U.S. Army Corps of Engineers
Walla Walla District

Long-term, One-dimensional Simulation of Lower Snake River Temperatures for Current and Unimpounded Conditions

Final Report

W.A. Perkins
M. C. Richmond

February 2001

Prepared by: Pacific Northwest National Laboratory
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Richland, WA 99352

Pacific Northwest National Laboratory
Operated by Battelle for the
U.S. Department of Energy

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Summary

The objective of the study was to compare water temperatures in the Lower Snake River for current (impounded) and unimpounded conditions using a mathematical model of the river system. A long-term analysis was performed using the MASS1 one-dimensional (1D) hydrodynamic and water quality model. The analysis used historical flows and meteorological conditions for a 35-year period spanning between 1960 and 1995. Frequency analysis was performed on the model results to calculate river temperatures at various time exceedance levels. Results were also analyzed to compute the time when, during the year, water temperatures rose above or fell below various temperature levels.

The long-term analysis showed that the primary difference between the current and unimpounded river scenarios is that the reservoirs decrease the water temperature variability. The reservoirs also create a thermal inertia effect which tends to keep water cooler later into the spring and warmer later into the fall compared to the unimpounded river condition. Given the uncertainties in the simulation model, inflow temperatures, and meteorological conditions the results show only relatively small differences between current and unimpounded absolute river temperatures.

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1 Introduction

Breaching or removal of the lock and dam projects on the Lower Snake River is one option being considered by the Pacific Northwest region to aid in the recovery of endangered salmon. The Lower Snake River Feasibility Study, being conducted by the Walla Walla District of the U.S. Army Corps of Engineers, is performing an extensive investigation of this option.

Breaching or removing the projects would return the Lower Snake River to a unimpounded, free-flowing condition. However, total river flow rate or discharge would still be subject to some control from upstream projects. In addition, the reach from Ice Harbor Dam to the mouth would be affected by forebay elevations at McNary Dam and Columbia River discharge. Hydraulic conditions through the Lower Snake River would then be a function of local channel morphology and flow rate; these conditions are the subject of a companion report by Richmond et al. (1999).

Thermal conditions are also significant in determining habitat suitability. Water temperature is a key physical quantity that affects the time of smolt emergence and predator dynamics, among many other components of the river ecosystem. An improved understanding of the differences in thermal regimes between the current (impounded) and unimpounded river conditions is an important element of the Feasibility Study.

The objective of the work reported here was to compare water temperatures in the Lower Snake River for current and unimpounded conditions using a mathematical model of the river system. A long-term analysis was performed using the MASS1 (Modular Aquatic Simulation System 1D) one-dimensional hydrodynamic and water quality model (See Richmond et al., 2000, Appendix B). The analysis used historical flows and meteorological conditions for a 35-year period spanning between 1960 and 1995. Frequency analysis was performed on the model results to calculate river temperatures at various percent of time exceeded levels. Results were also analyzed to compute the time when, during the year, water temperatures rose above or fell below various temperature levels.

The key assumptions of the analysis are:

- temperature differences between current and unimpounded river conditions are adequately represented by the vertically and laterally averaged 1D model
- historical flows and weather conditions are representative of future variability
- meteorological conditions at Lewiston and Pasco are representative of conditions along the Snake River

This report is organized into sections which discuss verification simulations for the thermal transport module of the MASS1 model, long-term analysis for unimpounded river conditions, and long-term analysis for the current river conditions. Results are presented in graphical and tabular form in the report. The results are also available in electronic and GIS format directly from the authors.

2 MASS1 Temperature Model Verification

The MASS1 model has applied to the Lower Snake River by Richmond et al. (2000) and Hanrahan et al. (1998). The primary use of MASS1 by Richmond et al. (2000) was the simulation of total dissolved gas, in which temperature plays an integral role. That work also calibrated the hydrodynamics. For this work, the verification of Richmond et al. (2000) was repeated, but with some slight improvement in the representation of the Palouse and Snake River flow and temperature. This section only briefly presents the model configuration. The full details of the verification are presented by Richmond et al. (2000) (Appendix F). Verification simulation results pertinent to this work are presented and summarized.

2.1 MASS1 Mathematical Formulation

Unsteady flow and water temperature in rivers and canals are simulated in MASS1 by solving the one-dimensional equations of mass (2.1), momentum (2.2), and energy (2.6) conservation. The governing equations and solution methods are briefly summarized in this section. Richmond et al. (2000) (Appendix B) provides more extensive model documentation.

Unsteady hydrodynamics are simulated by solving the following equations which are often referred to as the St. Venant equations:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial t} = 0 \tag{2.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\alpha \frac{Q^2}{A}) + gA\frac{\partial y}{\partial x} + gAS_f = 0 \tag{2.2}$$

where

$A =$	river cross-sectional area (ft^2)
$Q =$	water discharge $(\mathrm{ft}^3/\mathrm{sec})$
$y =$	water surface elevation (ft)
$g =$	gravitational acceleration $\mathrm{ft}/\mathrm{sec}^2$
$S_f =$	friction slope $(\mathrm{ft}/\mathrm{ft})$ as defined in (2.3)
$\alpha =$	momentum friction correction factor
$t =$	time (sec)
$x =$	coordinate along the channel (ft)

The friction slope term can be computed using either the Manning or Chezy equations (see Chow (1959)). In MASS1 the friction slope is expressed in terms of the discharge and channel conveyance (K) as

$$S_f = \frac{Q \mid Q \mid}{K^2} \tag{2.3}$$

and the conveyance is computed using the Manning equation

$$K = \frac{C_0}{n} AR^{2/3} \tag{2.4}$$

where

$C_0 =$ 1.49 for English units and 1.0 for metric units
$n =$ Manning channel roughness coefficient
$R =$ A/P hydraulic radius (ft)
$P =$ channel wetted perimeter (ft)

Equations 2.3 and 2.4 represent the combined effects of variable channel geometry and resistance to flow (roughness) on the hydrodynamic simulation.

The average shear stress acting on the channel bottom can be computed from

$$\tau = \gamma R S_f \tag{2.5}$$

where

$\tau =$ bed shear stress $(\mathrm{lb/ft^2})$
$\gamma =$ unit weight of water $(\mathrm{lb/ft^3})$

A transport equation describing the time and space distribution of thermal energy in a river can be derived by applying the conservation of energy principle to a channel reach. This results in the following equation for the cross-sectional average water temperature:

$$\frac{\partial(AT)}{\partial t} + \frac{\partial(QT)}{\partial x} = \frac{\partial}{\partial x}\left(K_T A \frac{\partial T}{\partial x}\right) + \frac{B\sum H}{c_p \rho} \tag{2.6}$$

where

$T =$ water temperature
$K_T =$ longitudinal dispersion coefficient $(\mathrm{ft^2/sec})$
$B =$ channel top-width
$\sum H =$ net surface heat flux
$\rho =$ density of water (mass/volume)
$c_p =$ specific heat of water

The net surface heat flux is computed using a flux balance method that is described in Appendix B.

The foregoing equations are individual and coupled systems of linear and nonlinear partial differential equations. In general, analytical solutions to these equations can only be obtained for simplified channel geometries and boundary conditions. Therefore numerical methods must be used to solve these equations for most practical situations. Finite-difference methods that are appropriate for each equation are used in MASS1.

In MASS1, the hydrodynamic equations (2.1 and 2.2) are discretized using the Preissmann four-point implicit finite-difference scheme and the resulting system of nonlinear algebraic equations are solved using the double sweep method as described in Cunge et al. (1980).

An explicit TVD scheme and split-operator method is used to solve transport equations such as the water temperature equation. A time sub-cycling scheme is used to allow the hydrodynamics to run at the larger time steps allowed by the implicit scheme while using a smaller time step that satisfies the explicit stability criteria. The Courant number for the transport computations must be less than 1.0 to maintain stability in the explicit method.

The first step in developing the numerical solution procedures implemented in MASS1 is to define the topology of the river systems that can be simulated. Here the topological definition defines how the channel system is connected as well as the location and type hydraulic control structures. Note that the current version of MASS1 is applicable to single and branched channel systems; looped or multiply-connected channel networks cannot be simulated at this time.

The topology of the channel system is represented by dividing the river system into a series of links and these are further divided into series of computational points along that link. Nodes occur at upstream or downstream boundary points and at the junction of two or more links. The following sections describe how the channel system was defined for current and unimpounded river conditions.

2.2 MASS1 Model Development

In the MASS1 verification by Richmond et al. (2000), MASS1 was configured to include the lower Columbia River as well as the Snake. A schematic of the Snake River portion of the model configuration is shown in Figure 2.1. The model extended from the mouth of the Clearwater River to its confluence with the North Fork Clearwater River (Clearwater river mile 40.5); from the mouth of the Snake River to just below its confluence with the Grand Rhonde River (Snake river mile 168.0); and (for the purposes of this work) from McNary dam to Priest Rapids dam along the Columbia River. The Tucannon and Palouse rivers were included as tributaries to the Snake, although they are of little importance. Bathymetric data, in the form of cross sections, were developed from modern bathymetric data (see Hanrahan et al., 1998, Section 5).

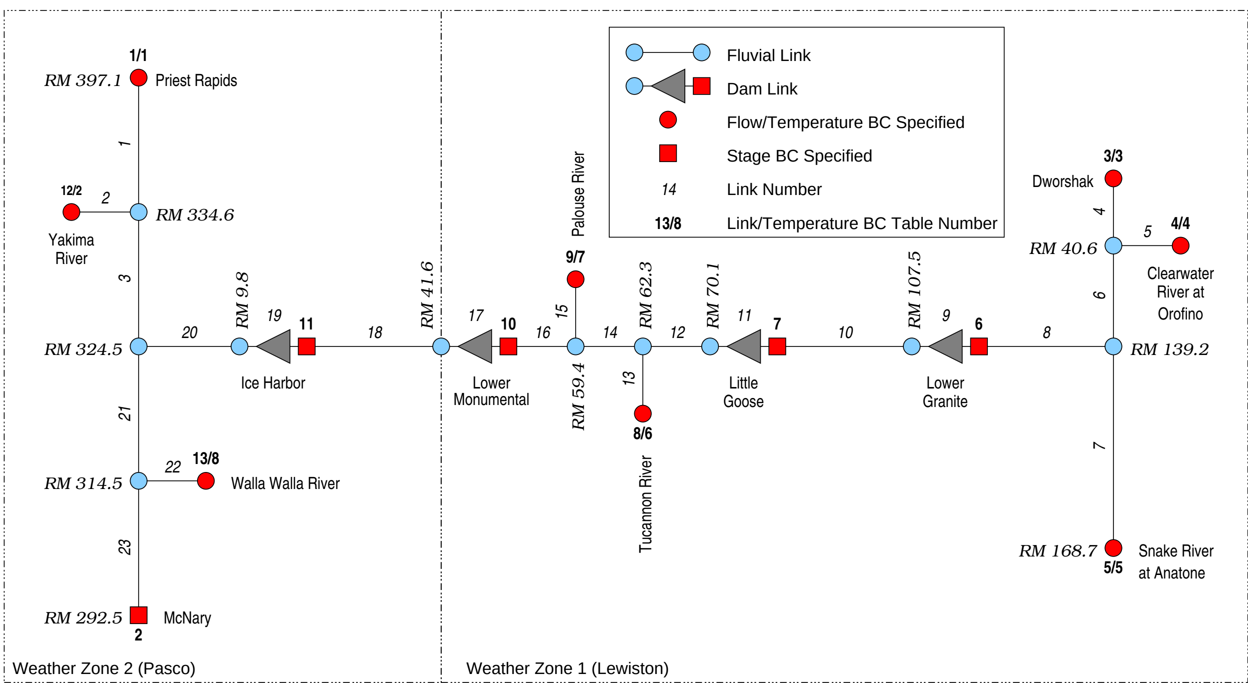

Figure 2.1: Schematic of MASS1 configuration used for temperature model verification.

2.3 Boundary Conditions

Table 2.1 shows the sources of boundary condition data used for MASS1 verification simulations. Hourly Snake River flows and temperatures from the gage near Anatone (USGS gage 13334300) and Clearwater River flows and temperatures from the gage near Orofino (USGS gage 13342500) were obtained directly from the USGS. Hourly project stages and flows were obtained from the Dissolved Gas Abatement Study (DGAS) project operations database (see Carroll et al., 1998). North Fork Clearwater and Columbia River temperatures were obtained from permanent water quality monitors part of the USACE total dissolved gas (TGD) monitoring network. Actual data was obtained from the DGAS water quality database (Carroll et al., 1998).

Flows from USGS stream gages were used for the Tucannon and Palouse Rivers. Some very sparse temperature measurements have been made by the USGS on both rivers, but not during the period considered by this verification. The available temperature data was used to compute an average value by month, shown in Figure 2.2 for the Palouse and Figure 2.3 for the Tucannon, and these were used as temperature boundary conditions for these tributaries. The Palouse and Tucannon tributaries probably have a negligible impact on the temperature of the Lower Snake River: the average annual flow from both are about 1.5% of the average annual Snake River flow.

Table 2.1: Sources of data used for boundary conditions during MASS1 temperature model verification simulations.

Boundary	Data	Frequency	Source
Snake River	Flow	hourly	USGS Gage 13334300
	Temperature	hourly	USGS Gage 13334300
Clearwater River	Flow	hourly	USGS Gage 13340000
	Flow	hourly	USGS Gage 13340000
Dworshak Dam	Flow	hourly	DGAS Operations Database
	Temperature	hourly	TDG Monitor DWQI
Priest Rapids Dam	Flow	hourly	DGAS Operations Database
	Temperature	constant	5°C
Lower Granite Dam	Stage	hourly	DGAS Operations Database
Little Goose Dam	Stage	hourly	DGAS Operations Database
Lower Monumental Dam	Stage	hourly	DGAS Operations Database
Ice Harbor Dam	Stage	hourly	DGAS Operations Database
McNary Dam	Stage	hourly	DGAS Operations Database
Tucannon River	Flow	daily	USGS Gage 13344500
	Temperature	month avg.	USGS Gages 13344500 and 13344520
Palouse River	Flow	daily	13344500
	Temperature	month avg.	13344500

2.4 Meteorology

Two weather zones were used for the verification simulations. The first zone included all river reaches upstream of Lower Monumental dam. Meteorological data, except for barometric pressure,

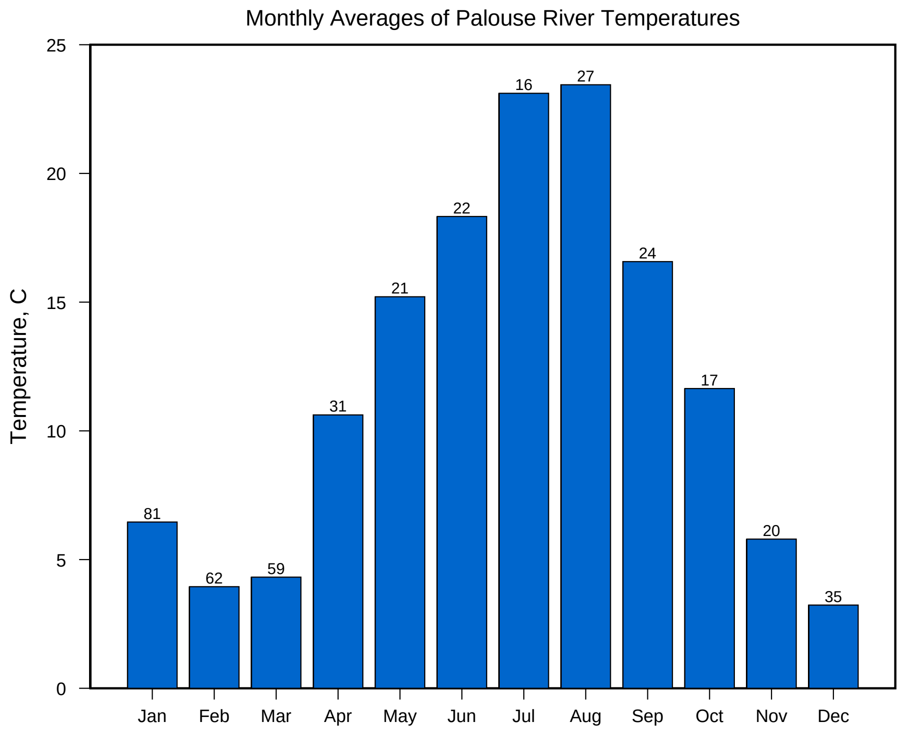

Figure 2.2: Averages of Palouse River temperature observations at Hooper (USGS Gage 13351000) by month. The numbers above the bars are the number of observations.

from the Lewiston, Idaho NWS station was used for this upper zone. Barometric pressure data was taken from the LWG TDG monitor near Lower Granite dam. The second zone included that part of the model below Lower Monumental dam. Meteorological data from Pasco, Washington NWS station and barometric pressure from the IHR TDG monitor was used for this lower zone.

Fixed monitor data was obtained from the DGAS water quality database (Carroll et al., 1998). Weather data was obtained from the DGAS weather database (Carroll et al., 1998).

2.5 Results

Verification simulations were carried out for two periods: from March 1 to October 1, 1996 and March 1 to October 1, 1997. MASS1 used a hydrodynamic time step of 0.5 hours (30 minutes) and a transport time step of 0.025 hours (1.5 minutes).

Simulation results were compared to temperatures measured by several TDG water quality monitors located in dam tailwaters. The stations used are shown in Table 2.2. Data was obtained from the DGAS water quality database (Carroll et al., 1998) for the fixed forebay and tailwater monitors. Data for the scrollcase monitors was obtained from the Water Management Division.

Table 2.3 very generally summarizes the overall predictive ability of MASS1 using various measures. The r^2 coefficient, bias, and root-mean-error (RMS) in Table 2.3 were computed according to the definitions presented by Lettenmaier and Wood (1993). The average mean error

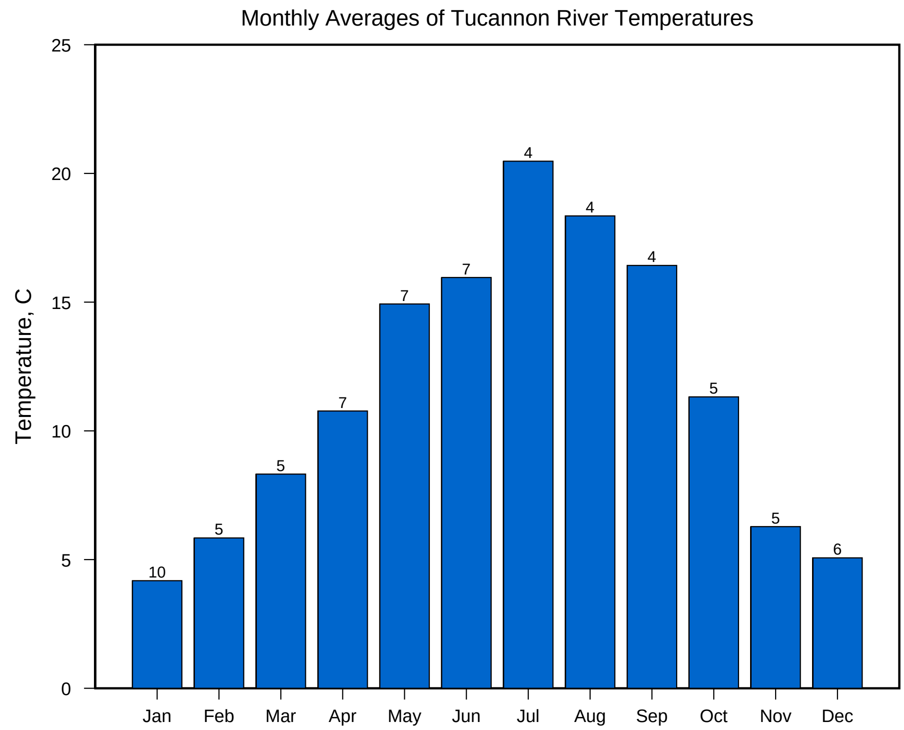

Figure 2.3: Averages of Tucannon River temperature observations at Hooper (USGS Gages 13344500 and 13344520) by month. The numbers above the bars are the number of observations.

(AME) is the mean of the absolute value of the difference between observed and simulated temperature. In general, MASS1 appears to predict Snake River temperatures to within ± 1 to 1.5°C, but slightly underestimates them.

Figures 2.4 and 2.6 compare, respectively, 1996 and 1997 simulated and observed temperature time series at the Snake River tailwater monitors. Figure 2.5 and 2.7 show the same for the forebay monitors. Figure 2.8 compares the time series for the Clearwater River monitor.

During these two simulation periods, several field studies were in progress as part of the Dissolved Gas Abatement Study (DGAS Carroll et al., 1998). During these studies water quality monitors were deployed for short periods of time during the spill season. Simulation results were also compared to temperatures measured during these studies. See Appendix A for more details.

Table 2.2: USACE fixed water quality monitors to which MASS1 verification simulations were compared.

Dam	Monitor Name	River	Location (River Mile)
Tailwater Monitors			
Ice Harbor	IDSW	Snake	6.2
Lower Monumental	LMNW	Snake	40.8
Little Goose	LGSW	Snake	69.5
Lower Granite	LGNW	Snake	106.8
Forebay and Scrollcase Monitors			
Ice Harbor	IHR	Snake	9.5
Lower Monumental	LMN	Snake	41.6
Little Goose	LGS	Snake	70.1
Lower Granite	LWG	Snake	107.5
Other Monitors			
	LEWI	Clearwater	2.0

Table 2.3: Statistical summary of temperature model verification results.

	1996				1997			
Monitor	r^2	Bias	RMS	AME	r^2	Bias	RMS	AME
Tailwater Monitors								
LGNW	0.99	−0.08	0.45	0.35	0.99	−0.55	0.76	0.61
LGSW	0.95	−0.48	0.97	0.62	0.96	0.22	1.20	1.11
LMNW	0.90	0.49	1.31	1.04	0.98	−0.38	0.73	0.53
IDSW	0.95	0.29	0.99	0.77	0.99	−0.55	0.76	0.61
Forebay Monitors								
LWG	0.92	−0.13	1.35	1.07	0.99	−0.57	0.87	0.64
LGS	0.93	−0.60	1.33	0.81	0.98	−0.37	0.69	0.53
LMN	0.95	−0.19	1.20	0.98	0.97	−0.49	0.84	0.63
IHR	0.85	−0.33	1.60	1.13	0.99	−0.54	0.74	0.60
Scrollcase Monitors								
LWG	0.97	−0.04	0.57	0.42	0.98	−0.70	0.92	0.76
LGS	0.93	−0.41	1.17	0.79	0.96	−0.73	1.16	0.88
LMN	0.95	−0.38	0.91	0.70	0.98	−0.43	0.77	0.64
IHR	0.88	−0.16	1.34	0.79	0.97	−0.37	0.82	0.70

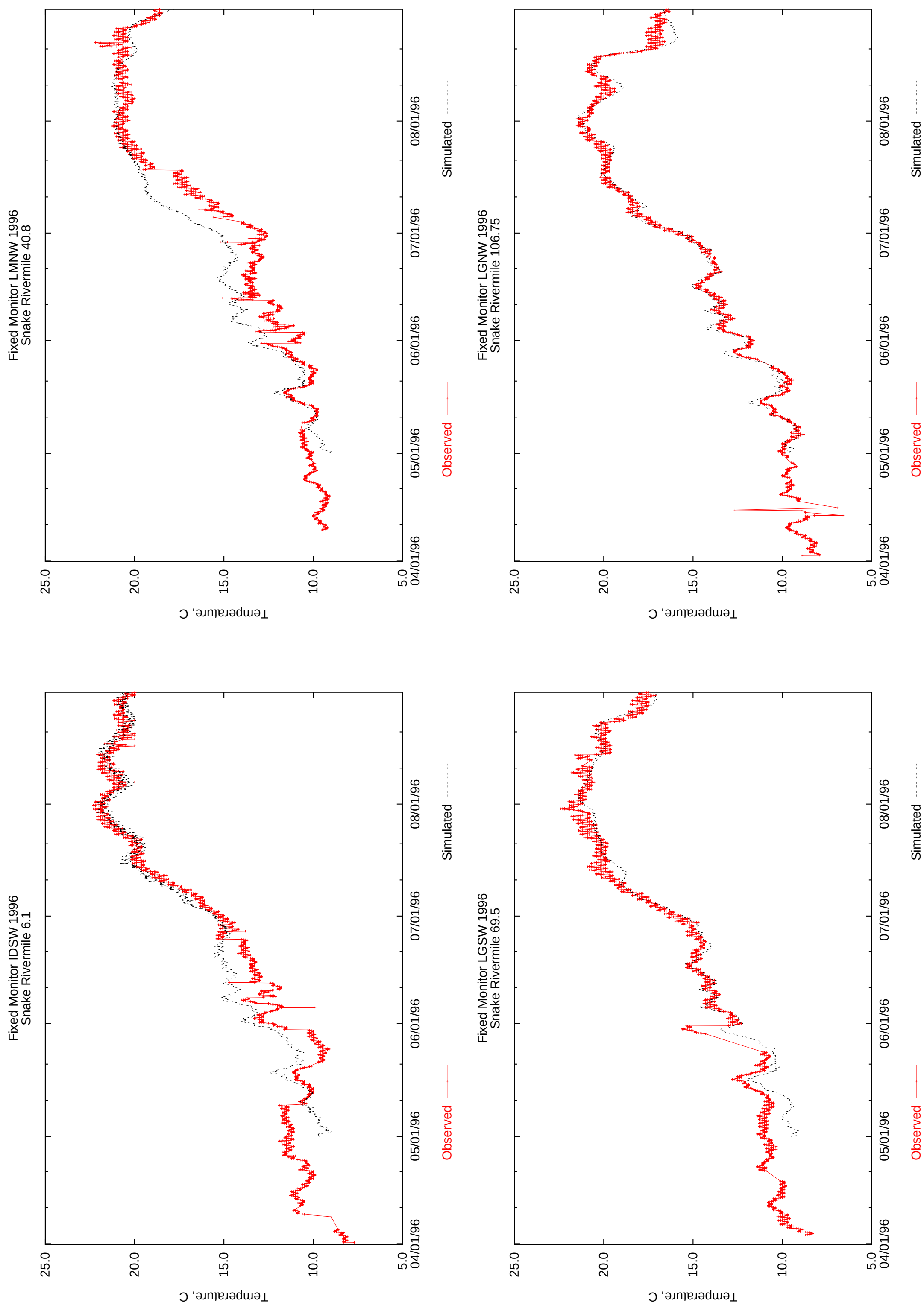

Figure 2.4: Comparison of MASS1 simulated temperatures and Snake River temperatures measured by tailwater fixed monitors during 1996.

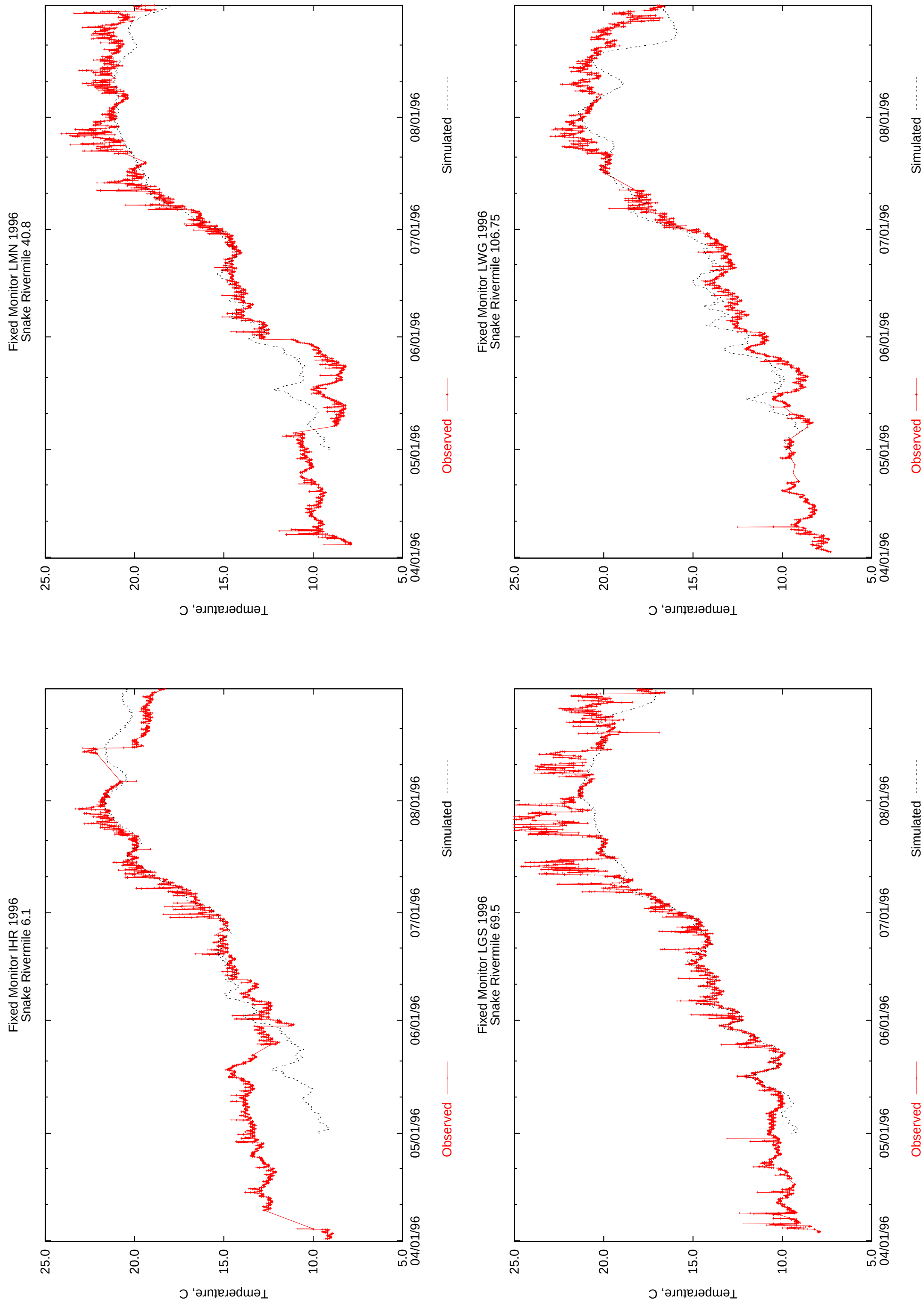

Figure 2.5: Comparison of MASS1 simulated temperatures and Snake River temperatures measured by forebay fixed monitors during 1996.

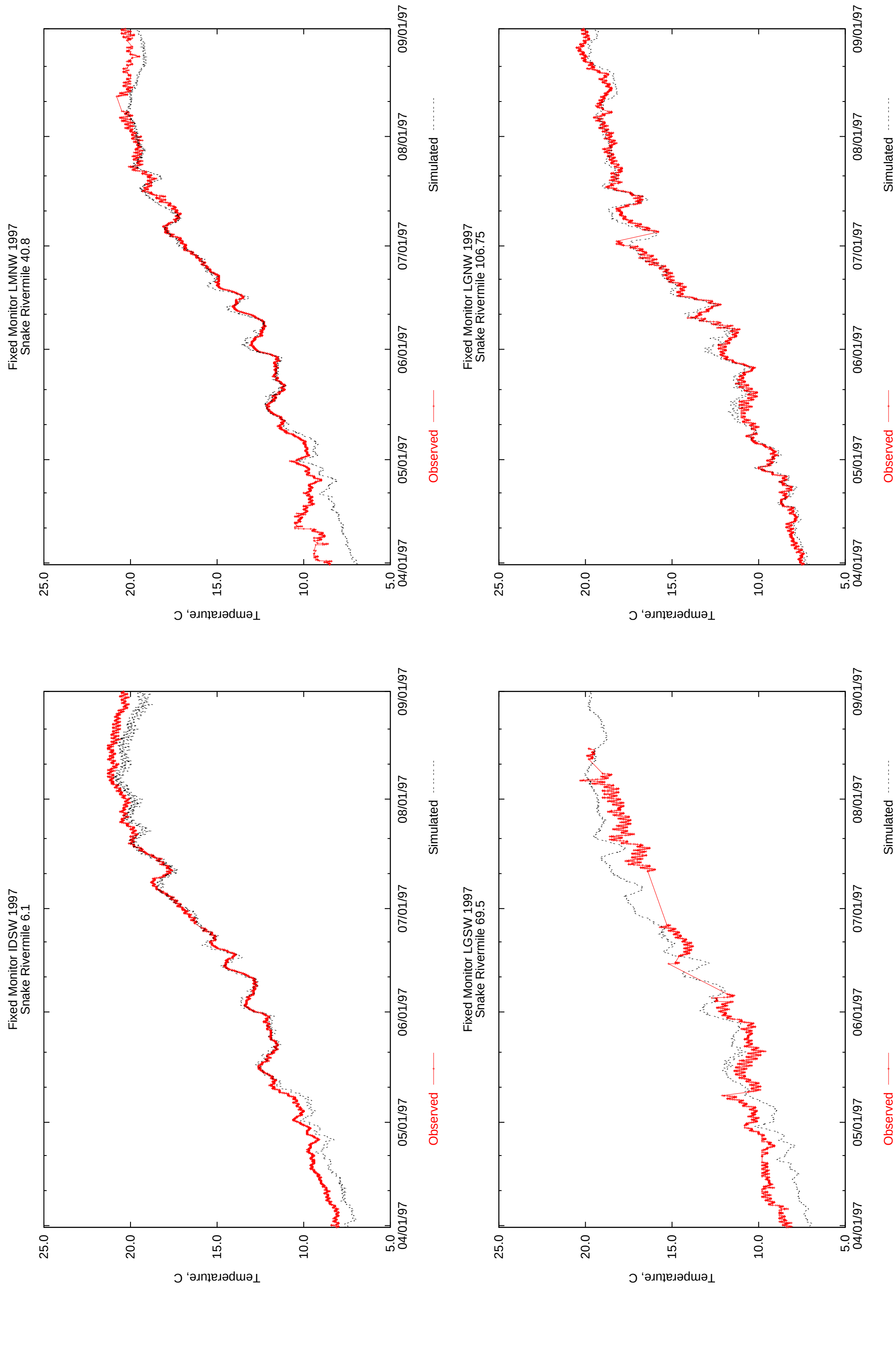

Figure 2.6: Comparison of MASS1 simulated temperatures and Snake River temperatures measured by tailwater fixed monitors during 1997.

