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Temperature Modeling of the Pend Oreille River, Boundary Hydroelectric Project
CE-QUAL-W2 Model Calibration Report

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Acronyms and Abbreviations

1-DMax	maximum daily temperature
AME	absolute mean error
cfs	cubic feet per second
FERC	Federal Energy Regulatory Commission
ft	foot or feet
IDEQ	Idaho Division of Environmental Quality
m	meter(s)
ME	mean error
NAD	North American Datum
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
Project	Boundary Hydroelectric Project
RAWS	remote automated weather station
RM	river mile
RMS	root mean square error
SCL	Seattle City Light
STP	sewage treatment plants
TDG	total dissolved gas
TMDL	total maximum daily load
USGS	United States Geological Survey
WDOE	Washington Department of Ecology
WA	Washington

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1.0 Introduction

1.1 Background

The Boundary Hydroelectric Project (Project) and Boundary Dam are located on the Pend Oreille River in northeastern Washington State (Figures 1.1 and 1.2). The Project is owned and operated by Seattle City Light (SCL). The Project was first licensed in 1961 by Federal Energy Regulatory Commission (FERC), and the existing license (FERC No. 2144) will expire in 2011. SCL is currently involved in the Integrated Licensing Process for the relicensing effort. As part of the ILP, SCL is conducting studies to support the relicensing of the project. The studies are focused on determining and evaluating the impacts of the project, and ultimately, developing protection, mitigation, and enhancement measures to address those impacts as the project continues to operate under a new license.

Section 401 of the Clean Water Act requires a Water Quality Certificate from the Washington Department of Ecology (WDOE) for the issuance of a new license by FERC. The purpose of the 401 Water Quality Certificate process is to assess and document the extent and significance of water quality impacts of the Project and its continued operations. Water quality parameters of interest on the Pend Oreille River include the following.

- Total dissolved gas (TDG)
- Temperature
- Dissolved oxygen (DO)
- pH
- Nutrients and chlorophyll a
- Turbidity
- Toxics
- Fecal coliform

Out of these parameters, temperature is of particular interest since it has been observed above the 20°C water quality criterion at several locations in the Pend Oreille River. Consequently, the river was included in the 303(d) list as impaired for temperature, and WDOE is developing a total maximum daily load (TMDL) for the main stem of the river from the Idaho border to the international boundary with Canada.

SCL is conducting the temperature modeling in the Boundary reach of the Pend Oreille River to support the relicensing and the 401 certification process. This effort is being conducted in collaboration with WDOE. As part of the Pend Oreille River TMDL for temperature, the WDOE is conducting the modeling for the upstream reach of the Pend Oreille River up to Idaho border and is helping to coordinate with Idaho Department of Environmental Quality (IDEQ) to address the reach of Pend Oreille River in Idaho.

1.2 Study Objectives and Approach

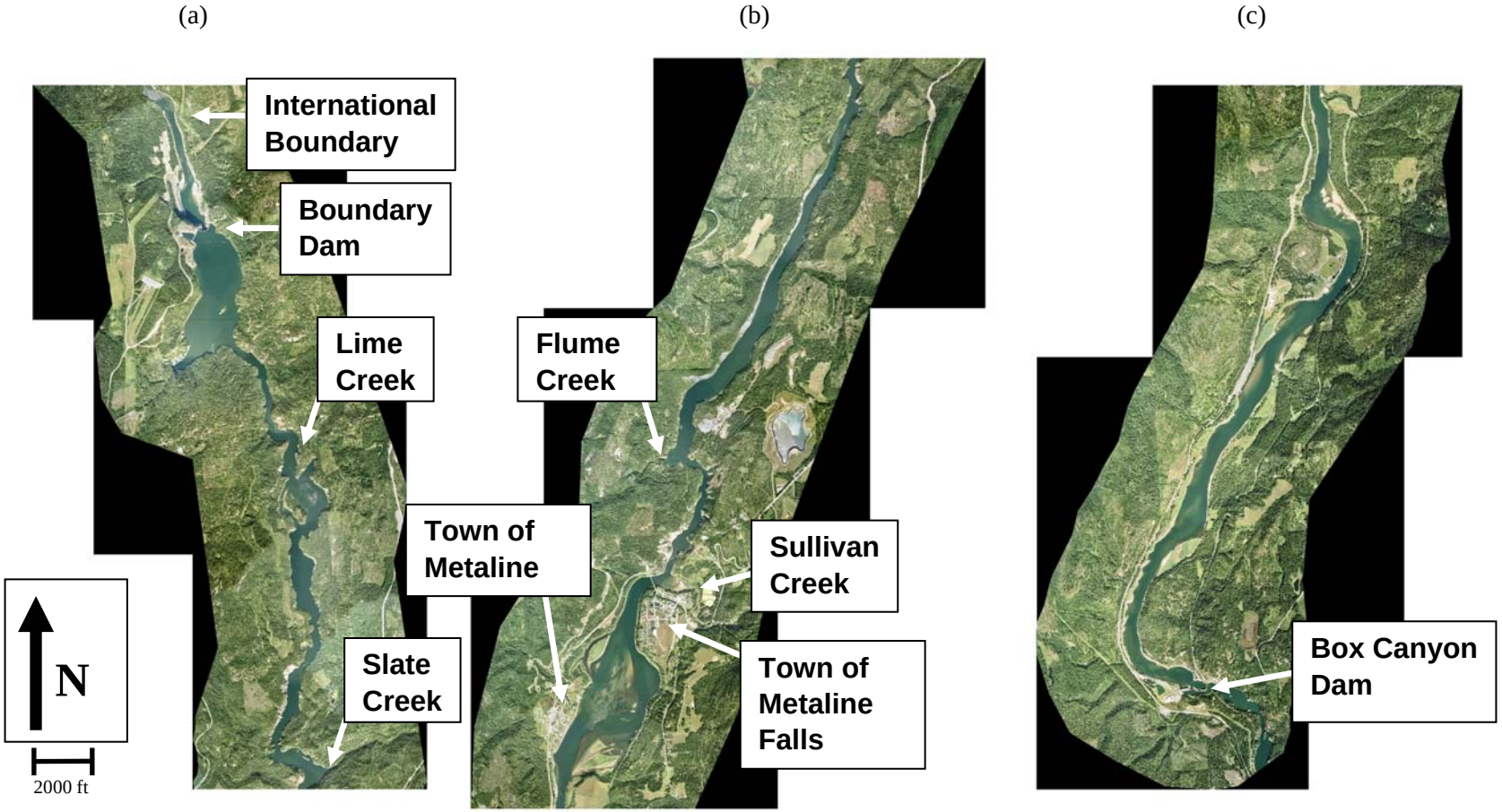
The overall objective of this study is to establish a predictive model of temperature for the Boundary Reservoir and the Pend Oreille River from the tailrace of Box Canyon Dam to the International Boundary downstream of the Boundary Dam. The model will be used to evaluate the existing conditions and

understand the physical processes controlling the temperature of the system.[a] The model is expected to serve as a tool for evaluating the effects of the Boundary Hydroelectric Project on the river and reservoir temperatures. The model selected for this study is CE-QUAL-W2 (Cole and Wells 2006).

This report presents two of the primary aspects of the study:

- Reviewing and processing the available bathymetric, hydrologic, meteorological, and temperature data available for the Project study area.
- Set up and calibration of the water quality model for simulation of hydrodynamics and temperature.

[a] The model has the ability to simulate the full water quality constituents including algal kinetics, nutrient balance and eutrophication if required.



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Note: (1) The length scale is approximate.
(2) Images were provided by Zablotney (2006).
(3) The figures (a) through (c) are ordered from the north to the south.

Figure 1.1

Pend Oreille River in the Vicinity of Boundary Reservoir

Seattle City Light
Seattle, Washington

Note: Drawing provided by Filbert (2006)

Figure 1.2

Plan View Detail of the Structures of Boundary Dam

Seattle City Light
Seattle, Washington

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2.0 Review of Available Data

2.1 Introduction

The hydrodynamic and water quality model (CE-QUAL-W2) used for the hydrodynamic and temperature analyses requires data inputs for the Boundary Reservoir system. These data include the topographic and bathymetric data that describe the geometry of the system, the Pend Oreille River and important tributary flows and temperatures, and the meteorological data. A data quality review was made to asses the suitability of the available data for use in the modeling analyses. Outliers and unreasonable data were eliminated from the analyses. Where data gaps existed, estimates were made so as to have complete data sets for the period of analysis (2004 through 2005). This section describes the data review and presents the data that were used for the calibration of the model to temperature.

The available data came from several sources including SCL, Longview Associates, Taylor and Associates, R2, United States Geological Survey (USGS), and WDOE. Note that all elevations in this study are given in NGVD 1929 as feet (or meters).

2.2 General Study Area

Boundary Reservoir is one of five impoundments on the Pend Oreille River, each of which generates hydroelectric power. From upstream to downstream, the dams creating the impoundments are Albeni Falls Dam, Box Canyon Dam, Boundary Dam, Seven Mile Dam, and Waneta Dam (Table 2.1). The Pend Oreille River originates in Lake Pend Oreille, Idaho, flows north through Washington State, and into Canada at RM 16 before entering the Columbia River. The impoundments upstream of Boundary Dam influence the conditions within Boundary Reservoir by altering the flow and changing the travel times of the river. The annual average flow entering Boundary Reservoir from the Box Canyon Dam releases is approximately 21,000 cfs (595 m^3/s). Seven Mile Dam, downstream of Boundary Dam, also exerts an influence on Pend Oreille River between Boundary Dam and the International Boundary by altering the water level due to operations of Seven Mile Dam.

Table 2.1. The Dams and Their Locations along the Pend Oreille River (SCL 2006)

Project	River Mile	Country	Storage Volume (MAF)
Albeni Falls	90.1	USA	1.2
Box Canyon	34.5	USA	0.01
Boundary	17.0	USA	0.04
Seven Mile	6.0	Canada	NA
Waneta	0.5	Canada	NA

NA – not available
MAF – million acre-feet

The Project is located in the Selkirk Mountains with extensive forest coverage extending to near the high water level of Boundary Reservoir (Figure 1.1). There are two small towns (Metaline and Metaline Falls) adjacent to the Pend Oreille River midway between Box Canyon Dam and Boundary Dam. The river between Box Canyon Dam and the town of Metaline Falls is relatively wide and shallow, and the river bed has a small gradient. Downstream of Metaline Falls, the river changes drastically, becoming a narrow and deep channel, and the river bed has a large gradient.

There are several tributaries that enter Boundary Reservoir, but these contribute less than 2% of the annual flow. Only four of the tributaries are considered in this study (Figure 2.1) because they have been through the TMDL process. These are Sullivan, Flume, Lime, and Slate Creeks. Their locations by river mile (RM) and daily average discharges are given in Table 2.2.

Table 2.2. The Tributaries to the Pend Oreille River including Locations and Daily Average Discharges

Tributary	River Mile along the Pend Oreille River	Daily Average Discharge (cfs) [a]
Sullivan Creek	26.8	213
Flume Creek	25.8	29
Slate Creek	22.2	31
Lime Creek	20.3	4.5

(a) The flows were computed for 2004-2005, the period of analysis. The daily flow data from which the averages are computed were obtained from Pickett (2006).

There are four point sources that discharge to the Boundary Reservoir (Figure 2.1). These include Selkirk High School and Pend Oreille Mine (Teck Cominco) as well as the sewage treatment plants (STP) for the towns of Metaline and Metaline Falls. The point sources are regulated under the National Pollutant Discharge Elimination System (NPDES) (Pickett 2006). Their locations and average discharges are given in Table 2.3.

Table 2.3. The NPDES Dischargers to Boundary Reservoir including Locations Average Discharge

Facility (NPDES ID)	River Mile	Average Discharge (cfs)[a]
Selkirk High School (545)	30.9	0.004
Town of Metaline (514)	27.9	0.042
Town of Metaline Falls (545)	26.8	0.019
Teck Cominco -Pend Oreille Mine (408)	24.8	0.82

(a) Computed for 2004-2005. The daily flow data from which the averages were computed were obtained from Pickett (2006).

2.3 Boundary Dam Geometry

The Boundary Dam is a concrete arch dam with the forebay of the powerhouse intakes located upstream of the left (west) abutment (Figure 1.2). The structural height of the dam is 340 ft (606.55 m). The dam impounds the Pend Oreille River to a normal high-water level of 1,990 ft (606.55 m). Downstream of the dam, the normal river water level is 1,729 ft (527.00 m).

Water releases from Boundary Reservoir can be made via several discharge structures (Figure 2.2). These consist of the following gates and intakes:

- Skimmer gate – a single flap gate on the west side of Boundary Dam that is 26-ft wide by 9-ft high (7.92 m by 2.74 m) with a crest elevation of 1,982 ft (604.11 m) (Figure 2.2a).
- Spillway gates – two radial gates on either side of Boundary Dam that are 50-ft high by 45-ft wide (15.24 m by 13.72 m) with a crest elevation of 1,946 ft (593.14 m) (Figure 2.2a).

- Sluice gates – seven fixed wheel gates on the lower face of Boundary that are 21-ft high by 17-ft wide (6.40 m by 5.18 m) with a crest elevation of 1,791.5 ft (546.05 m) (Figure 2.2a).
- Powerhouse intakes – six intakes that draw from the forebay and are 30-ft wide by 34-ft high with a centerline elevation of 1903 ft (580.03 m) (Figure 2.2b).

Discharges from the various structures may influence temperature in Boundary Reservoir because each pulls water from a different elevation. For the 2004 through 2005 period, flow was released primarily through the powerhouse intakes, except for short periods during 2005 when there was some spill flow[a].

2.4 Bathymetry and Topography Data

A recent bathymetric survey was made by Battelle (2006) of the Boundary Reservoir and river reach immediately downstream of the Boundary Dam (Figure 2.3). The horizontal projection was Washington State Plane North (Zone 4601). The horizontal datum was NAD83, U.S. survey feet. The vertical datum was NGVD29, U.S. survey feet. These data were obtained during high water in the reservoir with a horizontal resolution of 3.28 ft (1 m). Two sections of the Pend Oreille River were not included in this survey, however, due to high flows and fast-moving water that created unsafe conditions.

The thalweg profile from the bathymetric survey is shown in Figure 2.4a. The missing sections at RM 16 to 17 and 26 to 27 are indicated by gaps in the profile. Above RM 27 (Metaline Falls), the river has a gradual bed slope of 0.00038. Between Boundary Dam and RM 26, it has a steeper bed slope of 0.0050, with occasional deep holes present in the bed. Just upstream of Boundary Dam (RM 17), the bed elevation drops considerably.

A previous cross-sectional survey was made for use in an extreme flood analyses (Morrison Knudsen 1997). The thalweg elevations from Box Canyon Dam to the International Boundary are shown in Figure 2.4b. Comparison with the bathymetric survey shows they have the same general characteristics, with a small bed slope upstream of RM 25, a larger bed slope downstream, and the steepest bed slope is in the vicinity of Boundary Dam.

2.5 Flow and Water Surface Elevation Data

The Pend Oreille River is one of the larger rivers in the Pacific Northwest with an hourly average flow of 20,900 cfs (590 m^3/s) for the 2004 through 2005 period. Several tributaries enter the Pend Oreille River along the Boundary Reservoir reach. Only the Sullivan, Flume, Slate, and Lime Creeks are considered in this study.[b]

[a] At the time of writing this report, the spill flows were not available.

[b] These tributaries are of interest to the WDOE for use in the temperature TMDL study of the Pend Oreille River. The combined flow contribution from the four tributaries is approximately 1.3% of the Pend Oreille River's annual average flow.

2.5.1 Pend Oreille River, Tributary, and Point Source Flows

Flows into the Boundary Reservoir was measured by the USGS at the Box Canyon gauge (12396500) and are shown in Figure 2.5a. The peak-measured hourly flow for the 2004 and 2005 periods was 86,100 cfs (2,439 m^3/s) on June 9, 2005. The minimum-hourly flow measured for 2004 and 2005 was 4,772 cfs (135 m^3/s) on September 11, 2005. The peak flows occurred during late spring and early summer, which is typical for rivers influenced by snow-melt runoff. The minimum flows occurred during late summer and early fall. On a daily basis, the flows downstream of Box Canyon Dam vary only slightly reflecting the run-of-the-river hydroelectric operation of Box Canyon Dam.

The flow releases from Boundary Dam were provided by SCL (2006) and are shown in Figure 2.5b. The peaking-mode operation of Boundary Dam is evident in the large daily variation of flows. Peaking-mode operation calls for power generation to follow electrical demand, so that the highest flows occurred during the daytime with no flow releases at night.

Tributary flows were provided by Pickett (2006) and are shown in Figure 2.5c. Of the four tributaries examined, Sullivan Creek had the largest flow. It is also the only tributary with measured flows. The flows of other the tributaries (Flume, Slate, and Lime Creeks) were estimated from watershed characteristics.

The point source flows were also provided by Pickett (2006) and are shown in Figure 2.5d. These flows were very small, less than 1 cfs (0.03 m^3/s), and are an insignificant portion of the total flow of the Pend Oreille River (<0.1%).

2.5.2 Pend Oreille River and Boundary Reservoir Water Levels

Water-surface elevations were measured at three locations along the Pend Oreille River in the Boundary Reservoir reach (Figure 2.6): at the USGS gauge downstream of Box Canyon Dam, at Boundary Dam, and in the Boundary Dam tailrace.

The full-pool elevation of Boundary Reservoir is 1990 ft (606.55 m). The water levels downstream of Box Canyon Dam were near the full-pool elevation (Figure 2.6a); however, during the high flow periods of May, June, and July, water levels were greater than the full-pool elevation. The daily variations in water level were primarily due to the peaking-mode operation of Boundary Dam.

The maximum water levels near Boundary Dam are governed by the full pool operational requirement of 1,990 ft (606.55 m) (Figure 2.6b). The minimum water levels measured during 2004 and 2005 were about 1,970 ft (600.46 m). The daily range was 20 ft (6.10 m), except during the summer-recreation season, when SCL restricts variations to 10 ft (3.05 m) to allow user access (SCL 2006).

Downstream of Boundary Dam the water levels were affected by releases from both Boundary Dam and Seven Mile Dam (Figure 2.6c). This resulted in considerable daily variation in water level. Note that the difference in water level between Boundary Reservoir and the tailrace was approximately 260 ft (79 m) which provides the head for hydroelectric power generation.

2.6 Temperature Data

The temperatures of Boundary Reservoir are influenced by the physical setting of the Pend Oreille River and the valley in which it lies. The mountainous topography and the Pend Oreille River's deep canyon below Metaline Falls affect the temperature by restricting direct solar radiation during the morning and afternoon hours. At least half the downstream length of the reservoir is in a deep channel, and the flow of the Pend Oreille River is large. The residence time is less than four days (SCL 2006), so there is little time for surface heat exchange to influence the temperature. These characteristics tend to reduce any increases in temperature along the reservoir's length, and also reduce the daily temperature variations.

The examination of the temperature data was conducted to evaluate the suitability for use in modeling and also to help develop an understanding of how Boundary Reservoir typically responds to upstream and atmospheric forcing.

Temperature measurements were made at several stations along the Pend Oreille River in the Boundary Reservoir reach (Figure 2.7). Temperature measurements in the Pend Oreille River consisted of time series and vertical profiles. The time series data gave the temperatures over a long-time period at one location and one depth. The vertical profile data provided a snapshot of temperatures at one location but at many depths. Each of these data sets is discussed in this section.

2.6.1 Time Series

Temperature measurements were collected from July 2004 through December 2005. In conducting the QA/QC review for this study, temperature data were considered anomalous if there were unexpected jumps in temperature away from the evident trends in the data. The unexpected jumps in data were seen on a seasonal basis, and for some stations, on a daily basis. Comparing data sets, particularly to those at depth, with few anomalous data, clearly showed the trends, especially since there was little thermal stratification present and surface and deep temperatures were similar.

After conducting the QA/QC on the temperature data, the temperature time series were considered suitable for use for temperature modeling. The data from Box Canyon Dam tailrace and the tributaries are to be used for model boundary conditions, while the other data within Boundary Reservoir and the Boundary Dam tailrace are to be used for model calibration. The temperature time-series data after QA/QC are presented in Figures 2.8 through 2.12. A summary of annual maximum temperatures and temperature ranges are given in Table 2.4.

As mentioned previously, the four tributaries included in this study are Sullivan, Flume, Slate, and Lime Creeks, and estimated temperatures for these tributaries provided by WDOE (Picket 2006) are shown in Figure 2.8. Sullivan and Slate Creeks also had measured temperature data which are also shown in Figures 2.8a and 2.8b. Temperatures for Sullivan Creek were the highest of the four tributaries, though they did not exceed 20.0°C.

The maximum temperatures for each year were determined to assess annual variation (Table 2.4). Temperature ranges (daily maximum minus daily minimum) were computed to look at typical daily variations through Boundary Reservoir. As seen in Table 2.4 and Figures 2.9 through 2.12, the maximum temperatures were nearly 25°C. However, the maximum temperatures entering Boundary Reservoir from Box Canyon Dam were already near 25°C. The maximum temperatures did not increase from upstream to downstream and actually appear to drop slightly (Table 2.4).

The tailrace temperatures downstream of Box Canyon and Boundary Dams show little daily variation in temperature (Figure 2.9 and Table 2.4), with the largest mean daily variation being 0.35°C in the Box Canyon Dam tailrace. The tailrace temperatures are an average of the temperatures in the reservoirs they draw from, and as such, provide the general trends of the system. Also, because of this averaging process, tailrace temperatures tend to show little daily variation. The maximum daily ranges seen were larger in 2005 than in 2004 in both Box Canyon Dam and Boundary Dam tailraces. The relatively high maximum ranges show that there were periods during the summer 2005 when significant surface heating occurred in both reservoirs. Even with the relatively high level of heating seen in summer 2005, the annual 1-DMax temperature was about 0.5°C less than that seen in 2004 for both the Box Canyon Dam and Boundary Dam tailraces. For the Box Canyon Dam tailrace, the annual maximum of the daily maximum (1-DMax) temperature for 2004 was 24.46°C, and for Boundary Dam tailrace, it was 24.32°C (Table 2.4), while for 2005 these values were 23.85°C and 23.79°C. These suggest that the system was cooling slightly.

At station T2 (RM 27.1), the temperature data cover the period from mid-July 2004 through November 2004 and August 2005 into November 2005 (Figure 2.10). It is unclear if the 2005 data included the maximum temperature for the year, which is why no values for 1-DMax are provided in Table 2.4 for 2005. For 2004 and 2005, the mean daily range of temperatures at station T2 was larger (approximately 0.6°C) than for the Box Canyon tailrace (0.3°C) entering Boundary Reservoir (Table 2.4). The same was true for the maximum daily temperature range in 2004, but not in 2005, suggesting the maximum ranges are short term fluctuations. The temperature ranges decreased with depth, indicating the surface layers were subject to some limited surface heat exchange. The largest measured temperature occurred in 2004 with a 1-DMax temperature of 24.73°C near the surface. Because it was unclear if the 2005 measurements covered the period of maximum temperature, no 1-DMax temperatures are given.

At station T6 (RM 21.2), the temperature data covered the period from mid-July 2004 through November 2004, mid-May 2005 through mid-June 2005, and August 2005 into November 2005 (Figure 2.11). It is unclear if the 2005 data included the maximum temperatures for the year, which is why no values for 1-DMax are provided in Table 2.4 for 2005. The daily ranges of temperature at station T6 in 2004 were smaller than at station T2 (Table 2.4), but, in 2005, they were larger. The maximum temperature in 2004 was 24.43°C. As for Station T2, it is unclear if the 2005 measurements covered the period of maximum temperature, so no 1-DMax temperatures are given.

The temperature measurements for Station T7 (RM 16.0) were more complete than at the other time series stations; they began in mid-July 2004 and ended in mid-November 2005 (Figure 2.12). Station T7 had the largest maximum temperature ranges as compared with the upstream stations (Table 2.4). For 2004, the maximum range was 1.71°C, and for 2005 the maximum range was 3.19°C. These indicate that some surface heating occurred, at least for a short period. However, the mean temperature ranges were either the same as or smaller than the upstream station T6. The maximum temperature measured for 2004 was 24.68°C, and for 2005 it was 24.77°C.

At all the Boundary Reservoir stations where time series data of temperature were collected (T2, T6, and T7), the maximum temperatures and temperature ranges decreased with depth during both 2004 and 2005. This is expected and reflects the occurrence of some heat exchange at the surface, even though it was relatively small.

Table 2.4. Annual Maximum Temperature from the Measured Temperature Time Series and the Daily Temperature Ranges.

Station (Depth)	Annual 1-DMAX Temperatures (ºC)		Daily Temperature Range (ºC)[a]			
	2004	2005	July 1 – Sept 30, 2004 (JD 183-274)		July 1 – Sept 30, 2005 (JD 548-639)	
			Maximum	Mean	Maximum	Mean
Box Canyon Dam Tailrace	24.46	23.85	0.89	0.35	1.75	0.28
T2a (1 m)	24.73	b	1.06	0.59	1.13	0.61
T2b (3.2 m)	24.61	b	0.99	0.55	0.89	0.52
T2c (5.4 m)	24.70	b	0.99	0.52	0.82	0.48
T2d (7.6 m)	24.68	b	0.99	0.51	0.77	0.48
T2e (9.8 m)	24.58	b	0.99	0.51	0.77	0.48
T6a (1 m)	24.70	b	0.89	0.48	1.71	0.71
T6b (11 m)	24.58	b	0.82	0.43	1.50	0.42
T6c (21 m)	24.48	b	0.82	0.43	1.50	0.41
T6d (31 m)	24.56	b	0.85	0.45	1.46	0.41
T7a (5 m)	24.68	24.77	1.71	0.49	3.19	0.64
T7b (11 m)	24.46	23.83	1.50	0.31	2.32	0.30
T7c (17 m)	24.18	23.76	0.91	0.29	1.29	0.26
T7d (23 m)	24.12	23.69	0.78	0.28	1.29	0.26
T7e (29 m)	24.12	b	0.74	0.27	c	c
Boundary Dam Tailrace	24.32	23.79	0.71	0.28	1.40	0.28

(a) The daily range of temperature is the difference between the maximum and minimum temperatures at the depth for the day.
(b) There are data missing from the time series for 2005, and so the available data do not necessarily include the maximum for the year.
(c) No data were available to compute the mean daily temperature range.

