping on the Mainstem Trinity River at Willow Creek and on the Klamath River at Big Bar, 1990. U.S. Fish and Wildlife Service. Annual Report No. AFF-1-FRO-92-13; 59 pp.

Crisp, D.T. 1981. A Desk Study of the Relationship Between Temperature and Hatching Time for the Eggs of Five Species of Salmonid Fishes. Freshwater Biology 11(4):361-368.

Curet, T.S. 1994. Habitat Use, Food Habits and the Influence of Predation on Subyearling Chinook Salmon in Lower Granite and Little Goose Reservoirs, Washington. M.S. Thesis, University of Idaho; 70p.

Curtis, Lawrence R. 1983. Glucuronidation and biliary excretion of phenolphthalein in temperature-acclimated steelhead trout (*Salmo gairdneri*). Comparative Biochemistry and Physiology, Part C: Comparative Pharmacology and Toxicology 76(1):107-111.

Daily, M.K. 1971. Adult Steelhead Migration Patterns in Relation to Temperature and Total Dissolved Solids. M.S. Thesis, University of Idaho; 55 pp.

Dalton, M.G. 2001. El Niño, Expectations, and Fishing Effort in Monterey Bay, California. Journal of Environmental Economics and Management 42(3):336-359.

Dambacher, J.M. 1990. Rearing Ecology of Juvenile Steelhead (*Oncorhynchus mykiss*), and Habitat Analysis of Steamboat Creek Basin, Oregon. Northwest Science 64(2):105.

Dauble, D.D. and D.G. Watson. Status of fall Chinook salmon populations in the Mid-Columbia River, 1948- 1992. North American Journal of Fisheries Management 17(2):283-300.

Davidson, F.A. and S.J. Hutchinson. 1938. The geographic distribution and environmental limitations of the Pacific salmon (genus *Oncorhynchus*). Bulletin of the U.S. Bureau of Fisheries Vol. XLVIII(26):667-692.

Davis, G.E. 1974. Phase II: Temperature Requirements of Salmonids in Relation to Their Feeding, Bioenergetics, Growth and Behavior. Oregon Water Resources Research Institute, Corvallis, Completion Report, OWRR B-027-ORE(4):24 pp.

Davis, G.E., J. Foster, C.E. Warren, and P. Doudoroff. 1963. The Influence of Oxygen Concentration on the Swimming Performance of Juvenile Pacific Salmon at Various Temperatures. Transactions American Fisheries Society 92(2):111-124.

Dawson, V.K. and P.A. Gilderhus. 1979. Ethyl-p-Aminobenzoate (Benzocaine): Efficacy as an Anesthetic for Five Species of Freshwater Fish. Investigations in Fish Control Report 87, 5 pp.

Dean, J.M. 1969. The Response of Juvenile Salmonids to Acute Thermal Shock. Biological Effects of Thermal Discharges: Annual Progress Report for 1968, pp 41-46.

Dean, J.M. and C.C. Coutant. 1968. Lethal temperature relations of juvenile Columbia River Chinook salmon. U.S. Atomic Energy Commission. BNWL-714:9.5-9+.

Deas, M.L. and G.T. Orlob. 1999. Klamath River Modeling Project. U.S. Fish and Wildlife Service. Report No. 99-04, 380 pp.

Denton, D. 1987. Experimental Production of Triploid Chinook Salmon at Deer Mountain Hatchery. Alaska Department of Fish and Game, Div. Fisheries Rehabilitation, Enhancement & Development (FRED) Report No. 74; 19 pp.

Dickhoff, W.W., B.R. Beckman, D.A. Larsen, C.V.W. Mahnken, C.B. Schreck, C. Sharpe, and W.S. Zaugg. 1995. Quality assessment of hatchery-reared spring Chinook salmon smolts in the

Columbia River basin. Proceedings of the 15th International Symposium and Workshop on Uses and Effects of Cultured Fishes in Aquatic Ecosystems, American Fisheries Society, 15:292-302.

Dreher, K.J. 1995-1998. Review of Survival, Flow, Temperature and Migration Data for Hatchery-Raised, Subyearling Fall Chinook Salmon Above Lower Granite Dam. Idaho Department of Water Resources.

Durkin, J.T., D.L. Park, and R.F. Raleigh. 1971. Distribution and Movement of Juvenile Salmon in Brownlee Reservoir, 1962-65. US Fish Wildl Serv Fish Bull. 68(2):219-243.

Eales, J.G. 1964. The influence of temperature on thyroid histology and radioiodine metabolism of yearling steelhead trout, *Salmo gairdneri*. Canadian Journal of Zoology 42(5), pp. 829-841.

Ebel, W.J. and H.L. Raymond. 1976. Effect of Atmospheric Gas Supersaturation on Salmon and Steelhead Trout of the Snare and Columbia Rivers. Marine Fisheries Review 38(7):1-14.

Ebel, W.J., E.M. Dawley, and B.H. Monk. 1971. Thermal Tolerance of Juvenile Pacific Salmon and Steelhead Trout in Relation to Supersaturation of Nitrogen Gas. Fishery Bull. 69(4):833-843.

Ebel, W.J. 1970. Supersaturation of nitrogen in the Columbia River and its effect of salmon and steelhead trout. Fishery Bulletin 68(1):1-11.

Ebel, W.J., E.M. Dawley, and B.H. Monk. 1970. Thermal Tolerance of Juvenile Salmon in Relation to Nitrogen Supersaturation. Report, 28 pp.

Ebersole, J.L. 2002. Heterogeneous thermal habitat for northeast Oregon stream fishes. PhD Dissertation. Oregon State University, Corvallis, OR. Dissertation Abstracts International Part B: Science and Engineering 63(3):1098.

Eldridge, E. F. 1963. Proceedings of the twelfth Pacific Northwest Symposium on water pollution research: Water temperature, influences, effects, and control. U.S. Department of Health, Education, and Welfare, Public Health Service, Pacific Northwest Water Laboratory, Corvallis, Oregon, November 7, 1963.

Elliott, J.W. 1969. The oxygen requirements of Chinook salmon. Progressive Fish-Culturist 31(2):67-73.

Emadi, H. 1972. Yolk-Sac Malformation in Pacific Salmon: Annual Report 1971-72. Oregon Cooperative Fishery Research Unit; 1 pp.

Emadi, H. 1973. Yolk-Sac Malformation in Pacific Salmon in Relation to Substrate, Temperature, and Water Velocity. Journal of the Fisheries Research Board of Canada 30(8):1249-1250.

Engelking, H.M. and J.C. Leong. 1981. IHNV persistently infects Chinook salmon embryo cells. Virology, 109(1), 47-58.

Envirocon Limited and E.V.S. Consultants Limited. 1983. Studies on the fish pathogen *Ceratomyxa shasta*; its effects on Chinook salmon of the Fraser System. I. Stock resistance and salinity testing. Supply Serv. Canada 1906/WP 1377. 48 pp.

Envirocon Limited and E.V.S. Consultants Limited. 1983. Studies on the fish pathogen *Ceratomyxa shasta*: its effects on Chinook salmon of the Fraser system. II. Seasonal testing. Supply Serv. Canada 1906/WP 1443. 22 pp.

Estes, C., K. Hepler, and A. Hoffmann. 1981. Willow and Deception Creeks Instream Flow Demonstration Study. Alaska Department of Fish and Game 1: 144 pp.

Everest, F.H., JR. 1971. Ecological and Fish Cultural Study of Steelhead Trout: An Ecological and Fish Cultural Study of Summer Steelhead in the Rogue River, Oregon. Oregon State Game Commission; 50 pp.

Everts, C.M. 1963. Temperature as a water quality parameter. Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Corvallis, Oregon, November 7, 1963. Water temperature influences, effects and control; Nov, pp. 2-5.

Ewing, R.D., B.P. McPherson, and T.D. Satterthwaite. 1990. Effects of varied rearing temperatures and feeding regimes on retention of Bismarck Brown Y stain in alevins of Chinook salmon. Progressive Fish-Culturist 52(4):231-236.

Ewing, R.D., H.J. Pribble, S.L. Johnson, and J.A. Lichatowich. 1979. Temperature and Photoperiod Effects on Gill (NA + K)-atpase Activity in Chinook Salmon (Oncorhynchus tshawytscha). Canada. Fisheries Research Board 36(11):1347-1353.

Fairgrieve, W.T., Jr. 1983. An Epidemiological Examination of the Role of Nutritional and Environmental Factors in the Development of Spring Mortality Syndrome in Chinook Salmon Alevins. M.S. Thesis, University of Idaho; 52 pp.

Falter, C.M. and R.R. Ringe. 1974. Pollution Effects on Adult Steelhead Migration in the Snake River. EPA-660/3-73-017, 101 pp

Fast, A.W., F.M. D'itri, D.K. Barclay, S.A. Katase, and C. Madenjian. 1990. Heavy Metal Contents of Coho *Oncorhynchus kisutch* and Chinook Salmon *O. tschawytscha* Reared in Deep Upwelled Ocean Waters in Hawaii. World Aquaculture Society Journal 21(4):271-276.

Field-Dodgson, M.S. 1988. Size characteristics and diet of emergent Chinook salmon in a small, stable, New Zealand stream. Journal of Fish Biology 32(1):27-40.

Fisher, J.P. and W.G. Pearcy. 1995. Distribution, migration, and growth of juvenile Chinook salmon, *Oncorhynchus tshawytscha*, off Oregon and Washington. Fishery Bulletin 93(2):274-289.

Foott, J.S., A. Miller, R. Steiner, and R.P. Hedrick. 1992. Erythrocytic inclusion body syndrome (EIBS) infection of Chinook salmon in Idaho. Journal of Aquatic Animal Health 4(4):306-308.

Foster, R.F. 1970. Effects of Hanford Reactors on Columbia River and Adjacent Land Areas. Report for Battelle Memorial Inst., Richland, WA, Pacific Northwest Labs. 48 P.

Fowler, L.F. 1983. Effect of Dietary Protein and Energy on Growth and Survival of Fall Chinook Salmon Fry. Progressive Fish-Culturist 45(2):128-129.

Fowler, L.G., E. Burrows, D. Combs, and J.L. Banks. 1980. Effect of Two Rearing Environments on the Survival of Adult Fall Chinook Salmon. U.S. Fish and Wildlife Service, Abernathy Salmon Cult. Dev. Cent. Technol. Transfer Ser. No. 80-4; 13 pp.

Fowler, L.G., J.L. Banks, and J.W. Elliott. 1972. Tests of Variations of the Abernathy Salmon Diet, 1970. U S Bur Sport Fish Wildl Tech Paper 61:3-13.

Franklin, C.E., W. Davison, and M.E. Forster. 1992. Seawater adaptability of New Zealand's sockeye (*Oncorhynchus nerka*) and Chinook salmon (*O. tshawytscha*): physiological correlates of smoltification and seawater survival. Aquaculture 102(1/2):127-142.

Fraser, F.J., E.A. Perry, and D.T. Lightly. 1983. Big Qualicum River salmon development project, Volume 1: A biological assessment, 1959-1972. Can. Tech. Rep. Fish. Aquat. Sci. 1189: 216 pp.

Frederiksen, Kamine and Associates, Sacramento, CA. 1980. Proposed Trinity River Basin Fish and Wildlife Management Program, Appendix C, Fish and Wildlife Analysis, Final, Volume 1. Report prepared for Water and Power Resources Service, 389 pp.

Fryer, J.L., K.S. Pilcher, J.E. Sanders, J.S. Rohover, and J.L. Zinn. 1976. Temperature, Infectious Diseases, and the Immune Response in Salmonid Fish. Environmental Protection Agency, Report EPA 600/3-76-021, 72 pp.

Fryer, J.L. and K.S. Pilcher. 1974. Effects of Temperature on Diseases of Salmonid Fishes. Environmental Protection Agency, Ecological Research Series Report EPA-660/3-73-020, 114 pp.

Fujihara, M.P., P.A. Olson, and R.E. Nakatani. 1971. Some Factors in Susceptibility of Juvenile Rainbow Trout and Chinook Salmon to *Chondrococcus columnaris*. Canada Fisheries Research Board Journal 28(11):1739-1743.

Fukuwaka, M.and I. Yukimasa. 2000. Ocean condition and Pacific salmon stock assessment in the North Pacific Ocean, 2000. NPAFC Doc. 481: 9 pp.

Garling, D.L., Jr. and M. Masterson. 1985. Survival of Lake Michigan Chinook Salmon Eggs and Fry Incubated at Three Temperatures. Progressive Fish-Culturist 47(1):63-66.

Garton, R.R. and A.V. Nebeker. 1977. A Multiple Approach to Solving the Gas Supersaturation Problem. Recent Advances in Fish Toxicology, Environmental Protection Agency, Ecological Research Series EPA 600/3-77-085, pp 4-19.

Gauldie, R.W. 1996. Effects of temperature and vaterite replacement on the chemistry of metal ions in the otoliths of *Oncorhynchus tshawytscha*. Canadian Journal of Fisheries and Aquatic Sciences 53(9):2015-2026.

Gauldie, R.W. 1991. The Morphology and Periodic Structures of the Otolith of the Chinook Salmon (Oncorhynchus tshawytscha), and Temperature-Dependent Variation in Otolith Microscopic Growth Increment Width. Acta Zoologica 72(3):159-179.

Gauldie, R.W., D.A. Fournier, D.E. Dunlop, and G. Coote. 1986. Atomic emission and proton microprobe studies of the ion content of otoliths of Chinook salmon aimed at recovering the temperature life history of individuals. Comparative Biochemistry and Physiology, A. 84A(4):607-615.

Gauldie, R.W. 1985. Vaterite Otoliths from Chinook Salmon (*Oncorhynchus tshawytscha*). New Zealand Journal of Marine and Freshwater Research 20(2):209-217.

Gebhards, S.V. 1961. Emergence and mortality of Chinook salmon fry in a natural redd. Progressive Fish-Culturist 23(2):91.

Gedamu, L., B. Culham, and J.J. Heikkila. 1983. Analysis of the temperature-dependent temporal pattern of heat-shock-protein synthesis in fish cells. Bioscience Reports 3(7):647-658.

Geen, G.H. 1975. Ecological Consequences of the Proposed Moran Dam on the Fraser River. Journal of the Fisheries Research Board of Canada 32(1):126-135.

Geen, G.H. 1974. Effects of Hydroelectric Development in Western Canada on Aquatic Ecosystems. Journal of Canada. Fisheries Research Board 31(5):913-927.

Geist, D.R. 2000. Hyporheic discharge of river water into fall Chinook salmon (*Oncorhynchus tshawytscha*) spawning areas in the Hanford Reach, Columbia River. Canadian Journal of Fisheries and Aquatic Sciences 57(8):1647-1656.

George, A. 1989. Investigation of salmonid erythrocytes comparative and smoltification-associated characteristics. Dissertation Abstracts International Part B: Science and Engineering 49(11): 365 pp.

Gilderhus, P.A., J.L. Allen, T.D. Bills, and G.E. Howe. 1990. Investigations in fish control. (100, 101, and 102). National Fishery Research Lab., La Crosse, WI (USA), 12 pp.

Gilderhus, P.A. 1989. Efficacy of benzocaine as an anesthetic for salmonid fishes. North American Journal of Fisheries Management 9(2):150-153.

Giorgi, A.E., T.W. Hillman, J.R. Stevenson, S.G. Hays, and C.M. Peven. 1997. Factors that influence the downstream migration rates of juvenile salmon and steelhead through the hydroelectric system in the mid-Columbia River basin. North American Journal of Fisheries Management 17(2):268-282.

Glude, J.B. 1978. The Pacific and Atlantic Salmon Genera *Oncorhynchus* and *Salmo*. A Literature Review and Analysis of the Use of Thermal Effluent in Culture of Pacific and Atlantic Salmon. John B. Glude Aquaculture Consultant, Report, pp. 1-66.

Goldstein, J.N., D.F. Woodward, and A.M. Farag. 1999. Movements of adult Chinook salmon during spawning migration in a metals-contaminated system, Coeur d'Alene River, Idaho. American Fisheries Society. Transactions 128(1):121-129.

Goyke, A.P. and S.B. Brandt. 1993. Spatial models of salmonine growth rates in Lake Ontario. Transactions of the American Fisheries Society 122:870-883.

Grabowski, S.J. 1973. Effects of Fluctuating and Constant Temperatures on Some Hematological Characteristics, Tissue Glycogen Levels, and Growth of Steelhead Trout (*Salmo gairdneri*). Ph.D. Dissertation, University of Idaho; 77 pp.

Gray, D.M. 1970. Snow Hydrology of the Prairie Environment. In: Snow Hydrology, Proceedings of Workshop Seminar at New Brunswick University, Frederiction, February 28-29, 1969; Published by Secretariat, Canadian National Committee for the International Hydrological Decade, Ottawa, pp 21-33.

Gray, R.H. 1990. Fish Behavior and Environmental Assessment. Environmental Toxicology and Chemistry 9(1):53-67.

Gray, R.H., R.G. Enoway, and S.A. Barraclough. 1977. Behavior of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in Relation to Simulated Thermal Effluent. American Fisheries Society. Transactions 106 (4):366-370.

Greenbank, J.D., S.L. Rendek, and I.K. Birtwell. 2001. Salmonid migration in tributaries of Port Moody Arm, Burrard Inlet, BC. Can. Manuscr. Rep. Fish. Aquat. Sci. 2557: 46 pp.

Greulich, R. 1994. Propagating the Pisces. Conservationist 48(3):18-21.

Groberg, W.J., Jr., S.T. Onjukka, and N.L. Hurtado. 1994. Elevated water temperature therapy for clinical erythrocytic inclusion body syndrome in juvenile spring Chinook salmon (*Oncorhynchus tshawytscha*). High Performance Fish: Proceedings of an International Fish Physiology Symposium at the University of British Columbia, Vancouver, Canada, July 1994. Fish Physiology Association, Vancouver, BC (Canada), 1994, pp. 470-475.

Groberg, W.J., Jr., R.H. McCoy, K.S. Pilcher, and J.L. Fryer. 1978. Relation of water temperature to infections of coho salmon *Oncorhynchus kisutch*, Chinook salmon *O.tshawytscha*, and steelhead trout *Salmo gairdneri* with *Aeromonas salmonicida* and *A. hydrophila*. J. Fish. Res. Board Can., 35(1):1-7.

Groves, P.A. and J.A. Chandler. 1999. Spawning habitat used by fall Chinook salmon in the Snake River. North American Journal of Fisheries Management 19(4):912-922.

Gun'kovskij, S.A. and G.A. Khudolej. 1989. Lerneosis in cultured salmons. Vestnik Zoologii/Zoological Record 1:65-67.

Hahn, P.K.J. 1978. Effects of Fluctuating and Constant Temperatures on Behavior or Steelhead Trout (*Salmo gairdneri*). Ph.D. Dissertation, University of Idaho; 142 pp.

Hale, S.S. 1987. Time-series analysis of discharge, turbidity, and juvenile salmon outmigration in the Susitna River, Alaska. Common Strategies of Anadromous and Catadromous Fishes. Proceedings of an International Symposium held in Boston, Massachusetts, 9-13 March 1986, Am. Fish. Soc. Symp. Ser. 1:554.

Hallock, R.J., R.F. Alwell, and D.H. Fry, Jr. 1970. Migrations of Adult King Salmon *Oncorhynchus tshawytscha* in the San Joaquin Delta as Demonstrated by the Use of Sonic Tags. Calif. Dep. Fish Game Fish. Bull. 151: 92 pp.

Hamel, O.S. 2002. The dynamics and effects of bacterial kidney disease in Snake River spring Chinook salmon (*Oncorhynchus tshawytscha*). PhD Dissertation, University of

Washington. Dissertation Abstracts International Part B: Science and Engineering 62(12):5446.

Hamlin, D.J. 1993. The Potential for Natural Reproduction of Chinook Salmon in the Chippewa River, Isabella County, Michigan. M.S. Thesis, Central Michigan University; 80p.

Hanavan, M.G. and G.K. Tanonaka. 1956. Experimental Fishing to Determine Distribution of Salmon in the North Pacific Ocean and Bering Sea, 1956. U.S. Fish and Wildlife Service; 26 pp.

Harding, M. 1994. The wild and scenic Grand. Explorer 36(1):8-9.

Hargis, M.T. 1999. Stress Proteins As Molecular Biomarkers To Monitor Stress in Chinook Salmon (*Oncorhynchus tshawytscha*). PhD Dissertation. Dissertation Abstracts International Part B: Science and Engineering 60(1):57.

Harrahy, L.N., C.B. Schreck, and A.G. Maule. 2001. Antibody-producing cells correlated to body weight in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) acclimated to optimal and elevated temperatures. Fish & Shellfish Immunology 11(8):653-659.

Harvey, B.C., J.L. White, and R.J. Nakamoto. 2002. Habitat relationships and larval drift of native and nonindigenous fishes in neighboring tributaries of a coastal California River. American Fisheries Society Transactions 131(1):159-170.

Havis, R.N., C.V. Alonso, J.G. King, and R.F. Thurow. 1992. Gravel siltation mechanisms in salmonid spawning habitat. Sediment Management, 5th International Symposium on River Sedimentation, Karlsruhe, 1992. Proceedings II:1085-1091.

Havis, R.N., C.V. Alonso, J.G. King, and R.F. Thurow. 1993. A mathematical model of salmonid spawning habitat. Water Resources Bulletin 29(3):435-444.

Hay, C.H. 1990. The distribution of Macrocystis (*Phaeophyta: Laminariales*) as a biological indicator of cool sea surface temperature, with special reference to New Zealand waters. Journal of the Royal Society of New Zealand 20(4):313-336.

Haynes, J.M., D.C. Nettles, K.M. Parnell, M.P. Voiland, R.A. Olson, and J.D. Winter. 1986. Movements of Rainbow Steelhead Trout (*Salmo gairdneri*) in Lake Ontario and a Hypothesis for the Influence of Spring Thermal Structure. Journal of Great Lakes Research 12(4):304-313.

Haynes, J.M. 1983. Finding Salmon and Trout in Lake Ontario. Water Spectrum 15(1):30-37.

Heath, D.D., R.H. Devlin, J.W. Heath, and G.K. Iwama. 1994. Genetic, environmental and interaction effects on the incidence of jacking in *Oncorhynchus tshawytscha* (Chinook salmon). Heredity 72(2):146-154.

Heath, D.D., N.J. Bernier, J.W. Heath, and G.K. Iwama. 1993. Genetic, environmental, and interaction effects on growth and stress response of Chinook salmon (*Oncorhynchus tshawytscha*) Fry. Canadian Journal of Fisheries and Aquatic Sciences 50(2):435-442.

Heikkila, J.J., G.A. Schultz, K. Iatrou, and L. Gedamu. 1982. Expression of a set of fish genes following heat or metal ion exposure. , The Journal Of Biological Chemistry 257(20):12000-12005.

Heikkila, J.J., L.W. Browder, L. Gedamu, R.W. Nickells, and G.A. Schultz. Heat-shock gene expression in animal embryonic systems. Canadian Journal Of Genetics And Cytology 28(6):1093-1105.

Heming, T.A., J.E. McInerney, and D.F. Alderdice. Effect of temperature on initial feeding in alevins of Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 39(12):1554-1562.

Heming, T.A. 1982. Effects of Temperature on Utilization of Yolk by Chinook Salmon (*Oncorhynchus tshawytscha*) Eggs and Alevins. Canadian Journal of Fisheries and Aquatic Sciences 39(1):184-190.

Hemmingsen, A.R., E.K. Birks, J.L. Dentler, and R.D. Ewing. 1982. Hatchery Practices. Oregon Department of Fish and Wildlife; 31 pp.

Henriette, I.J., H.E. Cardwell, M.J. Sale, M.S. Bevelhimer, C.C. Coutant, and W.Van Winkle. 1997. Modeling the linkages between flow management and salmon recruitment in rivers. Ecological Modeling 103(2-3):171-191.

Higley, D.L. and C.E. Bond. 1973. Ecology and Production of Juvenile Spring Chinook Salmon, *Oncorhynchus tshawytscha*, in a Eutrophic Reservoir. NOAA Fishery Bulletin 71(3):877-891.

Hillman, T.W., J.W. Mullan, and J.S. Griffith. 1992. Accuracy of underwater counts of juvenile Chinook salon, coho salmon, and steelhead. North American Journal of Fisheries Management 12(3):598-603.

Hillman, T.W., W. Chapman, and J.S. Griffith. 1989. Seasonal Habitat Use and Behavioral Interaction of Juvenile Chinook Salmon and Steelhead. I: Daytime Habitat Selection. Summer and Winter Ecology of Juvenile Chinook Salmon and Steelhead Trout in the Wenatchee River, Washington. Final Report to Chelan County Public Utility District, Washington, June 1989. Don Chapman Consultants, Inc.; pp. 42-82.

Hillman, T.W. 1987. Summer and Winter Habitat Selection by Juvenile Chinook Salmon in a Highly Sedimented Idaho Stream. M.S. Thesis, Idaho State University; 40 pp.

Holmes, B. 1995. Saving Snake River's Wild Salmon. New Scientist 146(1974):14-15.

Holt, R.A., Amandi, S. Rohovec, and J.L. Fryer. 1989. Relation of Water Temperature to Bacterial Cold-Water Disease in Coho Salmon, Chinook Salmon, and Rainbow Trout. Journal of Aquatic Animal Health 1(2):94-101.

Holt, R.A., J.E. Sanders, J.L. Zinn, J.L. Fryer, and K.S. Pilcher. 1975. Relation of water temperature to Flexibacter columnaris infection in steelhead trout (*Salmo gairdneri*), coho (*Oncorhynchus kisutch*) and Chinook (*O.tshawytscha*) salmon. J. Fish. Res. Board Can. 32(9):1553-1559.

Homolka, K. and T.W. Downey. 1995. Assessment of thermal effects on salmon spawning and fry emergence, upper McKenzie River, 1992. Informational Report, Fish Division, Oregon Dept. Fish & Wildlife 95-4:38 pp.

Horne, B.D., E.S. Rutherford, and K.W. Wehrly. 2001. Simulating ecological and economic effects of temperature regime restoration on steelhead production in a Lake Michigan tributary. American Fisheries Society Annual Meeting 131, p. 214.

Horne, B. 2000. Temperature and steelhead production. 62nd Midwest Fish and Wildlife Conference, Minneapolis, MN, 3-6 Dec 2000. Minnesota Cooperative Fish and Wildlife Research Unit, Minneapolis, MN.

Horns, W.H. and E.J. Hammer. 1991. Incidental Catch of Salmonids in Commercial Gill Nets in Illinois. Illinois Natural History Survey. Aquatic Ecology Technical Report 91/14; 36 pp.

Hostetler, S.W. 1991. Analysis and modeling of long-term stream temperatures on the Steamboat Creek Basin, Oregon: Implications for land use and fish habitat. Water Resources Bulletin 27(4):637-648.

Hubert, W.A., K.L. Grannemann, J.M. Wyatt, R.S. Pile, C.E. Madewell, and J.B. Glude. 1978. Waste Heat Utilization for Agriculture and Aquaculture. State of the Art, Section 9. – Aquaculture. Tennessee Valley Authority and Electric Power Research Institute, pp. 1-133.

Hughes, R.M. and G.E. Davis. 1986. Production of Coexisting Juvenile Coho Salmon and Steelhead Trout in Heated Model Stream Communities. Community Toxicity Testing. A Symposium Sponsored by ASTM Committee D-19 on Water, Colorado Spring, Colorado May 6-7, 1985. ASTM Special Technical Publication 920:322-337.

Hughes, R.M., G.E. Davis, and E. Warren. 1978. Temperature Requirements of Salmonids in Relation to Their Feeding, Bioenergetics, Growth and Behavior. Oregon Water Resources Research Institute Completion Report, OWRT B-041-ORE(1), 40 pp.

Hutchison, J.M. and W.W. Aney. 1964. Fisheries Stream Flow Requirements: Fish and Game Resources of the Lower Willamette Basin, Oregon, and Their Water Use Requirements. Fish Resources. Oregon State Game Commission; pp. 46-60, 77-136.

Ignell, S. 1991. Zonal variability in salmonid driftnet catch rates in the central North Pacific Ocean. Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone. Selected Papers from the North Pacific Transition Zone Workshop held in Honolulu, Hawaii, 9-11 MAY 1988. NOAA TECH. REP., pp. 89-96.

Jacobs, S.E., W.T. Noll, and J.D. Rodgers. Increase in Growth of Juvenile Spring Chinook Salmon (Oncorhynchus tshawytscha) Rearing Immediately Below Lost Creek Dam on the Rogue River. Oregon Department of Fish and Wildlife. Information Report No. 84-6; 16 pp.

Jager, H.I., H.E. Cardwell, M.J. Sale, M.S. Bevelhimer, C.C. Coutant, and W. Van Winkle. 1997. Modeling the linkages between flow management and salmon recruitment in rivers. Ecological Modeling 103(2-3):171-191.

Jensen, J.O.T. and M.E. Jensen. 1999. IncubWin: A new Windows 95/98/NT computer program for predicting embryonic stages in Pacific salmon and steelhead trout. Aquaculture Canada 99(4):28-30.

Jensen, J.O.T. and E.P. Groot. 1991. The effect of moist air incubation conditions and temperature on Chinook salmon egg survival. Fisheries Bioengineering Symposium 10, Bethesda, MD, pp. 529-538, American Fisheries Society Symposium.

Jensen, J.O.T. 1988. A microcomputer program for predicting embryonic development in Pacific salmon and steelhead trout. Proceedings of Aquaculture International Congress and Exposition, Vancouver, British Columbia, Canada, 6-9 September 1988, p. 78.

Jensen, J.O.T., J. Schnute, and D.F. Alderdice. 1986. Assessing juvenile salmonid response to gas supersaturation using a general multivariate dose-response model. Canadian Journal of Fisheries and Aquatic Sciences 43(9):1694-1709.

Jensen, J.O.T. and D.F. Alderdice. 1984. Effect of Temperature on Short-Term Storage of Eggs and Sperm of Chum Salmon (*Oncorhynchus keta*). Aquaculture 37(3):251-265.

Jensen, J.O.T. 1981. Some spawning and incubation conditions that affect salmonid gamete viability and embryo development. Salmonid Broodstock Maturation. Proceedings of Workshops held at Seattle, Washington, May 20-22, 1980, and March 11, 1981. Publ. Wash. Sea Grant, pp. 50-53.

Jerrett, A.R., R.A. Law, and A.J. Holland. 2000. Optimum postmortem chilled storage temperature for summer and winter acclimated, rested, Chinook salmon (*Oncorhynchus tshawytscha*) white muscle. Journal of Food Science 65(5):750-755.

Jerrett, A.R., A.J. Holland, and S.E. Cleaver. 1998. Rigor contractions in "rested" and "partially exercised" Chinook salmon white muscle as affected by temperature. Journal of Food Science 63(1):53-56.

Johnson, H.E. and R.J. Brice. 1953. Use of impounded water for fish culture. U.S. Department of the Interior: Fish and Wildlife Service, Research Report Issue 35:1-35.

Johnson, J.H. and J.E. McKenna, J.E. 2000. Longitudinal distribution of salmonid production in Lake Ontario tributaries. International Association for Great Lakes Research Conference Program and Abstracts, pp. A-72-83.

Johnson, S.C., G.A. Chapman, and D.G. Stevens. 1983. Sensitivity of steelhead trout embryos to handling. Progressive Fish-Culturist 45(2):103-104.

Johnson, S.L. 1988. The Effects of the 1938 El Nino on Oregon's Coho (*Oncorhynchus kisutch*) and Chinook (O. tshawytscha) Salmon. Fisheries Research 6(2):105-123.

Johnsson, J.I., W.C. Clarke, and J. Blackburn. 1994. Hybridization with domesticated rainbow trout reduces seasonal variation in seawater adaptability of steelhead trout (*Oncorhynchus mykiss*). Aquaculture 121(1-3):73-77.

Johnsson, J. and W.C. Clarke. 1988. Development of seawater adaptation in juvenile steelhead trout (*Salmo gairdneri*) and domesticated rainbow trout (*Salmo gairdneri*)-effects of size, temperature and photoperiod. Aquaculture 71(3):247-263.

Jones, W.E. 1980. Summer Steelhead (Salmo gairdneri) in the Middle Fork Eel River and Their Relationship to Environmental Changes, 1966 through 1978. CA Dept. of Fish and Game; 25 pp.

Julin, A.M. and H.O. Sanders. 1977. Toxicity and Accumulation of the Insecticide Imidan in Freshwater Invertebrates and Fishes. Transactions: American Fisheries Society 106(4):386-392.

Junge, C.O. and L.A. Phinney. 1963. Factors influencing the return of fall Chinook salmon (*Oncorhynchus tshawytscha*) to Spring Creek Hatchery. U.S. Fish and Wildlife Service Issue 445:1-32.

Katzman, S.M. 2002. Swimming performance and muscle function in juvenile California salmon: Hormonal and temperature influences during the transition from freshwater to seawater. PhD Dissertation. University of California, Davis. Dissertation Abstracts International Part B: Science and Engineering 62(7):3020.

Katzman, S.M. and J.J. Cech, Jr. 1999. Temperature and flow effects on juvenile salmon swimming and muscle dynamics: Research in progress. Fish Performance Studies: pp. 97-100.

Kent, M. L., and R. P. Hedrick. 1985. PKX, the causative agent of proliferative kidney disease (PKD) in Pacific salmonid fishes and its affinities with the Myxozoa. The Journal Of Protozoology 32(2):254-260.

Kerr, J.E. 1953. Studies on Fish Preservation at the Contra Costa Steam Plant of the Pacific Gas and Electric Company. CA Dept. of Fish and Game; 67 pp.

Kinnison, M.T., M.J. Unwin, W.K. Hershberger, and T.P. Quinn. 1998. Egg size, fecundity, and development rate of two introduced New Zealand Chinook salmon (*Oncorhynchus tshawytscha*) populations. Canadian Journal of Fisheries and Aquatic Sciences 55(8):1946-1953.

Kiryu, Y. and C.M. Moffitt. 2002. Models of comparative acute toxicity of injectable erythromycin in four salmonid species. Aquaculture 211(1-4):29-41.

Kjelson, M.A. and P.L. Brandes. 1989. The use of smolt survival estimates to quantify the effects of habitat changes on salmonid stocks in the Sacramento-San Joaquin Rivers, California. Proceedings of The National Workshop on Effects of Habitat Alteration on Salmonid Stocks, Can. Spec. Publ. Fish. Aquat. Sci.105:100-115.

Kocan, R.M. and P.K. Hershberger. 2001. Ichthyophonus causes serious disease in Yukon River Chinook salmon. American Fisheries Society Annual Meeting 131:64.

Kope, R.G. and L.W. Botsford. 1990. Determination of factors affecting recruitment of Chinook salmon *Oncorhynchus tshawytscha* in central California. Fishery Bulletin 88(2):257-269.

Kopperdahl, F.R., J.W. Burns, and G.E. Smith. 1971. Coastal Salmon and Steelhead Study: Water Quality of Some Logged and Unlogged California Streams. CA Dept. of Fish and Game; 18 pp.

Kreiberg, H. 1991. Effect of ration level and water temperature on growth and conversion efficiency in Chinook salmon in seawater. World Aquaculture 22(1):84-85.

Kreiberg, H. 1990. Salmonid growth under different environmental conditions: Toward a general growth model for Chinook salmon. Proceedings of Canada-Norway Finfish Aquaculture Workshop, 11-14 September 1989, Can. Tech. Rep. Fish. Aquat. Sci. 1761:133-136.

Kucera, P.A. and D.B. Johnson. 1986. Biological and Physical Inventory of the Streams within the Nez Perce Reservation: Juvenile Steelhead Survey and Factors that Affect Abundance in Selected Streams in the Lower Clearwater River Basin, Idaho. Nez Perce Tribe Lapwai, ID. Fisheries Resource Management. DOE Report No. DOE/BP/10068--T1, 252 pp.

Larsen, D.A., S. Moriyama, W.W. Dickhoff, and B.R. Beckman. 1995. Endocrine and growth control of salmon smoltification. Aquaculture 135(1-3):147.

Larson, D.W. 1984. Effectiveness of Reservoir Releases to Provide River Temperatures and Flows Optimal for Pacific Salmon and Steelhead Trout in the Pacific Northwest. U.S.A. Regulated Rivers. Albert Lillehammer and Svein Jakob Saltveit, editors; p. 365-385.

Leitritz, E. and R.C. Lewis. 1976. Trout and Salmon Culture: Trout and Salmon Diseases. California Department of Fish and Game. Fish Bulletin 164:138-160.

Leman, V.N. 1988. Classification of spawning grounds of salmons of the genus Oncorhynchus on the basis of filtration and thermal characteristics of ground in the Kamchatka River basin. J. Ichthyol. 28(5):754-763.

Levanduski, M.J., J.C. Beck, and J.E. Seeb. 1990. Optimal thermal shocks for induced diploid gynogenesis in Chinook salmon (*Oncorhynchus tshawytscha*). Aquaculture 90(3-4):239-250.

Levin, A.A., T.J. Birch, R.E. Hillman, and G.E. Raines. 1970. A Comprehensive Appraisal of the Effects of Cooling Water Discharge on Aquatic Ecosystems. Report for Battelle Memorial Inst., Columbus, OH. Columbus Labs. 45 pp.

Levy, D.A. and C.D. Levings. 1978. A description of the fish community of the Squamish River estuary, British Columbia: relative abundance, seasonal changes, and feeding habits of salmonids. Manuscr. Rep. Fish. Mar. Serv. (Can.) 1475: 67 pp.

Li, H.W., C.B. Schreck, and R.A. Tubb. Comparison of Habitats Near Spur Dikes, Continuous Revetments, and Natural Banks for Larval, Juvenile, and Adult Fishes of the Willamette River. Water Resources Research Institute Publication WRRI-95, 15 pp.

Lieberman, D.M., M.J. Horn, S. Duffy. 2001. Effects of a temperature control device on nutrients, POM and plankton in the tailwaters below Shasta Lake, California. Hydrobiologia 452(1-3):191-202.

Lieberman, D.M., D.A. Sisneros, M.J. Horn, C.B. Stalnaker, C.R. Liston, R.W. Bachmann, J.R. Jones, R.H. Peters, and D.M. Soballe (eds). 1995. Effects of a temperature control device on limnology of Shasta Reservoir, California: Preoperational ecology study of a western reservoir. Lake and Reservoir Management 11(2):161.

Loeffelman, P.H., D.A. Klinect, and J.H. Van Hassel. 1991. Fish protection at water intakes using a new signal development process and sound system. Waterpower 91 New View Hydro Resources, ASCE, New York, NY, (USA), pp. 355-365.

Longenbaugh, M.H. and J.R. Chan. 1994. Fisheries Investigations on Blue Creek, Tributary to Klamath River, Northern California: Final Progress Report FY 1993. U.S. Fish and Wildlife Service, 64 pp.

MacDonald, J.S., I.K. Birtwell, and G.M. Kruzynski. 1987. Food and Habitat Utilization by Juvenile Salmonids in the Campbell River Estuary. Canadian Journal of Fisheries and Aquatic Sciences 44(6):1233-1246.

MacFarlane, R.B. and E.C. Norton. 2002. Physiological ecology of juvenile Chinook salmon (Oncorhynchus tshawytscha) at the southern end of their distribution, the San Francisco Estuary and Gulf of the Farallones, California. Fishery Bulletin 100(2):244-257.

MacFarlane, R.B., S. Ralston, C. Royer, and E.C. Norton. 2002. Influences of the 1997-1998 El Nino and 1999 La Nina on juvenile Chinook salmon in the Gulf of the Farallones. North Pacific Marine Science Organization: PICES Scientific Report 20:25-29.

MacKinlay, D.D. and R.F. Fielden. 1987. Rearing of Chinook salmon (*Oncorhynchus tshawytscha*) in cold water: Kalum Pilot Hatchery experiences 1980-1983. Can. Manuscr. Rep. Fish. Aquat. Sci. 1943:52 pp.

MacPhee, C. and F. Cheng. 1974. Development of Selective Fish Toxins: Factors Affecting Degradation of Squoxin and Toxicity of Squoxin to Six Fish Species. Idaho Fish and Game Dept.; 35 pp.

Mahnken, C.V.W. 1975. Salmon Farming, An Emerging Industry. The Commercial Fish Farmer and Aquaculture News 2(1):6-11.

Margolis, L., T.E. McDonald, and D.J. Whitaker. 1992. Assessment of the impact of the myxosporean parasite Ceratomyxa shasta on survival of seaward migrating juvenile Chinook salmon, *Oncorhynchus tshawytscha*, from the Fraser River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 49(9):1883-1889.

Martenson, G.A. and D. Dauble. 1994. Evaluation of water sources for the artificial production of anadromous salmonids. Northwest Science 68(2):137.

Martin, R.M., A.C. Wertheimer, F. Thrower, and J.E. Joyce. 2001. Growth and survival of Alaska stream-type Chinook salmon cultured in estuarine net-pens or freshwater raceways. North American Journal of Aquaculture 63(3):256-261.

Mauck, W.L. and L.E. Olson. 1976. Toxicity of natural pyrethrins and five pyrethroids to fish. Archives of Environmental Contamination and Toxicology 4(1):18-29.

Maxwell, J. 1995. Swimming with salmon. Natural History 104(9):26-36.

Mayo, R.D. 1971. Appendix A. Hatchery Design and Operating Information. Aquaculture - A New England Perspective, NEMRIP Sea Grant, Univ. R.I.; pp. 71-83.

McDonald, M.E., C.A. Tikkanen, R.P. Axler, C.P. Larsen, and G. Host. 1996. Fish Simulation Culture Model (FIS-C): A Bioenergetics Based Model for Aquacultural Wasteload Application. Aquacultural Engineering 15(4):243-259.

McHugh, P.A. and P. Budy. 2001. A model-based approach to assessing the potential response of selected Snake River spring/summer Chinook salmon populations to spawning and rearing habitat improvements. American Fisheries Society Annual Meeting 131:20.

McIntosh, B.A. and H.W. Li. 1998. Klamath Basin Pilot Project: Coldwater Refugia Study and Videography. Oregon Coop. Fish Res. Unit. Final Report, 22 pp.

McLean, R.F. and J.A. Raymond, 1983. Chandalar-Christian Rivers Area Fisheries Rehabilitation and Enhancement Study. Alaska Department of Fish and Game, Div. Fisheries Rehabilitation, Enhancement & Development (FRED) Report No. 13; 58 pp.

McLean, W.E., J.O.T. Jensen, and P.J. Rombough. 1991. Microcomputer models for salmonid hatcheries. Fisheries Bioengineering Symposium 10, Bethesda, MD, pp. 516-528, American Fisheries Society Symposium.

Meadors, P.I. 1978. Weyerhaeuser 's Raising Salmon -- Uses Mill Cooling Water at Hatchery. Pulp and Paper 42(12):148-149.

Merrell, T.R., M.D. Collins, and J.W. Greenough. 1971. An Estimate of Mortality of Chinook Salmon in the Columbia River Near Bonneville Dam During the Summer Run of 1955. US Fish Wild Serv Fish Bull. 68(3):461-492.

Merz, J.E. 2002. Comparison of diets of prickly sculpin and juvenile fall-run Chinook salmon in the lower Mokelumne River, California. Southwestern Naturalist 47(2):195-204.

Milhous, R.T. and K.D. Bovee. 1978. The Stochastic Variation of Instream Values in Rivers Verification of Mathematical and Physical Models in Hydraulic Engineering. Proceedings of the 26th Annual Hydraulics Division Specialty Conference, Maryland University, College Park , MD. August 9-11, 1978, p 630-637.

Miller, K.A. and D.L. Fluharty. 1991. Societal impacts of El Nino and variability in the Northeast Pacific salmon fishery. Northwest Environ. I. 7(2):366-368.

Miller, W. and D.W. Chapman. 1970. Salmon and Steelhead Investigations: Downstream Emigration of Chinook Salmon Fry. Idaho Fish and Game Dept.; 50 pp.

Miller, W.H. 1970. Factors Influencing Migration of Chinook Salmon Fry (*Oncorhynchus tshawytscha*) in the Salmon River, Idaho. Ph.D. Dissertation, Univ. Idaho; 80 pp.