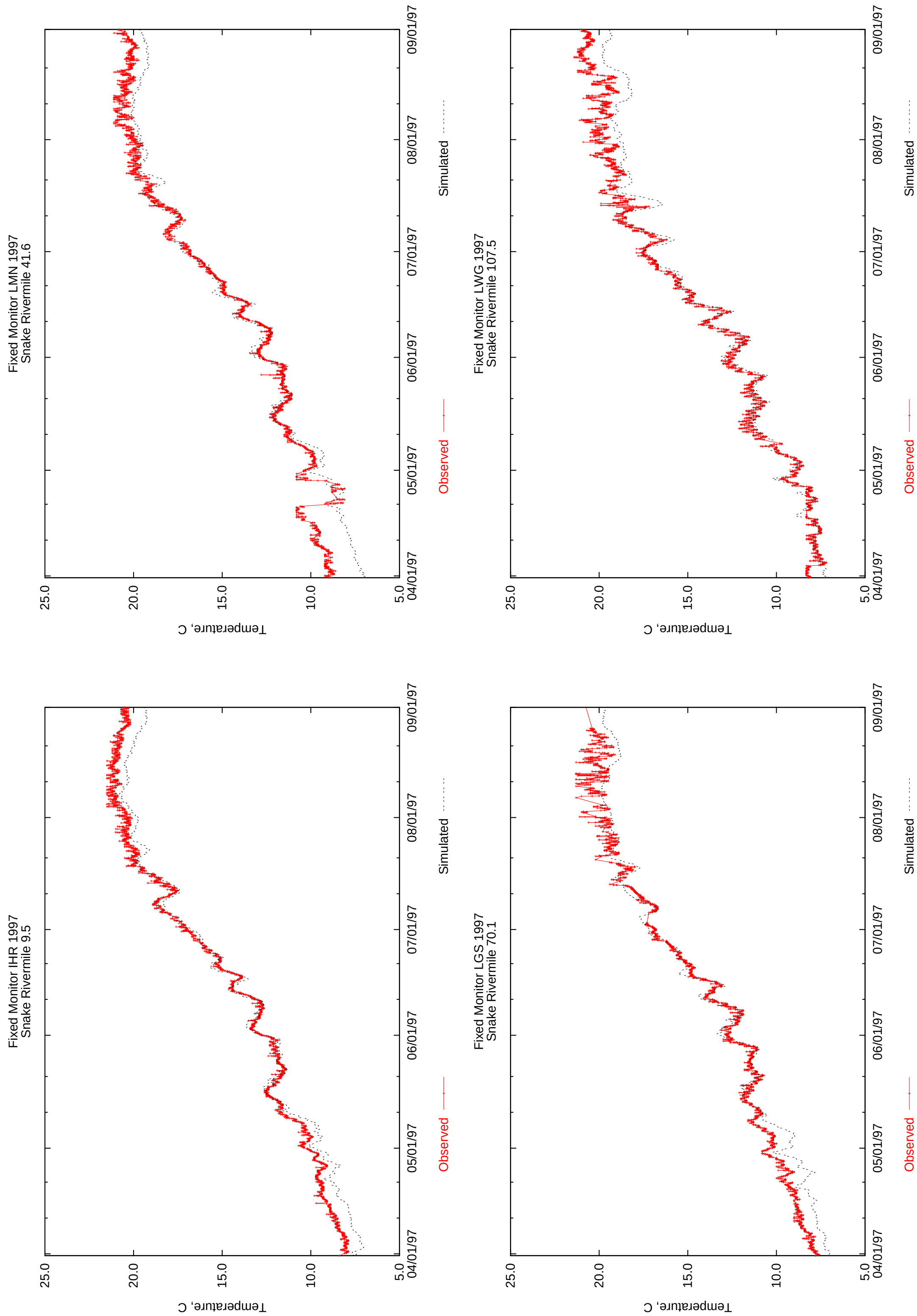

Figure 2.7: Comparison of MASS1 simulated temperatures and Snake River temperatures measured by forebay fixed monitors during 1997.

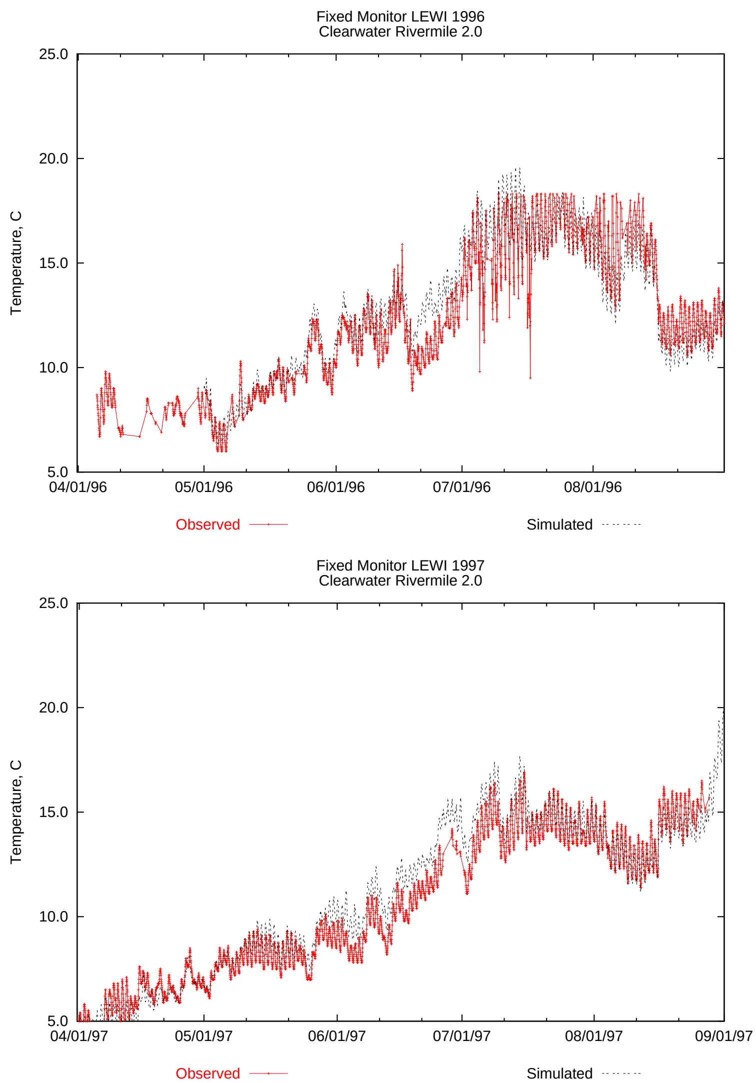

Figure 2.8: Comparison of MASS1 simulated temperatures and Clearwater River temperatures measured by the LEWI fixed monitor during 1996 and 1997.

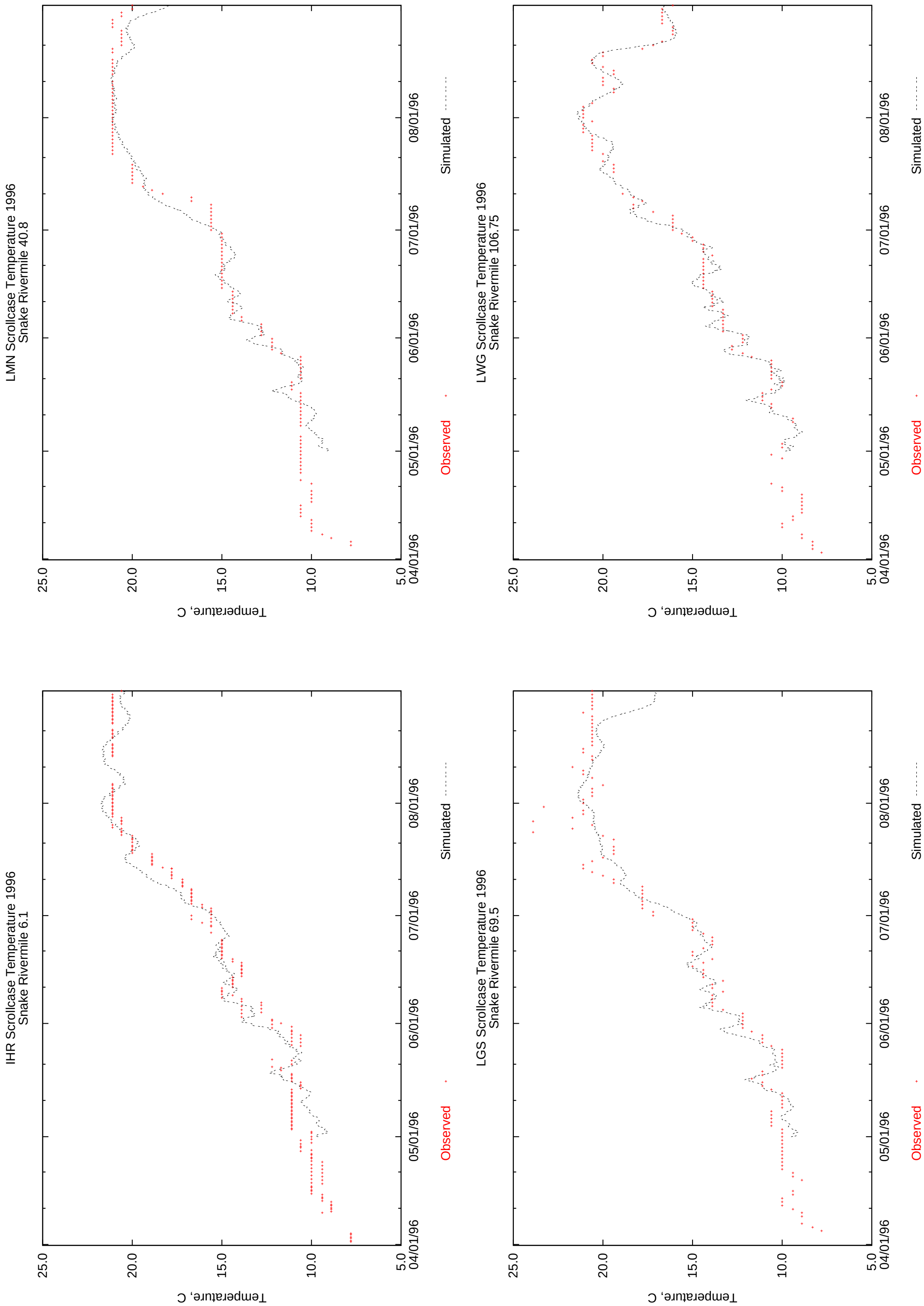

Figure 2.9: Comparison of MASS1 simulated temperatures and Snake River temperatures measured project turbine scrollcase monitors during 1996.

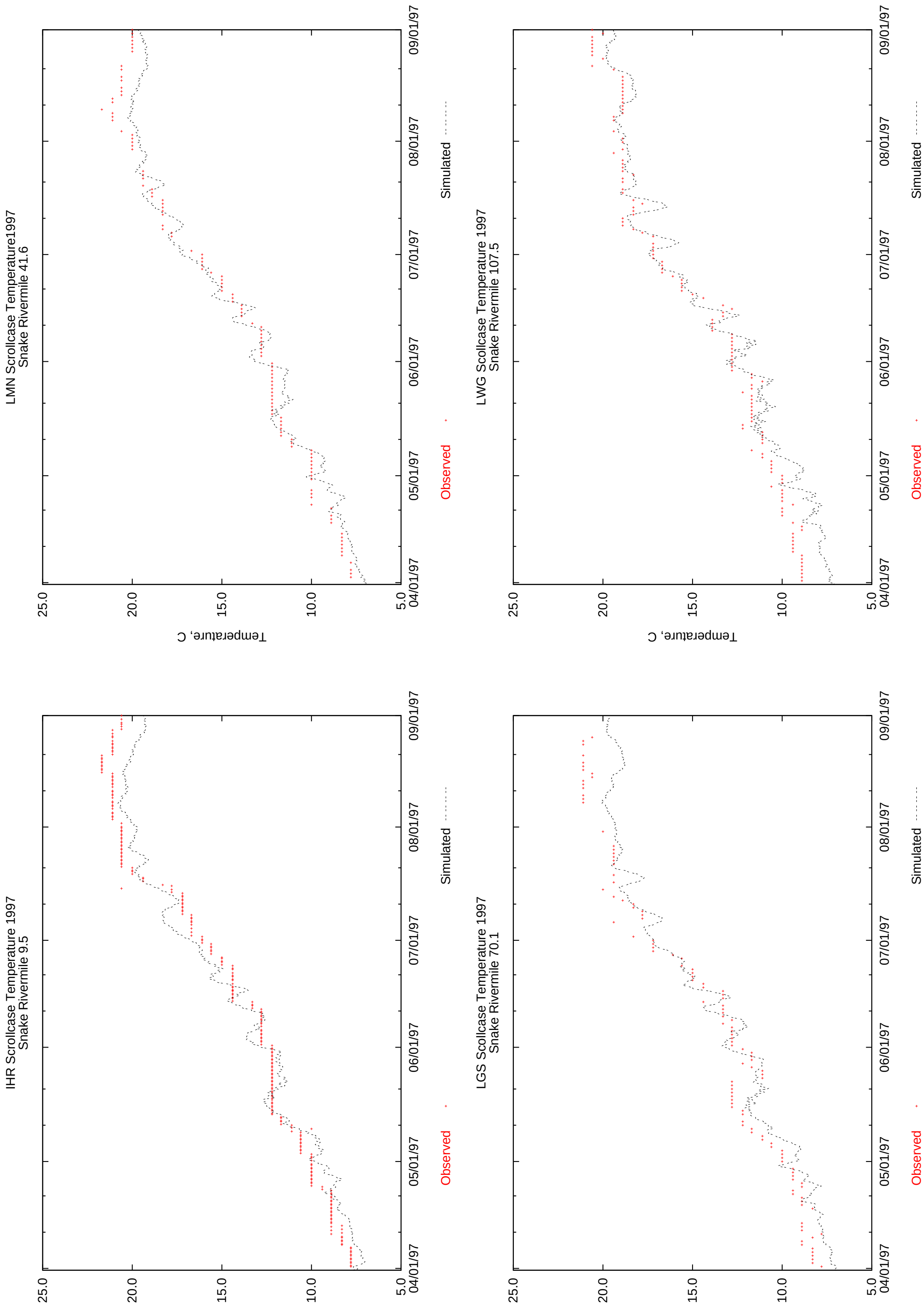

Figure 2.10: Comparison of MASS1 simulated temperatures and Snake River temperatures measured project turbine scrollcase monitors during 1997.

3 Unimpounded River Scenario

The unimpounded river scenario represents the lower Snake River in a more natural state – before construction of dams. MASS1 was configured to simulate the lower Snake River using a long period of observed flows and pre-dam bathymetry: 35 years, 1960 to 1995. The resulting simulated temperatures were statistically summarized.

3.1 MASS1 Model Development

A schematic of the MASS1 configuration used for the unimpounded river scenario is shown in Figure 3.1. The model extended along the Snake River from river mile 167.0, near the confluence with the Grand Rhonde River to the mouth. The Clearwater, Tucannon, and Palouse Rivers were represented by one-mile long river segments of constant size (links 5, 6 and 7, respectively in Figure 3.1).

Bathymetry, in the form of cross-sections, was developed from electronically digitized versions of USACE (1934). The process of cross section development was similar to that described by Hanrahan et al. (1998).

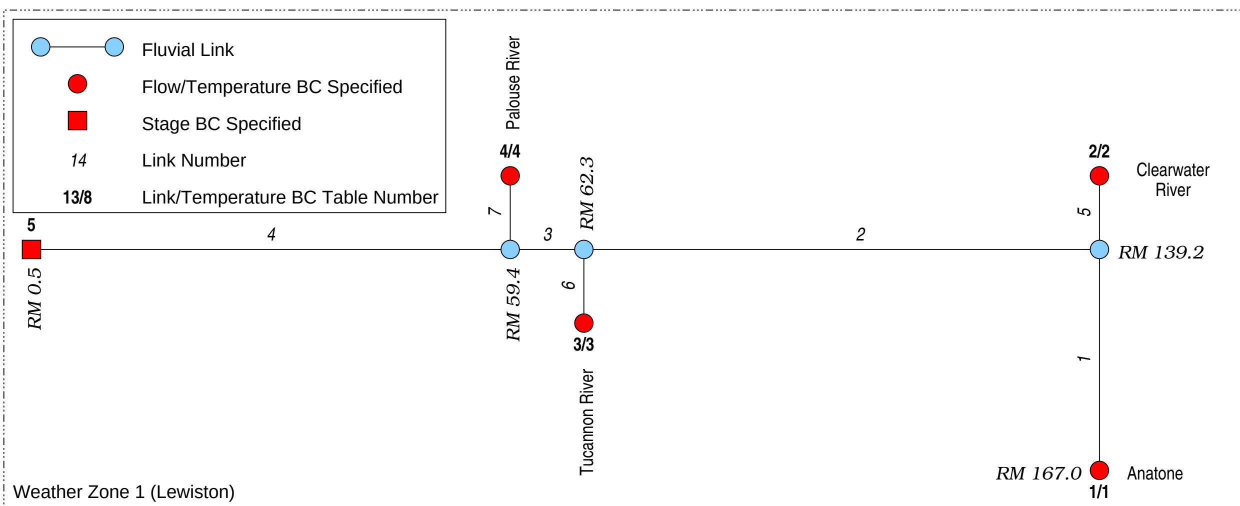

Figure 3.1: MASS1 configuration used for the unimpounded river scenario simulation.

3.2 Boundary Conditions

The unimpounded river scenario was simulated with MASS1 for an extended period of time. The length of the period was determined by the availability of data used to provide boundary conditions. Table 3.1 lists the boundary conditions needed and their sources of data. Figure 3.2 shows the availability of boundary condition data during that period.

Daily USGS flows and temperatures were obtained from EarthInfo (1997). Snake River flow and temperature were taken from the USGS gage at Anatone (13334300). Figure 3.3 shows a summary of observed Snake River temperature variation at Anatone.

Clearwater River flow and temperature was taken from the USGS gage at Spalding (13342500). Figure 3.4 shows a summary of observed Clearwater River temperature variation at Spalding.

There were significant periods of missing data in the Anatone and Spalding temperature records, as can be seen in Figure 3.2. In both the Anatone and Spalding records, temperature in the month of December was not available.

The downstream Snake River stage was held at 341.0 feet, which is slightly above the normal elevation of McNary pool. Daily Tucannon and Palouse River flows from USGS gages were used. There were a few large gaps in the records for these rivers. Within those gaps, the average annual flow was used: 605 cfs for the Palouse, and 175 cfs for the Tucannon. Temperature for these tributaries was the same monthly averages used for the verification (Section 2.3).

Table 3.1: Sources of data used for Snake River temperature simulations.

Boundary	Data	Frequency	Source
Snake River	Flow	daily	USGS Gage 13334300
	Temperature	daily	USGS Gage 13334300
	Downstream Stage	constant	341.0 feet
Clearwater River	Flow	daily	USGS Gage 13342500
Clearwater River	Temperature	daily	USGS Gage 13342500
Tucannon River	Flow	daily	USGS Gage 13344500
	Temperature	month avg.	USGS Gages 13344500 and 13344520
Palouse River	Flow	daily	13344500
	Temperature	month avg.	13344500

3.3 Meteorology

A single weather zone was used during the unimpounded river scenario simulation. Hourly weather data for Lewiston, Idaho (Nez Perce County Airport, WBAN 24149) was obtained from EarthInfo (1998) from 1948 to 1997. It would have been desirable to divide the domain between the Lewiston and Pasco stations as was done in the verification. However, Pasco weather data was not immediately available. Incoming radiation was calculated, as described in Appendix B.

3.4 Results

The MASS1 simulation was performed from January 5, 1960 through June 30, 1996. A time step of 0.075 hours (4.5 minutes) was used for both hydrodynamics and temperature simulation. The maximum temperature was saved at daily intervals. The statistical summaries which follow are based on those daily maximums. The simulation was continued through the times of missing data shown in Figure 3.2, but these times were not included in the statistical computations.

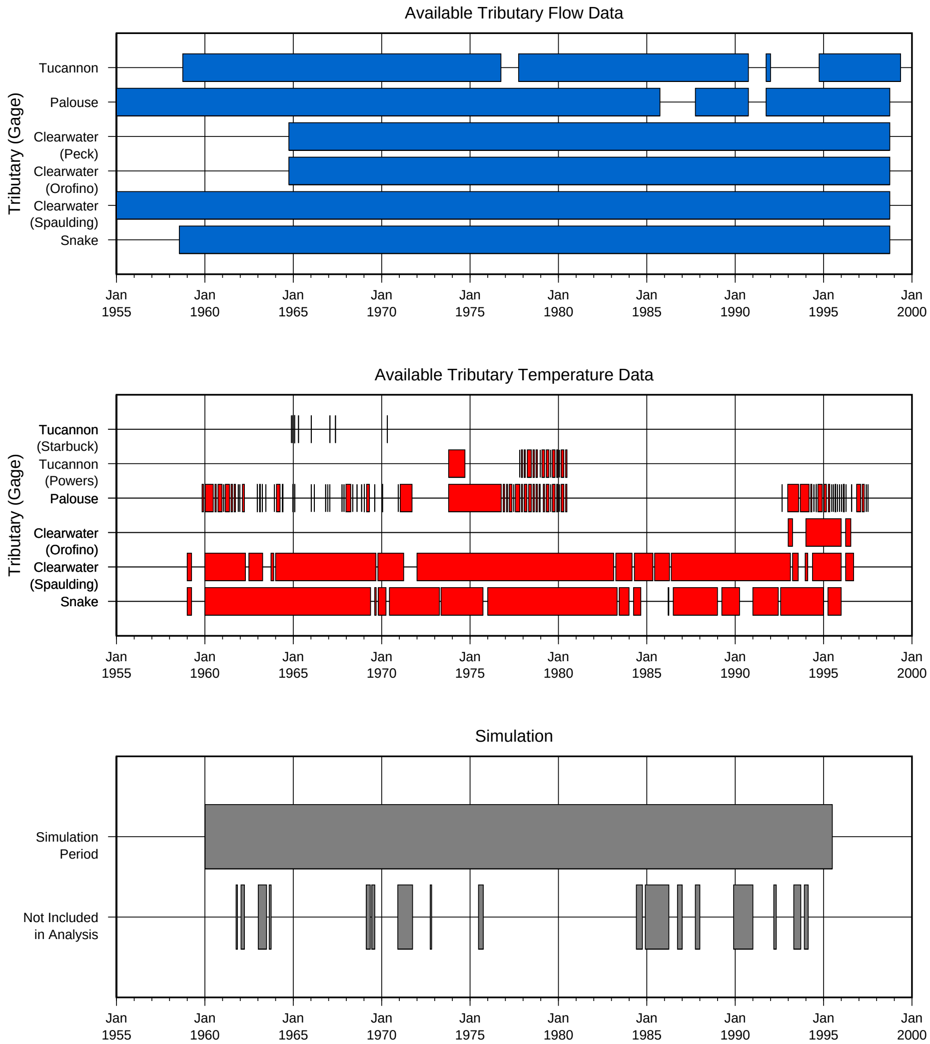

Figure 3.2: Available flow and temperature data for the Snake and Clearwater River model boundaries. Long periods of missing data were excluded from statistical analysis.

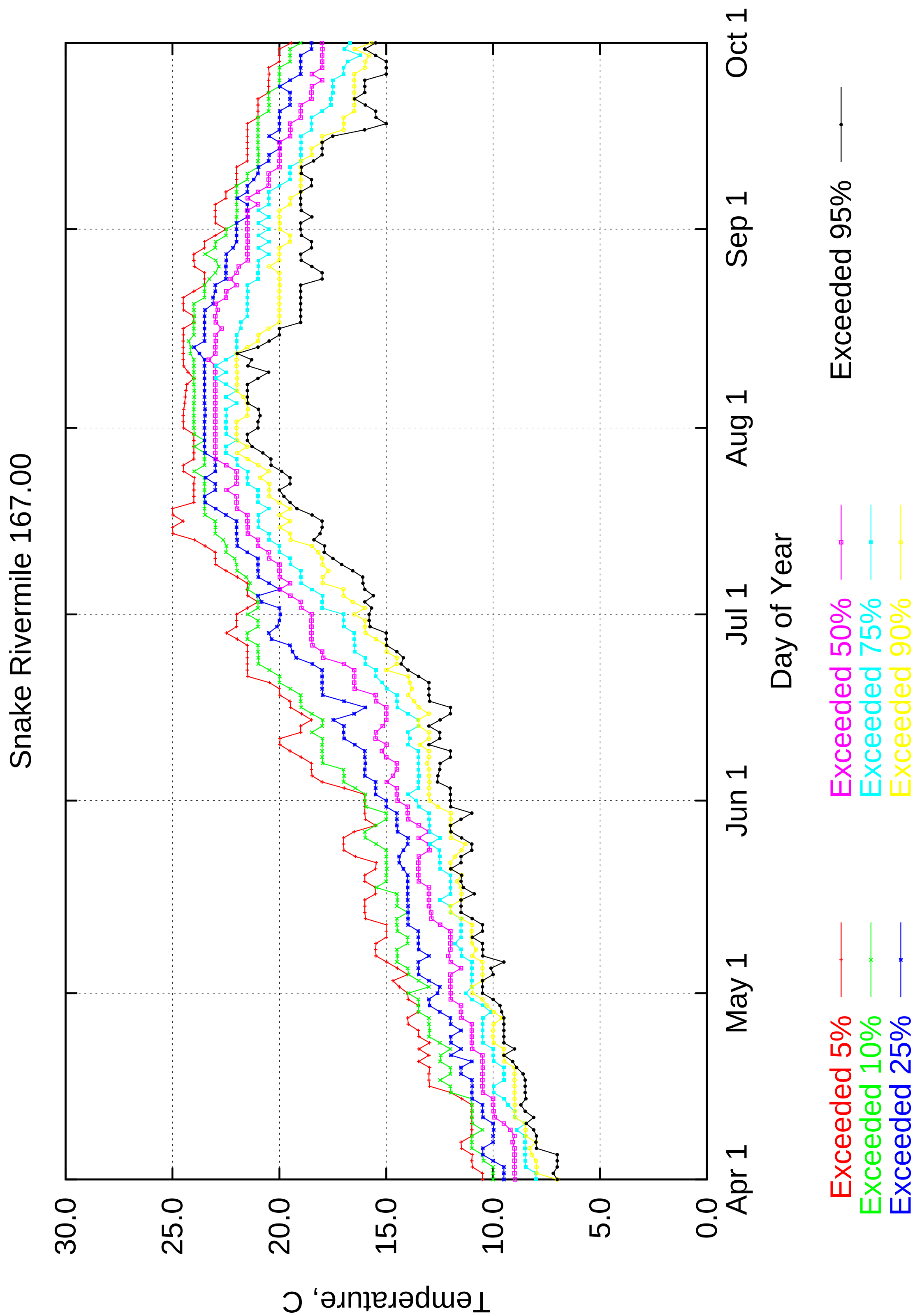

Figure 3.3: Summary of observed temperature variation in the Snake River near Anatone.

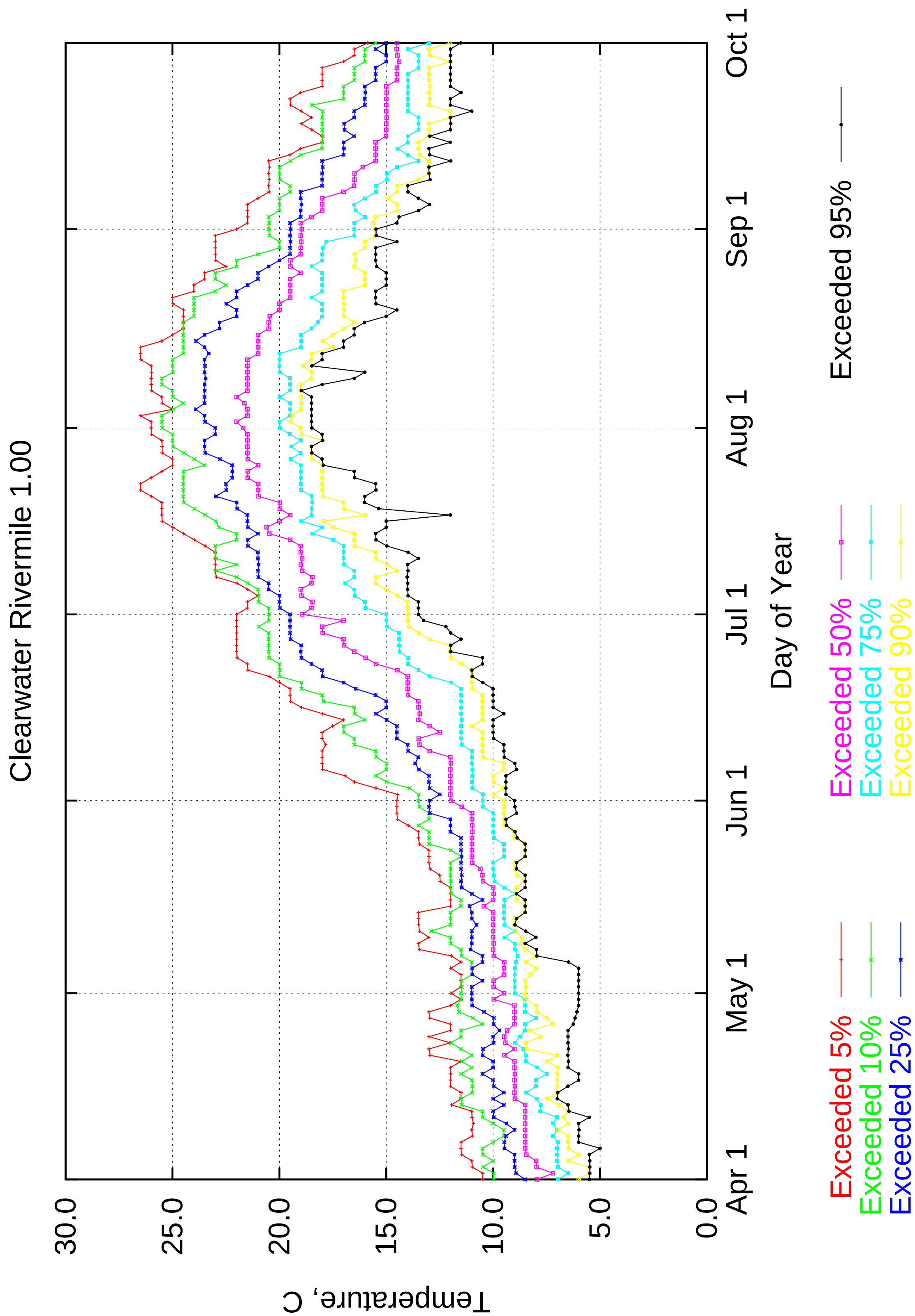

Figure 3.4: Summary of observed temperature variation in the Clearwater River.

Figure 3.5 shows simulated temperature time series plots for several locations in 1988. Also shown are some plots of temperature with Snake River mile at individual times. Similar plots for 1991 are shown in Figure 3.6.

Figures 3.7 through 3.17 summarize temperatures simulated in the months of January through November, respectively. These figures were produced by collecting all simulated temperatures in a given month and computing values exceeded 5, 10, 25, 50, 75, 90, and 95 percent of the time at each location simulated by MASS1. December is not shown since Clearwater and Snake River temperatures were not available for December in any year of the simulation. Each line in these figures connects similar exceedance values for each simulated location along the Snake River. The lines on these graphs connect points of similar exceedance value for each computational point along the river. Table 3.2 shows these exceedance values for present-day dam locations.

For those same locations, exceedance values were similarly computed for each day of the year. These are summarized in Figures 3.18, 3.19, 3.20, and 3.21 for the locations of Lower Granite, Little Goose, Lower Monumental, and Ice Harbor dams, respectively. The lines of these plots connect points of similar exceedance value for each day of the year, and help to visually summarize the variation of simulated temperature throughout the year.

Table 3.3 shows the 90, 75, 50, 25, and 10 percentiles of day of year number. This table was prepared by noting, for each year of the simulation, the first (last) day of the year simulated temperature rose above (fell below) the specified temperature. In order for that first (last) day to be considered, the simulated temperature must have stayed above (below) for a certain number of days:

- 10°C: 50 days
- 15°C: 35 days
- 20°C: 21 days
- 25°C: 3 days

Once such a period was identified within the year, the number of the first (last) day was included in statistical calculations.