2.6.2 Vertical Profiles

Vertical profile measurements of temperature were made in 2004 and 2005 at the following locations in Boundary Reservoir (Taylor, 2006):

- Wolf Creek (Station V1, RM 30.1)
- Metaline Old (Station V2, RM 28.1)
- Pend Oreille Mine (Station V3, RM 25.31)
- Slate Pool (Station V4, RM 21.9)
- Everett Creek (Station V5, RM 20.3)
- Boundary Reservoir (Station V6, RM 17.5)

The vertical temperature profiles were spot measurements taken during five separate days in 2004 and four separate days in 2005.

The temperature profiles generally show little variation with depth, indicating that Boundary Reservoir was well mixed (Figures 2.13 through 2.18). There were some slight increases in surface temperature during the mid to late summer in 2004 and 2005 (as suggested by the time series data described in Section 2.6.1) at many of the stations, but the degree of stratification was minimal and would not be expected to reduce vertical mixing. For example, on August 23, 2005, at the Slate Pool station (V4) the surface temperature was 23.47°C and the bottom-most temperature was 23.01°C (Figure 2.16): a 0.46°C difference. On the same date, at the Everett Creek station (V5), the surface temperature was 22.45°C and the bottom-most temperature was 21.96°C (Figure 2.17): a 0.49°C difference. The largest temperature variations with depth were seen at the Boundary Reservoir station on August 17, 2004 with the surface temperature of 24.24°C and the bottom-most temperature of 22.45°C (a 1.79°C difference), and on August 1, 2005 with the surface temperature of 23.32°C and the bottom-most temperature of 22.23°C (a 1.09°C difference). However, these variations were likely transient given the generally well mixed nature of Boundary Reservoir.

In general, the vertical temperature variations as seen in the vertical profiles are less than 1°C. Also, the vertical variations in temperature agree with the summary data shown in Table 2.4 from the time series for both the mean and maximum temperatures with depth.

2.7 Meteorological Data

Meteorological data describe the atmospheric conditions that control, in part, the temperatures of Boundary Reservoir. These conditions vary on daily, seasonal, and annual periods. The meteorological data were collected by SCL at Boundary and Box Canyon Dams. However, these weather stations were not set up until August 2004 at Boundary Dam, and June 2005 at Box Canyon Dam. Because the period of analysis for the Boundary Reservoir covered the calendar years 2004 and 2005, it was necessary to fill in the periods that had missing data using the data from meteorological stations nearby. The stations used are shown in Figure 2.19. The meteorological data from Remote Automated Weather Stations (RAWS) and National Oceanic and Atmospheric Administration (NOAA) were used to fill in missing data by means of regression analyses with data from overlapping periods.

If the correlation between stations was high ($r^2 > 0.80$), the regression equations were used to adjust the RAWS or NOAA data to Boundary Reservoir conditions. If the correlation was small, the RAWS or NOAA data were used directly.

2.7.1 Air Temperature

The air temperature data collected from Boundary and Box Canyon Dams did not cover the whole period of the temperature modeling analyses of 2004 and 2005. The missing data were estimated after regression analysis with a complete set of air temperature data from the NOAA station in Sandpoint, Idaho (Figure 2.20). The goodness-of-fit between the air temperature data sets was very good: $r^2 = 0.948$ between Sandpoint and Box Canyon Dam and $r^2 = 0.889$ between Sandpoint and Boundary Dam. The negative value of the y-intercept in the regression equations indicates the air temperatures at the Boundary Reservoir were slightly cooler on average than at the Sandpoint station. The nearly one to one slope of the regression equations indicates that the air temperature ranges were similar between Sandpoint and Boundary Reservoir.

The regression equations were used to estimate the missing air temperature data for the Boundary and Box Canyon Dam stations (Figure 2.21).

2.7.2 Dew Point Temperature

The dew point temperature[a] data collected from Boundary and Box Canyon Dams did not cover the whole period of the temperature modeling analyses of 2004 and 2005. Estimates of the missing data were provided, after regression analysis with a complete dew point temperature data set from the NOAA station in Sandpoint, Idaho (Figure 2.22). The goodness-of-fit between the dew point temperature data sets was very good: $r^2 = 0.877$ between Sandpoint and Box Canyon Dam and $r^2 = 0.876$ between Sandpoint and Boundary Dam. The positive value of the y-intercept in the regression equations indicates the dew point temperatures (and the relative humidity) at the Boundary Reservoir were higher on average than at the Sandpoint station. The nearly one to one slope of the regression equation between the Box Canyon Dam and Sandpoint data indicates that the dew point temperature ranges were similar. For the Boundary Dam to Sandpoint regression, the slope was 0.954 which indicates the range of dew point temperatures was slightly smaller at the Boundary Dam station than at the Sandpoint station.

The regression equations were used to estimate the missing dew point temperature for the Boundary and Box Canyon Dam stations (Figure 2.23).

2.7.3 Wind

There was no correlation for the wind data (speed and direction) between the Boundary Reservoir stations and the other available data (RAWS and NOAA) ($r^2 < 0.1$). There was also no correlation between the Boundary Dam and the Box Canyon Dam wind data. Averaging over longer time periods (day or week) produced only slight improvement in the goodness of fit, but r^2 was still less than 0.1. Consequently, wind data from the stations in the vicinity of Boundary Reservoir were used directly for the periods when data were missing. The combined data sets for wind speed at Boundary and Box Canyon Dam stations are shown in Figure 2.24 and for wind direction in Figure 2.25. Wind speed and direction are both presented in wind-rose plots for the Boundary and Box Canyon Dam stations in Figure 2.26.

---

[a] Dew point temperatures are an indication of relative humidity and are always less than the air temperature. A dew point temperature equal to the air temperature indicates 100% relative humidity. Dew point temperatures that are close to the air temperature indicate higher moisture content in the air than if the dew point temperature is low. A larger difference between air and dew point temperatures means that more evaporative cooling can occur (called the latent heat loss).

2.7.4 Solar Radiation and Cloud Cover

While there was a correlation of the solar radiation data between the Boundary Reservoir stations and the Priest Lake RAWS data, the correlation coefficient value was not as good as needed ($r^2 \leq 0.7$). Consequently, the data from stations in the vicinity of Boundary Reservoir for to the periods of missing data were examined directly without the use of regression equations. The combined data sets for solar radiation at Boundary and Box Canyon Dam stations are shown in Figure 2.27.

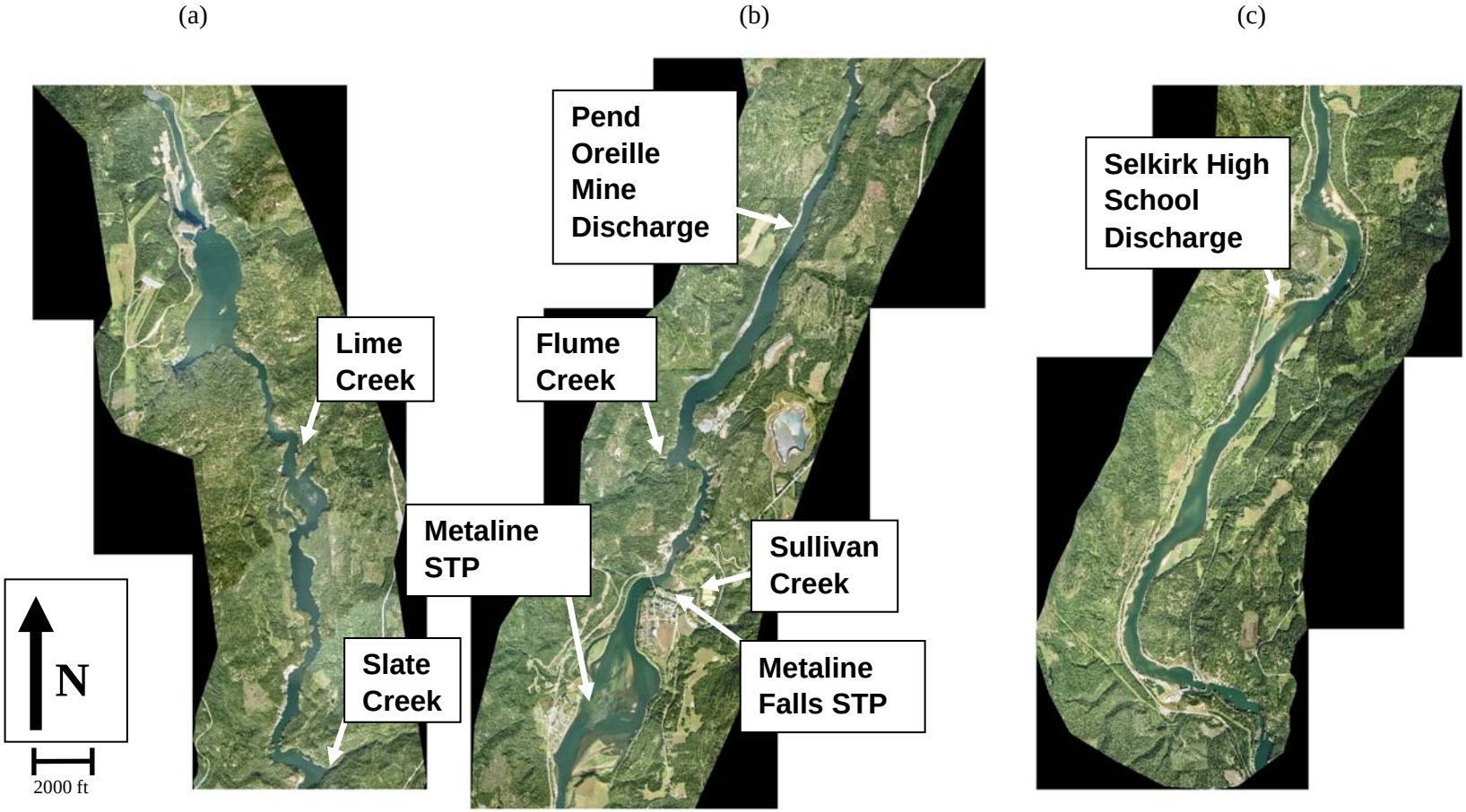
Observations of cloud cover were available at Boundary Dam, where the observations were made at 8 am daily. The observations were converted to sky coverage in tenths (clear = 0, partly cloudy = 5, mostly cloudy = 8, overcast = 9, cloudy, fog, precipitation = 10) and then interpolated to hourly intervals. The cloud cover data are shown in Figure 2.28.

2.8 Shade Data

Shade data consisted of two components: the topographic features and the vegetation. The topographic shade data for Boundary Reservoir were computed using digital elevation models from USGS (2004). The digital elevation models topographic data were analyzed along lines radiating from the points along the centerline of Boundary Reservoir (Figure 2.29). At each centerline point, 18 slices, at 20 angles, were made that were 10,000 m long. The slices started at the north and rotated in the clockwise direction (the same as the compass angle). Along each slice, the elevations at 32.81-ft (10-m) intervals were determined and the angles from the beginning of the slice above the horizontal were calculated. The maximum angle along each slice was specified as the topographic shade angle in the direction of the slice.

Example topographic shade angles along the Boundary Reservoir in three directions (east, south, and west) are shown in Figure 2.30a. Because the Boundary Reservoir is oriented in the north-south direction, the topographic shade angles are smallest for the south direction, except when the reservoir makes a sharp bend. The topographic shade angles to the west are the largest of the three corresponding to the higher bluffs that overlook Boundary Reservoir.

Vegetative shade height and fraction of cover were provided by WDOE (Pickett 2007). These are shown in Figures 2.30b.



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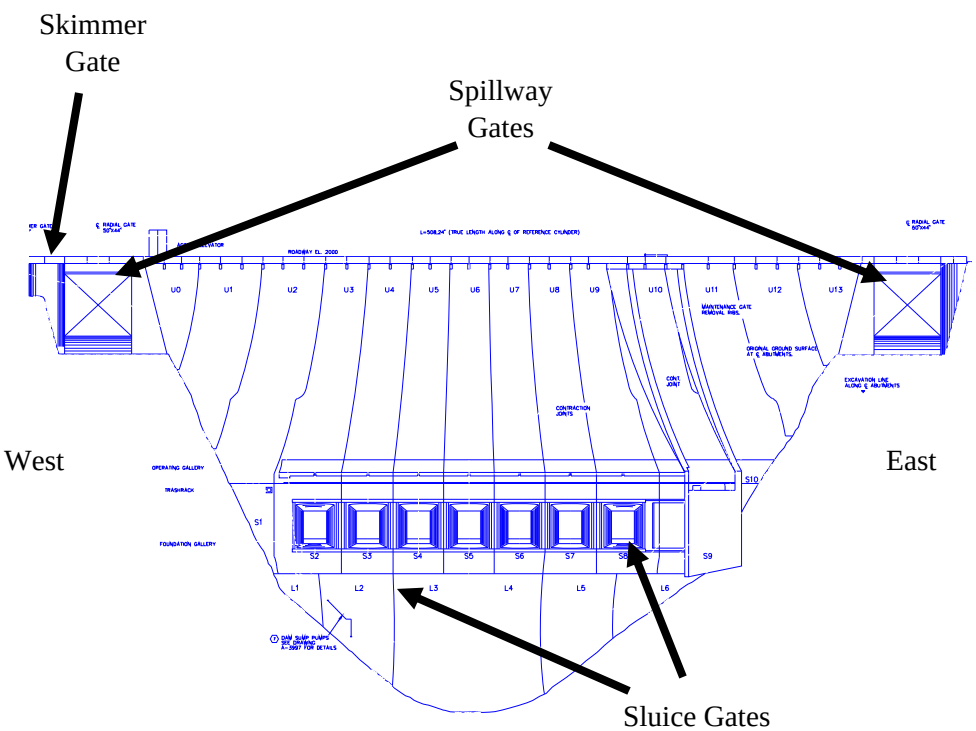
Note: (1) The length scale is approximate.
(2) The images were provided by Zablotney (2006).
(3) The figures (a) through (c) are ordered from north to south.
(4) The point source locations were provided by Pickett (2006).

Figure 2.1

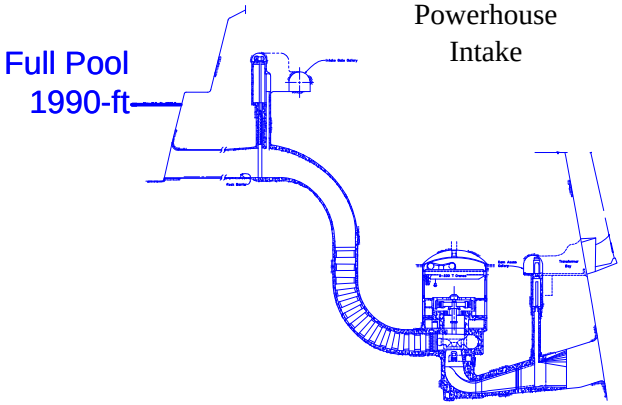
Tributary and Point Source Discharge Locations

Seattle City Light
Seattle, Washington

(a)



(b)



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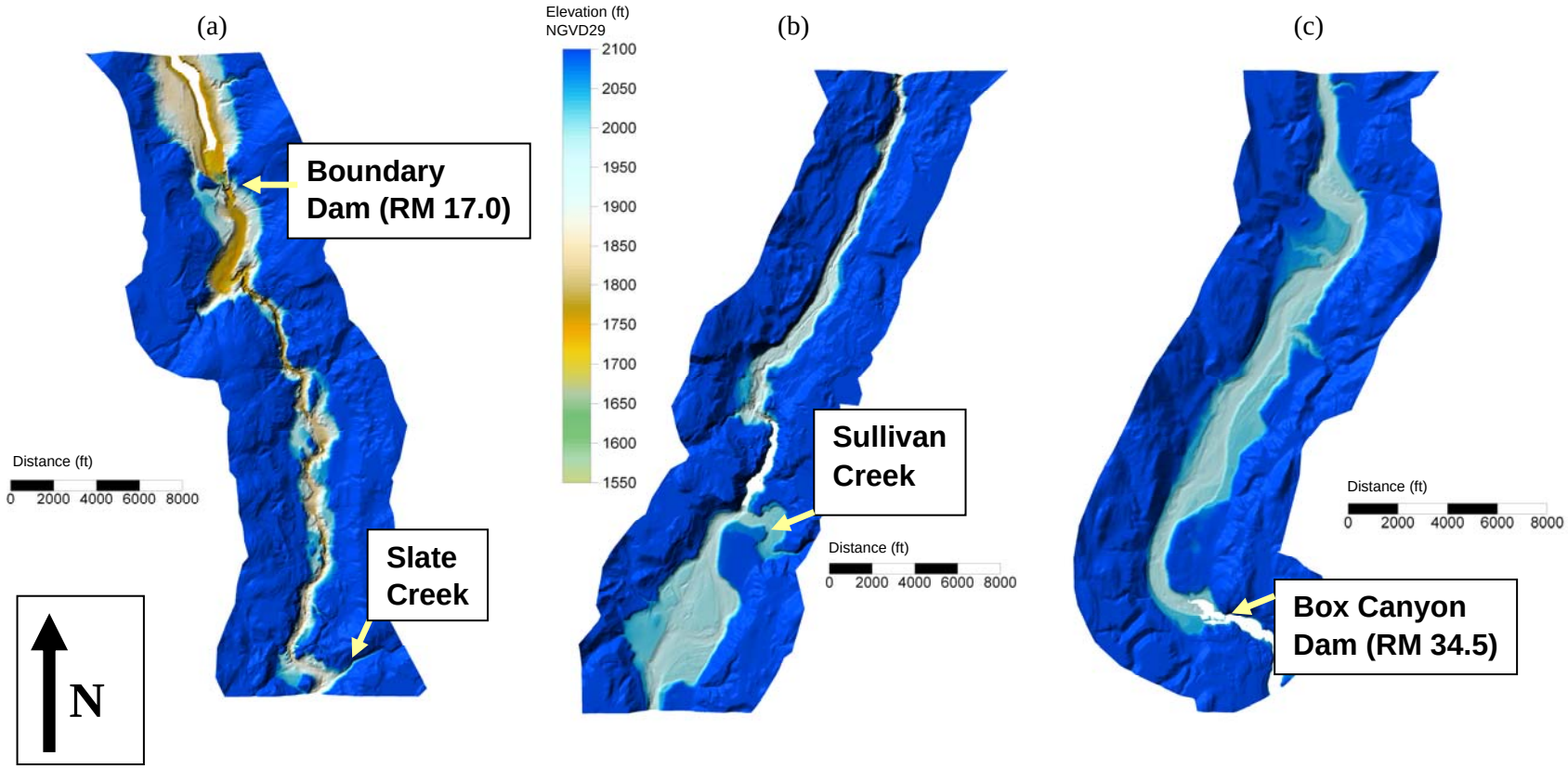
Note: The CAD images were provided by Filbert (2006).

Figure 2.2

Boundary Dam and Its Discharge Structures

Seattle City Light
Seattle, Washington



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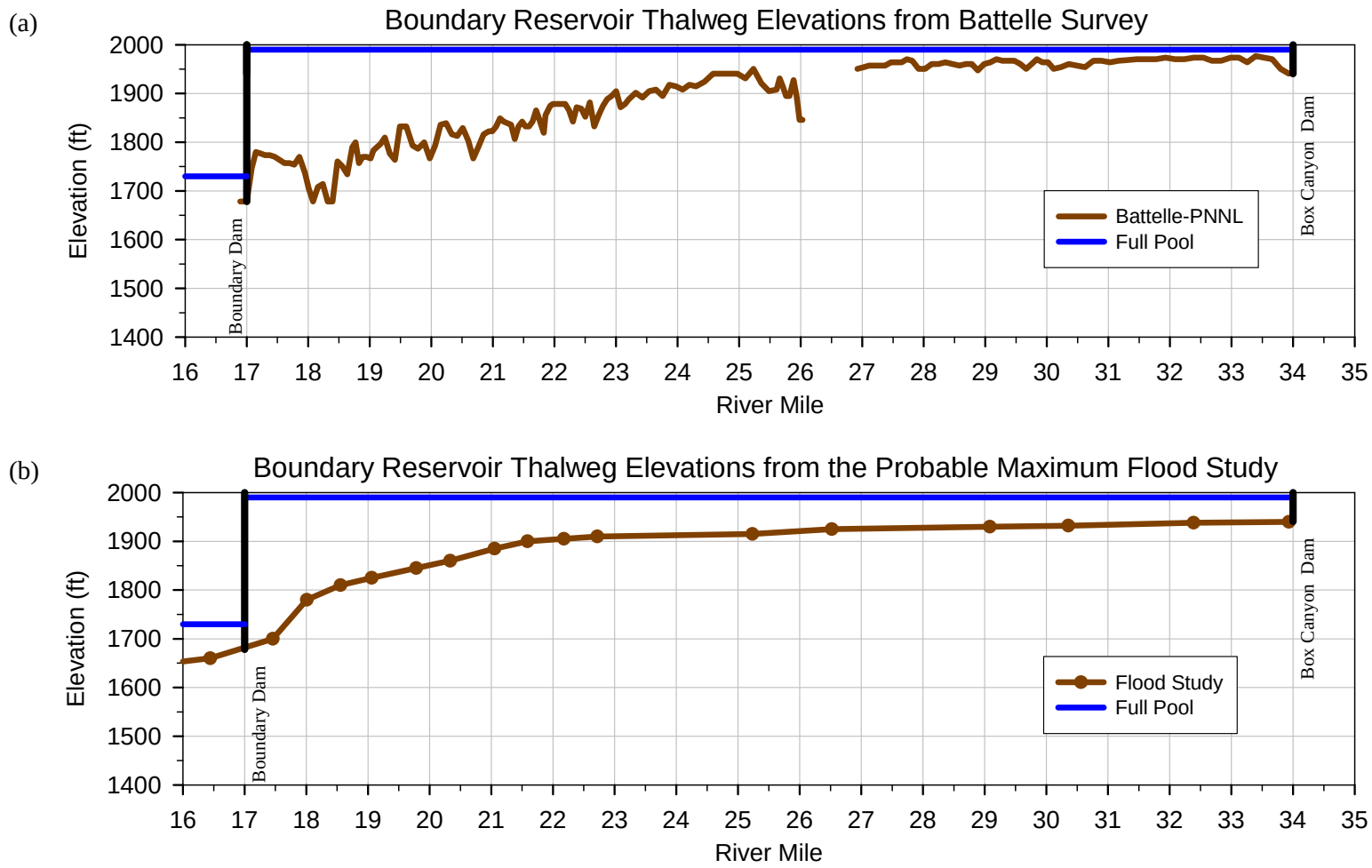
Note: (1) The full pool elevation for Boundary Reservoir is 1,990 ft (606.55 m), while downstream of Boundary Dam the full pool elevation is 1,730 ft (527.0 m) as impounded by Seven-Mile Dam in British Columbia, Canada.
(2) The figures (a) through (c) depict the topography from north to south.

Figure 2.3

Bathymetry and Adjacent Topography of the Boundary Reservoir

Seattle City Light
Seattle, Washington



Note: (1) The Battelle survey data were from Battelle (2006).
(2) The Maximum Probable Flood Study data were from Morrison Knudsen (1997). The cross-section locations in (b) are indicated by the dots.
(3) The full pool elevation for Boundary Reservoir is 1,990 ft (606.55 m) and for the Seven-Mile Dam Reservoir is 1,730 ft (527.0 m).
(4) The dam locations are indicated by vertical black lines.

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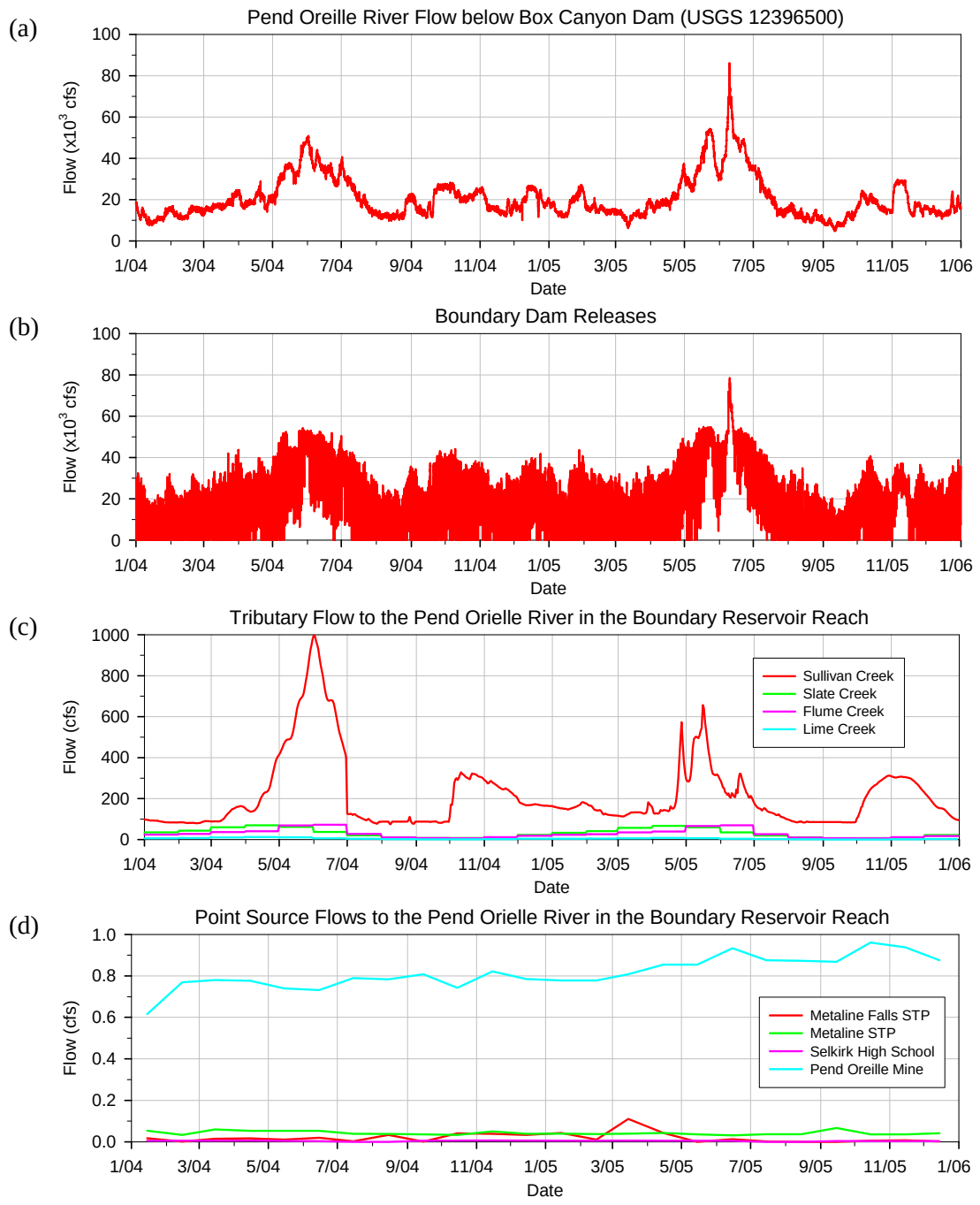
Figure 2.4

Thalweg Profiles for the Boundary Reservoir

Seattle City Light
Seattle, Washington



Note: (1) The Sullivan Creek and Pend Oreille River flows below Box Canyon Dam were provided by USGS (2006).
(2) The Boundary Dam flows were provided by SCL (2006). The Boundary Dam flows combine the powerhouse flows and any spill flows. No spills occurred in 2004, while the few spills in 2005 were small.
(3) The Slate, Flume, Lime Creek, and point sources flows were provided by Pickett (2006).