Mitchell, A.C., C.B. James, and J.E. Edinger. 1995. Analyses of flow modification on water quality in Nechako River. Journal of Energy Engineering 121(2):73-80.

Moring, J.R. 1975. Alsea Watershed Study: Effects of Logging on the Aquatic Resources of Three Headwater Streams of the Alsea River, Oregon. Part III – Discussion and Recommendations. Oregon Dept. of Fish and Wildlife; 26 pp.

Morrill, C.F. and T.C. Bjornn. 1972. Migration Response of Juvenile Chinook Salmon to Substrates and Temperatures. Idaho Water Resources Research Institute, Moscow, Completion Report, 27 pp.

Muir, W.D., A.E. Giorgi, and T.C. Coley. Behavioural and physiological changes in yearling Chinook salmon during hatchery residence and downstream migration. Aquaculture 127(1):69-82.

Muir, W.D., W.S. Zaugg, A.E. Giorgi, and S. McCutcheon. 1994. Accelerating smolt development and downstream movement in yearling Chinook salmon with advanced photoperiod and increased temperature. Aquaculture 123(3-4):387-399.

Muir, W.D., W.S. Zaugg, S. McCutcheon, and J.G. Williams. 1992. Biological manipulation of migration rate: The use of advanced photoperiod to accelerate smoltification in yearling Chinook salmon, 1990. Annual Report, U.S. Dept. of Energy BP50301-3:37 pp.

Mundy, P.R. 1982. Computation of migratory timing statistics for adult Chinook salmon in the Yukon River, Alaska, and their relevance to fisheries management. North American Journal of Fisheries Management 2(4):359-370.

Murray, C.B. and T.D. Beacham. 1987. The development of Chinook (*Oncorhynchus tshawytscha*) and chum salmon (*Oncorhynchus keta*) embryos and alevins under varying temperature regimes. Canadian Journal of Zoology 65:2672-2681.

Myers, K.W., N.D. Davis, W.W. Dickhoff, and S. Urawa. 1998. Blood plasma levels of insulin-like growth factor-I in Pacific salmon in offshore waters in winter. NPAFC Bulletin 1:129-137.

Myers, K.W. and R.L. Bernard. 1993. Biological information on Pacific salmon and steelhead trout in observer samples from the Japanese squid driftnet fishery in 1990. International North Pacific Fisheries Commission Bulletin 53(II):217-238.

Myrick, C.A. and J.J. Cech. 2002. Growth of American River Fall-Run Chinook Salmon in California's Central Valley: Temperature and Ration Effects. California Fish and Game 88(1):35-44.

Myrick, C. 1999. Temperature, Genetic, and Ration Effects on Juvenile Rainbow Trout (Oncorhynchus mykiss) Bioenergetics. Dissertation Abstracts International Part B: Science and Engineering 60(2):433.

Myrick, C.A. and J.J. Cech, Jr. 1999. The effects of ration size and temperature on the bioenergetics of juvenile California steelhead, *Oncorhynchus mykiss*. Fish Performance Studies. pp. 23-27.

Nakatani, R.E. 1968. Biological Effects of Hanford Heat on Columbia River Fishes – A Review. US Atomic Energy Commission, BNWL-SA-1682, 24 pp.

Nakamoto, R.J. 1994. Characteristics of Pools Used by Adult Summer Steelhead Over-summering in the New River, CA. American Fisheries Society Transactions 123(5):757-765.

Namdari, R., S. Abedini, L. Albright, and F.C.P. Law. 1998. Tissue distribution and elimination of oxytetracycline in sea-pen cultured Chinook salmon, *Oncorhynchus tshawytscha*, and Atlantic salmon, *Salmo salar*, following medicated-feed treatment. Journal of Applied Aquaculture 8(1):39-52.

Namdari, R., S. Abedini, and F.C.P. Law. 1996. Tissue distribution and elimination of oxytetracycline in seawater Chinook and coho salmon following medicated-feed treatment. Aquaculture 144(1-3):27-38.

Nash, C.E. 1976. The Southern Ocean Salmon Project, Phases I + II. ICLARM, 141 pp.

Neave, F. 1958. Stream ecology and production of anadromous fish. The Investigation of Fish-Power Problems, H.R. MacMillan Lectures in Fisheries, Univ. of British Columbia, pp. 43-48.

Nebeker, A.V., A.K. Hauck, and F.D. Baker. 1979. Temperature and Oxygen-Nitrogen Gas Ratios Affect Fish Survival in Air-Supersaturated Water. Water Research 13(3):299-303.

Nebeker, A.V., J.D. Andros, J.K. McCrady, and D.G. Stevens. 1978. Survival of Steelhead Trout (*Salmo gairdneri*) Eggs, Embryos, and Fry in Air-Supersaturated Water. Canada. Fisheries Research Board Journal 35(2):261-264.

Negus, M.T. 2000. Determination of Smolt Status in Juvenile Anadromous Rainbow Trout and Chinook Salmon. Minnesota Department of Natural Resources Invest. Report No. 486, 48 pp.

Negus, M.T. 1995. Bioenergetics Modeling as a Salmonine Management Tool Applied to Minnesota Waters of Lake Superior. North American Journal of Fisheries Mgmt.15(1):60-78.

Negus, M.T. 1992. Evaluation of Bioenergetics Modeling in the Study of Predator-Prey Dynamics in Minnesota Waters of Lake Superior. Minnesota Department of Natural Resources. Invest. Report 414; 74 pp.

Neilson, J.D., G.H. Geen, and D. Bottom. 1985. Estuarine growth of juvenile Chinook salmon (Oncorhynchus tshawytscha) as inferred from otolith microstructure. Canadian Journal of Fisheries and Aquatic Sciences 42(5):899-908.

Neilson, J.D. and G.H. Geen. 1985. Effects of feeding regimes and diel temperature cycles on otolith increment formation in juvenile Chinook salmon, *Oncorhynchus tshawytscha*. Fishery Bulletin 83(1):91-101.

Neilson, J.D., G.H. Geen, and B. Chan. 1985. Variability in dimensions of salmonid otolith nuclei: Implications for stock identification and microstructure interpretation. Fishery Bulletin 83(1):81-89.

Neilson, J.D. and G.H. Geen. Otoliths of Chinook salmon (*Oncorhynchus tshawytscha*): Daily growth increments and factors influencing their production. Canadian Journal of Fisheries and Aquatic Sciences 39(10):1340-1347.

Neitzel, D.A., T.M. Poston, T.L. Page, and C.S. Abernethy. 1986. Laboratory Simulation of Fish Passage through a Heated-Water Discharge. Aquatic Toxicology and Environmental Fate: Ninth Volume. A Symposium Sponsored by ASTM Committee E-47 on Biological Effects and Environmental Fate, Philadelphia, PA April 14-16, 1985. ASTM Special Technical Publication 921:122-134.

Neitzel, D.A. and C.D. Becker. 1985. Tolerance of eggs, embryos, and alevins of Chinook salmon to temperature changes and reduced humidity in dewatered redds. Transactions of the American Fisheries Society 114(2):267-273.

Nelson, J. 1994. Summary of Steelhead Population and Habitat Sampling Santa Rosa Creek, San Luis Obispo County, 1993. California Dept. Fish and Game; 132 pp.

Nelson, J. 1994. Coho Salmon and Steelhead Habitat and Population Surveys of Scott Creek, Santa Cruz County, 1993. California Dept. Fish and Game; 54 pp.

Newcomb, T.J. 1999. Productive Capacity of the Betsie River Watershed for Steelhead Smolts. Dissertation Abstracts International Part B: Science and Engineering 59(7):3139.

Newcomb, T.J. and T.G. Coon. 1997. Assessment of Management Alternatives for Altering the Thermal Regime of the Betsie River, Michigan. Michigan Department of Natural Resources, Fisheries Research Report No. 2047, 42 pp.

Newcomb, T.J. and T.G. Coon. 1997. Environmental Variability and Survival of Steelhead Parr in a Thermally Diverse Watershed. Michigan Department of Natural Resources, Fisheries Research Report No. 2046, 58 pp.

Newsted, J.L. and J.P. Giesy. 1984. Relationship between residue contamination in Chinook salmon and rearing temperature on rearing mortality. 27th Conference and Annual Meeting of the International Association for Great Lakes Research, St. Catharines, Ontario (Canada). Prog. Conf. Great Lakes Res. 27:58.

Nielsen, J.L., T.E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society 123:613-626.

Oberlander, P.L. and D.A. Myers. Groundwater Temperature Fluctuations at Lyons Ferry Fish Hatchery, Washington. Water Resources Bulletin 23(3):487-492.

Olson, A.D. and O.J. Dix. 1993. Lower Salmon River Sub-basin Fish Habitat Condition and Utilization Assessment 1990/1991. Klamath River Basin Fisheries Task Force. Final Report; 106 pp.

Olson, A.F. and T.P. Quinn. 1993. Vertical and horizontal movements of adult Chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River estuary. Fishery Bulletin 91(1):171-178.

Olson, P.A., R.E. Nakatani, and T. Meekin. 1970. Effects of Thermal Increments on Eggs and Young of Columbia River Fall Chinook. Battelle Memorial Inst., Richland, Wash. Pacific Northwest Labs, BNWL-1538, 57 pp.

Olson, P.A. and R.E. Nakatani. 1968. Effect of elevated temperatures on mortality and growth of young Chinook salmon. U.S. Atomic Energy Commission. BNWL-714: 9.3-9+.

Olson, P.A. and R.E. Nakatani. Effects of Chronic Variable Water Temperatures on Survival and Growth of Young Chinook Salmon. Biological Effects of Thermal Discharges: Annual Progress Report for 1968, pp. 17-20.

Olson, P.A. and R.F. Foster. 1957. Temperature Tolerance of Eggs and Young of Columbia River Chinook Salmon. Transactions American Fisheries Society 85:203-207.

Olson, R.A., J.D. Winter, D.C. Nettles, and J.M. Haynes. 1988. Resource partitioning in summer by salmonids in south-central Lake Ontario. Transactions of the American Fisheries Society 117(6):552-559.

Ordal, E.J. and R.E. Pacha. 1963. The effects of temperature on disease in fish. Proceedings of the 12th Pacific Northwest Symposium on Water Pollution Research, Corvallis, Oregon, November 7, 1963. Water temperature influences, effects, and control; Nov, pp. 39-56;

Oregon State University, Water Resources Research Inst. 1972. Temperature Requirements of Salmonids in Relation to their Feeding, Bioenergetics, Growth, and Behavior. Summary Progress Report, B-012-ORE(1) AND B-027-ORE(1), 23 pp.

Owsley, D.E., J.S. Jeris, and R. Owens. 1989. Ammonia Removal Allows Effluent Reuse at Fish Hatchery Using Fluidized Bed Reactors. Proceedings of the 43rd Industrial Waste Conference May 10-12, 1988, Purdue University, West Lafayette, Indiana. Lewis Publishers, Chelsea, Michigan, p 449-457, 10 fig, 4 tab, 4 ref.

Palmisano, A.N., J.R. Winton, and W.W. Dickhoff. 2000. Tissue-Specific Induction of Hsp90 mRNA and Plasma Cortisol Response in Chinook Salmon following Heat Shock, Seawater Challenge, and Handling Challenge. Marine Biotechnology 2(4):329-338.

Palmisano, A.N. 1998. Nucleotide Sequence and Tissue-distribution of Chinook Salmon Hsp90 Messenger Rna: Response To Heat Shock, Handling, and Seawater, and Comparison To Plasma Cortisol Concentration. Dissertation Abstracts International Part B: Science and Engineering 59(6):2502.

Parnell, K.M., D.C. Nettles, J.M. Haynes, R.A. Olson, and J.D. Winter. 1983. Steelhead/rainbow trout movements in Lake Ontario. Proceedings of the 26th Conference on Great Lakes Research. May 23-27, 1983, State University of New York at Oswego, p. 19.

Pauley, G.B., K. Oshima, K.L. Bowers, and G.L. Thomas. 1989. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest). Sea-run cutthroat trout. Biol. Rep. U.S. Fish Wildl. Serv., 28 pp.

Pauley, G.B., B.M. Bortz, and M.F. Shepard. 1986. Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (Pacific Northwest): Steelhead Trout. U.S. Fish and Wildlife Service Biological Report 82(11.62): viii+24 pp.

Pautzke, C.F. and R.C. Meigs. 1940. Studies on the life history of the Puget Sound steelhead trout (Salmo gairdneri). American Fisheries Society. Transactions 70:209-220.

Pereira, D.L. and D.R. Adelman. 1985. Interactions of temperature, size and photoperiod on growth and smoltification of Chinook salmon (*Oncorhynchus tshawytscha*). Aquaculture 46(3):185-192.

Perez-Sanchez, J., H. Marti-Palanca, and P-Y Le Bail. 1994. Homologous growth hormone (GH) binding in gilthead sea bream (*Sparus aurata*). Effect of fasting and refeeding on hepatic GH-binding and plasma somatomedin-like immunoreactivity. Journal of Fish Biology 44(2):287-301.

Peters, C.F. and D.D. Weber. 1975. DDT: effect on the lateral line nerve of steelhead trout. Presented at: Symposium on the Physiological Responses of Marine Biota to Pollutants, CT (USA).

Pettit, S.W. 1976. Dworshak Fisheries Studies: Evaluation of Game and Rough Fish Populations Below Dworshak Dam and Relationship to Changes in Water Quality. Idaho Fish and Game Dept.; 58 pp.

Pollock, R.D. 1969. Tehama-Colusa Canal to serve as spawning channel. Progressive Fish-Culturist 31(3):123-130.

Poston, T.M., D.A. Neitzel, C.S. Abernethy, and D.W. Carlile. 1985. Effects of Suspended Volcanic Ash and Thermal Shock on Susceptibility of Juvenile Salmonids to Disease. Aquatic Toxicology and Hazard Assessment: Eighth Symposium, Fort Mitchell, Kentucky April 15-17, 1984. ASTM Special Technical Publication 891:359-374.

Powell, J.L. and M.W. Loutit. 1994. The detection of fish pathogen *Vibrio anguillarum* in water and fish using a species-specific DNA probe combined with membrane filtration. Microbial Ecology, New York, NY 28(3):375-383.

Powell, M.J. and M. Miller. Shoal spawning by Chinook salmon in Lake Huron. North American Journal of Fisheries Management 10(2):242-244.

Prepejchal, W., M.M. Thommes, S.A. Spigarelli, and G.P. Romberg. 1976. Temperature Selection and Avoidance Behavior of Salmonids. Argonne National Lab., Radiological and Environmental Research Div. Report ANL-75-60, Part III , pp 87-89.

Quinn, T.P., J.A. Peterson, V.F. Gallucci, W.K. Hershberger, and E.L. Brannon. 2002. Artificial Selection and Environmental Change: Countervailing Factors Affecting the Timing of Spawning by Coho and Chinook Salmon. Transactions of the American Fisheries Society 131(4):591-598.

Radovich, J. 1961. Relationship of Some Marine Organisms of the Northeast Pacific to Water Temperatures Particularly During 1957 through 1959. CA Dept. of Fish and Game; 61 pp.

Rand, P.S., D.J. Stewart, P.W. Seelbach, M.L. Jones, and L.R. Wedge. 1993. Modeling Steelhead Population Energetics in Lakes Michigan and Ontario. American Fisheries Society Transactions 122(5):977-1001.

Rathbun, G.B., M.R. Jennings, T.G. Murphey, and N.R. Siepel. 1993. Status and Ecology of Sensitive Aquatic Vertebrates in Lower San Simeon and Pico Creeks, San Luis Obispo County, California. U.S. Fish and Wildlife Service, 114 pp.

Raymond, H.L. 1988. Effects of Hydroelectric Development and Fisheries Enhancement on Spring and Summer Chinook Salmon and Steelhead in the Columbia River Basin. North American Journal of Fisheries Management NAJMDP 8(1):1-24.

Redding, J.M. and C.B. Schreck. 1979. Possible adaptive significance of certain enzyme polymorphisms in steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can., 36(5), 544-551.

Reese, C.D. and B.C. Harvey. 2002. Temperature-dependent interactions between juvenile steelhead and Sacramento pikeminnow in laboratory streams. Transactions of the American Fisheries Society 131(4):599-606.

Reeves, G.H. 1985. Interaction and behavior of the redside shiner (*Richardsonius balteatus*) and the steelhead trout (*Salmo gairdneri*) in western Oregon: The influence of water temperature. Dissertation Abstracts International Part B: Science and Engineering 46(2): 109 pp.

Reeves, G.H., F.H. Everest, and J.D. Hall. 1987. Interactions between the redside shiner (Richardsonius balteatus) and the steelhead trout (*Salmo gairdneri*) in western Oregon: The influence of water temperature. Canadian Journal of Fisheries and Aquatic Sciences 44(9):1603-1613.

Reimers, P.E. 1973. The Length of Residence of Juvenile Fall Chinook Salmon in Sixes River, OR. Research Reports of the Fish Commission of Oregon 4(2): 43 pp.

Reingold, M. 1975. Evaluation of Transplanting Snake River Steelhead Trout to the Pahsimeroi River, 1974. Idaho Fish and Game Dept.; 23 pp.

Reiser, D.W. and R.G. White. 1983. Effects of complete redd dewatering on salmonid egg-hatching success and development of juveniles. Transactions of the American Fisheries Society 112(4):532-540.

Richards, C. and P.J. Cernera. 1987. Salmon River Habitat Enhancement. Annual Report: FY 1986, Part 1. Shoshone-Bannock Tribal Fisheries Dept. Fort Hall Reservation, ID. Report No. DOE/BP/14383, 109 pp.

Ricker, W.E. 1981. Changes in the average size and average age of Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 38(12):1636-1656.

Robards, M.D. and T.P. Quinn. 2002. The migratory timing of adult summer-run steelhead in the Columbia River over six decades of environmental change. Transactions of the American Fisheries Society 131(3):523-536.

Roberson, K. 1967. An occurrence of Chinook salmon beach spawning in Lake Washington. American Fisheries Society. Transactions 96(4):423-424.

Robinson, C.L.K. and D.M. Ware. 1994. Modeling pelagic fish and plankton trophodynamics off southwestern Vancouver Island, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 51(8):1737-1751.

Rohrer, R.L. and G.H. Thorgaard. 1986. Evaluation of Two Hybrid Trout Strains in Henry's Lake, Idaho, and Comments on the Potential Use of Sterile Triploid Hybrids. North American Journal of Fisheries Management 6(3):367-371.

Romberg, G.P. and W. Prepejchal. 1976. Thermal Discharge Residence by Lake Michigan Salmonids. Argonne National Lab., Radiological and Environmental Research Div. Report ANL-75-60, Part III, pp 78-80.

Romberg, G.P., S.A. Spigarelli, W. Prepejchal, and M.M. Thommes. 1974. Migratory Behavior of Fish Tagged at a Nuclear Power Plant Discharge into Lake Michigan. In: Proceedings, Seventeenth Conference on Great Lakes Research, Part 1; McMaster University, Hamilton (Ontario), August 12-14. International Association for Great Lakes Research, pp 68-77.

Rombough, P.J. 1988. Growth, aerobic metabolism, and dissolved oxygen requirements of embryos and alevins of steelhead, Salmo gairdneri. Can. J. Zool./J. Can. Zool. 66(3):651-660.

Rombough, P.J. 1986. Mathematical model for predicting the dissolved oxygen requirements of steelhead (Salmo gairdneri) embryos and alevins in hatchery incubators. Aquaculture 59(2):119-137.

Rombough, P.J. 1985. Initial egg weight, time to maximum alevin wet weight, and optimal ponding times for Chinook salmon (*Oncorhynchus tshawytscha*). Canadian Journal of Fisheries and Aquatic Sciences 42(2):287-291.

Roper, B.B. and D.L. Scarnecchia. 1999. Emigration of age-0 Chinook salmon (*Oncorhynchus tshawytscha*) smolts from the upper South Umpqua River basin, Oregon, USA. Canadian Journal of Fisheries and Aquatic Sciences 56(6):939-946.

Roper, B.B., D.L. Scarnecchia, and T.J. LaMarr. 1994. Summer Distribution of and Habitat Use by Chinook Salmon and Steelhead within a Major Basin of the South Umpqua River, Oregon. American Fisheries Society. Transactions 123(3):298-308.

Rucker, R.R. and P.M. Kangas. 1974. Effect of nitrogen supersaturated water on coho and Chinook salmon. Progressive Fish-Culturist 37(3):152-156.

Sams, R.E. and K.R. Conover. 1969. Water Quality and the Migration of Fall Salmon in the Lower Willamette River. Oregon Fish Commission. Final Report, 58 pp.

Sanders, J.E., K.S. Pilcher, and J.L. Fryer. 1978. Relation of Water Temperature to Bacterial Kidney Disease in Coho Salmon (*Oncorhynchus kisutch*), Sockeye Salmon (*O. nerka*), and Steelhead Trout (*Salmo gairdneri*). Canada. Fisheries Research Board Journal 35(1):8-11.

Saunders, R.L., G.L. Fletcher, and C.L. Hew. 1998. Smolt development in growth hormone transgenic Atlantic salmon. Aquaculture 168(1-4):177-194.

Sauter, S.T., L.I. Crawshaw, A.G. Maule. 2001. Behavioural thermoregulation by juvenile spring and fall Chinook salmon, *Oncorhynchus tshawytscha*, during smoltification. Environmental Biology of Fishes 61(3):295-304.

Scarnecchia, D.L. and B.B. Roper, B.B. 2000. Large-scale, differential summer habitat use of three anadromous salmonids in a large river basin in Oregon, USA. Fisheries Management and Ecology 7(3):197-209.

Scheeler, C.A. 1991. Umatilla river basin anadromous fish habitat enhancement project. Annual report, 1990. Report of U.S. Department of Energy. 21pp.

Schmidt, S.P. and E.W. House. 1979. Precocious sexual development in hatchery-reared and laboratory-maintained male steelhead trout (*Salmo gairdneri*). J. Fish. Res. Board Can., 36(1):90-93.

Serbura, Z.P. 1967. The Effect of Chinook (Foehn) on Surface Ablation of Alibek Glacier (Russian). Kharkov Univ, Vestnik Geol I Geogr, Ser 25(2):104-105

Servizi, J.A. and R.W. Gordon. 1990. Acute Lethal Toxicity of Ammonia and Suspended Sediment Mixtures to Chinook Salmon (*Oncorhynchus tshawytscha*). Bulletin of Environmental Contamination and Toxicology 44(4):650-656

Seymour, A. 1959. Effects of Temperature upon the Formation of Vertebrae and Fin Rays in Young Chinook Salmon. Transactions American Fisheries Society 88(1):58-69.

Shepard, M. 1972. Effects of flow and temperature on timing of steelhead trout runs in Washington. Res. Fish. Coll. Fish. Univ. Wash. 1971(355): 47 pp.

Short, Z. and P.R. Olson. 1970. Oyster shells and foam formation used to improve quality of water recirculated in a fish hatchery incubator. Progressive Fish-Culturist 32(3):180-182.

Shrimpton, J.M., J.F. Bourgeois, J.T. Quigley, and D.M. Blouw. 1999. Forest harvesting increases stream temperature: potential impacts on juvenile chinook? Stress in fish. pp. 77-82.

Shumway, D.L., C.E. Warren, and P. Doudoroff. 1964. Influence of Oxygen Concentration and Water Movement on the Growth of Steelhead Trout and Coho Salmon Embryos. Transactions of the American Fisheries Society 93(4):342-356.

Silverstein, J.T. and D.D. Heath. 1994. Comment on "Genetic, environmental and interaction effects on growth and stress response of Chinook salmon (*Oncorhynchus tshawytscha*) fry" by Heath et al. (1993) and Reply. Canadian Journal of Fisheries and Aquatic Sciences 51(4):981-983.

Simon, T.P., P.M. Stewart, D. Sparks, A. Peine, J. Exl, J.T. Butcher, and J. Smith. 2000. A Study of the Distribution of Chinook Salmon (*Oncorhynchus tschawytscha*) in the Grand Calumet River and Indiana Harbor Canal, Lake County, Indiana. U.S. Fish and Wildlife Service Tech. Report 22 pp.

Sjolseth, D.E., E.O. Salo, and M. Katz. 1970. Effect of Water Quality in Bellingham Bay on Juvenile Salmon. Fifth International Water Pollution Research Conference, San Francisco. Paper I-26, 27 pp.

Skazkina, E.P. 1970. Energy Metabolism and Food Rations of Steelhead Trout under Conditions of the Chernaya Rachka Trout Industry, (In Russian) Tr Vses Nauchno-Issled Inst Morsk Rybn Khoz Okeanogr. 76:130-134, English Summary.

Skea, J.C., J. Symula, and J. Miccoli. 1985. Separating Starvation Losses from Other Early Feeding Fry Mortality in Steelhead Trout Salmo gairdneri, Chinook Salmon *Oncorhynchus tshawytscha*, and Lake Trout *Salvelinus namaycush*. Bulletin of Environmental Contamination and Toxicology 35(1):82-91.

Slater, D.W. 1963. Winter-Run Chinook Salmon in the Sacramento River, California with Notes on Water Temperature Requirements at Spawning. U.S. Fish and Wildlife Service Special Scientific Report -- Fisheries No. 461, 13 pp.

Smith, H.A. 1972. N_2 - Threat to Pacific Northwest Fisheries. Water Spectrum 4(2):41-48.

Smith, S.G., W.D. Muir, J.G. Williams, and J.R. Skalski. 2002. Factors Associated with Travel Time and Survival of Migrant Yearling Chinook Salmon and Steelhead in the Lower Snake River. North American Journal of Fisheries Management 22(2):385-405.

Smith, T., I. Werner, M.B. Johnson, and J. Feliciano. 2001. Heat-shock protein (HSP70) expression and apparent growth differ among steelhead parr along a coastal temperature gradient. American Fisheries Society Annual Meeting Vol. 131:108-109.

Smith, T. 2001. Heat-shock protein expression and growth of steelhead parr along a temperature gradient. 131st American Fisheries Society Annual Meeting, Phoenix, AZ, 19-23 Aug 2001. American Fisheries Society, Bethesda, MD.

Snyder, G.R., D.R. Craddock, and T.H. Blahm. 1970. Thermal Effects Studies on the Lower Columbia River, 1968-70. In: Proceedings of the Western Association of State Game and Fish Commissioners, 50th Conference, Victoria, British Columbia, pp 65-89.

Soderberg, R.W. 1992. Linear fish growth models for intensive aquaculture. Progressive Fish-Culturist 54(4):255-258.

Sommers, L.M., C. Thompson, S. Tainter, L. Lin, and T.W. Colucci. 1981. Fish in Lake Michigan: Distribution of Selected Species. Michigan Sea Grant Advisory Program. Report No. MICHU-S-G-81-600, 38 pp.

Southgate, D.R., V.L. Craig, and A.L. Jantz. 1989. Review of the Nass River test fishery biological program for 1987 and 1988. Can. Data Rep. Fish. Aquat. Sci., 738: 90 pp.

Spigarelli, S.A. and D.W. Smith. 1976. Growth of Salmonid Fishes from Heated and Unheated Areas of Lake Michigan-Measured by RNA-DNA Ratios. Thermal Ecology II, Proceedings of a Symposium held in Augusta, GA, April 2-5, 1975. CONF-750425, pp. 100-105.

Spigarelli, S.A. and D.W. Smith. 1975. Growth of Plume Resident Fishes in Lake Michigan. Argonne National Lab., Radiological and Environmental Research Div. In: Radiological and Environmental Research Division Annual Report - Ecology, pp 173-179.

Spigarelli, S.A. and J. Edwards. 1975. Effect of Plume Residence on the Accumulation of CS137 by Lake Michigan Salmonids. Argonne National Lab., Radiological and Environmental Research Div. In: Radiological and Environmental Research Division Annual Report – Ecology, pp180-183.

Stabler, D.F. 1981. Effects of Altered Flow Regimes, Temperatures, and River Impoundment on Adult Steelhead Trout and Chinook Salmon. M.S. Thesis, University of Idaho; 125 pp.

Steward, C. and T.C. Bjornn. 1990. Fill'er up: Stream carrying capacity. Focus Renewable Resour. 15:16-17.

Stober, Q.J. and C.H. Hanson. 1974. Toxicity of Chlorine and Heat to Pink (*Oncorhynchus gorbuscha*) and Chinook Salmon (*O. tshawytscha*). Transactions of the American Fisheries Society 103(3):569-576.

Strange, R.J. 1977. Changes in Plasma Cortisol Concentration of Juvenile Salmonids during Stress. Ph.D. Dissertation; Oregon State University; 107 pp.

Strange, R.J., C.B. Schreck, and J.T. Golden. 1977. Corticoid stress responses to handling and temperature in salmonids. Trans. Am. Fish. Soc., 106(3):213-218.

Swanson, C.and J. J. Cech, Jr. 1993. Effects of Chronically Elevated Water Temperature on Thermal Tolerance of Chinook salmon Smolts. American Zoologist 33(5):65A.

Sylvester, R. O. 1958. Water quality studies in the Columbia River basin. U.S. Fish and Wildlife Service, Special Scientific Report-Fisheries No. 239.

Synder, G.R. 1970. Thermal Pollution of Columbia River Might Threaten Smelt. Commercial Fisheries Review 32(12):58-64.

Takagi, S., Y. Sakurai, Y. Kamel, T. Miyo, K. Sakaoka, and N. Shiga. 1997. Oceanographic conditions and distribution of pelagic nekton in the Northwestern North Pacific Ocean during the summer and fall in 1995 and 1996. Hokkaido University. Faculty of Fisheries. Bulletin 48(1-2):13-28.

Tarp, F.H. 1970. Comprehensive Watershed Management-The Anadromous Fishery Resource. Report to the San Francisco Bay Conservation and Development Commission, 7 pp.

Taylor, E.B. 1990. Environmental correlates of life-history variation in juvenile Chinook salmon, *Oncorhynchus tshawytscha* (Walbaum). Journal of Fish Biology 37(1):1-17.

Taylor, E.B. 1988. Water temperature and velocity as determinants of microhabitats of juvenile Chinook and coho salmon in a laboratory stream channel. Transactions of the American Fisheries Society 117(1):22-28,

Templeton, W.L. and C.C. Coutant. 1970. Studies on the Biological Effects of Thermal Discharges from Nuclear Reactors to the Columbia River at Hanford. Sym. on Environmental Aspects of Nuclear Power Stations, United Nations Headquarters, New York, 37 pp.

Templeton, W.L., C.D. Becker, J.D. Berlin, C.C. Coutant, and J.M. Dean. 1969. Biological Effects of Thermal Discharges: Annual Progress Report for 1968. BNWL-1050, 49 pp.

Theurer, F.D., I. Lines, and T. Nelson. 1985. Interaction Between Riparian Vegetation, Water Temperature, and Salmonid Habitat in the Tucannon River. Water Resources Bull. 21(1):53-64.

Thomas, A.E. 1975. Migration of Chinook Salmon Fry from Simulated Incubation Channels in Relation to Water Temperature, Flow, and Turbidity. Progressive Fish-Culturist 37(4):217-223.

Thomas, A.E. and J.M. Shelton. 1968. Operation of Abernathy Channel for Incubation of Salmon Eggs. US Bur Sport Fish Wildl Tech Paper 23:3-19.

Tiffan, K.F., C.A. Haskell, and D.W. Rondorf. Thermal exposure of juvenile fall chinook salmon migrating through a lower Snake River reservoir. Northwest Science 77:100-109.

Tolokonnikov, G.Y. 1998. Resistance to low temperature in steelhead trout and beluga cultivated in the Black Sea water. Hydrobiological Journal 34(6):62-69.

Tolokonnikov, G. 1991. Features of growth of steelhead trout under the conditions of Egorlytskiy fishery. Journal of Ichthyology 31(4):157-160.

Torgersen, C.E., D.M. Price, H.W. Li, and B.A. McIntosh. 1999. Multiscale thermal refugia and stream habitat associations of Chinook salmon in northeastern Oregon. Ecological Applications 9(1):301-319.

Trefethen, P.S. and D.F. Sutherland. 1968. Passage of adult Chinook salmon through Brownlee Reservoir, 1960-62. Fishery Bulletin 67(1):35-45.

Tufescu, M.V.A. and T.B. Tufescu. 1996. Ratios of expected values (REX), a method for impact evaluation of thermal discharges on the fish community in the Pickering littoral waters of Lake Ontario. Hydrobiologia 328(1):75-83.

Tyler, J.A., C.C. Goller, and E.S. Rutherford. 2001. Modeling steelhead parr responses to habitat alterations in Great Lakes tributaries. Abstracts from the 44th Conference on Great Lakes Research, June 10-14, 2001. International Association for Great Lakes Research, Ann Arbor, MI.

U.S. Army Corps of Engineers, Portland, Oregon. 1995. Willamette River Temperature Control, McKenzie River Subbasin, Lane and Linn Counties, OR. EPA/950268F, Volume I--607 pp.; Volume II--624 pp.

U.S. Army Corps of Engineers, Walla Walla, WA and Bonneville Power Administration. 1993.

1992 Columbia/Snake Rivers Salmon Flow Measures Options Analysis - Oregon, Washington, and Idaho (Acquiring Replacement Power for that Lost from Additional Releases - Implementation). EPA/930133, 2 vol.

U.S. Army Corps of Engineers and Bonneville Power Administration. 1992. 1992 Columbia River Salmon Flow Measures Options Analysis - Oregon, Washington, and Idaho (Adoption of the Department of the Army, Corps of Engineers, Final Environmental Impact Statement of January 1992). EPA/920066F, 513 pp.

U.S. Army Corps of Engineers, Portland, Oregon. 1991. Elk Creek Lake, Rogue River Basin, Oregon (Final Supplement No. 2 to the Final Environmental Impact Statement of September 1971). EPA number: 910142FS2, 2 vol. and maps.

U.S. Army Corps of Engineers, Portland, OR. 1973. Operation of Cougar Lake Project and Construction of McKenzie River Salmon Hatchery, McKenzie River Basin, Lane County, OR (Final Environmental Impact Statement). NTIS EIS-OR-73-1918-F, 187 pp.

U.S. Department of Agriculture, Forest Service, Grants Pass, OR. 1988. Silver Fire Recovery Project, Siskiyou National Forest, Josephine and Curry Counties, OR. EPA/880212F.

U.S. Department of the Interior, Fish and Wildlife Service, Portland, OR 2001. Icicle Creek Restoration Project, Leavenworth National Fish Hatchery, Leavenworth, Chelan County, WA. EPA/010240D: 278 pp.

U.S. Department of the Interior, Bureau of Reclamation and East Bay Municipal Utility District, Sacramento, CA. 2000. Supplemental Water Supply Project and Water Service Contract Amendment between the U.S. Bureau of Reclamation and the East Bay Municipal Utility District, Sacramento County, CA. EPA/000433F; Volume I--821 pp, Volume II--611 pp.

U.S. Department of the Interior, Bureau of Reclamation and Fish and Wildlife Service and Hoopa Valley Tribe, County of Trinity, CA. 2000. Trinity River Main Stem Fishery Restoration, Humboldt and Trinity Counties, CA. EPA/000382F, Final EIS--894 pp.

U.S. Department of the Interior, Bureau of Reclamation and East Bay Municipal Utility District, Sacramento, CA. 2000. East Bay Municipal Utility District Supplemental Water Supply Project, Sacramento and San Joaquin Counties, CA. EPA/000337DS, 252 pp.

U.S. Department of the Interior, Fish and Wildlife Service, Sacramento, CA. Lower Mokelumne River Restoration Program, San Joaquin County, CA. EPA/000181F, 109 pp.

U.S. Department of the Interior, Bureau of Reclamation and Fish and Wildlife Service and Hoopa Valley Tribe; County of Trinity, CA. 1999. Trinity River Main Stem Fishery Restoration, Humboldt and Trinity Counties, CA. EPA/990374D.

U.S. Department of the Interior, Bureau of Reclamation and East Bay Municipal Utility District. 1997. Supplemental Water Supply Project, American River Division of the Central Valley Project, Sacramento County, CA. EPA/970424D, Volume I--391 pp.; Volume II--384 pp.

U.S. Department of the Interior, Bureau of Reclamation, Folsom, CA. 1997. Central Valley Project Water Supply Contracts under Public Law 101-514 (Section 206), Sacramento County, CA. EPA/970262D.

U.S. Department of the Interior, Bureau of Reclamation and Fish and Wildlife Service, U.S. Department of Commerce, National Marine Fisheries Service, and U.S. Department of Energy, Western Area Power Administration. 1991. Shasta Outflor Temperature Control, Shasta County, CA. EPA/910186F, 337 pp.

U.S. Department of the Interior, Bureau of Reclamation, Sacramento, California. 1986. Grass Valley Creek Debris Dam, Trinity County, California. EPA number 860337F, 2 volumes.

U.S. Department of the Interior, Fish and Wildlife Service and Bonneville Power Administration, Portland, OR. 1984. Natural Propagation and Habitat Improvement - Washington, Similkameen River Habitat Inventory. DOE/BP--247-Vol.2B, 73 pp.

Unwin, M.J., T.P. Quinn, M.T. Kinnison and N.C. Boustead. 2000. Divergence in juvenile growth and life history in two recently colonized and partially isolated Chinook salmon populations. Journal of Fish Biology 57(4):943-960.

Vaccaro, J.J. 1986. Simulation of Streamflow Temperatures in the Yakima River Basin, Washington, April to October 1981. USGS Water Resources Investigations Rpt. 85-4232, 91 pp.

Velsen, F.P.J. Temperature and incubation in Pacific salmon and rainbow trout: Compilation of data on median hatching time, mortality, and embryonic staging. Can. Data Rep. Fish. Aquat. Sci. 626: 66 pp.

Vermeyen, T.B. 1998. First-year selective withdrawal performance of the Shasta Dam temperature control device. Int. Water Res. Eng. Conf. Proc. Vol. 1:944-949.

Volk, E.C., S.L. Schroder, and J.J. Grimm. 1994. Use of a bar code symbology to produce multiple thermally induced otolith marks. Transactions of the American Fisheries Society 123(5):811-816.

Vronskii, B.B. and Leman, V.N. 1991. Spawning Stations, Hydrological Regime and Survival of Progeny in Nests of Chinook Salmon, Oncorhynchus tshawytscha, in the Kamchatka River Basin. Journal of Ichthyology 31(4):91-102.

Wadley, G.W. 1972. The effect of X-irradiation under various temperature conditions and embryonic developmental stages on the growth and mortality of Chinook salmon. Res. Fish. Coll. Fish. Univ. Wash. 1971(355):80.

Wagner, H.H. 1974. Photoperiod and temperature regulation of smolting in steelhead trout (*Salmo gairdneri*). Canadian Journal of Zoology 52(2):219-234.

Walker, R.V., K.W. Myers, N.D. Davis, K.Y. Aydin, K.D. Firedland, H.R. Carlson, G.W. Boehlert, S. Urawa, Y. Ueno, and G. Anma. 2000. Diurnal variation in thermal environment experienced by salmonids in the North Pacific as indicated by data storage tags. Fisheries Oceanography 9(2):171-186.

Walker, R.V., K.W. Myer, N.D. Davis, K.Y. Aydin, K.D. Friedland, KD; H.R. Carlson, G.W. Boehlert, U. Shigehiko, U. Yasuhiro, and G. Anma. Editors. 1999. Ambient temperatures and diurnal behaviour as indicated by data storage tags on salmonids in the North Pacific. ICES, Copenhagen (Denmark). 24 pp.

Walters, C.J., J.S. Collie, and T. Webb. 1989. Experimental designs for estimating transient responses to habitat alteration: Is it practical to control for environmental interactions?. Proceedings of The National Workshop on Effects of Habitat Alteration on Salmonid Stocks, Can. Spec. Publ. Fish. Aquat. Sci.105:13-20.

Walthers, L.C. and J.C. Nener. 1998. Water temperature monitoring in the Nicola River, B.C., 1995: Implications of measured temperatures for anadromous salmonids. Can. Manuscr. Rep. Fish. Aquat. Sci./Rapp. Manuscr. Can. Sci. Halieut. Aquat. 2443:65 pp.

Walthers, L.C. and J.D. Nener. 1997. Continuous water temperature monitoring in the Nicola River, B.C., 1994: Implications of high measured temperatures for anadromous salmonids. Canadian technical report of fisheries and aquatic sciences/Rapport technique Canadian des sciences halieutiques et aquatiques. Can. Tech. Rep. Fish. Aquat. Sci./Rapp. Tech. Can. Sci. Halieut. Aquat. 72 pp.

Walthers, L.C. and J.C. Nener. 1997. Water temperature monitoring in the Salmon River (Shuswap), B.C., 1995: Implications of measured temperatures for anadromous salmonids. Canadian manuscript report of fisheries and aquatic sciences/Rapport manuscrit canadien des sciences halieutiques et aquatiques. Can. Manuscr. Rep. Fish. Aquat. Sci./Rapp. Manuscr. Can. Sci. Halieut. Aquat. 62 pp.

Waples, R.S., R.P. Jones, B.R. Beckman, and G.A. Swan. 1991. Status review for Snake River fall Chinook salmon. NOAA Tech. Memo., 81 pp.

Ward, J.V. 1974. A temperature-stressed stream ecosystem below a hypolimnial release mountain reservoir. 74(2):247-275.

Waterstrat, P.R. 1997. Distribution and abundance of *Saprolegnia* in the water system of a Chinook salmon hatchery. Journal of Aquatic Animal Health 9(1):58-63.

Wedemeyer, G.A., R.W. Gould, and W.T. Yasutake. 1983. Some potentials and limits of the leucocrit test as a fish health assessment method. Journal of Fish Biology 23(6):711-716.

Wedemeyer, G. 1973. Some Physiological Aspects of Sublethal Heat Stress in the Juvenile Steelhead Trout (Salmo gairdneri) and Coho Salmon (*Oncorhynchus kisutch*). Canada. Fisheries Research Board Journal 30(6):831-834.

Weitkamp, D.E. and M. Katz. 1980. A Review of Dissolved Gas Supersaturation Literature. American Fisheries Society. Transactions 109(6):659-702.

Welch, D.W., Y. Ishida, K. Nagasawa, and J.P. Eveson. 1998. Thermal limits on the ocean distribution of steelhead trout (*Oncorhynchus mykiss*). NPAFC Bulletin Number 1: Assessment and status of Pacific Rim salmonid stocks, pp. 396-404.

Welsh, R.A. 1998. Sacramento - a river in repair. Int. Water Res. Eng. Conf. Proc. Vol. 1:702-707.

Wenger, M.N., R.M. Lichorat, and J.D. Winter. 1984. Pre-spawning and spawning behavior of coho salmon and Chinook salmon in eastern Lake Erie. New York Fish and Game Journal 31(2):146-164.

Westers, H. 1970. Carrying capacity of salmonid hatcheries. Progressive Fish-Culturist 32(1):43-46.

Whipple, J.A., M.B. Eldridge, and P. Benville Jr. 1981. Ecological Perspective of the Effects of Monocyclic Aromatic Hydrocarbons on Fishes. Biological Monitoring of Marine Pollutants, Proceedings of a Symposium on Pollution and Physiology of Marine Organisms, Milford, CT. Academic Press, New York, pp 483-551.

Whitney, L. 2000. Grande Ronde Section 319 National Monitoring Program Project. Temporary Monitoring Summary Report 1993-1998. BIO00-001.

Willey, R.G. 1990. Proceedings of 22nd Seminar on Coastal and Inland Water Quality, Las Vegas, NV, 333 pp.

Williams, J.G. 1995. Unconvinced about temperature tolerance of juvenile Chinooks. Fisheries 20(9):38.

Williams, J.G. and T.C. Bjornn. 1995. Fall Chinook salmon survival and supplementation studies in the Snake River and Lower Snake River reservoirs, 1995. Annual report, U.S. Department of Energy, Washington, DC [DOE/BP-10891-4].

Williamson, S.C., J.M. Bartholow, and C.B. Stalnaker. 1993. Conceptual Model for Quantifying Pre-smolt Production from Flow-dependent Physical Habitat and Water Temperature. Regulated Rivers Research & Management 8(1&2):15-28.