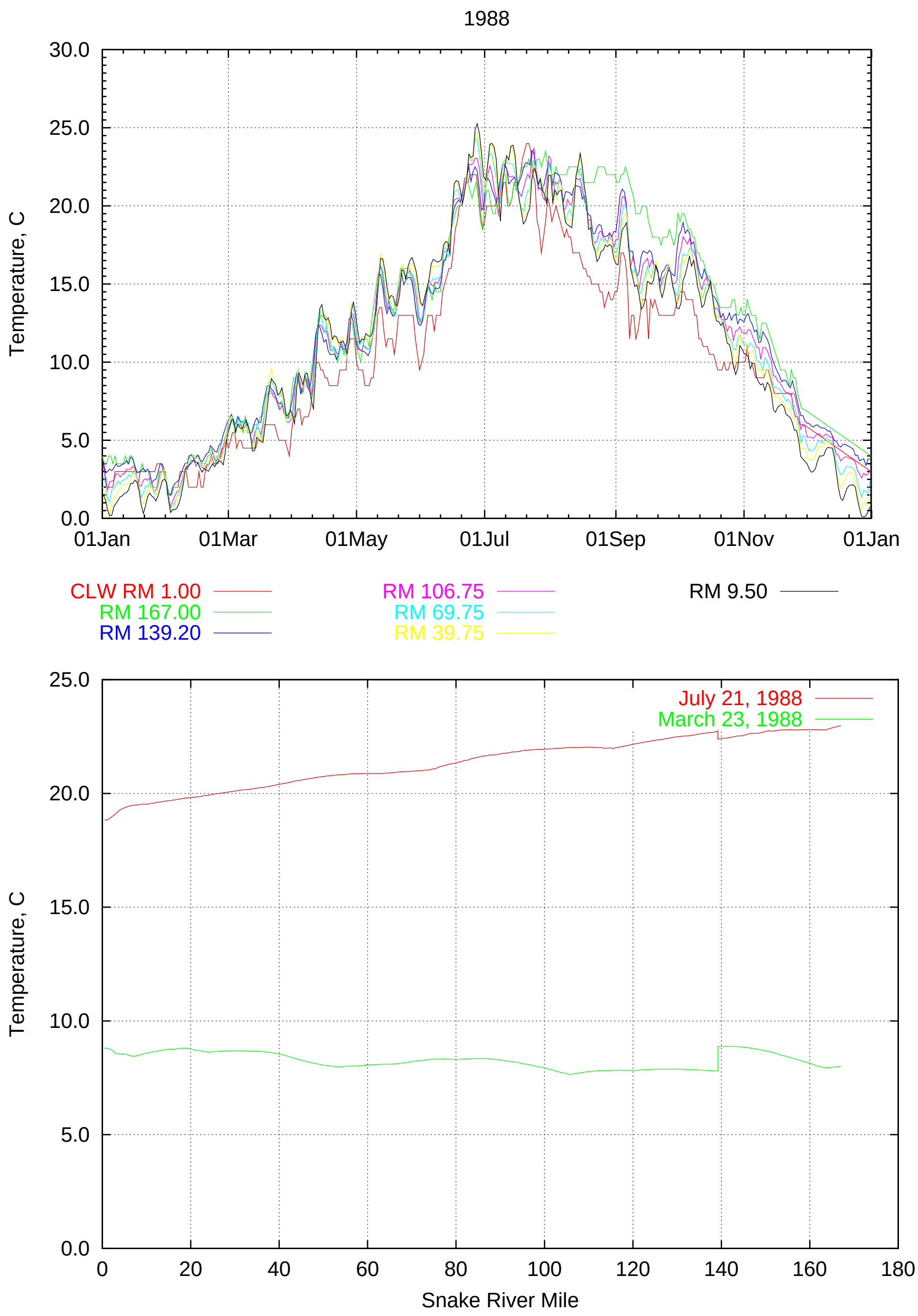

Figure 3.5: Time series (above) and sample profile plots (below) of Snake River temperatures simulated during 1988 in the unimpounded river scenario.

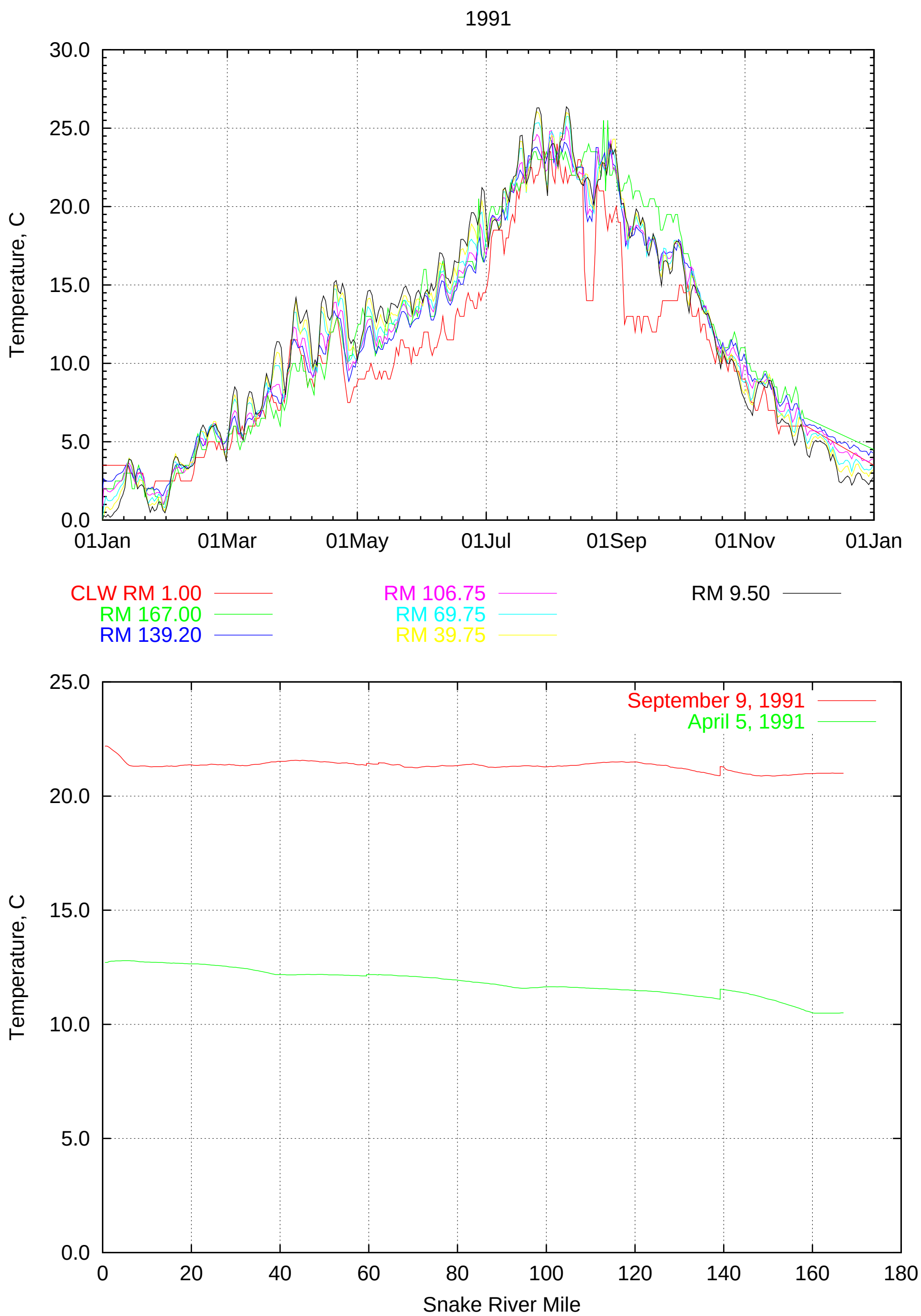

Figure 3.6: Time series (above) and sample profile plots (below) of Snake River temperatures simulated during 1991 in the unimpounded river scenario.

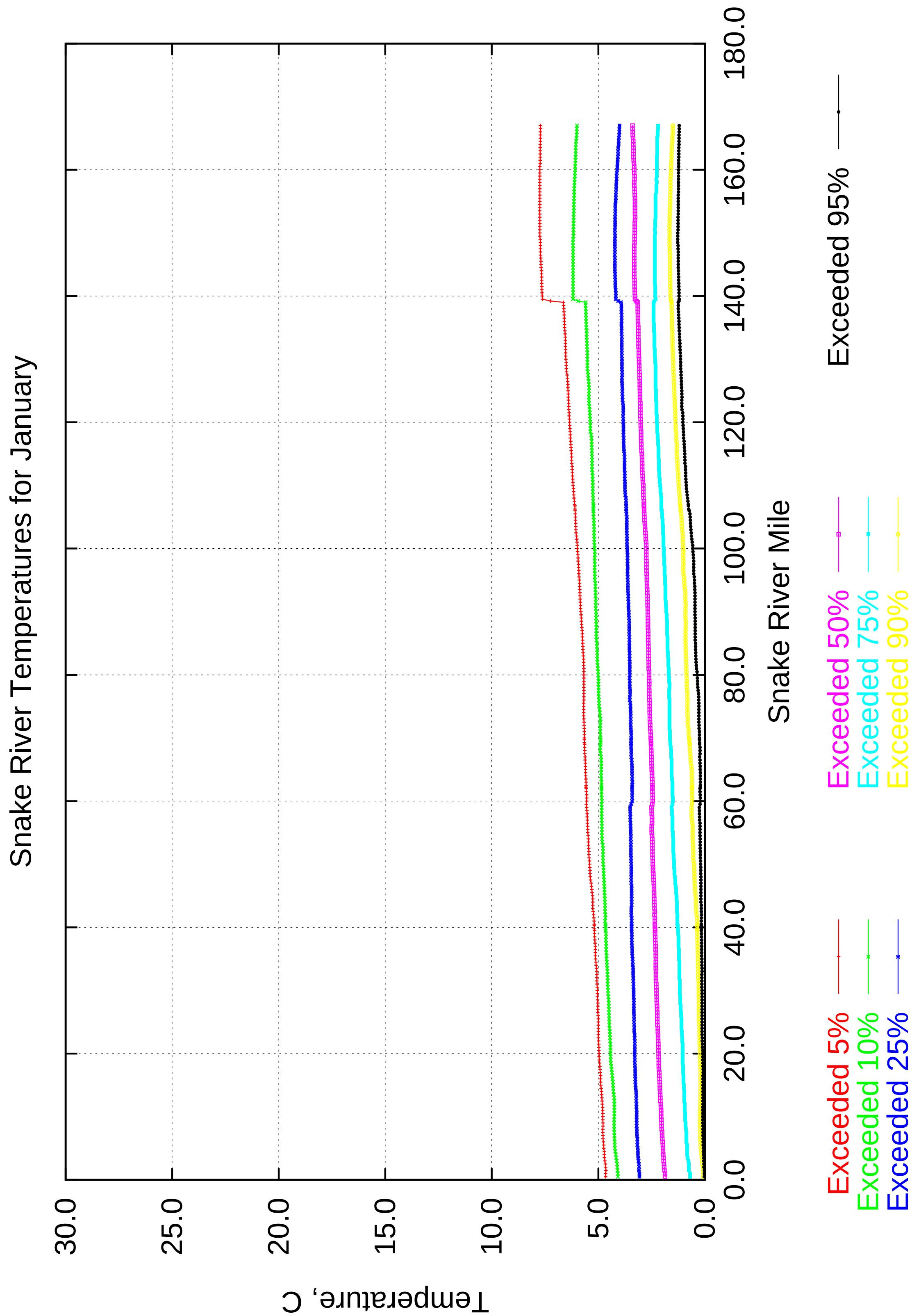

Figure 3.7: Summary of simulated temperature variation in January by Snake River mile for the unimpounded river scenario. Individual lines *do not* represent a single profile, but only connect similar exceedance values for each rivermile.

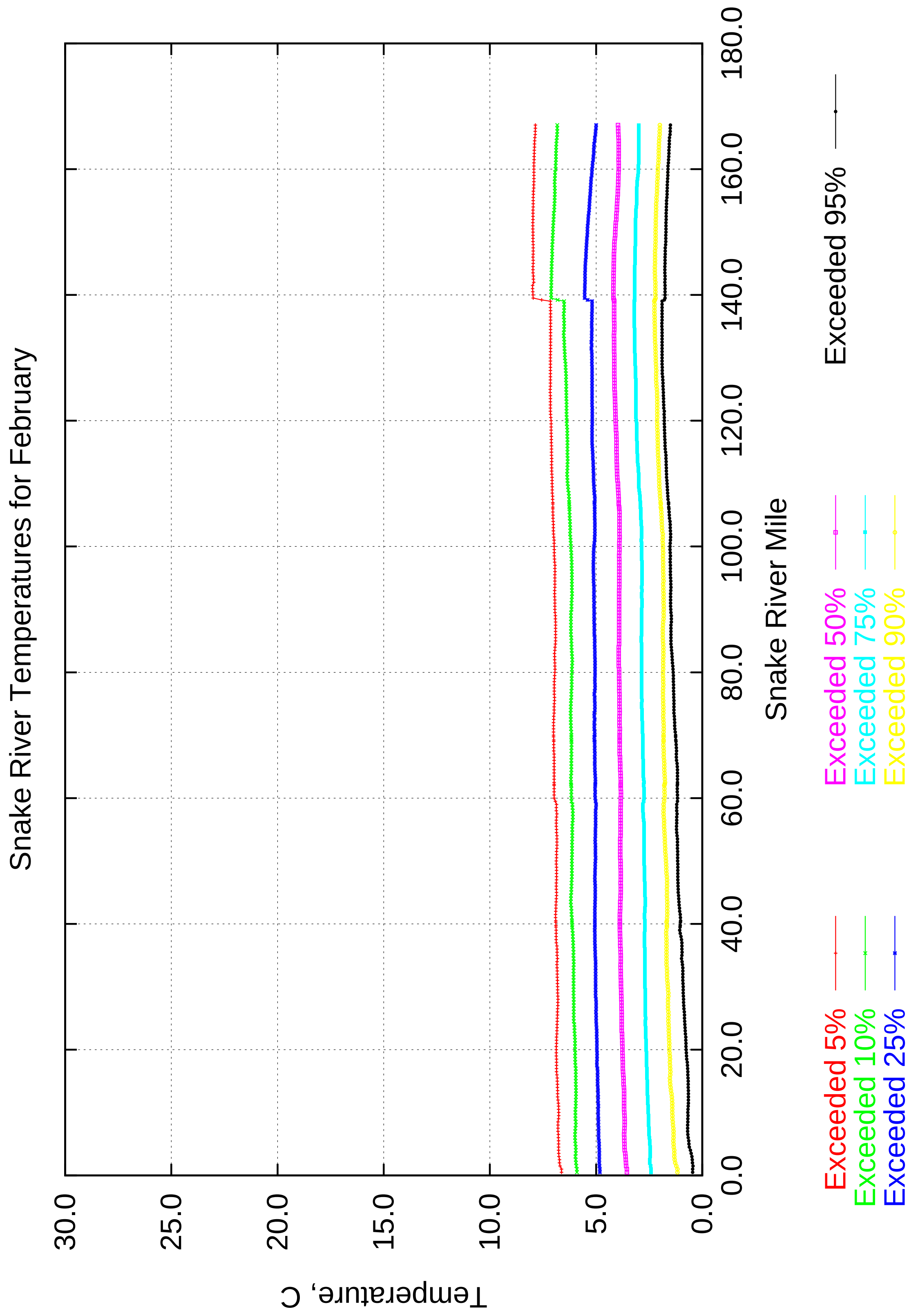

Figure 3.8: Summary of simulated temperature variation in February by Snake River mile for the unimpounded river scenario.

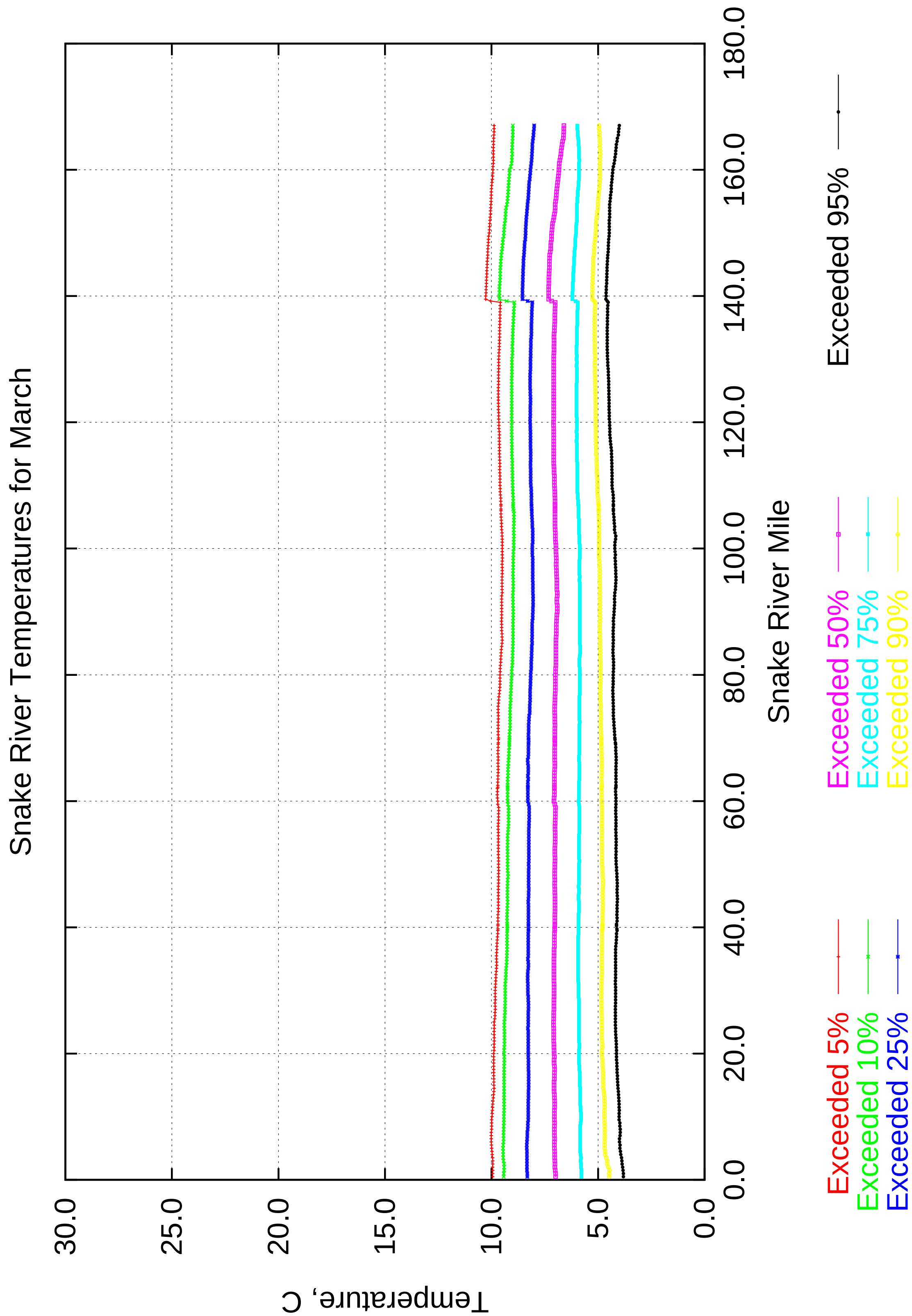

Figure 3.9: Summary of simulated temperature variation in March by Snake River mile for the unimpounded river scenario.

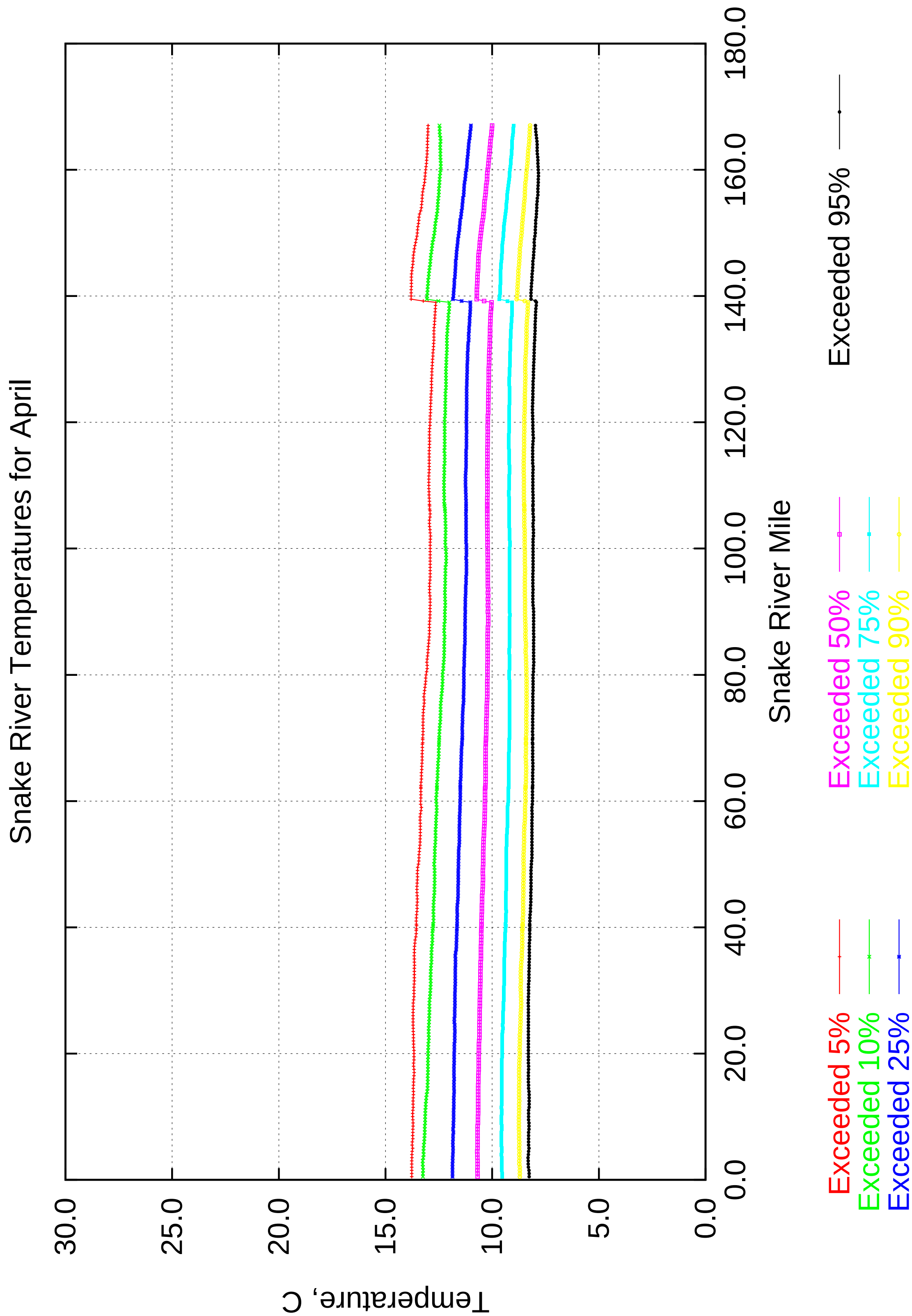

Figure 3.10: Summary of simulated temperature variation in April by Snake River mile for the unimpounded river scenario.

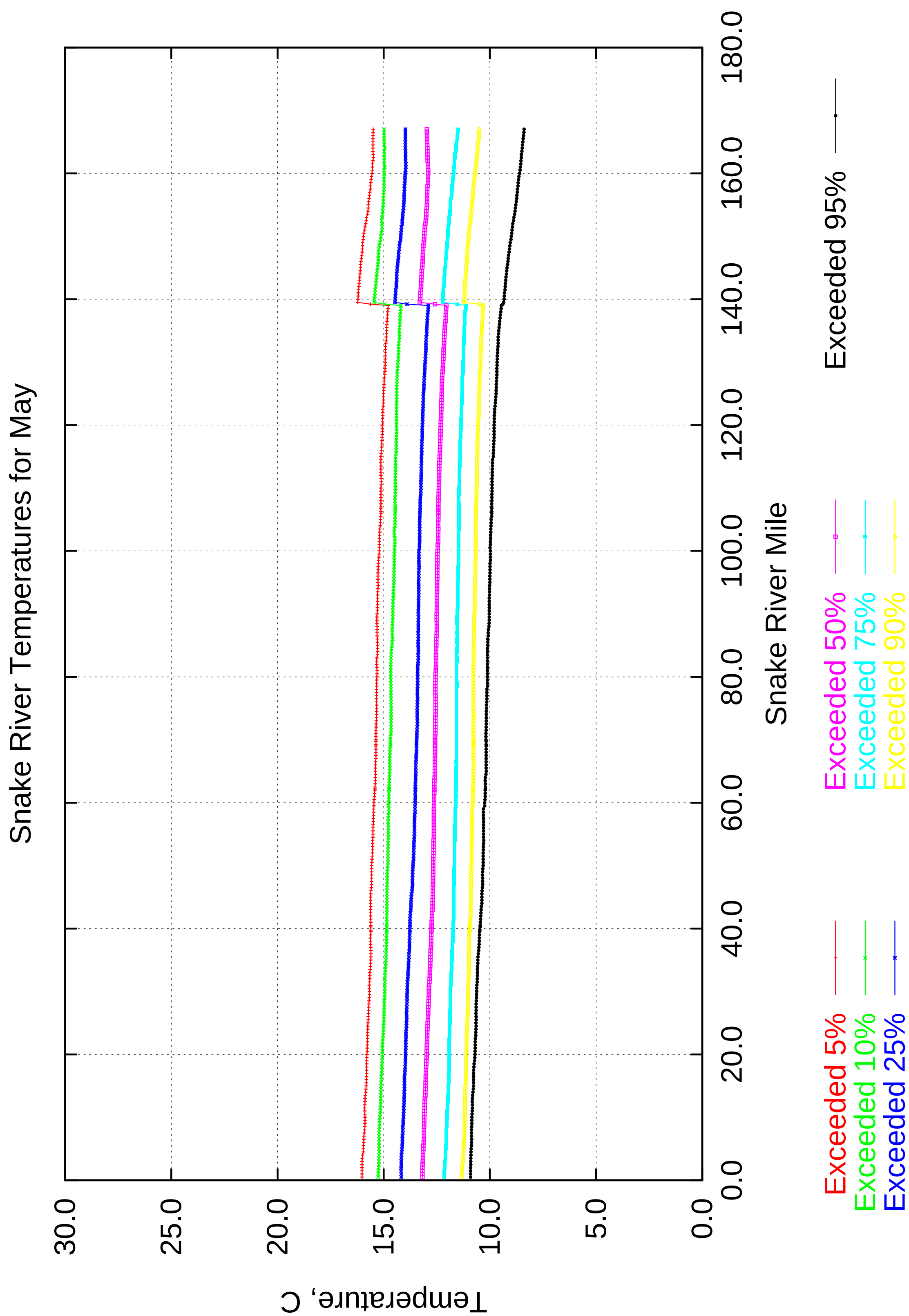

Figure 3.11: Summary of simulated temperature variation in May by Snake River mile for the unimpounded river scenario.

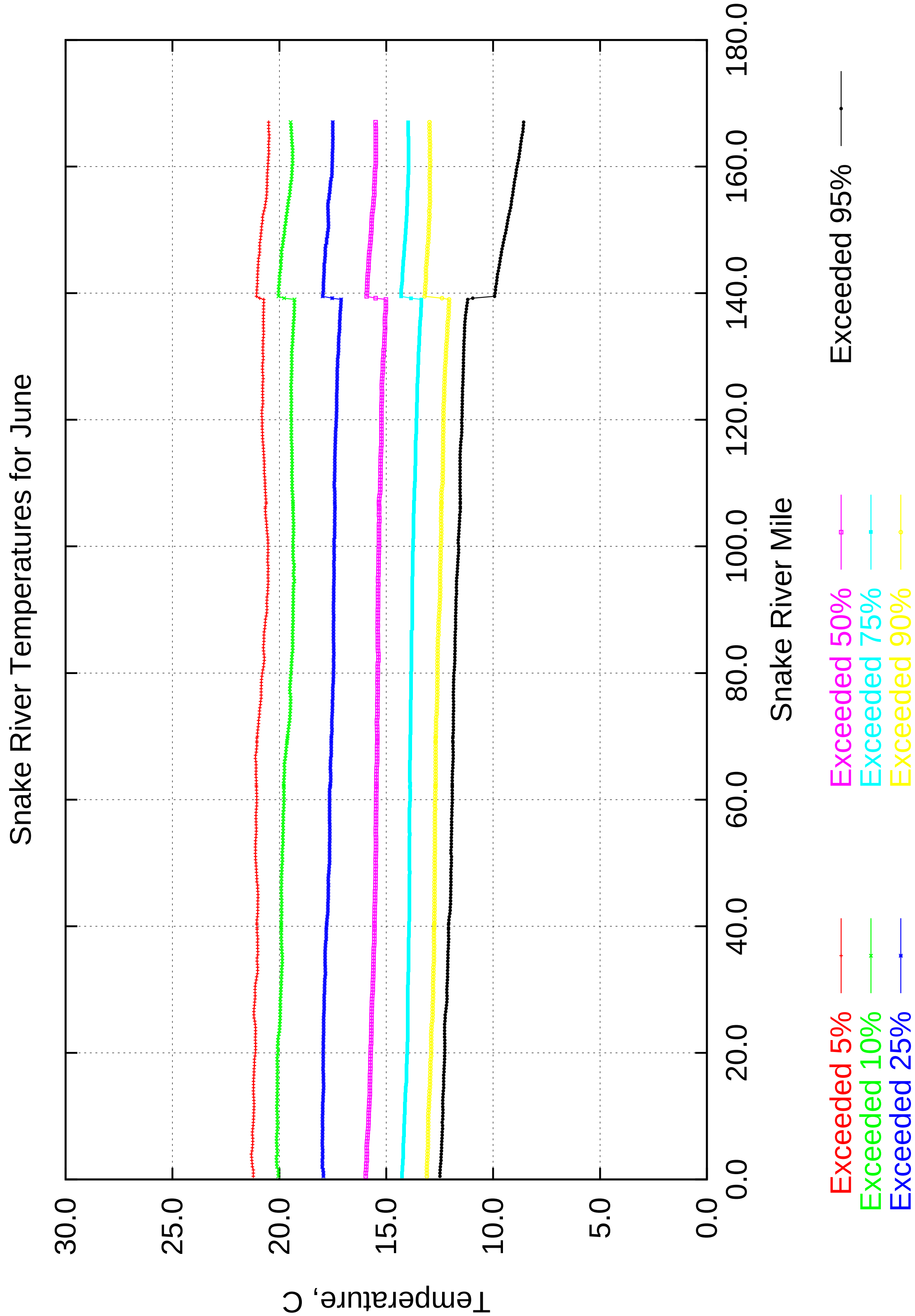

Figure 3.12: Summary of simulated temperature variation in June by Snake River mile for the unimpounded river scenario.

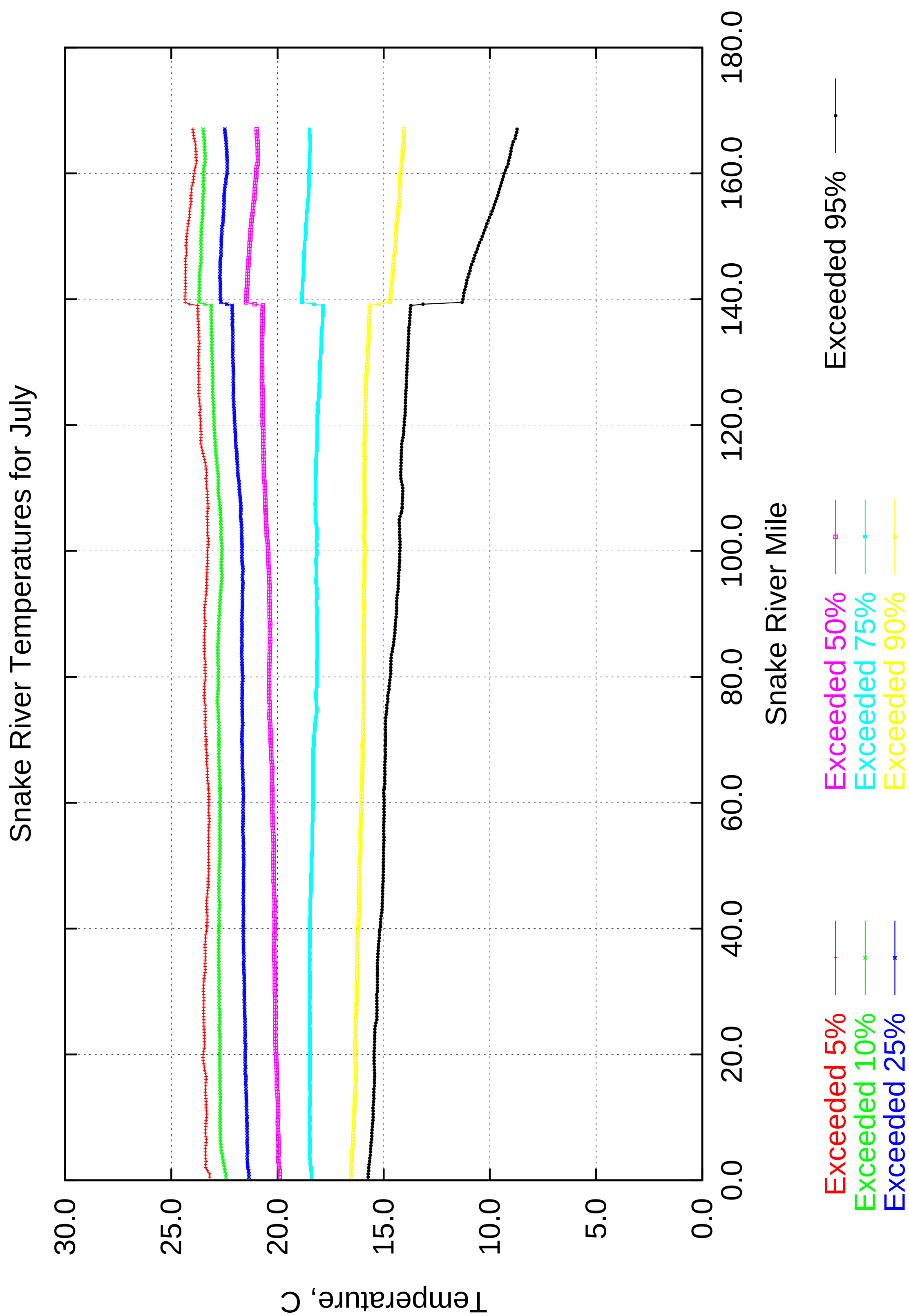

Figure 3.13: Summary of simulated temperature variation in July by Snake River mile for the unimpounded river scenario.