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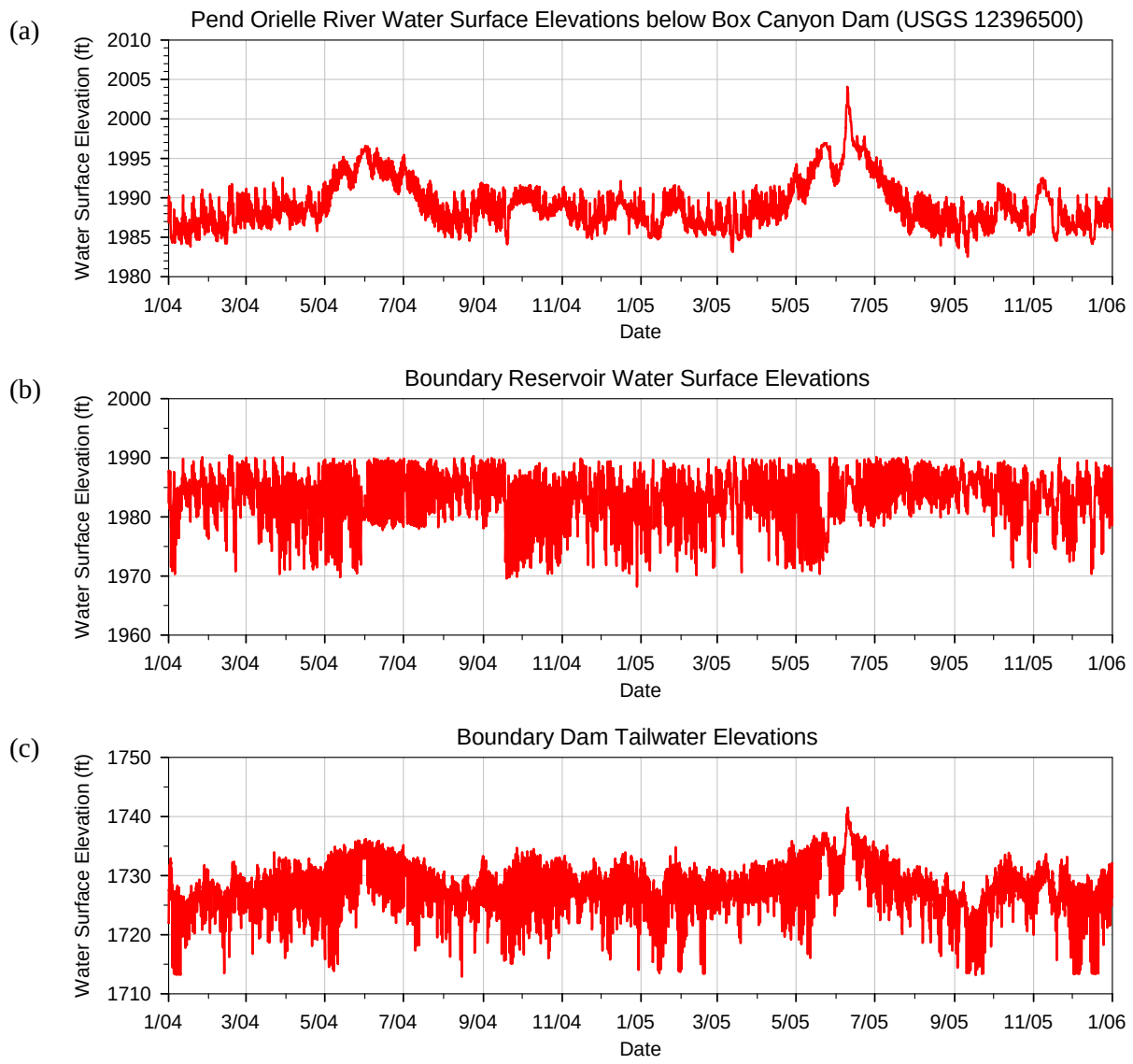
Figure 2.5
Pend Oreille River, Tributary, and Point Source Flows

Seattle City Light
Seattle, Washington



Note: (1) The Pend Oreille River water surface elevations below Box Canyon Dam were provided by USGS (2006) (2) The Boundary Reservoir and Boundary Dam tailrace water surface elevations were provided by SCL (2006).

Figure 2.6
Measured Water Surface Elevations in the Pend Oreille River and Boundary Reservoir

Seattle City Light
Seattle, Washington

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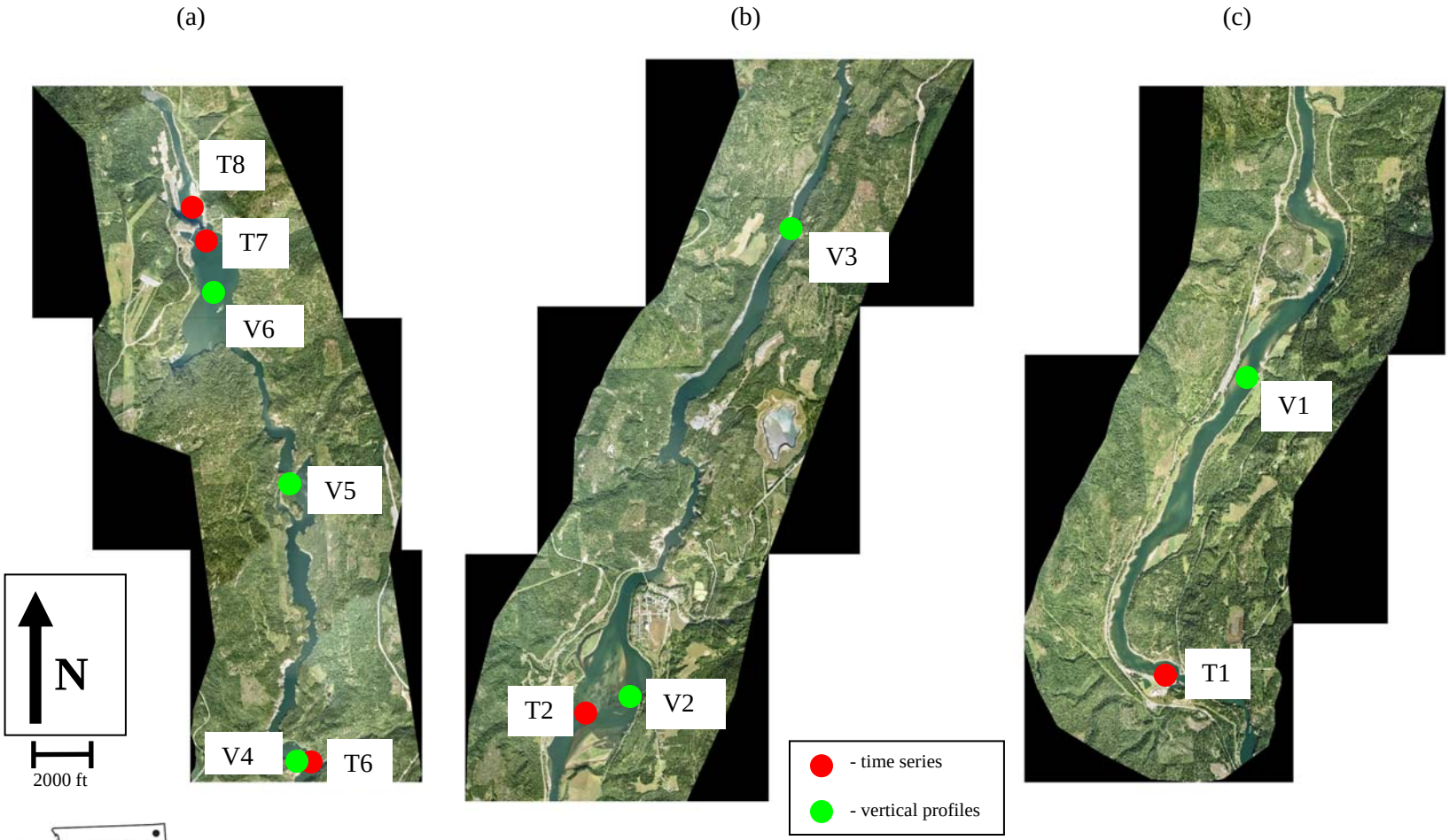

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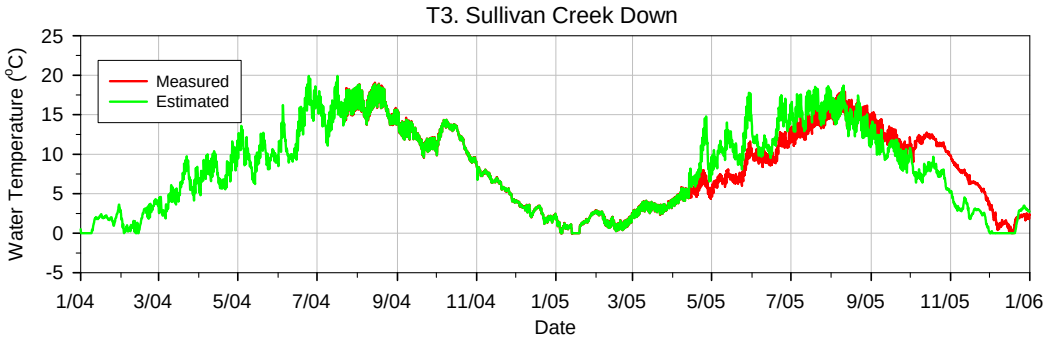
Note: (1) The length scale is approximate.
(2) The images were provided by Zablotney (2006).
(3) The figures (a) through (c) are ordered from north to south.
(4) The temperature data were collected by Taylor (2005).

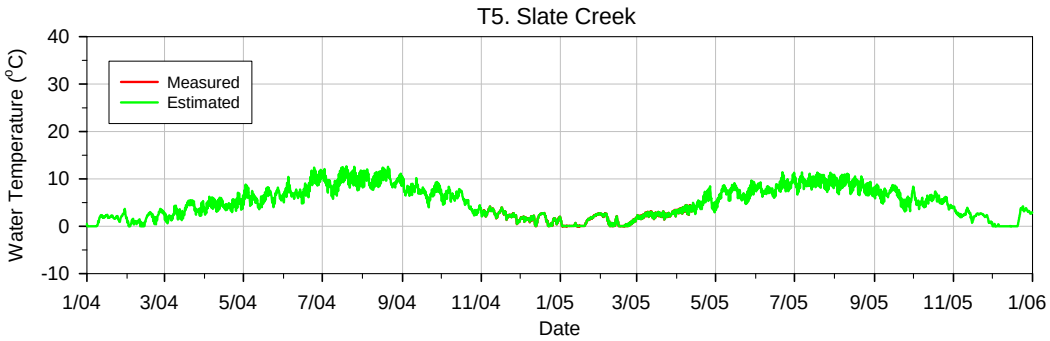
Figure 2.7
Locations of Temperature Measurement Stations

Seattle City Light
Seattle, Washington

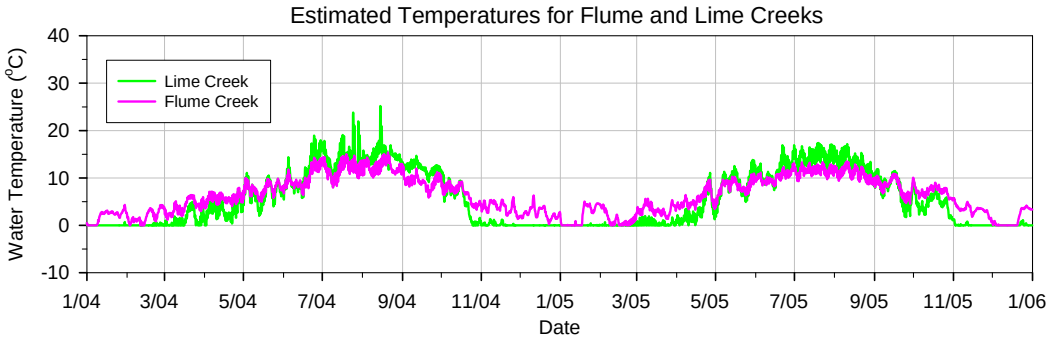
(a)



(b)



(c)



Note: (1) The measured data were provided by Taylor (2006).
(2) The estimated temperature for Sullivan, Slate, Lime, and Flume Creeks were from WDOE using the model rTemp (Pickett 2005).

Figure 2.8
Measured and Estimated Inflow Temperatures of the Pend Oreille River Tributaries

Seattle City Light
Seattle, Washington

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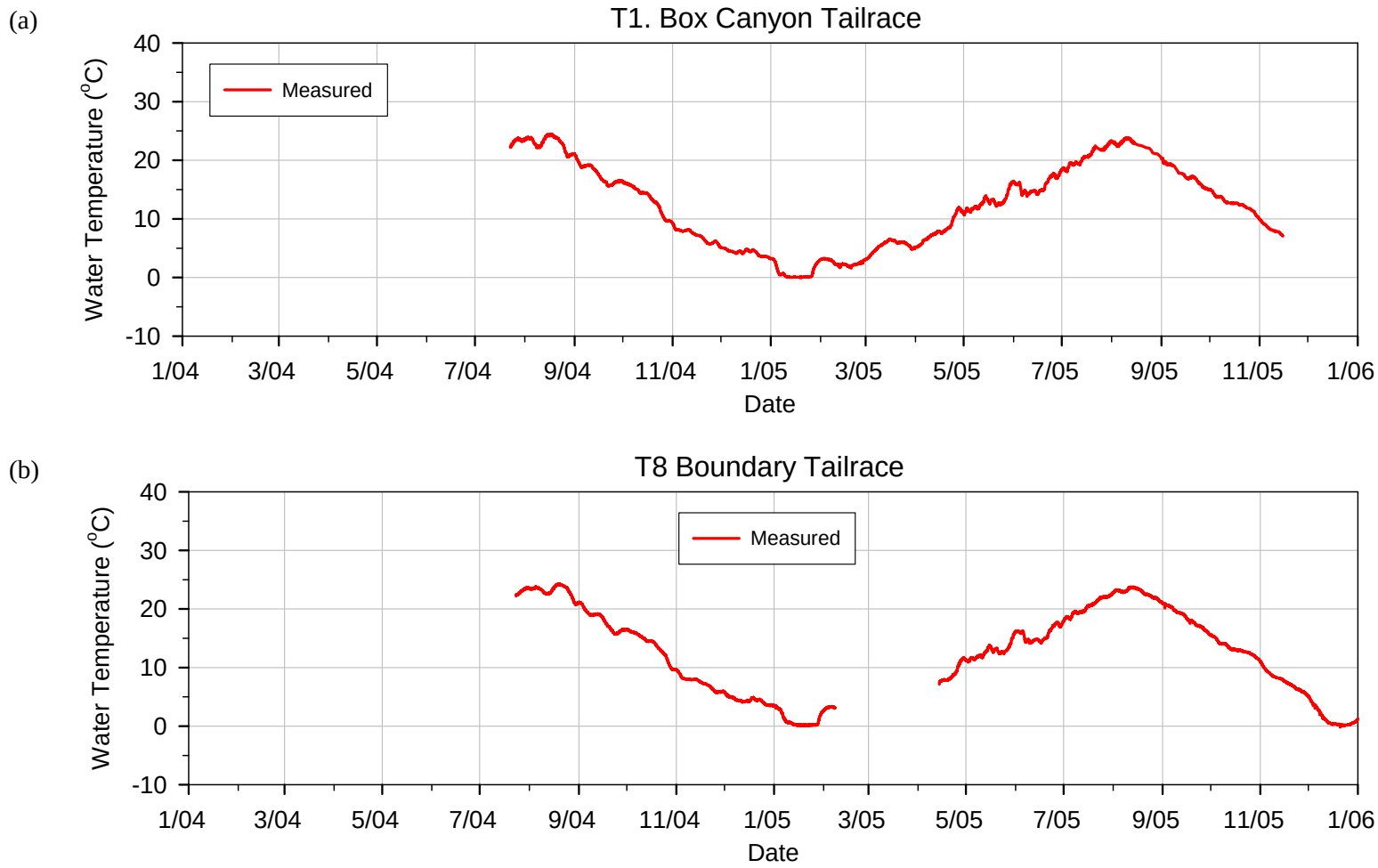

Note: (1) The measured data were provided by Taylor (2005).

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Figure 2.9
Measured Temperature Time Series in the Pend Oreille River in the Box Canyon and Boundary Dams Tailraces

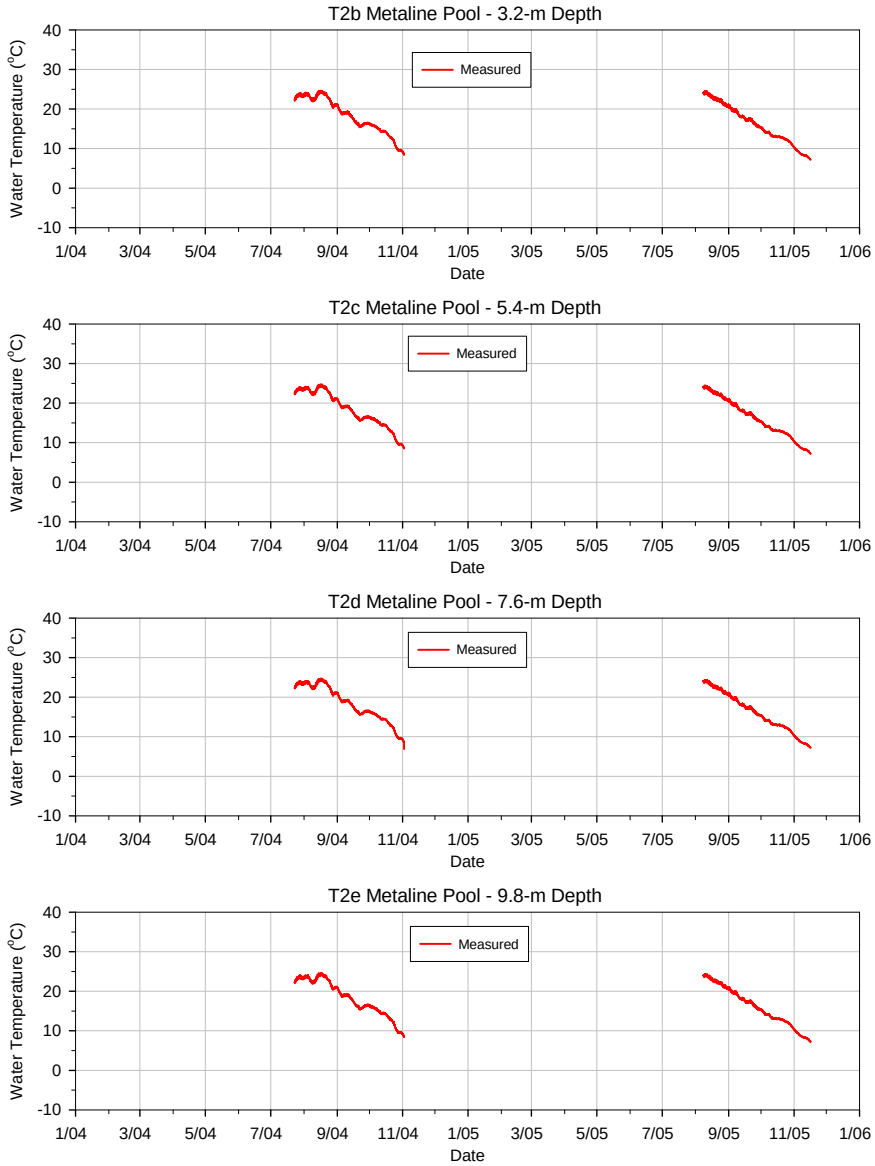
Seattle City Light
Seattle, Washington

(a)

(b)

(c)

(d)



Note: (1) The measured data were provided by Taylor (2005).

Figure 2.10
Measured Temperature Time Series in Boundary Reservoir at the Metaline Pool Station, T2 (RM 27.1)

Seattle City Light
Seattle, Washington

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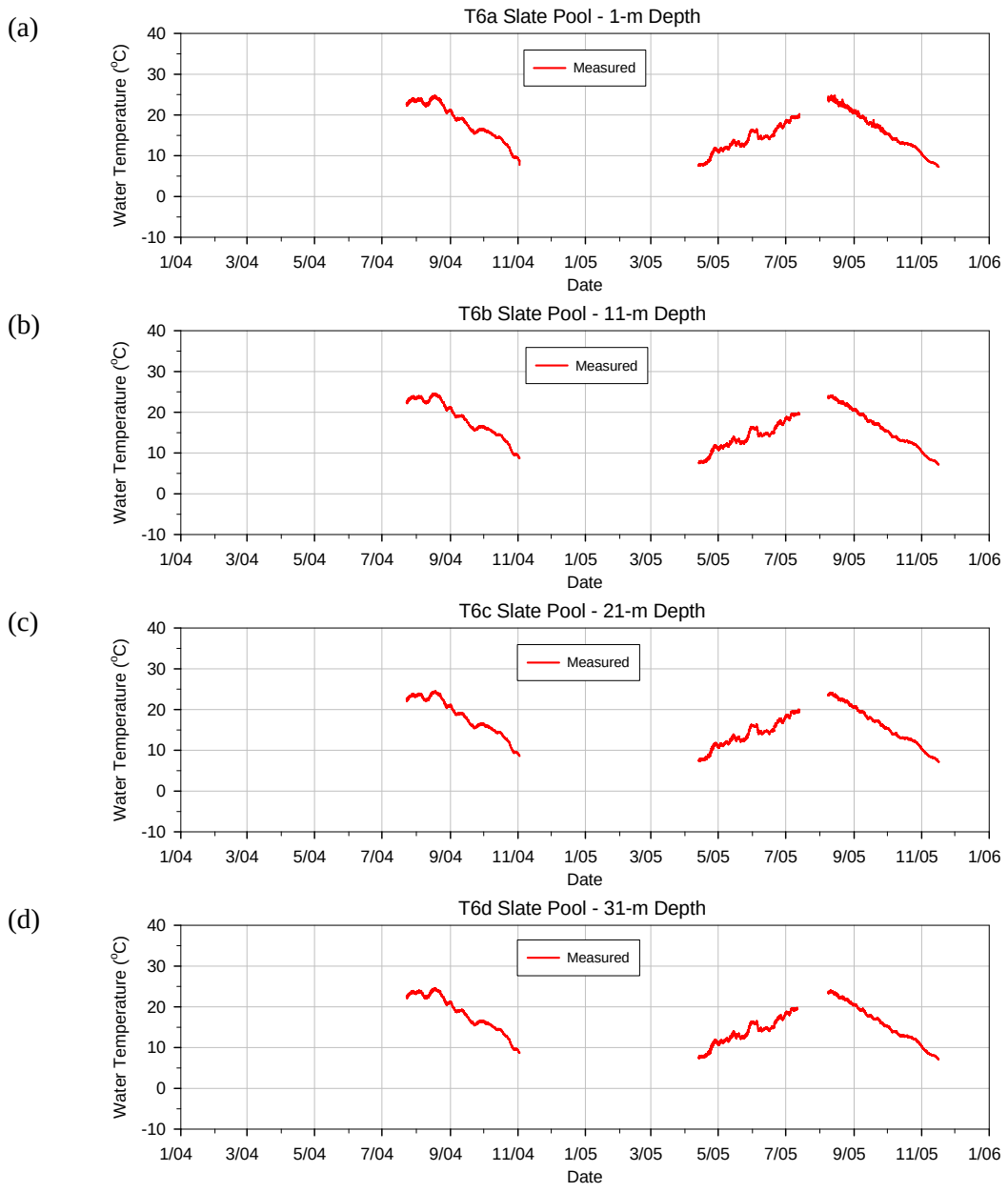

Note: (1) The measured data were provided by Taylor (2005).