Winfree, R.A., G.A. Kindschi, and H.T. Shaw. 1998. Elevated water temperature, crowding, and food deprivation accelerate fin erosion in juvenile steelhead. Progressive Fish-Culturist 60(3):192-199.

Workman, R.D., D.B. Hayes, and T.G. Coon. 2002. A model of steelhead movement in relation to water temperature in two Lake Michigan tributaries. Transactions of the American Fisheries Society 131(3):463-475.

Workman, R.D., D.B. Hayes, and T.G. Coon. 2000. Temperature-based model for predicting upstream movement of migratory steelhead in Lake Michigan. 130th American Fisheries Society Annual Meeting, St. Louis, MO, 20-24 Aug 2000. American Fisheries Society, Bethesda, MD.

Wurtsbaugh, W.A. and G.E. Davis. 1977. Effects of Temperature and Ration Level on the Growth and Food Conversion Efficiency of Salmo Gairdneri, Richardson. Journal of Fish Biology 11(2):87-98.

Wurtsbaugh, W.A. 1973. Effects of Temperature, Ration, and Size on the Growth of Juvenile Steelhead Trout, *Salmo gairdneri*. MS Thesis. Oregon State University, B-027-ORE, 69 pp.

Wurtz, C.B. and C.E. Renn. 1965. Water temperatures and aquatic life. Cooling water studies for Edison Electric Institute, Maryland; June(49):1-99.

Wyatt, E.J. 1978. Studies on the epizootiology of *Myxobolus insidiosus* Wyatt and Pratt, 1963 (Protozoa: Myxosporida). J. Fish. Dis., 1(3):233-240.

Yang, Z., T. Khangaonkar, C. DeGasperi, and K. Marshall. 2000. Three-dimensional modeling of temperature stratification and density-driven circulation in Lake Billy Chinook, Oregon. Proceedings of the Int. Conf. Estuarine Coast Model. pp. 411-425.

Zaugg, W.S. 1981. Advances photoperiod and water temperature effects on gill Na+-K+ adenosine triphosphatase activity and migration of juvenile steelhead (*Salmo gairdneri*). Canadian Journal of Fisheries and Aquatic Sciences 38(7):758-764.

Zaugg, W.S., B.L. Adams, and L.R. McLain. 1972. Steelhead Migration: Potential Temperature Effects as Indicated by Gill Adenosine Triphosphatase Activities. Science 176 (4033):415-416.

Zaugg, W.S. and H.H. Wagner. Gill ATPase activity related to parr-smolt transformation and migration in steelhead trout (*Salmo gairdneri*): Influence of photoperiod and temperature. Comparative Biochemistry and Physiology, Part B: Biochemistry and Molecular Biology 45(4):955-965.

Zhao, Z. and L. Niu. 1994. Isolation and preliminary study of a rhabdovirus from rainbow trout (*Oncorhynchus mykiss*) in Benxi, China. Acta hydrobiologica sinica/Shuisheng Shengwu Xuebao. Wuhan 18(4):348-353.

Appendix Table 2. Relationship between date and scrollcase temperature for juvenile yearling and subyearling chinook salmon, sockeye, and steelhead migrants passed Lower Granite Dam during two low flow years (1992, 1994) and two high flow years (1993, 1997). Numbers below each of the flow years represent the proportion of run passed Lower Granite Dam (e.g. 25-25% of run).

	Chinook Salmon							
	Yearling		SubYearling		Sockeye		Steelhead	
Year	**Date**	**Temp**	**Date**	**Temp**	**Date**	**Temp**	**Date**	**Temp**
1992	**LOW FLOW YEAR**							
25	4/22	11.96	6/18	17.95	5/09	13.7	5/03	13.17
50	4/30	11.97	6/24	22.73	5/15	12.69	5/07	13.44
75	5/06	13.21	6/30	22.73	5/24	15.47	5/19	13.93
90	5/15	12.69	7/17	20.83	6/21	18.78	5/15	17.19
1994	**LOW FLOW YEAR**							
25	4/26	10.76	7/08	21.97	5/11	14.73	5/01	11.01
50	5/03	10.93	7/15	18.61	5/12	14.88	5/08	13.15
75	5/09	13.93	8/09	22.82	5/23	12.8	5/12	14.88
90	5/13	14.72	8/23	23.88	6/03	15.97	5/19	12.39
1993	**HIGH FLOW YEAR**							
25	4/22	10.51	7/07	17.06	5/20	12.6	5/04	10.81
50	5/02	11.00	7/22	18.08	5/25	12.84	5/08	10.93
75	5/09	13.26	8/14	20.35	6/06	13.88	5/16	12.62
90	5/13	12.42	8/26	21.5	6/24	16.62	5/21	12.62
1997	**HIGH FLOW YEAR**							
25	5/01	10.6	7/07	18.3	4/26	10.0	4/27	10.6
50	5/05	11.1	7/18	18.9	5/17	11.7	5/04	10.6
75	5/12	11.1	8/01	18.9	5/22	15.6	5/13	12.2
90	5/17	11.7	8/26	20.6	7/23	18.9	5/23	12.2

APPENDIX D: DATA COLLECTION ACTIVITIES IN LOWER SNAKE RIVER BASIN, 2002

Table 1. Water Temperature, Other Water-Quality and Flow Data from Lower Snake River and Tributaries

[A separate table at bottom indicates how to contact agency for data; us = upstream; N = north; S = south; Br = bridge; NF = North Fork; RM = River Mile; SF = South Fork; ds = downstream; nr = near; St = street; R = river; lb = left bank:pt = point; therm = thermistor; opp = opposite; m = meters; ig = incremental gap between recorded temperatures; TDG = total dissolved gas; Bar = barometric pressure; DO = dissolved oxygen; SP = Specific Conductance]

Site name/number	Latitude	Longitude	RM	Agency	Data type	Season	Interval	Site location	Sampling info.	QA	Comments
Snake River RM 229	45.4600	116.5642	229.8	ID Power	Temp	1/1/02-1/13/03	hourly		Therm in stream	calibrated	
Snake River RM 202	45.7786	116.5921	202.3	ID Power	Temp	1/1/02-1/13/03	hourly		Therm in stream	calibrated	
Snake River RM 170	46.0756	116.9569	169.8	ID Power	Temp	1/1/02-1/13/03	hourly		Therm in stream	calibrated	
Snake R US Grande Ronde R (SNKCLW01)	46.07638	116.95945	169.7	ID DEQ	Temp	5/30/02 to 11/13/02	30 min	Stream bottom	Therm in stream	Unknown	
Snake R us Grande Ronde R	?	?	?	USACE-1	Temp TDG SC	7/30/02-8/6/02	15 min		Hydrolab at 3m	calibrated	
Snake R us Grande Ronde R	?	?	?	USACE-1	Temp	7/30/02-8/6/02	15 min		Thermistor in stream	calibration	
Grande Ronde R	?	?	?	USACE-1	Temp	7/30/02-8/6/02	15 min	Stream bottom	Thermistor in stream	calibration	
Grande Ronde R	?	?	?	USACE-1	Temp SC	7/30/02-8/6/02	15 min	Stream bottom	Hydrolab in stream		instrument was tampered with while in stream
Snake R at Anatone (13334300)	46.0972	116.9767	167.2	USGS-1	Temp, Flow	1/1/02 to 12/31/02	15 min	Left bank	Real-time fixed monitor	Preliminary data	
Snake R at Anatone (ANQW)	46.0972	116.9767	167.2	USACE-3	Temp TDG Bar	3/27/02 to 8/29/02 3/27/02 to 7/31/02 3/27/02 to 8/29/02	hourly	Left bank	Real-time fixed monitor	Unknown Calibrated Unknown	Depth unknown temp & TDG affected by Grande Ronde R
Snake R ds Anatone	?	?	?	USACE-1	Temp TDG SC	7/30/02-8/6/02	15 min	Right Bank	Hydrolab at 1.5m	Calibrated Calibrated Calibrated	
Snake R ds Anatone	?	?	?	USACE-1	Temp TDG SC	7/30/02-8/6/02	15 min	Left Bank	Hydrolab at 5.5m	Calibrated Calibrated Calibrated	
Snake River RM 165	46.1104	116.9503	165.7	ID Power	Temp	1/1/02-1/13/03	hourly		Therm in stream	calibrated	
Snake River RM 156	46.2181	116.9595	156.7	ID Power	Temp	1/1/02-1/13/03	hourly		Therm in stream	calibrated	
Snake R at backwater interface	46.3443	117.0517	145.25	U of ID	Temp	May-Oct	hourly	Center of stream	2-3m, median, 1 m from bottom		
Snake R at backwater interface	46.3443	117.0517	145.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Snake R at Southway St Br (Site 9)	46.39483	117.03932	141.4	PNNL	Temp	June - Oct	15 min	us bridge pier	Thermistor string at each 2 m	cal check	
Snake R nr Lewiston	46.4154	117.0337	139.9	U of ID	Temp	May - Oct	monthly	4 pt transect	each m of depth, twice in Jul and Aug		

Site Name/Number	Latitude	Longitude	RM	Agency	Data type	Season	Interval	Site location	Sampling info.	QA	Comments
Snake R at Bridge St Br (Site 8)	46.42025	117.03661	139.6	PNNL	Temp	June - Oct	15 min	us bridge pier	Thermistor string at each 2 m	cal check	
Snake R at Clarkston-Lewiston Br	46.42040	117.03480	139.5	USGS-2	Temp	July - Aug	15 min		Depths of 0.5, 1.5, 3, 5, 7, 9m		
Clearwater R us SF Clearwater R (SNKCLW06)	46.14597	115.97957	74.7	ID - DEQ	Temp	6/1/02 to 10/30/02	30 min	stream bottom	Therm in stream		
Clearwater R at Orofino (13340000)	46.4785	116.2563	44.6	USGS-3	Temp, Flow	1/1/02 to 12/31/02	15 min	gaging station	Real-time fixed monitor		
Clearwater R us NF Clearwater R (SNKCLW07)	46.49837	116.30502	41.8	ID - DEQ	Temp	6/1/02 to 11/1/02	30 min	stream bottom	Therm in stream		
NF Clearwater R, Dworshak Pool (DWKFB)	46.51623	116.29458	2	USACE-1	Temp	6/10/02 to 11/25/02	15 & 30 min	us of dam	Depths of 0.5, 1.5, 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60 m	ig = 0.02 and 0.16 °C	Corrected for bias
Dworshak Dam forebay (T1-T21)	46.5153	116.295	1.9	USACE-2	Temp	Apr - Oct.	daily	face of dam	21 therm at \various depths		
Dworshak powerhouse tailwater (DWKDTD)	46.51483	116.29895	1.9	USACE-1	Temp	6/10/02 or 11/25/02	15 & 30 min	draft tube deck	Single thermistor	therm replicate after 8/13/03 ig = 0.02 °C	Corrected for bias
Dworshak tailwater (DWKTW)	46.51135	116.30101	1.8	USACE-1	Temp	8/13/02 to 11/25/02	15 & 30 min	nr left bank	Replicate thermistors	ig = 0.02 °C	Corrected for bias
NF Clearwater River ds Dworshak Dam (DWQIP5)	46.50380	116.32510	0.1	USACE-1	Temp	8/13/02 to 11/25/02	15 & 30 min	right bank	Replicate thermistors	ig = 0.02 °C	Corrected for bias
Dworshak Dam tailrace (DWQI) at mouth NF Clearwater R	46.5031	116.3217	0.1	USACE-3	Temp TDG Bar	1/1/02 to 12/31/02 1/1/02 to 12/31/02 1/1/02 to 12/31/02	hourly	lb at fish hatchery	Real-time fixed monitor	Unknown Unknown Unknown	Missing data Some bad data Missing data
Clearwater R ds of NF (PEKI)	46.5406	116.3919	36	USACE-3	Temp TDG Bar	3/27/02 to 10/8/02 3/27/02 to 12/31/02 3/27/02 to 12/31/02	hourly	lb	Real-time fixed monitor	Unknown Unknown Unknown	Scroll case data every 24 hours
Clearwater R nr Peck (13341050)	46.5000	116.3917	37.4	USGS-3	Temp, Flow	1/1/02 to 12/31/02	15 min	gaging station	Real-time data		
Clearwater R at Spalding (13342500)	46.4486	116.8264	11.6	USGS-4	Temp, Flow	1/1/02 to 9/30/02	15 min	discharge station	Real-time fixed monitor		
Clearwater R at Lapwai Creek / Spalding (SNKCLW05)	46.45072	116.82292	11.6	ID - DEQ	Temp	6/1/02 to/10/30/02	30 min	stream bottom	Therm in water		
Clearwater R nr Lewiston (LEWI)	46.4350	116.9600	4	USACE-3	Temp Tdg Bar	3/27/02 to 10/7/02 3/27/02 to 10/7/02 1/1/02 to 1/28/02, 3/14/02 to 3/20/02, 3/27/02 to 10/7/02	hourly	Right bank	Real-time fixed monitor	Unknown Unknown Unknown	
Clearwater R nr backwater interface	46.4249	116.985	2.8	U of ID	Temp	May - Oct	hourly	Center of stream	2-3m, median, 1 m from bottom		
Clearwater R nr backwater interface	46.4249	116.985	2.8	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Clearwater R, Site 11, Lewiston Mem. Br	46.41942	117.00001	2	PNNL	Temp	6/25/02-12/17/02	15 min	us bridge pier	every 2 m in depth	cal check	
Clearwater R, Site 10, Railroad Br	46.42599	117.02516	0.5	PNNL	Temp	6/25/02-9/25/02	15 min	us bridge pier	every 2 m in depth	cal check	
Clearwater R at Railroad Br	46.42599	117.02516	0.5	USGS-2	Temp	July - Aug	15 min		Depths of 0.5, 1.5, 3, 5, 7, 9 m		
Snake R ds Clearwater, Site 7	46.42555	117.04097	139.2	PNNL	Temp	6/26/02-7/12/02 8/7/02-9/25/02	15 min	Nr center of stream	string every 2 m	cal check	
Snake R nr Lewiston	46.4265	117.0408	139.0	U of ID	Temp	May - Oct	monthly	4 pt transect	each m of depth, twice in Jul and Aug		

Site Name/Number	Latitude	Longitude	RM	Agency	Data type	Season	Interval	Site location	Sampling info.	QA	Comments
Snake R ds Clearwater, Site 6	46.43012	117.04423	138.8	PNNL	Temp	6/26/02-9/25/02	15 min	Nr center of stream	every 2 m in depth	cal check	
Snake R nr Lewiston	46.4230	117.0744	138.0	U of ID	Temp	May - Oct	monthly	4 pt transect	each m of depth, twice in Jul and Aug		
Snake R, Site 5, us Red Wolf Br	46.42532	117.07227	137.5	PNNL	Temp	6/26/02-12/17/02	15 min	At Red Wolf Bridge	every 2 m in depth	cal check	
Snake R at Red Wolf Br	46.42425	117.07131	137.5	USGS-2	Temp	7/4/2002 - 8/19/2002	15 min	At Red Wolf Bridge	Depths of 0.5, 1.5,		
Snake R in Lower Granite Pool	46.4241	117.0733	137.25	U of ID	Temp	6/28/02-11/18/02	hourly	Center of river	Depths of 3, 6, 12 m		
Snake R in Lower Granite Pool	46.4241	117.0733	137.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Snake R nr Lewiston	46.4216	117.0784	137.0	U of ID	Temp	May - Oct	monthly	4 pt transect	each m of depth, twice in Jul and Aug		
Snake R, Site 4, us Silcott Island	46.42309	117.17505	132	PNNL	Temp.	6/26/02-9/26/02	15 min	Left Bank	every 2 m in depth	cal check	
Snake R, Site 3, us Silcott Island	46.42519	117.17593	132	PNNL	Temp	6/26/02-8/8/02 8/9/02-9/26/02	15 min	Right Bank	every 2 m in depth	cal check	
Snake R, Steptoe Canyon barge	46.4525	117.2092	128	USGS-2	Temp	July - Aug	15 min		Depths of 0.5, 1.5, 3, 5, 7, 10, 14 m		
Snake R in Lower Granite Pool	46.4558	117.2125	127.75	U of ID	Temp	6/19/02-11/19/02	hourly	Center of river	Depths of 3, 13, 27 m		
Snake R in Lower Granite Pool	46.4558	117.2125	127.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Lower Granite Pool, Site 2	46.49265	117.23254	125	PNNL	Temp	6/27/02-8/8/02 8/9/02-9/26/02	15 min	Nr center of stream	every 2 m in depth	cal check	
Snake R, Water Canyon barge	46.57960	117.30330	117	USGS-2	Temp	July - Aug	15 min		Depths of 0.5, 1.5, 3, 5, 10, 15, 20, 26 m		
Lower Granite Pool, Site 1	46.58187	117.31726	116.5	PNNL	Temp	6/27/02-9/26/02	15 min.	Nr right bank	every 2 m in depth	cal check	
Snake R in Lower Granite Pool	46.6414	117.3839	110.25	U of ID	Temp	6/19/02-11/19/02	hourly	Center of river	Depths of 3, 18, 36 m		
Snake R in Lower Granite Pool	46.6414	117.3839	110.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Snake R, Lower Granite forebay barge	46.6559	117.3963	109	USGS-2	Temp	July - Aug	15 min		Depths of 0.5, 1.5, 3, 5, 10, 15, 21 m		
Lower Granite Pool (LWG1079A) (LWGFBP2)	46.65604	117.42195	107.90	USACE-1	Temp	6/11/02 to 11/25/02	15 and 30 min	Therm. string nr lb	Depths of 0.5, 1.5, 3, 5, 10, 15, 20, 25, 30, 35 m	ig = 0.02 and 0.16 ^{o}C	Corrected for bias
Lower Granite Pool (LWG1079B) (LWGFBP3)	46.66074	117.41808	107.90	USACE-1	Temp	6/11/02 to 11/25/02	15 and 30 min	Therm. string nr rb	Depths of 0.5, 1.5, 3, 5, 10. 15, 25 m	ig = 0.02 and 0.16 ^{o}C	Corrected for bias
Lower Granite Pool (LWGFX)	46.58297	118.02632	107.60	USACE-1	Temp	6/11/02 to 11/25/02	15 and 30 min	Fish ladder exit	Depths of 0.5, 1.5, 3, 5, 10, 15, 20 m	ig = 0.02 and 0.16 ^{o}C	Corrected for bias
Lower Granite forebay (LWG)	46.6592	117.4250	107.6	USACE-3	Temp TDG Bar	1/1/02 to 12/31/02 1/1/02 to 12/31/02 1/1/02 to 12/31/02	hourly	Dam face	About 15 foot depth, real-time data	Unknown Calibration Unknown	Nonrepresentative temp & bar at times
Lower Granite Dam	46.6592	117.4250	107.5	USACE-3	Temp	3/6/02 to 12/13/02	daily	Scroll case	Read manually		
Lower Granite powerhouse tailwater (LWGDTD)	46.65792	117.43135	107.5	USACE-1	Temp	5/21/02 - 11/25/02	15 and 30 min	Off of turbine 3	Replicate thermistors	ig = 0.02 and 0.16 ^{o}C	Corrected for bais

Site Name/Number	Latitude	Longitude	RM	Agency	Data type	Season	Interval	Site location	Sampling info.	QA	Comments
Lower Granite tailrace (LGNW)	46.6661	117.4383	106.8	USACE-3	Temp TDG Bar	1/1/02 to 12/31/02 1/1/02 to 12/31/02 1/1/02 to 12/31/02	hourly	Right bank	About 15 foot depth, real-time data	Unknown Calibration Unknown	
Snake R in Little Goose Pool	46.6252	117.8522	81.25	U of ID	Temp	7/17/02-11/22/02	hourly	Center of river	Depths of 3, 14, 28 m		
Snake R in Little Goose Pool	46.6252	117.8522	81.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Little Goose Pool (LGS0700A) (LGSFBP1)	46.58497	118.01835	70.6	USACE-1	Temp	5/21/02 to 11/26/02	30 min	Therm. string Nr left bank	Depths of 0.5, 3, 5, 10, 25, 40 m	ig = 0.16 ^oC	Corrected for bais
Little Goose Pool (LGS0700B) (LGSFBP2)	46.58646	118.02011	70.6	USACE-1	Temp	6/11/02 to 11/26/02	30 min	Therm. string Center of river	Depths of 0.5, 1.5, 3, 5, 10, 15, 20, 25, 30, 35 m	ig = 0.02 and 0.16 ^oC	Corrected for bias
Little Goose Pool (LGS0700C) (LGSFBP3)	46.58830	118.02031	70.6	USACE-1	Temp	6/11/02 to 11/26/02	30 min	Therm. string Nr right bank	Depths of 0.5, 1.5, 3, 5, 10, 20, 35 m	ig = 0.02 and 0.16 ^oC	Corrected for bais
Little Goose Pool (LGSFX)	46.58297	118.02632	70.5	USACE-1	Temp	6/20/02 to 11/26/02	15 min	Fish ladder exit	Depths of 0.5, 1.5, 3, 5, 10, 15, 20 m	ig = 0.02 ^oC	Corrected for bais
Little Goose forebay (LGS)	46.5847	118.0256	70.5	USACE-3	Temp TDG Bar	3/26/02 to 10/4/02	hourly	Mid channel on dam	About 15 foot depth, real-time data	Unknown Calibration Unknown	Nonrepresentative temp data at times
Little Goose Dam	46.5847	118.0256	70.4	USACE-3	Temp	4/1/02 to 10/31/02	daily	Scroll case	Manually read	Unknown	
Little Goose powerhouse tailwater (LGSDTD)	46.58220	118.02900	70.4	USACE-1	Temp	5/21/02 to 11/26/02	15 & 30 min	Outside gate entrance	Replicate thermistors	ig = 0.02 and 0.16 ^oC	Corrected for bais
Little Goose tailrace (LGSW)	46.5831	118.0419	69.7	USACE-3	Temp TDG Bar	3/26/02 to 10/4/02	hourly	Right bank	About 15 foot depth, real-time data	Unknown Calibrated Unknown	
Tucannon R nr mouth (TRV)	46.5174	118.12920	0.1	USACE-1	Temp	6/11/02 to 11/26/02	30 min		Replicate therm on stream bottom	ig = 0.02 and 0.16 ^oC	Corrected for bais
Palouse R nr mouth (PRV)	46.7436	118.2023	0.1	USACE-1	Temp	5/22/02 to 11/26/02	30 min	Old CR 26 bridge on stream bottom	Replicate therm on stream bottom	ig = 0.02 and 0.16 ^oC	Corrected for bais
Snake R in Lower Monumental Pool	46.5796	118.4904	44.25	U of ID	Temp	7/16/02-11/20/02	hourly	Center of river	Depths of 3, 14, 29 m		
Snake R in Lower Monumental Pool	46.5796	118.4904	44.25	U of ID	Temp	May - Oct	monthly	At therm. site	each m of depth, twice in Jul and Aug		
Lower Monumental Pool (LMN0418A (LMNFBP1)	46.56457	118.53046	41.8	USACE-1	Temp	5/22/02 - 11/26/02	30 min	Therm. string nr lb	Depths of 0.5, 1.5, 3, 5, 10, 25, 40 m	ig = 0.16 ^oC	Corrected for bais
Lower Monumental Pool (LMN0418B (LMNFBP2)	46.56571	118.53154	41.8	USACE-1	Temp	5/22/02 to 11/26/02	30 min	Therm. string nr river center	Depth of 0.5, 1.5, 3, 5, 10, 20, 30 m	ig = 0.16 ^oC	Corrected for bais
Lower Monumental Pool (LMN0418B (LMNFBP3)	46.56719	118.53273	41.8	USACE-1	Temp	5/22/02 to 11/26/02	30 min	Therm. string nr rb	Depths of 0.5, 1.5, 3, 5, 10, 12.5, 15 m	ig = 0.16 ^oC	Corrected for bais
Lower Monumental Forebay (LMN)	46.5631	118.5372	41.7	USACE-3	Temp TDG Bar	3/26/02 to 10/4/02 3/26/02 to 10/4/02 3/26/02 to 10/4/02	hourly	Mid channel on dam	About 15 ft depth, real-time data	Unknown Calibrated Unknown	
Lower Monumental Dam	46.5631	118.5372	41.6	USACE-3	Temp	4/1/02 to 10/31/02	daily	Scroll case	Manual reading	Unknown	
Lower Monumental powerhouse flow (LMNDTD)	46.56345	118.53995	41.6	USACE-1	Temp	5/22/02 to 11/26/02	15 & 30 min	Drafttube deck	Between turbines 2 and 3	Replicate therm. ig = 0.02 and 0.16 ^oC	Corrected for bais
Lower Monumental tailrace (LMNW)	46.5536	118.5475	40.8	USACE-3	Temp TDG Bar	3/26/02 to 10/4/02 3/26/02 to 10/4/02 3/26/02 to 10/4/02	hourly	Left bank	About 15 ft depth, real-time data	Unknown Calibrated Unknown	Missing temp and TDG data

Site Name/Number	Latitude	Longitude	RM	Agency	Data type	Season	Interval	Site location	Sampling info.	QA	Comments
Snake R in Ice Harbor pool	46.2904	118.7890	15.5	U of ID	Temp	7/1/02-11/20-02	hourly	Center of river	Depths of 3, 14, 28 m		
Snake R in Ice Harbor pool	46.2904	118.7890	15.5	U of ID	Temp	May - Oct	monthly	At therm. site	Each m of depth, twice in Jul and Aug		
Snake R in Ice Harbor Pool (IHRO100A) (IHRFBP1)	46.24894	118.87247	10.0	USACE-1	Temp	6/11/02 to 11/26/02	15 & 30 min	Therm. string nr lb	Depths of .5, 1.5, 3, 5, 10, 15, 20 m	ig = 0.02 and 0.16 °C	Corrected for bais
Snake R in Ice Harbor Pool (IHRO100B) (IHRFBP2)	46.25122	118.87372	10.0	USACE-1	Temp	6/11/02 to 11/26/02	15 & 30 min	Therm. string nr rb	Depths of .5, 1.5, 3, 5, 10, 15, 20, 25, 30, m	ig = 0.02 and 0.16 °C	Corrected for bais
Ice Harbor forebay (IHR)	46.2494	118.8783	9.8	USACE-3	Temp	1/1/02 to 12/31/02	hourly	Mid channel on dam	About 15 ft depth,	unknown	
					TDG	1/1/02 to 12/31/02			real-time data	calibration	
					Bar	1/1/02 to 12/31/02				unknown	
Ice Harbor Dam	46.2494	118.8783	9.7	USACE-3	Temp	1/1/02 to 12/31/02	12 or 24 hrs	Scroll case	Manual reading	unknown	
Ice Harbor tailwater (IHRDTD)	46.24813	118.88023	9.7	USACE-1	Temp	6/20/02 to 11/26/02	15 & 30 min	Draft-tube deck	Replicate therm.	ig = 0.02 and 0.16 °C	Corrected for bais
Ice Harbor Tailrace (IDSW)	46.2422	118.9389	6.1	USACE-3	Temp	1/1/02 to 12/31/02	hourly	Right bank	About 15 ft depth,	unknown	Bad & missing data
					TDG	1/1/02 to 12/31/02			real-time data	calibration	Bad & missing data
					Bar	1/1/02 to 12/31/02				unknown	Bad & missing data

ID DEQ = Don Essig, 208-373-0119, dessig@DEQ.State.ID.US

ID Power = Ralph Myers, 208-388-2358, rmyers@idahopower.com; request data with a letter to Ralph Meyers identifying specific data desired and how the data will be used.

PNNL = Chris Cook, Battelle, Chris.Cook@pnl.gov

U of ID = Dave Bennett, 208-885-6337,

USACE-1 = Joe Carroll, 541-298-6656, joe.h.carroll@nwp01.usace.army.mil

USACE-2 = Rick Emmert/Jerry Wren, 509-527-7536, Rick.L.Emmert@usace.army.mil

USACE-3 = Dick Cassidy, 503-808-3938, http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/months.html

USACE-4 = Russ Heaton, 509-527-7282, Russ.D.Heaton@usace.army.mil, http://www.nwd-wc.usace.army.mil/report/tdg.htm or tdo.htm

USGS-1 = Greg Ruppert, 509-547-2571, http://wa.water.usgs.gov/realtime/current.html

USGS-2 = Ken Tiffan, 509-538-2299x279, ken_tiffan@usgs.gov

USGS-3 = Alvin Sablan, 208-387-1399, aasablan@usgs.gov

USGS-4 = H. Russ Christensen, 208-773-4938, hrchrist@usgs.gov

Table 2. Water Temperatures from Fish Ladders in 2002

March 26, 2003

[A separate table at bottom indicates how to contact agency for data; us = upstream; N = north; S = south; ds = downstream; LWG = Lower Granite Dam; LGS = Little Goose Dam; LMN = Lower Monumental Dam; IHR = Ice Harbor Dam; RM = River Mile; QA = Quality Assurance]

Site name/number	Latitude	Longitude	RM	Agency	Data type	Season	Frequency	Site location	Sampling information
LWG Juvenile Collection Channel by Unit 1 (LWGFWT11)	46.6579	117.4293	107.5	USACE-5	Temp	May - Sept.	hourly	Fish Ladder	Thermistor in fish ladder
LWG Juvenile Collection Channel by Unit 6 (LWGFWT12)	46.6586	117.4288	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG Exit Pool (LWGFWT06)	46.6576	117.4294	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG Diffuser 14 (LWGFWT03)	46.6576	117.4302	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG ds Diffuser 14 (LWGFWT04)	46.6581	117.4314	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG Between Lower Diffusers (LWGFWT07)	46.6579	117.4309	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG Junction Pool (LWGFWT05)	46.6579	117.4307	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
N Powerhouse Channel (LWGFWT02)	46.6591	117.4293	107.5	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LWG N Shore Collection Channel (LWGFWT01	46.6607	117.4283	107.5	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water
LWG Separator (LWGFWT08)	46.65595	117.4335	107.5	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water
LWG Raceway (LWGFWT09)	46.65595	117.4335	107.5	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water
LWG Sample Holding Tank (LWGFWT10)	46.65595	117.4335	107.5	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water
LGS Exit Pool (LGSFWT05)	46.5827	118.0251	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS Primary Dewatering Structure (LGSFWT06)	46.5827	118.0253	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS 2 Pools ds Diffuser No. 13 (LGSFWT01)	46.5826	118.0257	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS Viewing room (LGSFWT10)	46.5826	118.0273	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS Junction Pool - ds side (LGSWT03)	46.5827	118.0259	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS Diffuser 1 S Shore Entrance (LGSFWT02)	46.5827	118.0259	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS N Shore Entrance (LGSFWT04)	46.586	118.0269	70.4	USACE-5	Temp	April - Sept.	hourly	Fish ladder	Thermistor in fish ladder
LGS Separator (LGSFWT07)	46.5823	118.0296	70.4	USACE-5	Temp	April - Sept.	hourly	Smolt collection	Thermistor in flowing water
LGS Raseway 10 (LGSFWT08)	46.5824	118.0297	70.4	USACE-5	Temp	April - Sept.	hourly	Smolt collection	Thermistor in flowing water
LGS B side Sample Holding Tank (LGSFWT09)	46.5824	118.0297	70.4	USACE-5	Temp	April - Sept.	hourly	Smolt collection	Thermistor in flowing water

Site Name/Number	Latitude	Longitude	RM	Agency	Data type	Period	Frequency	Site location	Sampling info.	QA
LMN S Ladder Exit Pool (LMNFWT06)	46.5616	118.5357	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN N Ladder Exit Pool (LMNFWT02)	46.5647	118.5393	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN Juvenile Collection Channel (LMNFWT10)	46.5630	118.5373	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN N Ladder ds Upper Diffuser (LMNFWT03)	46.5645	118.5392	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN S Ladder ds Upper Diffuser (LMNFWT07)	46.5613	118.5363	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN N Ladder us Uppermost Lower Diffuser (LMNFWT04)	46.5640	118.5399	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN S Ladder us Uppermost Lower Diffuser (LMNFWT08)	46.5613	118.5369	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN N Ladder junction pool (LMNFWT01)	46.5643	118.5393	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN S Ladder Entrance (LMNFWT09)	46.5614	118.5365	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN N Ladder end collection channel (LMNFWT05)	46.5600	118.5300	41.6	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
LMN Primary Dewatering (LMNFWT11)	46.5643	118.5403	41.6	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water	
LMN Separator (LMNFWT13)	46.5627	118.5402	41.6	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water	
LMN Sample Holding Tank (LMNFWT14)	46.5627	118.5420	41.6	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water	
LMNRaceway (LMNFWT12)	46.5627	118.5419	41.6	USACE-5	Temp	May - Sept.	hourly	Smolt processing	Thermistor in flowing water	
IHR N Juvenile Collection Channel (IHRFWT12)	46.2489	118.8782	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Collection Juvenile Channel (IHRFWT08)	46.2478	118.878	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Exit Pool (IHRFWT09)	46.2472	118.8779	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR N Ladder Exit Pool (IHRFWT05)	46.251	118.8788	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR N Ladder Upper Junction Pool (IHRFWT01)	46.2506	118.8787	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Upper Diffuser (IHRFWT07)	46.2473	118.8782	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR N Ladder Upper Diffuser (IHRFWT03)	46.2507	118.8796	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR N Ladder Bottom Diffuser (IHRFWT04)	46.2505	118.8797	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Bottom Diffuser (IHRFWT06)	46.2469	118.8795	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Collection Chamber (IHRFTW11)	46.2489	118.8792	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR S Ladder Junction Pool (IHRFWT10)	46.2494	118.8783	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	
IHR N Ladder Lower Junction Pool (IHRFWT02)	46.2494	118.8783	9.7	USACE-5	Temp	May - Sept.	hourly	Fish ladder	Thermistor in fish ladder	

USACE-5 = Gene Spangrude, 509-527-7292, Gene.R.Spangrude@usace.army.mil

Table 3. Locations and Types of Meteorlogical Data Collected in 2002

[NWS = National Weather Sevice; COOP = Cooperative Westher Station with the National Weather Service]

Site name	Source	Latitude	Longitude	Elevation (ft)	Starting date	Ending date
Dworshak/Dent Acres (DENI)	AgriMet	46.62333	116.22056	1660	4/19/2002	12/31/2002
Hermiston (HERO)	AgriMet	45.82111	119.51222	550	1/1/2002	12/31/2002
Hermiston (HRMO)	AgriMet	45.81944	119.28333	607	1/1/2002	12/31/2002
Lake Bryan/Rice Bar (LBRW)	AgriMet	46.68750	117.65417	630	4/18/2002	12/31/2002
Silcott Island (SILW)	AgriMet	46.41861	117.18472	825	7/17/2002	12/31/2002

Parameters, units and frequency of data available from AgriMet

AgriMet recorded air temperature in ^{o}F every 15 minutes, cumulative precipitation in inches every hour, cumulative solar radiation in Langleys every hour, dew point temperature in^{o}F every 15 minutes, relative humidity in percent every 15 minutes, wind speed in nautical miles per hour every hour, peak wind gusts in nautical miles per hour every 15 minutes, wind direction in degrees azimuth every 15 minutes, cumulative wind run in miles every hour, and barometric pressure in inches of mercury every hour.

Comments about AgriMet data

Barometric pressure converted to millimeters of mercury in database.
Peak wind gusts and wind speed converted to miles per hour.

Site name	Source	Latitude	Longitude	Elevation (ft)	Starting date	Ending date
Pasco (24168) or (KPSC)	NWS	40.45	119.20	407	1/1/2002	12/31/2002

Parameters, units and frequency of data available from NWS

NWS recorded air temperature in ^{o}F, dewpoint in ^{o}F, relative humidity in percent, windspeed in miles per hour, peak wind gusts in miles per hour, wind direction in degrees azmith, barometric pressure corrected for mean sea level in millibars, cloud cover in eighths of the sky, cloud height in hundreds of feet, visibility in miles and incremental rain in inches.

Comments about NWS data

Barometric pressure converted to millimeters of mercury in database.

Site name	Source	Latitude	Longitude	Elevation (ft)	Starting date	Ending date
Lewiston-Nez Perce County Airport (105241)	COOP	49.37	117.02	1436	1/1/2002	12/31/2002
Dworshak Fish Hatchery	COOP	46.50	116.32	995	1/1/2002	12/31/2002
Asotin 14 SW (450294)	COOP	46.20	117.25	3499	1/1/2002	12/31/2002
Ice Harbor Dam (453883)	COOP	46.25	118.87	368	1/1/2002	12/31/2002
Kennewick (454154)	COOP	46.22	119.10	390	1/1/2002	12/31/2002
Richland (457015)	COOP	46.32	119.27	372	1/1/2002	12/31/2002
Eltopia 8 SWS (452542)	COOP	46.40	119.17	700	1/1/2002	12/31/2002

Parameters, units and frequency of data available from COOP sites

COOP stations recorded daily maximum, minimum and observed temperature in ^{o}F and daily precipitation in inches.

Table 4. Operations Data for Lower Snake Dams in 2002

[A separate table at bottom indicates how to contact agency for data; RM = River Mile; MWH = megawatt hours;
[MW = megawatts; KCFS = thousands of cubic feet per second; KAF = thousands of acre feet]

Site name/number	Latitude	Longitude	RM	Agency	Season	Data type	Units	Frequency
Dworshak Dam	46.5153	116.2950	1.9	USACE-4	1/1/02 to 12/31/02	Reservoir storage	KAF	Mean daily
Lower Granite Dam	46.6592	117.4250	107.5	USACE-4	1/1/02 to 12/31/02	Lewiston gage height at midnight	feet	Mean daily
Little Goose Dam	46.5847	118.0256	70.4	USACE-4	1/1/02 to 12/31/02			
Lower Monumental Dam	46.5631	118.5372	41.6	USACE-4	1/1/02 to 12/31/02			
Ice Harbor Dam	46.2494	118.8783	9.7	USACE-4	1/1/02 to 12/31/02			

All of the following data types are available from each of the dams

Total power generation	MWH	Daily
Power generation	MW	Mean daily
Total power used by station	MWH	Daily
Inflow to dam	KCFS	Mean daily
Total flow from dam	KCFS	Mean daily
Outflow through powerhouse	KCFS	Mean daily
Outflow over spillway	KCFS	Mean daily
Reservoir elevation at midnight	feet	Daily
Reservior elevation at forebay	feet	Mean daily
Water elevation at tailwater	feet	Mean daily
Head	feet	Mean daily

Site name/number	Latitude	Longitude	RM	Agency	Season
Dworshak Dam	46.5153	116.2950	1.9	USACE-3	1/1/02 to 12/31/02
Lower Granite Dam	46.6592	117.4250	107.5	USACE-3	1/1/02 to 12/31/02
Little Goose Dam	46.5847	118.0256	70.4	USACE-3	1/1/02 to 12/31/02
Lower Monumental Dam	46.5631	118.5372	41.6	USACE-3	1/1/02 to 12/31/02
Ice Harbor Dam	46.2494	118.8783	9.7	USACE-3	1/1/02 to 12/31/02

All of the following data types are available from each of the dams

Data type	Units	Frequency
Outflow over spillway	KCFS	Hourly
Total flow from dam	KCFS	Hourly
Reservoir elevation at forebay	feet	Hourly
Water elevation at tailwater	feet	Hourly

Site name/number	Latitude	Longitude	RM	Agency	Season	Spill gates	Power turbines
Lower Granite Dam	46.6592	117.4250	107.5	USACE-2	4/18/02 to 12/31/02	8	6
Little Goose Dam	46.5847	118.0256	70.4	USACE-2	3/1/02 to 12/31/02	8	6
Lower Monumental Dam	46.5631	118.5372	41.6	USACE-2	5/1/02 to 12/31/02	8	6
Ice Harbor Dam	46.2494	118.8783	9.7	USACE-2	5/1/02 to 12/31/02	10	6

All of the following data types are available from each of the dams

Data type	Units	Frequency
Reservoir elevation at forebay	feet	5 minute
Water elevation at tailwater	feet	5 minute
Head	feet	5 minute
Generation for each turbine	MW	5 minute
Discharge for each turbine	KCFS	5 minute
Gate setting for each spillway	Setting	5 minute
Discharge for each spillway	KCFS	5 minute
Total power generation	MW	5 minute
Total discharge through powerhouse	KCFS	5 minute
Total discharge over all spillways	KCFS	5 minute
Total discharge for dam	KCFS	5 minute

USACE-2 = Rick Emmert/Jerry Wren, 509-527-7536, Rick.L.Emmert@usace.army.mil

USACE-3 = Dick Cassidy, 503-808-3938, http://www.nwd-wc.usace.army.mil/tmt/wed/tdg/months.html

USACE-4 = Dick Cassidy, 503-808-3938, http://www.nwd-wc.usace.army.mil/ftppub/project-data/daily/(dam name).txt
Dam names are as follows: ihr = Ice Harbor Dam, lmn = Lower Monumental Dam, lgs = Little Goose Dam and lwg = Lower Granite Dam

Appendix E. Lower Snake River Temperature/Water Quality Studies 2002

Walla Walla District
Engineering Research and Development Center
Corps of Engineers

Prepared by Joe Carroll with Kathryn Barko

April 15, 2003

Appendix E. Lower Snake River Temperature/Water Quality Studies 2002

Introduction

Background/Problem Statement. Water temperature and associated water quality processes are known to have significant effects on both the indigenous biological community as well as the anadromous fishes in the Columbia River system. Continued development and refinement of the understanding of system wide aquatic thermal processes could greatly enhance our ability to manage project operation for the Lower Snake River projects.

The National Marine Fisheries Biological Opinion for 2000 (NOAA, 2000) lists 199 “Reasonable and Prudent Alternatives” (RPAs) which address environmental concerns in the Snake River System. Alternatives 131, 132, 133, and 143 specifically address total dissolved gas and temperature issues in relation to fish passage and survival. Successful completion of these RPAs will depend to some extent on adequate water temperature data for the system. All future analytical water research tasks will remain dependent on the support of adequate water temperature data for system characterization. This need has been reviewed and pointed out by research efforts by the Environmental Protection Agency (EPA), the University of Idaho (UI), the US Fish and Wildlife Service, Idaho Power, Inc. (IDPWR), the Corps of Engineers (COE), the Pacific Northwest National Laboratory (PNNL), and Tribal water quality agencies. RPA 143 specifically states:

> *“The Action Agencies shall develop and coordinate with NMFS and EPA on a plan to model the water temperature effects of alternative Snake River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NMFS, and state and Tribal water quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations.”*

Spatial gradients in water temperature have significant influence on community metabolism, dissolved gas tension and saturation, mixing processes, biological communities, chemical and biological reaction rates, and other aquatic processes. Any efforts to better understand the biological and physical processes in the river system can benefit from a more complete description of the thermal gradients and processes associated with the Lower Snake River hydropower projects.

Historical trend evaluations, impact assessment, management strategies, and abatement investigations and initiation can all benefit from a comprehensive representative long-term water quality monitoring system operated throughout the river system. The current COE monitoring system does not address vertical or horizontal gradients in temperature that may exist in some of the project forebays. Nor does it effectively monitor powerhouse release temperatures, which may effectively represent mixed conditions of the forebay waters. This system relies on single point/depth monitors for the Snake River projects. Powerhouse water temperatures are recorded manually in most cases using mercury thermometers accurate to ±1° F. Adequate representative sampling of the well-mixed powerhouse release waters could provide needed support to ongoing and future research on the river system.

Previous water temperature monitoring on the Lower Snake River pools done by the University of Idaho has demonstrated dramatic water temperature decreases associated with increased upstream releases (Bennett et al. 1997). This phenomenon is readily observed from the hourly temperature data collected at multiple depths during these studies.

Vertical gradients in reservoir/river water temperature can result from solar warming at the surface coupled with convective exchange as well as advective inflow mixing of different waters such as two separate streams. The hydropower projects on the Lower Snake River are generally classified as short-retention-time, run-of-the-river projects, especially during high flow water years. Wind mixing can also impact them. Due to the high degree of associated mixing, these characteristics will normally impede the development of vertical gradients in temperature and hence density in the water column. Even though vertical temperature gradients in these projects have received little attention for describing the water quality and associated processes, there are events and locations where this phenomenon is significant, at least for short periods of time.