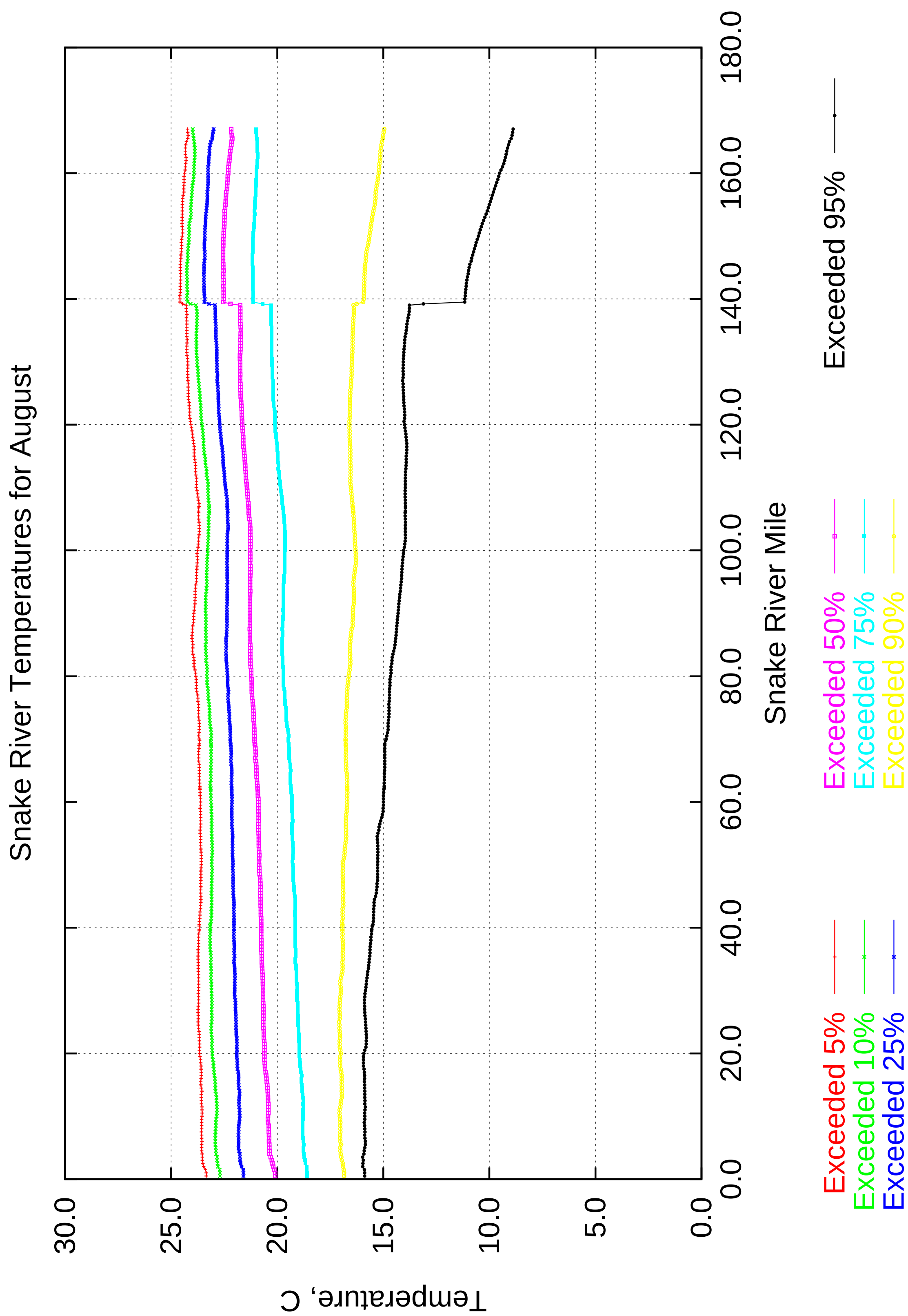

Figure 3.14: Summary of simulated temperature variation in August by Snake River mile for the unimpounded river scenario.

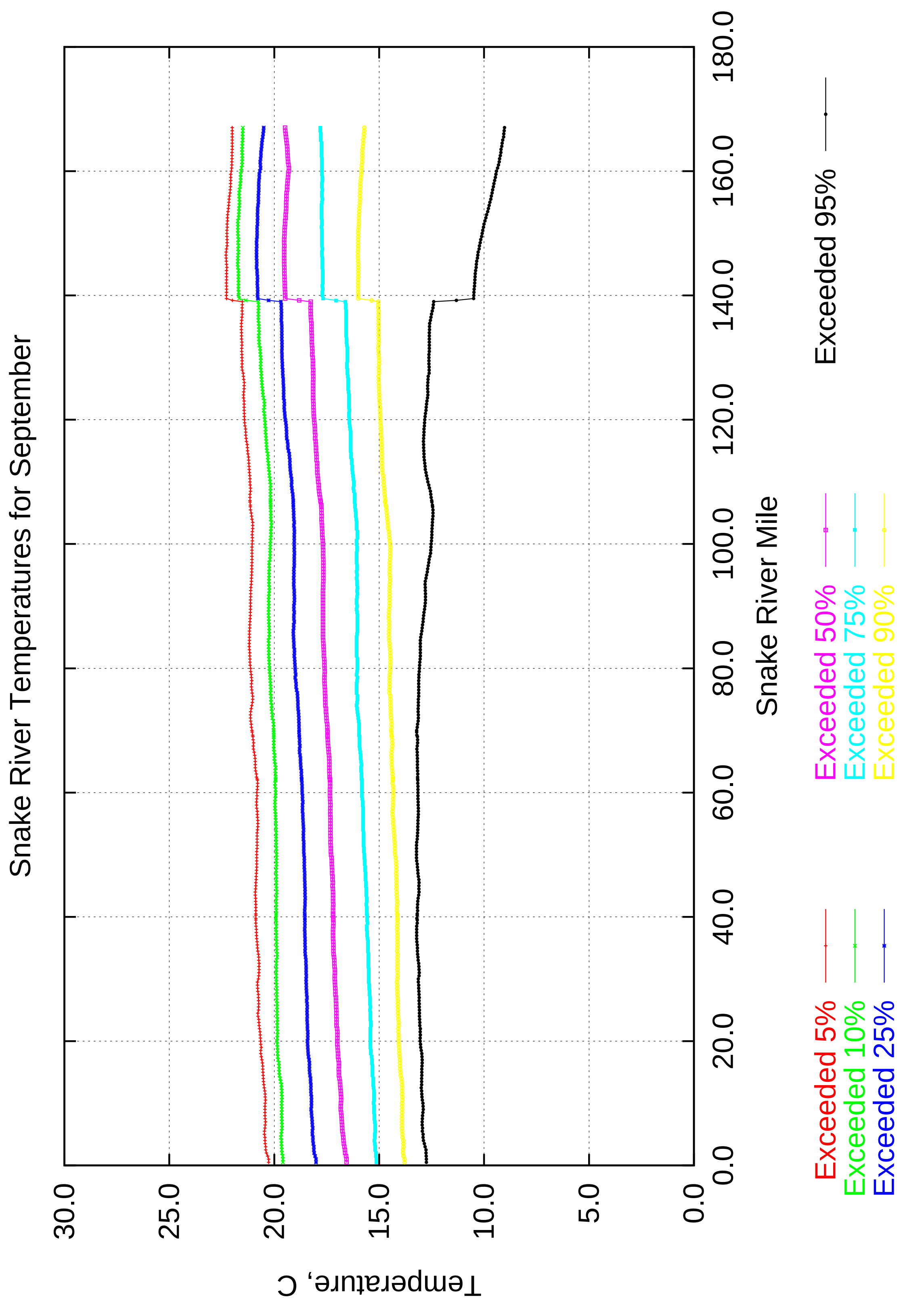

Figure 3.15: Summary of simulated temperature variation in September by Snake River mile for the unimpounded river scenario.

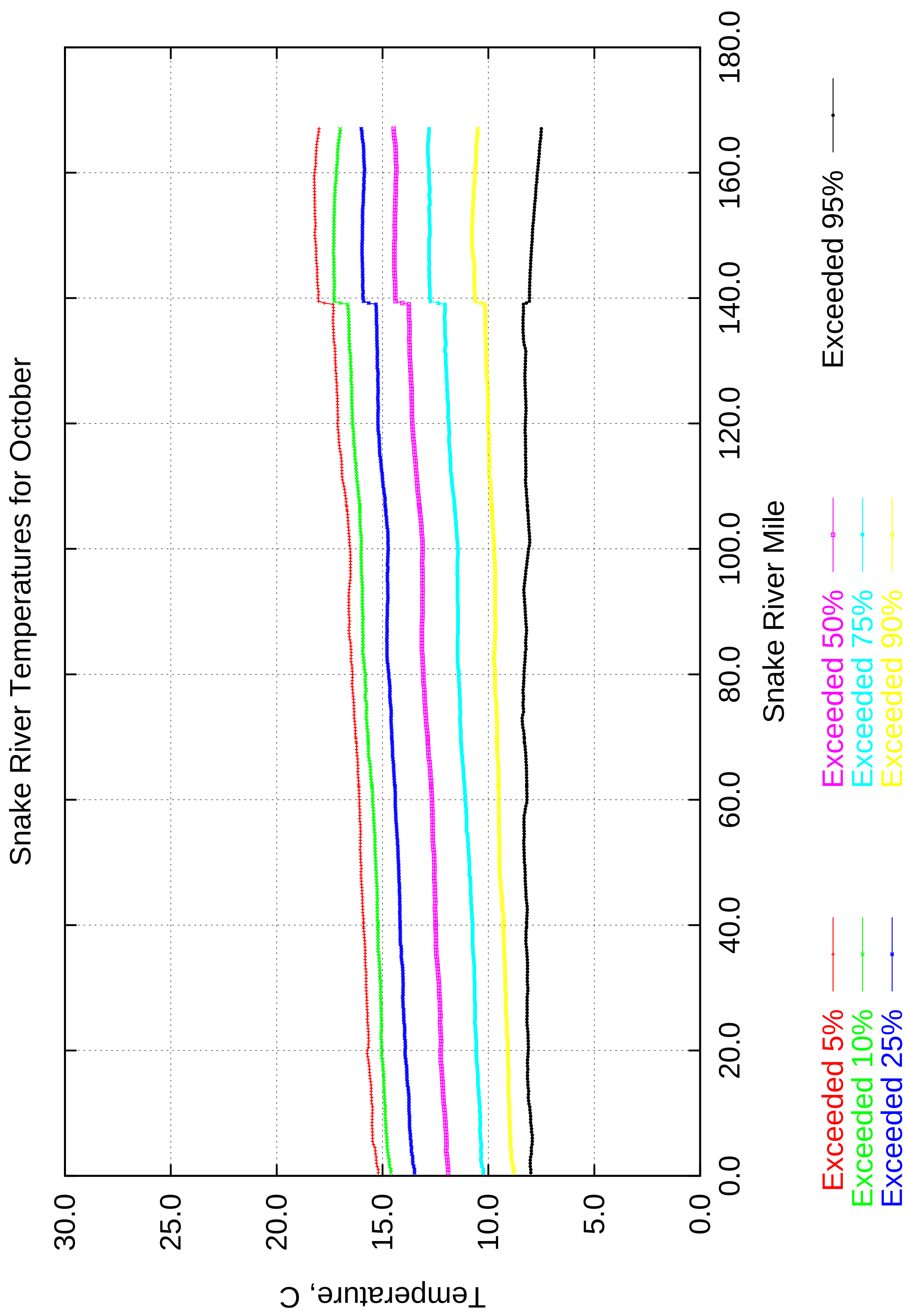

Figure 3.16: Summary of simulated temperature variation in October by Snake River mile for the unimpounded river scenario.

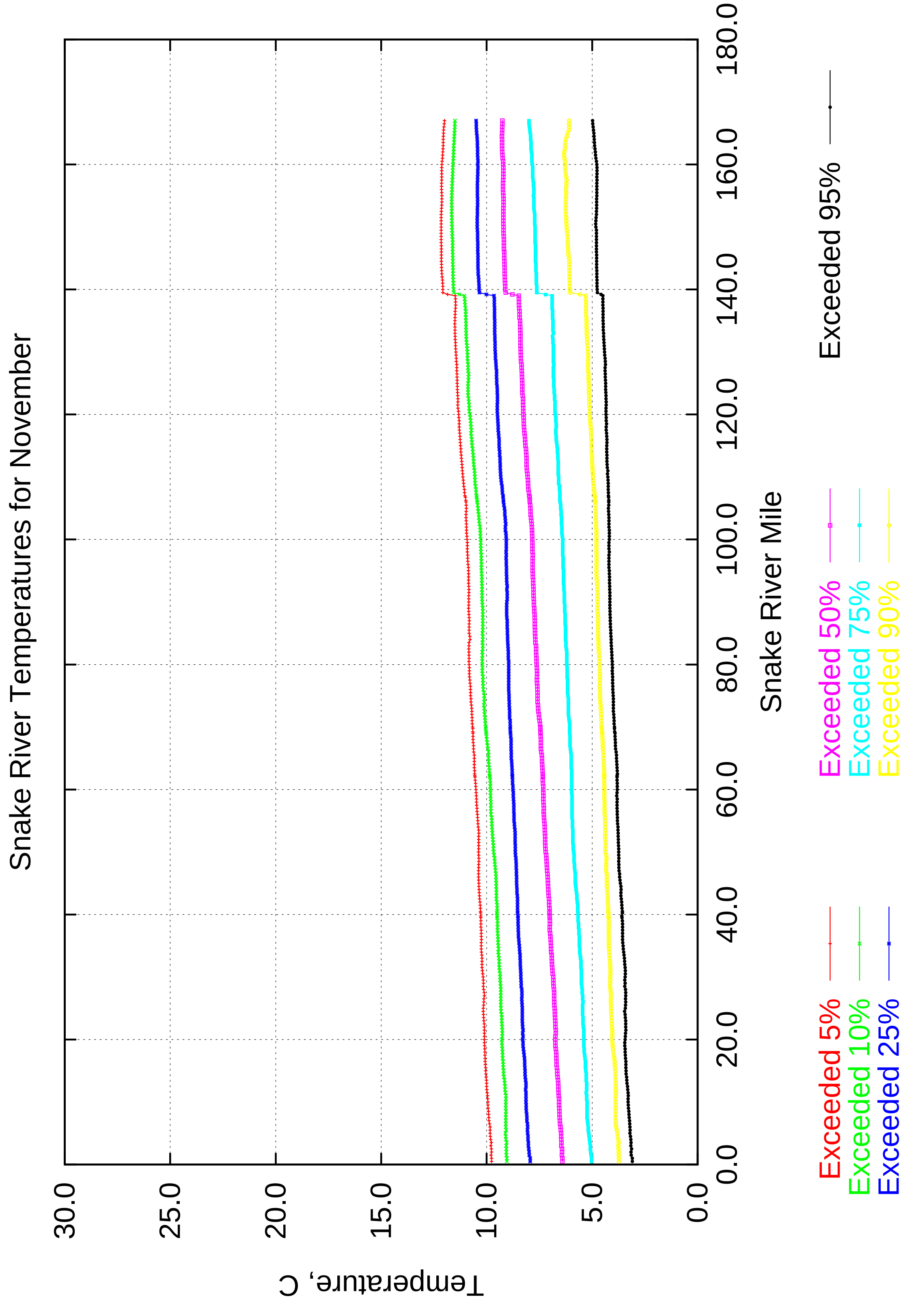

Figure 3.17: Summary of simulated temperature variation in November by Snake River mile for the unimpounded river scenario.

Table 3.2: Simulated temperature exceedance percentiles at selected Snake River locations for the unimpounded river scenario.

	River	Percent of Time Exceeded						
Month	Mile	5	10	25	50	75	90	95
January	9.50	4.79	4.26	3.20	2.04	0.92	0.23	0.10
	40.25	5.19	4.66	3.44	2.35	1.27	0.36	0.17
	70.00	5.65	4.90	3.45	2.54	1.63	0.74	0.25
	107.50	6.12	5.24	3.70	2.86	2.04	1.17	0.79
	139.00	6.64	5.59	3.93	3.16	2.42	1.56	1.25
	167.00	7.72	6.00	4.00	3.39	2.20	1.50	1.20
February	9.50	6.76	5.97	4.90	3.66	2.54	1.40	0.67
	40.25	6.90	6.13	5.06	3.88	2.71	1.68	1.03
	70.00	7.00	6.17	5.07	3.89	2.81	1.82	1.26
	107.50	7.05	6.27	5.06	3.93	2.93	1.97	1.61
	139.00	7.15	6.51	5.19	4.14	3.20	2.26	1.89
	167.00	7.86	6.83	5.00	3.97	3.00	2.00	1.50
March	9.50	9.99	9.42	8.28	7.05	5.81	4.70	4.01
	40.25	9.70	9.26	8.27	7.03	5.92	4.80	4.13
	70.00	9.67	9.16	8.27	7.03	5.87	4.85	4.21
	107.50	9.57	8.98	8.13	7.02	5.94	4.99	4.28
	139.00	9.58	8.93	8.08	7.01	5.95	5.14	4.53
	167.00	9.88	9.00	8.00	6.60	5.98	4.95	4.00
April	9.50	13.72	13.14	11.81	10.67	9.57	8.75	8.29
	40.25	13.54	12.77	11.65	10.50	9.37	8.57	8.24
	70.00	13.26	12.48	11.40	10.29	9.19	8.42	8.10
	107.50	12.94	12.25	11.22	10.23	9.21	8.50	8.08
	139.00	12.64	12.01	11.02	10.03	9.06	8.32	7.93
	167.00	13.00	12.47	11.00	10.00	9.00	8.22	7.97
May	9.50	15.88	15.19	14.08	13.09	12.03	11.19	10.85
	40.25	15.61	14.86	13.77	12.75	11.73	10.95	10.46
	70.00	15.37	14.69	13.45	12.58	11.56	10.77	10.19
	107.50	15.13	14.46	13.28	12.43	11.46	10.65	9.92
	139.00	14.79	14.19	12.90	12.05	11.13	10.31	9.46
	167.00	15.50	14.98	13.98	12.97	11.50	10.50	8.39
June	9.50	21.21	20.09	17.98	15.83	14.15	13.04	12.36
	40.25	21.05	19.91	17.79	15.55	13.94	12.76	12.09
	70.00	21.03	19.61	17.56	15.42	13.88	12.68	11.88
	107.50	20.63	19.37	17.41	15.33	13.69	12.42	11.54
	139.00	20.73	19.29	17.11	15.02	13.35	12.06	11.19
	167.00	20.50	19.47	17.50	15.50	13.98	12.98	8.57
July	9.50	23.36	22.70	21.45	19.99	18.48	16.40	15.51
	40.25	23.33	22.76	21.61	20.14	18.48	16.20	15.15
	70.00	23.36	22.75	21.68	20.33	18.29	15.97	14.91
	107.50	23.28	22.73	21.73	20.57	18.22	15.90	14.13

Table 3.2: (continued)

Month	River Mile	Percent of Time Exceeded 5	10	25	50	75	90	95
	139.00	23.76	23.12	22.13	20.69	17.86	15.66	13.72
	167.00	23.98	23.50	22.48	20.98	18.50	14.07	8.72
August	9.50	23.56	22.88	21.78	20.44	18.79	17.03	15.87
	40.25	23.68	23.16	22.05	20.76	19.15	16.93	15.52
	70.00	23.68	23.12	22.21	21.07	19.47	16.78	14.87
	107.50	23.69	23.22	22.36	21.36	19.76	16.46	13.96
	139.00	24.29	23.83	22.94	21.75	20.28	16.40	13.77
	167.00	24.23	23.98	23.00	22.17	21.00	14.96	8.88
September	9.50	20.44	19.65	18.23	16.83	15.25	13.90	12.91
	40.25	20.88	19.91	18.54	17.20	15.57	14.13	13.19
	70.00	21.06	20.03	18.81	17.47	15.95	14.43	13.21
	107.50	21.16	20.18	19.11	17.82	16.17	14.72	12.52
	139.00	21.52	20.76	19.68	18.26	16.61	15.04	12.40
	167.00	22.00	21.50	20.50	19.48	17.80	15.71	9.03
October	9.50	15.49	14.87	13.73	12.05	10.39	9.01	8.01
	40.25	15.90	15.21	14.17	12.49	10.75	9.30	8.20
	70.00	16.27	15.70	14.56	12.87	11.30	9.59	8.31
	107.50	16.72	16.09	14.89	13.28	11.62	9.86	8.17
	139.00	17.34	16.65	15.31	13.76	12.06	10.16	8.35
	167.00	18.00	17.00	16.00	14.48	12.80	10.50	7.50
November	9.50	9.94	9.10	8.13	6.57	5.24	3.89	3.29
	40.25	10.29	9.52	8.53	7.02	5.67	4.23	3.57
	70.00	10.67	10.05	8.88	7.46	6.07	4.55	3.94
	107.50	11.05	10.50	9.25	8.00	6.53	4.89	4.23
	139.00	11.49	11.06	9.65	8.48	6.90	5.30	4.49
	167.00	12.00	11.50	10.50	9.25	8.00	6.10	4.98

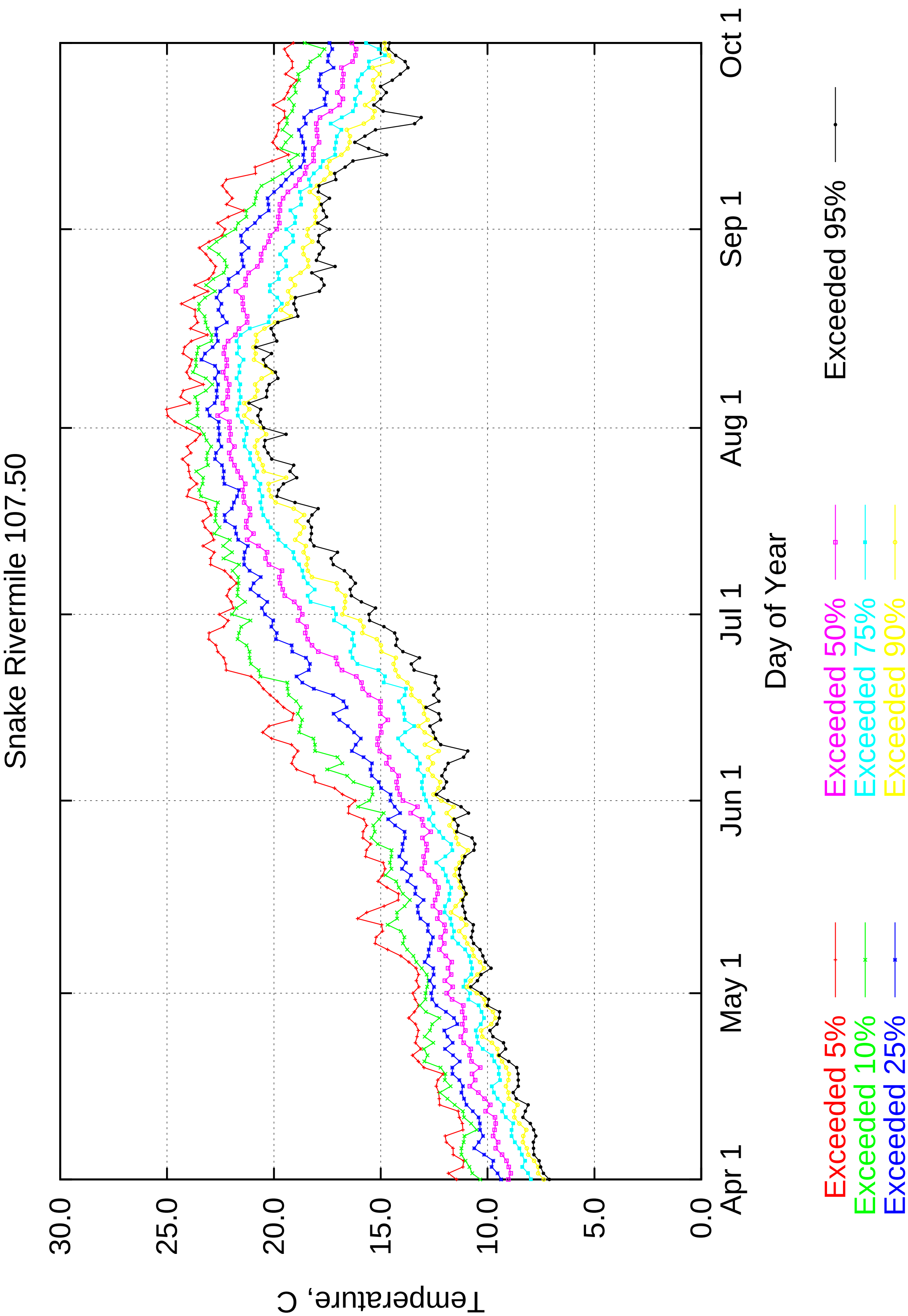

Figure 3.18: Summary of simulated temperature variation at Snake River mile 107.5 (Lower Granite Dam) in the unimpounded river scenario.

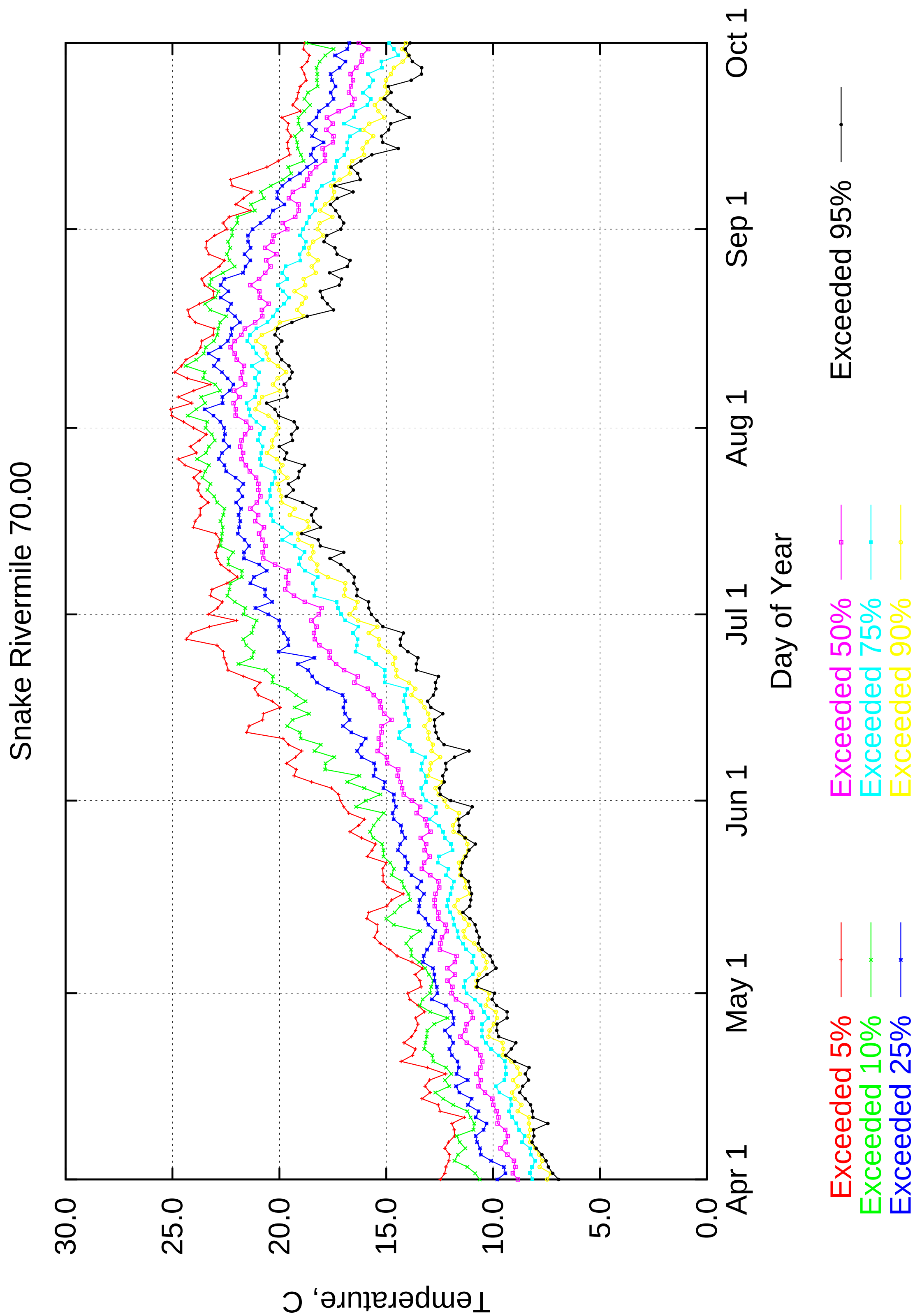

Figure 3.19: Summary of simulated temperature variation at Snake River mile 70.0 (Little Goose Dam).

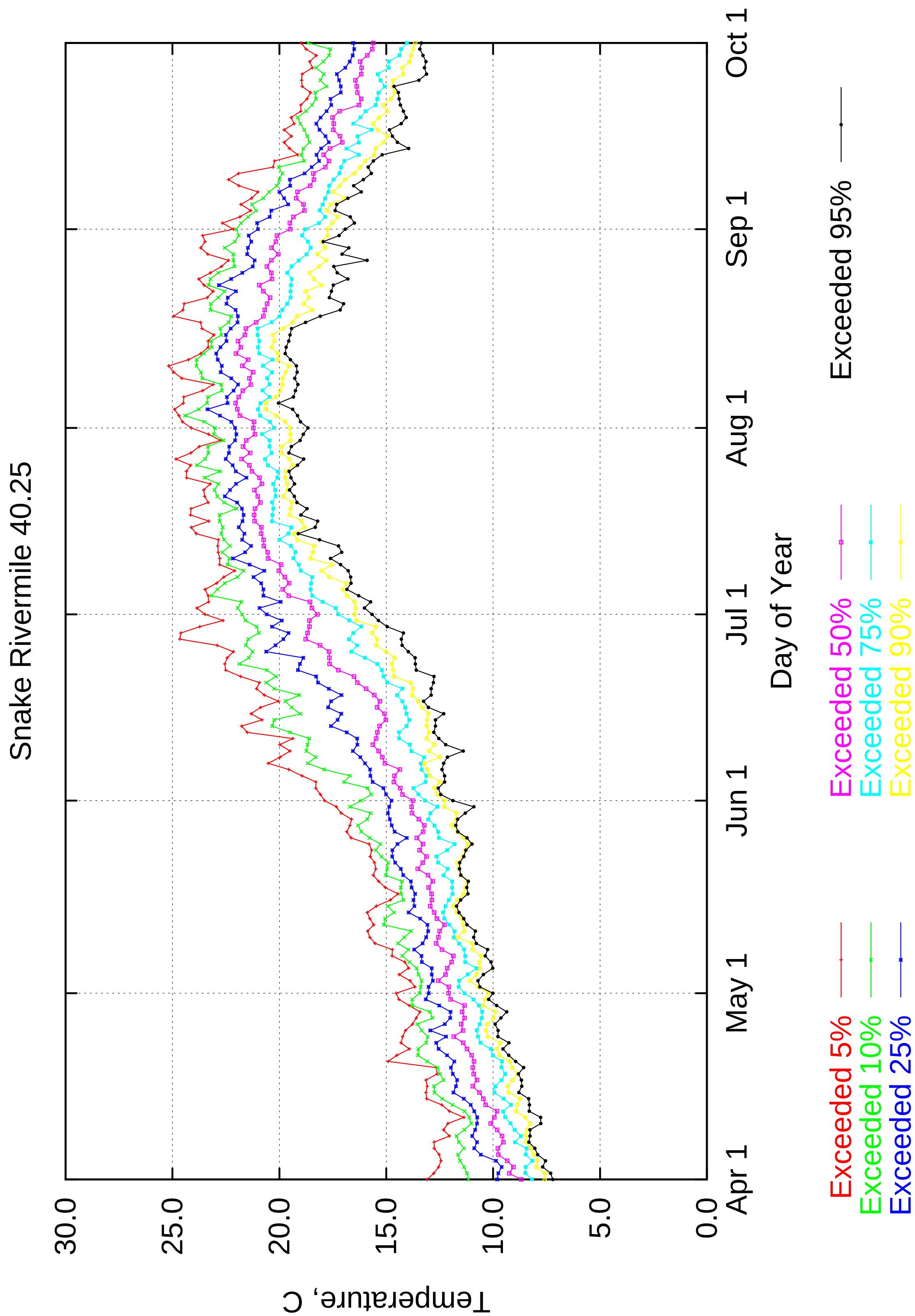

Figure 3.20: Summary of simulated temperature variation at Snake River mile 40.25 (Lower Monumental Dam).

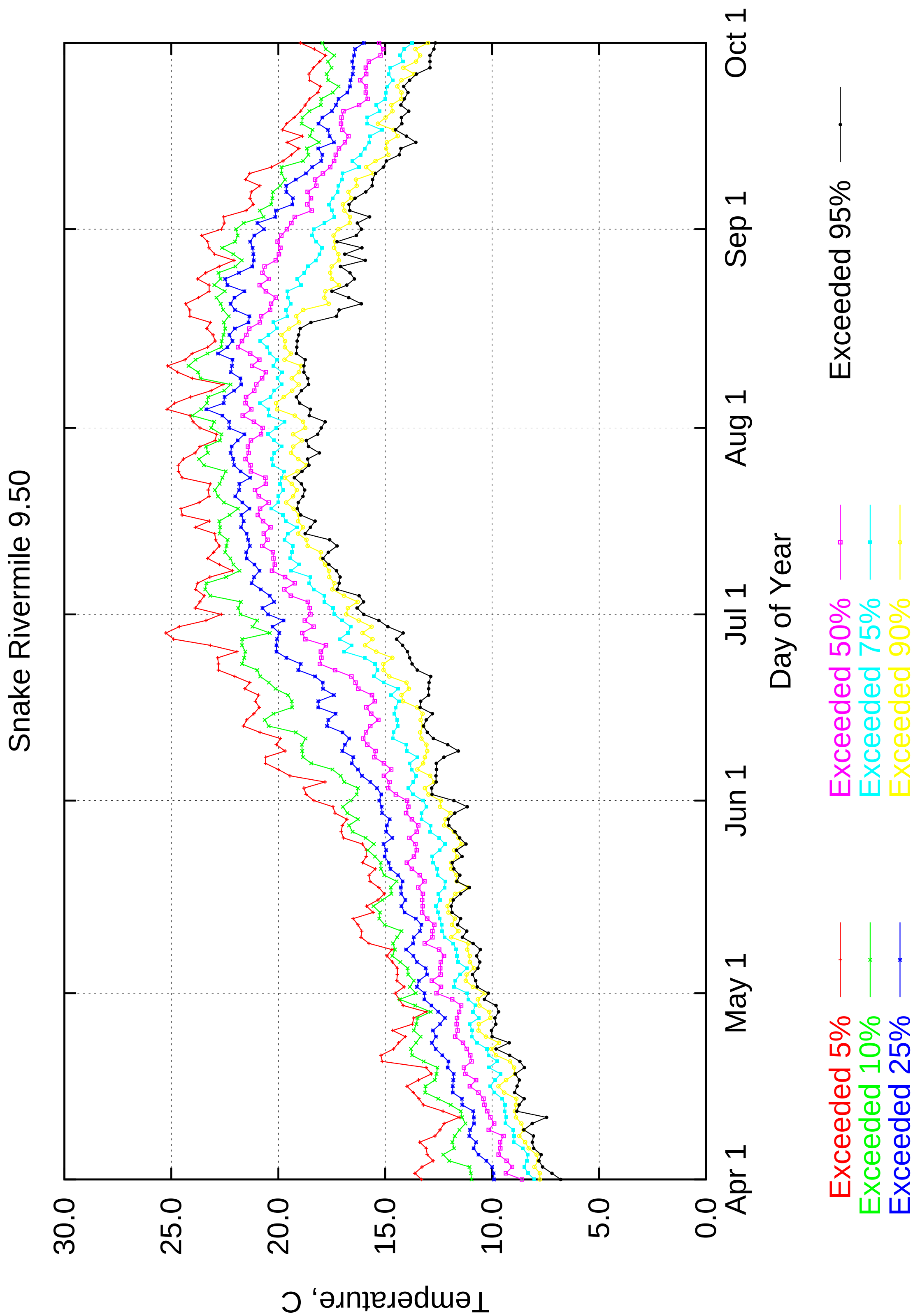

Figure 3.21: Summary of simulated temperature variation at Snake River mile 9.5 (Ice Harbor Dam) during the unimpounded river scenario.