Figure 2.11
Measured Temperature Time Series in Boundary Reservoir at the Slate Pool Station, T6 (RM 21.2)

Seattle City Light
Seattle, Washington

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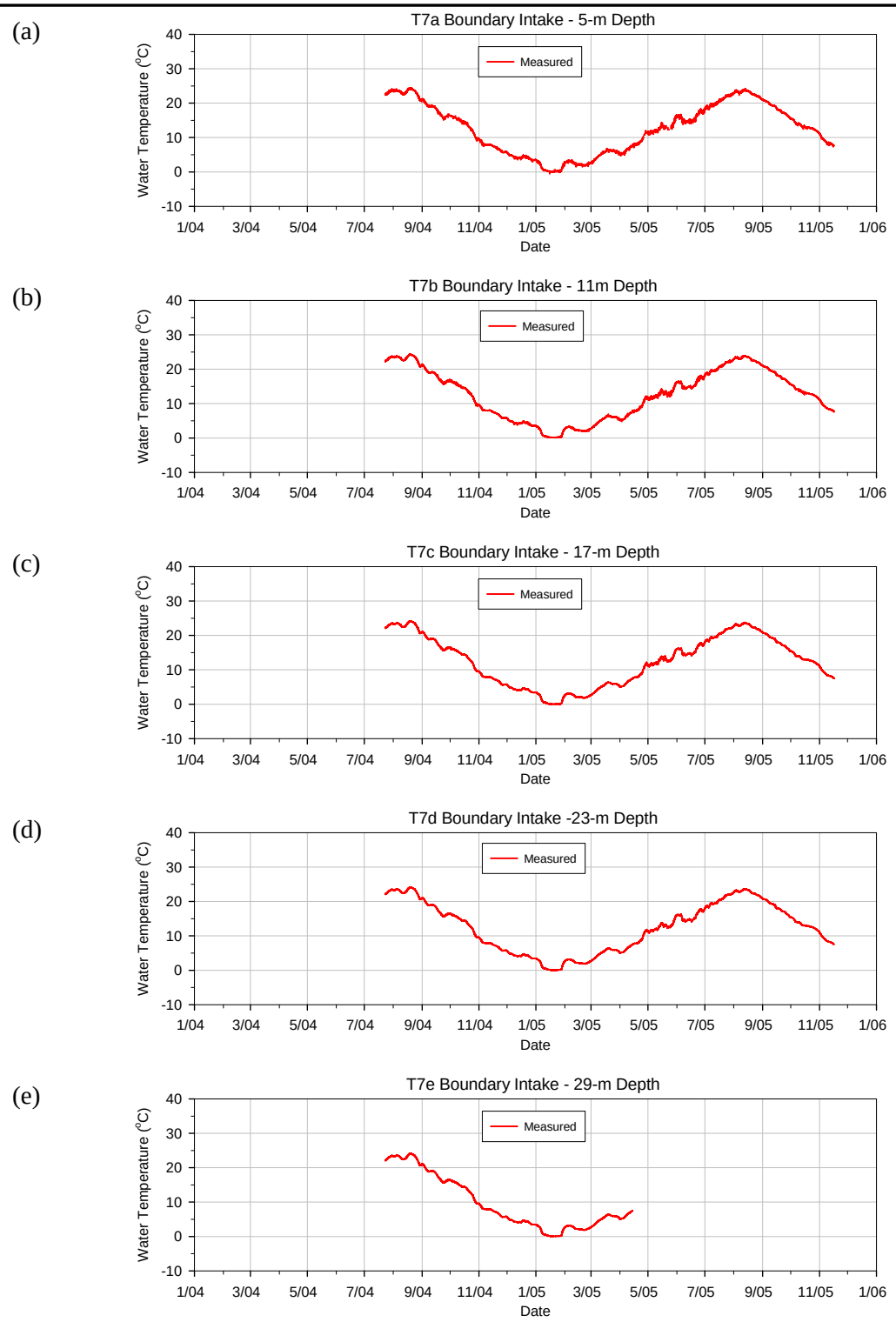

Note: (1) The measured data were provided by Taylor (2005).

Figure 2.12
Measured Temperature Time Series in Boundary Reservoir at the Boundary Dam Intake Station, T7 (RM 16.0)

Seattle City Light

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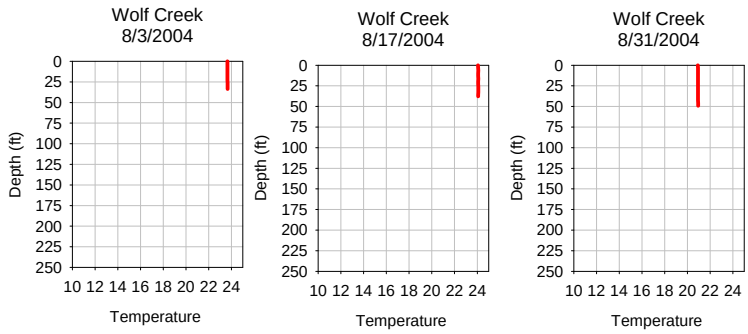
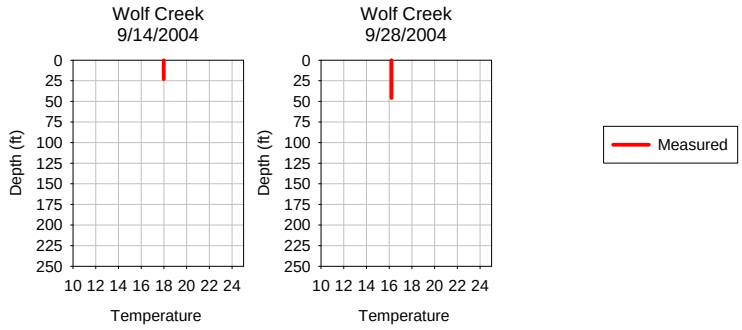
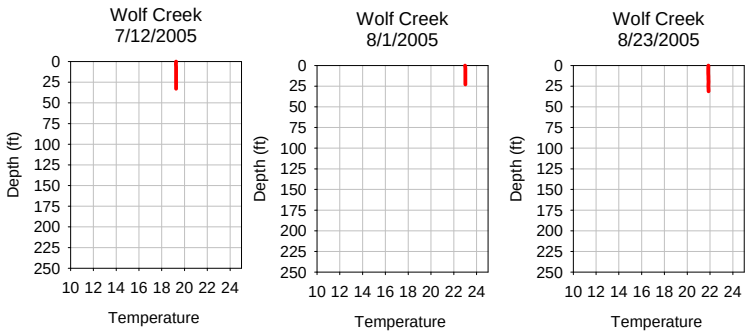
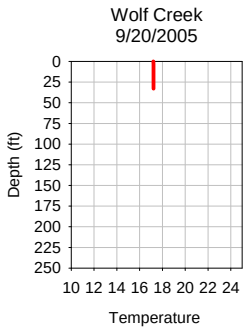
2004





2005





Note: (1) The measured data were provided by Taylor (2005).

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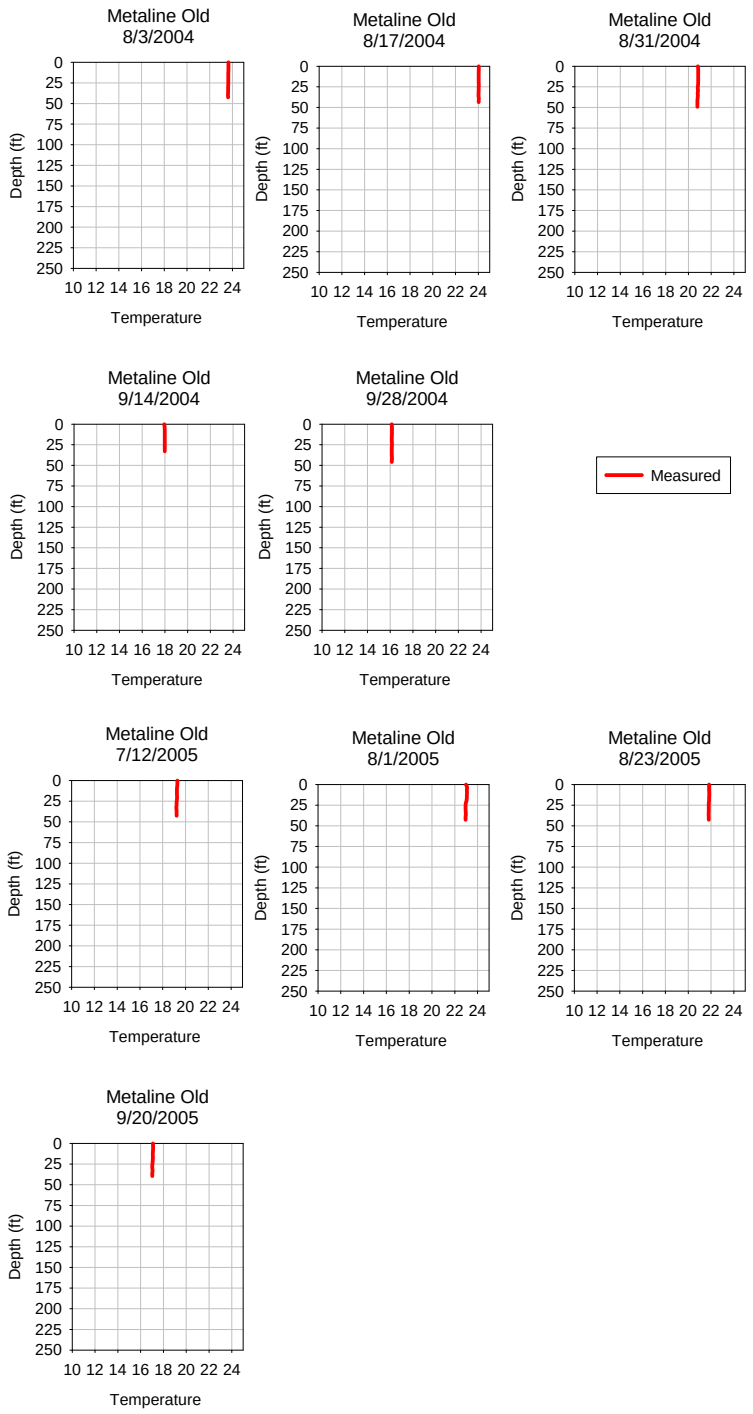
Figure 2.13
Measured Temperature Profiles in Boundary Reservoir at the Wolf Creek Station, V1 (RM 30.08)

Seattle City Light
Seattle, Washington

2004

2005



Note: (1) The measured data were provided by Taylor (2005).

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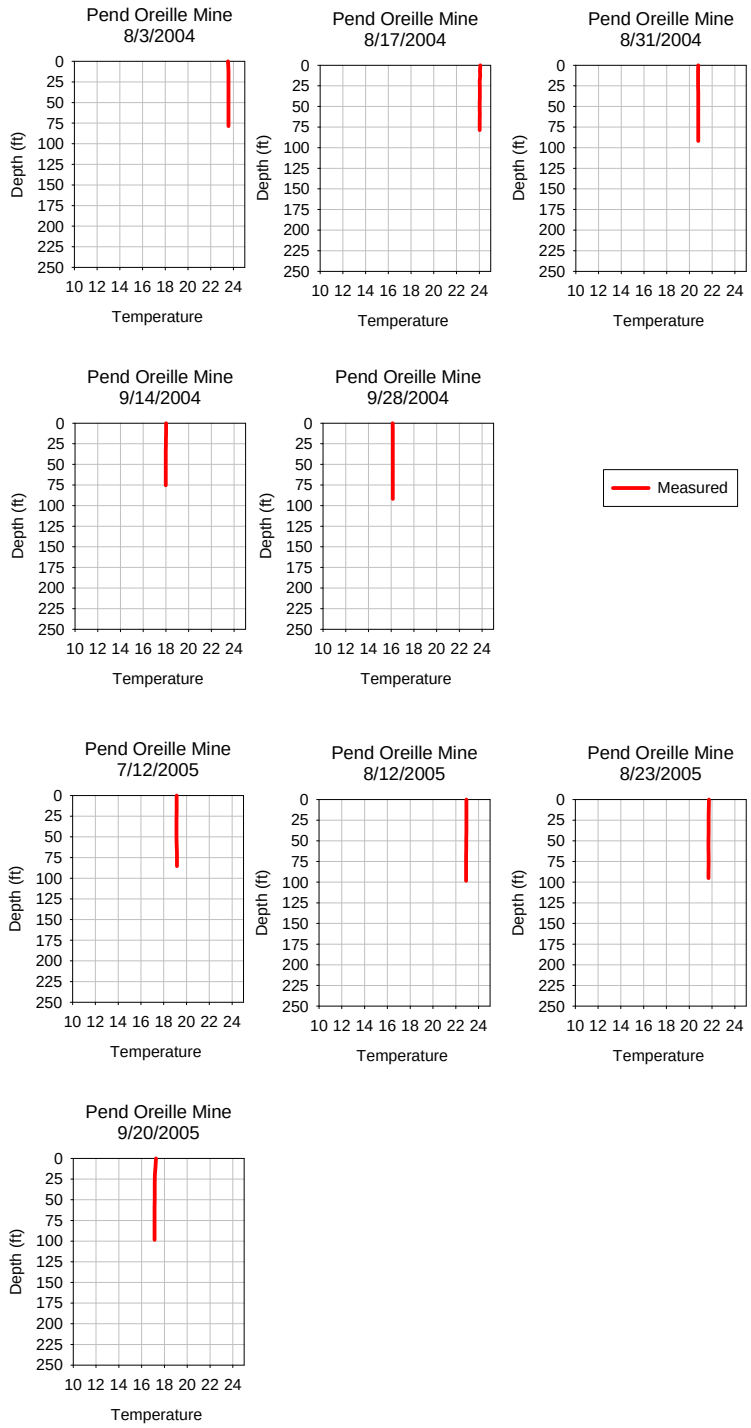
Figure 2.14
Measured Temperature Profiles in Boundary Reservoir at the Metaline Old Station, V2 (RM 28.09)

Seattle City Light
Seattle, Washington

2004

2005



Note: (1) The measured data were provided by Taylor (2005).

Figure 2.15
Measured Temperature Profiles in Boundary Reservoir at the Pend Oreille Mine Station, V3 (RM 25.33)

Seattle City Light
Seattle, Washington

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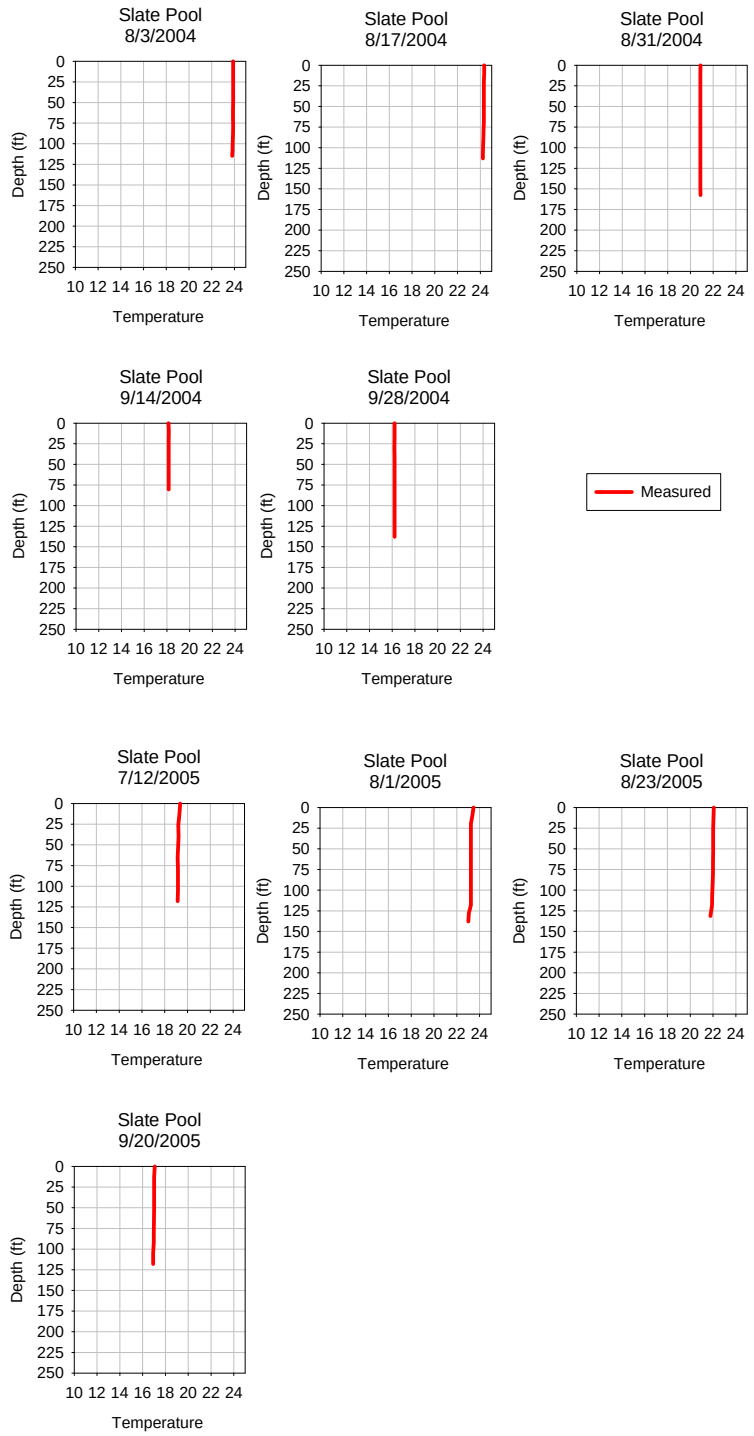
2004

2005



Note: (1) The measured data were provided by Taylor (2005).

Figure 2.16
Measured Temperature Profiles in Boundary Reservoir at the Slate Pool Station, V4 (RM 21.86)

Seattle City Light
Seattle, Washington

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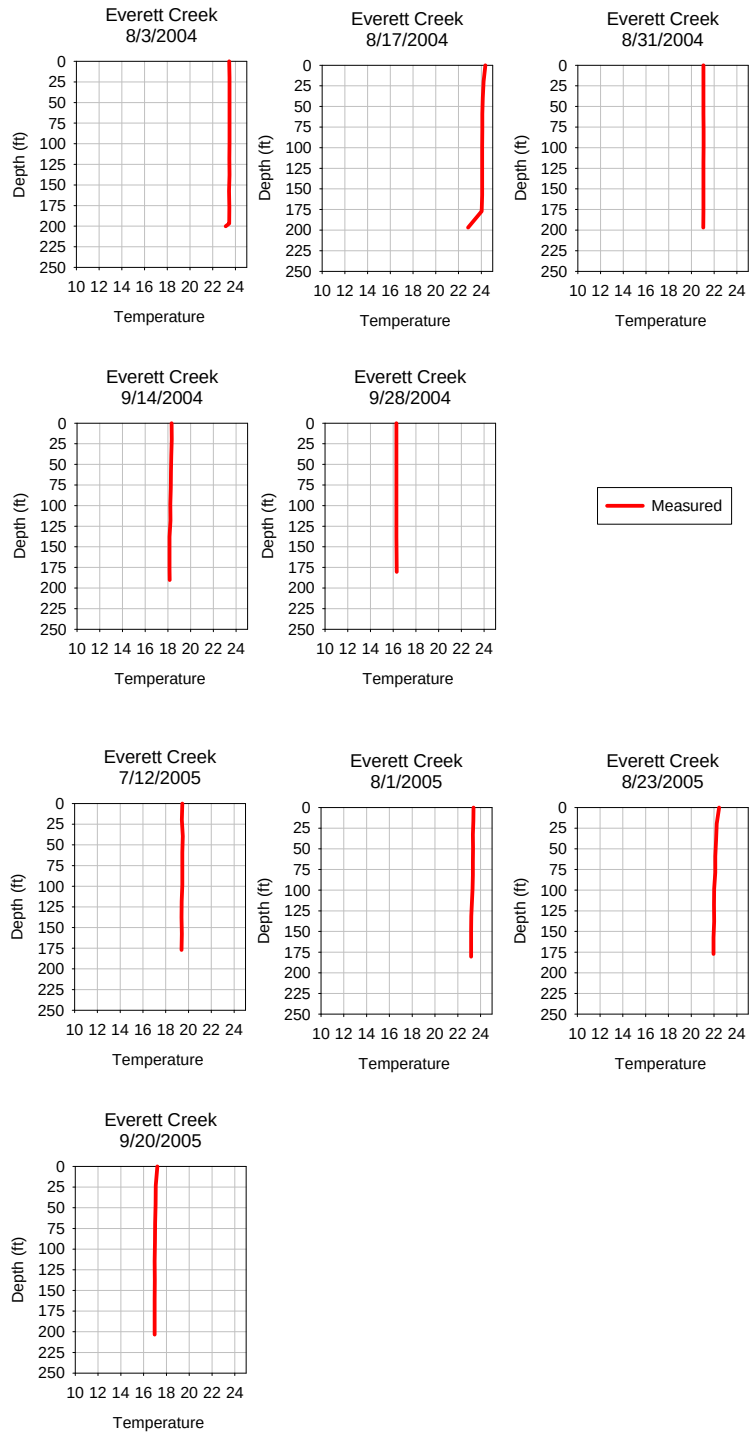
2004

2005



Note: (1) The measured data were provided by Taylor (2005).

Figure 2.17
Measured Temperature Profiles in Boundary Reservoir at the Everett Creek Station, V5 (RM 20.27)

Seattle City Light
Seattle, Washington

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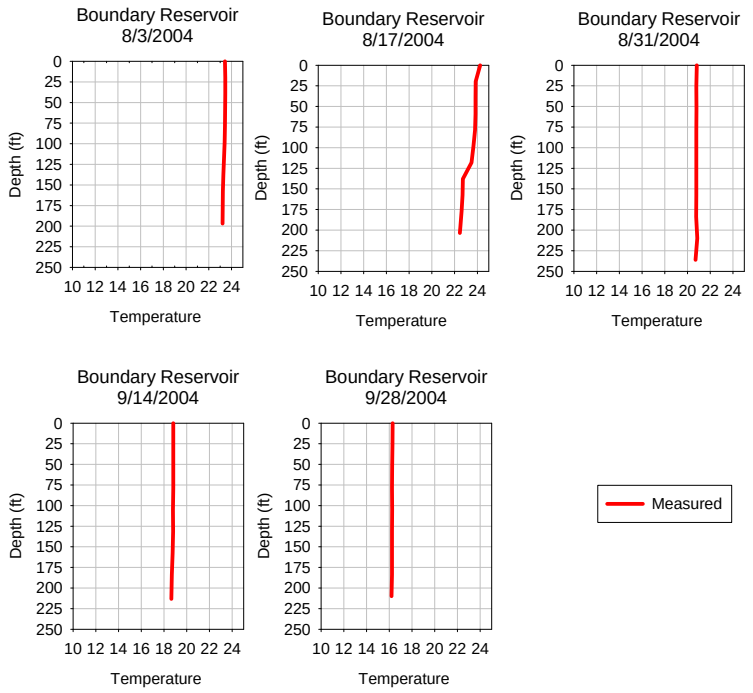
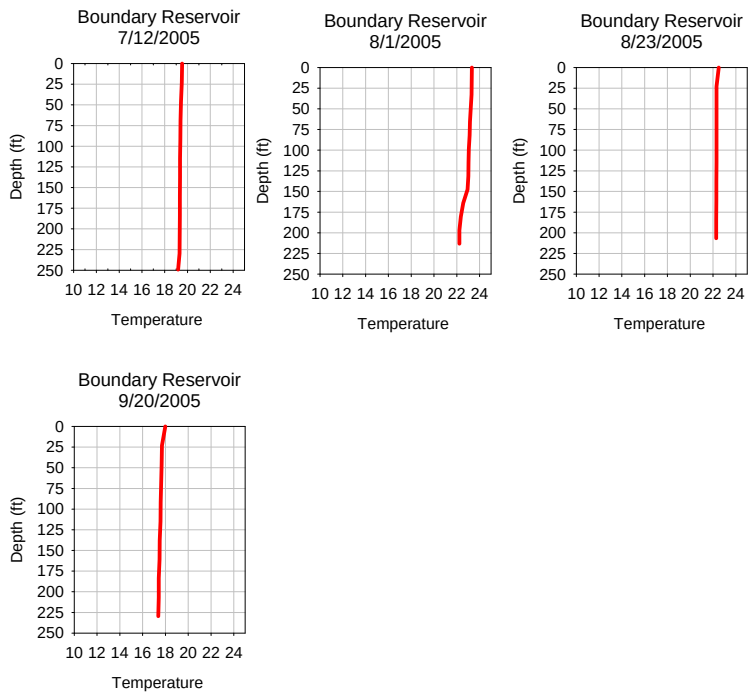
2004



2005



Note: (1) The measured data were provided by Taylor (2005).

Figure 2.18
Measured Temperature Profiles in Boundary Reservoir at the Boundary Reservoir Station, V6 (RM 17.46)

Seattle City Light
Seattle, Washington

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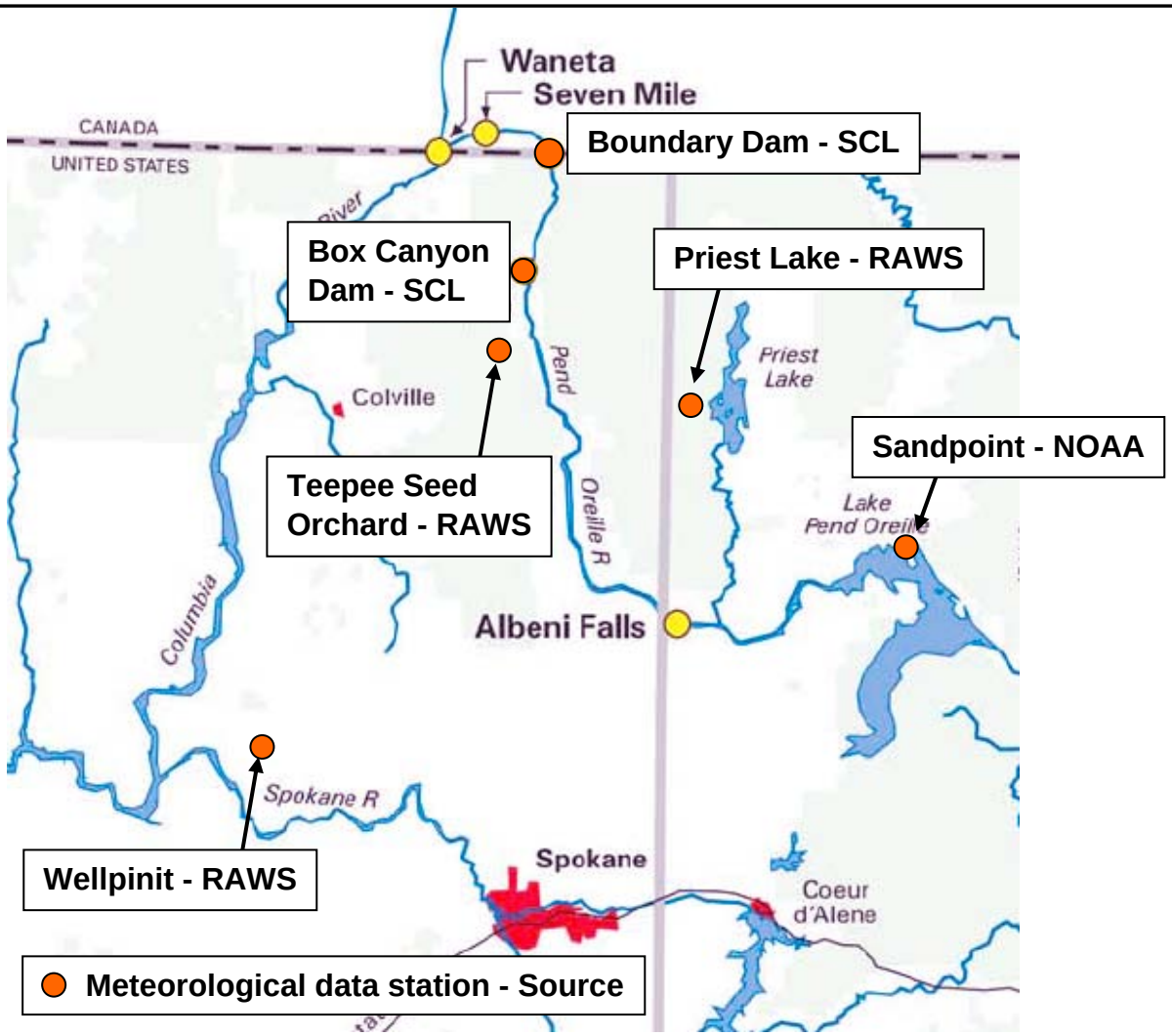

Note: (1) SCL – Seattle City Light; RAWS – Regional Agricultural Weather Station; NOAA – National Oceanic and Atmospheric Administration
(2) The GIS background was obtained from Zablotney (2006).