Vertical gradients have been demonstrated to occur in McNary and John Day pools located on the Lower Columbia River and in Lower Granite on the Lower Snake River. Both McNary and Lower Granite have confluences with major secondary tributaries contributing high ratios of often cooler waters, which can result in significant inflow mixing and advective heat exchange processes. This is in addition to the extreme daily solar warming cycles, which occur in this area of the country. Intermittent daily surface water temperature spikes have also been observed at all of the Snake River project forebay water quality stations indicating at least some localized warming of the waters.

Study Phases

Purpose/Goals/Scope. This report describes a water quality study with two major phases or study components. The focus of the study was on patterns in water quality and hydrodynamics determined to be important in addressing questions regarding standard and alternative operation of projects on the Lower Snake and how those operations relate to salmon passage and survival. The study was conducted as a screening study to provide guidance on what future sampling requirements would be needed to continue with trend analysis and characterization of the thermal and water quality patterns. Phase one was a field sampling effort whose primary objective was to characterize thermal and water quality patterns and processes in the Lower Snake River System during the fish passage season of 2002. Since extensive comprehensive field sampling was planned for the Lower Granite pool throughout the spill season by the USGS, PNNL (in conjunction with ongoing thermal modeling studies), and the UI (to monitor water temperatures in lower Snake River reservoirs to enhance the understanding of the thermal dynamics of the reservoirs), this work area focused primarily on Little Goose, Lower Monumental, and Ice Harbor pools. The study area extended from river mile 107 at Lower Granite Dam on the Snake River down to river mile 0 adjacent to the confluence with the Columbia River.

Additional sampling was required in Dworshak pool and downstream to the headwaters of the Lower Granite pool as well as in the area of the Anatone fixed monitor above the Lower Granite pool on the Snake River and upstream to the release from Hells Canyon Dam. Since much of the river upstream of Anatone was monitored by Idaho Department of Environmental Quality (ID DEQ), sampling in this reach was limited to an as-needed basis to fill in where necessary.

The field study was adequate in both temporal and spatial resolution to support the development of a more thorough understanding of the run-of-the-river one-dimensional reaches and time periods, as well as any of the more spatially diverse 2-3 dimensional reaches. The study results describe vertical temperature/density gradients in the water column and in cross sections where appropriate. Particular areas of interest/focus were the forebay areas for pools of interest on the Lower Snake and Dworshak on the Clearwater River with emphasis on both vertical and cross-sectional patterns.

Phase two of the proposed work assimilated all available data for 2002 from the Lower Snake River along with the Phase one field data in a final report addressing the proposed study objectives. Phase two thus required extensive coordination with other ongoing water quality studies on the Lower Snake River. This included work conducted by the PNNL, ID DEQ, and Idaho Power Company, in addition to USGS temperature work in relation to fish movement, UI tri-level temperature studies in Lower Granite Dam, COE temperature sampling in McNary forebay, and COE in-project temperature data collection.

Objectives

- Characterize thermal and water quality patterns in the Lower Snake River System during the 2002 summer and fall period
- Provide guidance on future sampling requirements (screening level study)
- Determine the fate and effects of releases from Dworshak Dam on the Lower Snake River System
- Determine representativeness of the current fixed temperature monitors of river conditions including scroll case temperature monitoring sites as well as the forebay and tailwater water quality monitoring sites

The field study only addressed questions that fell into the operational and discharge range characterized by the 2002 flow year.

Field Sampling Approach. Routine manual *in-situ* profiling of water quality parameters was combined with automated remote water temperature logging (temperature strings) to complete the study. Specific close interval detailed operations data was collected for each project in the study area for the entire season. Additional flow information on secondary tributaries of interest was documented. The study incorporated all available meteorological data in the vicinity of the Lower Snake River. All data was compiled and put into a research database adequate to support required analysis and future research needs.

Field Study Area. The study area extended from Columbia River mile 323 in McNary Pool up the Lower Snake River to the Lower Granite forebay river mile 108 (Figure E.1). Sampling was conducted at selected locations in the Dworshak forebay (Figure E.2), Clearwater River, and at the Anatone water quality monitor at Snake River mile 166-168 near the confluence of the Grande Ronde River with the Snake River (Figure E.3). Sampling was also conducted upstream of the Anatone gage as needed.

Study Design/Methods

Automated Temperature Monitoring. Automated thermal loggers were deployed upstream and downstream of each project in the study reach for the period of mid June through October. The loggers were deployed as a string in a vertical profile starting at the surface (0.5 m) down to 0.5 m off bottom. Sampling emphasis was placed on the depths ranging from the surface down through the thermocline, if present. This concentrated the effort in the region of the more significant temperature gradients. Recommended depths were 0.5 m, 1.5 m, 3 m, 5 m, then at 5 m intervals to within 0.5 m of bottom. Actual depths were determined based on column depth and the possibility of vertical gradients. The vertical profile stations were arranged in lateral transects of 2 to 3 stations to adequately describe the pool/river cross-sections. The lateral stations were spaced at near-equal distances apart, but included one station located in the deepest point (generally the old thalweg). Single logging instruments were placed in the releases from each project where mixed conditions have been documented. Sampling intervals were set at 30 minutes. The download/maintenance schedule was at 2-month intervals.

Primary temperature logging station locations:

1. McNary pool at Columbia River mile 323.4 (Stations MCNFBP1 and MCNFBP2 in Figure E.4) – 2 lateral stations with 6-7 loggers each, station P1 in Snake River flow and station P2 in Columbia River flow
2. McNary pool at Columbia River mile 326 (Station MCNPASCO in Figure E.4) located in the river thalweg
3. Walla Walla River (Station WRV) located upstream of any backwater effects from the Columbia River
4. Ice Harbor draft tube deck (station IHRDTD in Figure E.5) – 2 duplicate instruments in powerhouse release waters

5. Ice Harbor forebay (stations IHRFBP1 and IHRFBP2 in Figure E.5) – 2 lateral stations with 6-7 loggers each adjacent to Boating Restriction Zone (BRZ) boundary markers upstream of the dam
6. Lower Monumental draft tube deck (station LMNDTD in Figure E.6)– 2 duplicate instruments in the powerhouse release waters
7. Lower Monumental forebay (stations LMNFBP1, LMNFBP2, and LMNFBP3 in Figure E.6) – 3 lateral stations with 6-7 loggers each adjacent to forebay BRZ boundary markers upstream of the dam
8. Palouse River (PRV) – 2 duplicate instruments upstream of any backwater effects from Snake River
9. Tucannon River (TRV) – 2 duplicate instruments upstream of any backwater effects from the Snake River
10. Little Goose draft tube deck (station LGSDTD in Figure E.7)– 2 duplicate instruments in powerhouse release waters
11. Little Goose forebay adjacent to fish ladder exit (station LGSFX in Figure E.7
12. Little Goose forebay (stations LGSFBP1, LGSFBP2, and LGSFBP3 in Figure E7)– 3 lateral stations with 6-7 loggers positioned adjacent to BRZ boundary markers upstream of the dam
13. Lower Granite draft tube deck (station LWGDTD in Figure E.8) – 2 duplicate instruments in powerhouse release waters
14. Lower Granite forebay adjacent to fish ladder exit (station LWGFX in Figure E.8
15. Lower Granite forebay (stations LWGFBP1 and LWGFBP2 in Figure E.8) 2 lateral stations with 6-7 loggers positioned adjacent to BRZ boundary markers upstream of the dam
16. Dworshak draft tube deck (station DWKDTD in Figure E.2)– 1 instrument in powerhouse release waters
17. Dworshak forebay (station DWKFB in Figure E.2)– 1 station with 8-10 loggers positioned in the deepest area

Anatone Fixed Monitor Site. Field sampling was conducted to evaluate the representativeness of the Anatone water quality monitor sampling location. This was completed as a one-time effort in the July-August time frame to identify spatial thermal gradients that may be attributed to the confluence and mixing of the Snake and Grande Ronde rivers. The study also quantified any resulting sampling bias. Figure E3 shows the sampling station locations.

Additional Data Sources. Data was collected by various agencies within Idaho, Washington, and Oregon. These agencies include the Corps of Engineers, Idaho Power, Idaho DEQ, USGS, the University of Idaho, and the Pacific Northwest National Laboratory. Depending on the agency, data was collected from every fifteen minutes up to daily intervals. Sites of interest included the Lower Snake, Clearwater, Tucannon, Palouse, Grande Ronde, Salmon, and Imnaha Rivers.

Meteorological Data. Weather data was gathered from one National Weather Service station at Pasco, WA, and three Bureau of Reclamation AgriMet stations with the following locations: on Dworshak pool Dent Acres, ID: Lake Bryan-Rice Bar, WA, near Little Goose Dam: and Silcott Island, WA, upstream in Lower Granite pool. The parameters of interest were wind speed, wind direction, air temperature, barometric pressure, relative humidity, precipitation, and solar radiation. Evaporation was calculated from available measures. The data used was collected at 15-minute intervals.

Project Operations Data. Project operation records were compiled and stored in the database for Ice Harbor, Lower Monumental, Little Goose, Lower Granite, and Dworshak dams. The information was collected on a 15-minute interval with adequate detail to identify which generator units and spillway bays were operating, when they came on/off line, and house unit and other miscellaneous releases (fishways etc) when possible. Discharge by unit/spill bay was logged at each time interval. Records of inflow at Anatone plus secondary stream (Salmon, Clearwater, Palouse, Walla Walla, etc) discharges were included.

Data Management. All data gathered was archived, analyzed, and distributed in Microsoft Excel and Access files. Date used in this report can be acquired through the 2002 Lower Snake River Database. This database is made up of five tables, the hourly temperature data table, the weather data table, the Columbia Rive Operational Hydronet and Management System (CROHMS) data table, the detailed operations data table, and the USGS flow data table. Information found in each of these tables was collected by various agencies within Washington, Oregon, and Idaho. Copies of this database can be provided on CD-rom upon request.

The temperature table is a collection of hourly water temperature data from sites throughout the Snake, Tucannon, Palouse, and Clearwater Rivers. The agencies that took part in collecting this data include the COE, Idaho Power (IDPWR), Idaho DEQ (IDEQ), USGS (USGS), and the Pacific Northwest National Laboratory (PNNL). Since data was collected by various agencies, gaps of data are prevalent in this table. If information such as river, river mile, latitude, and longitude were not collected, they were found by using DCR (Digital Columbia River) or SMS v8.0 software. However, irretrievable data such as missing depths "Thermistor Z (m)" or "Hydrolab Z (m)" were marked –999, while missing string values were left blank. Within this table many abbreviations were used to minimize database size. For example, under the column "Instrument" the letters "T" and "H" specify which type of instruments were used in the sampling procedure, thermistors or hydrolabs. Since two types of Onset thermistors were used the "Model" column specifies whether a Hobo (H) or a StowAway (S) was used to collect the data.

COE, whose main contact is Joe Carroll Joe.H.Carroll@nwp01.usace.army.mil (541-298-6656), collected data from May/June through November 2002. This information was obtained by deploying strings of thermistors located at various depths from the surface to the bottom of the water column. Data was collected in the forebay and drafttube decks of Ice Harbor (IHRFB and IHRDTD), Lower Monumental (LMNFB and LMNDTD), Little Goose (LGSFB and LGSDTD), Lower Granite, and Dworshak Dams (DWKFB and DWKDTD). Temperature data was also collected at the fish exits at Little Goose (LGSFX) and Lower Granite Dams (LWGFX). Near Dworshak, thermistors were also placed in the tailwater (DWKTWP1) and across the river from the fixed monitoring station (DWKQIP5). Lastly, temperatures were collected at stream bottom in the Palouse River (PRV) and the Tucannon River (TRV). Midway through the field season, a replicate thermistor was added to sites that had only one thermistor collecting temperature data. These instruments are signified by a number "2" after the site name such as "PRV-2" or "LWGDTD-2". Subsequent to COE's data collection season all thermistors were placed in a water bath and tested for bias (see column "Bias"). Each instrument's temperature readings were subtracted by their bias and outputted into the column "Corrected Temp C". The COE is the only agency to have done this, so for every other agencies' data "Bias" fields are blank and "Temp C" equals "Corrected Temp C". Missing days, hours, or minutes in the COE's temperature data are due to instrument failure or instruments temporarily pulled out of the water for data retrieval and instrument reprogramming. Failures occurred randomly, while instrument reprogramming occurred on August 12th and 13th and September 4th and 5th.

Idaho Power and Ralph Myers, rmyers@idahopower.com (208-388-2358), collected temperature data along the Snake River near river miles 156, 165, 170, 202, and 229 for the entire 2002-year. At river miles 202 and 229 temperatures were recorded on a daily instead of hourly basis and are not included in the 2002 Lower Snake River Database.

Idaho DEQ and Don Essig, dessig@deq.state.id.us (208-373-0119), collected hourly temperature data from June through November 2002. Thermistors were deployed on the Clearwater River near Kooskia, ID (KOOSKIAIDEQ), the Clearwater River near Orofino, ID (OROFINOIDEQ), and the Clearwater River near Spalding, ID (SPALDINGIDEQ) and on the Snake River above the confluence of the Grande Ronde River (SNKABVGRIDEQ). The thermistors used to collect this information were programmed in Mountain Time and converted to Pacific Time before added to the database.

Data from four USGS sites were added to the hourly temperature table. These sites include the Snake River near Anatone, WA, the Clearwater at Spalding, ID, the Clearwater at Peck, ID, and the Clearwater at Orofino, ID. This data is preliminary and subject to change. Greg Ruppert, gruppert@usgs.gov, is the main point of contact for temperatures collected at the Snake River near Anatone site (MSRM197_2GS) during 2002. This data was converted from Mountain Time to Pacific Time before included in the database. H. Russ Christensen, hrchrist@usgs.gov (208-773-4938), is the main point of contact for temperatures gathered at the Clearwater River at Spalding site (SPALDINGGS) from January through September 2002. Lastly, Alvin Sablan, aasablan@usgs.gov (208-387-1399), is the main point of contact for data collected at both the Peck (PECKIDEQ) and the Orofino (OROFINOIDEQ) sites on the Clearwater River over the 2002-year.

Data collected by the Pacific Northwest National Laboratory (PNNL) were obtained from Chris Cook, chris.cook@pnl.gov , 509-375-6878. The data set includes 15-minute water temperate data collected at 11 sites throughout the Lower Granite Pool. At each site several loggers were suspended vertically throughout the water column. Data were collected using Onset Optical StowAways, with a stated accuracy of ±0.2°C.

Logger accuracy was confirmed by PNNL by immersing the loggers in a constant temperature bath and using two check points. All loggers were found to perform at or better than the stated accuracy. PNNL reports in progressdocumenting the data collection plan, data analysis, and numerical modeling of the Lower Snake can be obtained by contacting Chris Cook at the address above.

The CROHMS data included in the hourly temperature table was collected by the fixed monitoring sites DWQI, IDSW, IHR, LGS, LGSW, LMN, LMNW, LGNW, LWG, ANQW, LEWI, and PEKI. This information is preliminary and subject to change and can be found at the website http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/months.html. Before information was added to the database depths were converted from feet to meters.

The weather data table includes information collected by AgriMet and NWS weather stations. AgriMet stations collected data at Dworshak-Dent Acres, ID, Lake Bryan-Rice Bar, WA, and Silcott Island, WA every 15 minutes. The National Weather Service station (NWS) collected weather data at Pasco, Washington every hour. Conversion factors were used to obtain the same units of measure for all sites. Barometric pressures from both NWS and AgriMet stations were converted to millimeters of Hg. A column was added and BP (MSL) was converted to absolute pressure. NWS wind speed and wind peak data were converted from nautical miles per hour to statute miles per hour. Lastly, air temperature was converted to degrees Celsius and added to the database as a new column.

The NWS weather data is provisional (subject to change) and was pulled off the website http://www-12.atmos.washington.edu/k12/grayskies/nw_weather.html. The parameters collected include barometric pressure (mmHg), air temperature (Celsius and Fahrenheit), dew point (Fahrenheit), wind direction (clockwise degrees from North), wind speed (statute mph), wind peak (statute mph), cloud cover (8ths of the sky), cloud height (100’s of feet), visibility (miles), relative humidity (%), and incremental precipitation (inches).

Meteorological data from the US Bureau of Reclamation AgriMet stations were pulled off the website http://mac1.pn.usbr.gov/agrimet/ and is provisional. The parameters collected include barometric pressure (mmHg), air temperature (Celsius and Fahrenheit), dew point (Fahrenheit), wind direction (degrees), wind speed (statute mph), wind peak (statute mph), solar radiation (langleys), relative humidity (%), and cumulative precipitation (inches). AgriMet stations rely on solar power to revitalize the (Interstate 31-PHD Workaholic) batteries that keep stations working properly. When batteries run low and adequate sunlight is not available to replenish power, data is not collected. This is most likely the cause for missing data during the months of November and December at the Dworshak/Dent Acres station.

The fixed monitoring sites DWQI, IDSW, IHR, LGS, LGSW, LMN, LMNW, LGNW, LWG, ANQW, LEWI, and PEKI are included in the COE CROHMS data table. This is preliminary data and is subject to change. Data was gathered from the website http://www.nwd-wc.usace.army.mil/tmt/wcd/tdg/months.html and depths were converted from feet to meters before being added to the database. The CROHMS data found in the hourly temperature table includes temperature data only. This table includes not only temperature data but also parameters such as barometric pressure, total dissolved gas, total gas saturation, total spill, total generation, forebay elevation, and tailwater elevation.

The detailed operations table consists of operational data organized by Jerry Wren of The Corps of Engineers-Walla Walla District, Jerry.D.Wren@nww01.usace.army.mil (509-527-7422). Data from Lower Granite, Little Goose, Lower Monumental, and Ice Harbor dams were collected on five-minute intervals. Gate positions, spillway flows, turbine flows, power production, and elevations for each project can be found in this table for the months of May-December at Ice Harbor Dam, March-December at Little Goose Dam, May-December at Lower Monumental Dam and April-December at Lower Granite Dam. Since Ice Harbor Dam is the only project in this table to have a 9th and 10th gate, blank fields are found under the columns G9POS, S9KCFS, G10POS and S10KCFS for LWG, LGS, and LMN dams.

The USGS flow data table includes the sites Snake River near Anatone, WA, the Clearwater River at Spalding, ID, the Clearwater River at Peck, ID, and the Clearwater River at Orofino, ID. This data is preliminary and subject to change. Greg Ruppert, gruppert@usgs.gov, is the main point of contact for flow data collected at the Snake River near Anatone site (MSRM197_2GS) during 2002. This data was converted from Mountain Time to Pacific Time before being included in the database. H. Russ Christensen, hrchrist@usgs.gov (208-773-4938) is the main point of contact for flow data gathered at the Clearwater River at Spalding site (SPALDINGGS) during the 2002-year. Lastly, Alvin Sablan, aasablan@usgs.gov (208-387-1399), is the main point of contact for data collected at both the Clearwater at Peck site (PECKIDEQ) and the Clearwater at Orofino site (OROFINOIDEQ) during 2002. Station numbers are also included in this table, so that additional information can be retrieved off of the USGS website, http://www.usgs.gov/, if desired.

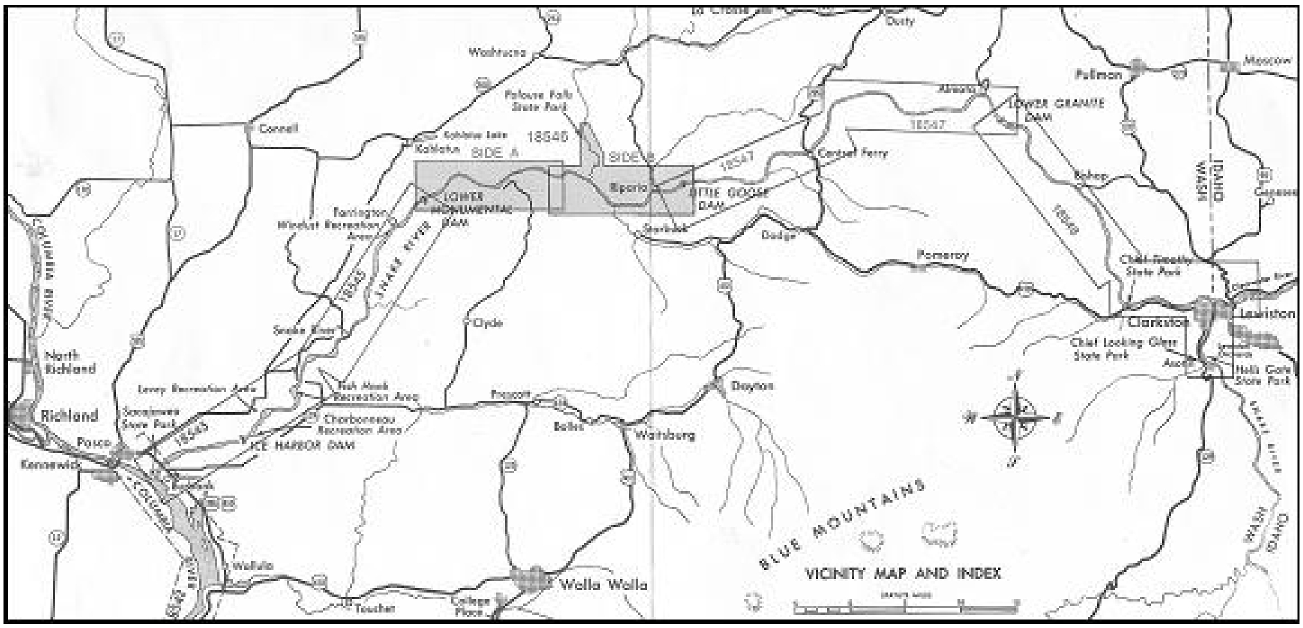


Figure E.1. Study Area for Temperature Monitoring on Lower Snake River Projects.

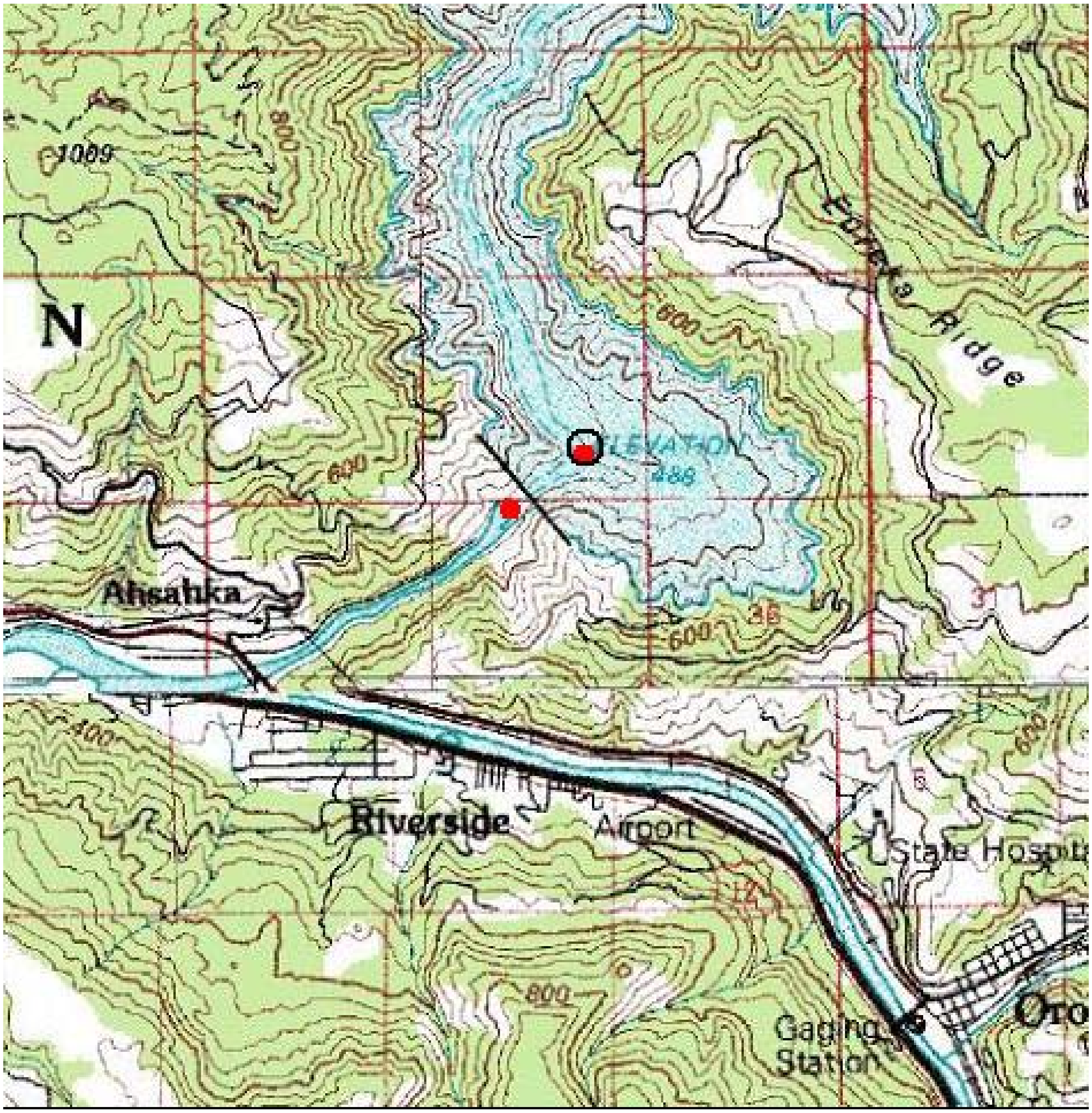


Figure E.2. Dworshak Pool Diagram with *In-Situ* Profile Station Locations (red dot) and Automated Temperature String (circle).

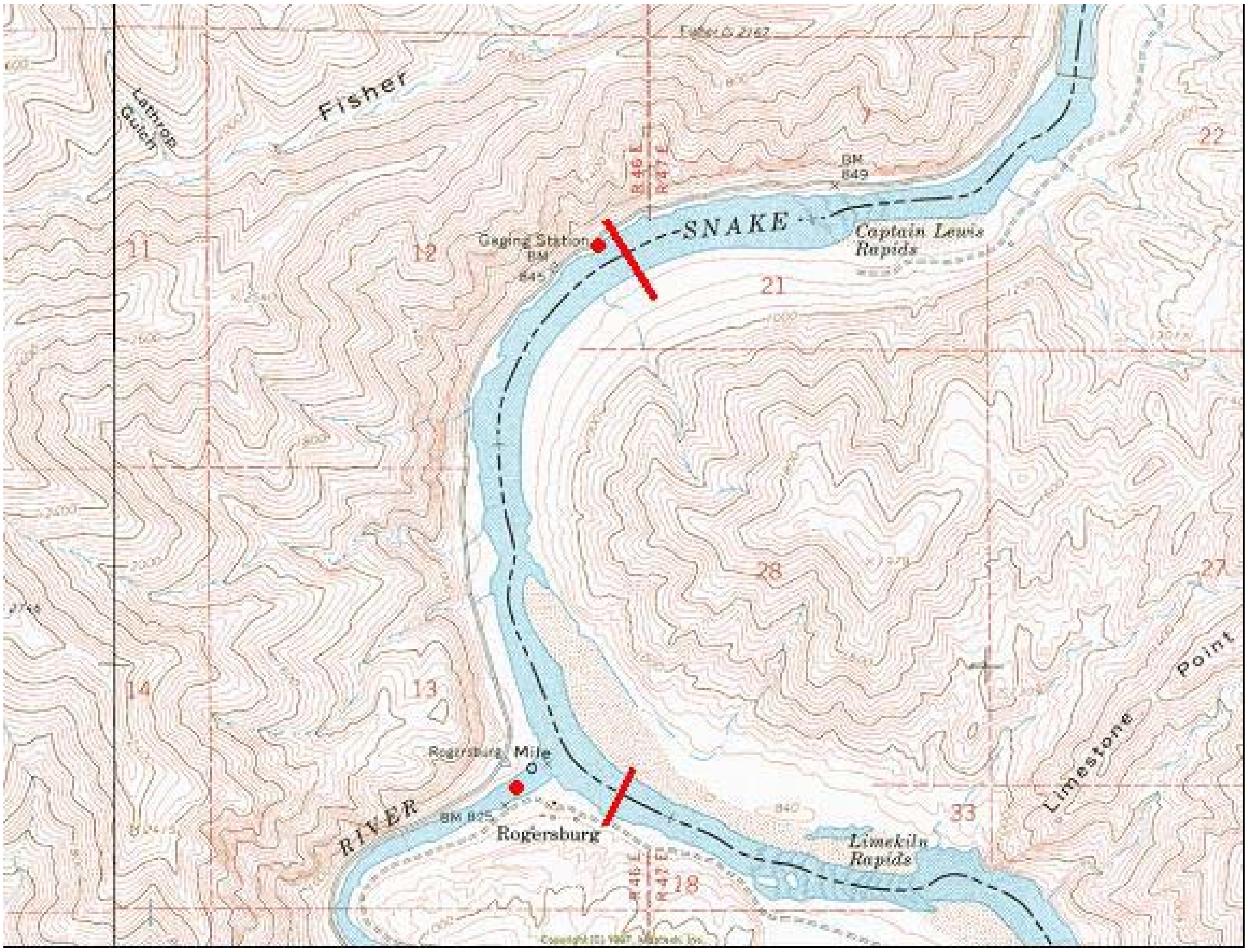


Figure E.3. Lower Snake River Mile 166-168 with Anatone Fixed Monitor Location and Proposed Evaluation Sample Transect (red bars) and Station Locations (red dots).

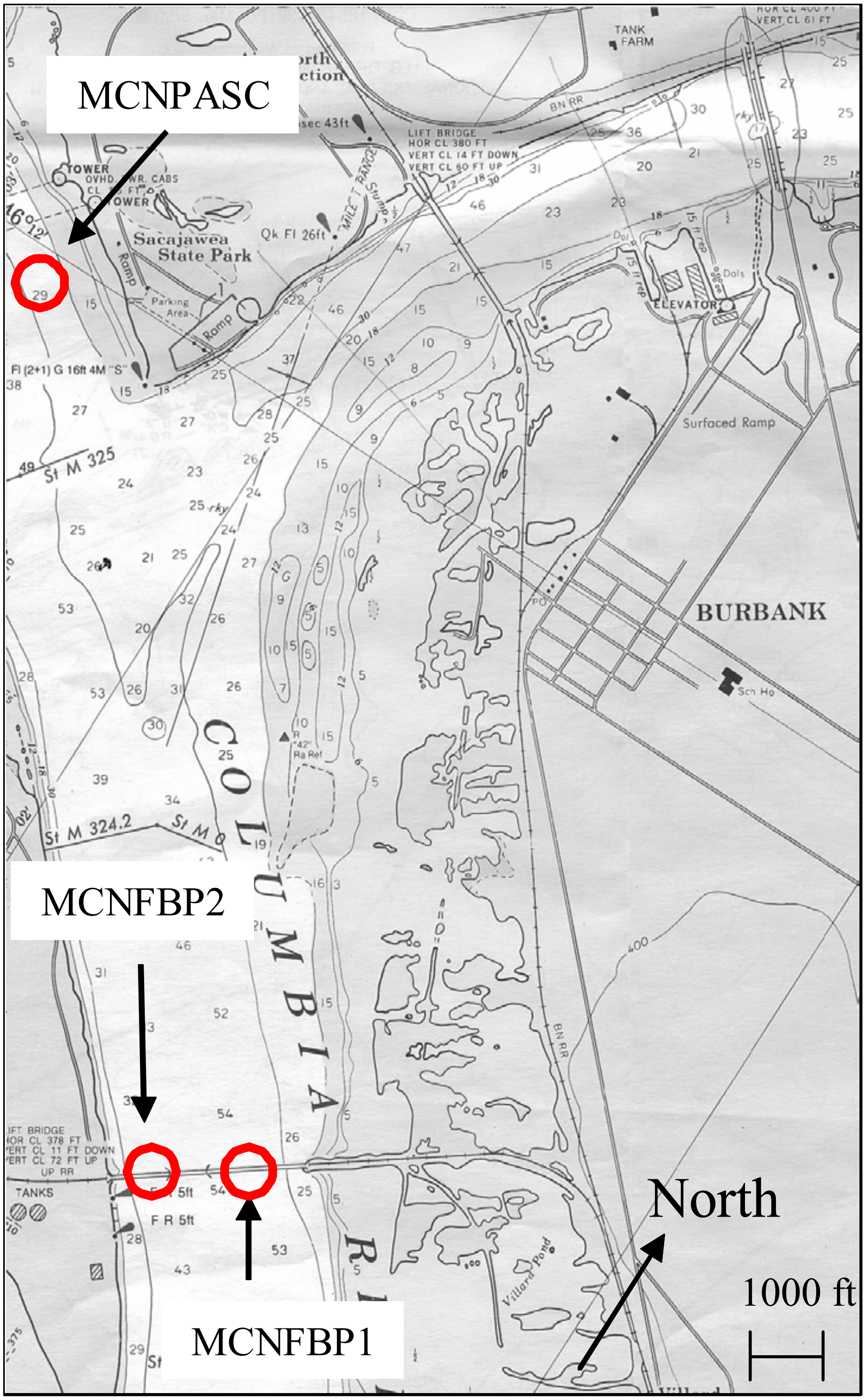


Figure E.4. McNary Pool Logging Temperature String Locations.

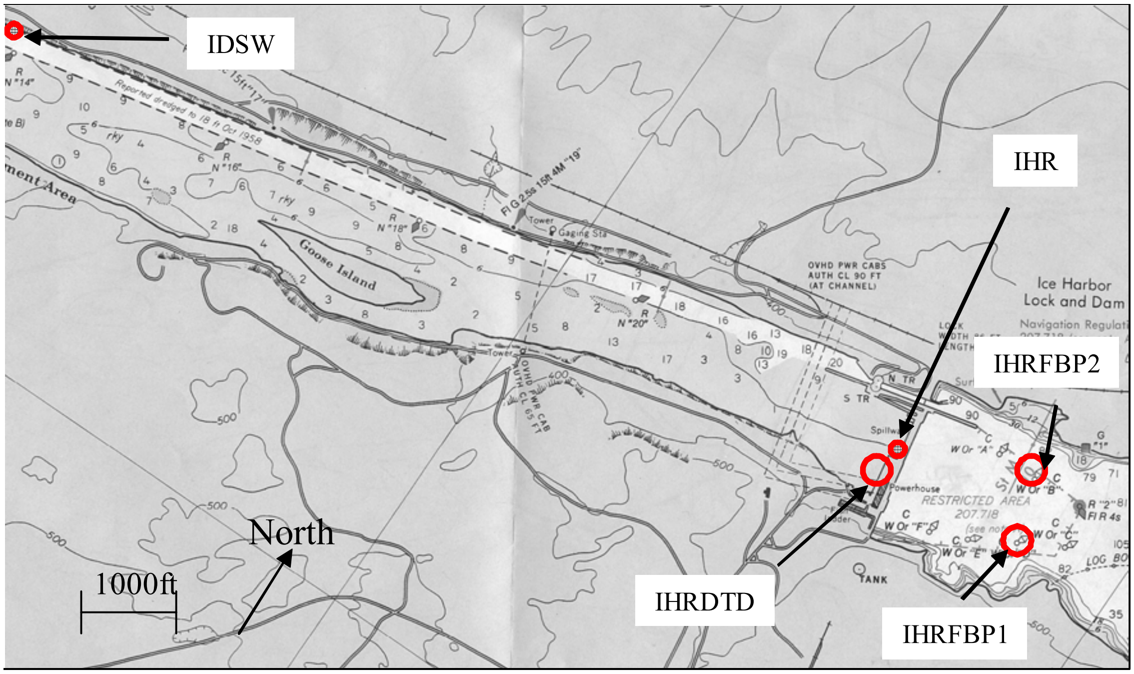


Figure E.5. Ice Harbor Dam with locations of Logging Temperature Strings.

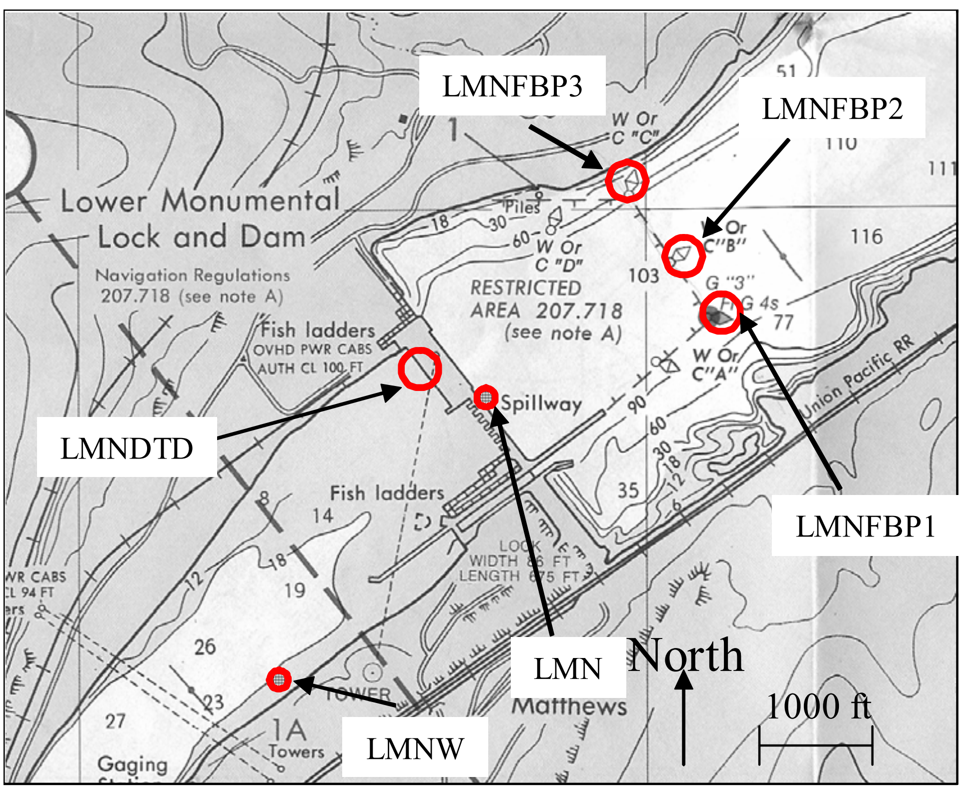


Figure E.6. Lower Monumental Dam with Locations of Logging Temperature Strings.

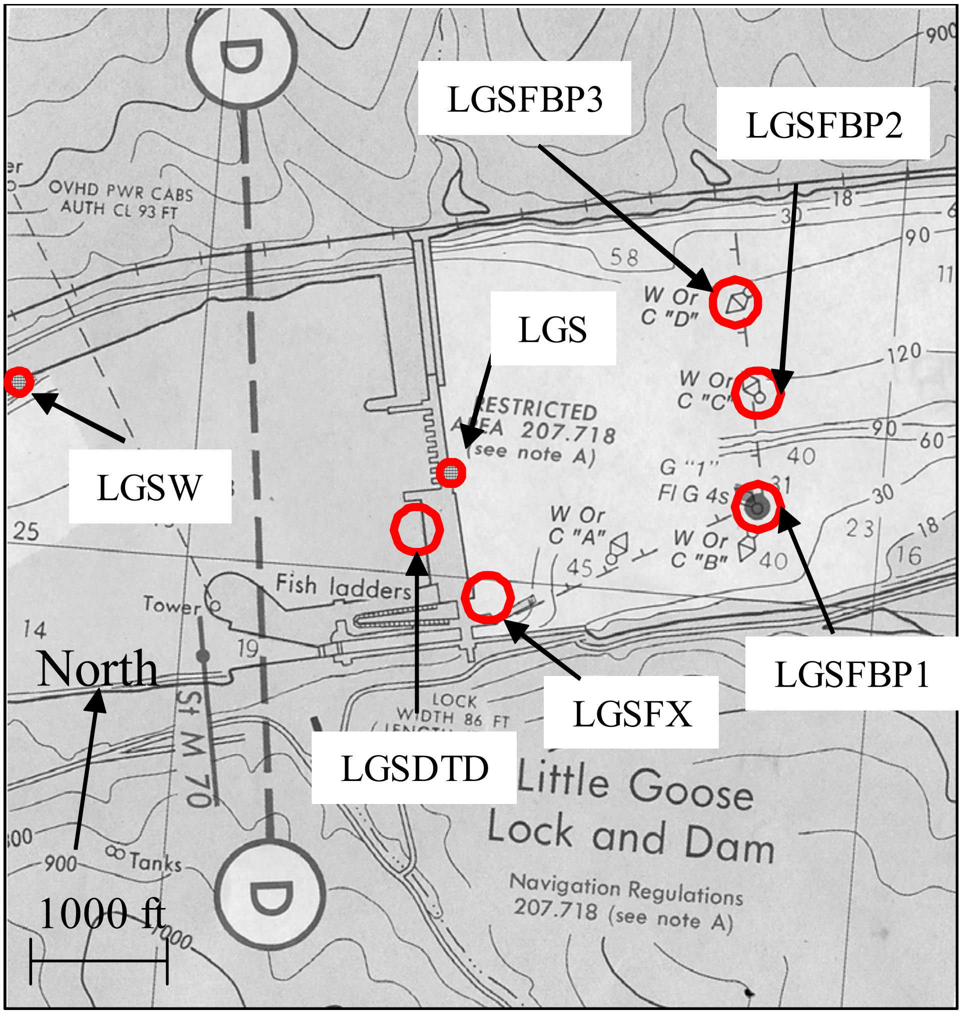


Figure E.7. Little Goose Dam with Locations of Logging Temperature Strings.

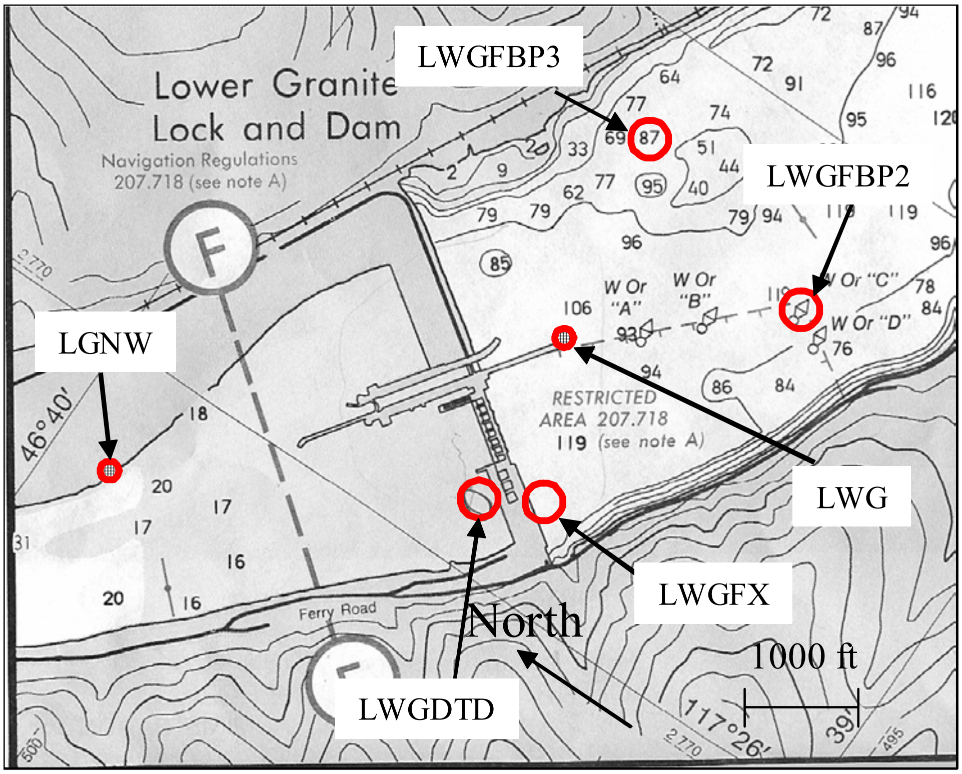


Figure E.8. Lower Granite Dam with Locations of Logging Temperature String.

Results

Project Operations/River Discharge. Figures E.9 through E.13 below describe total river discharge and spill at Dworshak, Lower Granite, Little Goose, Lower Monumental, and Ice Harbor dams during the months of April through November 2002. Releases at these projects began during the first 15 days in April 2002.