Table 3.3: Statistical summaries of the day of year when simulated Snake River temperatures rose above or fell below various levels in the unimpounded river scenario simulation.

Location	River Mile	Temperature Level	Percent Time Exceeded				
			10	25	50	75	90
Anatone	167.00	> 10.0	160	159	155	152	146
	167.00	> 15.0	212	208	202	195	184
	167.00	> 20.0	225	222	214	207	200
	167.00	> 25.0	239	239	239	215	215
	167.00	< 10.0	328	324	323	315	310
	167.00	< 15.0	300	298	293	289	282
	167.00	< 20.0	268	265	259	252	240
	167.00	< 25.0	241	241	241	218	200
Lower Granite	107.50	> 10.0	165	162	158	151	147
	107.50	> 15.0	214	211	203	197	187
	107.50	> 20.0	223	222	214	211	202
	107.50	> 25.0	229	229	229	229	216
	107.50	< 10.0	319	314	312	308	304
	107.50	< 15.0	290	289	282	277	271
	107.50	< 20.0	256	250	243	234	229
	107.50	< 25.0	231	231	231	231	217
Little Goose	70.00	> 10.0	165	161	157	151	145
	70.00	> 15.0	211	209	203	198	181
	70.00	> 20.0	223	222	216	211	200
	70.00	> 25.0	216	216	216	207	207
	70.00	< 10.0	314	314	309	306	302
	70.00	< 15.0	284	282	277	275	268
	70.00	< 20.0	248	240	236	229	217
	70.00	< 25.0	217	217	217	208	182
Lower Monumental	40.25	> 10.0	165	162	156	149	143
	40.25	> 15.0	209	208	204	195	182
	40.25	> 20.0	222	222	217	210	203
	40.25	> 25.0	233	233	216	216	207
	40.25	< 10.0	311	311	306	303	299
	40.25	< 15.0	281	280	277	270	263
	40.25	< 20.0	239	236	234	230	211
	40.25	< 25.0	234	234	217	217	209
Ice Harbor	9.50	> 10.0	161	159	156	149	141
	9.50	> 15.0	209	207	203	192	181
	9.50	> 20.0	228	226	221	216	199
	9.50	> 25.0	217	217	207	207	199
	9.50	< 10.0	310	309	306	301	297
	9.50	< 15.0	281	278	277	265	257
	9.50	< 20.0	248	239	234	227	213
	9.50	< 25.0	218	218	209	209	200

4 Current Conditions Scenario

In the current conditions scenario, the lower Snake River was represented as it is today. MASS1 was configured to represent the lower Snake River, and part of the Columbia River, including existing dams. Water temperature was simulated for the same period as for the unimpounded river scenario (Section 3) using the same upstream boundary conditions and meteorology.

4.1 MASS1 Model Development

For the current conditions scenario simulation, MASS1 was configured similarly to the verification simulations (Section 2.2), except that the Clearwater arm was shortened. A schematic of the configuration is shown in Figure 4.1. The modeled extent of the Clearwater River was shortened, from 40 river miles to about 11 river miles, in order to use flows and temperatures from the USGS gage at Spalding (13342500), which has a considerably longer record than at Orofino and on the North Fork. Note, in Figure 4.1, link number 3 remains in the model, but is assigned zero flow and does not represent any portion of the Clearwater River. This was done in order to maintain the same topology, i.e., link and node numbering and connectivity, as was used in the verification simulations. This was done in order to avoid a completely new MASS1 configuration. Links number 5 and 6 represent the approximately 12 miles of Clearwater between the gage at Spaulding and the mouth.

A small portion of the Columbia was also included in the simulations. This was also done to be consistent with verification simulations. Simulated temperatures from the Columbia were not analyzed.

4.2 Boundary Conditions

The sources of boundary condition data are summarized in Table 4.1. The upstream Snake and Clearwater River flow and temperature boundary conditions used for the current conditions scenario were identical to those used in the unimpounded river scenario (Section 3.2). In addition, constant stages were used at each of the lower Snake dams and a constant, artificial flow was supplied in the Columbia River.

4.3 Meteorology

A single weather zone was used for the current conditions scenario simulation. The same meteorology data used in the unimpounded river scenario simulation (Section 3.3) was used for the current conditions scenario.

4.4 Results

The current conditions MASS1 simulation was performed from January 15, 1960 to June 30, 1995. A hydrodynamic time step of 0.2 hours (12 minutes) was used; the transport time step was 0.02

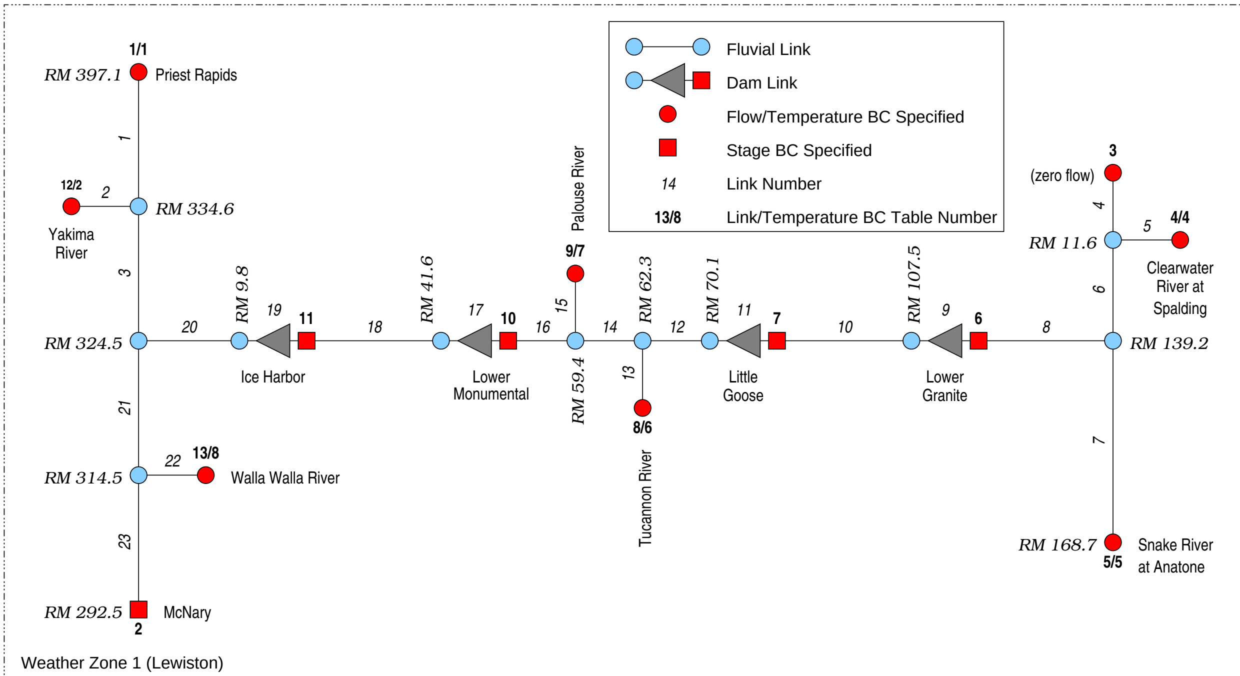

Figure 4.1: MASS1 configuration used for the current conditions scenario simulation.

Table 4.1: Sources of data used for boundary conditions during the current conditions scenario simulation.

Boundary	Data	Frequency	Source
Snake River	daily	Flow	USGS Gage 13334300
	daily	Temperature	USGS Gage 13334300
Clearwater River	daily	Flow	USGS Gage 13342500
	daily	Temperature	USGS Gage 13342500
Lower Granite Dam	Stage	constant	738.0 ft
Little Goose Dam	Stage	constant	635 ft
Tucannon River	Flow	daily	USGS Gage 13344500
	Temperature	month avg.	USGS Gages 13344500 and 13344520
Palouse River	Flow	daily	13344500
	Temperature	month avg.	13344500
Lower Monumental Dam	Stage	constant	540 ft
Ice Harbor Dam	Stage	constant	440.0 ft
Priest Rapids Dam	Flow	constant	200.0 kcfs
Yakima River	Flow	constant	1.0 kcfs
Walla Walla River	Flow	constant	1.0 kcfs
McNary Dam	Stage	constant	340.0 ft

hours (1.2 minutes). As with the unimpounded river scenario (Section 3.4), the maximum daily temperature was saved at daily intervals. The statistical summaries shown below are based on those daily maximums. The simulation was continued through the times of missing data shown in Figure 3.2, but these times were not included in the statistical computations.

Figures 4.2 and 4.3 show some sample plots of simulated temperature data in 1988 and 1991, respectively. The upper graph of these figures shows simulated temperatures at several locations; the lower graph shows some temperature profiles at individual simulation time steps.

Figures 4.4 through 4.14 summarize, by month, simulated temperatures as a function of Snake River mile. These were produced as described in Section 3.4 for the unimpounded river scenario. Table 4.2 lists those values presented in Figures 4.4 through 4.14 for dam locations.

Figures 4.15, 4.16, 4.17, and 4.18 summarize temperature exceedance values for each day of the year at dam locations. Table 4.3 summarizes when during the year the temperature rose above and fell below certain levels. See Section 3.4 for a description of how these figures were prepared. Direct comparisons of these results to those from the unimpounded river scenario are presented in Section 5.

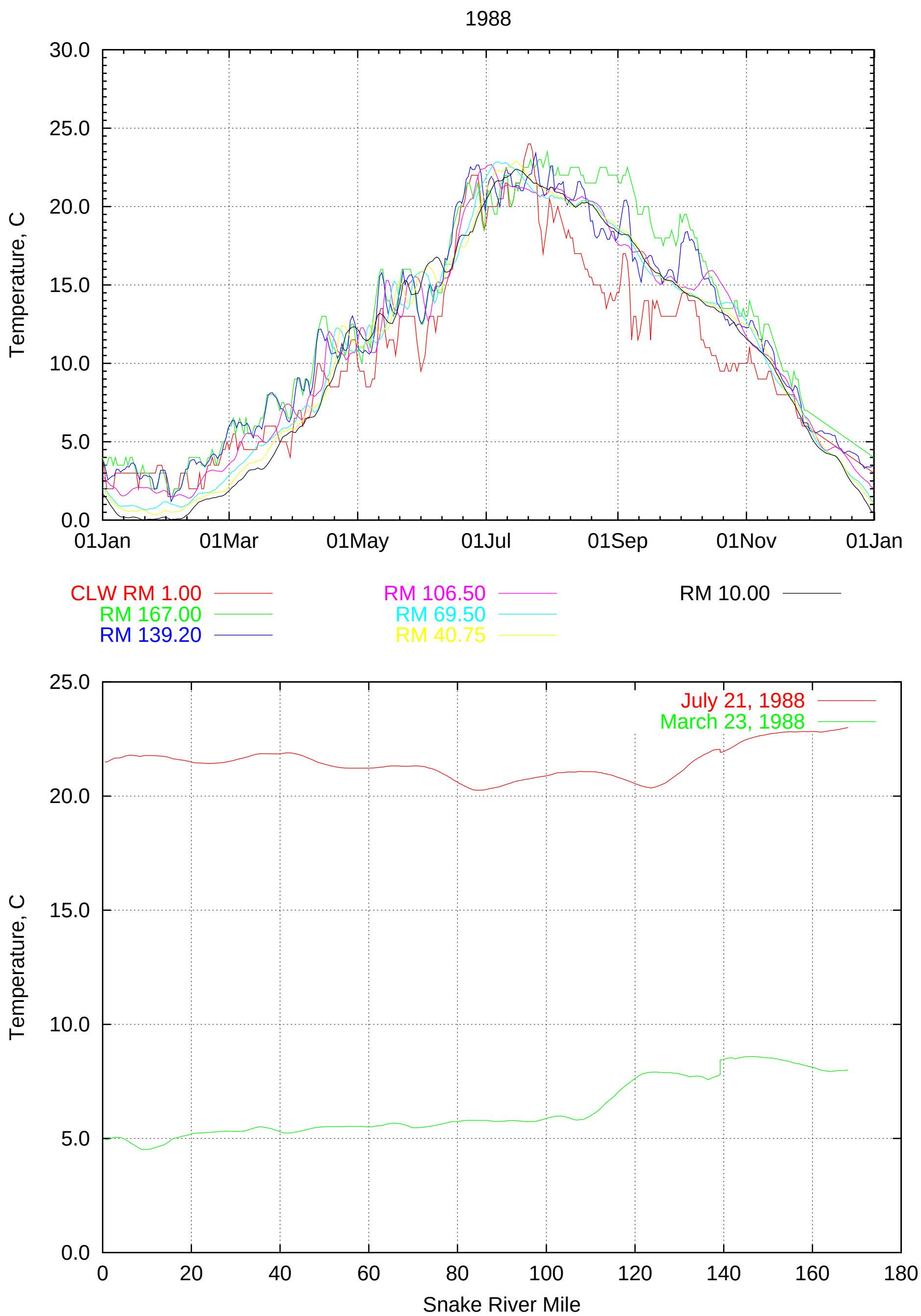

Figure 4.2: Time series (above) and sample profile plots (below) of Snake River temperatures simulated during 1988 in the current conditions scenario.

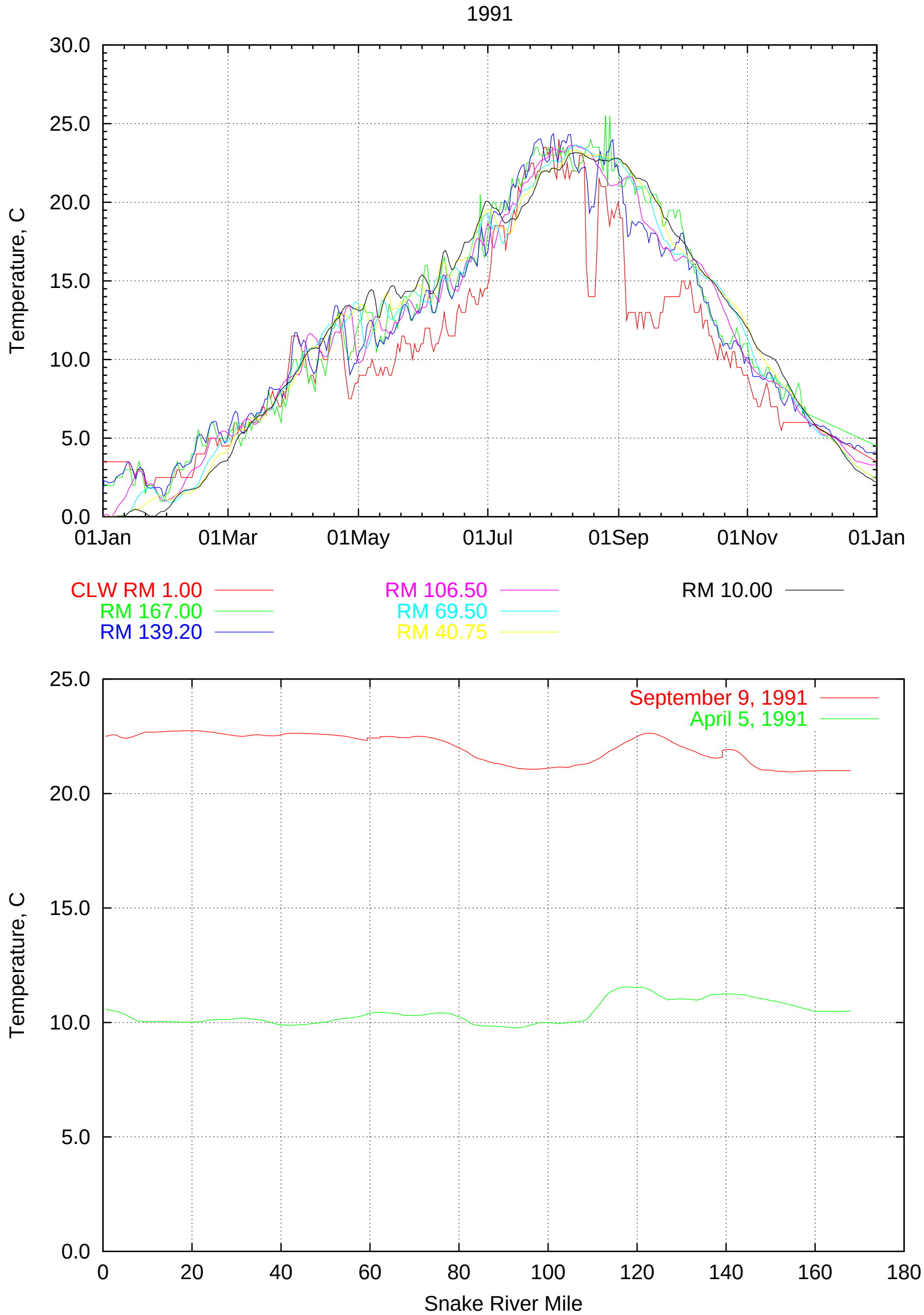

Figure 4.3: Time series (above) and sample profile plots (below) of Snake River temperatures simulated during 1991 in the current conditions scenario.

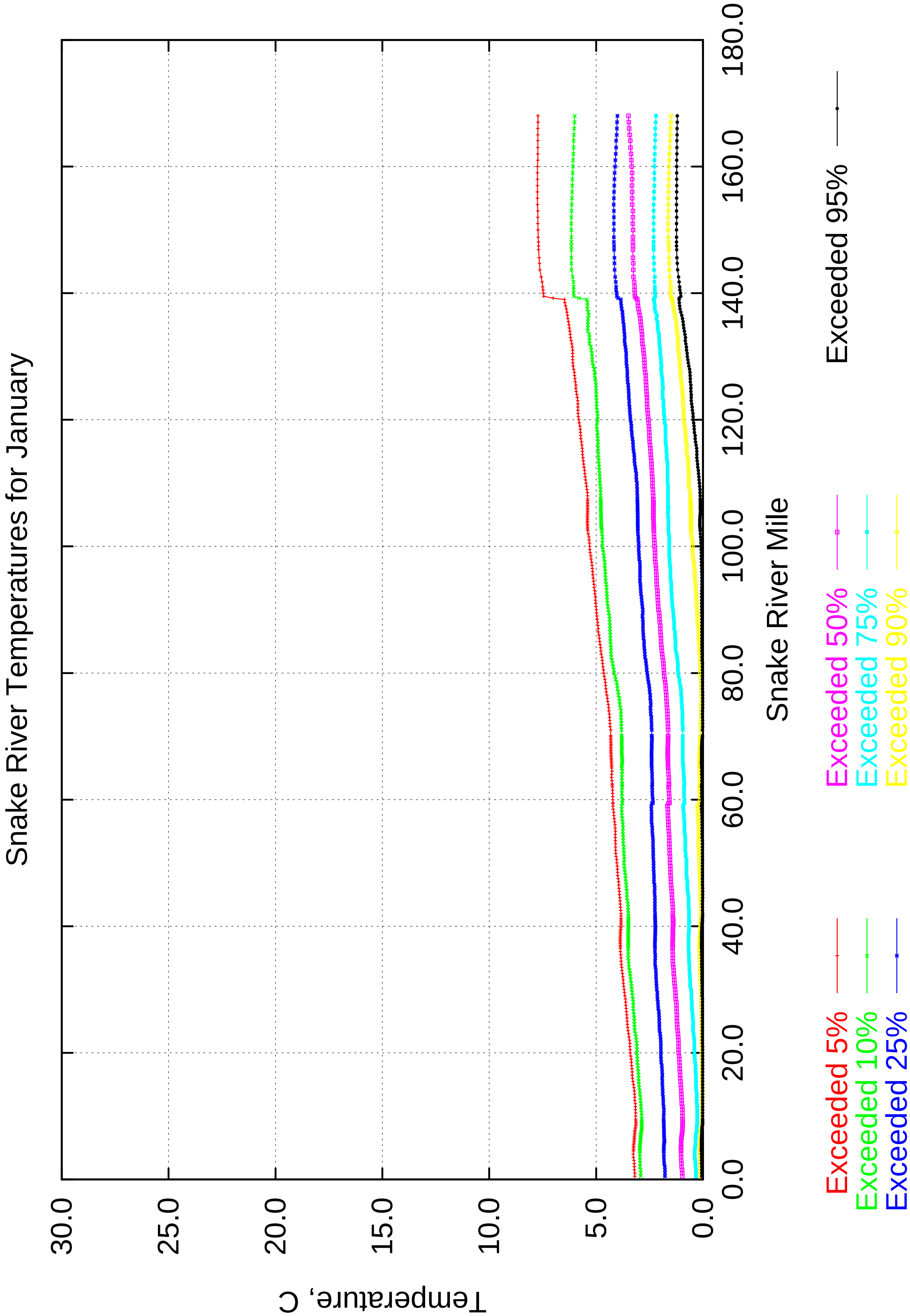

Figure 4.4: Summary of simulated temperature variation in January by Snake River mile for the current conditions scenario. Individual lines *do not* represent a single profile, but only connect similar exceedance values for each rivermile.

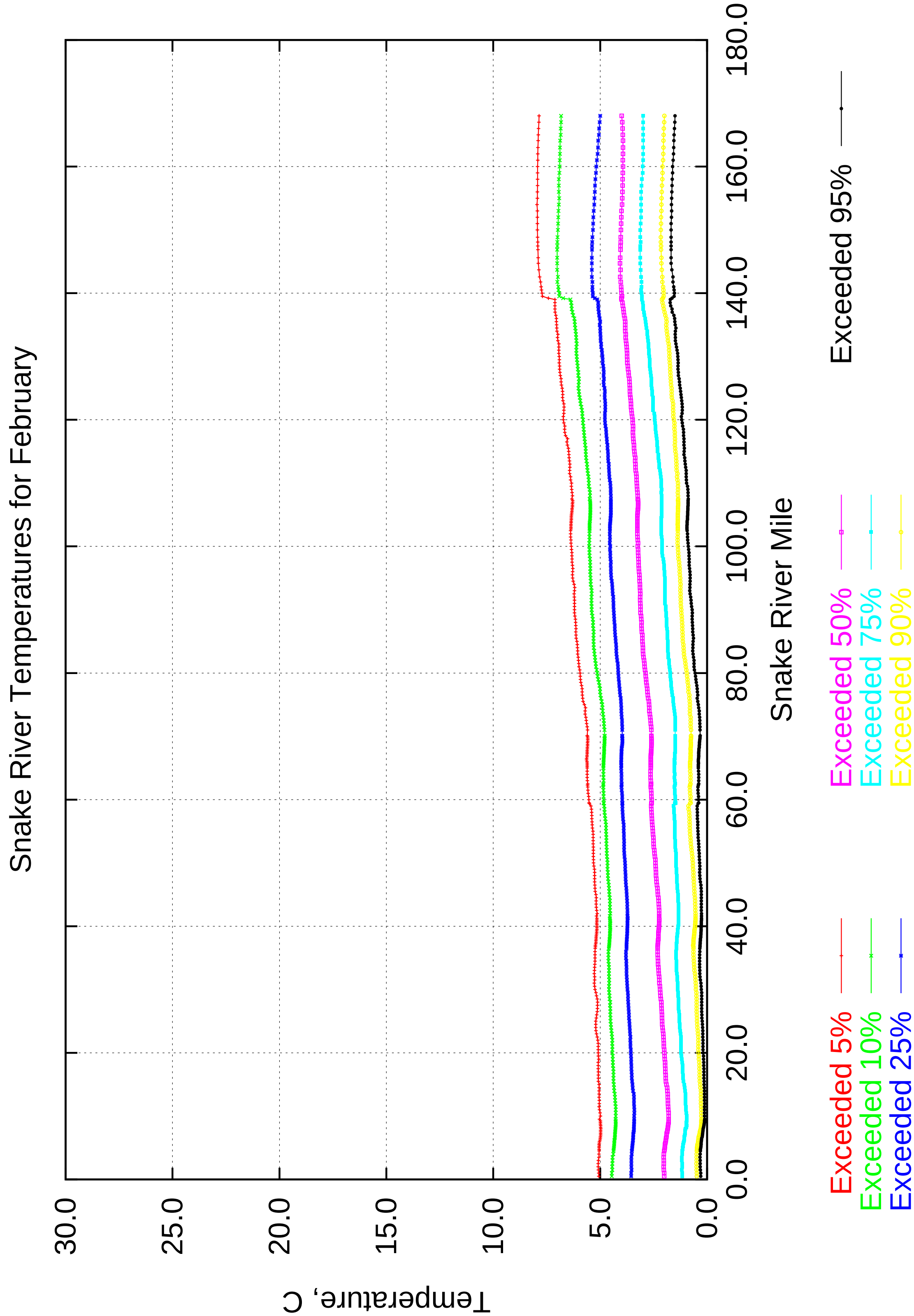

Figure 4.5: Summary of simulated temperature variation in February by Snake River mile for the current conditions scenario.

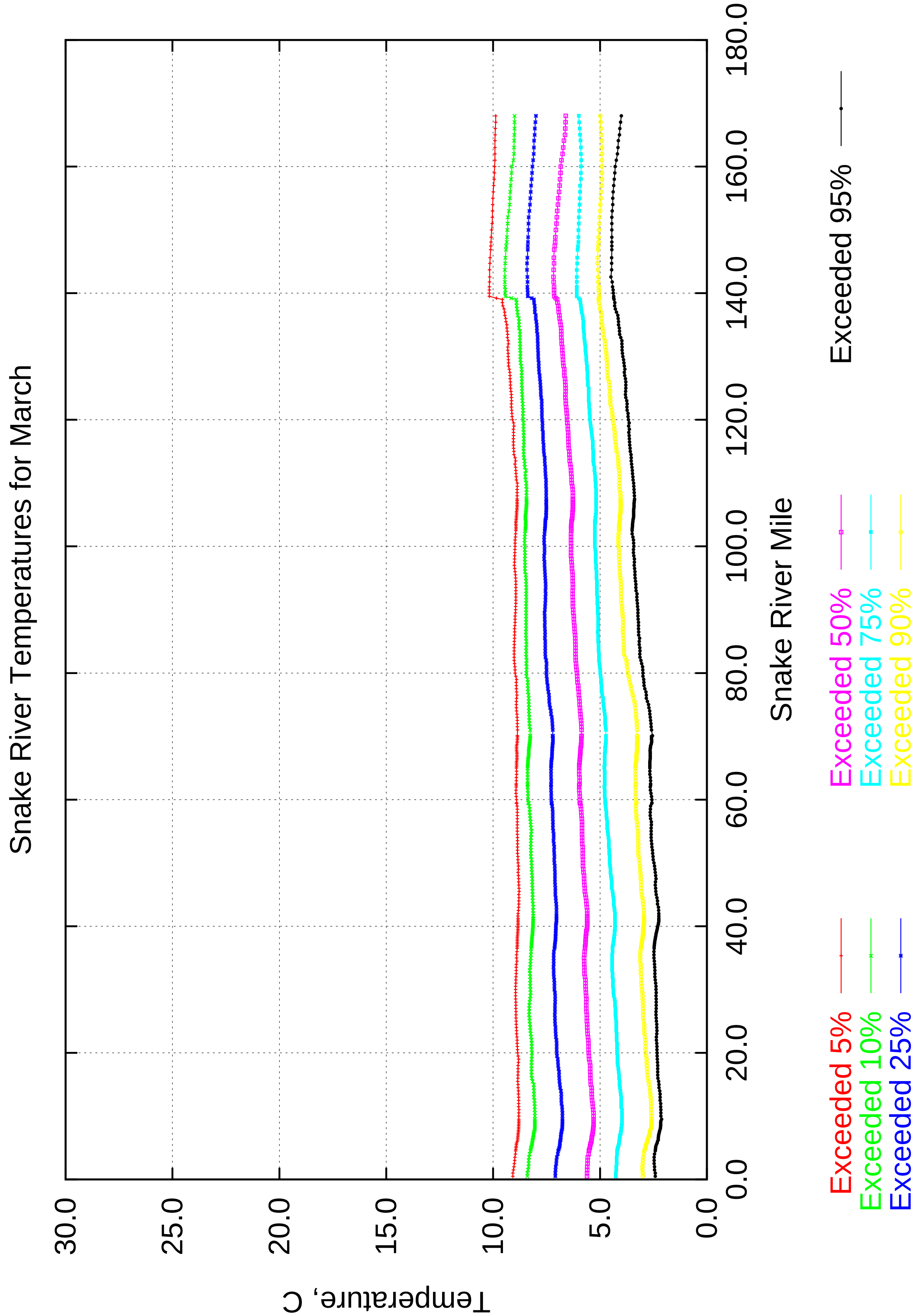

Figure 4.6: Summary of simulated temperature variation in March by Snake River mile for the current conditions scenario.

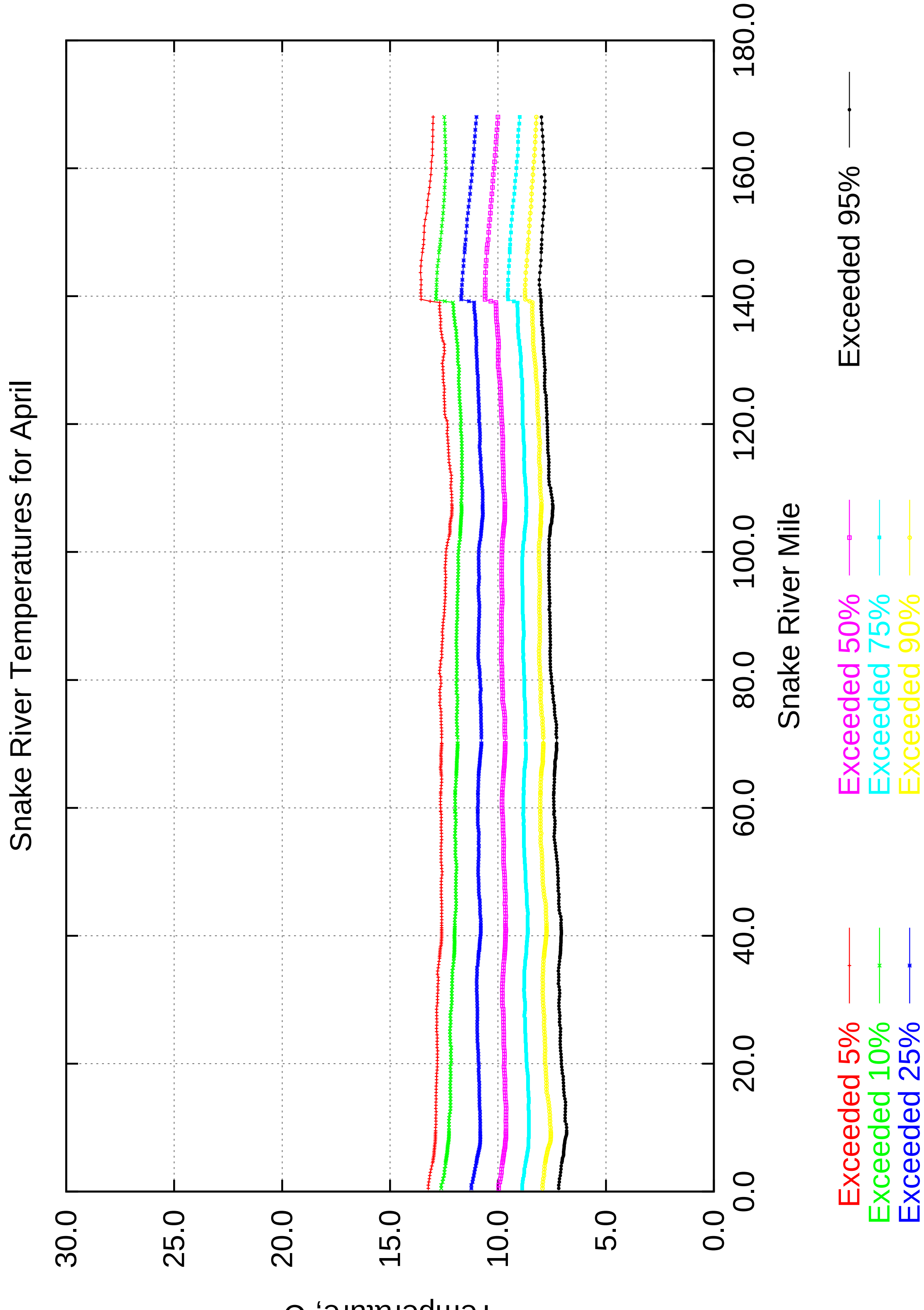

Figure 4.7: Summary of simulated temperature variation in April by Snake River mile for the current conditions scenario.