Figure 2.19
Locations of Meteorological Stations

Seattle City Light
Seattle, Washington

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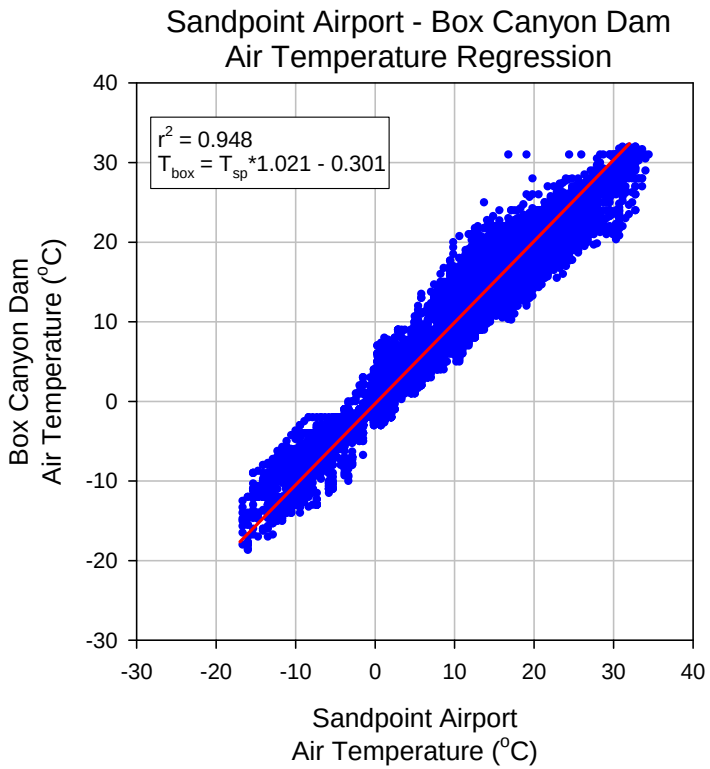
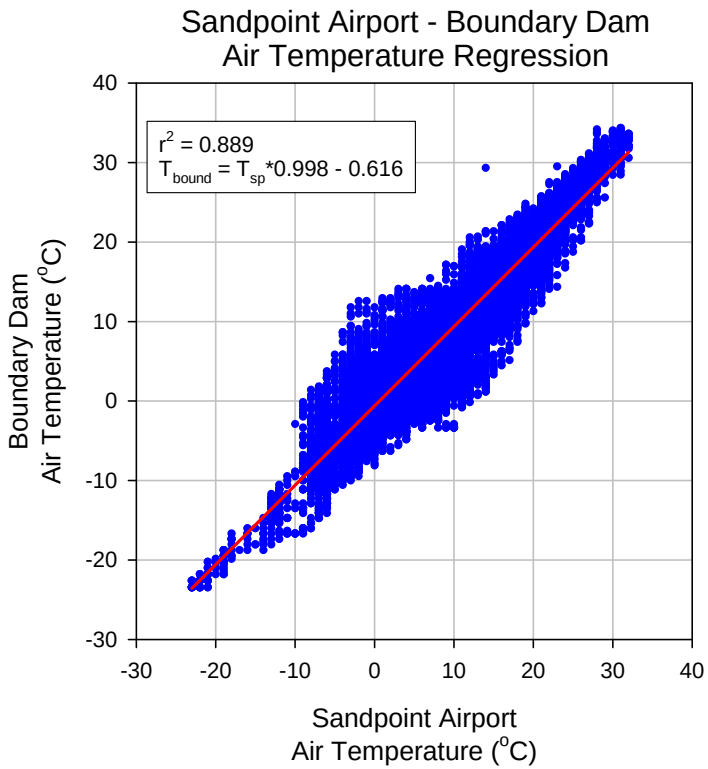
(a)



(b)



Note: (1) The regression line is indicated in red.

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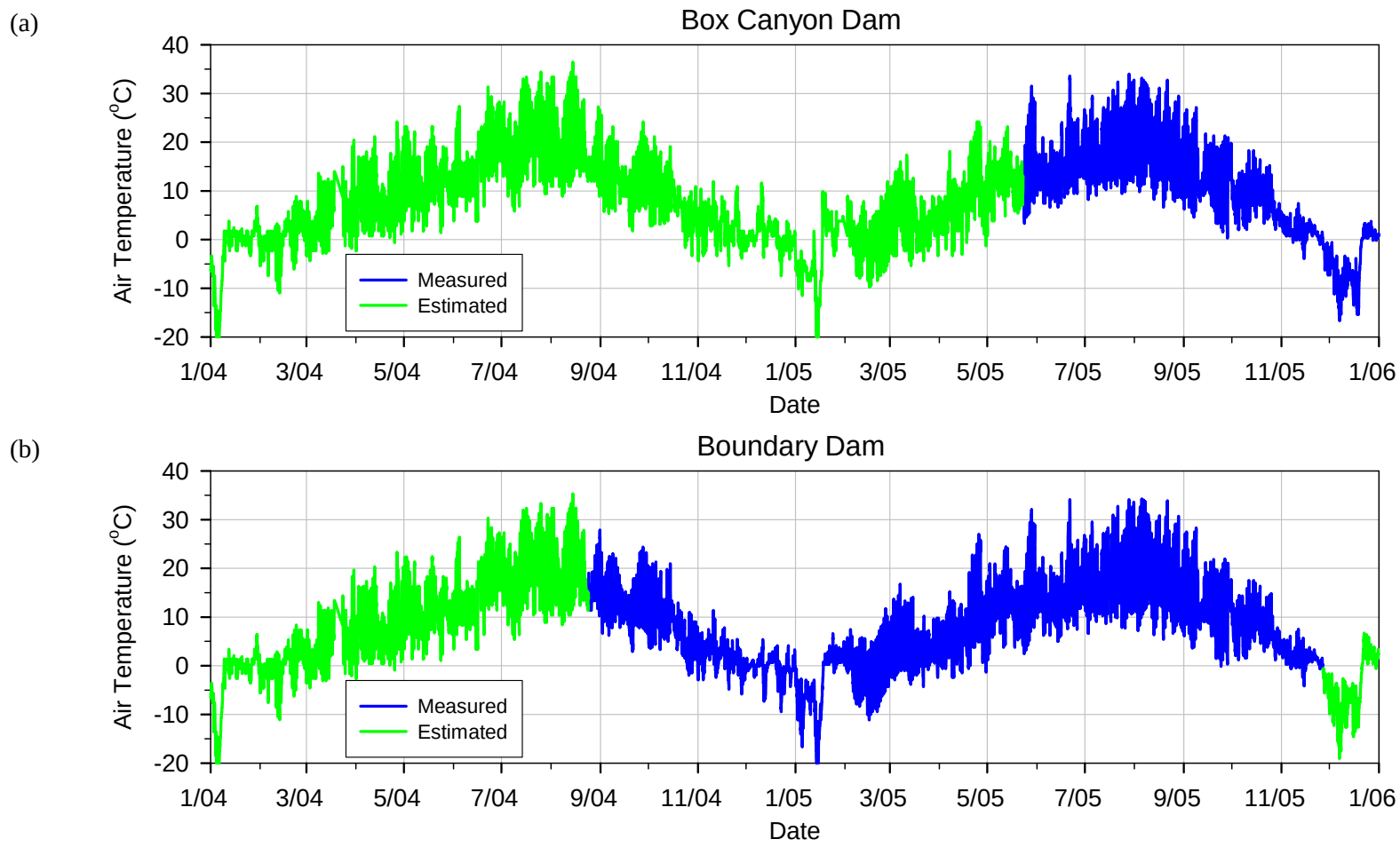
Figure 2.20

Air Temperature Regressions between Sandpoint Airport and Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington



Note: (1) The regression analyses with the air temperature data at the Sandpoint station were used to estimate air temperatures at Boundary and Box Canyon Dam locations when data were missing.

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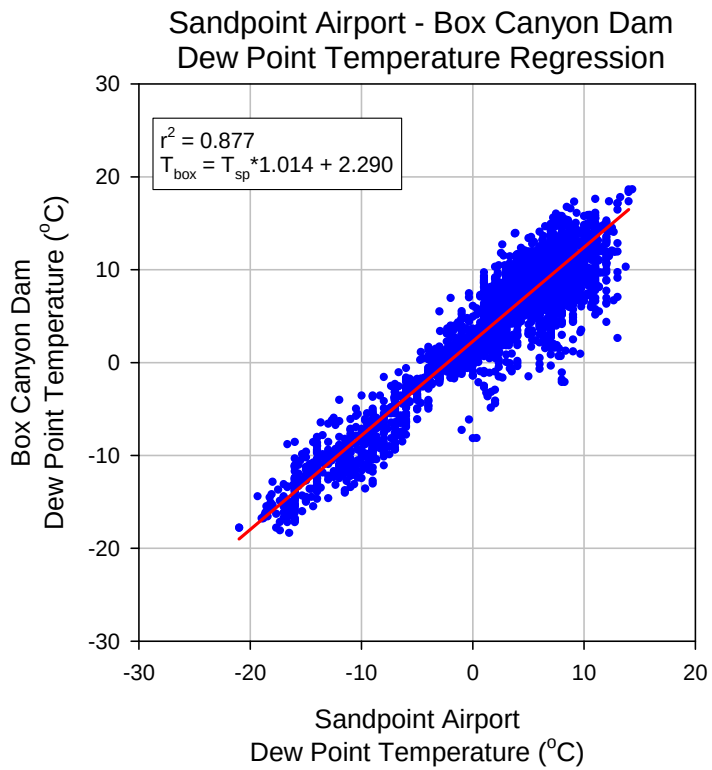
Figure 2.21

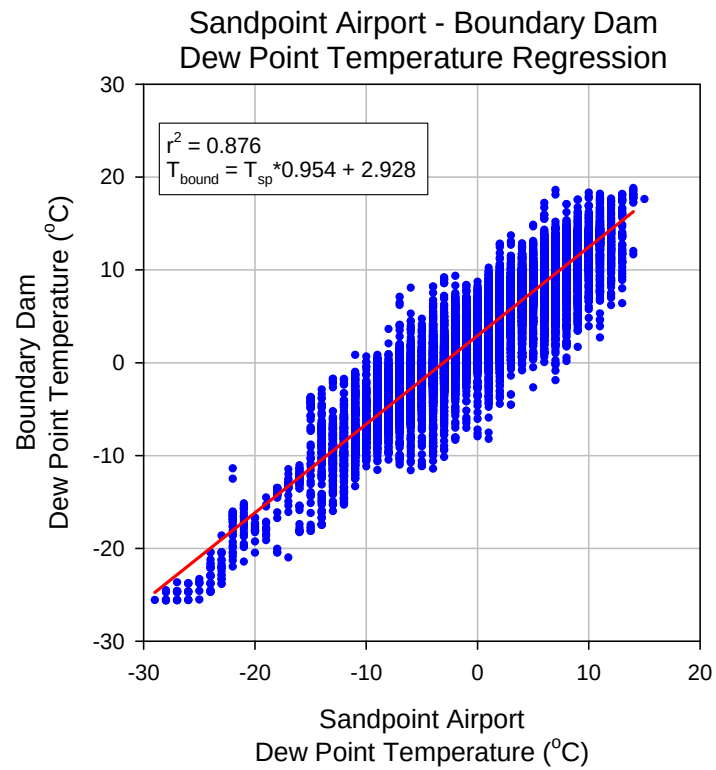
Measured and Estimated Air Temperatures at Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington

(a)



(b)



Note: (1) The regression line is indicated in red.

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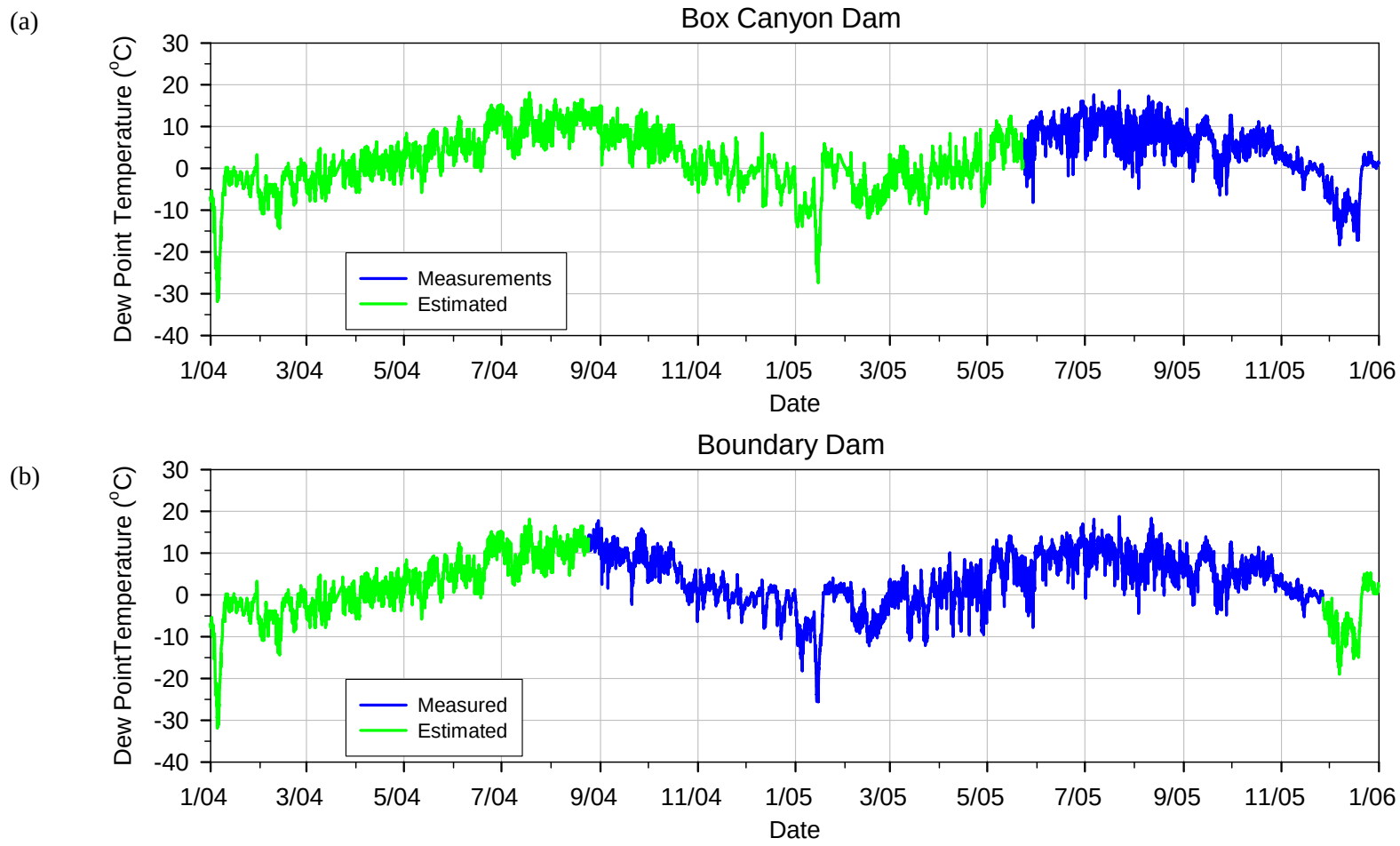
Figure 2.22

Dew Point Temperature Regressions between Sandpoint Airport and Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington



Note: (1) The regression analyses with the dew point temperature data at the Sandpoint station were used to estimate dew point temperatures at Boundary and Box Canyon Dam locations when data were missing.

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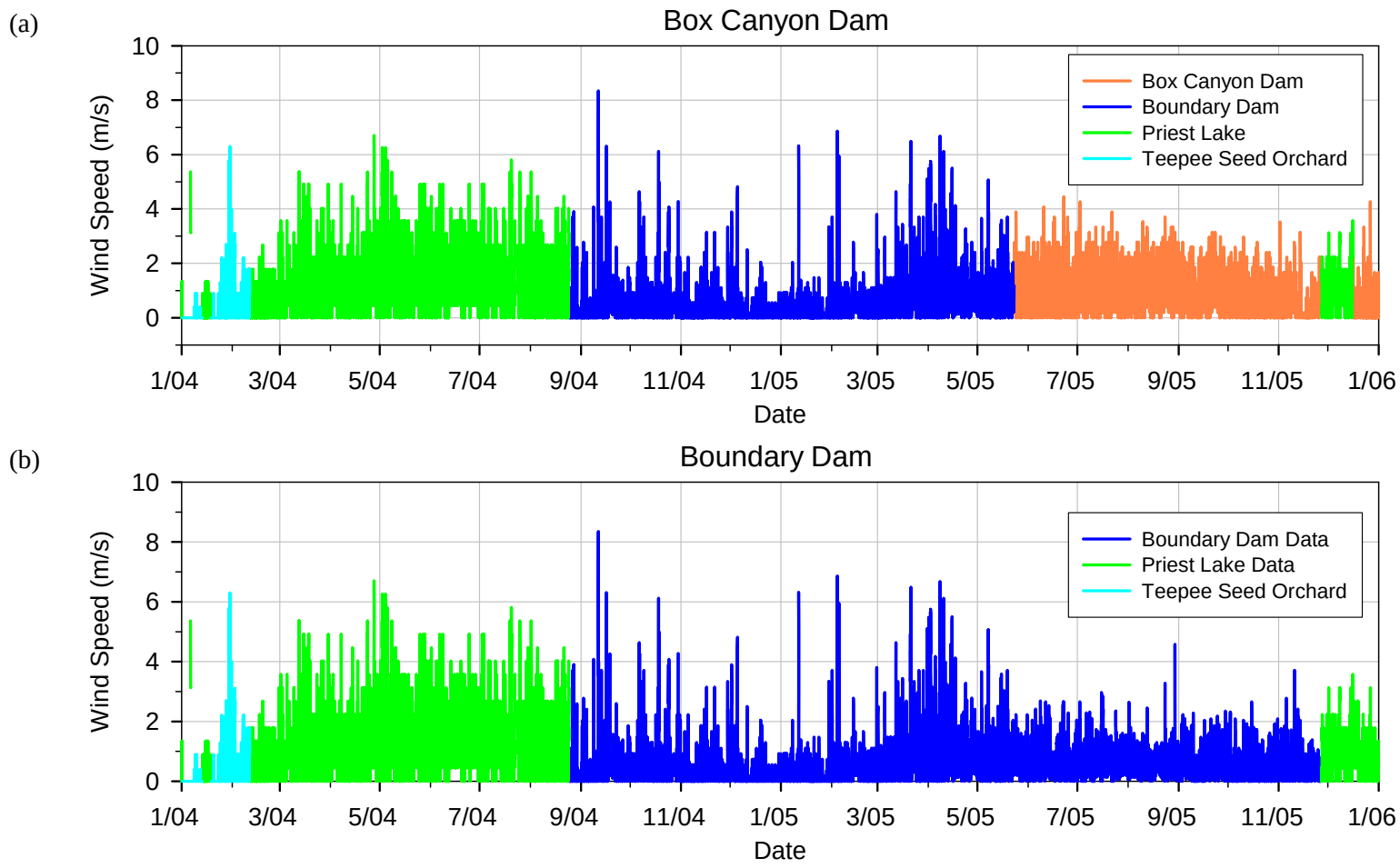
Figure 2.23

Measured and Estimated Dew Point Temperatures at Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington



Note: (1) The measured wind speed data from other stations were used directly when data were missing.

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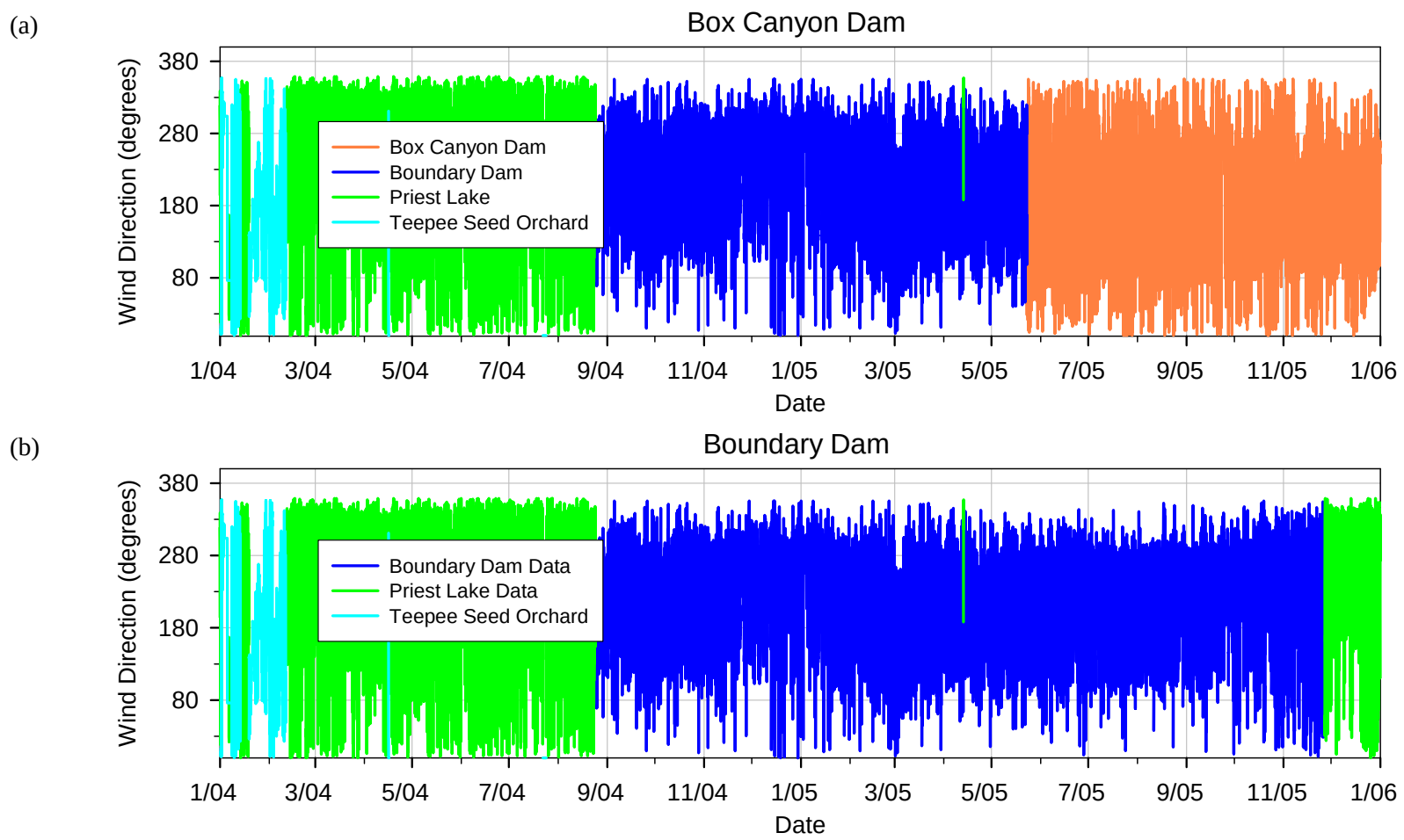
Figure 2.24

Measured and Estimated Wind Speed at Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington



Note: (1) The measured data from other stations were used directly when data were missing.