Dworshak Dam spilled from early April through mid May, mid June through July 2, and July 9 through the end of August as seen in Figure E.9. The highest day of spill at this project occurred on June 23 and 24 averaging 10.08 kcfs.

Lower Granite Dam (Figure E.10) spilled for the day of February 8. Spill resumed early April and continued through mid July. In mid August through the rest of the season, spill was initiated five times, August 14-15, September 9, and November 26 through the 27. The highest day of spill at this project occurred on June 5 averaging 68.53 kcfs.

Little Goose Dam spilled from early April through mid July and again in late August. The projects highest day of spill occurred on June 2 averaging 64.08 kcfs (Figure E.11).

Lower Monumental Dam's releases were quite less than that of any other Snake River project as seen in Figure E.12. LMN spilled on only two occasions, or a total of eight days during 2002, on April 15 and 16 and May 30 through June 4. The highest day of spill at this project occurred on May 31 averaging 16.27 kcfs.

Ice Harbor Dam (Figure E.13) spilled from mid April through the end of August, mid September and two days in November. Ice Harbor's highest day of spill occurred on June 2 averaging 102.15 kcfs. Compared to the other projects, this dam had the most active spill season of 2002.

.

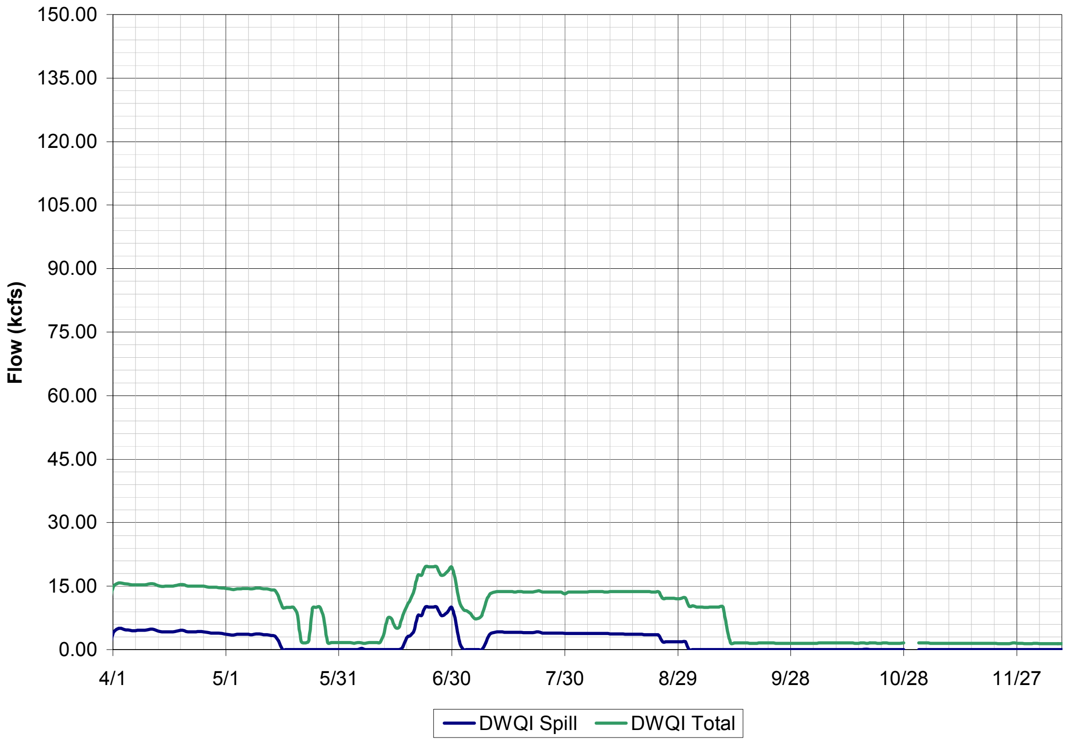


Figure E.9. Average daily total spill and discharge measured at Dworshak Dam, April-November, 2002.

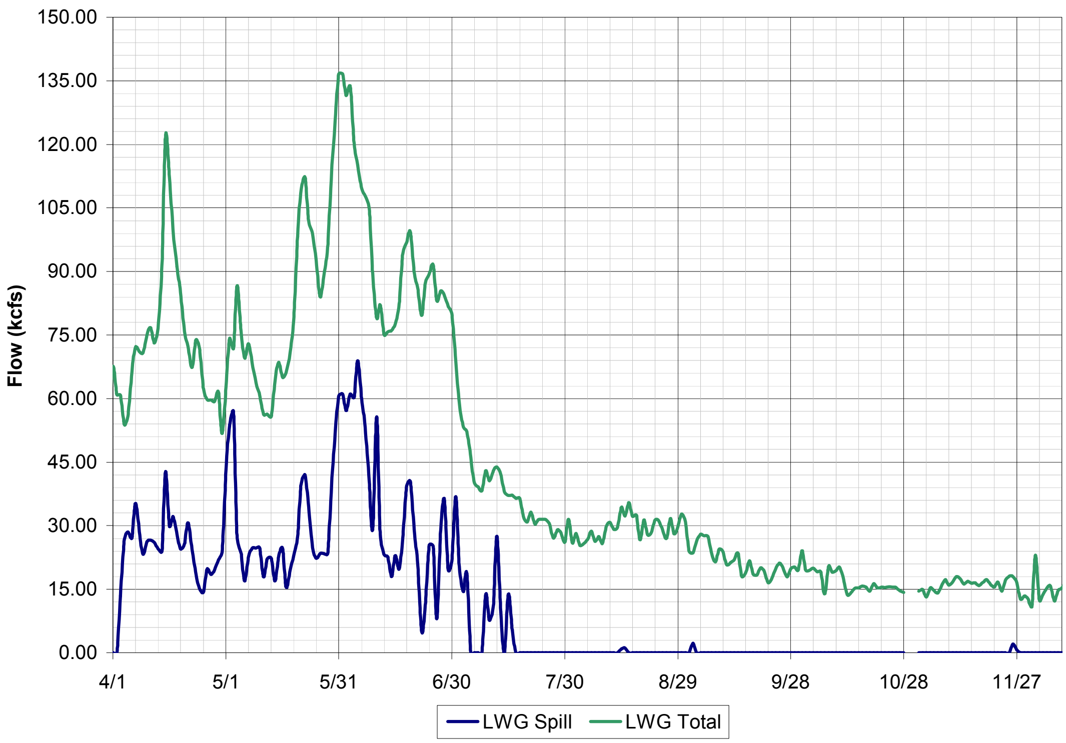


Figure E.10. Average daily total spill and discharge measured at Lower Granite Dam, April-November, 2002.

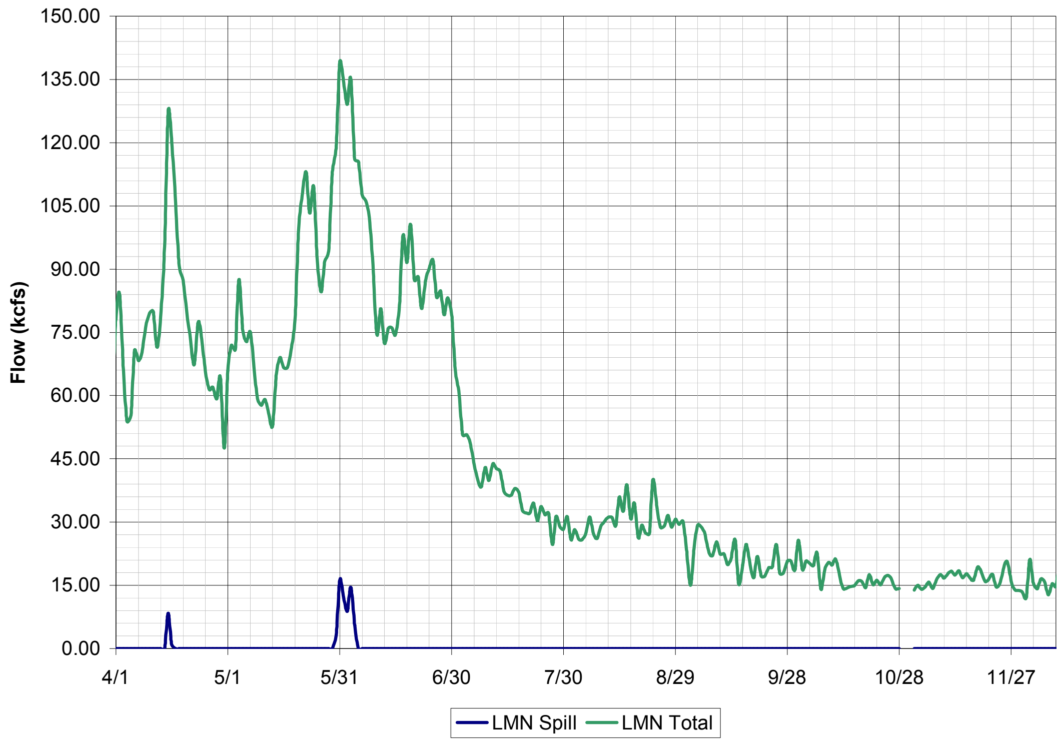


Figure E.11. Average daily total spill and discharge measured at Lower Monumental Dam, April-November, 2002.

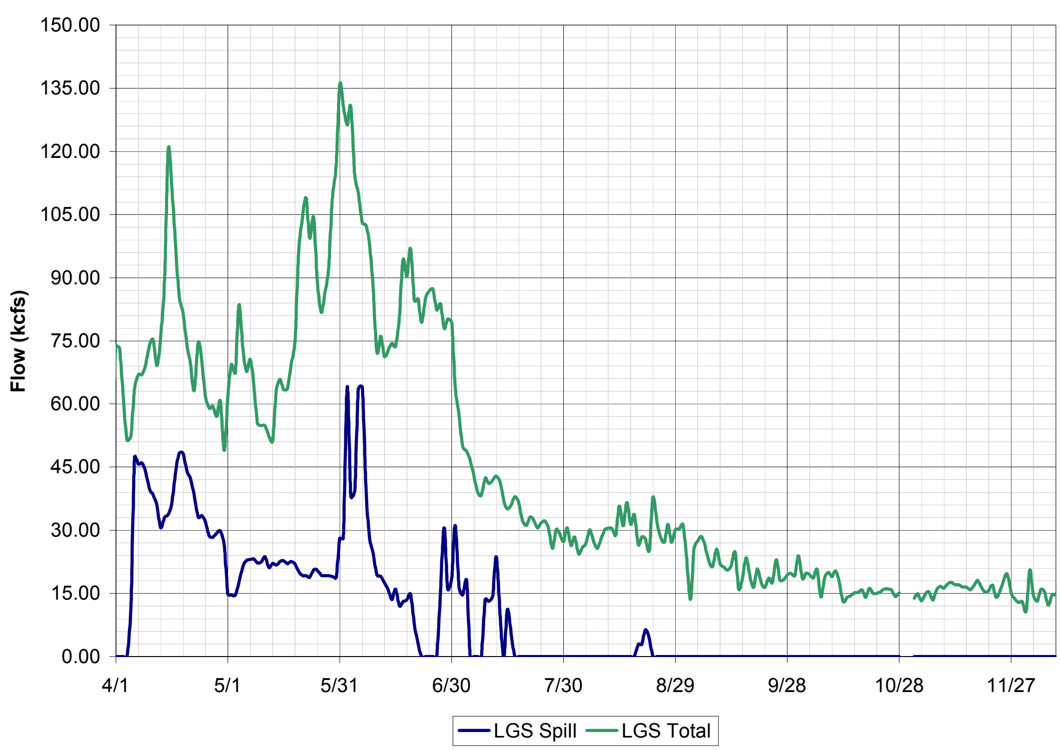


Figure E.12. Average daily total spill and discharge measured at Little Goose Dam, April-November, 2002.

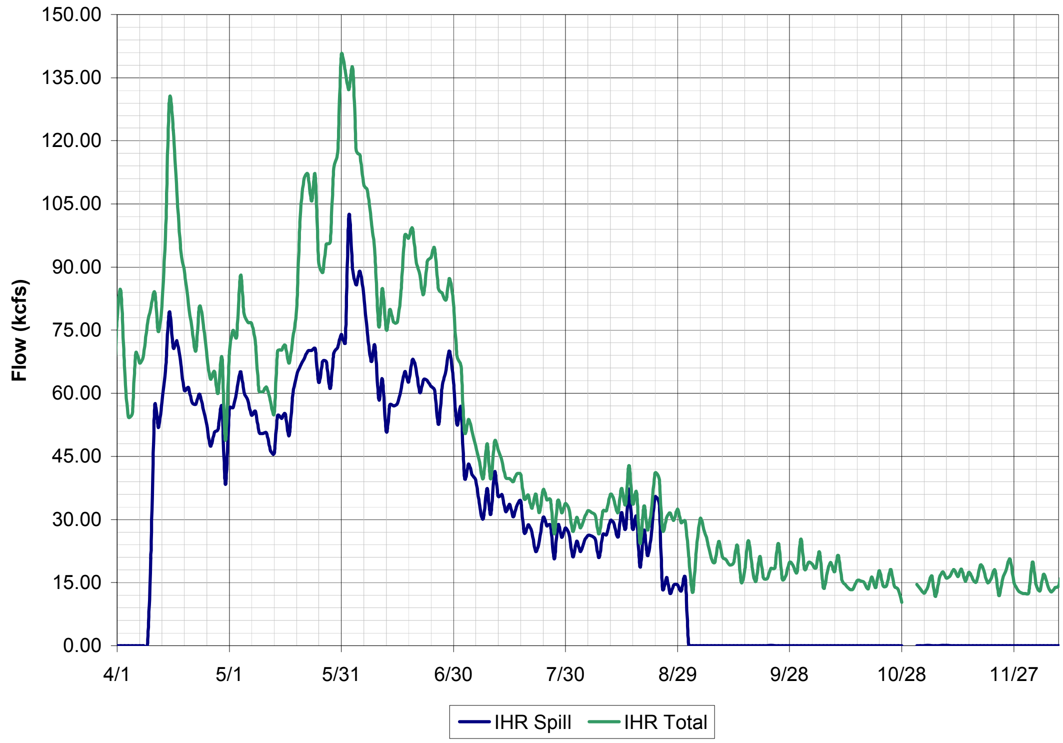


Figure E.13. Average daily total spill and discharge measured at Ice Harbor Dam, April-November, 2002.

Flow data collected by USGS from the Clearwater River at Orofino, ID, the Clearwater River at Spalding, ID, the Snake River near Anatone, WA, and the fixed monitor located along the north fork of the Clearwater River (DWQI) are shown in Figure E.14. With few exceptions, the majority of the season depicted relatively equal amounts of discharge from the Clearwater and Snake Rivers. The exception occurred from May 22 through June 20 when Anatone flows spiked 20% higher, on average, than flows out of the Clearwater River. During the latter part of September and through the end of the season, Dworshak releases fell off and Snake River flows at Anatone rose to 60-80% of the total flow.

In the upper portion of Figure E.15 a time history plot of Lower Snake River project river discharges is displayed. As seen, flows started in the spring at 35 kcfs (average daily) and peaked at 130 kcfs in mid April and again at 140 kcfs in early June. Flows began falling by early July on the Snake River and by September low flows of 15 kcfs were typical. The lower part of Figure E.15 depicts theoretical retention times, which were calculated by project using volume/surface elevation data to approximate flows through the system. The retention times varied from a low of 2 days for all projects during the April-June period to a high of 18 days for Little Goose and 12-14 days for the other projects during the fall low flows. Retention time for the Lower Snake River up through Lower Granite pool ranged from a low of 8 days for the system during May/June high flows, to a high of approximately 60 days during the fall low flows.

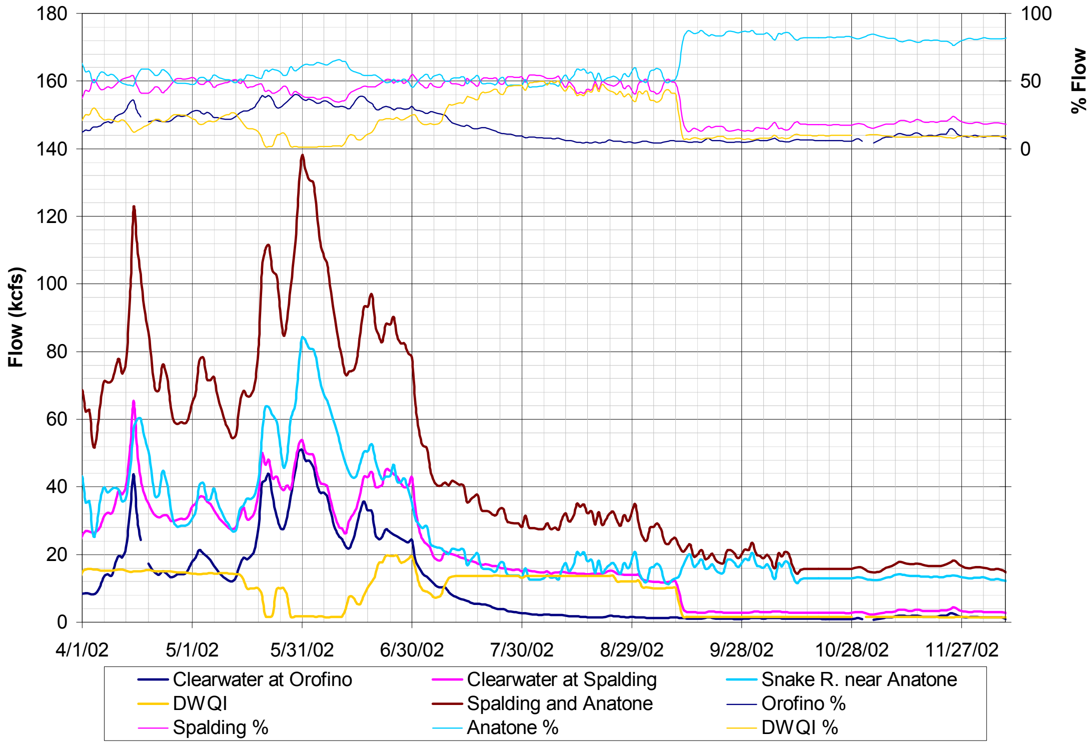


Figure E.14. Average daily flows and percent total flows from various USGS sites along the Snake and Clearwater Rivers.

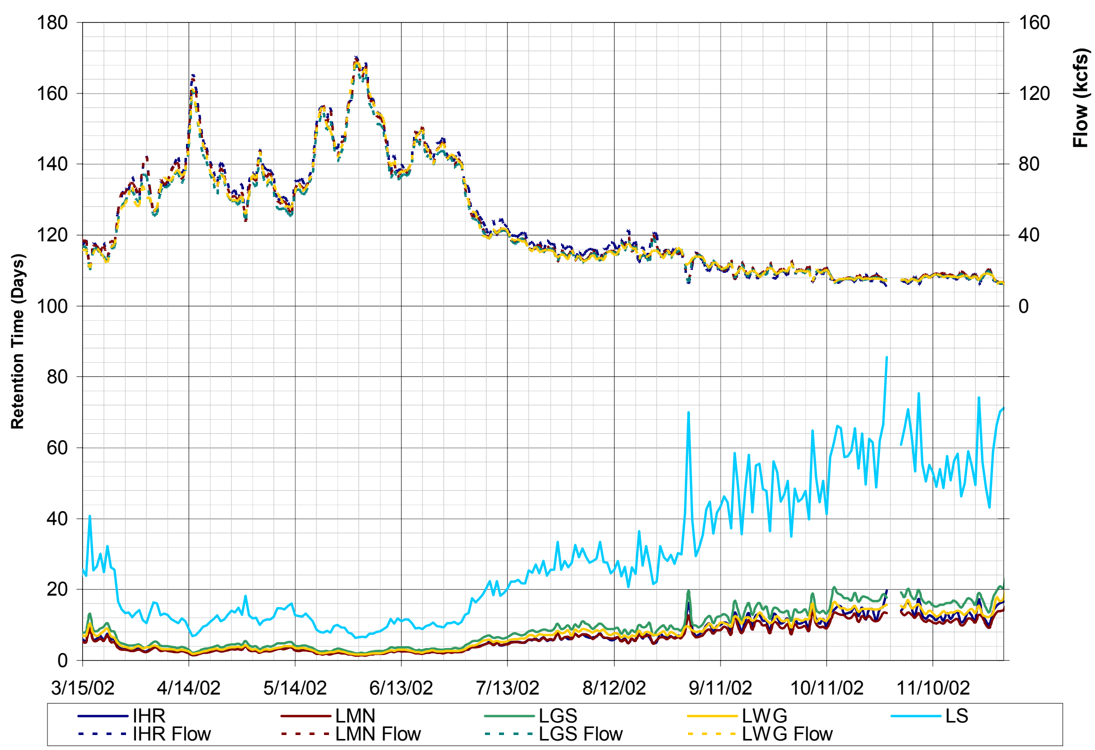


Figure E.15. Lower Snake River project discharge (average daily flow), theoretical retention time by project and the entire lower river.

Meteorological conditions. The weather stations chosen to monitor conditions in the Lower Snake River area during the study consists of one National Weather Service station at Pasco, WA, and three Bureau of Reclamation AgriMet stations located on Dworshak pool Dent Acres, ID, Lake Bryan-Rice Bar, WA, near Little Goose Dam, and Silcott Island, WA, upstream in Lower Granite pool. As seen in the Figures E.16 through E.18 the Pasco, Washington weather station collected data throughout the entire 2002 season. The AgriMet stations located at Dworshak/Dent Acres and Lake Bryan-Rice Bar were not installed until April 20, 2002 while the Silcott Island AgriMet weather station was not installed until almost two months later on July 17, 2002.

The highest daily temperatures recorded at Dworshak, Lake Bryan-Rice Bar, and Pasco occurred on July 13 (Figure E.16). Since the Silcott Island station was not recording data at this time the highest temperature at this site occurred 10 days later on July 23. The lowest temperatures recorded at Dworshak/Dent Acres took place on October 30 while the lowest temperature at Lake Bryan-Rice Bar, Pasco, and Silcott Island took place one day later on the 31. From the latter part of April through the end of November, the Dworshak/Dent Acres site was generally 1-3 °C cooler than that of Lake Bryan-Rice Bar, Pasco, and Silcott Island sites. Out of the three warmer sites, Lake Bryan-Rice Bar, Pasco, and Silcott Island, no one station was predominately warmer than the others throughout the season.

The weather station located at Pasco, WA measured the highest wind speeds out of the four sites seen in Figure E.17. The three highest daily wind speeds measured at the Pasco station occurred April 14, with an averaged wind speed of 17mph, July 8, with an averaged wind speed of 16mph, and on November 17, with an average wind speed of 18mph. At the other three sites, there was only one day when averaged wind speeds were recorded higher than 10 mph. This occurred at Silcott Island on November 16. None of the weather stations recorded daily wind speeds less than one mile per hour for the entire season.

Wind peaks measured at the weather stations shown in Figure E.18 followed similar patterns to that of the wind speed figure mentioned above. The Pasco, WA, weather station clearly shows higher daily wind peaks than the other stations. These highest measurements occurred on May 5 and 20 with peaks of about 33 mph and on July 8 with a peak of about 38 mph. None of the weather stations during the 2002 season recorded wind peaks below approximately three miles per hour.

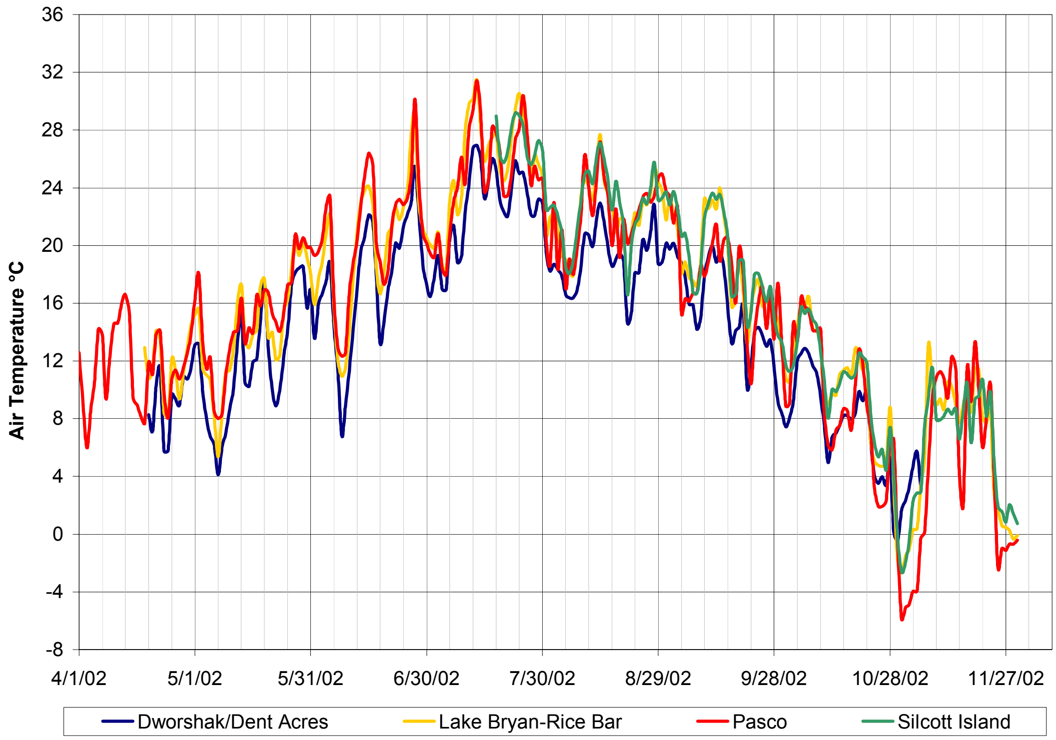


Figure E.16. Average daily air temperatures collected at Lower Snake River weather stations, April-November, 2002.

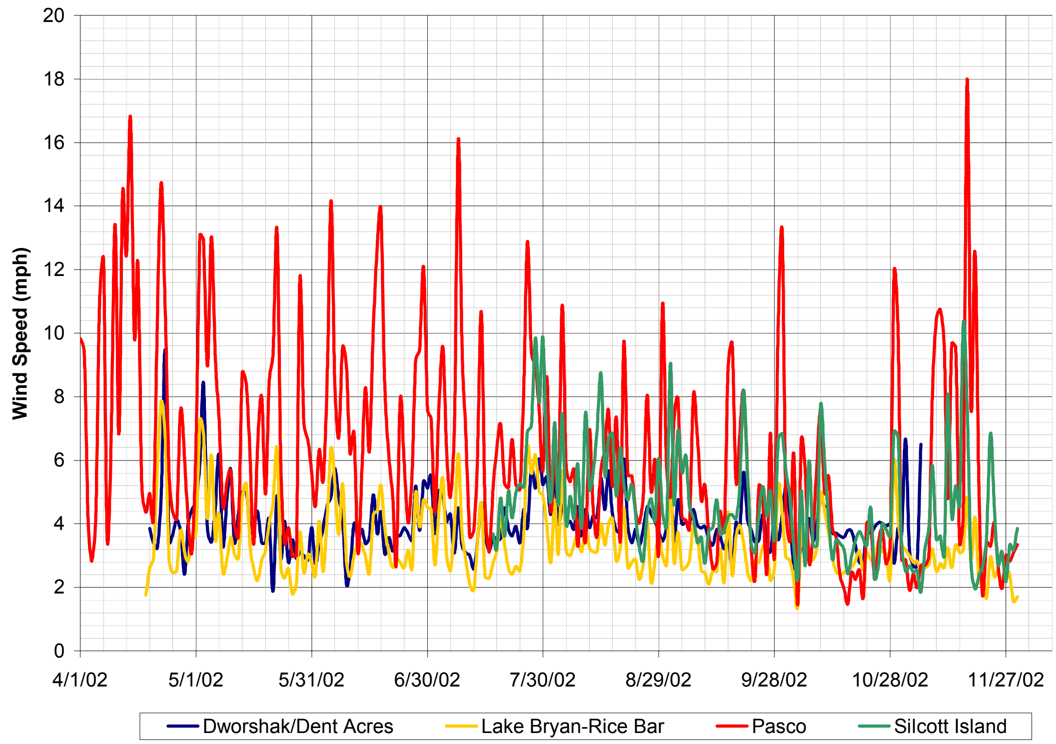


Figure E.17. Average daily wind speeds collected at Lower Snake River weather stations, April-November, 2002.

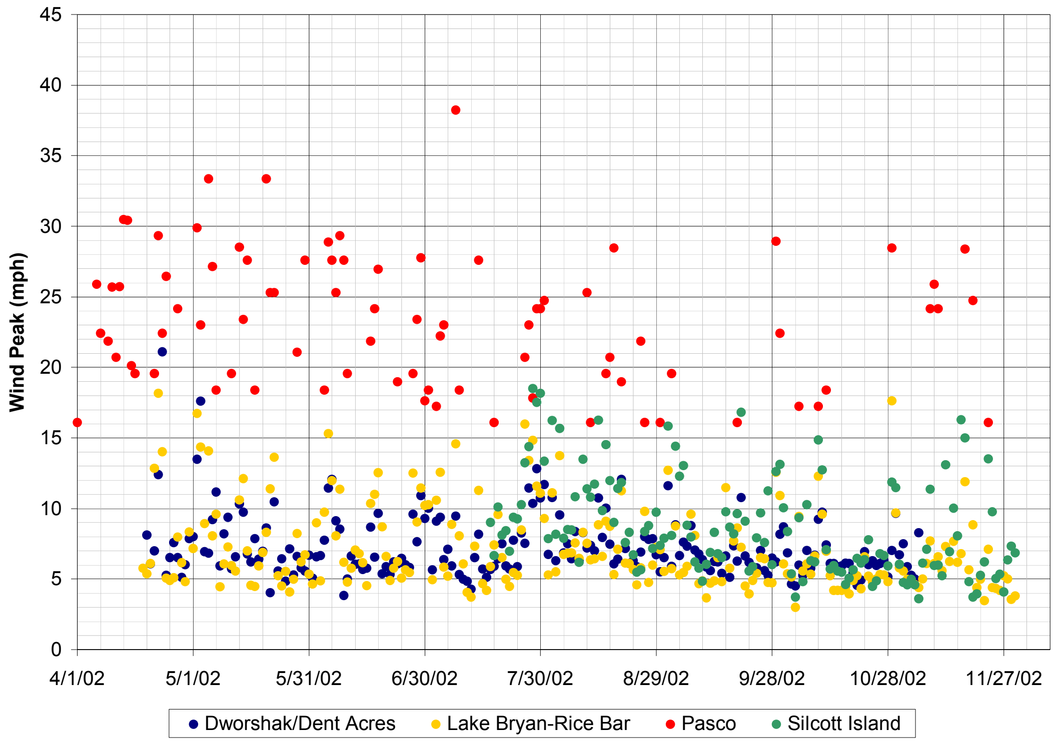


Figure E.18. Average daily wind peaks collected at Lower Snake River weather stations, April-November 2002.

River Temperatures.

COE Temperature Data. Strong vertical thermal gradients were present by mid June in the Dworshak forebay at station DWKFB as indicated in the 60 m deep profile described in Figure E.19. Maximum temperatures of 25-29 °C were achieved at the 0.5 m deep sensor by mid to late July. The surface mixed layer or the epilimnion progressed down to 5 m by late July and on down to 10 m by late September. The thermocline appeared to extend down to the 35-40 m depths with gradients up to 14 °C occurring. The hypolimnion, below the 40 m depth, remained at or below 6 °C for the duration of the sampling period. Figure 3.14 illustrates a daily average temperature profile of late August.

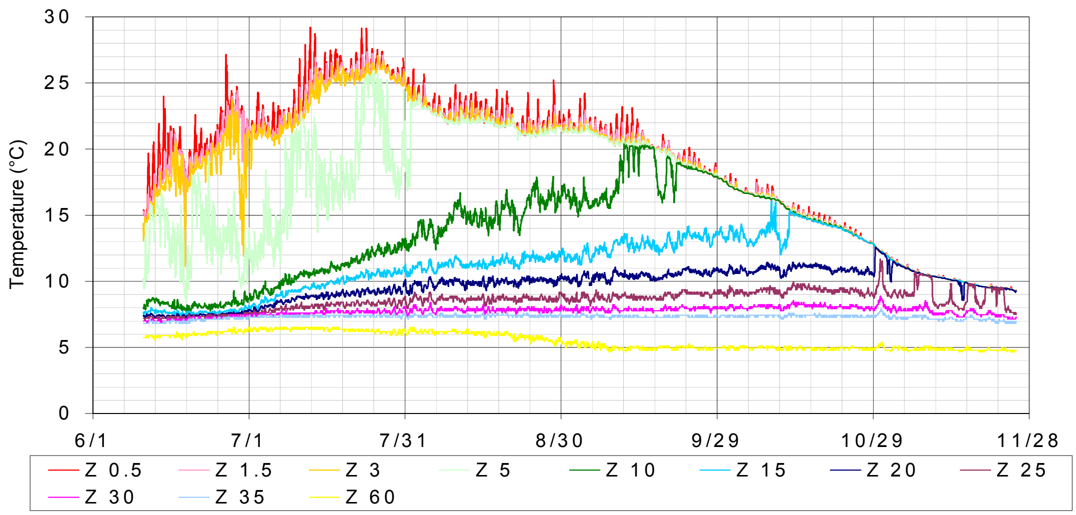


Figure E.19. Temperature profile time histories for Dworshak forebay station DWKFB and project discharge, 2002. (The sensor depths, Z, are in meters as indicated in the legend)

Figure E.20 depicts water temperatures collected at the fish exit of Lower Granite Dam (LWGFX) from June through November 2002. Vertical thermal gradients began during mid July and continued through mid September. Maximum temperatures were recorded by the 0.5 m thermistor on July 25 at approximately 25°C. During the stratified period, coolest temperatures were recorded in mid August at 16°C by the 20 m instrument. This instrument failed shortly thereafter and was never regained.

Lasting vertical thermal gradients started in early July and continued through mid September at the Lower Granite forebay stations LWGFBP2 and LWGFBP3 as indicated in the profile time histories described in Figures E.21 and E.22. Maximum temperatures of approximately 25 °C were achieved at the 0.5 m deep sensors by mid to late July. The surface mixed layers never extended beyond 5 m with little classical development of an epilimnion. An apparent thermocline extended down to near the bottom at the 25 to 30m depths with gradients of up to 6 °C occurring. The bottom temperatures remained between 16 and 19 °C during the stratified period.

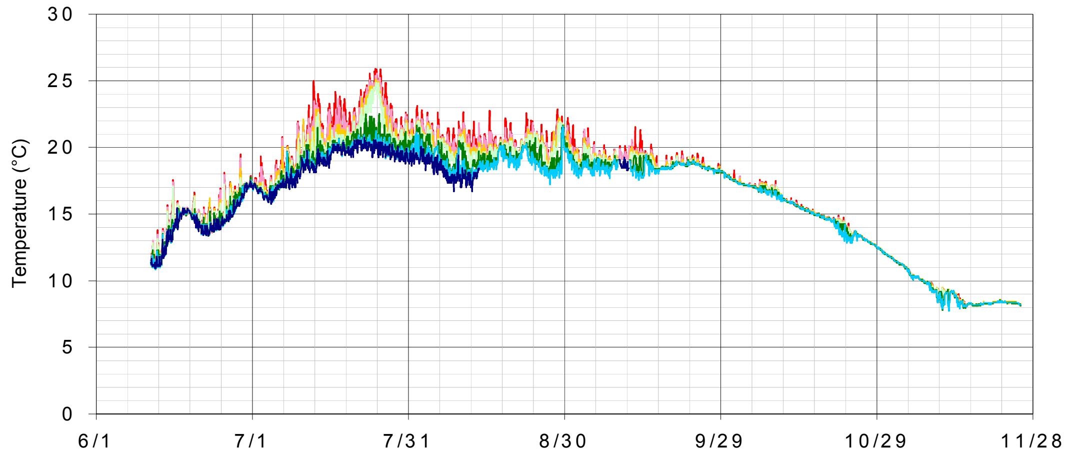


Figure E.20. Temperature profile time histories for Lower Granite fish exit station LWGFX and project discharge, 2002.

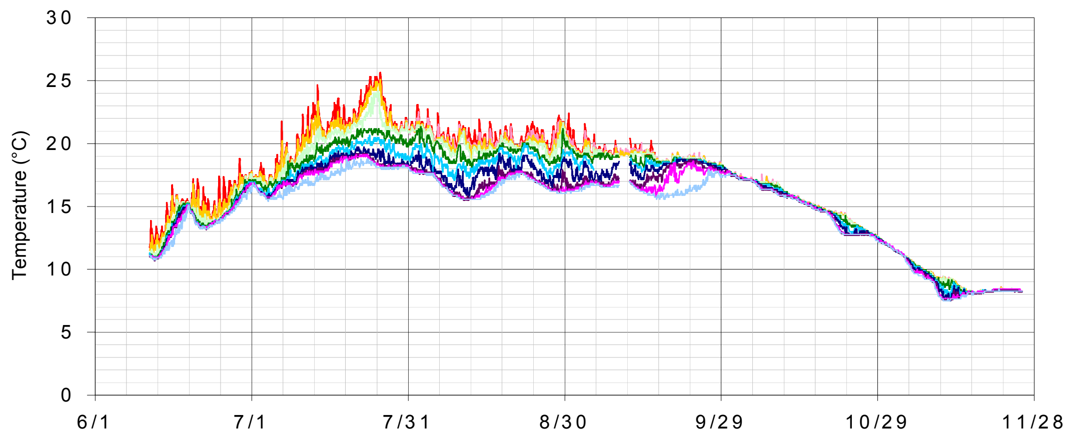


Figure E.21. Temperature profile time histories for Lower Granite forebay station LWGP2 and project discharge, 2002.

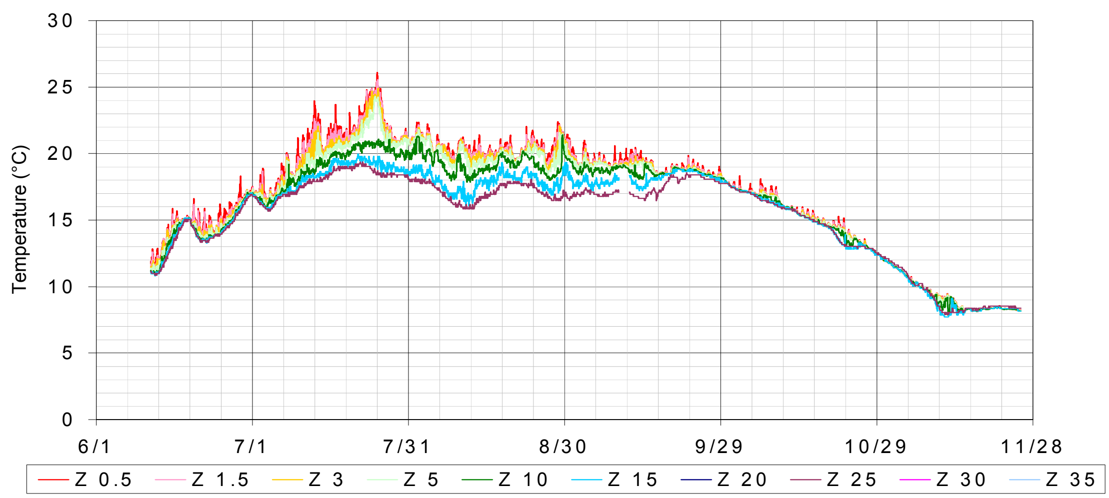


Figure E.22. Temperature profile time histories for Lower Granite forebay station LWGP3 and project discharge, 2002.

Figure E.23 describes the temperature conditions collected at the Little Goose Dam fish exit (LGSFX) during the months of June-November 2002. As shown, weak thermal gradients developed in mid June and continued through the end of September. Peak temperatures during this time occurred in mid July measuring approximately 27°C by the two surface instruments of 0.5 m and 1.5 m and approximately 21°C by the bottom two instruments of 15 m and 20 m. The two deepest instruments of 15 m and 20 m measured temperatures at or above 20 °C for approximately 32 out of the 45 days of mid July through August.

Vertical thermal gradients started to develop for short periods (3 to 5 days) in June at the Little Goose forebay stations LGSFBP1, LGSFBP2, and LGSFBP3 as depicted in the profile time histories described in Figures E.24 through E.26. These gradients would break up or mix due to surface cooling or wind mixing. Continuous but relatively weak thermal gradients of 2-4 °C were apparent by July 10 and, similar to Lower Granite, continued until mid September. Maximum temperatures of 25 °C were achieved at the 0.5 m deep sensors by mid to late July. The thermal gradients were more gradual from surface to bottom. The bottom temperatures remained between 16 and 20 °C during the stratified period.

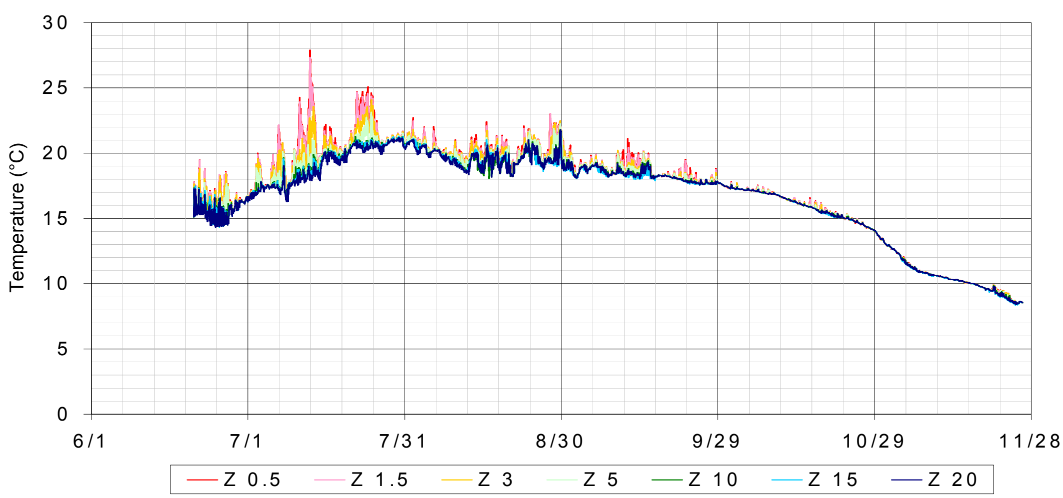


Figure E.23. Temperature profile time histories for Little Goose fish exit station LGSFX and project discharge, 2002.

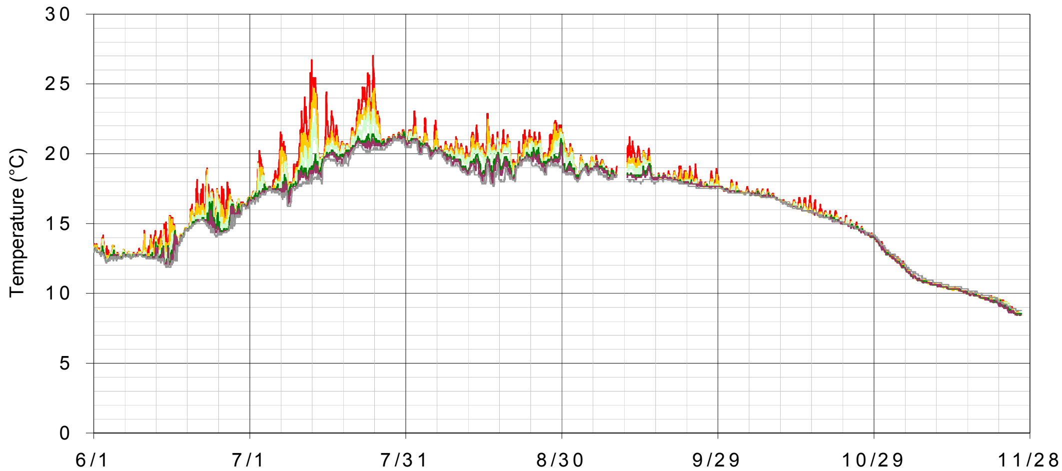


Figure E.24. Temperature profile time histories for Little Goose forebay station LGSFBP1 and project discharge, 2002.