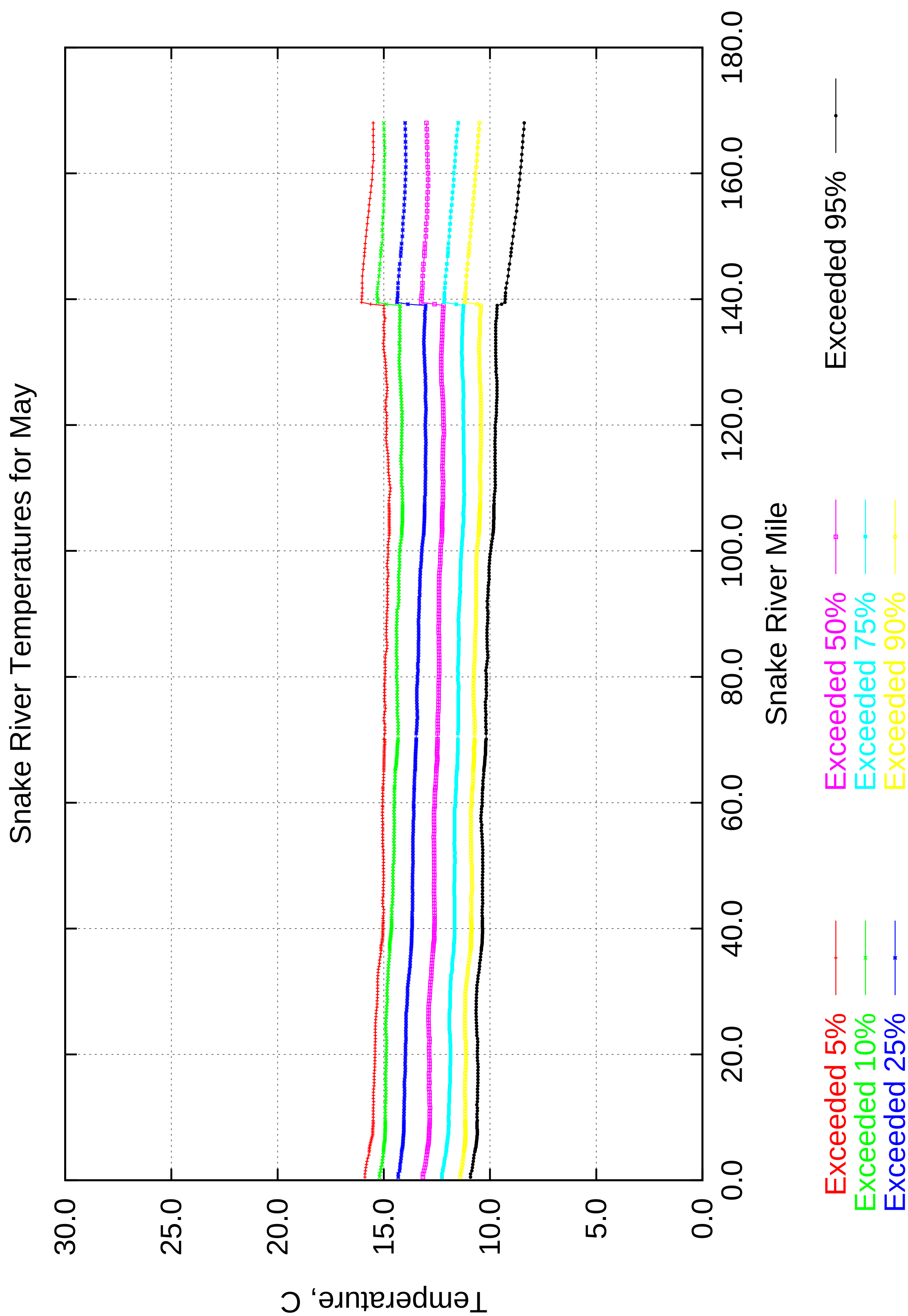

Figure 4.8: Summary of simulated temperature variation in May by Snake River mile for the current conditions scenario.

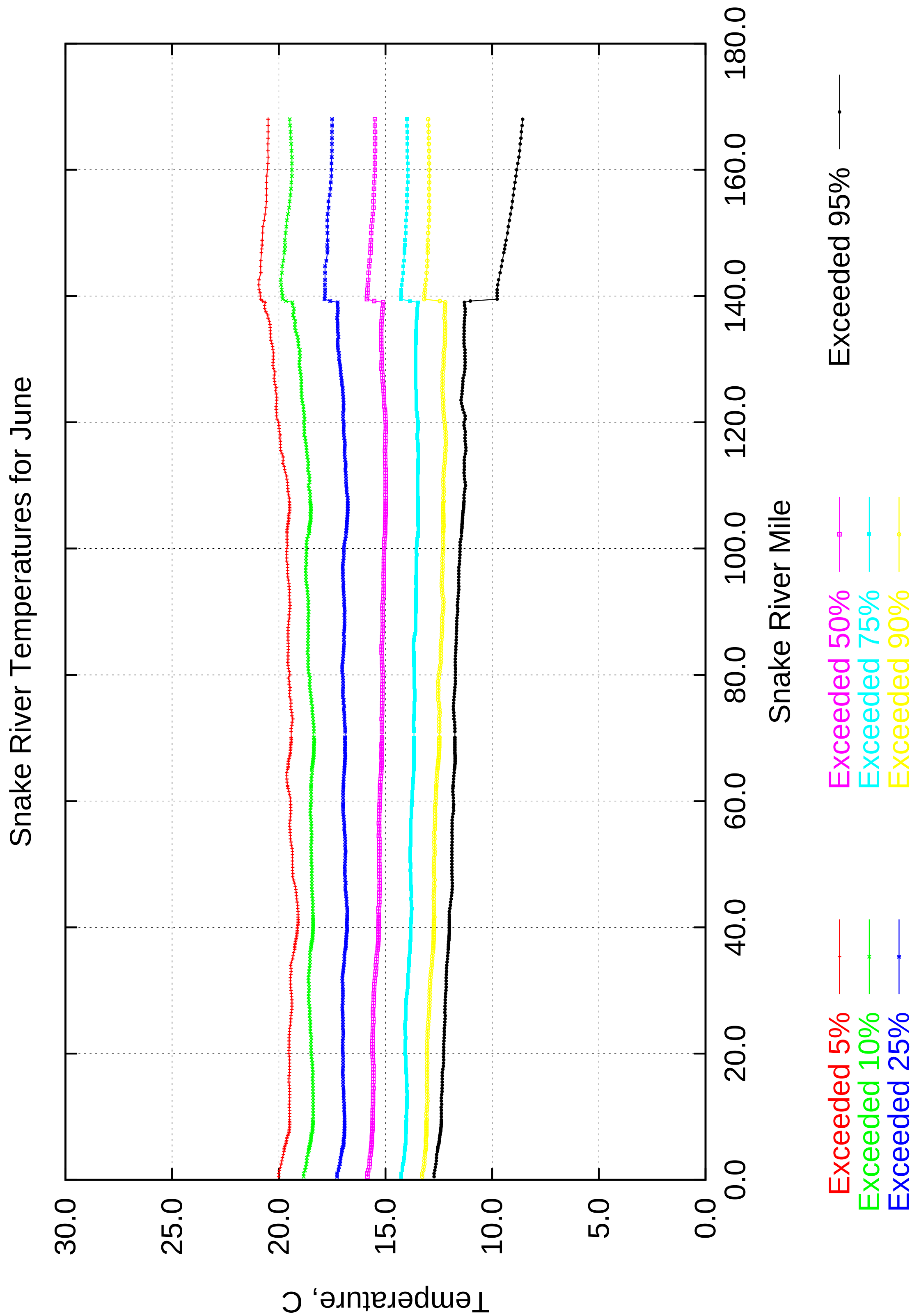

Figure 4.9: Summary of simulated temperature variation in June by Snake River mile for the current conditions scenario.

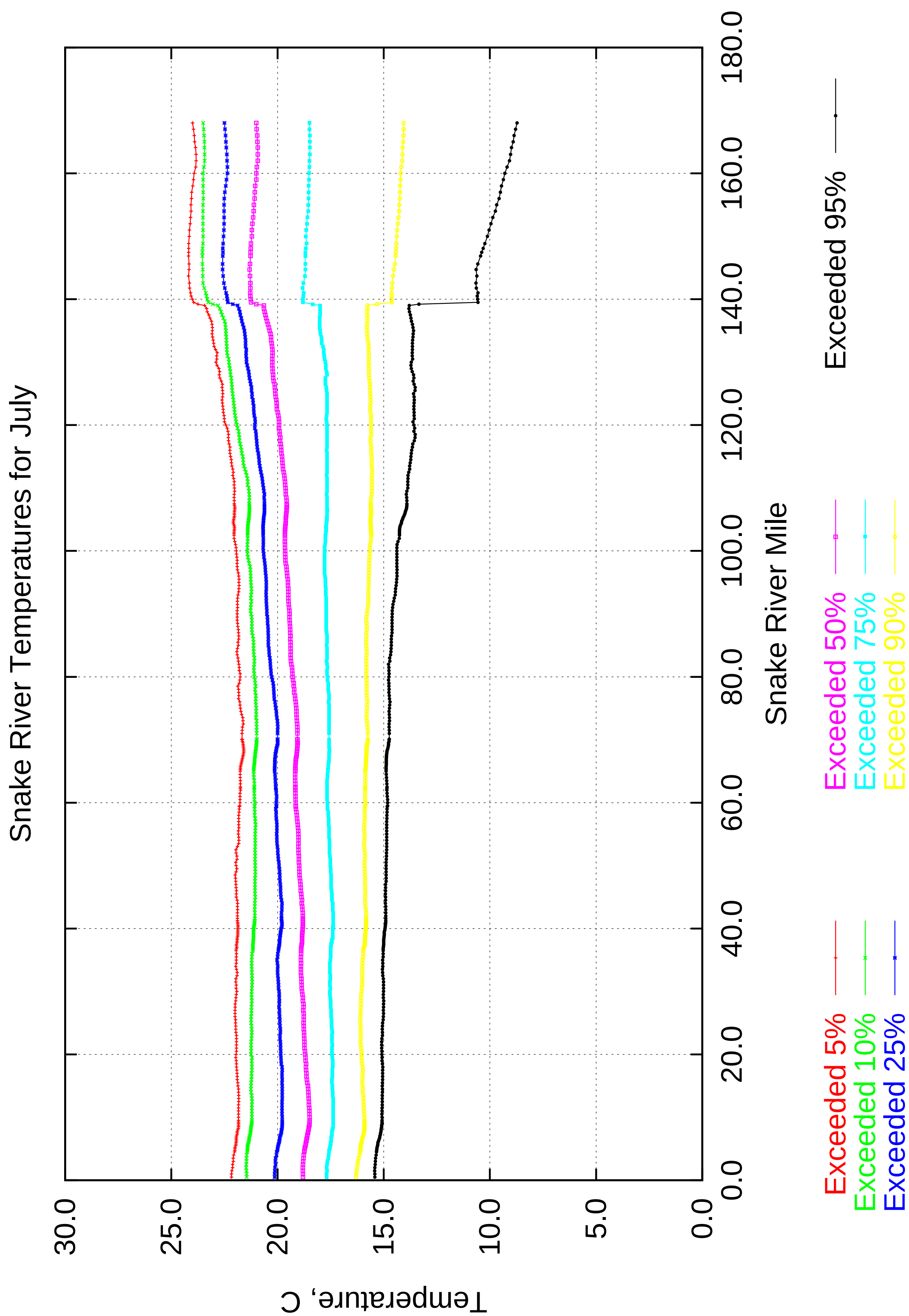

Figure 4.10: Summary of simulated temperature variation in July by Snake River mile for the current conditions scenario.

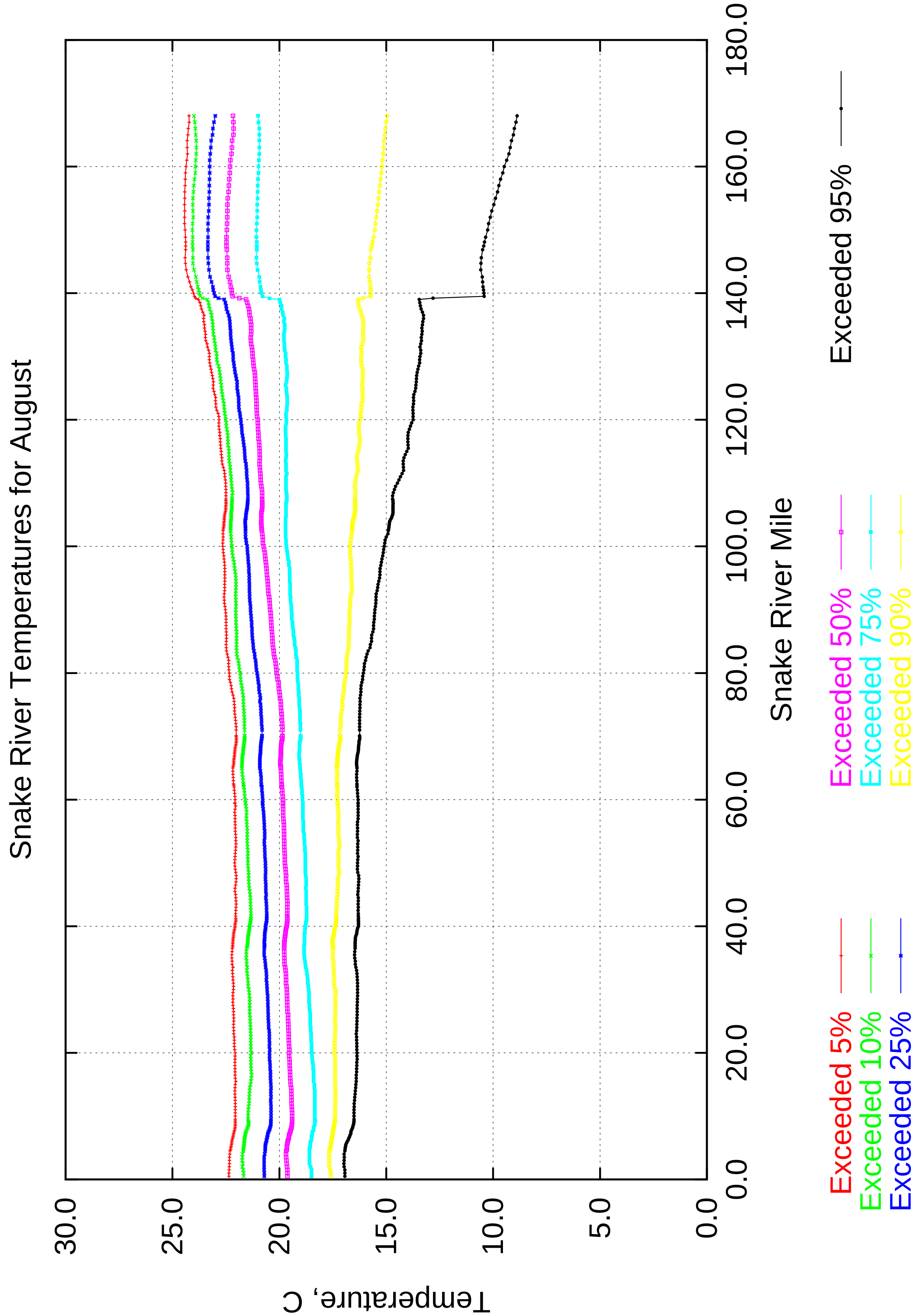

Figure 4.11: Summary of simulated temperature variation in August by Snake River mile for the current conditions scenario.

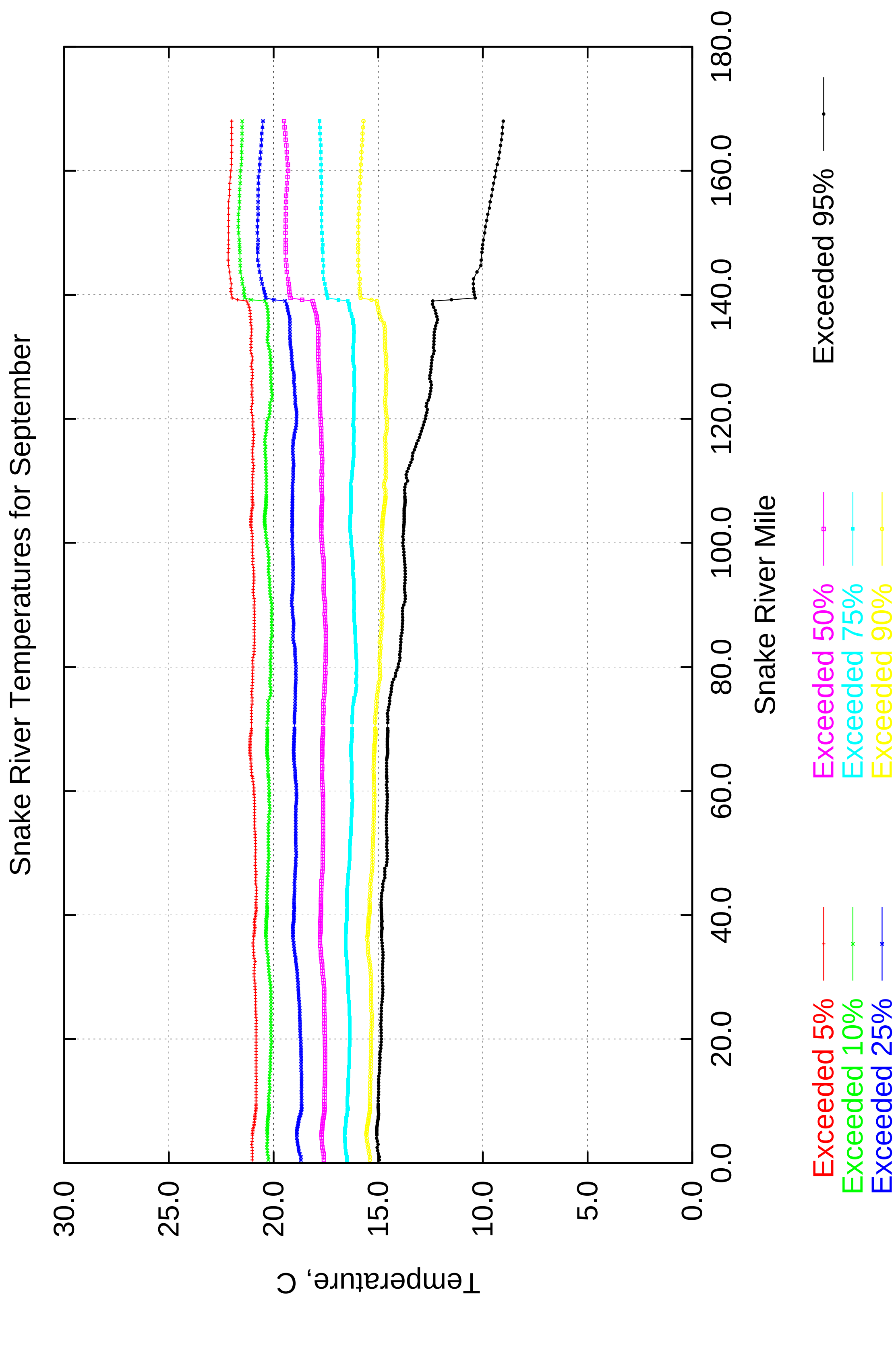

Figure 4.12: Summary of simulated temperature variation in September by Snake River mile for the current conditions scenario.

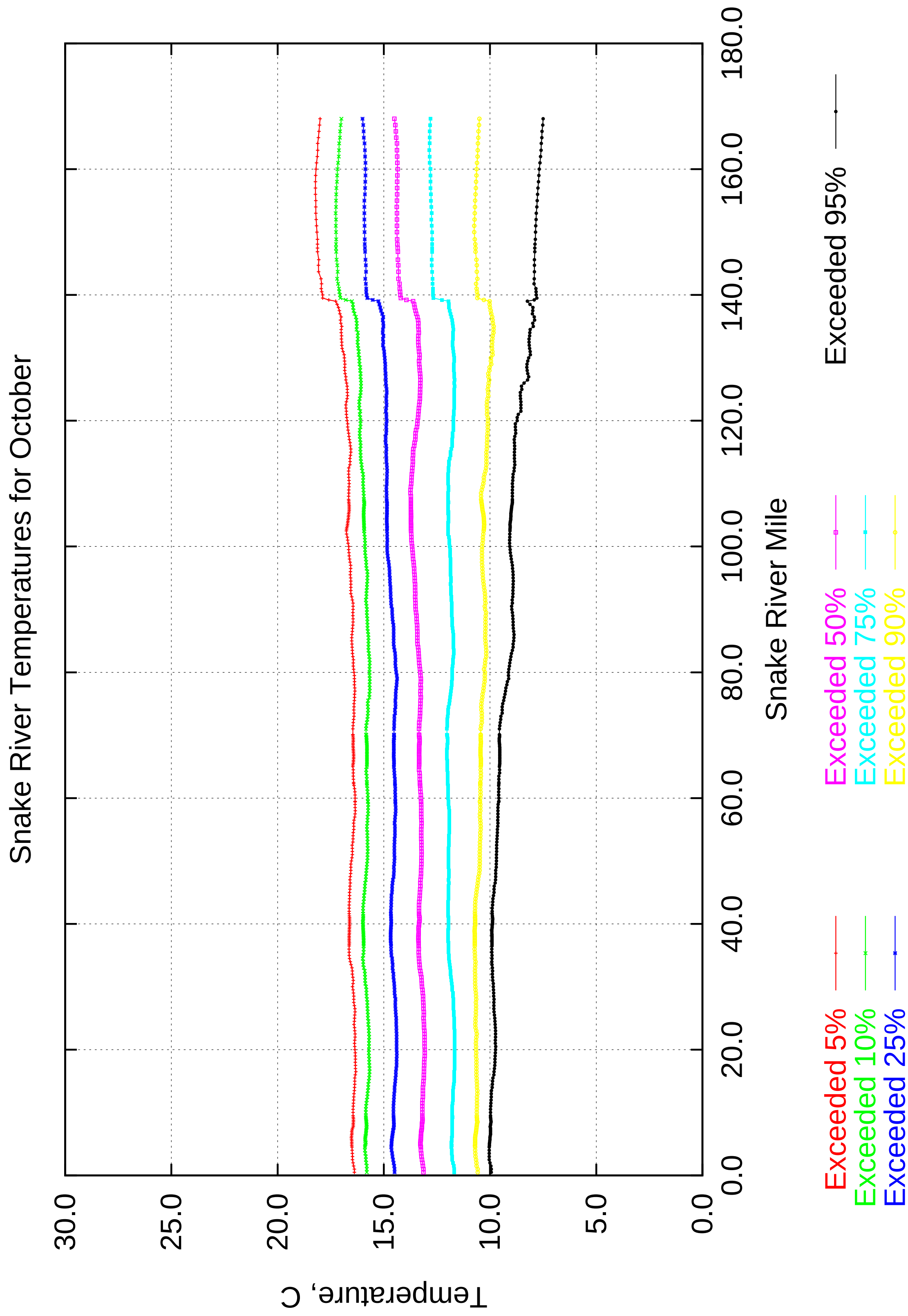

Figure 4.13: Summary of simulated temperature variation in October by Snake River mile for the current conditions scenario.

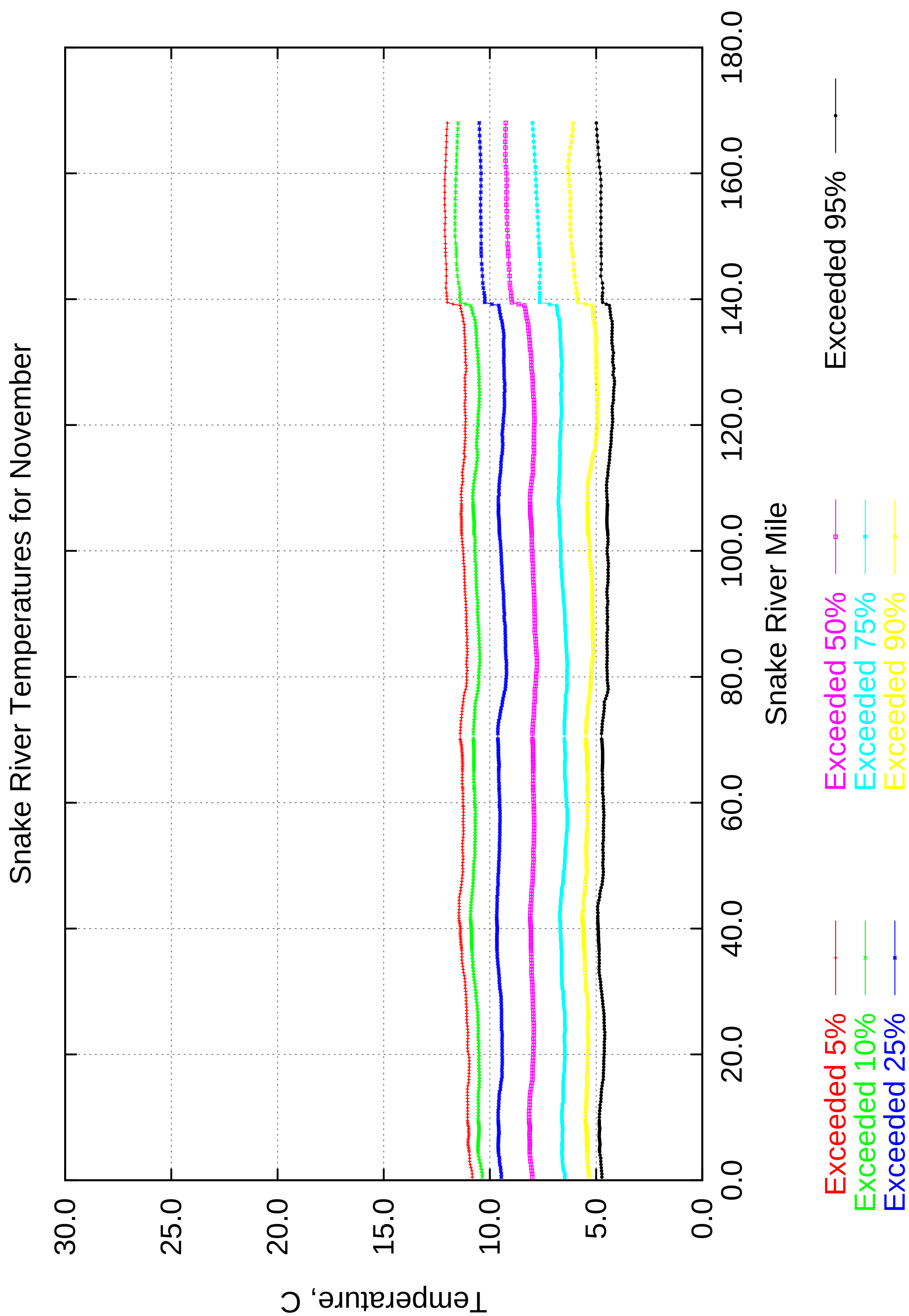

Figure 4.14: Summary of simulated temperature variation in November by Snake River mile for the current conditions scenario.

Table 4.2: Simulated temperature exceedance percentiles at selected Snake River locations for the current conditions scenario.

	River	Percent of Time Exceeded						
Month	Mile	5	10	25	50	75	90	95
January	9.25	3.14	2.87	1.84	0.95	0.27	0.04	0.02
	40.25	3.84	3.49	2.23	1.39	0.65	0.10	0.04
	70.00	4.32	3.80	2.40	1.63	0.94	0.11	0.03
	107.25	5.40	4.79	3.07	2.32	1.64	0.58	0.12
	139.00	6.48	5.43	3.85	3.07	2.30	1.44	1.12
	167.00	7.72	6.01	4.02	3.47	2.21	1.51	1.20
February	9.25	4.99	4.27	3.41	1.80	0.96	0.27	0.12
	40.25	5.15	4.54	3.72	2.24	1.34	0.56	0.27
	70.00	5.59	4.79	3.97	2.61	1.49	0.75	0.33
	107.25	6.29	5.47	4.50	3.23	2.13	1.36	0.89
	139.00	7.12	6.39	5.14	4.00	3.05	2.11	1.72
	167.00	7.87	6.83	5.02	3.97	2.99	2.01	1.51
March	9.25	8.80	8.05	6.76	5.30	3.97	2.59	2.15
	40.25	8.83	8.14	7.06	5.60	4.31	2.95	2.28
	70.00	8.86	8.27	7.21	5.87	4.73	3.26	2.59
	107.25	8.88	8.44	7.51	6.27	5.18	4.04	3.39
	139.00	9.57	8.92	8.09	7.00	5.93	5.07	4.34
	167.00	9.88	9.00	8.02	6.61	5.97	4.97	4.04
April	9.25	12.89	12.27	10.82	9.64	8.56	7.55	6.82
	40.25	12.61	12.01	10.80	9.65	8.63	7.75	7.06
	70.00	12.60	11.87	10.77	9.66	8.72	7.90	7.28
	107.25	12.13	11.69	10.71	9.68	8.69	7.99	7.46
	139.00	12.70	12.09	11.10	10.10	9.10	8.41	8.00
	167.00	13.01	12.46	11.02	10.02	9.02	8.23	7.97
May	9.25	15.50	14.93	14.05	12.84	11.94	11.17	10.61
	40.25	15.04	14.63	13.67	12.62	11.66	10.87	10.36
	70.00	14.95	14.33	13.47	12.47	11.51	10.73	10.19
	107.25	14.76	14.11	13.08	12.23	11.23	10.47	9.82
	139.00	14.99	14.23	13.03	12.19	11.25	10.43	9.66
	167.00	15.50	14.99	13.99	12.98	11.53	10.52	8.41
June	9.25	19.50	18.39	16.92	15.60	14.04	13.08	12.38
	40.25	19.12	18.39	16.81	15.32	13.81	12.73	12.01
	70.00	19.42	18.36	16.89	15.17	13.67	12.48	11.75
	107.25	19.50	18.52	16.77	14.99	13.48	12.30	11.33
	139.00	20.63	19.36	17.24	15.11	13.48	12.20	11.30
	167.00	20.50	19.47	17.50	15.50	13.99	12.99	8.60
July	9.25	21.84	21.21	19.78	18.49	17.39	15.91	15.08
	40.25	21.86	21.12	19.80	18.81	17.40	15.84	14.93
	70.00	21.66	20.97	20.00	19.06	17.57	15.75	14.75
	107.25	22.03	21.33	20.62	19.56	17.66	15.61	13.91

Table 4.2: (continued)

Month	River Mile	Percent of Time Exceeded						
		5	10	25	50	75	90	95
	139.00	23.43	22.80	21.88	20.64	18.00	15.77	13.80
	167.00	23.96	23.48	22.47	20.98	18.49	14.06	8.79
August	9.25	22.06	21.45	20.40	19.40	18.33	17.41	16.51
	40.25	22.07	21.38	20.63	19.65	18.76	17.37	16.30
	70.00	22.02	21.62	20.82	19.86	19.00	17.16	16.25
	107.25	22.50	22.21	21.48	20.81	19.66	16.46	14.69
	139.00	23.79	23.37	22.58	21.56	20.01	16.33	13.46
	167.00	24.22	23.96	23.06	22.15	20.97	15.01	8.93
September	9.25	20.84	20.22	18.66	17.56	16.47	15.39	15.00
	40.25	20.86	20.31	19.04	17.74	16.49	15.42	14.84
	70.00	21.05	20.29	19.00	17.63	16.25	15.14	14.55
	107.25	21.02	20.35	19.09	17.68	16.30	14.65	13.73
	139.00	21.28	20.41	19.45	18.14	16.46	15.07	12.39
	167.00	22.00	21.51	20.53	19.47	17.79	15.72	9.06
October	9.25	16.44	15.85	14.54	13.19	11.76	10.62	9.98
	40.25	16.61	15.99	14.65	13.33	11.95	10.70	9.88
	70.00	16.46	15.83	14.52	13.33	12.02	10.44	9.55
	107.25	16.65	15.93	14.86	13.73	11.97	10.40	8.95
	139.00	17.27	16.50	15.25	13.62	11.95	10.02	8.24
	167.00	18.03	17.03	15.97	14.46	12.82	10.52	7.52
November	9.25	11.05	10.54	9.60	8.15	6.60	5.49	4.85
	40.25	11.39	10.88	9.65	8.07	6.69	5.61	4.90
	70.00	11.39	10.77	9.62	7.99	6.50	5.48	4.73
	107.25	11.34	10.79	9.59	8.10	6.77	5.39	4.46
	139.00	11.40	10.90	9.58	8.38	6.86	5.18	4.38
	167.00	12.03	11.51	10.49	9.26	7.98	6.10	4.97

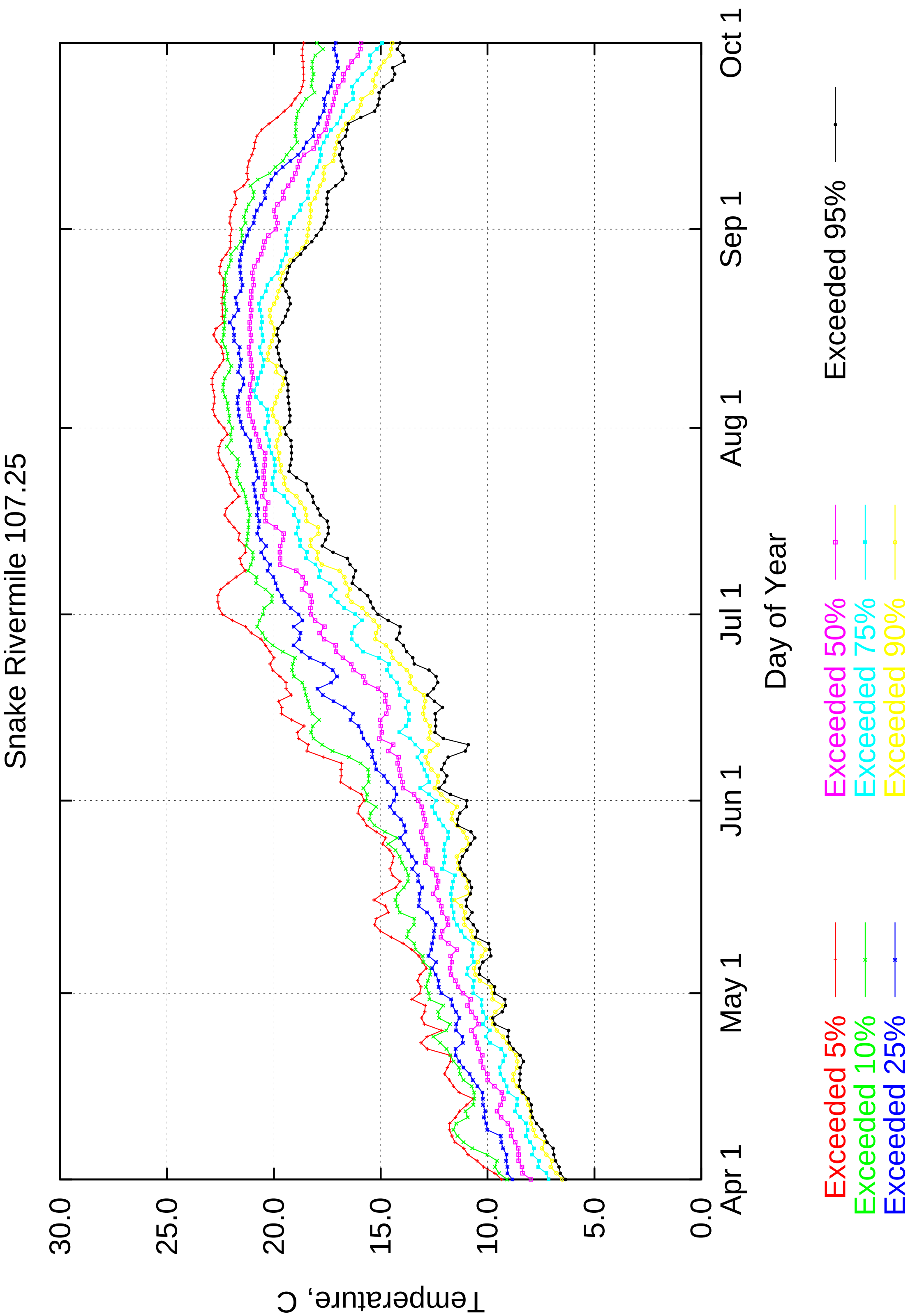

Figure 4.15: Summary of simulated temperature variation at Snake River mile 107.25 (Lower Granite Dam) in the current conditions scenario.