Figure 2.25

Measured and Estimated Wind Direction at Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington

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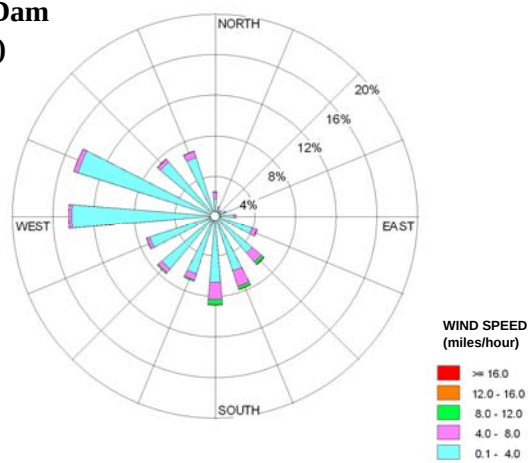
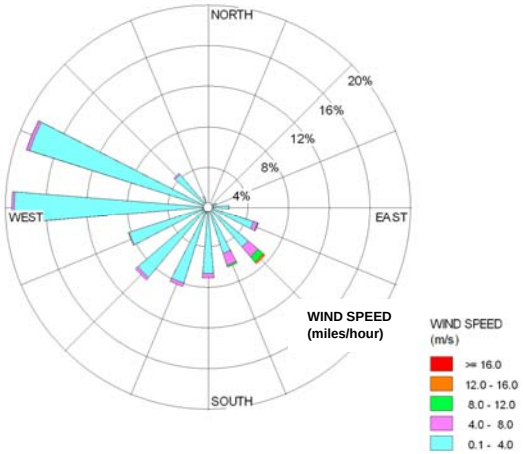
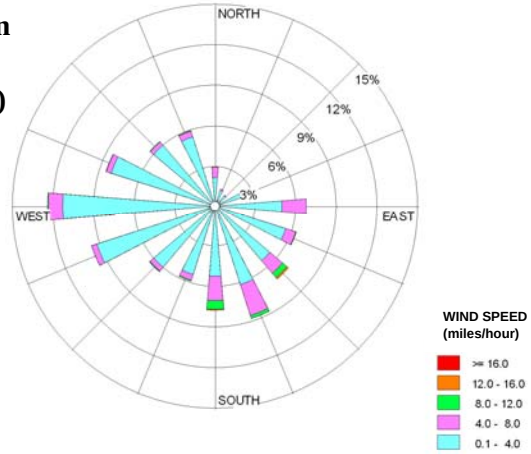
(a) **Boundary Dam (Combined)**



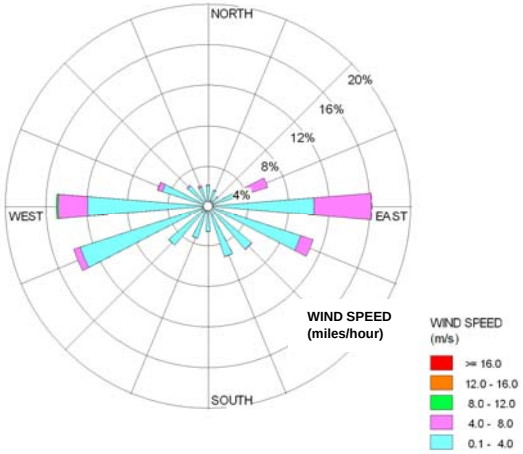
Boundary Dam (Only)



(b) **Box Canyon Dam (Combined)**



Box Canyon Dam (Only)



Note: (1) The winds are indicated as the direction from which they blow.
(2) The combined data included the measured data from other stations as shown in Figures 2.24 and 2.25.
(3) The zero values were removed from the plotting data sets.

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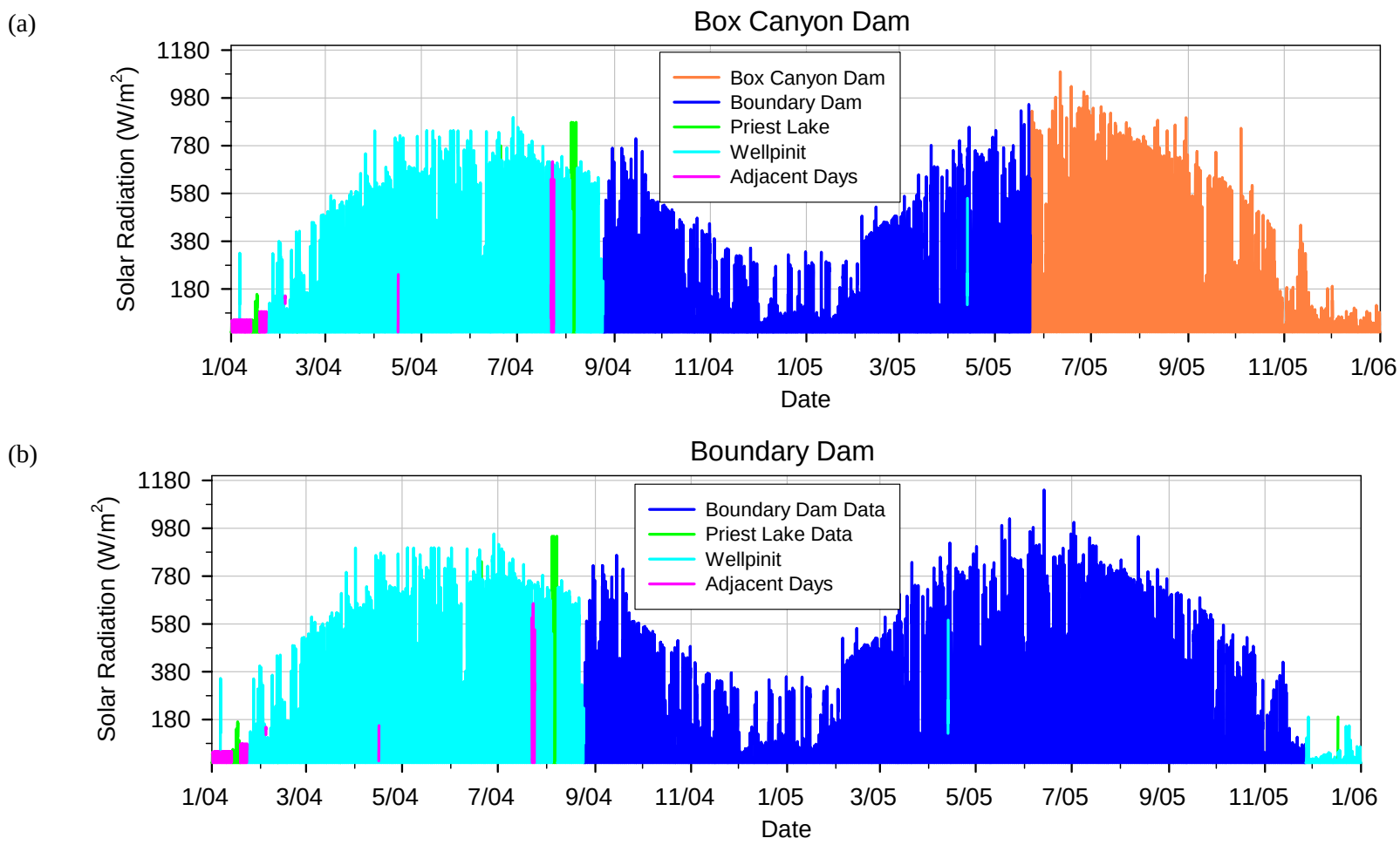
Figure 2.26

Wind Rose Plots at Boundary and Box Canyon Dams
Seattle City Light
Seattle, Washington



Note: (1) The measured solar radiation data from other stations were plotted directly when data were missing.
(2) The data specified as "adjacent days" were used if no data were available from an any of the stations examined.

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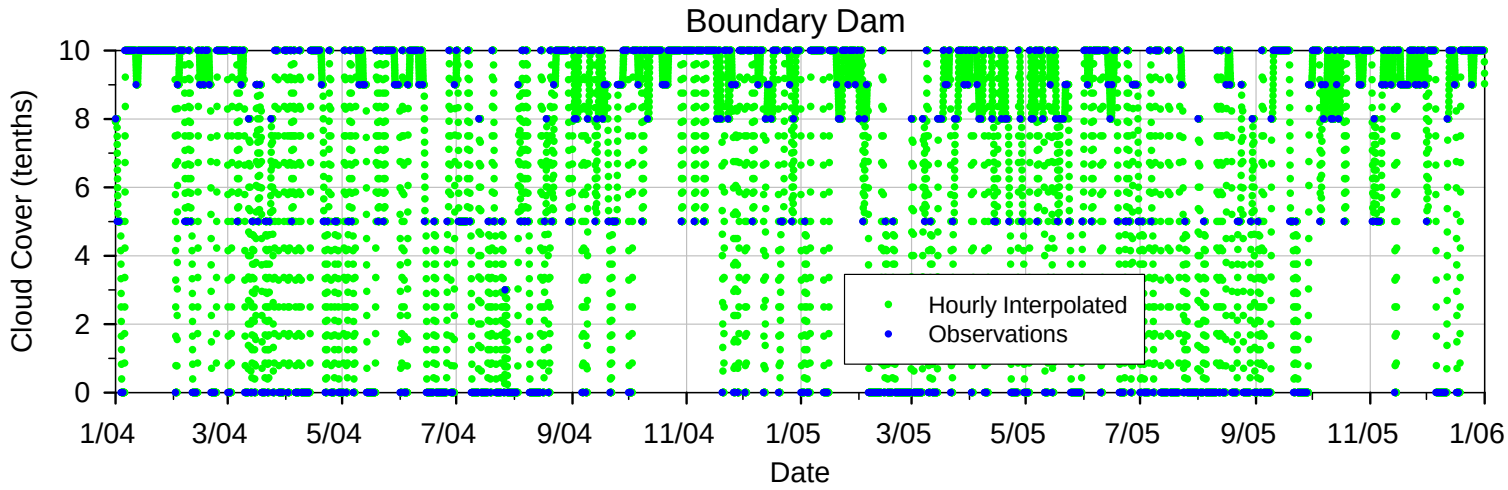
Figure 2.27

Measured and Estimated Solar Radiation at Boundary and Box Canyon Dams

Seattle City Light
Seattle, Washington



Note: (1) The cloud cover measurements were made daily at 8 am. The data were interpolated to hourly intervals.
(2) For the observed data, the following conversion was made: clear = 0, partly cloudy = 5, mostly cloudy = 8, overcast = 9, cloudy, fog, precipitation = 10

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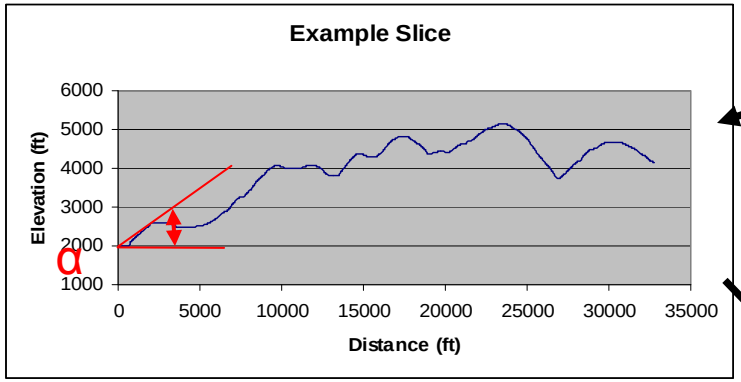
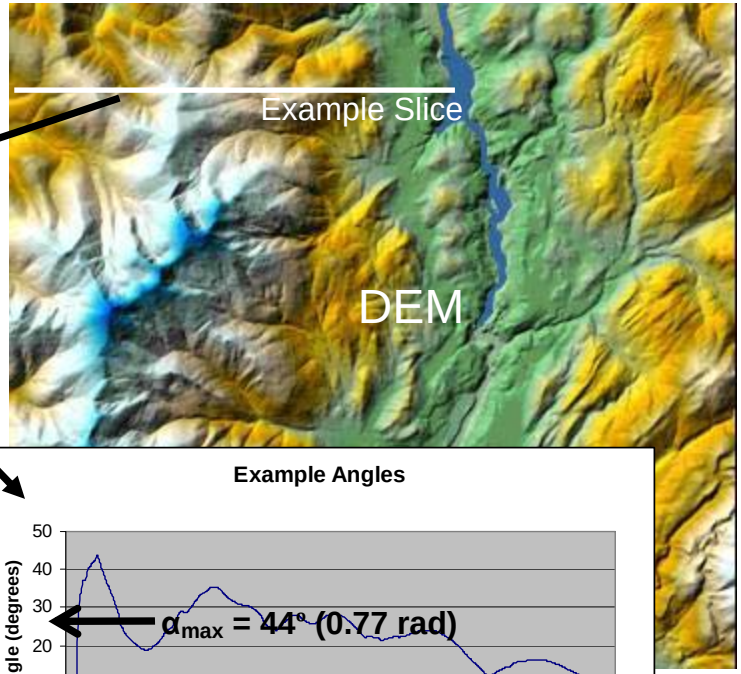
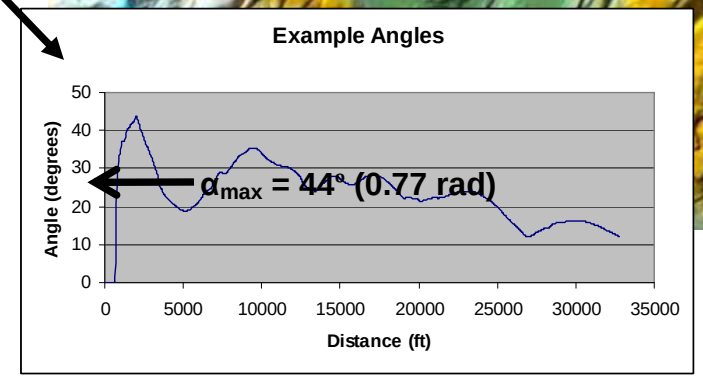
Figure 2.28

Measured and Estimated Cloud Cover at Boundary Dam
Seattle City Light
Seattle, Washington







- Slices taken from center of grid segment at 20º angles
- Maximum angle used in shade simulations

$$S_f = f\left(A_o, A_z, \theta_s, \alpha_t, \alpha_v, d_{cl}, o_v\right)$$

•A_o and A_z are the solar altitude and azimuth,
•θ_s = segment orientation
•α_t = topographic angles,
•d_{cl} = distance of vegetation from the centerline
•o_v = opaqueness of the vegetation

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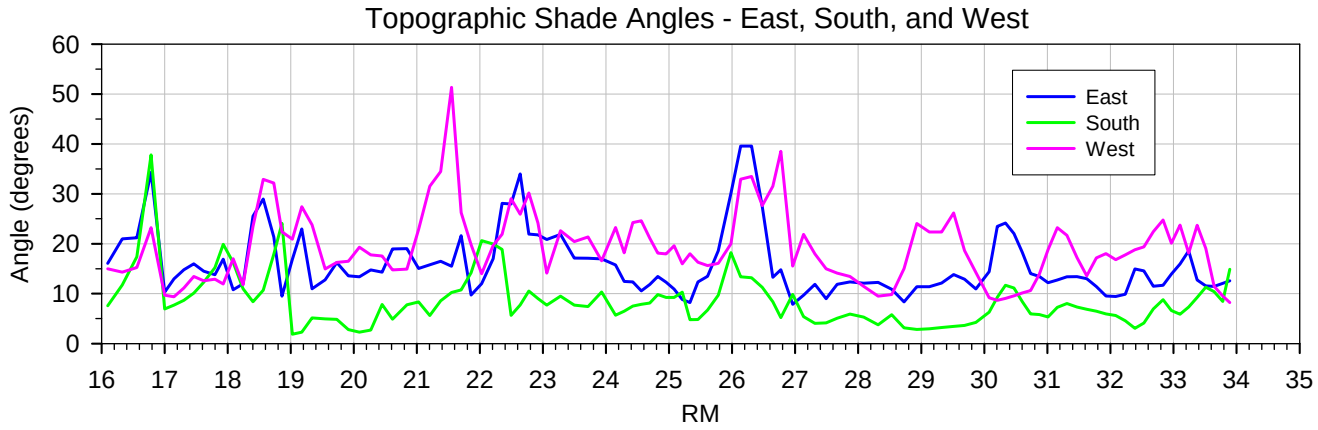
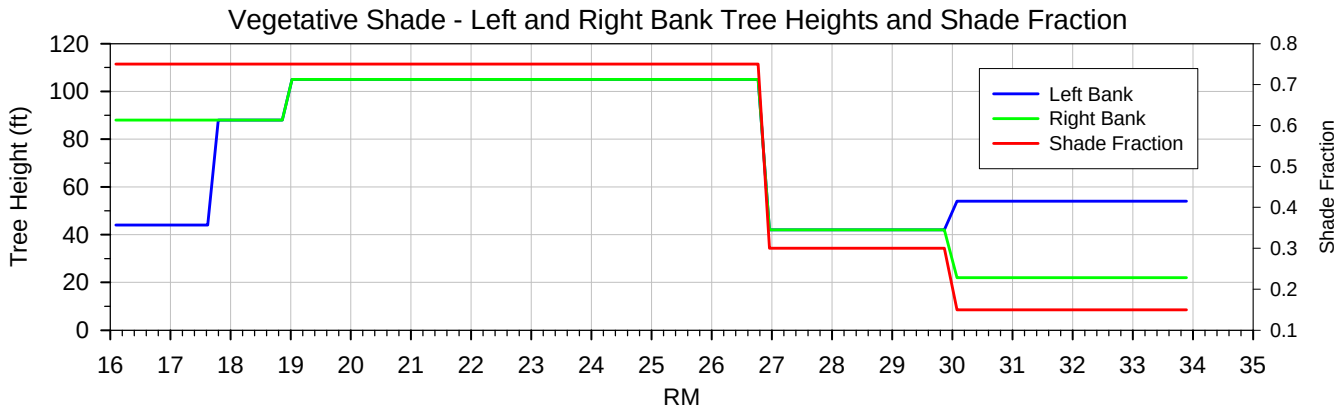
Figure 2.29
Example Calculation of Topographic Shade Angles
Seattle City Light
Seattle, Washington

(a)



(b)



Note: (1) The topographic shade angles are shown from only the easterly, southerly, and westerly directions. These correspond to 100º, 180º, and 260º.
(2) The vegetative shade data were provided by Picket (2006).
(3) The shade fraction reflects the leaf cover and varies from 0 to 1, with a value of 1 being complete shade.

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Figure 2.30
Computed Shade Angles
Seattle City Light
Seattle, Washington

3.0 Model Development and Calibration

3.1 Introduction

Following the completion of the review of data described in Section 2.0, the data were incorporated into the model CE-QUAL-W2. This section describes the development of the hydrodynamic and temperature model of Boundary Reservoir including the model setup and the calibration. The initial model development and calibration was for the existing condition. The existing condition is defined by the presence of Boundary Dam and other dams upstream (Albeni Falls and Box Canyon Dams), current conditions for the four tributaries identified in Table 2.2, and NPDES-permitted discharges listed in Table 2.3.

The period for model calibration was the 2004 and 2005 calendar years. As discussed in Sections 2.5 through 2.7, there were gaps in the measured data over some portion of the two years of analysis, and estimates of some of the missing data were made via regression analysis or through direct use of data from nearby stations. Complete data sets were required for input to the model CE-QUAL-W2 as boundary conditions of flow and temperature or as meteorological forcing. The temperature data within the Boundary Reservoir were used in the model calibration for comparison to the model's results.

3.2 Model Setup

The model setup involved creating the model grid, specifying the relevant physical characteristics of Boundary Dam, and defining the input parameters and boundary conditions. This section describes the setup of the model CE-QUAL-W2 for the Boundary Reservoir.

3.2.1 Model Description

The model CE-QUAL-W2 is a hydrodynamic and water quality model developed primarily for the analysis of reservoirs. The model uses the finite-difference method for solving the hydrodynamic and transport equations as a two-dimensional system in which the equations are averaged across the width of the reservoir. This results in a model grid that produces results by depth (layers) and along the length of the reservoir (segments). The model includes the ability to define several types of structures that alter the hydrodynamics of the system. These structures can include spillways, pipes, gates, and pumps.

The model is capable of simulating a wide variety of water quality constituents for eutrophication analyses, including temperature. For the purpose of the study of Boundary Reservoir, the only constituent simulated was temperature.

Although the model was originally developed for application to reservoirs, the model also has the capability for the analysis of rivers. This was not used in the model calibration phase of the existing conditions, but it becomes important for modeling the Pend Oreille River for the No Impoundment Condition or the Natural Condition, both without Boundary Dam.

For both the hydrodynamic and temperature simulations, boundary conditions, tributaries, and meteorological data were required for input. In the case of Boundary Reservoir, these included Box Canyon Dam flow release, tributary inflows, point source inflows, temperatures from all the releases and inflows, and available meteorological data.

3.2.2 Model Grid

The horizontal layout of the grid (model segmentation) was based on the digital orthophotographs (DOP) of Boundary Reservoir (Zablotney 2006). The horizontal coordinate system was US State Plane Zone Washington North (4601), NAD83, US Survey Feet. A grid for the model was overlaid on the DOPs to create the model segmentation shown in Figure 3.1. Also shown in the figure are the locations of the tributaries, the point source dischargers (NPDES permitees), the dams, and the downstream boundary.

The length of the segments was determined as the distance between the center points on the upstream and downstream faces of each segment. The sum of these provides the length along the centerline of Boundary Reservoir.

The bathymetry data plotted in Figure 2.3 and the segmentation data in Figure 3.1 were combined to estimate the average widths for each segment. The volume for each segment was computed at 0.328-ft (1-m) intervals, and dividing the volumes by the length of the segment and a Δz of 1 m gave the average width for that layer.

The geometry input data are given in the Appendix (Table A.3). The model was divided into four branches/water bodies to reflect the different hydrodynamic characteristics of each.

3.2.3 Model Parameters

In addition to the geometry data discussed above, there were other model inputs that defined the hydrodynamic and thermal characteristics of the Boundary Reservoir system. The Appendix (Table A.2) presents the hydrodynamic and temperature modeling parameters. The listed parameters primarily influence the turbulent mixing and heat exchange processes of Boundary Reservoir. For the Boundary Reservoir (and other deep water bodies), the bed friction coefficient had little influence on the velocity or depth of the reservoir, though in river systems (shallow water bodies) it can influence the hydrodynamics of the system.

The model inputs for the Boundary Dam and its powerhouse intakes are specified in Table A.3. Use of the intake structure in the model required input of the release flows, which are shown in Figure 2.5b. While other flow structures exist on Boundary Dam (the sluice, spillway, and skimmer gates), no or insignificant discharge occurred from these structures and so they were not included in the model. (However, they can be included as needed for future model runs.)

3.2.4 Model Boundary Conditions

The inflows to the Boundary Reservoir must be input to the model, CE-QUAL-W2. For the Boundary Reservoir, these included the upstream release from Box Canyon Dam, tributary discharges, and point source discharges, which are shown in Figure 2.5.

In addition to the inflows entering the Boundary Reservoir system, the temperatures associated with the inflows were specified. While the measured temperatures of the Box Canyon Dam release are shown in Figure 2.9a, they did not cover the whole simulation period of 2004 and 2005. Consequently, temperatures for the missing period prior to July 2004 were estimated as being the same as the season of the following year (Figure 3.2). The missing temperatures for winter 2005 were also estimated from the same season of the previous year.

The downstream model boundary, below Boundary Dam and at the International Boundary, was influenced by water levels behind the Seven-Mile Dam in British Columbia, Canada. Because the operational conditions of that dam were not known, the model's downstream boundary was specified to be the same as the measured water surface elevation downstream of Boundary Dam in the tailrace.

Distributed inflows into Boundary Reservoir are discussed in Section 3.3.1.

3.2.5 Meteorological Conditions

In addition to the boundary conditions, the meteorological conditions were required for the simulation of Boundary Reservoir temperatures. The meteorological input data included air temperature, dew point temperature, wind speed, wind direction, cloud cover, and solar radiation. These were examined in Section 2.7.

3.3 Model Calibration

Model calibration is conducted by comparing model predictions with measured data from within the Boundary Reservoir. Adjustments to model inputs were made to reduce the discrepancy between the predicted and measured values. For the Boundary Reservoir, model calibration was made to two sets of measured data: the water surface elevations and the water temperatures. The first set was used for the hydrodynamic model via a water balance; while the second set was used for the temperature model after the water balance was completed.

3.3.1 Water Balance

The water surface elevations from the Boundary Reservoir model were compared to measured data at three locations: downstream of Box Canyon Dam, upstream of Boundary Dam, and downstream of Boundary Dam. Iterative analyses were made between the predicted and measurement water levels, and for each new iteration, a new water balance flow was added to the model to account for the differences in water surface elevations. The water balance adds or removes water to bring the predicted and measured water levels into balance. The Boundary Reservoir has a peaking-mode operation that produces relatively large changes in water level during each day. To smooth out the water balance, it was done at 24-hr intervals. Daily comparisons reduced the large variations that otherwise occur when using more frequent analysis intervals.

The balance flows were applied as a distributed flow into the section of the model between Dead Man's Eddy and Boundary Dam (water body 3). The final water balance flows are shown in Figure 3.3d and are compared with the Box Canyon Dam release flows. The mean balance flow for the 2004 through 2005 simulation period was -359 cfs, indicating there was a net loss of flow from the system. The mean balance flow was 1.9 % of the Pend Oreille river flow. The temperature of the balance flow was specified as the same as that from the Box Canyon Dam release. Because there is a net outflow, the balance flow had little influence on the temperatures of Boundary Reservoir.

The final water levels at the three stations are shown in Figure 3.3a, b, and c. The agreement between the model predicted water surface elevations and measured values is good. Also, the model also has the correct daily trends of varying water level due to peaking mode operations at Boundary Dam.

3.3.2 Temperature Calibration

The parameters and the values used for the temperature calibration are given in Table A.4. Because only temperature was being simulated, the extinction coefficient for water was set to a value larger than the default to account for light-absorbing solids in the water column, such as inorganic sediment and phytoplankton. In addition, a small change to the elevation specification (ELBOT) of the branch upstream of Metaline Falls was made. Adjustment of the elevation variable provided a way to adjust the layer that the water surface occupied and hence the top width of the reservoir for surface heat exchange.

The temperature time series from the calibrated model are compared with the measured time series data in Figures 3.4 through 3.7. The predicted temperature values largely fall on top of the measured at all the stations and depths. Like the measured temperature, the model results show little daily variation in temperature.

The temperature profiles from the calibrated model are plotted with the measured profiles in Figures 3.8 through 3.13. These show that the model predicted the temperature profiles well, with the model results showing little stratification in the water column during the summer and fall periods of 2004 and 2005. The Everett Creek (V5) and Boundary Reservoir (V6) stations did show some temperature gradients over depth, but the temperature range was small. The temperature profiles from the model during the fall of 2005 were slightly cooler than the measured temperatures. Because the model produced predicted temperatures that matched the data well during previous period, this likely reflects the estimation of many of the meteorological inputs, and improvements in those would be expected to improve the model's temperature predictions at that time.