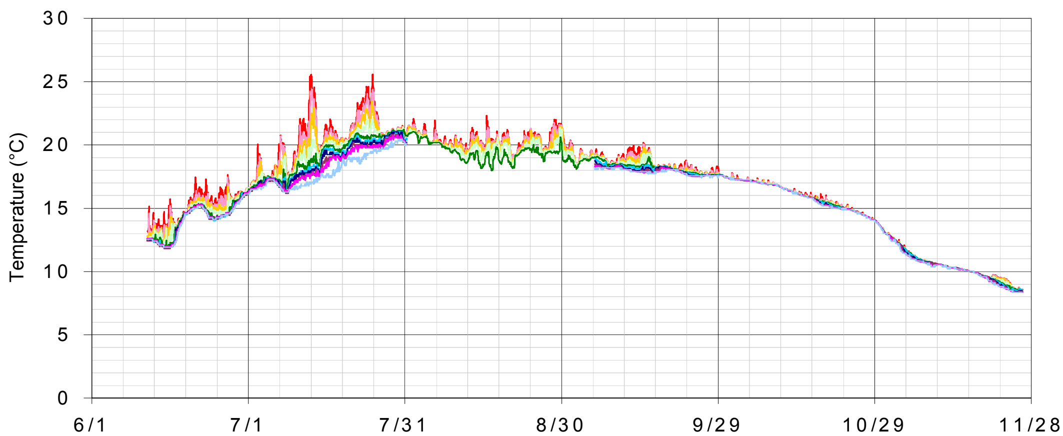


Figure E.25. Temperature profile time histories for Little Goose forebay station LGSFBP2 and project discharge, 2002.

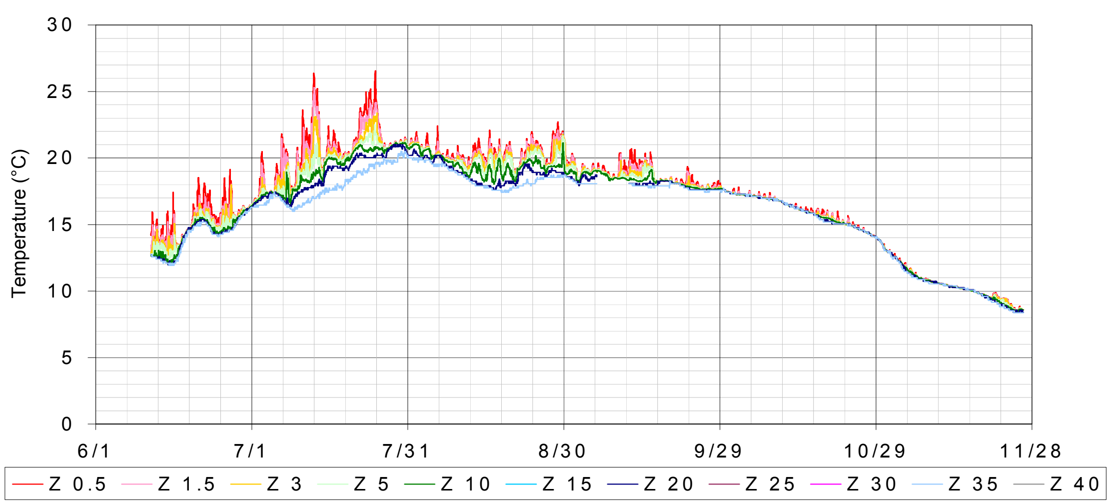


Figure E.26. Temperature profile time histories for Little Goose forebay station LGSFBP3 and project discharge, 2002.

Figure E.27 shown below describes the thermal conditions at the mouth of the Palouse and Tucannon Rivers. Duplicate thermistors were deployed at these sites, so an average temperature was calculated to produce the time series plot. Daily fluctuations were prominent at both of these sites throughout the season. Peak temperatures of approximately 28.9°C occurred on July 12 and 13 at the Palouse River site. Peak temperatures of approximately 27.3°C occurred on July 12 at the Tucannon River site. From June to late October, the Palouse River was slightly warmer than the Tucannon River. However, the end of October through November brought cooler conditions at the Palouse of 1-4°C.

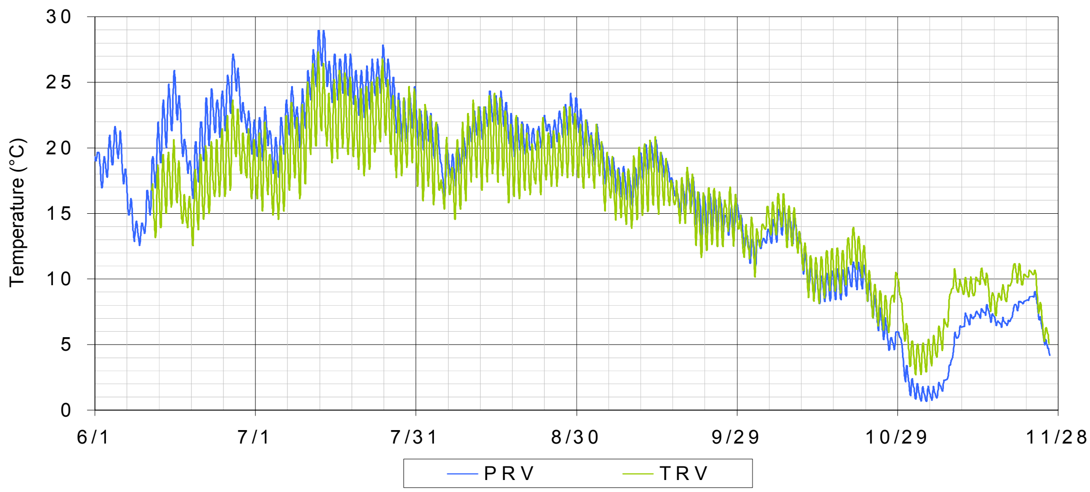


Figure E.27. Temperature profile time histories for sites along the Palouse and Tucannon Rivers, 2002.

Figures E.28 through E.30 depict thermal patterns measured at the Lower Monumental forebay sites of LMNFBP1, LMNFBP2, and LMNFBP3. On and off warming/cooling patterns began in early June and by mid July weak thermal gradients of 2-4 °C were apparent. During the stratification period, peak temperatures of 23-24°C were measured, while bottom temperatures increased from 17 to 21 °C. From July 31-August 5 data logs from the LMNFBP2 site were lost due to a programming error and no temperature readings were taken. At all three Lower Monumental forebay sites logs were lost from August 9-11 and again, no temperatures were taken during that time.

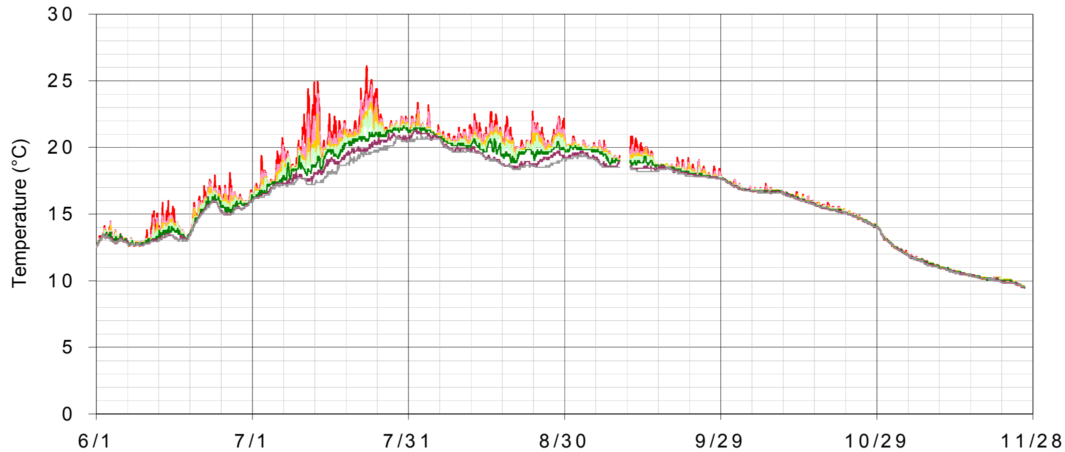


Figure E.28. Temperature profile time histories for Lower Monumental forebay station LMNFBP1 and project discharge, 2002

.

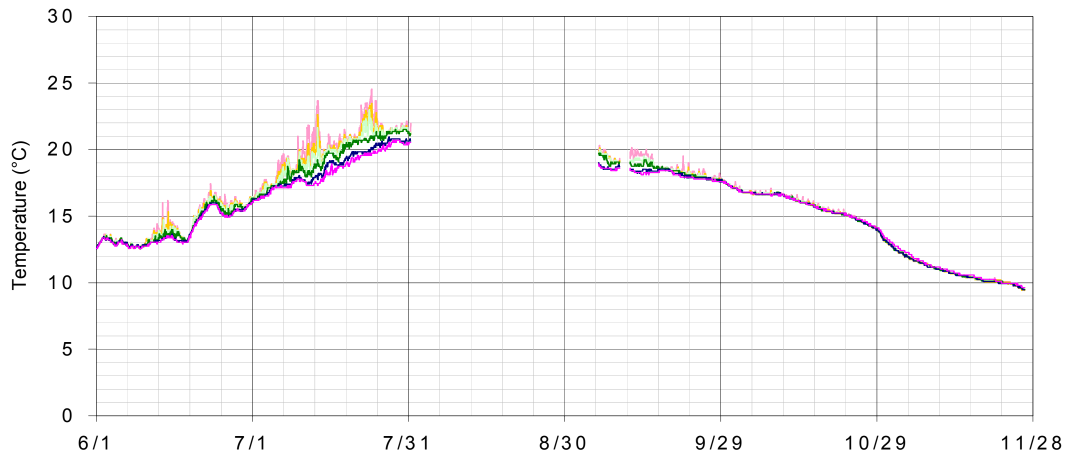


Figure E.29. Temperature profile time histories for Lower Monumental forebay station LMNFBP2 and project discharge, 2002.

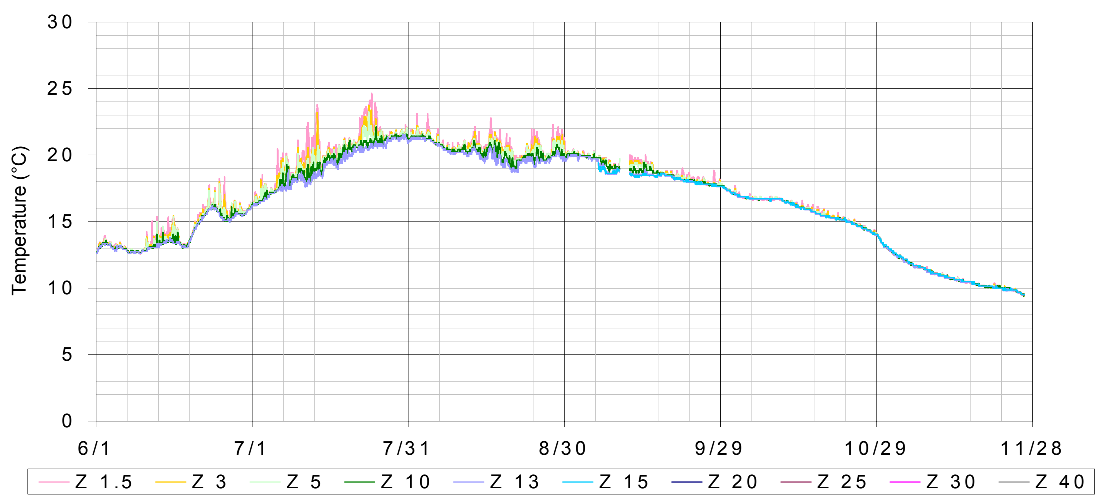


Figure E.30. Temperature profile time histories for Lower Monumental forebay station LMNFBP3 and project discharge, 2002.

The Ice Harbor forebay thermal profiles are characterized by intermittent daily surface warming throughout the season (Figures E.31 and E.32) with very gradual and weak vertical gradients of 1-2 °C. Maximum temperatures of 24 °C were observed in July. The bottom temperatures remained between 18 and 22 °C during the stratified period.

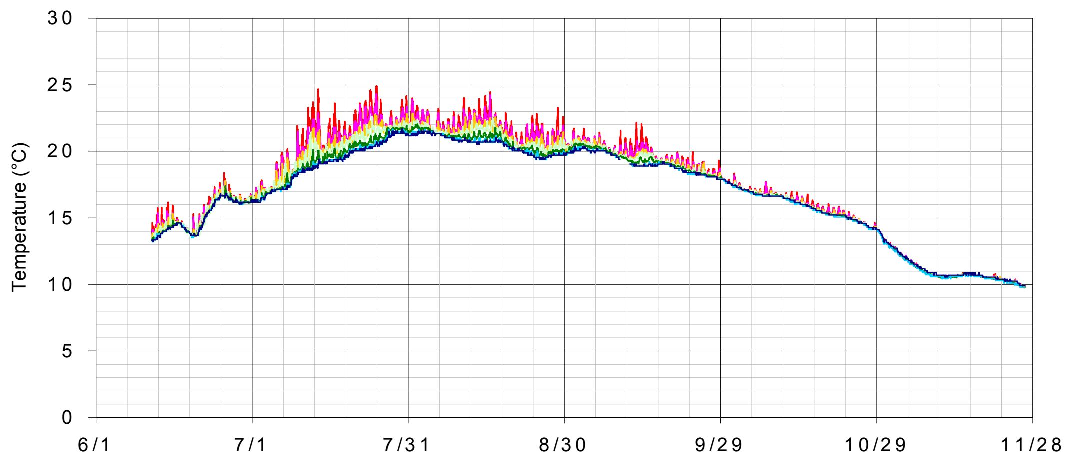


Figure E.31. Temperature profile time histories for Ice Harbor forebay station IHRFBP1 and project discharge, 2002.

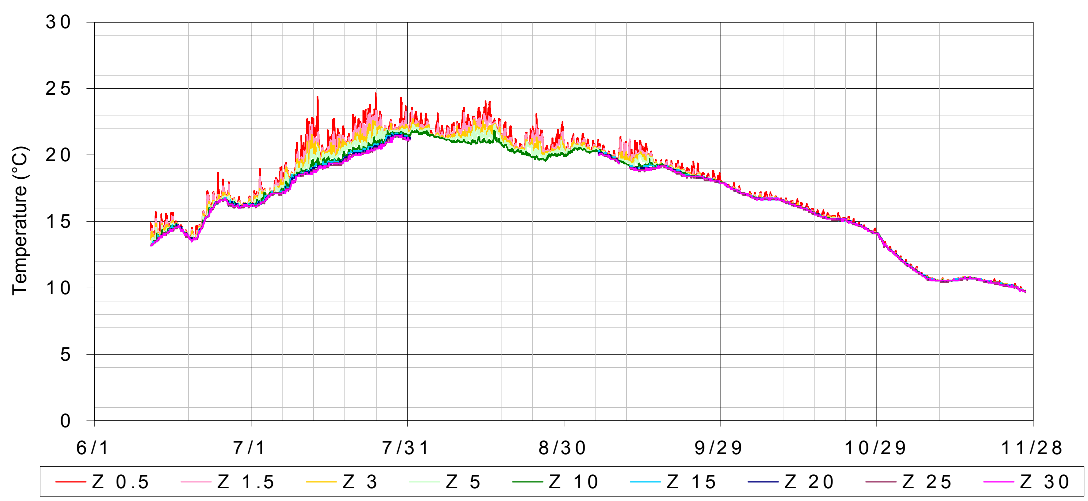


Figure E.32. Temperature profile time histories for Ice Harbor forebay station IHRFBP2 and project discharge, 2002.

Figure E.33 depicts temperature profiles measured at the drafttube decks of Dworshak, Lower Granite, Little Goose, Lower Monumental, and Ice Harbor Dams. Duplicate thermistors were deployed at these sites, so an average temperature was calculated to produce the time series plot. From mid June through mid October Dworshak's tailwater temperatures were between 5° and 12°C cooler than the four projects on the Snake River. The abrupt fluctuations in temperature at the Dworshak site, which can be seen on August 7 and 29, September 12, and October 18 are due to operational changes in spill. Comparing the Snake River projects during the months of June though October, Ice Harbor's tailwater temperatures, on average, were warmest, while Lower Granite's tailwater temperatures were coolest.

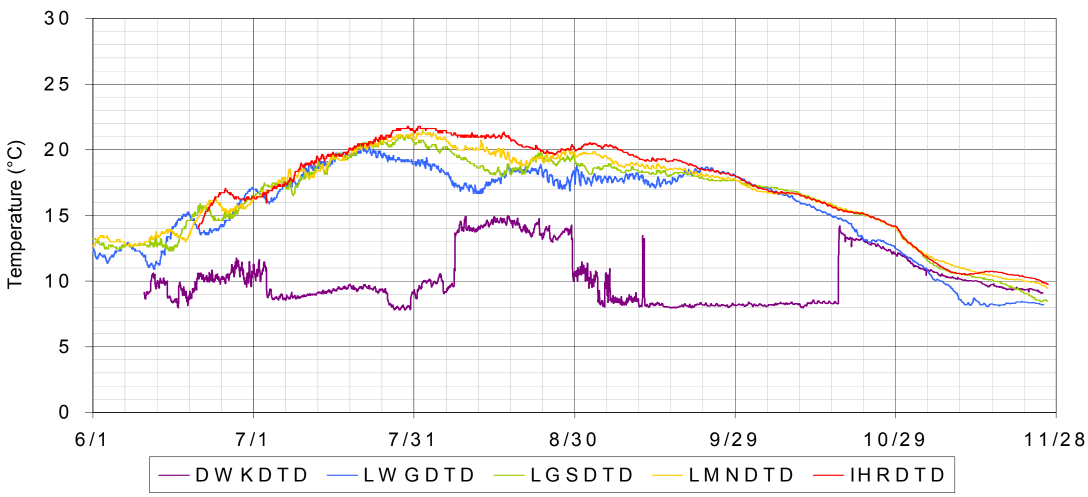


Figure E.33. Temperature profile time histories for all drafttube deck stations at the Lower Snake River projects, 2002.

Other Temperature Data. In addition to the forebay automated profiling supplementary river stations were monitored including locations on the middle Snake, Grande Ronde, Clearwater, Palouse, and Tucannon Rivers plus additional monitors were installed on each project draft tube deck. The following sections present a partial review of the individual river temperature monitor data collected in the screening study.

Water temperatures for the middle Snake River just upstream of Lower Granite headwaters increased to above 20 °C the second week in July and remained elevated until mid September. Maximum temperature was 22-23 °C for all five stations presented in Figure E.34. Diel cycles in temperature were 1-2 °C for all stations as well. Warming in the order of 0.5 °C from river mile 170 downstream to river mile 156 was identified in the middle Snake River data during July and August (provided by Idaho Power Company).

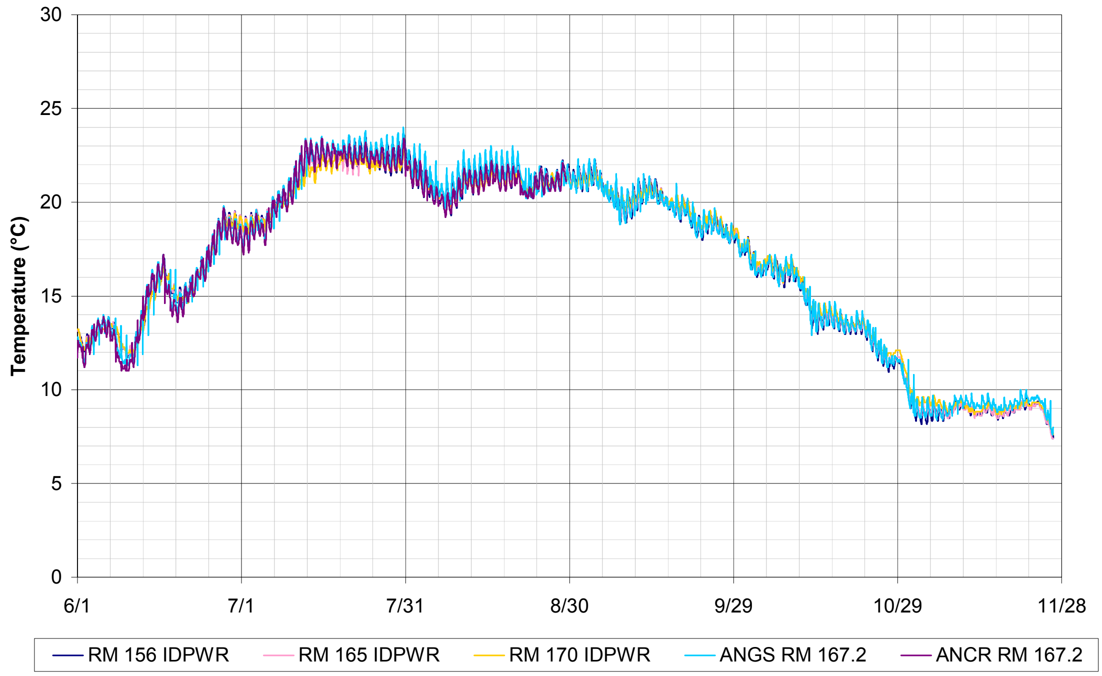


Figure E.34. Middle Snake River water temperature, river mile 156 to 170. (Data provided by Idaho Power, USGS, and COE)

Figure E.35 depicts Clearwater temperatures for the upstream main fork at Orofino, ID, and Kooskia, ID, plus lower river stations at Peck, ID, and Spalding, ID. The sources of data for these stations include both USGS and Idaho DEQ. As on the middle Snake River, the upstream Clearwater temperatures for the Kooskia and Orofino stations went above 20 °C by the second week in July and peaked at 22-25 °C during late July. Diel temperature cycles for these stations ranged from 2 to 5 °C. The downstream stations at Peck and Spalding peaked at around 15 °C with daily fluctuations of only 1-2 °C.

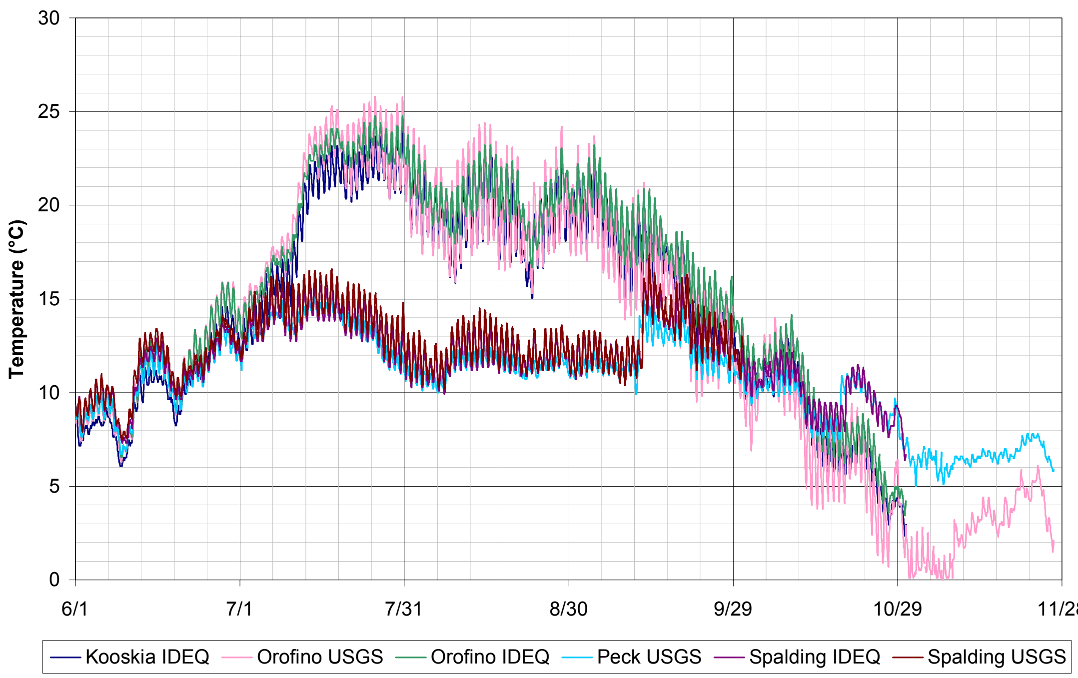


Figure E.35. Selected temperature monitoring stations on Clearwater River. (Data provided by Idaho DEQ and USGS)

Figure E.36 depicts water temperatures for the North fork of the Clearwater River, the releases from Dworshak Dam, and 1 mile downstream at the COE fixed monitoring station (DWQI). In general these temperatures fluctuated significantly in relation to the operation of Dworshak dam. Intake elevation for the powerhouse, powerhouse discharge, and discharge of the spillway affected the average release temperatures as recorded 1 mile downstream at the COE fixed monitor DWQI. Station DWQIP5 located directly across the river from station DWQI remained 0.5 °C warmer than the fixed monitor (DWQI) temperature log during the period of spill. These two stations would consist of a mix of the releases from the powerhouse and spillway at Dworshak.

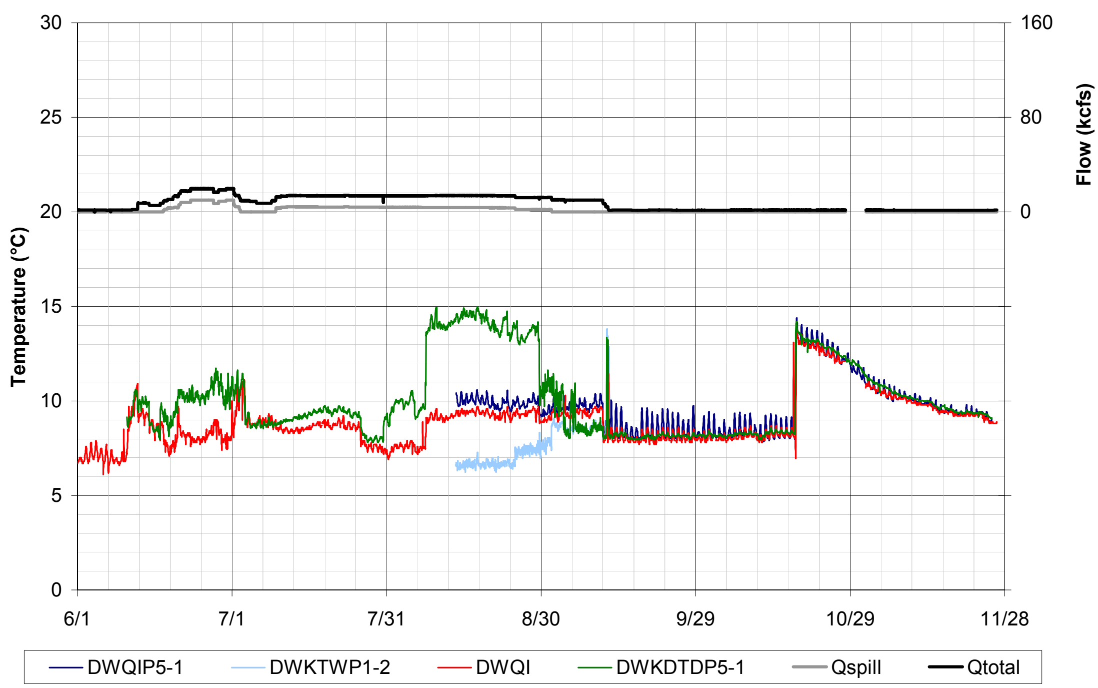


Figure E.36. Water temperatures downstream of Dworshak Dam on the North Fork Clearwater River and project discharge.

<u>CROHMS (Columbia River Operational Hydronet and Management System).</u> The COE has conducted routine monitoring at all Snake River projects plus selected in-river sites on both the middle Snake and Clearwater Rivers for several years. The stations associated with each project are located in the forebay, near or on the upstream dam face, and in the tailwater just downstream of each project. Sampling is on hourly intervals at discrete depths (generally approximately 15 ft) at each location. Neither vertical nor lateral gradients patterns are captured with this sampling strategy.

These water quality stations were designed to sample total dissolved gas saturation but have been used to document water temperatures as well. The general purpose of the forebay station has been to sample or represent an average cross section of the downstream forebay waters. In most cases, the purpose for monitoring in the tailwater areas has been to document spill water conditions on the river. These objectives can be met in both cases if the water is well mixed spatially at each reach of interest. Since the dams have no or little impact on water temperatures then the two stations should give comparable data throughout the sampling season for each project.

Figures E.37 through E.42 below depict temporal patterns for water temperatures collected at the fixed monitoring stations at Ice Harbor (IHR and IDSW), Lower Monumental (LMN and LMNW), Little Goose (LGS and LGSW), Lower Granite (LGS and LNGW), Dworshak (DWQI) Lewiston (LEWI), and Anatone (ANQW). The time frame of each plot is from April through November 2002.

Dworshak releases on the North Fork of the Clearwater River remained less than 10 °C until mid October (Figure E.37.). Daily thermal cycles on the middle fork of the Clearwater River ranged from 2-5 °C routinely during the period of July through October. Late in the season (November) water temperatures of Dworshak releases were still above 8 °C.

River stations at Lewiston, ID, (LEWI), and Anatone, WA, (ANQW) are shown in Figure E.38. Peak temperatures of 22-25 °C occurred on the Middle Snake at Anatone by mid July. The Lewiston gage registered water temperatures around 15 °C by early July then again by mid September. Daily thermal cycles were in the order of 1-2 °C with the greater daily cycles occurring on the lower Clearwater River at Lewiston.

The Snake River water began warming in late March and early April. The warming continued at all sites until late July and early August with peak temperatures of 20-22 °C on the Lower Snake River. The forebay and tailwater water temperature data for the lower Snake River projects are consistent with each other until early July when increased warming occurs at most forebay stations. The greatest differences in forebay and tailwater temperatures were observed at Lower Granite Dam (Figure E.39) and ranged from 2-4 °C consistently during the period of July through September. Daily temperature spikes as great as 4-5 °C were observed at the forebay stations until the water began cooling off in early October. The least prominent daily temperature spiking (less than 2 °C) was noted for Ice Harbor forebay waters (Figure E.42). The tailwater temperatures had minimal daily warming or spiking (generally less than 1 °C) and were more characteristic of the somewhat mixed releases from each of the projects.

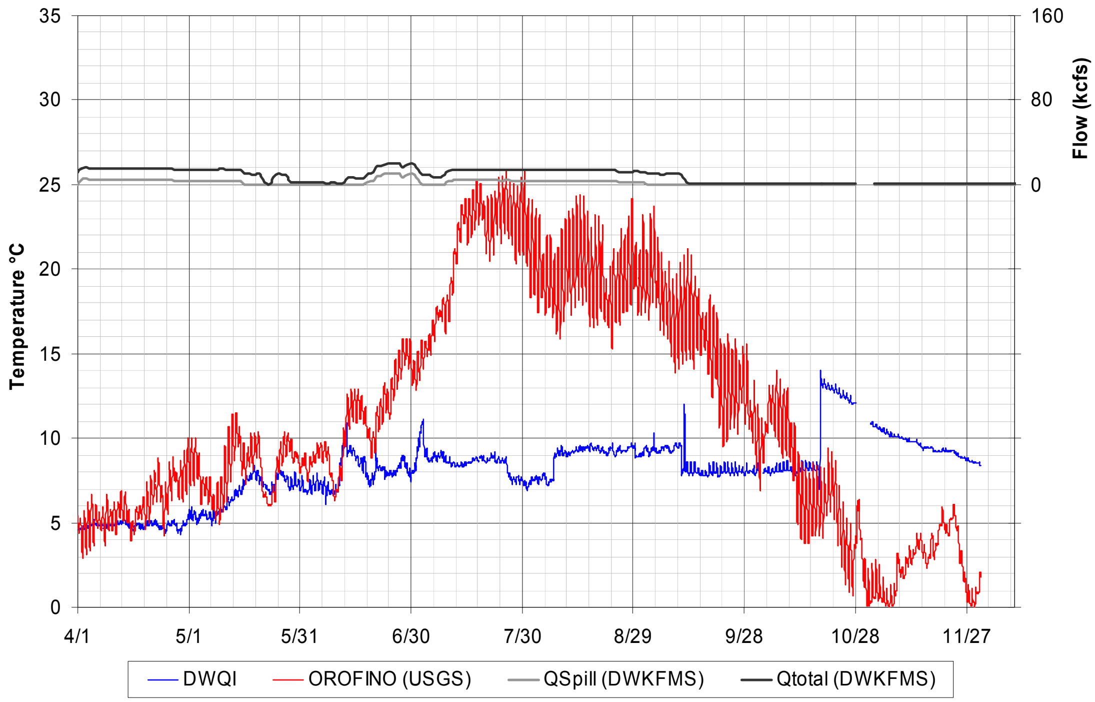


Figure E.37. Temperature profile time histories collected at the DWQI fixed monitoring station and the USGS Orofino gauging station with project operations, 2002.

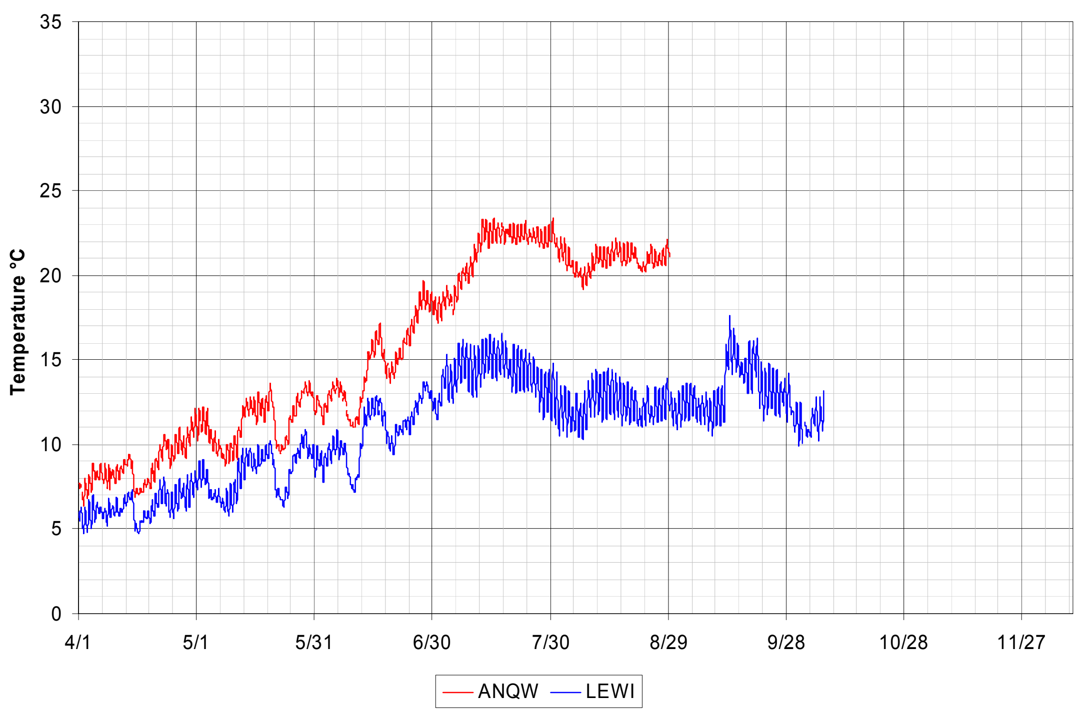


Figure E.38. Temperature profile time histories collected at the ANQW and LEWI fixed monitoring stations, 2002.

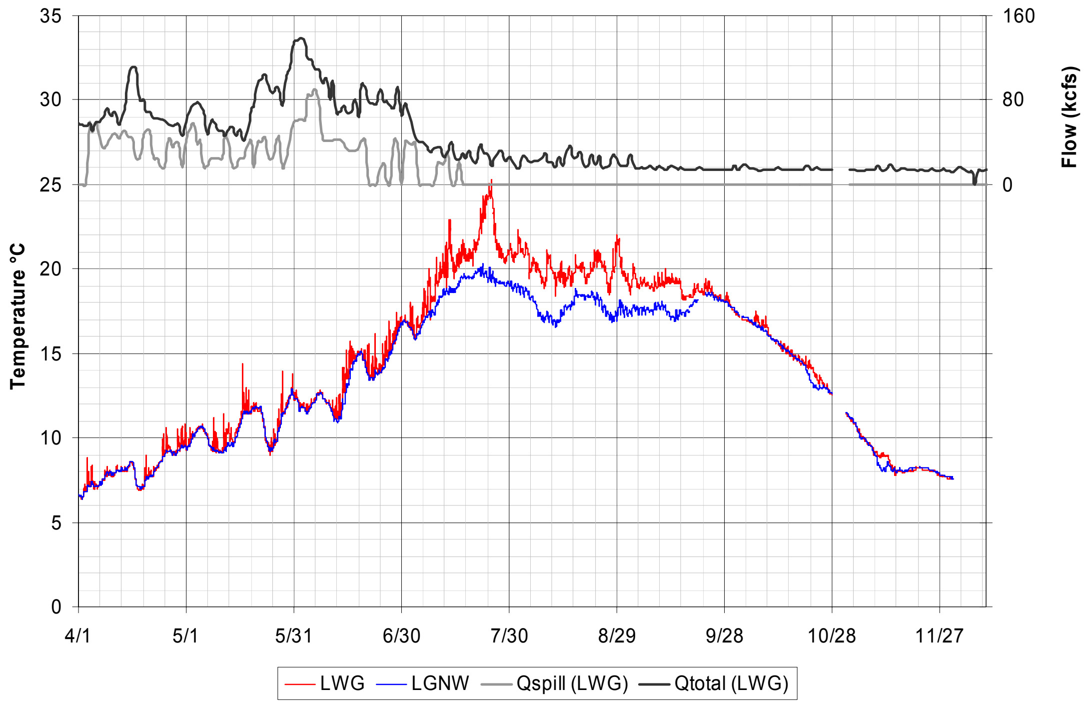


Figure E.39. Temperature profile time histories collected at the LWG and LGNW fixed monitoring stations with project operations, 2002.

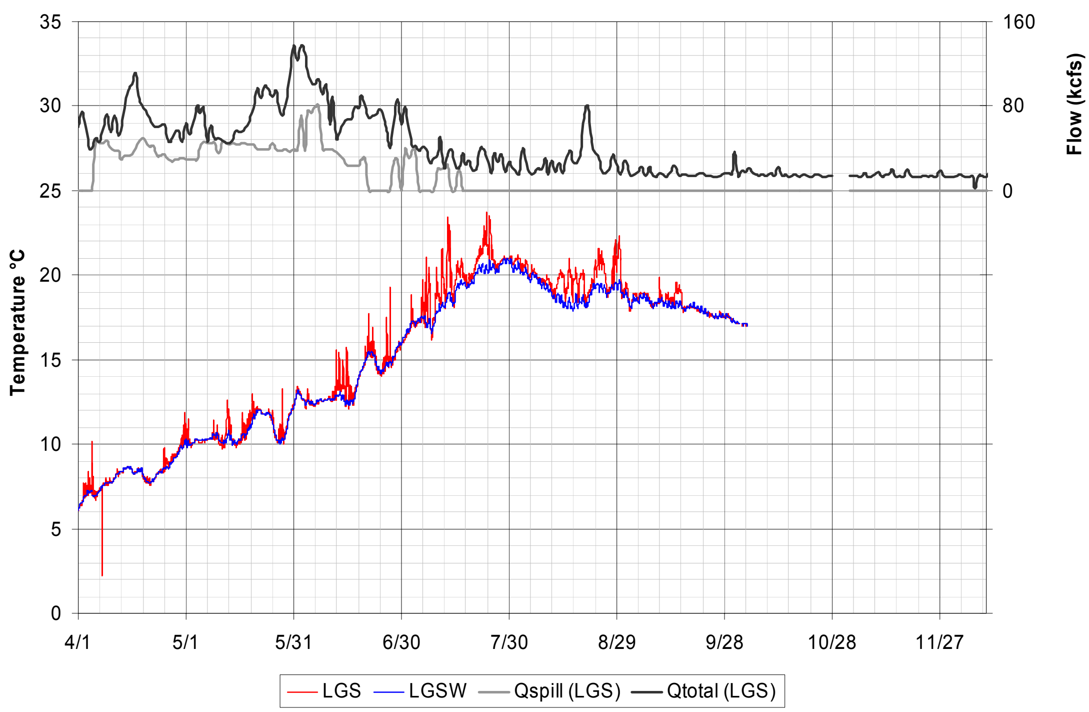


Figure E.40. Temperature profile time histories collected at the LGS and LGSW fixed monitoring stations with project operations, 2002

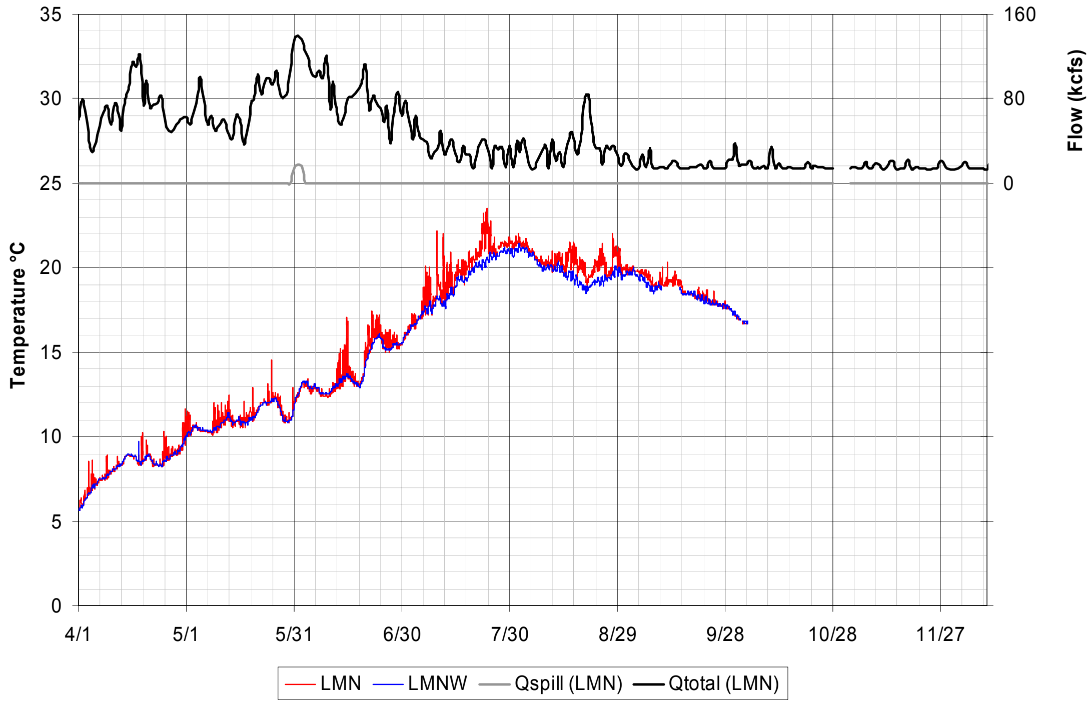


Figure E.41. Temperature profile time histories collected at the LMN and LMNW fixed monitoring stations with project operations, 2002

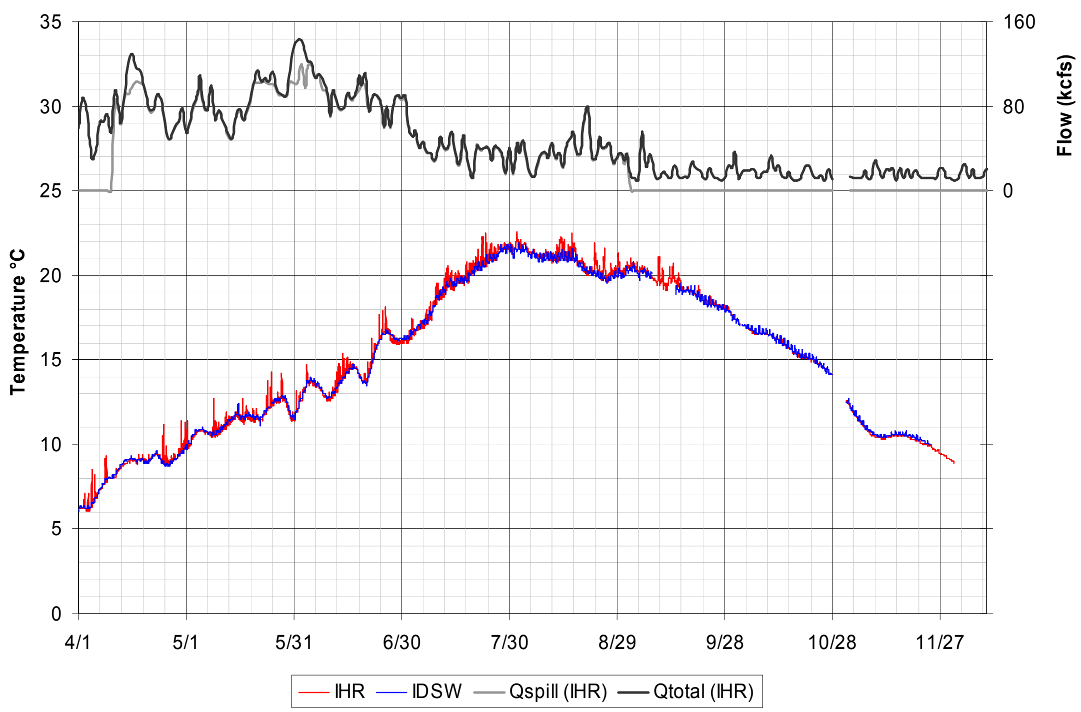


Figure E.42. Temperature profile time histories collected at the IHR and IDSW fixed monitoring stations with project operations, 2002

A longitudinal series of temperature data is depicted in figure E.43. Temperature data for each tailwater fixed monitor plus the Lewiston and Anatone sites are shown. The general pattern or trend is for increasing temperature in the downstream direction on the Lower Snake River indicating warming as would be expected. During the period of June through August the warming on the Lower Snake River appears to fall in the range of 1-3 °C (this observation assumes some lag as we progress downstream). The water temperature at Anatone was frequently 2 °C higher than that recorded further downstream at the projects. The Clearwater temperature at Lewiston remained cooler through the season due to the cold-water releases from Dworshak Dam.