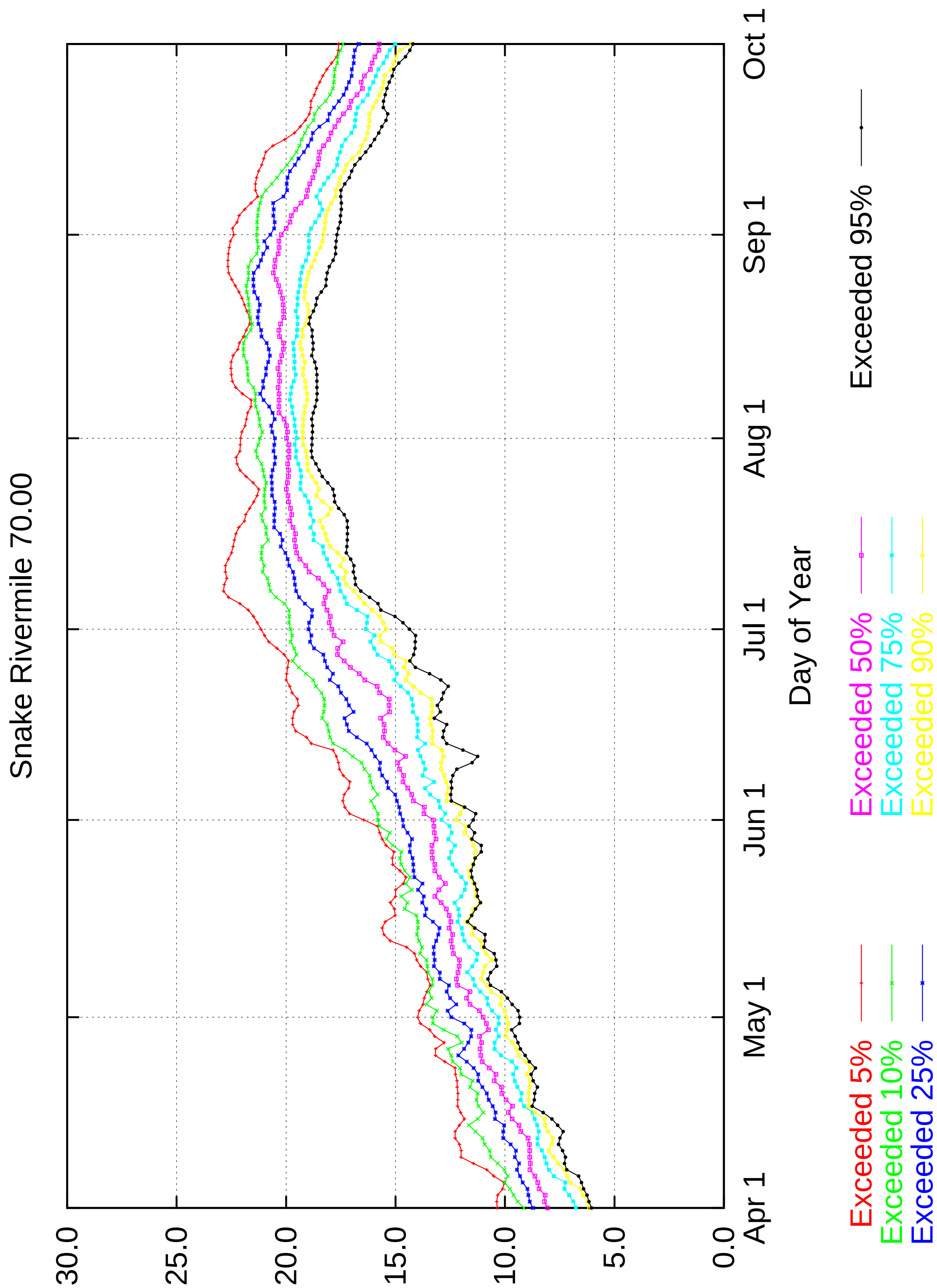

Figure 4.16: Summary of simulated temperature variation at Snake River mile 70.0 (Little Goose Dam) in the current conditions scenario.

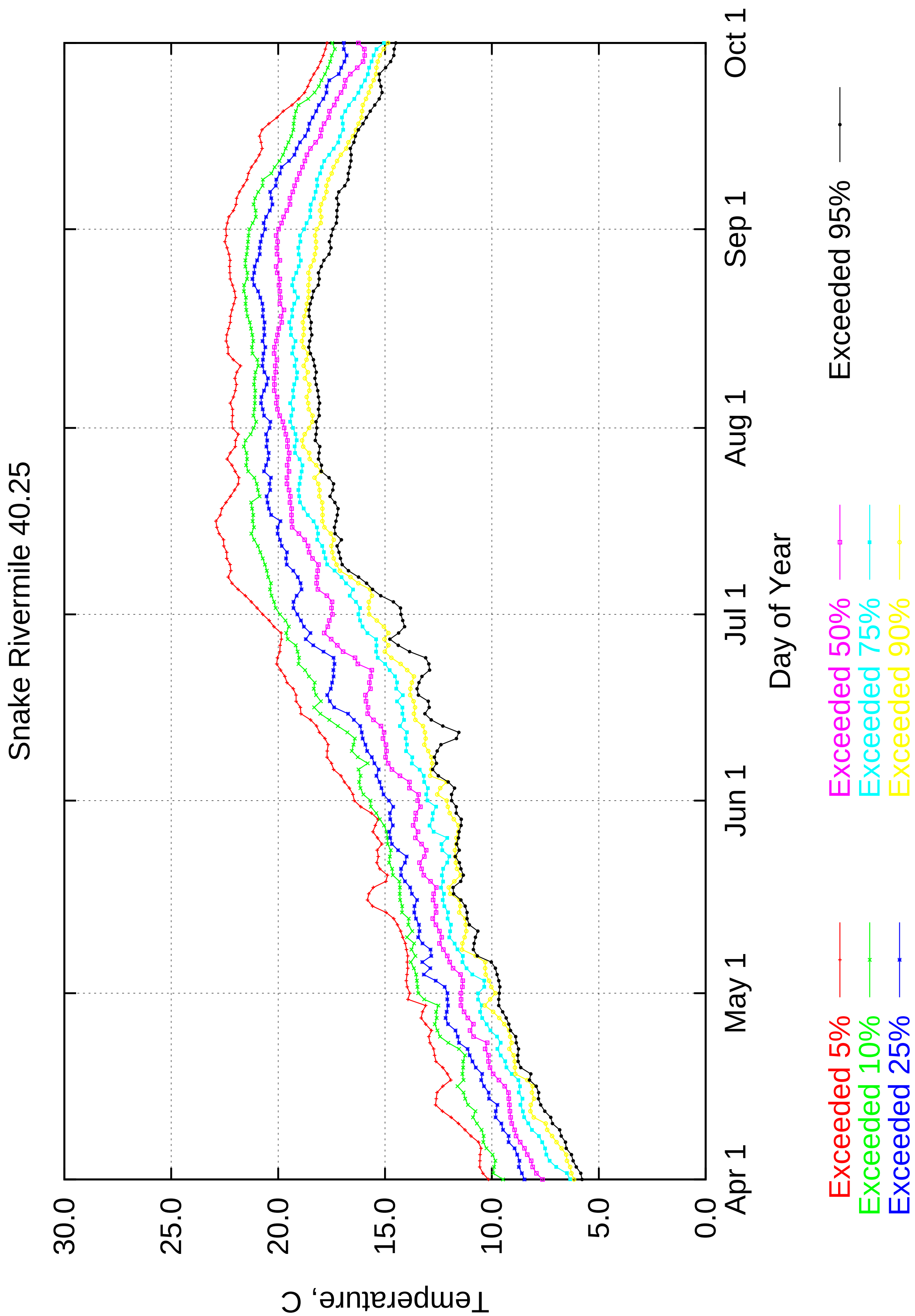

Figure 4.17: Summary of simulated temperature variation at Snake River mile 40.25 (Lower Monumental Dam) during the current conditions scenario.

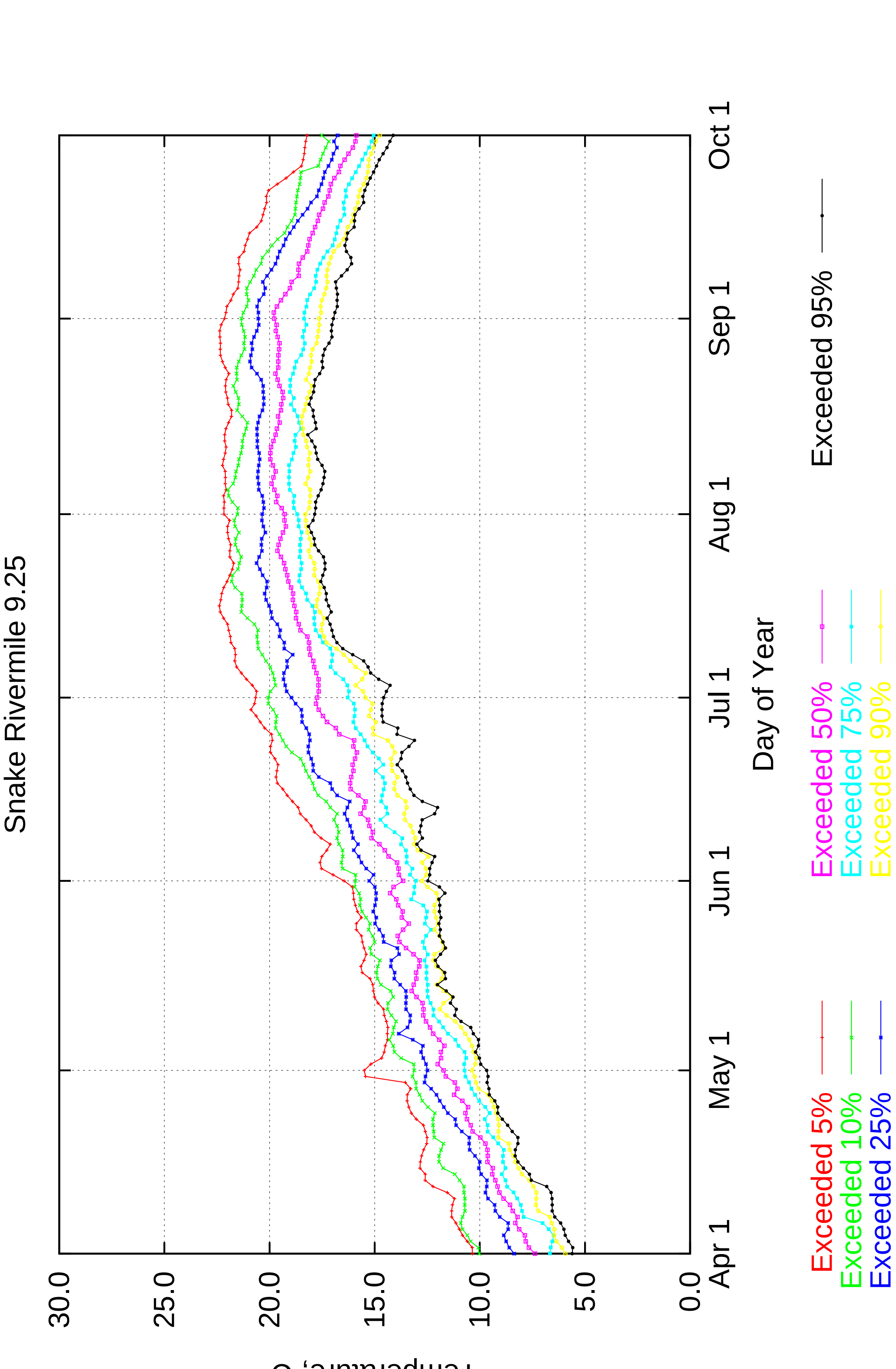

Figure 4.18: Summary of simulated temperature variation at Snake River mile 9.25 (near Ice Harbor Dam) during the current conditions scenario.

Table 4.3: Statistical summaries of the day of year when simulated Snake River temperatures rose above or fell below various levels in the current conditions scenario simulation.

Location	River Mile	Temperature Level	Percent Time Exceeded 10	25	50	75	90
Anatone	167.00	> 10.0	160	159	157	152	148
	167.00	> 15.0	212	208	202	195	185
	167.00	> 20.0	226	222	215	207	200
	167.00	> 25.0	239	239	239	215	215
	167.00	< 10.0	324	323	318	312	309
	167.00	< 15.0	299	298	292	286	281
	167.00	< 20.0	267	264	259	252	239
	167.00	< 25.0	241	241	241	217	199
Lower Granite	107.25	> 10.0	168	165	162	157	149
	107.25	> 15.0	213	212	207	201	188
	107.25	> 20.0	229	228	225	215	210
	107.25	< 10.0	319	316	313	311	309
	107.25	< 15.0	293	289	287	281	276
	107.25	< 20.0	262	254	251	244	236
Little Goose	70.00	> 10.0	170	168	162	159	153
	70.00	> 15.0	212	211	207	198	187
	70.00	> 20.0	244	240	233	227	212
	70.00	< 10.0	319	317	315	312	309
	70.00	< 15.0	292	291	288	281	274
	70.00	< 20.0	255	255	253	247	235
Lower Monumental	40.25	> 10.0	170	168	162	158	155
	40.25	> 15.0	214	212	206	197	184
	40.25	> 20.0	247	247	235	218	211
	40.25	< 10.0	320	317	315	314	309
	40.25	< 15.0	292	291	288	280	275
	40.25	< 20.0	255	254	254	251	227
Ice Harbor	9.25	> 10.0	168	165	163	160	155
	9.25	> 15.0	212	212	205	195	183
	9.25	> 20.0	242	242	235	219	212
	9.25	< 10.0	318	315	314	313	309
	9.25	< 15.0	291	291	288	280	275
	9.25	< 20.0	256	256	254	250	245

5 Discussion and Conclusions

Figures 5.1 through 5.16 compare, in several ways, the results of the two simulation scenarios for each of the Lower Snake dam locations. Figures 5.1, 5.5, 5.9, 5.13 compare the entire simulated temperature record, and that portion of the record above 14°C. These figure highlight the dampening of peak seasonal temperatures in the current conditions scenario. The effect becomes more prominent at the downstream projects.

Figures 5.2, 5.6, 5.10, and 5.14 show scatter plot comparison of the simulated daily maximum temperatures for the months of May through October at each of the dam locations. These figures highlight the temporal shift of water temperature between scenarios. At Lower Granite (Figure 5.2), the shift is relatively minor, with the unimpounded river scenario being slightly warmer during June and July. However, downstream at Ice Harbor (Figure 5.14), May temperatures from both scenarios are consistent, but the unimpounded scenario is clearly warmer in June, July, and August and cooler in September and October.

Figures 5.3, 5.7, 5.11, and 5.15 compare, for the months of May through October, cumulative frequency curves of the simulated daily maximum temperatures at each of the dam locations. These figures also highlight the temporal shift of water temperature between scenarios, and may help to quantify that shift.

Figures 5.4, 5.8, 5.12, and 5.16 summarize when, during the year, simulated temperatures rose and stayed above and fell and stayed below 10, 15, 20, and 25°C for the dam locations. The box and whisker plots show the 90, 75, 50, 25, and 10 percentiles of day of year number, shown in Tables 3.3 and 4.3. Their computation is described in Section 3.4.

The long-term analysis has shown that the primary difference between the current and unimpounded river scenarios is that the reservoirs decrease the water temperature variability. The reservoirs also create a thermal inertia effect which tends to keep water cooler later into the spring and warmer later into the fall compared to the unimpounded river condition. Vertical average temperatures at the 50% exceedance level tended to be about 1 degree C warmer near the Ice Harbor Dam location for unimpounded river conditions. However, since the model is vertically averaged temperatures in the upper part of the water column in the current conditions may be slightly underestimated. Given the uncertainties in the simulation model, inflow temperatures, and meteorological conditions the results show only relatively small differences between current and unimpounded absolute river temperatures.

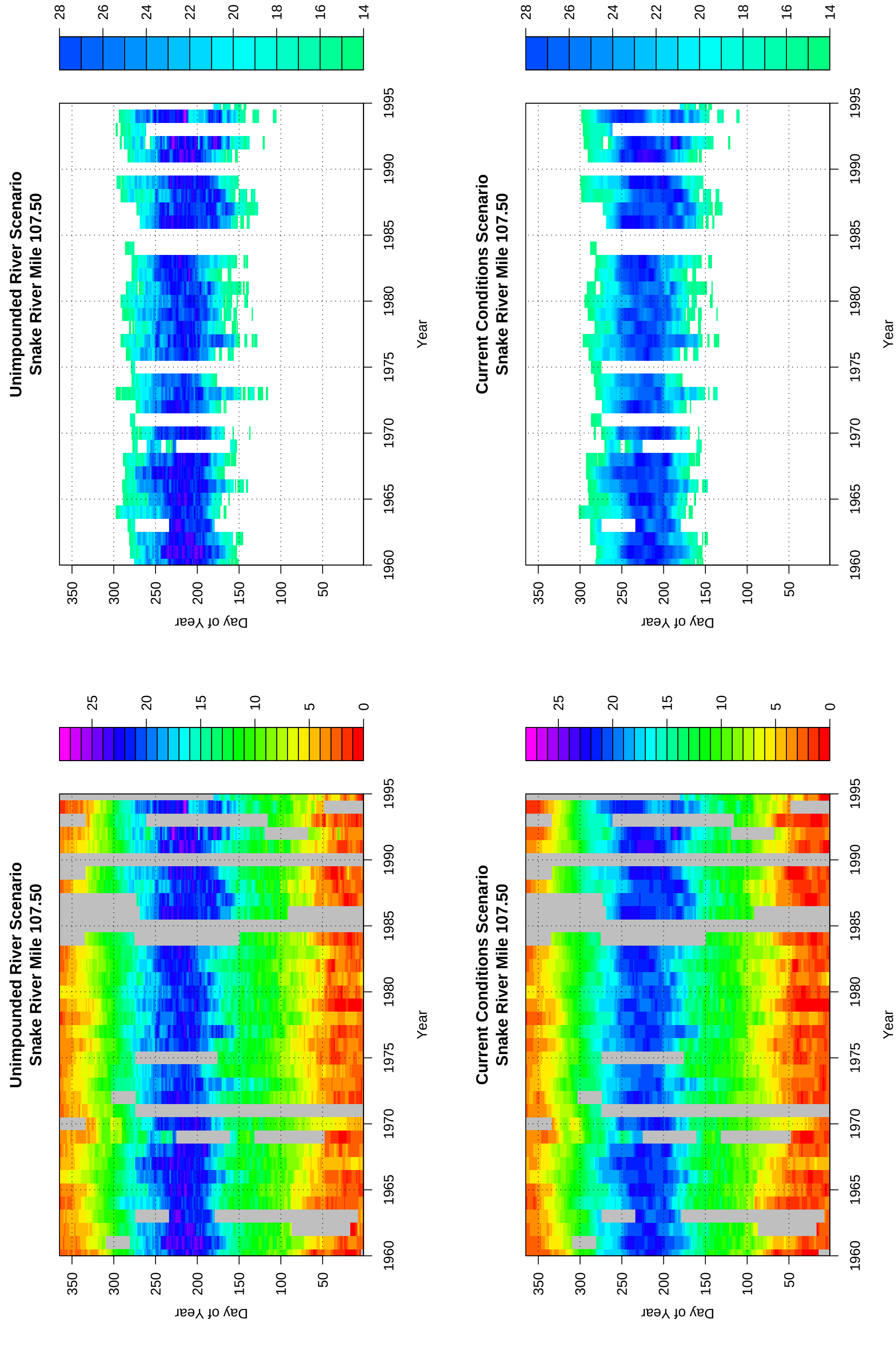

Figure 5.1: Comparison of the simulated temperature record from the unimpounded river (above) and current conditions (below) scenarios at the location of Lower Granite dam.

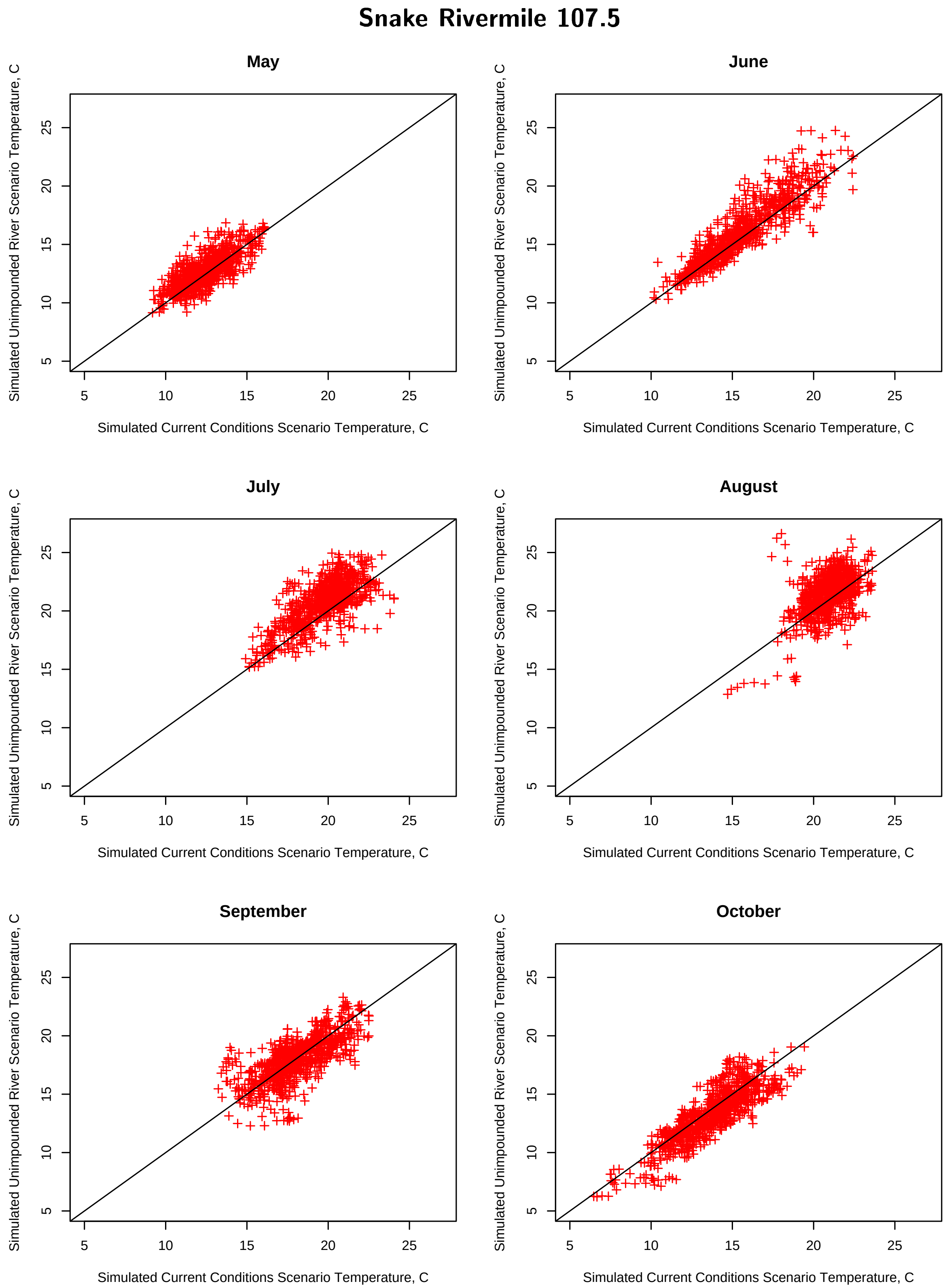

Figure 5.2: Scatter plot comparison, by month, of simulated temperature from unimpounded river and current conditions at the location of Lower Granite dam.

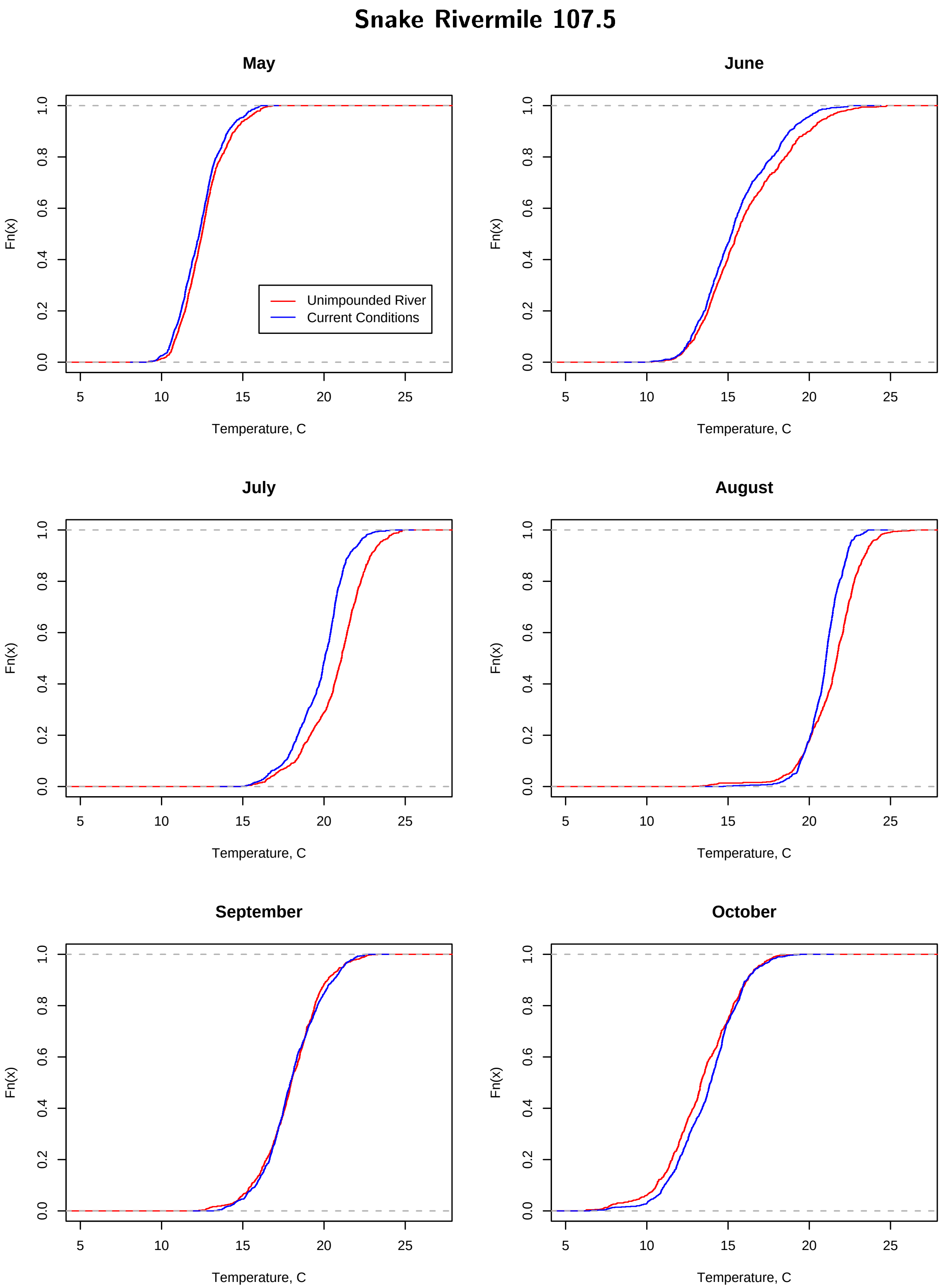

Figure 5.3: Cumulative frequency comparison, by month, of temperature at the location of Lower Granite dam from the unimpounded river and current conditions simulations.

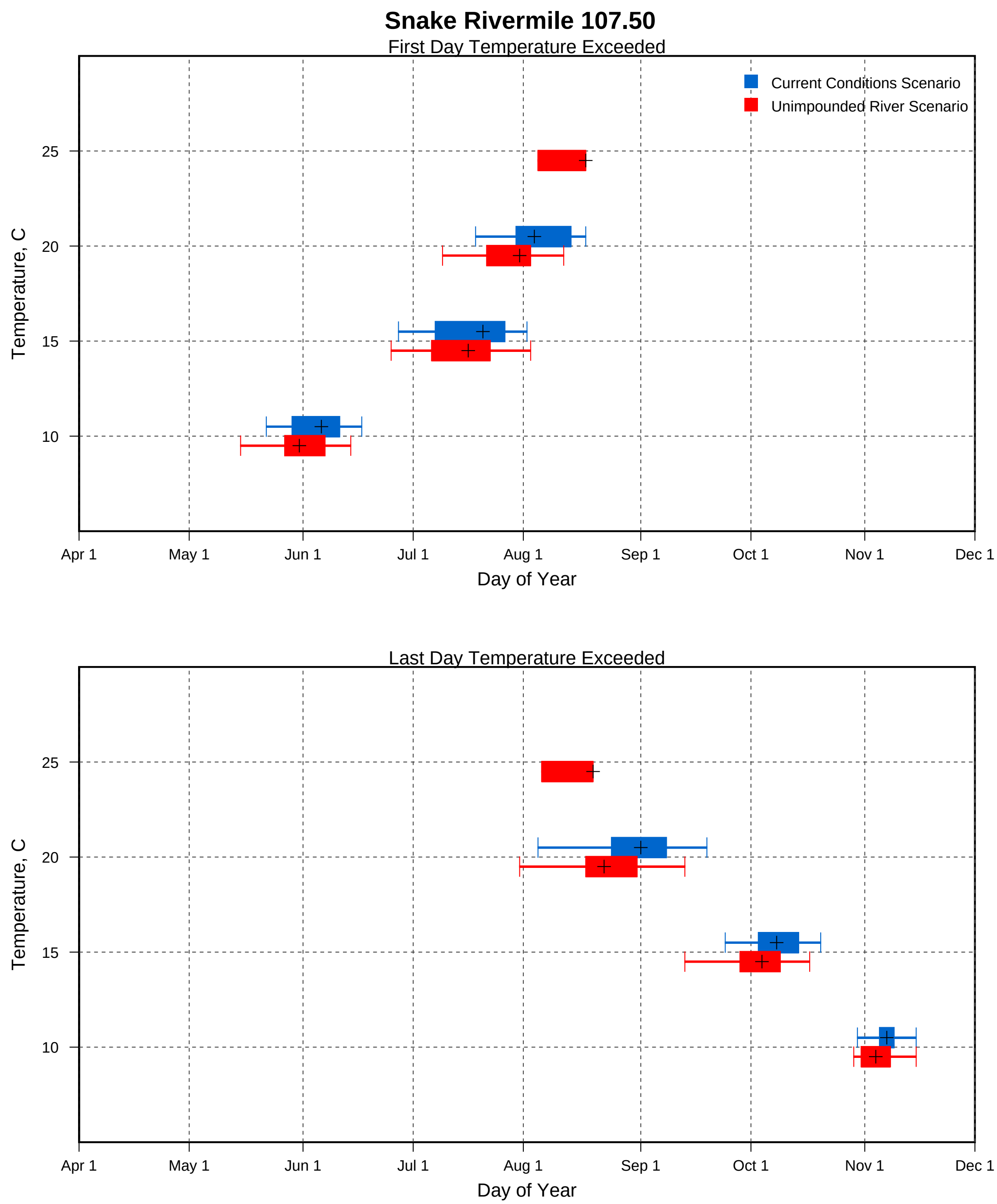

Figure 5.4: Comparison of when, during the year, simulated water temperature rose above (top) and fell below (bottom) various levels at the location of Lower Granite dam during the unimpounded and current conditions scenarios.