An error analysis was conducted and used to determine the acceptability of model results. These include the mean error (ME), the absolute mean error (AME), and the root mean square error (RMS). The ME is an indication of the bias of the model: a negative ME indicates the model produces temperatures cooler than the measured temperatures and a positive ME indicates the opposite. Comparison of the AME and RMS errors indicates if there are large individual errors that skew the RMS error. This will cause the RMS to be larger than the AME. Three sets of data were analyzed: the temperature time series, the maximum daily temperature time series, and the temperature profiles. The errors from each of these analyses are shown in Tables 3.1, 3.2, and 3.3.

The overall ME for each analysis were within -0.2°C (Table 3.1). Because the values were negative, the model results were slightly cooler than the measured data. The errors for the maximum daily temperature (Table 3.2) were less than for the complete temperature time series (Table 3.1). This suggests the model is well calibrated for compliance evaluations with maximum temperatures. The model-predicted temperature profile data were also good but also had a slightly negative bias (negative ME) (Table 3.3).

The temperature time series analyses in Tables 3.1 and 3.2 have RMS errors that were greater than the AME, indicating that some individual errors were larger than average error. For the profile data (Table 3.3), the AME and RMS are closer which indicates that the errors were consistent.

Table 3.1. Calibration Error Analyses for Temperature Time Series in the Boundary Reservoir and Boundary Dam Tailrace

Station	Depth (ft)	ME (ºC)	AME (ºC)	RMS (ºC)	N
T2. Metaline Pool	3.28 (1 m)	-0.268	0.299	0.368	14,537
	10.49 (3.2 m)	-0.189	0.244	0.317	14,536
	17.17 (5.4 m)	-0.257	0.278	0.340	14,537
	24.94 (7.6 m)	-0.249	0.272	0.336	14,538
	32.15 (9.8 m)	-0.218	0.264	0.345	14,538
T6. Slate Pool	3.28 (1 m)	-0.155	0.306	0.397	21,081
	36.09 (11 m)	-0.172	0.291	0.369	21,081
	68.90 (21 m)	-0.179	0.281	0.376	21,080
	101.7 (31 m)	-0.258	0.278	0.356	20,931
T7. Boundary Intake	16.41 (5 m)	-0.110	0.304	0.381	26,719
	36.09 (11 m)	-0.204	0.301	0.373	33,865
	55.78 (17 m)	-0.102	0.234	0.303	34,624
	75.46 (23 m)	-0.136	0.235	0.310	34,626
	95.15 (29 m)	-0.113	0.168	0.212	19,071
T8. Boundary Dam Tailwater	-	-0.051	0.436	0.790	32,844
Overall Averages		-0.163	0.284	0.409	338,608

AME = Absolute mean error; ME = mean error; RMS = Root mean square error.

Table 3.2. Calibration Error Analyses for Maximum Daily Temperature Time Series in the Boundary Reservoir and Boundary Dam Tailrace

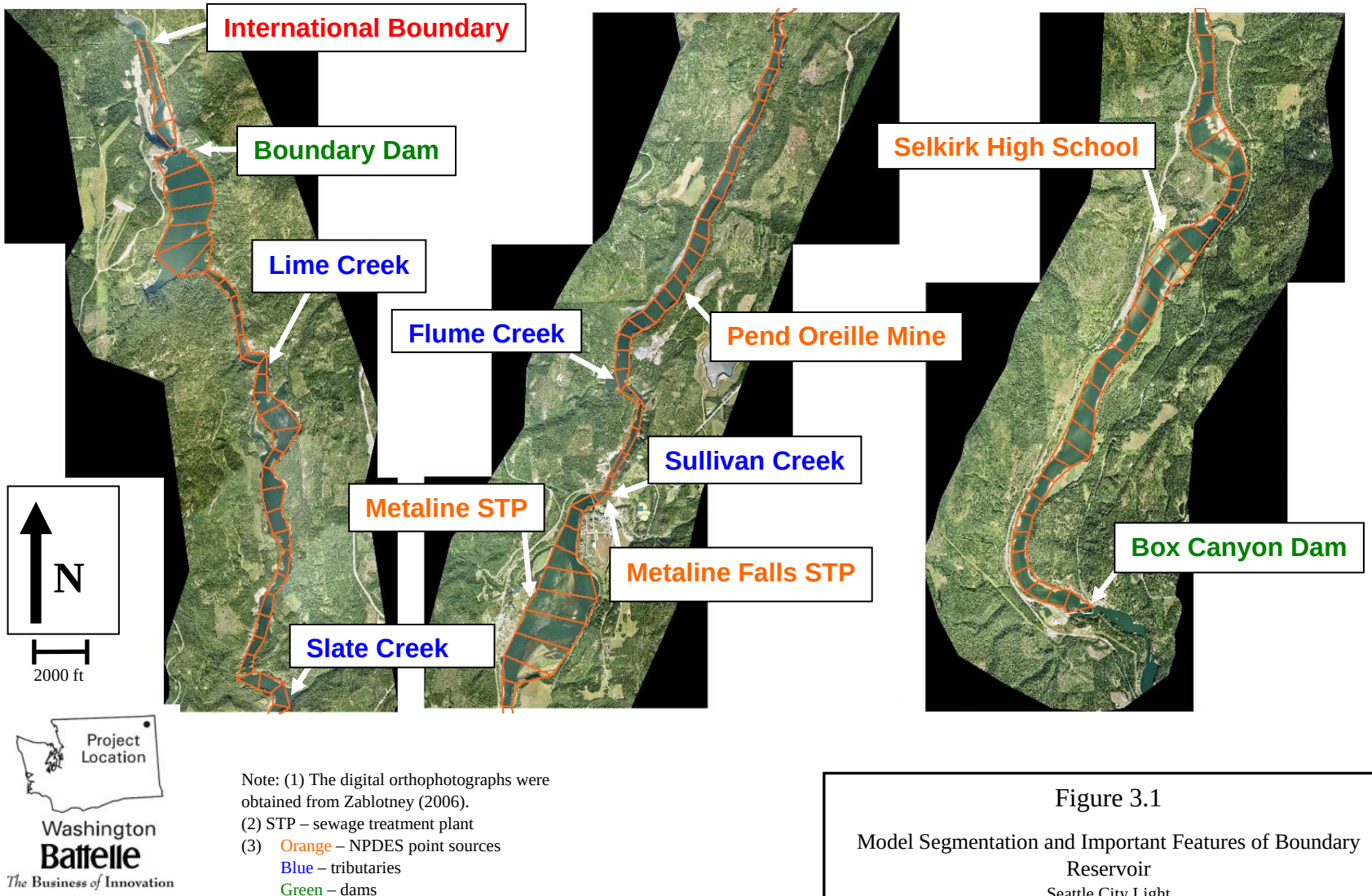
Station	Depth (ft)	ME (ºC)	AME (ºC)	RMS (ºC)	N
T2. Metaline Pool	3.28 (1 m)	-0.194	0.279	0.337	203
	10.49 (3.2 m)	-0.092	0.220	0.274	203
	17.17 (5.4 m)	-0.144	0.231	0.280	203
	24.94 (7.6 m)	-0.129	0.223	0.273	203
	32.15 (9.8 m)	-0.104	0.238	0.292	203
T6. Slate Pool	3.28 (1 m)	-0.126	0.298	0.395	295
	36.09 (11 m)	-0.074	0.259	0.327	295
	68.90 (21 m)	-0.095	0.254	0.329	295
	101.7 (31 m)	-0.226	0.252	0.322	293
T7. Boundary Intake	16.41 (5 m)	-0.168	0.342	0.436	424
	36.09 (11 m)	-0.022	0.311	0.381	203
	55.78 (17 m)	-0.082	0.224	0.290	481
	75.46 (23 m)	-0.117	0.214	0.291	481
	95.15 (29 m)	-0.096	0.146	0.184	265
T8. Boundary Dam Tailwater	-	-0.057	0.450	0.803	461
Overall Averages	-	-0.113	0.271	0.401	4,508

AME = Absolute mean error; ME = mean error; RMS = Root mean square error.

Table 3.3. Calibration Error Analyses for Temperature Profiles in the Boundary Reservoir.

Station	ME (ºC)	AME (ºC)	RMS (ºC)	N
V1. Wolf Creek	0.000	0.095	0.144	101
V2. Metaline Old	-0.074	0.122	0.190	114
V3. Pend Oreille Mine	-0.201	0.212	0.247	70
V4. Slate Creek	-0.075	0.228	0.249	99
V5. Everett Creek	-0.138	0.282	0.364	82
V6. Boundary Reservoir	-0.167	0.307	0.417	94
Overall Averages	-0.102	0.201	0.280	560

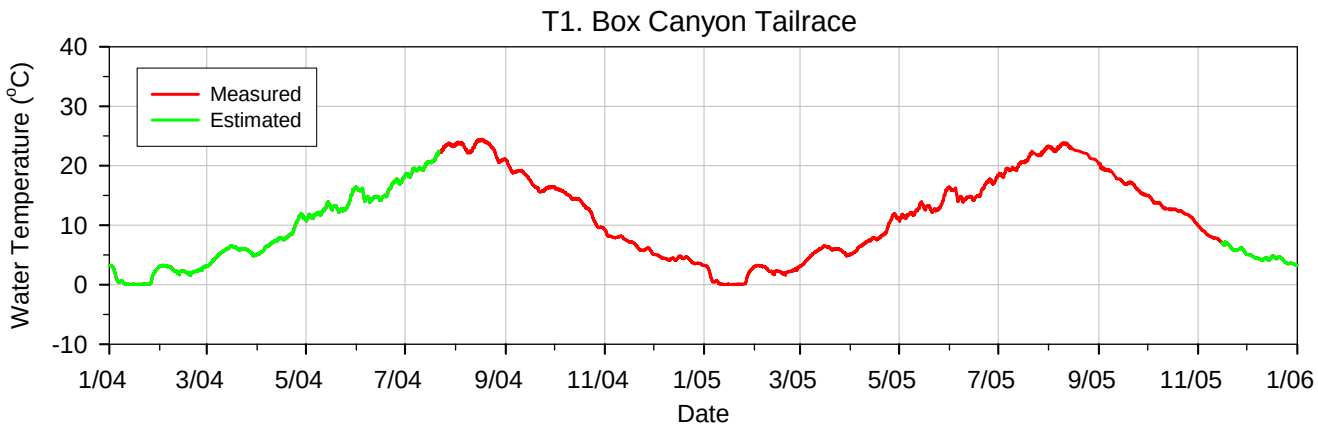
AME = Absolute mean error; ME = mean error; RMS = Root mean square error.



Note: (1) The digital orthophotographs were obtained from Zablotney (2006).
(2) STP – sewage treatment plant
(3) Orange – NPDES point sources
Blue – tributaries
Green – dams
Red – downstream boundary

Figure 3.1

Model Segmentation and Important Features of Boundary Reservoir
Seattle City Light
Seattle, Washington



Note: (1) The estimated temperature for the winter and spring 2004 were taken from the same seasons in 2005. The winter 2005 estimated temperatures were taken from the same season in 2004.

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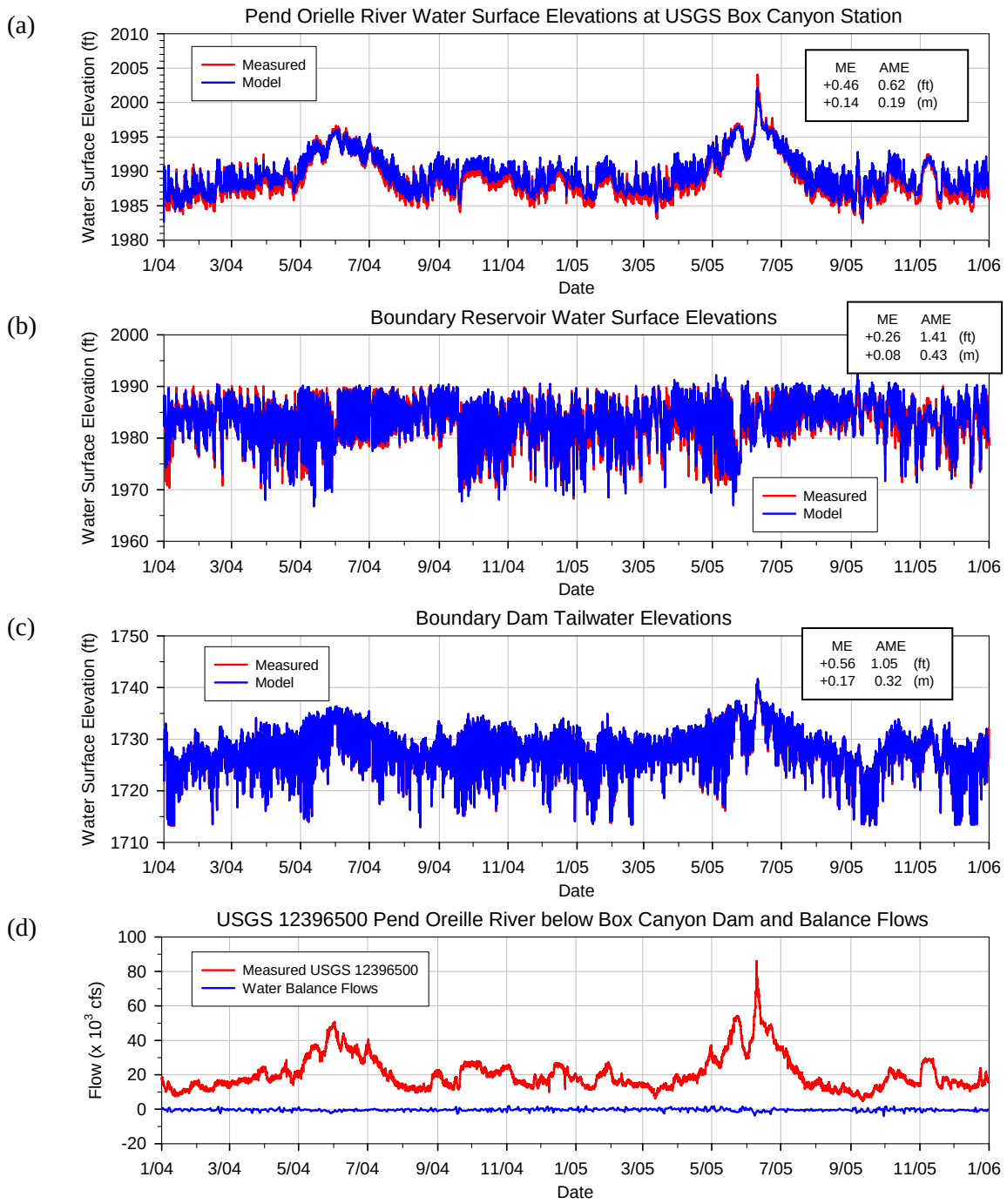
Figure 3.2
Box Canyon Dam Release Temperatures

Seattle City Light
Seattle, Washington



Note: (1) The water surface elevations from the model were achieved following completion of the water balance.
(2) ME – mean error, AME – absolute mean error.
(3) The mean water balance flow was -359 cfs for the 2004 and 2005 simulation period.

Figure 3.3
Water Surface Elevations and Water Balance Flows

Seattle City Light
Seattle, Washington

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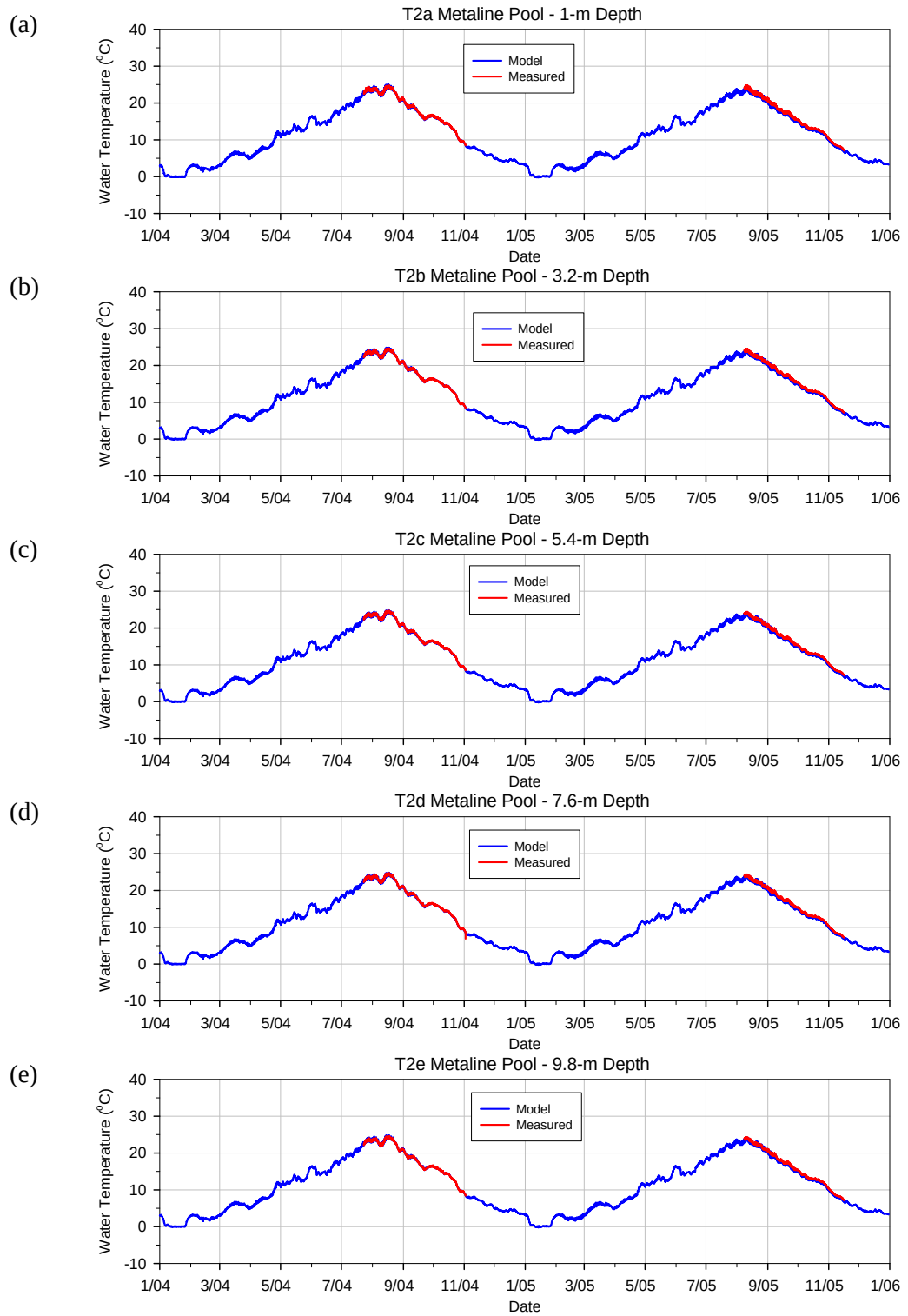

Figure 3.4

Model Calibration Results for Temperature at the Metaline Pool Station, T2

Seattle City Light
Seattle, Washington

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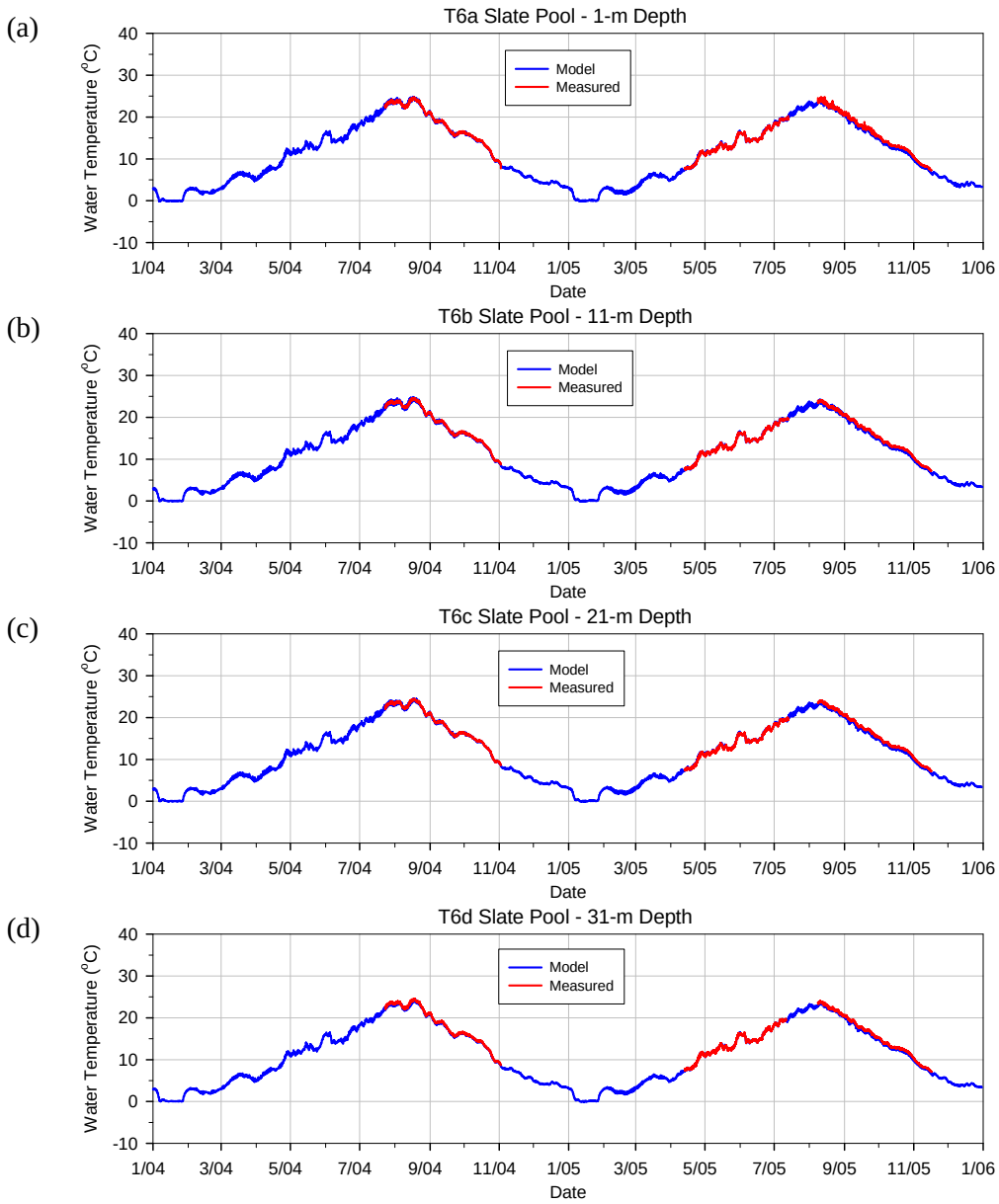

Figure 3.5
Model Calibration Results for Temperature at the Slate Pool Station, T6

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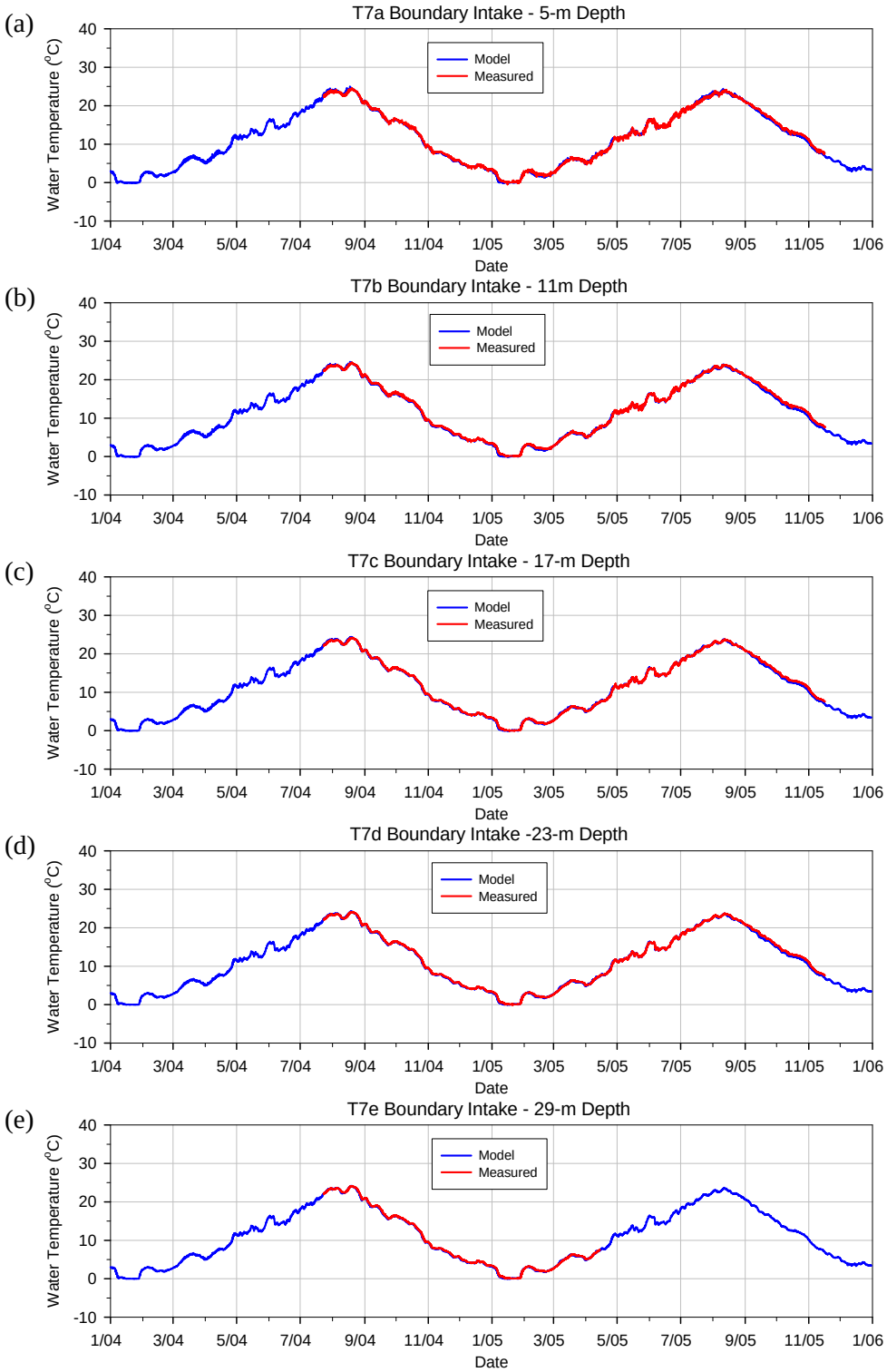