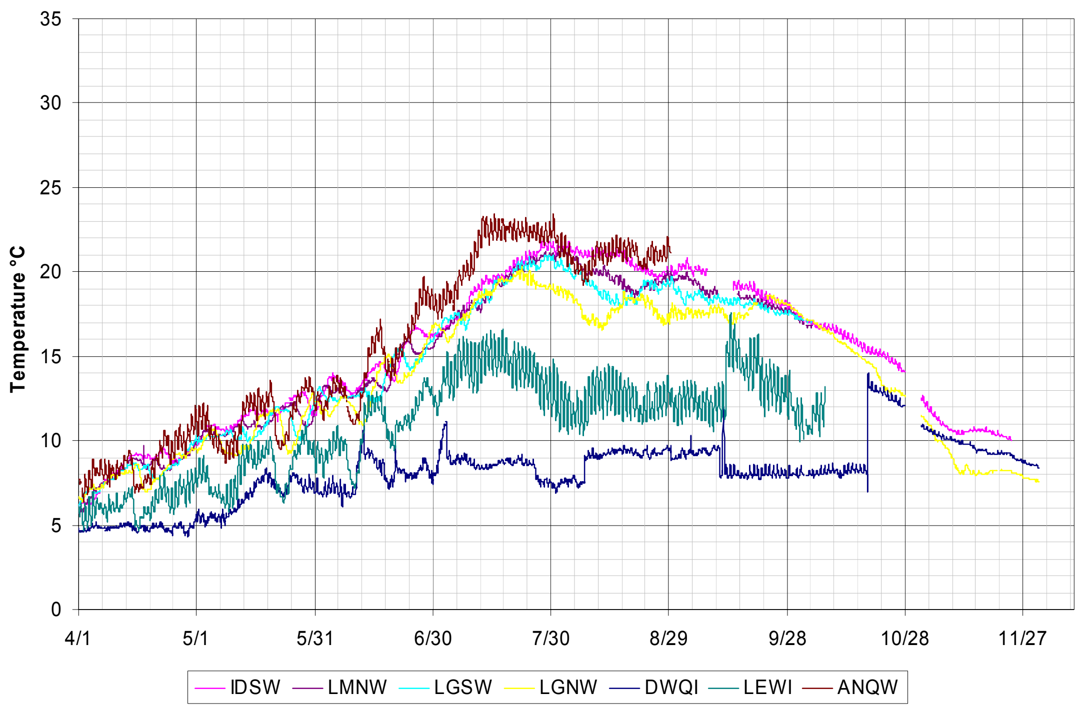


Figure E.43. Tailwater fixed monitor temperature data for the Lower Snake River Projects plus water temperature for the LEWI and ANQW gages.

Figures E.44 through E.47 below depict project release temperatures at Lower Granite, Little Goose, Lower Monumental, and Ice Harbor dams. Temporal patterns collected by both the Corp's tailwater fixed monitoring stations and CE's drafttube deck instruments agree well at all four projects. Drafttube deck temperatures were slightly warmer than those temperatures downstream with the largest temperature difference seen at Lower Granite Dam of approximately 1°C in the end of August.

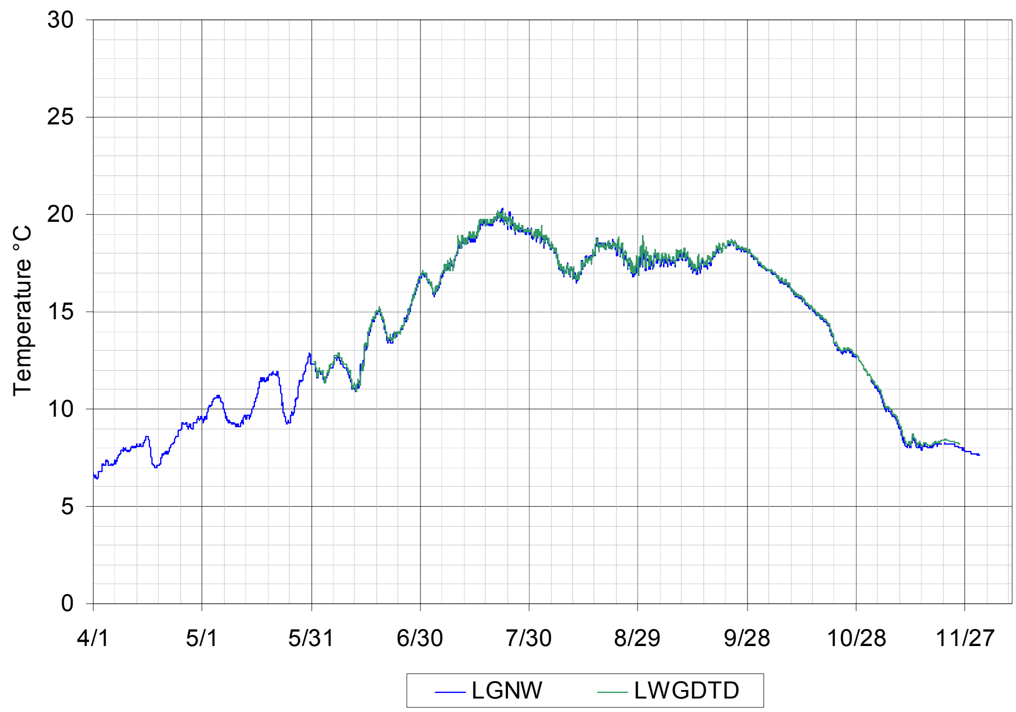


Figure E.44. Temperature profile time histories collected at the LGNW fixed monitoring station and drafttube deck (LWGDTD), 2002.

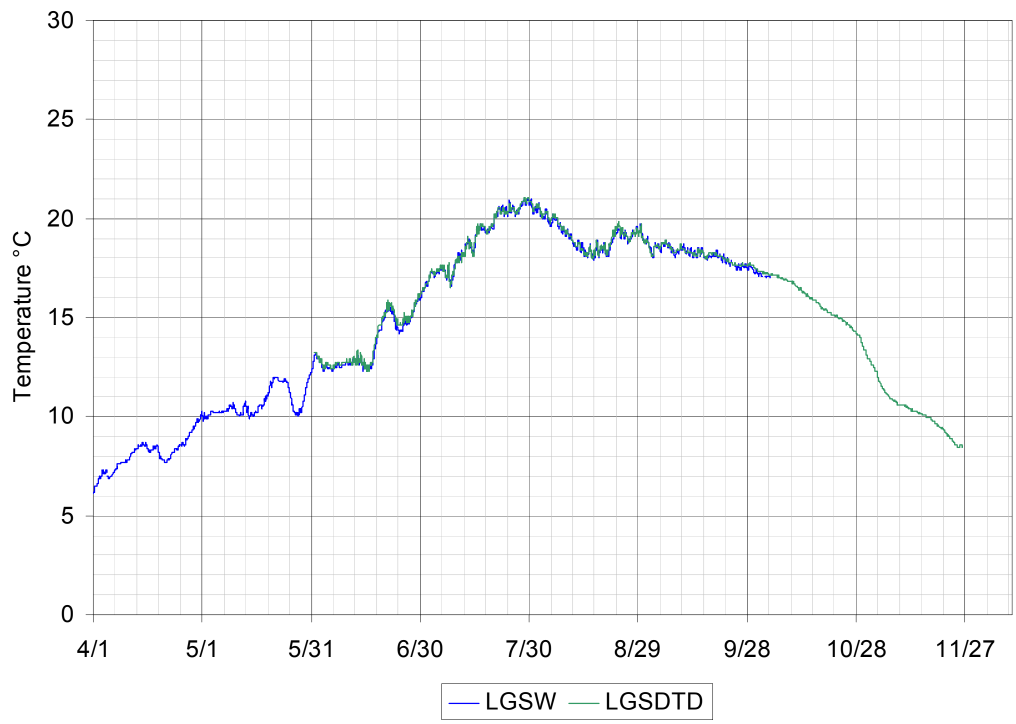


Figure E.45. Temperature profile time histories collected at the LGSW fixed monitoring station and drafttube deck (LGSDTD), 2002.

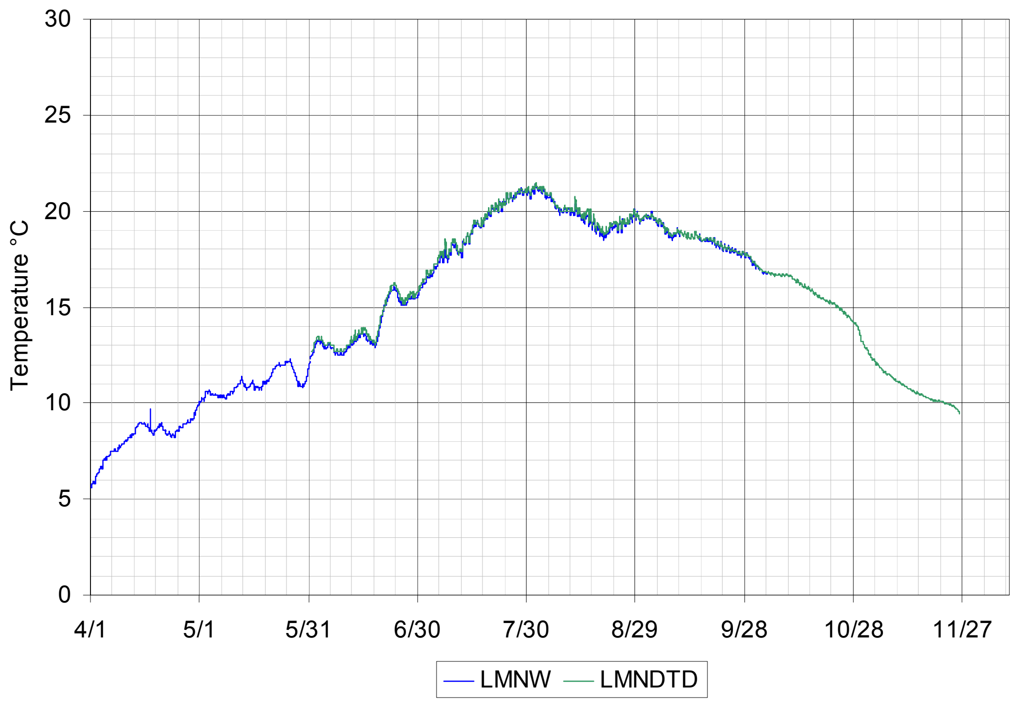


Figure E.46. Temperature profile time histories collected at the LMNW fixed monitoring station and drafttube deck (LMNDTD), 2002.

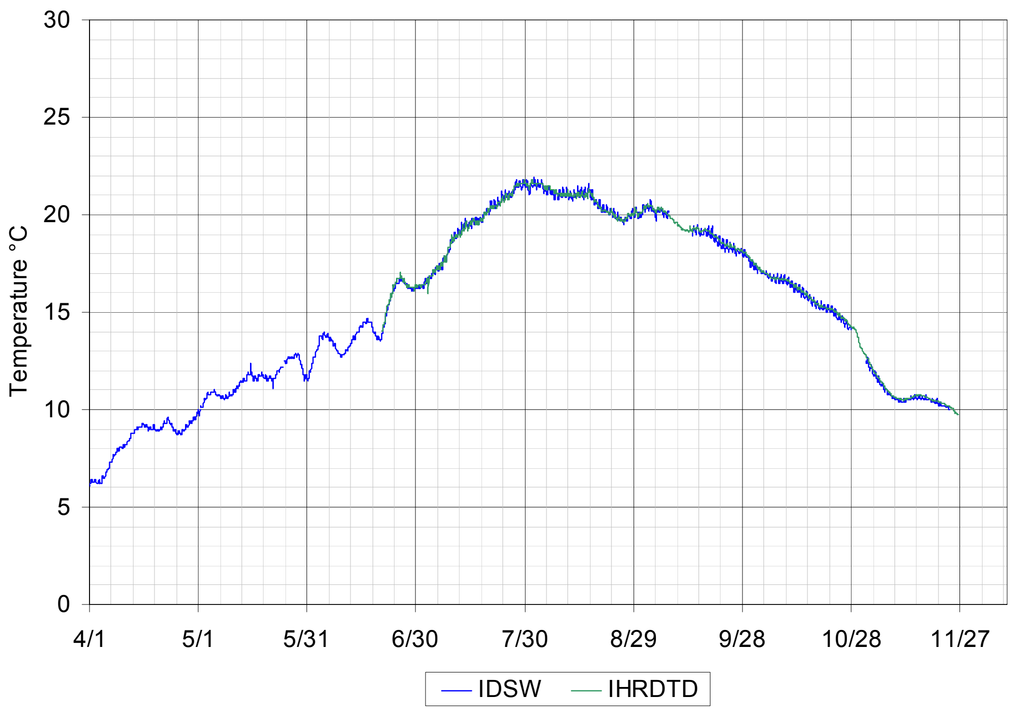


Figure E.47. Temperature profile time histories collected at the IDSW fixed monitoring station and drafttube deck (IHRDTD), 2002.

Discussion

Comparisons were made across stations for the Lower Snake River forebay profile monitoring. Paired sample statistical analyses were conducted by pairing by depth and time between two stations. This was completed in a way to compare each station in a forebay to all the other locations for that forebay. Table E.1 shows the results of these tests across the entire sampling season of June through November. The abbreviations used in referencing the paired strings in Table E.1 started with the project initials such as "I" for Ice Harbor followed by "F" for forebay station, and then followed with a number indicating the lateral position of the station. Lateral station numbers start on the looking downstream left bank side. The analysis was a t-test to determine if the calculated mean difference for each pair was significantly different from zero. The analyses showed each pair to be significantly different; however, the maximum mean difference for all the tests was –0.17 °C for the LWF3-LWFX pair. These data indicate only minor bias (+- 0.2 °C) associated with the lateral positioning of stations in any of the Lower Snake River project forebays. These small differences can easily be accounted by possible differences in instruments depths or occasional seiche action.

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	IF1 - IF2	.0372	.24998	.00154	.0341	.0402	24.129	26344	.000
Pair 2	LMF1 - LMF2	.0266	.17689	.00138	.0239	.0293	19.306	16521	.000
Pair 3	LMF1 - LMF3	-.0088	.27889	.00192	-.0125	-.0050	-4.556	21066	.000
Pair 4	LMF2 - LMF3	-.0158	.22458	.00175	-.0193	-.0124	-9.029	16427	.000
Pair 5	LGF1 - LGF2	-.0534	.42692	.00391	.1929	.2029	77.841	19015	.000
Pair 6	LGF1 - LGF3	-.0816	.49092	.00449	.1512	.1623	55.312	15910	.000
Pair 7	LGF1 - LGFX	-.1256	.59462	.00560	.0929	.1052	31.631	15051	.000
Pair 8	LGF2 - LGF3	-.0213	.24101	.00149	-.0243	-.0184	-14.316	26142	.000
Pair 9	LGF2 - LGFX	-.1033	.39940	.00253	-.1083	-.0984	-40.860	24944	.000
Pair 10	LGF3 - LGFX	-.1057	.38733	.00257	-.1107	-.1007	-41.133	22715	.000
Pair 11	LWF2 - LWF3	.0795	.32124	.00204	.0755	.0835	39.019	24878	.000
Pair 12	LWF2 - LWFX	-.1021	.41403	.00277	-.1075	-.0967	-36.883	22375	.000
Pair 13	LWF3 - LWFX	-.1718	.42087	.00272	-.1772	-.1665	-63.079	23873	.000

Table E.1. Paired samples test for each profile temperature string of a forebay.

These paired sample analyses were also conducted by month (Figure E.48). The stratified periods of July and August resulted in some of the highest mean differences in paired stations of about –0.3 °C. The stations located nearer the project and adjacent to the fish ladder exits (FX) were generally warmer than those stations further upstream of the projects.

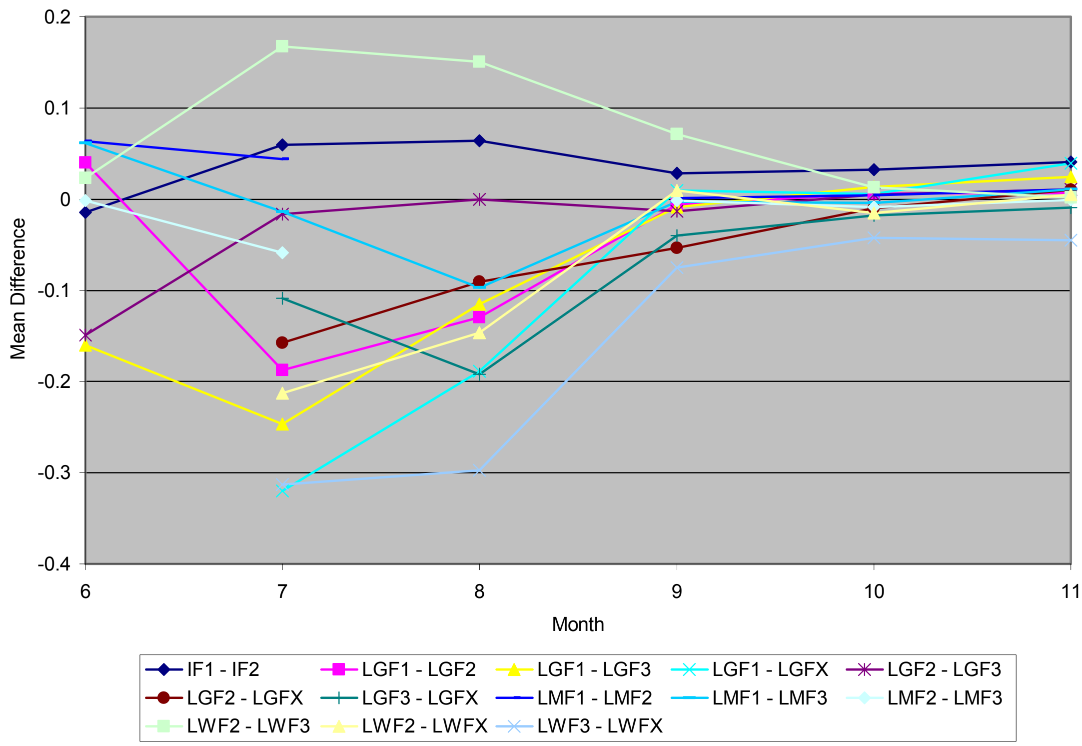


Figure E.48. Paired samples mean differences for each profile temperature string of a forebay by month.

Figure E.49 depicts a flow weighted average temperature calculation for the lower Clearwater River at Lewiston using discharge and temperatures at the Orofino site on the Clearwater River and at the DWQI site on the North Fork of the Clearwater River. During the July 14 through September 11 period the average water temperature at Lewiston was 12.9 °C. The average calculated temperature was 2.2 °C cooler at 10.7 °C for the same period. The average temperature at PEKI on the Clearwater was 11.6 for the same period. The difference of 2.2 °C at Lewiston and 0.9 °C at PEKI are due to the solar warming of the river. The water at Lewiston also experienced wider daily swings in temperature than shown in the flow weighted calculated average. Decreases in Dworshak's cold waters releases on September 12 resulted in quick increases in water temperatures for both the measurements and calculated values for the Peck station.

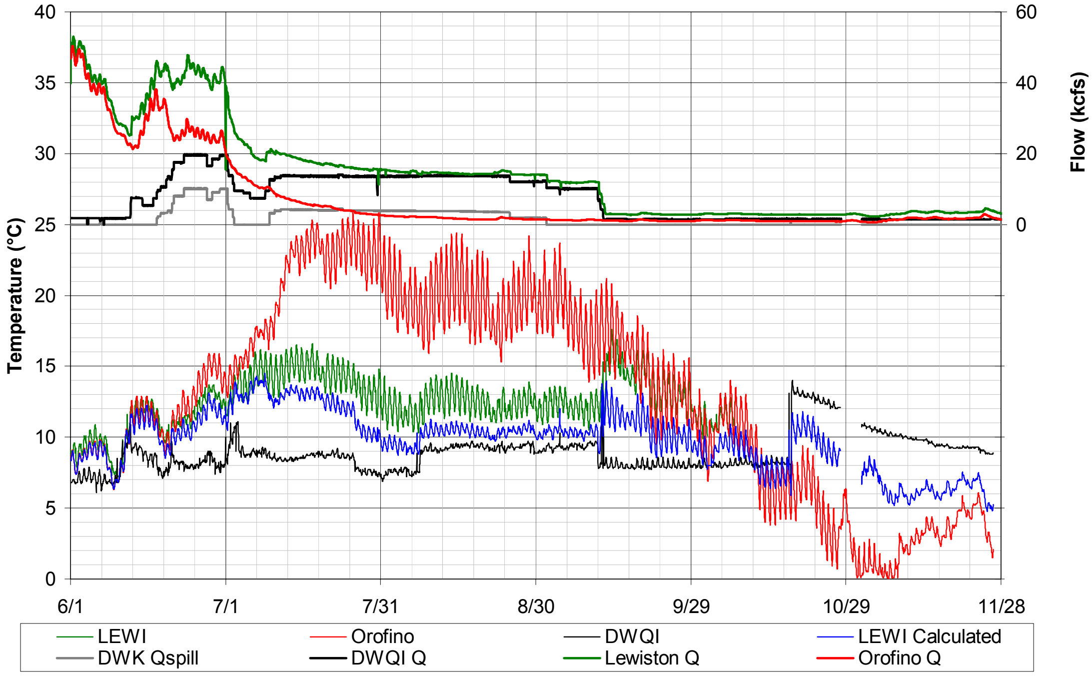


Figure E.49. Clearwater River temperatures and discharges at Orofino on the middle fork, DWQI on the North fork, and Lewiston on the lower Clearwater plus a flow weighted average resulting in a calculated temperature for the lower Clearwater at Lewiston.

Figure E.50 presents a similar calculation for the waters at the confluence of the Clearwater and Snake Rivers using river temperature and discharge for the lower Clearwater (Lewiston) and middle Snake River (Anatone) to calculate the flow weighted average temperature of waters flowing into the Lower Granite pool. The calculated inflow temperature was compared to LGNW values by first adding the time of travel to the time stamp for the calculated values. The calculated inflow values averaged 17.5 °C for the period of July 14 to September 12 while the releases from Lower Granite for the same period average 18.2 °C or 0.7 °C warmer. The difference was determined first by calculating a time of travel from the headwaters to the dam using the theoretical retentions presented in Figure E.15. The average retention time for Lower Granite changed from 5 days to 7 days during the period of comparison. The 0.7 °C warming in Lower Granite pool would be primarily attributed to solar warming since there are only minimal tributary and other sources of heat present in the system.

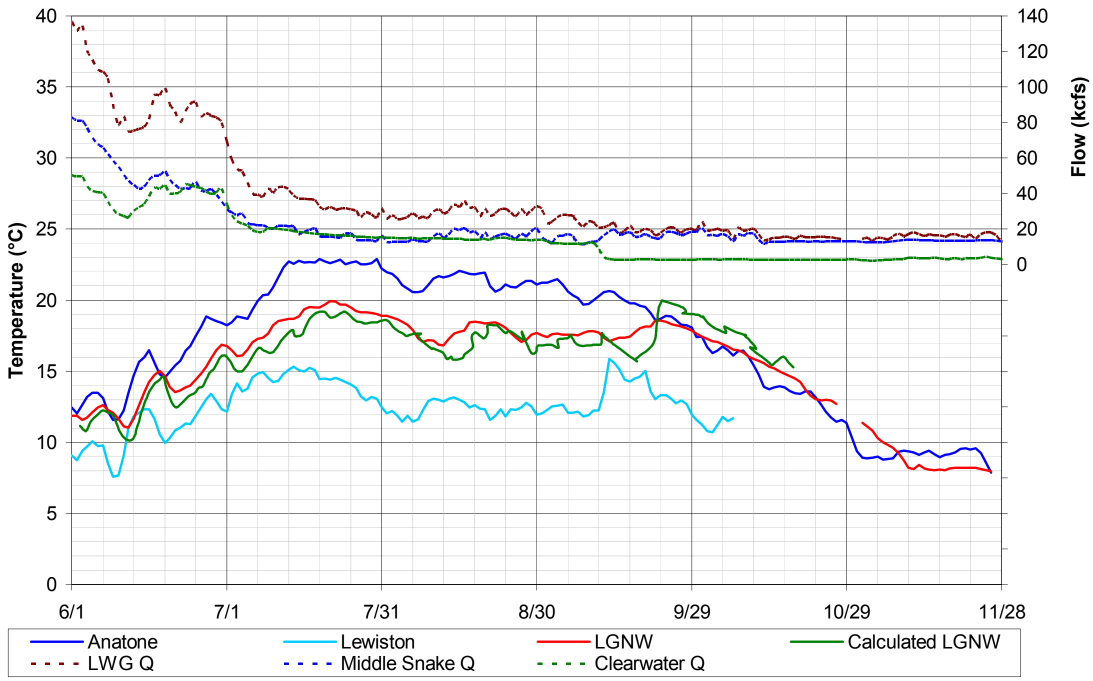


Figure E.50. Clearwater (Lewiston), Snake River (Anatone) daily average temperatures, and Lower Granite releases (LGNW), discharges at each station plus a flow weighted average resulting in a calculated temperature for outflows from to Lower Granite pool (Calculated LGNW).

Clearwater River temperatures at Lewiston increased 4 °C on September 12, 2002 (Figure E.50). This increase immediately followed the decreased cold-water releases from Dworshak. Over the next twelve days, there was a gradual increase by 2 °C in Snake River water at LGNW. Other responses in Snake River temperatures further down river were likely overshadowed by complicated heated and cooling cycles responding to changing weather conditions. Figure E.51 depicts the longitudinal trend in warming on down the Lower Snake River to the Ice Harbor tailwater monitor. Indications from this data are for coincidental responses downstream as significant water temperature changes occur at Lower Granite dam. It is, however, difficult to determine whether the causes are due to coincidental weather changes in the system or release changes at Dworshak Dam.

When considering time of travel, the warming by project is presented in the following table from the last week of June through mid August with waters at the confluence of the Snake and Clearwater Rivers. Average warming for the entire 140 miles for the Lower Snake River during this period was 3.2 °C, which is only 1 °C higher than the 2.2 °C reported above for the 40 miles of the Lower Clearwater River.

Table 2. Average Water Temperature at Lower Snake Project Tailwaters During Late June to Mid August, 2002			
Station	River Mile	Average Temperature	Average Warming
FWCLWG	140	17.4 °C	
LWGN	107	18.3 °C	0.9 °C
LGSW	70	19.2 °C	0.9 °C
LMNW	42	19.7 °C	0.5 °C
IDSW	6	20.6 °C	0.9 °C

(FWCLWG = Flow weighted calculated inflow to Lower Granite Pool)

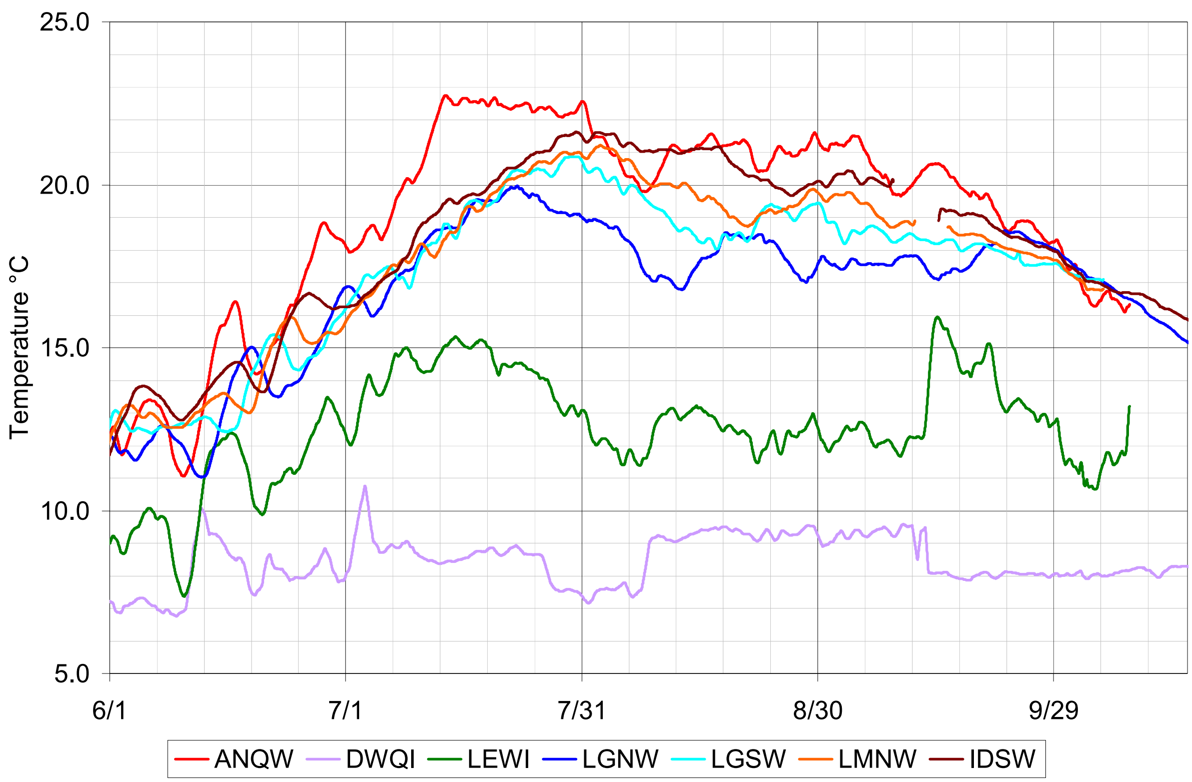


Figure E.51. Twenty-four hour running average water temperatures showing longitudinal trend from Lewiston (LEWI) and Anatone (ANQW) downstream to the Ice Harbor tailwater (IDSW).

Conclusions/Recommendations

Thermal and hydrologic processes result in significant thermal spatial and temporal temperature gradients in the Lower Snake River. One of the more important features is the extreme vertical density and temperature gradients resulting in Dworshak reservoir. The annually occurring 12-14 °C change in water from the surface down to 60 m results in 4-6 °C temperatures stored in the lower depths, some of which can be released through the selective withdrawal system on the dam.

Release of the cold waters into the North Fork of the Clearwater River can result in rapid and significant changes in the lower Clearwater River temperatures depending on the ratio of the warmer middle fork Clearwater River to that from the North Fork. The resulting change in Lower Granite forebay water temperature is more subtle/dampened and highly dependent on the ratios of middle Snake and Clearwater River water, total discharge (travel time), and weather conditions.

Annual thermal cycles are consistent at all of the study area sampling stations as would be expected. Spring warming trends start in the March timeframe with most stations temperatures (both in-pool and in river) peaking in late July followed by fall cooling. Maximum temperatures were observed a few weeks earlier in Dworshak pool. Daily solar warming results in significant diel temperature cycles as well as lasting general warming on most of the riverine reaches. This is true for both the middle Snake as well as the Clearwater Rivers.

Based on the screening study data in conjunction with data from PNNL collected upstream on the Lower Granite pool, an under flow of the Clearwater River water results when mixing in with the middle Snake River waters. This incomplete mixing persists throughout the length of Lower Granite pool with the colder Clearwater River water flowing underneath the warmer Snake River waters. There appears to be slight warming of the surface waters but once the Clearwater has at least partially mixed in there is little change in the bottom water temperatures by the time they reach the Lower Granite Dam. The resulting forebay temperature profiles may have as much as a 6 °C gradient from surface to bottom. This condition of a thermally induced density gradient exists from early July until mid September.

Data for the stations further downstream of Lower Granite dam indicated much weaker and often shorter-lived vertical thermal gradients. Data from the Ice Harbor forebay indicated surface warming but a very small temperature gradient from top to bottom. Longitudinal thermal gradients due to warming as the river flowed down the Lower Snake were indicated by the mixed river measures such as the tailwater fixed monitor data collected by the COE. The change was gradual from project to project with a total change of 2 °C from Lower Granite Dam down to Ice Harbor Dam during the July-August period. In addition, a longitudinal increase of approximately 1 °C occurred in the Lower Granite pool from the headwaters down to the dam. Changes of approximately 1 °C were indicated in the downstream reaches of the Clearwater River as well. Occasional warming by 0.5 °C was detected on the middle Snake River from river mile 170 down to river mile 156 during the July-August period.

Lateral thermal gradients were not found to be a major component of the spatial patterns. Some minor differences were determined between stations and depths for any one forebay. However, these differences were minimal in relation to the vertical and few longitudinal gradients. The average differences recorded were generally in the order of 0.2 °C and comparable to instrument/measurement uncertainty. Greater differences were observed for specific times but likely can be explained by water movement, (wave or seiche action) and/or minor differences in the recorded depths of the instruments.

In general the tailwater monitor was a good measure of average forebay water temperature even during periods of significant vertical gradients. This is illustrated in Figures E.52 and E.53 for Lower Granite and Ice Harbor projects, which compare the fixed monitor (tailwater and forebay) and profile time histories temperatures during 10 days in July. In both cases the profile column average data was no different from the tailwater fixed monitor data. On the other hand, the forebay monitors LWG and IHR were both very comparable to the 5 m profile instruments as would be expected during the stratified period. Both are point measures in space but the tailwater reaches are generally well mixed and made up of a fairly uniform blend of the forebay waters, especially in the case of the Lower Snake projects. The forebay instrument is positioned at one discreet depth in an area that can experience some significant vertical thermal gradients that will be a biased measure of forebay temperatures. These relationships were found to be the same for other the two projects Lower Monumental and Little Goose.

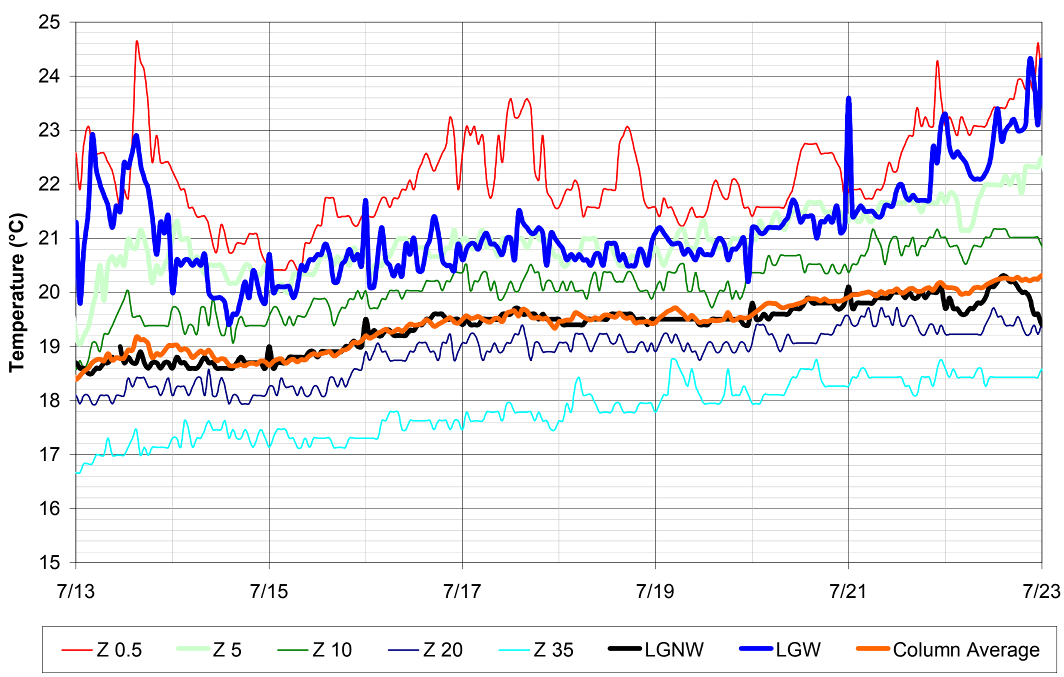


Figure E.52. Temperature profile for Lower Granite forebay, LWGFBP2, with fixed monitor and column average data overlaid during July.

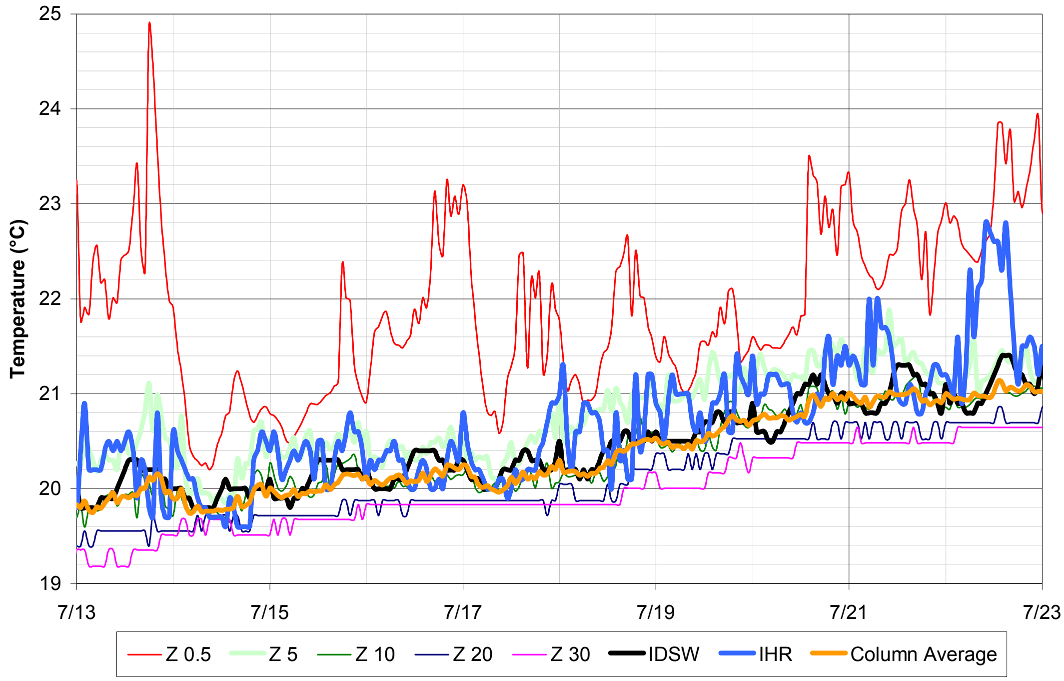


Figure E.53. Temperature profile for Ice Harbor forebay, IHRFBP2, with fixed monitor and column average data overlaid during July.

In future applications and/or studies the potential bias associated with the forebay temperature monitoring during stratified periods should be recognized and accounted for while doing analysis or decision making. It would be desirable to install permanent automated profiling instrument strings to describe vertical thermal patterns associated with Lower Snake River project forebays. The recommended depths are 0.5, 1.5, 3, 5, 10 meters and then at 5 meter intervals to within 1 m of bottom. Since minimal lateral bias was indicated in the screening study then one station located at the deepest point, preferably in the thalweg, will be adequate to get representative temperature measures of the forebay waters. This station should be located an adequate distance upstream to avoid any affects from the dam on water movement such as mixing, down welling or upwelling. Depending on how the data will be used will determine the need for real-timing the data flow.

The tailwater fixed monitors were determined to be representative of the well-mixed project releases, which is generally a good indicator of average column conditions in the project forebay. No change is recommended for the Lower Snake River tailwater instruments.

The Lower Snake River can experience a high degree of stratification, which supports vertical density gradients. This results from incomplete inflow mixing of waters of different temperatures such as the Snake and Clearwater Rivers. The other factors heavily influencing the vertical and longitudinal gradients in temperature is solar warming and wind mixing. With this understood, the multiple dimensional properties of the Lower Snake River must be taken into account when modeling is required. If the purpose is to describe or quantify habitat then a 2-dimensional approach is called for to provide adequate resolution in the entire Lower Snake River. If the purpose is to forecast average temperatures at some point downstream then a 1-dimensional approach will address most of the Lower Snake River. The exception is likely in Lower Granite pool, which experiences some of the more extreme variability in the thermal patterns.

References

Bennett, D.H., M.H. Karr, and M.A. Madsen. 1997. Thermal and velocity characteristics in the lower Snake River reservoirs, Washington, as a result of regulated upstream water releases. Completion Report. US Army, Corps of Engineers. Walla Walla, WA.

NOAA, 2000, Endangered Species Act Section 7 Biological Opinion on the Reinitiation of Consultation on Operation of the Federal Columbia River Power System, Including the Juvenile Fish Transportation Program, and 19 Bureau of Reclamation Projects in the Columbia Basin: NOAA Fisheries.

Appendix F

Models Considered for the Lower Snake River Temperature Modeling Effort

CE-QUAL-ICM http://www.wes.army.mil/el/elmodels/index.html	
Proprietary/Non-Proprietary	Public
Peer-Reviewed (Y/N)	Yes
Documentation	Yes
Previous Applications	Chesapeake Bay, the New York Bight, Lower Green Bay, Los Angeles - Long Beach Harbor, and Indian River - Rehoboth Bay
Dimensionality (1,2,3-D)	Multi-dimensional water quality model (1,2,3- D)
Time Increment Range (min/max)	Sub-hourly
Simulation Period Range (min/max)	Unlimited
Steady State/Dynamic Simulation	Dynamic
Solution Technique – benefits	Finite volume
River Hydrodynamics-Steady/Unsteady/Momentum	None- coupled to hydrodynamics
Reservoir Hydrodynamics-Continuity/Momentum	None – coupled to hydrodynamics
Heat Budget Formulations/References	
Outlet Structure Options (2 and 3-D)	None
Source Code Language/Version	Coded in ANSI Standard FORTRAN F77
Hardware Requirements	Operates on a variety of platforms including 486 PC, Silicon Graphics and Hewlett Packard workstations, and Cray Y-MP and C-90 mainframes.
Run Time - 1 year simulation	Highly Dependent on grid resolution and number and type of constitutes
Input File Database Requirements	Constituent loading
Developer Aids (e.g., interfaces, utilities)	Easily ported to scientific visualization post processors.
User Support Availability	US Army Corps of Engineers, Engineer Research Development Center Staff and Web Site
Other Features	A versatile, multidimensional model (CE-QUAL-ICM), based on the finite volume modeling approach, has been developed for 2D horizontal (i.e., depth-averaged) and 3D studies. CE-QUAL-ICM has evolved from a 3D water quality model developed for Chesapeake Bay to evaluate the effectiveness of nutrient reduction proposals on

Other Features (cont.)	Bay eutrophication. This model contains a bottom sediment chemistry sub-model that interacts with the water column for simulating sediment oxygen demand and nutrient fluxes. The CE-QUAL-ICM modeling approach involves first applying a 2D or 3D hydrodynamic model and coupling the output to CE-QUAL-ICM for driving the transport terms. The water quality model can then be applied for a variety of conditions without having to rerun the hydrodynamic model

CE-QUAL-W2

http://www.ce.pdx.edu/w2/Applications.html

Proprietary/Non-Proprietary	Public
Peer-Reviewed (Y/N)	Yes
Documentation	Yes
Previous Applications	Application list too long to list here. See the following Web site: http://www.ce.pdx.edu/w2/w2app.htm
Dimensionality (1,2,3-D)	1D-2D (quasi 3D)
Time Increment Range (min/max)	Variable, surface gravity wave restrictions
Simulation Period Range (min/max)	Unlimited
Steady State/Dynamic Simulation	Unsteady
Solution Technique – benefits	Finite volume
River Hydrodynamics-Steady/Unsteady/Momentum	Unsteady one-dimension shallow water equations (water surface and velocity)
Reservoir Hydrodynamics-Continuity/Momentum	Unsteady coupled continuity and momentum equations
Heat Budget Formulations/References	Surface heat exchange options (equilibrium temperature and exchange coefficient: Edinger et al. (1974) or term by term representation)
Outlet Structure Options (2 and 3-D)	Point, line, distributed source
Source Code Language/Version	Fortran
Hardware Requirements	PC-Pentium class
Run Time - 1 year simulation	Depends on grid resolution (hours, generally)
Input File Database Requirements	Flow and constituent loading, meteorological parameters, project operations
Developer Aids (e.g., interfaces, utilities)	Output easily ported to scientific visualization post processors
User Support Availability	US Army Corps of Engineers, Engineer Research Development Center Staff and Web site
Other Features	Dissolved oxygen, nutrient, algal dynamics, sediment interactions Coupled reservoir and river systems

COLTEMP	
Proprietary/Non-Proprietary	Public
Peer-Reviewed (Y/N)	Yes
Documentation	? Subset of HEC 5Q
Previous Applications	Columbia River Basin, Dworshak/Snake River Temperature Management
Dimensionality (1,2,3-D)	1-D
Time Increment Range (min/max)	Daily/hourly
Simulation Period Range (min/max)	Unlimited
Steady State/Dynamic Simulation	
Solution Technique – benefits	Dynamic
River Hydrodynamics-Steady/Unsteady/Momentum	Linked node routing
Reservoir Hydrodynamics-Continuity/Momentum	Steady or unsteady
Heat Budget Formulations/References	Equilibrium temperature and exchange coefficient, Edinger et al. (1974))
Outlet Structure Options (2 and 3-D)	Empirical selective withdrawal approximations
Source Code Language/Version	Fortran
Hardware Requirements	Microcomputer version (MS DOS compatible; Extended Memory: 2 - 10Mb)
Run Time - 1 year simulation	Depends on system size (minutes)
Input File Database Requirements	Flow and constituent time histories; can be coupled with DSS
Developer Aids (e.g., interfaces, utilities)	?
User Support Availability	?
Other Features	The COLTEMP numerical model is a one-dimensional water temperature model that provides conceptual information about water temperature conditions in Columbia River reservoirs. COLTEMP is a water management tool used to evaluate how reservoir regulation changes could impact the water temperature structure of reservoirs. The potential changes in the water temperature structure of the reservoirs are taken into consideration during water-release scheduling. COLTEMP is a simplified

Other Features (cont.)	version of the Corps' HEC-5Q water quality model. The model uses the concept of mass balance to move water downstream. The fundamental transport mechanisms are advection (the horizontal movement of a mass of water) and diffusion (movement from a region of higher concentration to a region of lower concentration). External sources determining water temperature include point sources and water withdrawals. Point sources include headwater flow, tributary stream flow, and water withdrawals. The major non-point source is solar radiation. Point sources are represented by daily flow rates multiplied by the corresponding water temperatures. Withdrawals remove mass at the rate of the outflow multiplied by the computed ambient water temperature. As a one-dimensional model, COLTEMP does not consider any degree of thermal stratification within the reservoir. Accuracy of the water temperature output depends on the accuracy of water temperature, weather, and river flow data. In the 1994 interagency Columbia River System Operation Review, the model showed that it adequately represented the one-dimensional thermal dynamics of reservoirs during summer seasons in the Columbia reservoirs.

EFDC (Environmental Fluid Dynamics Code)	
Proprietary/Non-Proprietary	Non-proprietary
Peer-Reviewed (Y/N)	Yes
Documentation	Jin, K.-R., J. H. Hamrick, and T. Tisdale (2000). Application of Three-Dimensional Hydrodynamic Model for Lake Okeechobee. *J. Hydraulic Engineering*, 126:758–771.
Previous Applications (Columbia and Snake Rivers)	Perkins, W.A., M.C. Richmond, A. Coleman, and J. Serkowski. 2002. Three-Dimensional Temperature Simulation of the Lower Snake River and McNary Reservoirs. Battelle Pacific Northwest Division, Richland, WA Perkins, W.A., M.C. Richmond, A. Coleman, and J. Serkowski. 2002. Three-Dimensional Temperature Simulation of the Wanapum and Priest Rapids Reservoirs. Battelle Pacific Northwest Division, Richland, WA
Dimensionality (1,2,3-D)	3D, 2D and 1D
Time Increment Range (min/max)	Seconds to hours
Simulation Period Range (min/max)	Seconds to year
Steady State/Dynamic Simulation	Dynamic simulation
Solution Technique – benefits	Code uses a curvilinear grid system to efficiently model large river/reservoir/coastal systems.
River Hydrodynamics-Steady/Unsteady/Momentum	Unsteady momentum
Reservoir Hydrodynamics-Continuity/Momentum	Unsteady momentum
Heat Budget Formulations/References	Hamrick, J, and W. Mills, (undated). Three-Dimensional Hydrodynamic and Reactive Transport Modeling of Power Plant Impacts on Surface Water Systems. Unpublished article. Tetra-Tech, Inc. Rosati, A. K., and K. Miyakoda, 1988: A general circulation model for upper ocean simulation. J. Phys. Ocean., 18, 1601-1626.
Outlet Structure Options (2, 3-D)	Specify forebay stage
Source Code Language/Version	Fotran77
Hardware Requirements	Runs on Windows, Linux, and Unix operating systems using common hardware (P3-P4 processor, 512 Mb RAM, and >10 Gb disk storage)

Run Time - 1 year simulation	Example: Lower Granite Pool, Intel P4 (1.7 GHz) 20 CPU days to perform a 1-year simulation
Input File Database Requirements	ASCII files with specific data requirements in a space delimited format
Developer Aids (e.g., interfaces, utilities)	Tecplot interface exists
User Support Availability	Existing model applications on the Columbia and Snake River; contact Marshall Richmond 509-372-6241. Other applications: Contact John Hamrick (the EFDC code developer) at TetraTech, Inc.
Other Features	Includes capabilities for sediment transport, sediment-contaminant interaction, wetting/drying of cells.

MASS1 (Modular Aquatic Simulation System 1D)	
Proprietary/Non-Proprietary	Non-Proprietary
Peer-Reviewed (Y/N)	Yes
Documentation	Richmond, M.C., W.A. Perkins, and Y. Chien. 2000. Numerical Model Analysis of System-wide Dissolved Gas Abatement Alternatives. Battelle Pacific Northwest Division, Richland, Washington. Perkins, W.A., M.C. Richmond, A. Coleman, and J. Serkowski. 2002. Effects of Wanapum and Priest Rapids impoundments on Columbia River Temperature. Battelle Pacific Northwest Division, Richland, Washington.
Previous Applications	Corps of Engineers: Dissolved Gas Abatement Study, Lower Snake River Feasibility Study, Dworshak Operations Study Washington Dept. of Fish and Wildlife: Hanford Reach Fish Stranding Department of Energy: Columbia River Hydraulics and Contaminant Transport Studies Grant County PUD: Effects of Wanapum and Priest Rapids Impoundments on Columbia River Temperatures, Hanford Reach Fish Stranding
Dimensionality (1,2,3-D)	1D cross-sectional average
Time Increment Range (min/max)	Seconds to hours
Simulation Period Range (min/max)	Seconds to decades
Steady State/Dynamic Simulation	Dynamic (unsteady) simulation for both hydraulics and transport calculations
Solution Technique – benefits	Model couples both hydrodynamics and transport simulations thus avoiding the need for a separate hydrodynamics code. Accurate solution methods (TVD) are used for the transport equation to minimize numerical diffusion. Dynamic memory allocation
River Hydrodynamics-Steady/Unsteady/Momentum	Unsteady momentum (St. Venant Equations)
Reservoir Hydrodynamics-Continuity/Momentum	Unsteady momentum (St. Venant Equations)
Heat Budget Formulations/References	Surface heat exchange based on individual flux components. Edinger et al. (1974). Brown and

	Barnwell (1987). TVA(1972).
Outlet Structure Options	Specified forebay stage, specified project discharge, specified stage *target*, specified discharge *target* - these are boundary condition types
Source Code Language/Version	Fortran95
Hardware Requirements	Runs on Windows, Linux, and Unix operating systems using common hardware (P3-P4 processor, 256 Mb RAM, and 1 Gb disk storage)
Run Time - 1 year simulation	Example: Mid-Columbia Application on a 1,7 GHz P4 (460 river miles, 1094 cross sections, hydro time step = 30 min, temperature time step = 3 min) = 90 min/year
Input File Database Requirements	ASCII files with specific data requirements in a space delimited format
Developer Aids (e.g., interfaces, utilities)	Input and output files are directly readable by many analysis and plotting packages, like gnuplot, R (a stats package), Excel, etc. GUI's have been developed for specific applications such as the Hanford Reach.
User Support Availability	Available through the code developers at Pacific Northwest National Laboratory. Contact Marshall Richmond 509-372-6241
Other Features	Also includes capabilities for total dissolved gas transport, equation of state for dissolved gas, lateral inflow/outflow to simulate groundwater interaction, and a process control theory based method for hydroproject operations. Model bathymetry is based on a survey data from the Corps and other sources.

MASS2 (Modular Aquatic Simulation System 2D)	
Proprietary/Non-Proprietary	Non-proprietary
Peer-Reviewed (Y/N)	Yes
Documentation	Richmond, M.C., W.A. Perkins, and Y. Chien. 2000. Numerical Model Analysis of System-wide Dissolved Gas Abatement Alternatives. Battelle Pacific Northwest Division, Richland, Washington. Perkins, W.A. and M.C. Richmond. 2002. Evaluation of Time-varying Physical Fish Habitat in the Hanford Reach. Battelle Pacific Northwest Division, Richland, Washington.
Previous Applications	Corps of Engineers: Dissolved Gas Abatement Study, Lower Snake River Feasibility Study, The Dalles Tailwater Predator Study Department of Energy: Columbia River Hydraulics and Contaminant Transport Studies Grant County PUD: Hanford Reach Fish Stranding
Dimensionality (1,2,3-D)	2D depth-averaged
Time Increment Range (min/max)	Seconds to minutes. Typical applications use time steps in the range of 10 to 60 seconds.
Simulation Period Range (min/max)	Seconds to years. Typical applications have simulated time periods of a few days to several months.
Steady State/Dynamic Simulation	Unsteady solution of the 2D depth-averaged thermal energy and other general transport equations.
Solution Technique – benefits	Code uses a curvilinear multiblock grid system to efficiently model large river/reservoir/coastal systems.
River Hydrodynamics-Steady/Unsteady/Momentum	Unsteady solution of the 2D depth-averaged momentum equations.
Reservoir Hydrodynamics-Continuity/Momentum	Unsteady solution of the 2D depth-averaged momentum equations.
Heat Budget Formulations/References	Surface heat exchange based on individual flux components. Edinger et al. (1974); Brown and Barnwell (1987); TVA (1972).
Outlet Structure Options (2 and 3-D)	Can simulate a point withdrawal in 2D. Specified forebay stage, specified project discharge – boundary condition types

Source Code Language/Version	Fotran95
Hardware Requirements	Runs on Windows, Linux, and Unix operating systems using common hardware (P3-P4 processor, 512 Mb RAM, and >1 Gb disk storage)
Run Time - 1 year simulation	Example: Bonneville Pool on a Intel P4 (1,7 Ghz) system = 10 CPU days to simulate 1 year
Input File Database Requirements	ASCII files with specific data requirements in a space delimited format
Developer Aids (e.g., interfaces, utilities)	Input files are directly readable by many analyses and plotting packages, like gnuplot, R (a stats package), Excel, etc. 2-D output files use net CDF standard format, for which many manipulation tools exist. 2-D output files are directly readable by tecplot.
User Support Availability	Available through the code developers at Pacific Northwest National Laboratory. Contact Marshall Richmond 509-372-6241.
Other Features	Also includes capabilities for total dissolved gas transport, equation of state for dissolved gas, sediment transport, sediment-contaminant interaction and wetting/drying of cells. Model bathymetry is based on a survey data from the Corps and other sources.

MIKE11	
Proprietary/Non-Proprietary	Proprietary
Peer-Reviewed (Y/N)	Yes
Documentation	DHI, 2002, MIKE11 User Manual DHI, 2002. MIKE11 Reference Manual On-line context-specific help
Previous Applications	Numerous applications worldwide (see www.dhigroup.com) Idaho Power Co., Snake River Hells Canyon complex FERC Re-Licensing. IDWR, Clearwater/Lower Snake reservoirs (in progress). IDWR, South Fork Clearwater Sediment model (in progress). Cape Fear River Basin Project, North Carolina Pudding River Flood Management, Oregon Napa River Flood Plain and Marsh Restoration Eutrophication of Klamath Lake, Oregon Salt River project modeling of irrigation canals, Arizona
Dimensionality (1,2,3-D)	1-D river flow 2-D laterally averaged reservoir model
Time Increment Range (min/max)	Not limited, depends on selection of model simulation algorithm.
Simulation Period Range (min/max)	Not limited
Steady State/Dynamic Simulation	Dynamic
Solution Technique – benefits	The hydrodynamic module is a fully implicit, finite difference computation of unsteady flow. Uses double sweep method for matrix solution.
River Hydrodynamics-Steady/Unsteady/Momentum	Solves the complete Saint-Venant non-linear equations of open channel flow. Offers a choice of high-order fully dynamic, diffusive wave, kinematic wave, and quasi-steady state solution methods. Solution scheme by Abbott and Ionescu. (Abbott, M.B. and Ionescu, F., 1967: On the numerical computation of nearly-horizontal flows. J.Hyd.Res., 5, pp. 97-117.) Includes advective and dispersive transport.

Reservoir Hydrodynamics-Continuity/Momentum	Continuity/momentum
Heat Budget Formulations/ References	Sinkrot and Gulliver, Journal of Hydraulic Research, Vol 38, 2000, No.5 Muhammed Iqbal, An introduction to solar radiation, Academic Press, 1983. M.E. Jensen, R.D. Burman, and R.G. Allen, Evaporatranspiration and Irrigation Requirements, ASCE 1990. Peter S. Eagleson, Dynamic Hydrology McGraw-Hill, 1970. Swedish Council for Building Research, Jorgen Sahlberg, A hydrodynamic model for heat conduction calculation on lakes at the ice formation date. Document D4:1984, 1984. Gunnar Lindh and Martin Falkenmark, En inledning til vatteresurslaren, Norway 1972. Poul; Harremoes and Anders Malmgren-Hansen, Laerebog i vandforurening, Polyteknish forlag, Denmark, 1990. Robert G. Wetze. Limnology, Saunders College Publishing, 1983.
Outlet Structure Options (2- and 3-D)	Weirs, culverts, regulating structures, control structures, dam-break, user-defined, tabulated.
Source Code Language/Version	Proprietary. Runs under Microsoft Windows/NT operating system. Written in Pascal using Borland DELPHI.
Hardware Requirements	PC running Windows /95/98/2000/NT. Minimum Pentium processor, 200 Mhz, 64 MB Ram, 1 GB hard drive, SVGA monitor 1024x768 resolution, 1 MB memory on graphics card, 8 x speed CD ROM drive.
Run Time - 1 year simulation	Depends on numerous factors
Input File Database Requirements	Proprietary input/output format. Utilities for importing some data types.
Developer Aids (e.g., interfaces, utilities)	GUI interface for data control, analysis and presentation of results. Graphic presentation includes river network plan plots, cross-sectional plots, pre-selection of longitudinal profiles, time series plots, comparison of measured/simulated and simulated/simulated time series, animation of flows and water levels on both plans and profiles, control of plotting parameters, etc.

User Support Availability	Part of DHI annual maintenance contract. Offices in Pennsylvania, Florida, Oregon. Representatives in Boise, Idaho. Research collaborators with University of Idaho Ecohydraulics Research Group. Additional professional consulting with DHI available.
Other Features	Many add-on modules are available including sediment transport, rainfall/runoff, water quality, advection dispersion, flood forecasting, dam break, structure operation, quasi steady state, heat balance, TDG modeling and 2-D reservoir modeling. Integrates with other DHI modeling products. User defined structure allowing for the customization of almost specialist application or modification to MIKE11.

RBM10	
Proprietary/Non-Proprietary	Non-Proprietary
Peer-Reviewed (Y/N)	Yes
Documentation	EPA, 2001. Application of a 1-D Heat Budget Model to the Columbia River System. EPA, 2001. Evaluation of Water Temperature Regimes in the Snake River using Transect Measurements and the RBM10 Model.
Previous Applications	Draft TMDL for Temperature for Mainstem Columbia/Snake Rivers Annual Dworshak Dam Operation planning Box Canyon Dam FERC Re-Licensing
Dimensionality (1,2,3-D)	1-D
Time Increment Range (min/max)	Hourly - daily
Simulation Period Range (min/max)	1 hour to 30 years
Steady State/Dynamic Simulation	Dynamic
Solution Technique – benefits	Mixed Eulerian-Lagrangian approach (reverse particle tracking) reduces numerical dispersion and allows longer time steps without instability. Kalman filter using model estimates and measurements.
River Hydrodynamics-Steady/Unsteady/Momentum	Steady, gradually-varied
Reservoir Hydrodynamics-Continuity/Momentum	Continuity
Heat Budget Formulations/References	Wunderlich and Gras (1967); Chapra (1997); Bowie et al (1985)
Outlet Structure Options (2 and 3-D)	NA
Source Code Language/Version	Fortran (Microsoft Powerstation 4.0)
Hardware Requirements	PC Workstation (500-900 Mhz, 256 MB RAM, 500 MB hard drive space)
Run Time - 1 year simulation	Less than 1 minute for Snake/Clearwater rivers
Input File Database Requirements	Flat Files (space delimited), Naming Conventions
Developer Aids (e.g., interfaces, utilities)	Input/Output interface
User Support Availability	EPA Region 10 support

WQRRS (**http://www.hec.usace.army.mil/**)	
Proprietary/Non-Proprietary (P/NP)	Public
Peer-Reviewed (Y/N)	Yes
Documentation	Yes
Previous Applications	
Dimensionality (1,2,3-D)	1D
Time Increment Range (min/max)	Daily-Hourly
Simulation Period Range (min/max)	Unlimited
Steady State/Dynamic Simulation	Dynamic
Solution Technique – benefits	Linked Node
River Hydrodynamics-Steady/Unsteady/Momentum	Steady or Unsteady
Reservoir Hydrodynamics-Continuity/Momentum	Hydrologic Routing
Heat Budget Formulations/References	Equilibrium Temperature and Exchange Coefficient; Edinger et al. (1974)
Outlet Structure Options (2 and 3-D)	Empirical Selective Withdrawal Approximations
Source Code Language/Version	Fortran
Hardware Requirements	Microcomputer version (MS DOS compatible; 640Kb RAM)
Run Time - 1 year simulation	Minutes
Input File Database Requirements	Flow and Constituent Time Histories
Developer Aids (e.g., interfaces, utilities)	Can be coupled with DSS (WQRRSR, WQRRSQ, and SHP) that are able to be integrated into a system analysis or to be used as separate programs. Three other programs (GEDA, HEATX, and WEATHER) are used to develop model input and parameters
User Support Availability	US Army Corps of Engineers, Hydrologic Engineering Center
Other Features	The WQRRS package of computer programs has been assembled to evaluate water quality (ecological cycle) conditions in river and reservoir systems. The package provides vertical profiles of water quality conditions in reservoirs and longitudinal conditions in river networks of branching channels and/or around

Other Features (cont.)	islands. This type of modeling is referred to as one-dimensional modeling. The package includes three separate modules (WQRRSR, WQRRSQ, and SHP) that are able to be integrated into a system analysis or to be used as separate programs.

REFERENCES

Abbott, M.B. and Ionescu, F., 1967: On the Numerical Computation of Nearly Horizontal Flows. J.Hyd.Res., 5, pp. 97-117.

Bowie et al, 1985, Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition): EPA/600/3-85/040.

Brown, L. and Barnwell, T. Jr., 1987, The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual, Technical report, U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA. EPA/600/3-87/007.

Chapra, 1997, Surface Water-Quality Modeling: McGraw-Hill.

DHI, 2002, MIKE11 User Manual

DHI, 2002, MIKE11 Reference Manual

Edinger, J.E., Brady D.K., and Geyer, J.C., 1974, Heat Exchange and Transport in the Environment: Electric Power Research Institute (EPRI) Publication No. 74-049-00-3, Palo Alto, CA., p. 125.

Eagleson, Peter S., 1979, Dynamic Hydrology: McGraw-Hill.

EPA, 2001a, Application of a 1-D Heat Budget Model to the Columbia River System: U.S. Environmental Protection Agency, Region X, Seattle, WA.

EPA, 2001b, Evaluation of Water Temperature Regimes in the Snake River using Transect Measurements and the RBM10 Model, U.S. Environmental Protection Agency, Region X, Seattle, WA.

Hamrick, J. M., 1992, A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects. Special Report 317, Virginia Institute of Marine Science, College of William and Mary, Gloucester, Virginia 23062.

Hamrick, J.M., and Mills, W., (undated), Three-Dimensional Hydrodynamic and Reactive Transport Modeling of Power Plant Impacts on Surface Water Systems: Unpublished article, Tetra-Tech, Inc.

Harremoes, Poul and Malmgren-Hansen, Anders, 1990, Laerebog i vandforurening; Polyteknish forlag, Denmark, 1990.

Iqbal, Muhammed, 1983, An Introduction to Solar Radiation: Academic Press.

Jensen, M.E., Burman, R.D., and Allen, R.G., 1990, Evaporatranspiration and Irrigation Requirements: ASCE.

Ji, Z., Morton, M. and Hamrick, J., 2001, Wetting and Drying Simulation of Estuarine Processes: Estuarine, Coastal and Shelf Science, 53(5):683–700.

Jin, K.R., Hamrick, J.H., and Tisdale, T., 2000, Application of Three-Dimensional Hydrodynamic Model for Lake Okeechobee: Journal of Hydraulic Engineering, 126(10):758–771.

Lindh, Gunnar and Falkenmark, Martin, 1972, En inledning til vatteresurslaren: Norway.

Perkins, W.A. and Richmond, M.C., 2001. Long-Term, One-Dimensional Simulation of Lower Snake River Temperatures for Current and Unimpounded Conditions. PNNL-13443, Pacific Northwest National Laboratory, Richland, Washington.

Perkins, W.A., Richmond, M.C., Coleman, A. and Serkowski, J., 2002a, Three-Dimensional Simulation of Temperature in the Lower Snake River and McNary Reservoir: Battelle Pacific Northwest Division, Richland, WA.

Perkins, W.A., Richmond, M.C., Coleman, A. and Serkowski, J., 2002b, Three-Dimensional Temperature Simulation of the Wanapum and Priest Rapids Reservoirs: Battelle Pacific Northwest Division, Richland, WA.

Poul, Harremoes and Anders Malmgren-Hansen, 1990, Laerebog i vandforurening, Polyteknish forlag: Denmark

Rosati, A. K., and Miyakoda, K., 1988: A General Circulation Model for Upper Ocean Simulation. J. Phys. Ocean., 18, 1601-1626.

Sahlberg, Jorgen, 1984, A Hydrodynamic Model for Heat Contdnts Calculation on Lakes at the Ice Formation Date. Swedish Council for Building Research, Document D4.

Sinkrot and Gulliver, 2000, Journal of Hydraulic Research, Vol. 38, 2000, No.5,

TVA, 1972, Heat and Mass Transfer Between A Water Surface and the Atmosphere: Tennessee Valley Authority Report No. 0-6803, Division of Water Control Planning, Engineering Laboratory, Norris, Tennessee, April.

Wetzel, Robert G., 1983, Limnology: Saunders College Publishing.

Wunderlich and Gras, 1967, Heat and Mass Transfer between a Water Surface and the Atmosphere: Tennessee Valley Authority, Division of Water Cont. Planning, Norris, Tennessee.

Appendix G

Protocol for Water Temperature Instrumentation Validation

Corps of Engineers, Walla Walla District,
Joe H. Carroll, 2002

Introduction

Background/Problem Statement Water temperature and associated water quality processes are known to have significant effects on both anadromous and indigenous fishes in the Columbia River system. Continued development and refinement of the understanding of system-wide aquatic thermal processes could greatly enhance our ability to manage project operation for the Lower Snake River projects. Spatial gradients in water temperature have significant influence on community metabolism, dissolved gas tension and saturation, mixing processes, biological communities, chemical reaction rates, and other aquatic processes. Any efforts to better understand the biological and physical processes in the river system can benefit from a complete description of the thermal gradients and processes associated with the Lower Snake River hydropower projects.

The National Marine Fisheries Biological Opinion for 2000 (NMFS BiOp 2000) Reasonable and Prudent Alternatives (RPA's) 131, 132, 133, and 143 all relate to total dissolved gas and temperature issues in relation to fish passage and survival. Successful completion of these RPA's will depend to some extent on adequate water temperature data for the system. All future analytical water research tasks will remain dependent on the support of adequate water temperature data for system characterization. This need has been reviewed and pointed out by research efforts staffed by the Environmental Protection Agency (EPA), the University of Idaho (UI), the US Fish and Wildlife (USFW), Idaho Power, Inc. (IPI), the Corps of Engineers (COE), the Pacific Northwest National Laboratory (PNNL), and Tribal water quality agencies. RPA 143 specifically states: "The Action Agencies shall develop and coordinate with NMFS and EPA on a plan to model the water temperature effects of alternative Snake River operations. The modeling plan shall include a temperature data collection strategy developed in consultation with EPA, NMFS and state and Tribal water quality agencies. The data collection strategy shall be sufficient to develop and operate the model and to document the effects of project operations."

Extensive comprehensive water temperature field measurements are either ongoing or planned for the Lower Snake River to address the requirements as specified in the RPA 143 and in conjunction with ongoing routine water quality monitoring which extends throughout the Columbia River basin. Specific studies include the Lower Granite pool and McNary fishway and forebay temperature measurements throughout the spill season by the United States Geological Survey, PNNL in conjunction with ongoing thermal modeling studies, and the UI to monitor water temperatures in lower Snake River reservoirs to enhance the understanding of the thermal dynamics of the reservoirs. The COE has a multiyear plan to review and evaluate the function and the representativeness of forebay water quality monitoring for both the Lower Snake and Lower Columbia hydropower projects. The COE also is involved in ongoing fishway water temperature monitoring at all projects on the Lower Snake and Lower Columbia Rivers. EPA is currently preparing the final draft of the temperature TMDL requirements for the Lower Columbia and Lower Snake Rivers complete with requirements for monitoring.

Measurement requirements (accuracies and precision) for much of the ongoing work routinely falls into the range of ± 0.2 °C; or with repeated measurements depending on sampling variability mean estimates should be within 0.1-0.2 °C of the true mean of the water temperatures. This level of accuracy is generally required to address issues concerning impacts on the biology of the system as water quality standards or compliance issues. This certainly agrees with the data quality criteria established by the US Army Corps of Engineers COE developed for fixed monitoring stations on the Columbia River (USACE, 2003). For thermistor calibrations the COE requires that instruments must agree within ± 0.2 °C with a primary National Institute of Standards and Technology (NIST) standard mercury thermometer.

With this level of water temperature monitoring including both the intensity and variety of researchers it is highly desirable to adapt standard procedures utilizing instruments of known and verifiable quality. The methods of instrument validation should be supported with well-documented and incorporated quality assurance/quality control programs to ensure the compatibility and comparability of data across the various research projects. **This document provides recommendations for instrument data quality criteria and instrument evaluations, which would ensure known and adequate data quality to meet the needs of most of the field study requirements and provide comparable/compatible data across the studies**.

<u>Sources of Error</u> The goal of any field data collection program is to collect data of known quality that best represent conditions in the study site and to compile those data as accurately as possible in data sets for later use in regulatory or scientific applications. This goal is achieved by minimizing data inaccuracies and by understanding variations in the actual sample water temperature and instrument measures of that water temperature. There are essentially three sources of errors: instrument error (theoretical limits due to design), errors caused by sampling (study design and technique of measuring water temperature), and errors which arise from database management. There are two types of variations in water temperature, spatial (differences in water quality laterally, longitudinally, or vertically) and temporal (changes in water temperature over time).

To minimize sampling errors, careful sampling techniques, instrument selection, instrument calibration/validation checks, and sample analyses are carried out in close accord with documented methods. The quality of these activities is quantified by error analysis. Again the focus of this document is on instrument error. The combined accuracy and precision of available electronic water temperature monitoring equipment (thermistors) is commonly around ± 0.2°C, but some manufacturers' specifications go as low as ± 0.0002 °C (Seabird model 39). This lower limit on precision is of limited use or need in river and reservoir field monitoring due to the potential magnitudes of total sampling uncertainty that may be encountered. Other than careful maintenance, there is little that can be done to minimize instrument precision beyond manufacturer specifications. However, accuracy or systematic bias characteristic of most field instruments can be accounted for or minimized through careful instrument validation and calibration checks. Once the temperature logging instruments have been calibrated and set to read as accurately as possible, most remain stable and consistent. Generally, temperature-logging instruments remain stable and require little in the way of measurement corrections or recalibrations, and calibration activities are normally left to the manufacturer on some time basis such as annually.

Measurement Uncertainty Analysis As mentioned above, measurement or inaccuracies in data collection arise from many sources. They can originate from the position, location or operation of the instruments, or from the instrument itself. An error in any one measurement is considered a fixed, given value. The possible magnitude of that error is described as an uncertainty. It is a statistical variable that can be arrived at through a process of uncertainty analysis. Typically, the measurement reported is considered to be the mean estimate. The uncertainty describes the variation of the measurement about the mean. The uncertainty of any measurement is defined as a combination of precision (random) uncertainty and bias (fixed or systematic) uncertainty (Abernathy, Benedict, and Dowdell 1985). Precision as defined by Standard Methods is a measure of the closeness with which multiple measures or analyses of a given sample agree with each other (American Public Health Association, 2000). Precision uncertainty can be introduced into any repeated measurement by the variability of the instrument. Bias uncertainty will similarly effect each measurement resulting from a calibration or position error.

Using a modification of total uncertainty as expressed in Standard Methods, single-point sample uncertainty can be expressed as follows (American Public Health Association, 1992, Geldert and Gulliver, 1995, and Kline, 1985):

$$U^2 = (\mathrm{W}^2_{\mathrm{manuf}} + \mathrm{W}^2_{\mathrm{sample}}) + B^2$$

Where:

U is the total single-point field sample/measure uncertainty,
$\mathrm{W}^2_{\mathrm{manuf}}$ = the manufacturer precision specification for the instrument
$\mathrm{W}^2_{\mathrm{sample}}$ = the short-term temporal variation in samples and
B is the total instrument bias uncertainty as calculated from calibration and sampling bias.

In order to validate instrument uncertainty for equipment used in temperature monitoring activities, it is necessary to verify or calculate both the precision specifications and the instrument measurement bias on some routine basis, such as before deployment and following retrieval of logging instruments in the field activities.

The reporting of temperature measurements should include a statement of uncertainty. The simplest method for estimating typical measurement bias is to measure a known standard, then compute the difference between the measured (M) and known value (T), assumed to be the true value being measured (American Public Health Association, 2000).

$$M - T = B + Z$$

Where:

B = total instrument bias uncertainty and
Z = the random or precision uncertainty of the measure

In the case of temperature measurements the true value should be verified with a primary National Institute of Standards and Technology (NIST) standard or a secondary standard traceable to an NIST standard instrument. The NIST primary standard can be acquired from most laboratory supply houses complete with the certification. The primary standard should be readable to 0.1 °C, which would allow estimation to 0.05 °C. Based on the known study requirements and the data quality criteria established in the COE "Data Quality Criteria for Fixed Water Quality Monitors" (USACE, 2003) all instruments must agree to within ± 0.2 °C of the NIST primary or secondary standard instrument. If random uncertainty is negligible ($Z=0$), the difference, M-T, will provide an estimate of bias (B).

If random uncertainty is not negligible, it can be observed and quantified by making a measurement repeatedly on the same test specimen under control conditions to minimize variability of the measures. This should be a part of most QA/QC procedures and is a standard analysis for precision or standard deviation for the mean of the repeated measures. Since no controllable source of variability, which may affect the measure, is allowed during this testing, then the repeatability is the minimal variability of the measurement system (American Public Health Association, 2000). Repeatability may be an underestimate for routine field measures but will provide a good estimate of the instrument precision which will allow the computation of uncertainty intervals, ± U, which can be referred to as ultimate instrument variability.

Protocol for Temperature Logging Instrument Validation Validation of instruments should take place both before deployment and after retrieval of the field equipment to describe any changes, which may occur over time. Where possible, one should follow the manufacturer's recommendations for the validation/calibration process. Since most temperature instruments are only calibrated by the manufacturer, the validation procedure will determine if an individual instrument is operating within required specifications, and if not, the instrument data should be corrected based on the known bias to bring it within the required specifications.

The following protocol is recommended for temperature instrument validation based on the above approach to estimate total uncertainty. This protocol is adapted from that described in Standard Methods, "Sections 1030 Measurement Uncertainty and 1040 Measurement Method Validation" where an individual instrument will be checked against a known standard an adequate number of times to calculate the instrument bias and precision (American Public Health Association, 2000). The measurement or instrument uncertainty can then be reported as a mean bias with a stated level of confidence. The instrument uncertainty is reported as a 95% confidence interval, meaning that for approximately 95% of the time the uncertainty measure should fall within the range of ± U or 2 times the repeatability standard deviation.

The validation procedure is conducted by taking 10 or more measurements in a constant temperature water bath at each of three different test water temperatures. Since the instruments can rapidly take repeated measures of the same sample without changing the sample, then the number of measures or sample size can easily be in the 100s. The known test water temperature should be verified using an NIST primary or secondary standard. If the water temperature cannot be held constant, an alternative would be to log temperatures using the NIST primary or secondary standard instrument. The test temperatures should cover the range of expected field water temperatures to be monitored by the device. For most areas on the Lower Columbia and Lower Snake Rivers, this range would be from 4°C to 26°C. Three candidate test temperatures ranges are 4-6°C, 12-15°C, and 22-26°C; however, validation in the expected zone or range would be adequate.

Table 1 shows calculation of precision and bias for 12 StowAway Temp instruments (Onset Corporation, Optic StowAway® Temp) using the above approach. The results are then reported as total instrument uncertainty (mean difference ± 2 STD). This information can then be compared to both the manufacturers' specifications plus the test requirements for accuracy. If the total uncertainty for a particular instrument is outside of the acceptable or advertised specification, it would be possible to correct the data for the instrument bias and possibly bring it back into the required specifications. From Table 1, instruments T360f, T368f, and T452f with total uncertainties of -0.24, -0.21, and 0.22 would be considered borderline and questionable in performance; however none of the three are much higher than the manufacturers specification of ± 0.2.

It would also be useful to produce control charts for both the instrument bias and precision as presented in Figures 1 and 2. This would allow a quick review of the instrument uncertainty to look for individual instruments that did not give accurate results or true measures of water temperature. Based on Figure 1, the bias for instruments T360f, T368f, T371, T386f, and T451 are significantly different (99% confidence level) from the mean bias to justify data correction to improve the accuracy. From Figure 2, the precision estimate from instrument T452f is outside of acceptable limits (99% confidence level) in relation to the other 11 instruments tested.

It is recommended that similar analyses be completed for two additional temperature ranges that bracket the expected field temperatures. This routine should typically be conducted before and after each long-term deployment (one season or 3-4 months). The "National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations" recommends a similar protocol for testing to be conducted on a 3-4 month interval for thermistor thermometer calibration check (D.B. Radtke, J.K. Kurklin, and F.D. Wilde, 1998). Records should be kept by instrument serial number to both correct measures for bias if needed and to identify any instrument drift as needed to resolve data analysis problems. Logbooks complete with all calibrations, make, model descriptions, serial number, etc are recommended.

The described protocol for examining the total uncertainty of temperature monitoring equipment complete with adequate records should ensure a minimum standard of temperature data for field sampling on the Lower Columbia and Lower Snake Rivers. The recommended data quality for most work is ± 0.2°C which should be verified for each instrument before and following each long term monitoring deployment. Instruments that fail to meet this qualification could either be removed from use or returned to the manufacturer for refurbishment; or resulting data could be corrected to improve accuracy to within acceptable limits. One obvious technique used to correct data would be to apply a linear correction factor based on time step used to calculated percent of total bias. If there is some distinct shift in temperature due to handling or other environmental factors, it may be conceivable to make a one-time shift of the entire bias as in an instrument calibration. The recommended approach for most instances would be to make an across the entire log shift of the average bias for the instrument in question, again similar to an instrument calibration.

Table 1. Instrument Uncertainty, Precision, and Bias Calculated for StowAway Temp Loggers Pre-Deployment, September 2001, for a Temperature Range of 23 to 25°C.

Instrument Serial Number	N	Mean Difference (Bias/*B*)	Precision (Repeatability STD/*Z*)	Total Instrument Uncertainty (E = ***B*** ± 2***Z***)	Original Specs
T192	21	-0.0024	0.049	-0.10	±0.2 °C
T332f	21	0.0343	0.055	0.14	±0.2 °C
T360f	21	-0.0933	0.071	-0.24	±0.2 °C
T364	21	-0.0148	0.050	-0.11	±0.2 °C
T365	21	-0.0033	0.052	-0.105	±0.2 °C
T368f	21	-0.0614	0.070	-0.21	±0.2 °C
T371	21	0.0471	0.049	0.14	±0.2 °C
T375f	21	0.0076	0.076	0.16	±0.2 °C
T386f	21	0.0552	0.058	0.17	±0.2 °C
T438f	21	0.0110	0.049	0.109	±0.2 °C
T451	21	-0.0619	0.048	-0.16	±0.2 °C
T452f	21	0.0210	0.097	0.22	±0.2 °C

Figure 1. Control Chart of Mean Values of Instrument Differences by Serial Number.

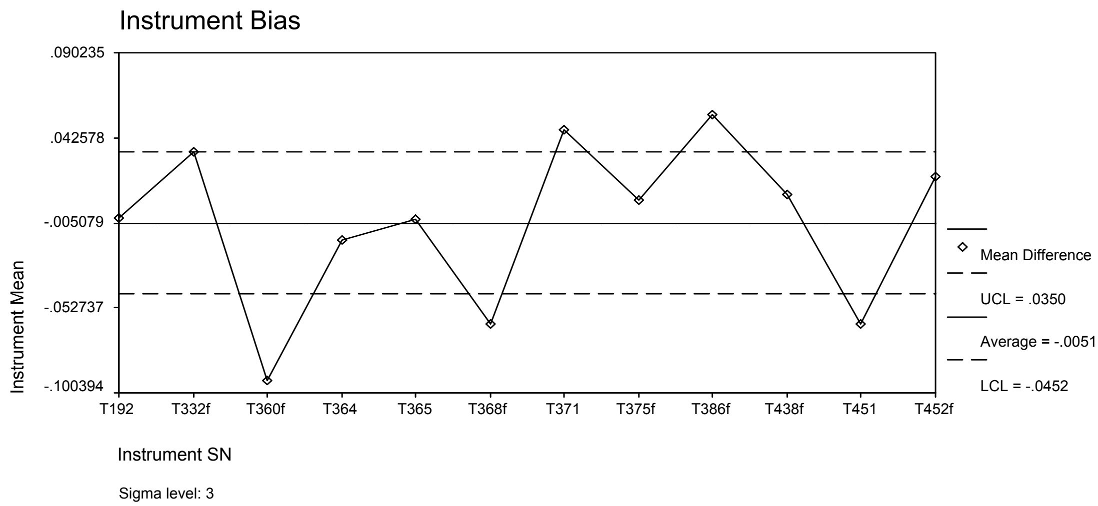
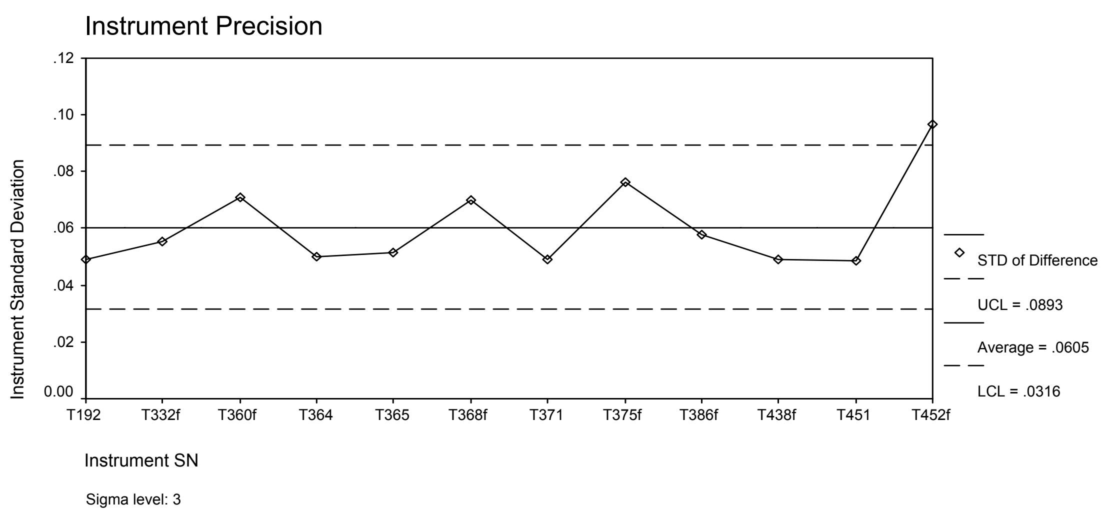


Figure 2. Control Chart of Standard Deviations of Mean Differences by Serial Number. (UCL=Upper Control Limit and LCL = Lower Control Limit using a sigma level=3))



References

Abernathy, R. B., Benedict, P. P., and Dowdell, R. B. (1985). "ASME measurement uncertainty." *Journal of Fluids Engineering*, ASME, 107(2), 161-164.

American Public Health Association. (1998). *Standard methods for the examination of water and wastewater*. 20th ed., American Public Health Association, Washington, DC.

Bennett, D.H., M.H. Karr, and M.A. Madsen. 1997. Thermal and velocity characteristics in the lower Snake River reservoirs, Washington, as a result of regulated upstream water releases. Completion Report. US Army, Corps of Engineers. Walla Walla, WA.

D.B. Radtke, J.K. Kurklin, and F.D. Wilde, 1998, Preparations for water sampling, *in*> National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6, accessed __12/10/2002__ at http://pubs.water.usgs.gov/twri9A1

Geldert, D., and J. S. Gulliver, 1996. Uncertainty Analysis of Total Dissolved Gas Measurements on the Colombia and Snake Rivers taken by the U.S. Army Corps of Engineers. Memo to Portland District Office, U.S. Army Corps of Engineers, Portland, OR.

Kline, S. J. (1985). "The Purposes of Uncertainty Analysis." *Journals of Fluids Engineering.* ASME, 107, 153-164.

USACE, 2003 (Report in progress), "2003 Dissolved Gas and Water Temperature Monitoring Report". Water Quality Unit, Reservoir Control Center, Water Management Division, U. S. Army Corps of Engineers North Pacific Division, Portland, Oregon.