Figure 3.6

Model Calibration Results for Temperature at the Boundary Dam Intake Station, T7

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Seattle, Washington

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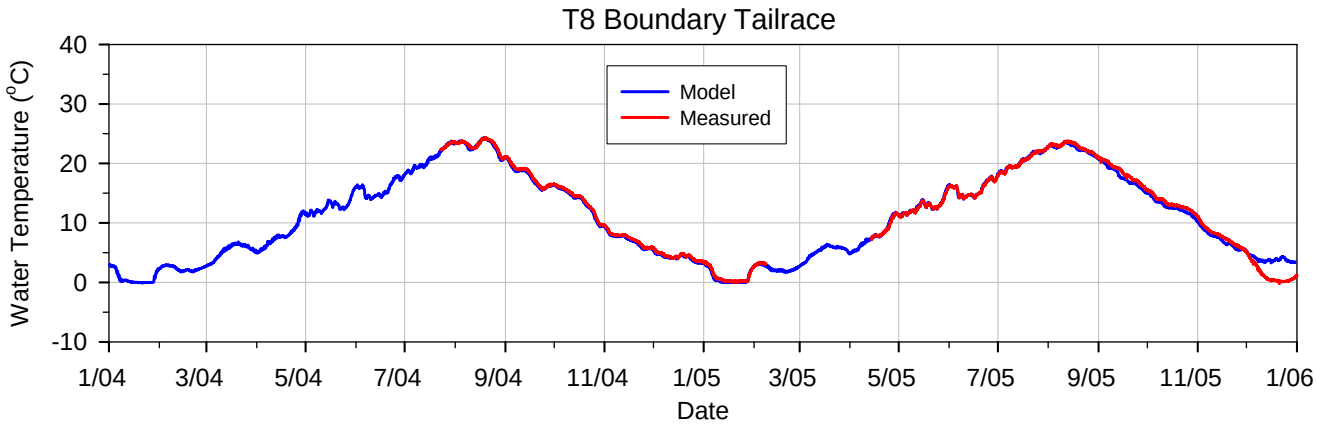

Figure 3.7
Model Calibration Results for Temperature at the Boundary Dam Tailrace Station, T8

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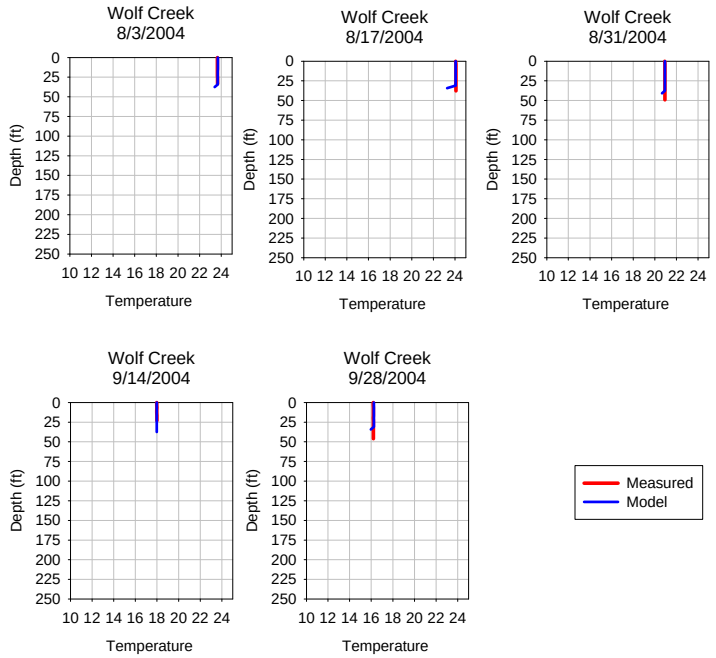

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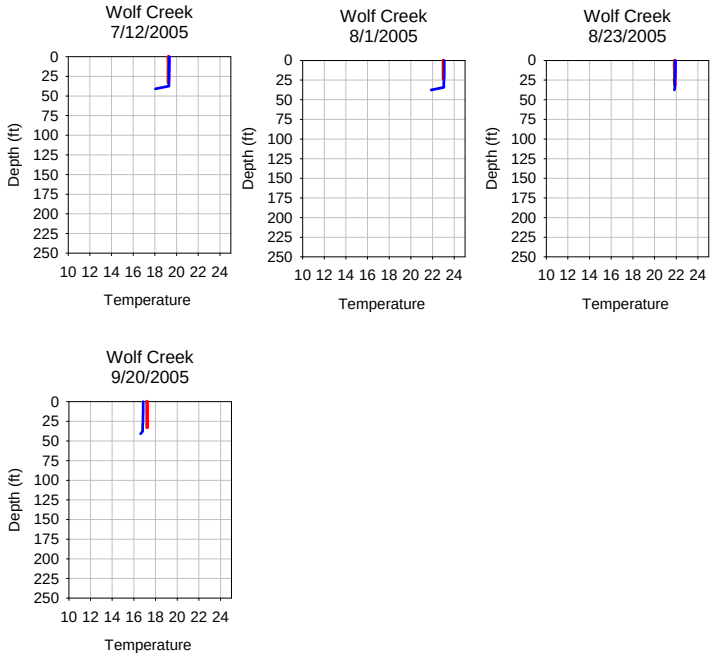

Figure 3.8
Model Calibration Results for Temperature in the Boundary Reservoir at the Wolf Creek Station, V1

Seattle City Light
Seattle, Washington

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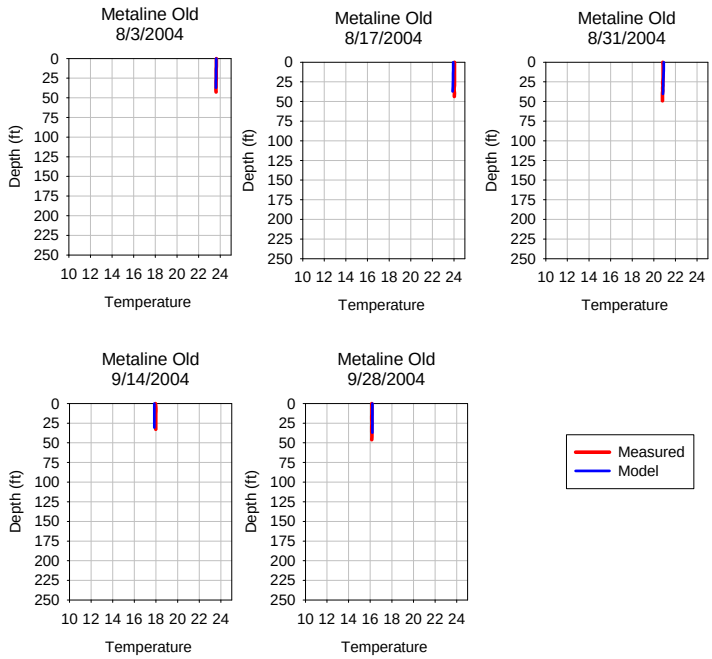
2004



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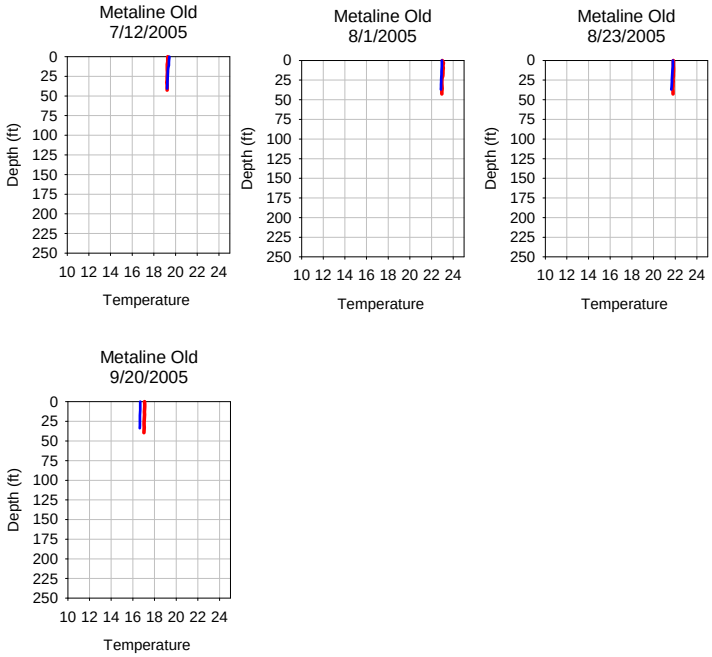

Figure 3.9
Model Calibration Results for Temperature in the Boundary Reservoir at the Metaline Old Station, V2

Seattle City Light
Seattle, Washington

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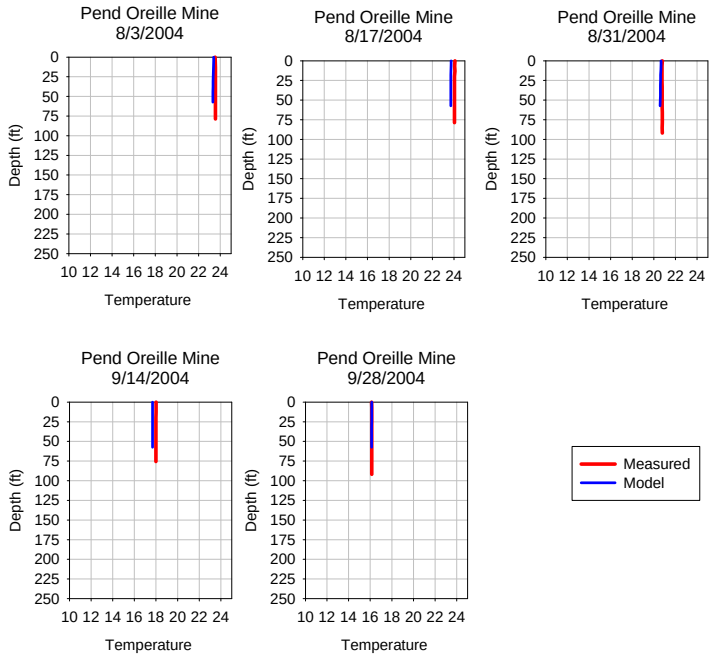
2004



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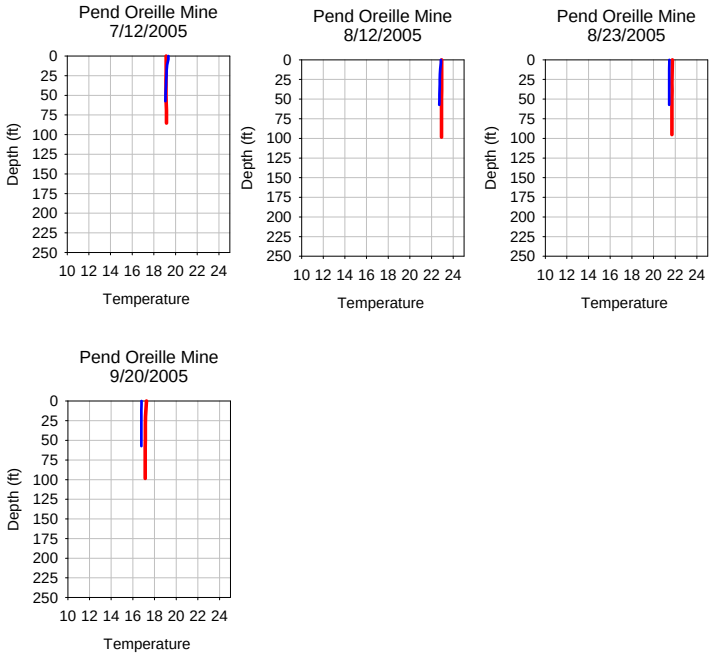

Figure 3.10
Model Calibration Results for Temperature in the Boundary Reservoir at the Pend Oreille Mine Station, V3

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Seattle, Washington

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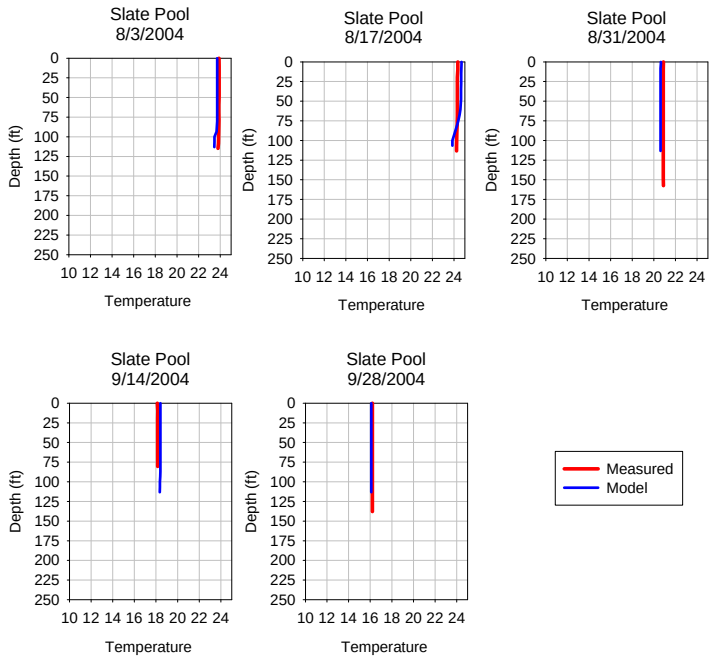

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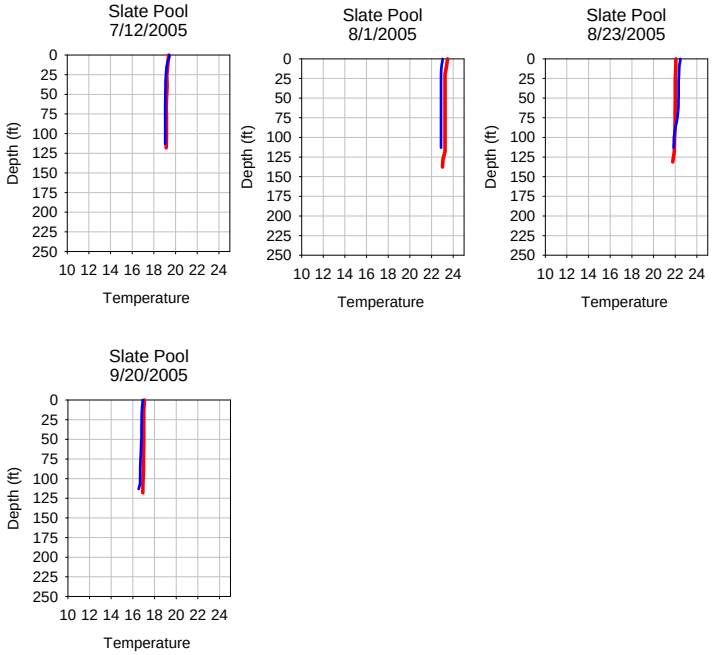

Figure 3.11
Model Calibration Results for Temperature in the Boundary Reservoir at the Slate Creek Station, V4

Seattle City Light
Seattle, Washington

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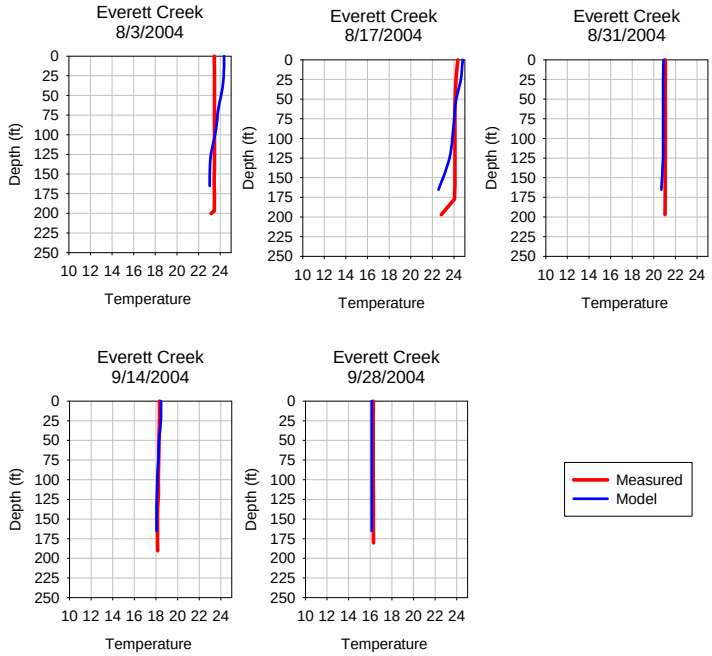

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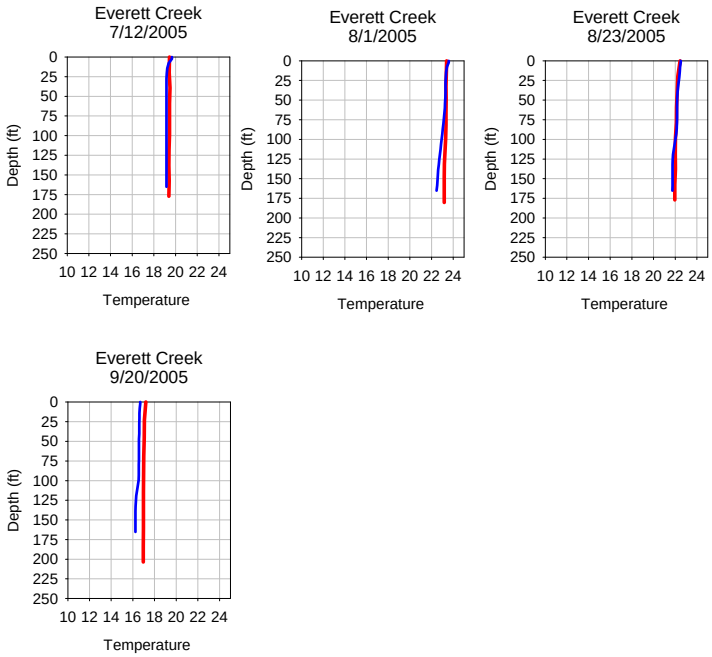

Figure 3.12
Model Calibration Results for Temperature in the Boundary Reservoir at the Everett Creek Station, V5

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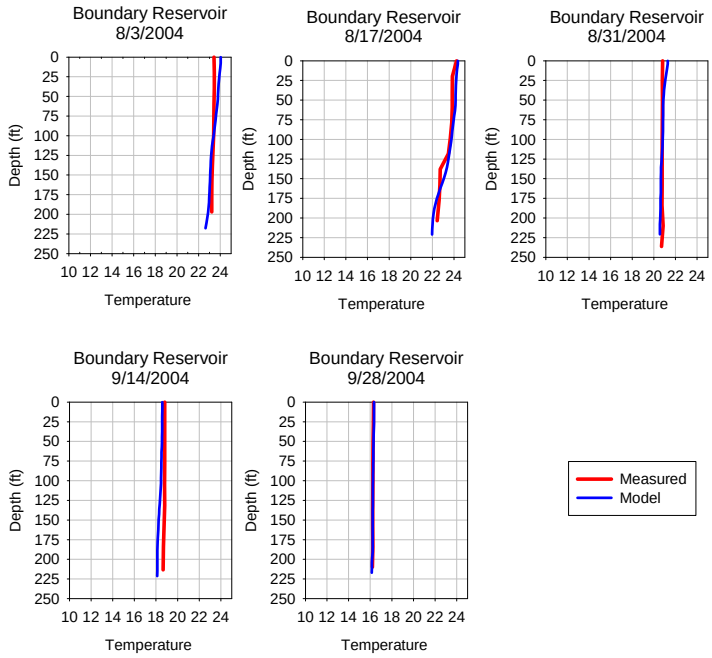

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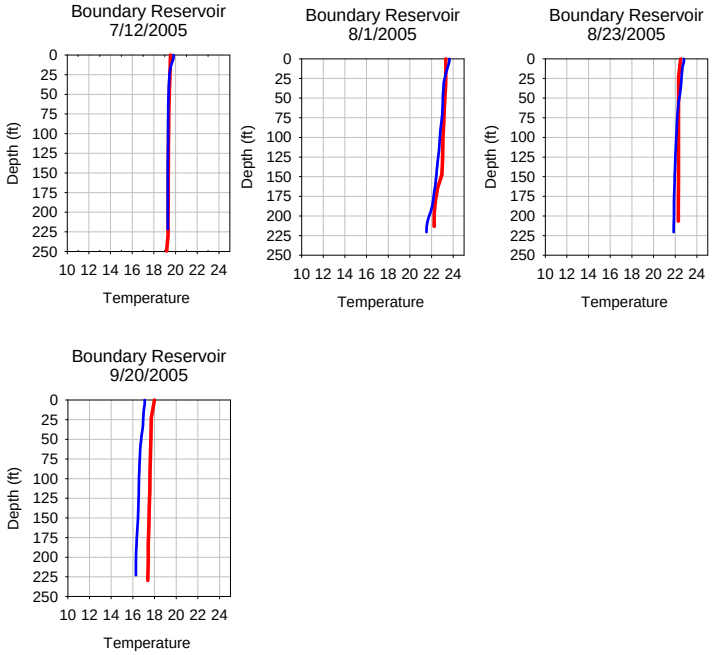

Figure 3.13
Model Calibration Results for Temperature in the Boundary Reservoir at the Boundary Reservoir Station, V6

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4.0 Summary

The Project and the Boundary Dam are located on the Pend Oreille River in northeastern Washington State. The Project is owned and operated by SCL. SCL is currently involved in the relicensing the Project with the FERC. The issuance of a license by FERC requires a Water Quality Certificate to be issued by the WDOE. To determine that water quality standards are being met, a temperature model was set up for the Project on the Pend Oreille River in northeastern Washington State.

The model CE-QUAL-W2 was used to conduct the temperature modeling analysis of Boundary Reservoir. The model is a two-dimensional horizontally averaged hydrodynamic and water quality model; however, for this study, the only water quality constituent analyzed was temperature.

The model was set up using newly collected bathymetry data combined with a cross-section data from a previous flood study. Project flows for the upstream Box Canyon Dam and Boundary Dam were provided by SCL and the tributary flows were provided by the USGS and WDOE. The release flows from the Box Canyon Dam exhibited little daily variation in flow, while the release flows from the Boundary Dam had large daily-flow variations because its peaking-mode operations. Temperature data of the inflows and within the Boundary Reservoir were collected for the study. The temperatures at all the stations showed little daily variation due to the large flow rate and short hydraulic residence time of the Boundary Reservoir and the deep canyon through which it flows. Meteorological data were from the Box Canyon Dam and Boundary Dam sites. When meteorological data were missing, they were supplemented with data from nearby meteorological stations.

After completion of the model setup, a flow balance was made in order to match model-predicted water surface elevations with observation in Boundary Reservoir. Then the model was calibrated to the measured temperatures within the Boundary Reservoir. The results from the temperature calibration matched the measured data well, with the ME within -0.2°C, and the AME within 0.3°C, and the RMS error around 0.4°C. With the completion of model calibration for temperature, the model is available for conducting additional analyses of the Boundary Reservoir system.

5.0 References

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Appendix

Tables

Table 0.1. Geometry Inputs

Geometry Data		Inputs
Number of water bodies		4
Number of branches		4
Elevation of downstream segment of branch (ELBOT):	Branch 1 Branch 2 Branch 3 Branch 4	1944.16 ft (592.55 m) 1845.73 ft (562.55 m) 1678.40 ft (511.55 m) 1654.61.ft (504.30 m)
Layer thickness		6.56 ft (2 m)
Segment lengths	Average Range	870-ft (265 m) 590 to 1,220-ft (180 to 373-m)
Segment widths	Average Range	694-ft (212-m) 227 to 3,061-ft (69 to 933-m)

Table 0.2. CE-QUAL-W2 Model Parameters for Hydrodynamics and Temperature Simulations

Parameter	Default Value[b]	Calibration Value (Existing Condition)
Longitudinal eddy viscosity (AX) (m^2 sec^{-1})	1.0	1.0
Longitudinal eddy diffusivity (DX) (m^2 sec^{-1})	1.0	1.0
Manning's friction factor	-	0.04[a]
Maximum vertical eddy viscosity (AZMAX) (m^2 sec^{-1})	1.0	1.0
Coefficient of bottom heat exchange (CBHE) (W m^{-2} sec^{-1})	0.3	7E-08
Fraction of radiant heat absorbed by the bed that is returned to the water column (TSEDF)	1.0	1.0
Heat exchange coefficients AFW BFW CFW	 9.2 0.46 2.0	 9.2 0.46 2.0
Wind speed measurement height (WINDH) (m)	-	2.0
Wind sheltering coefficient (WSC)	0.5 – 0.9 mountainous terrain[b] 1.0 – open terrain	1.0

(a) Manning's friction varies by waterbody.
(b) Cole and Wells (2006)

Table 0.3. Structural Specifications for Boundary Dam

Boundary Dam Powerhouse Structural Parameters	
Selective withdrawal range	Top layer = 2 Bottom layer = 49
Sink type	Point
Centerline elevation	1903 ft (580.03 m)

Table 0.4. CE-QUAL-W2 Model Coefficients that Affect Temperature

Coefficients	**Default Value**[a]	**Calibrated Value**
Longitudinal eddy viscosity (AX) (m^2 sec^{-1})	1.0	1.0
Longitudinal eddy diffusivity (DX) (m^2 sec^{-1})	1.0	1.0
Manning's friction factor	-	0.04
Wind sheltering coefficient (WSC)	-	1.0
Solar radiation absorbed in surface layer (BETA)	0.45	0.45
Extinction coefficient in pure water (EXH2O) (m^{-1})	0.45	0.25

(a) Cole and Wells (2006)