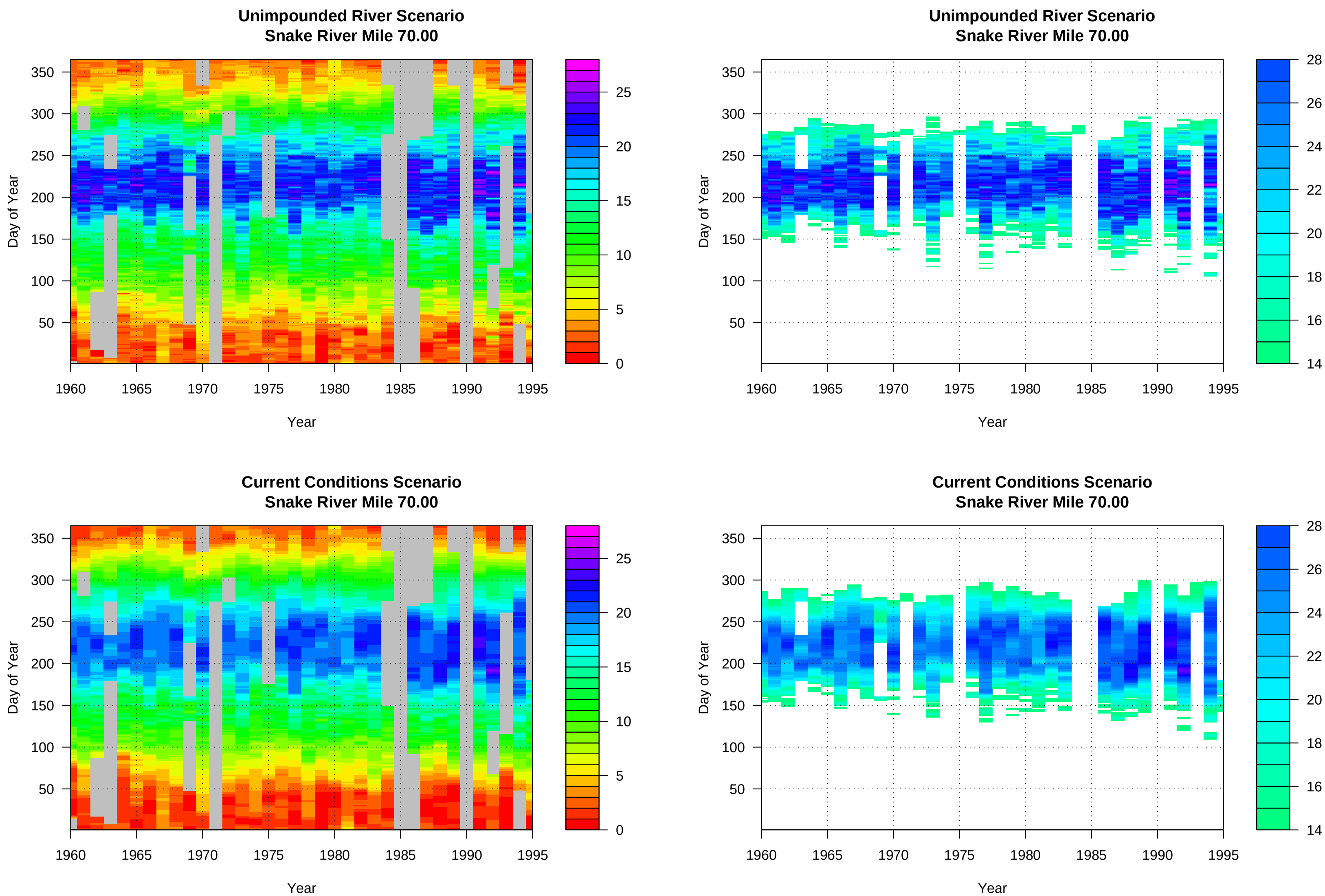

Figure 5.5: Comparison of the simulated temperature record from the impounded river (above) and current conditions (below) scenarios at the location of Little Goose dam.

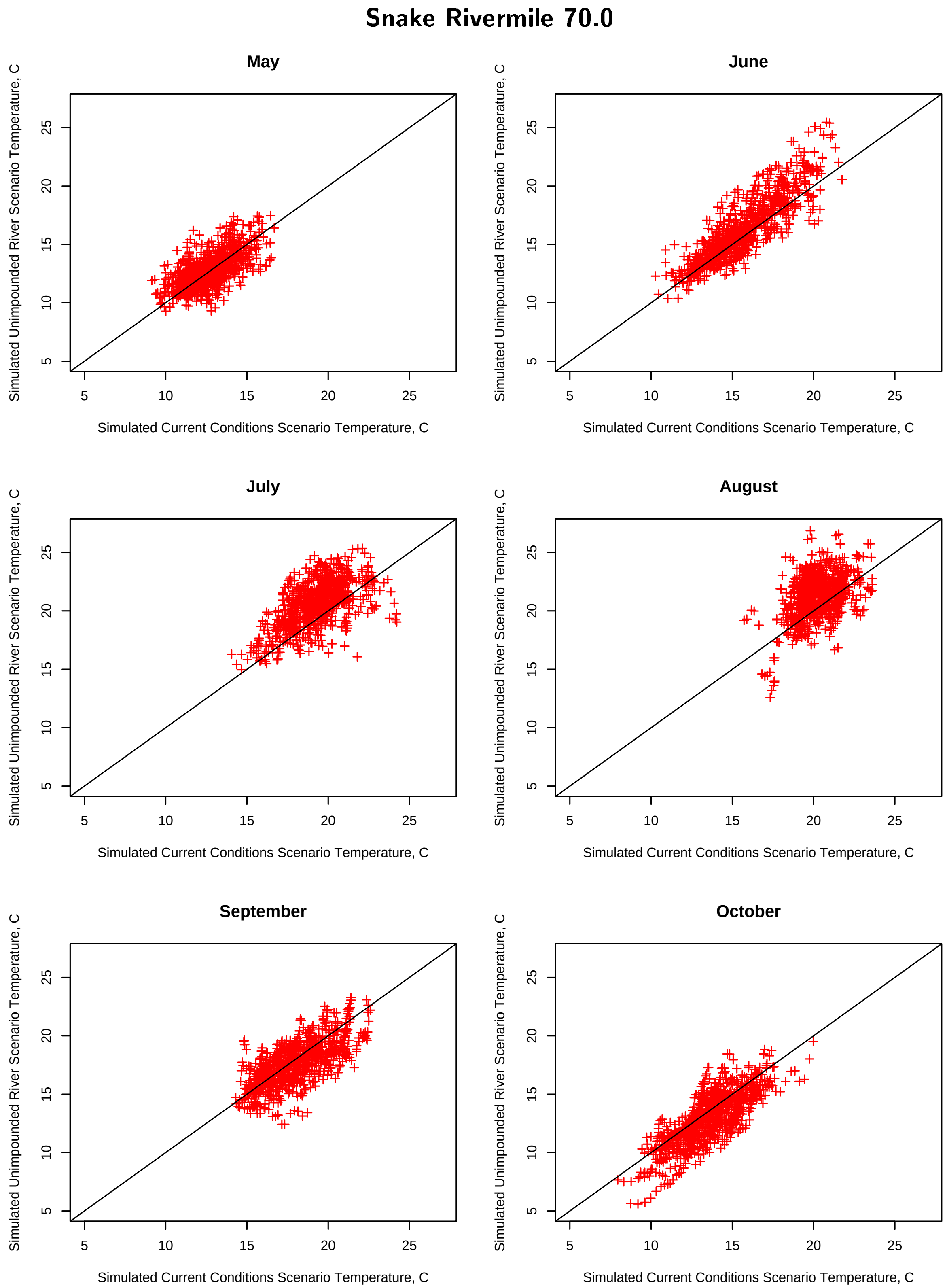

Figure 5.6: Scatter plot comparison, by month, of simulated temperature from unimpounded river and current conditions at the location of Little Goose dam.

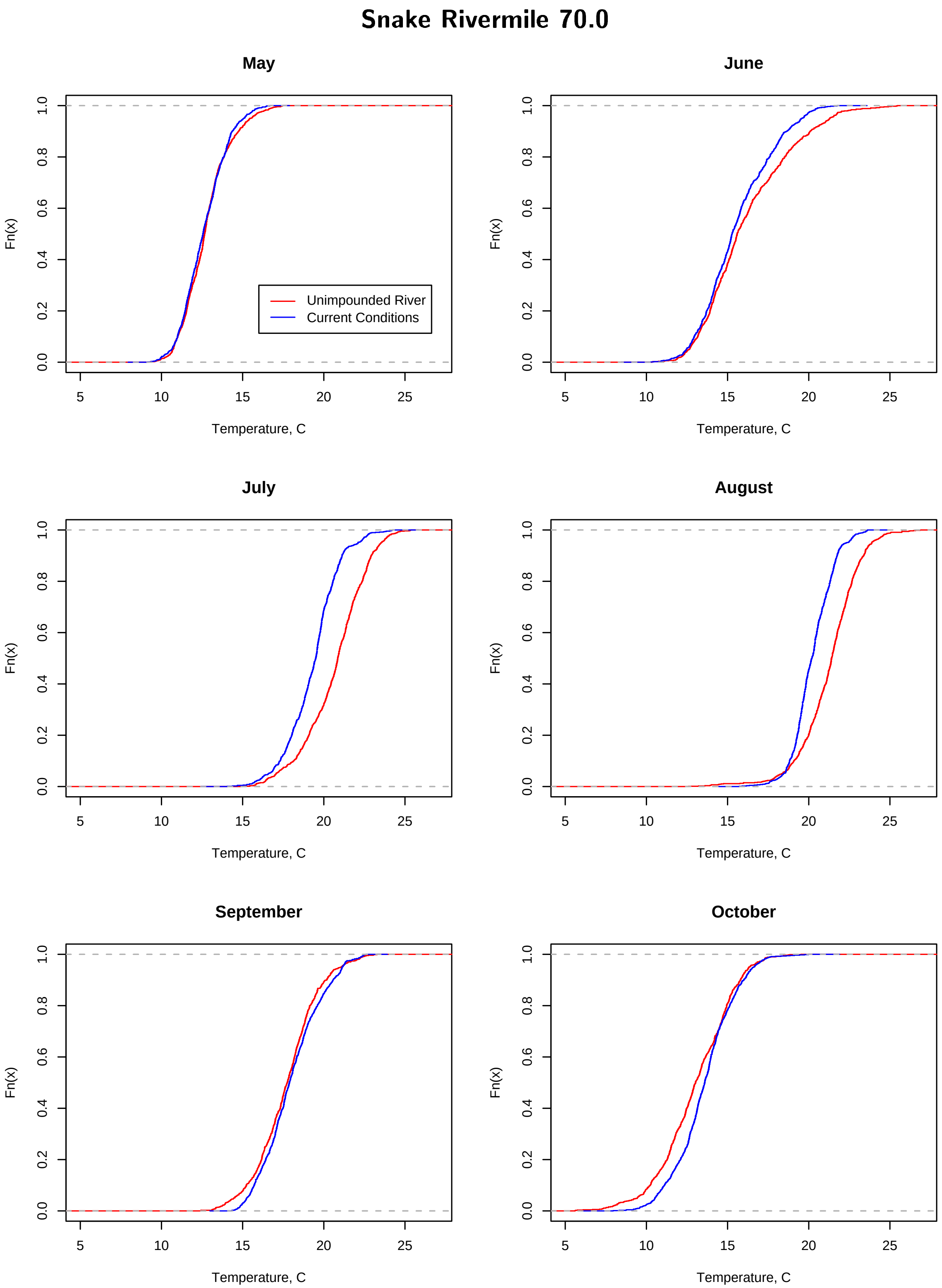

Figure 5.7: Cumulative frequency comparison, by month, of temperature at the location of Little Goose dam from the unimpounded river and current conditions simulations.

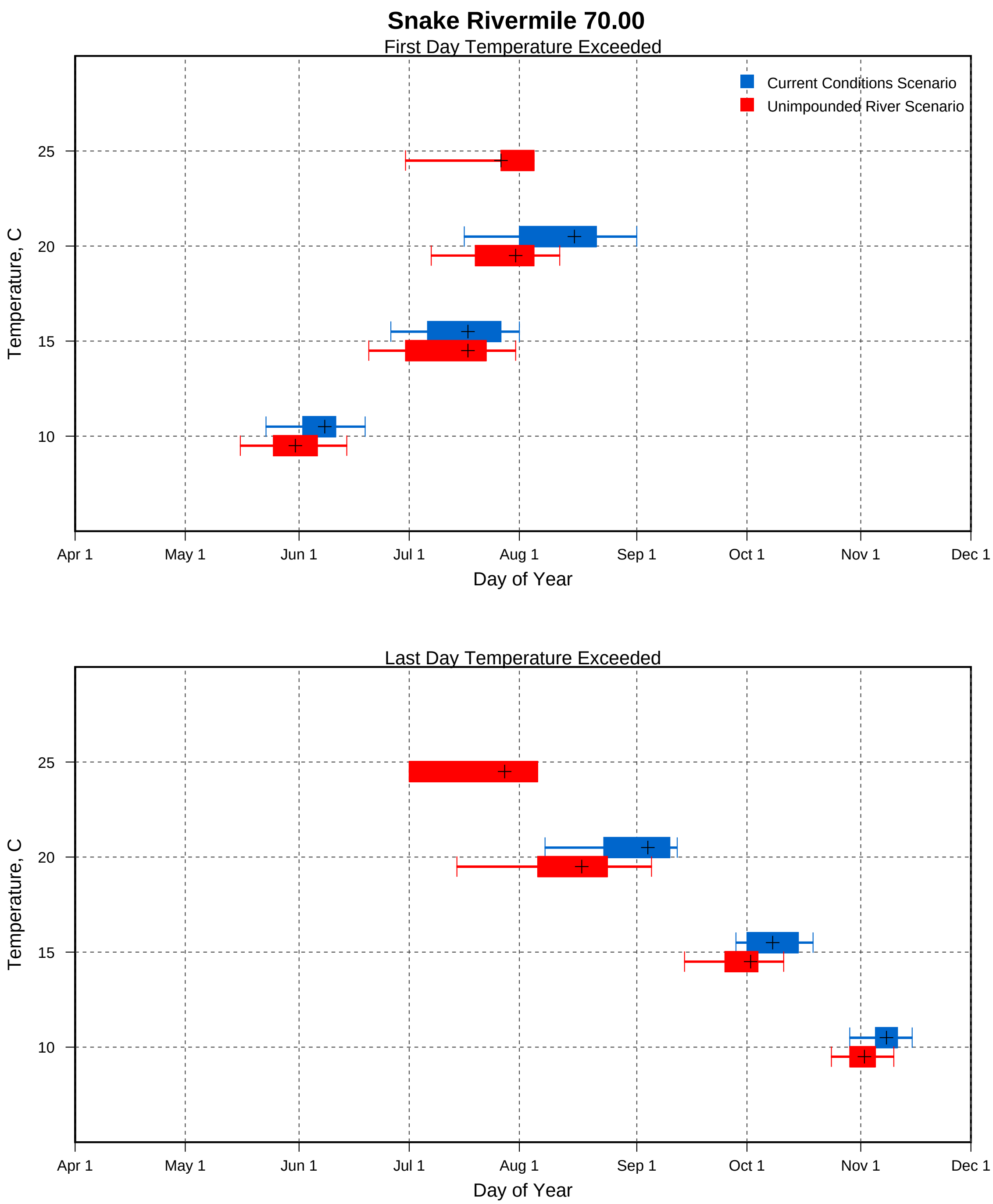

Figure 5.8: Comparison of when, during the year, simulated water temperature rose above (top) and fell below (bottom) various levels at the location of Little Goose dam during the unimpounded and current conditions scenarios.

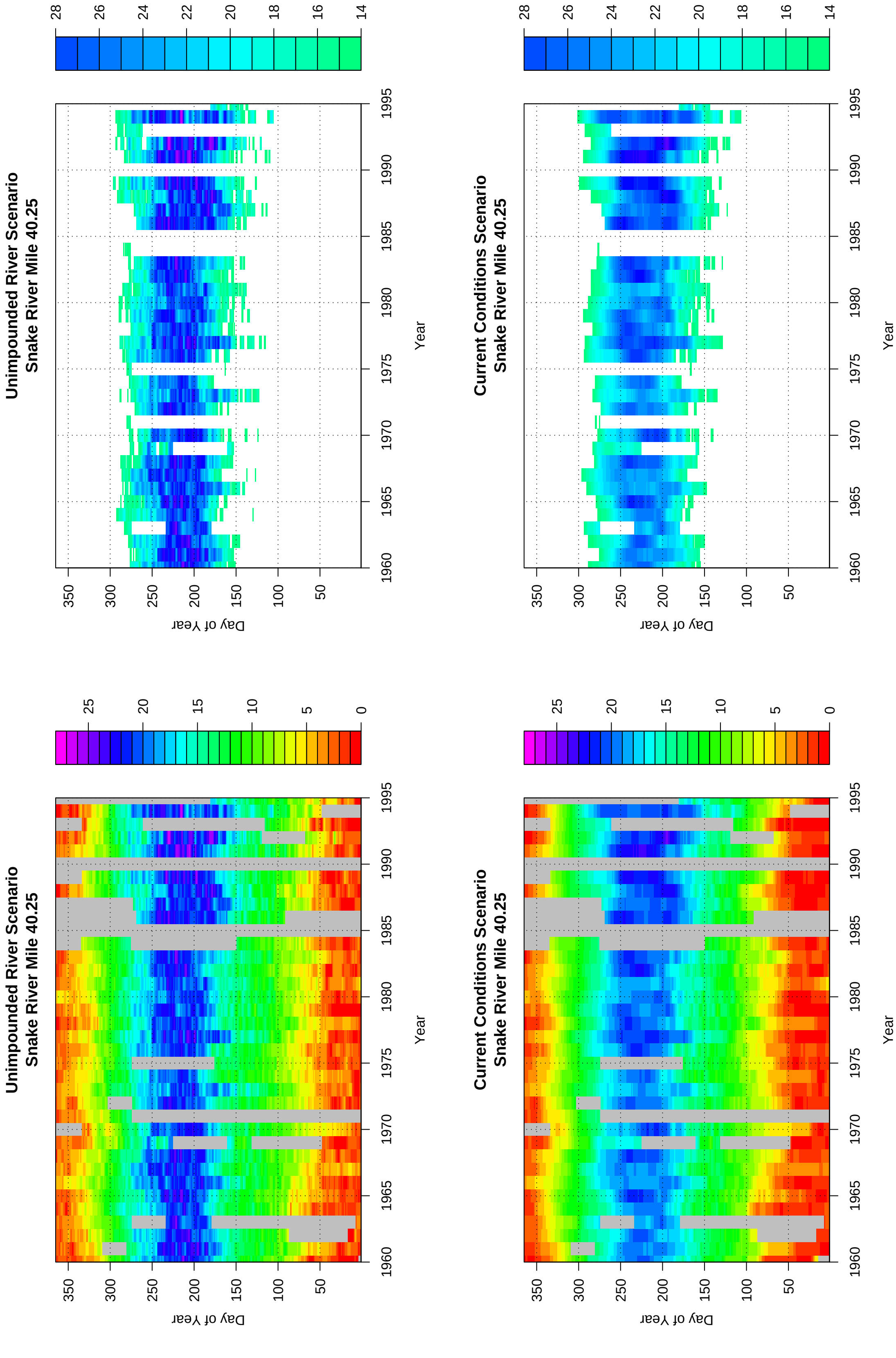

Figure 5.9: Comparison of the simulated temperature record from the unimpounded river (above) and current conditions (below) scenarios at the location of Lower Monumental dam.

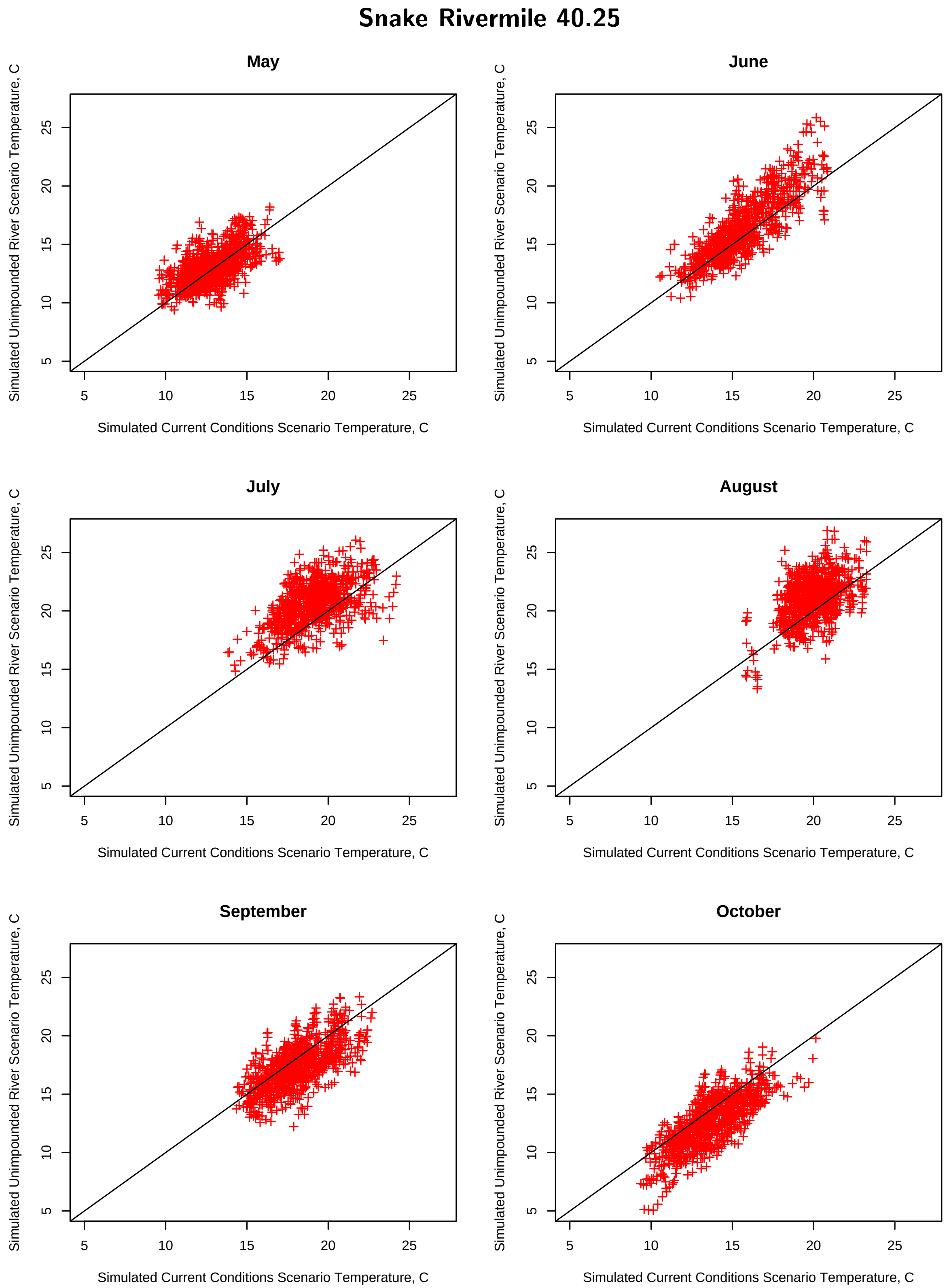

Figure 5.10: Scatter plot comparison, by month, of simulated temperature from unimpounded river and current conditions at the location of Lower Monumental dam.

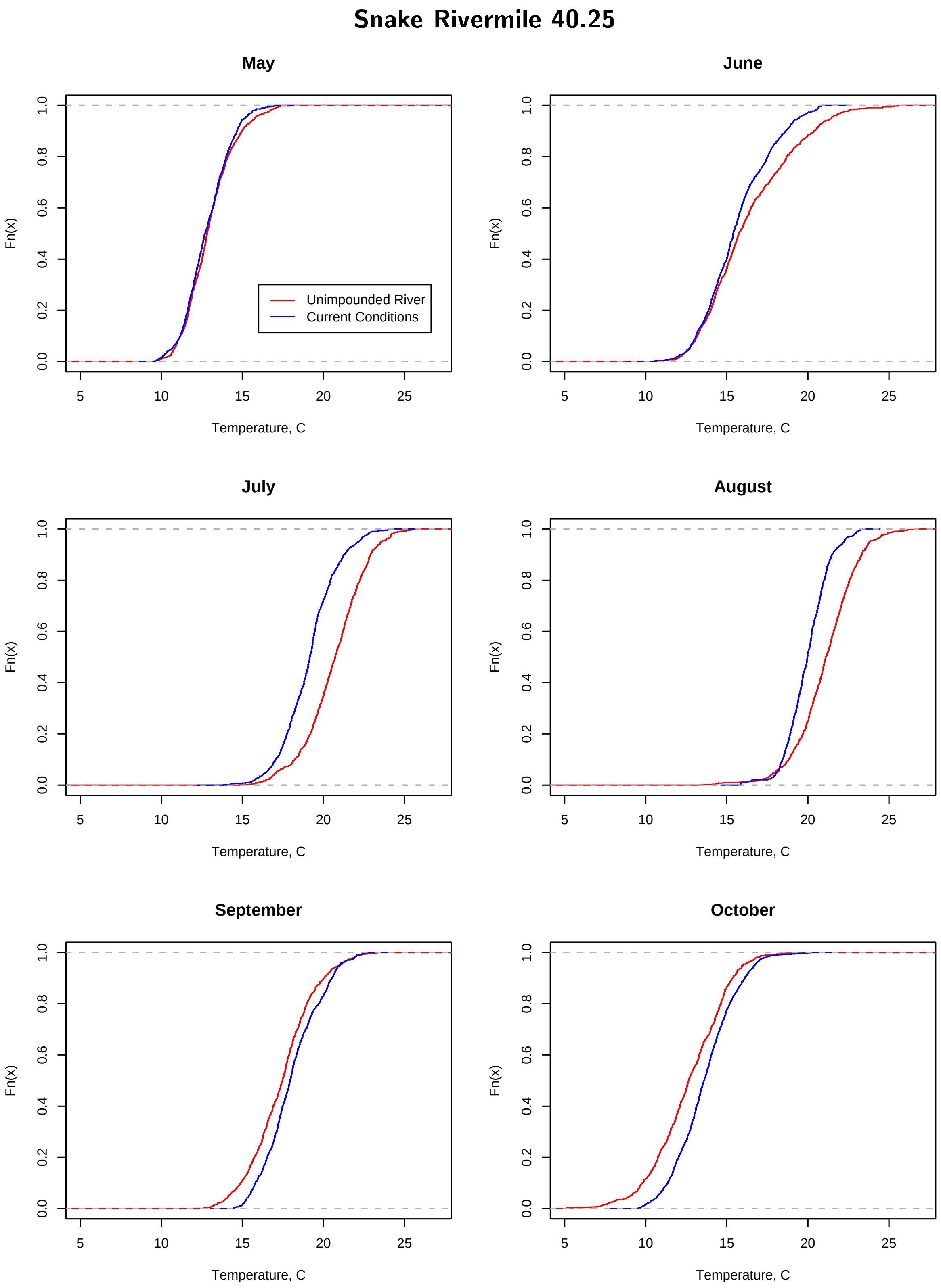

Figure 5.11: Cumulative frequency comparison, by month, of temperature at the location of Lower Monumental dam from the unimpounded river and current conditions simulations.

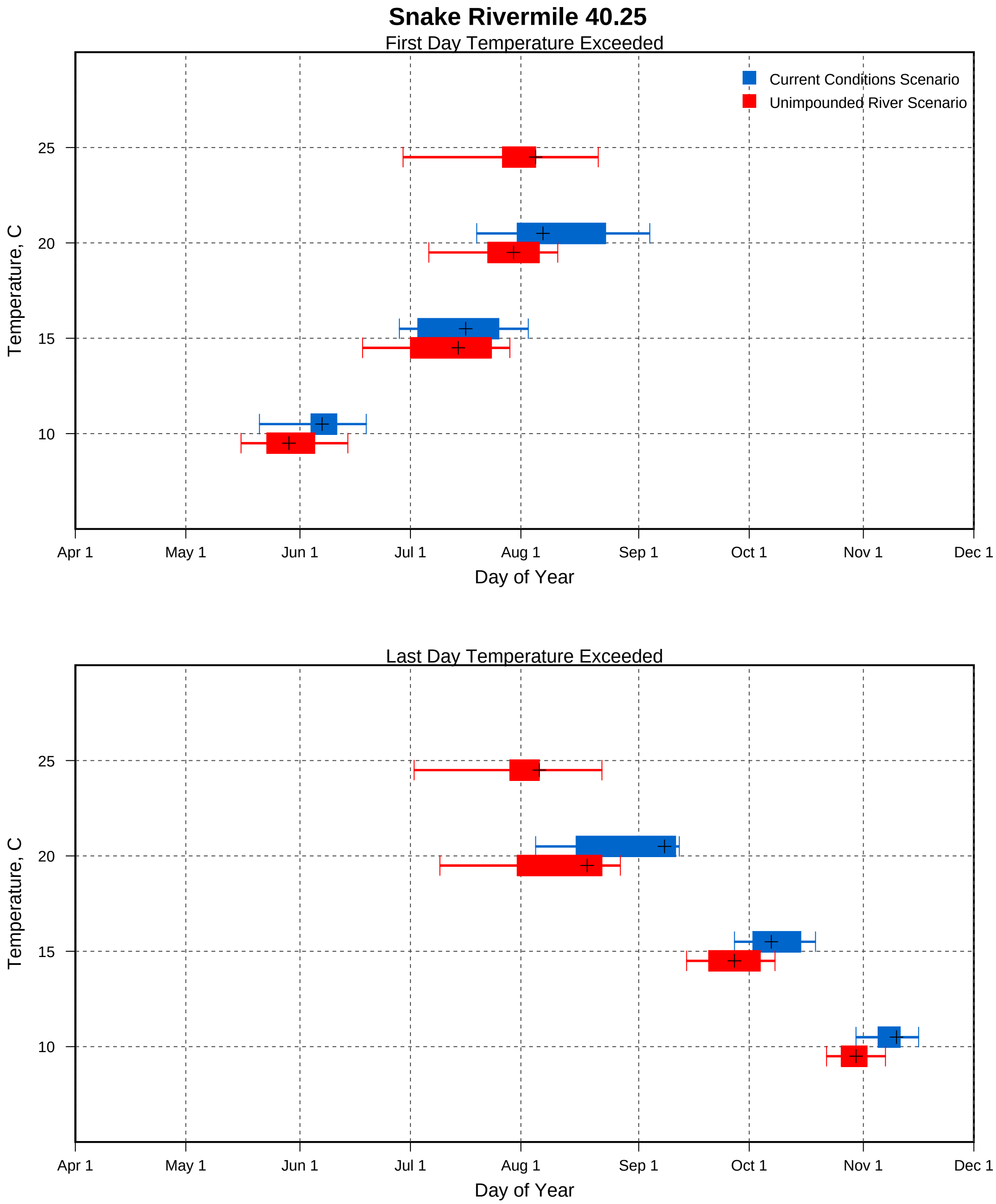

Figure 5.12: Comparison of when, during the year, simulated water temperature rose above (top) and fell below (bottom) various levels at the location of Lower Monumental dam during the unimpounded and current conditions scenarios.

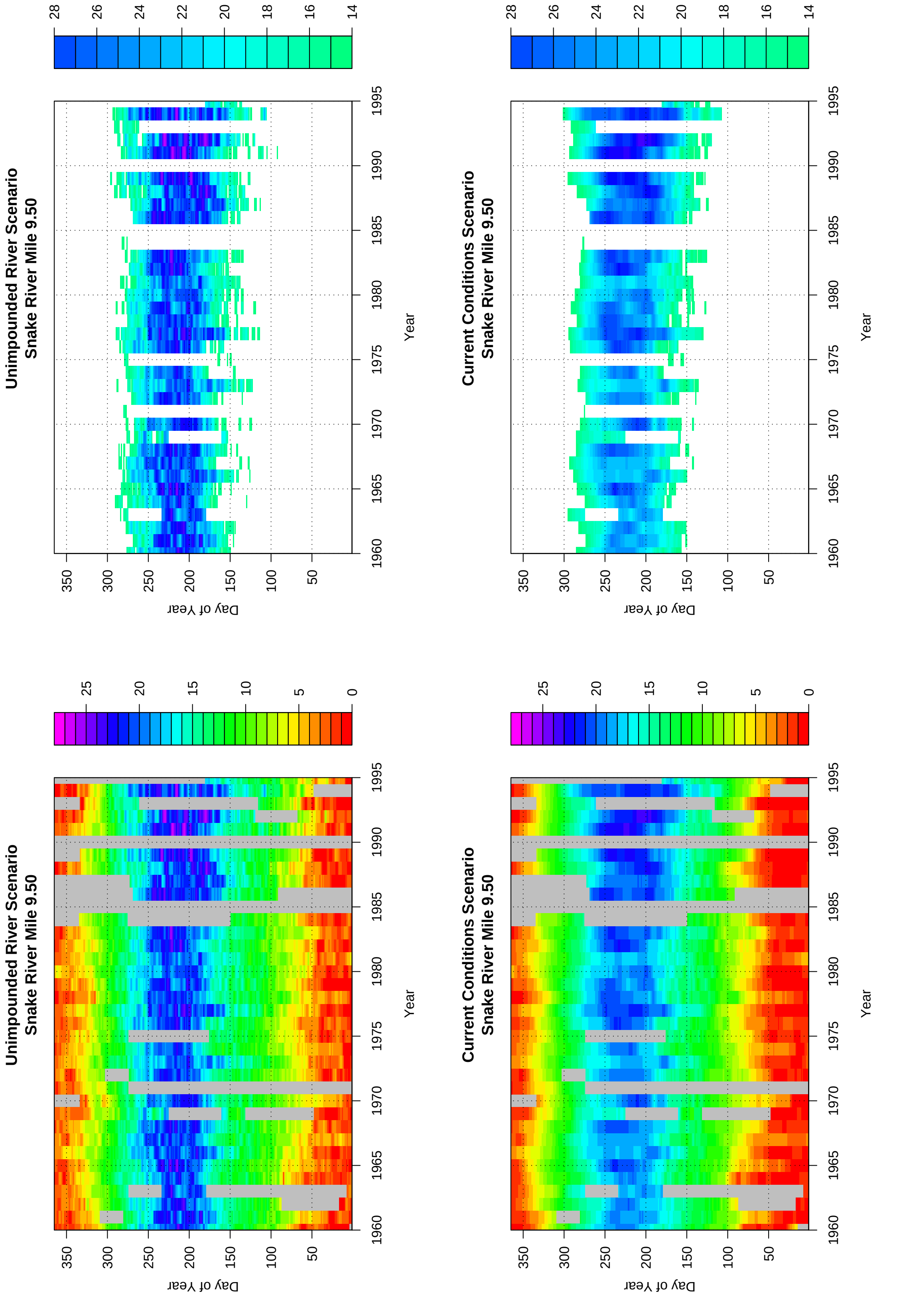

Figure 5.13: Comparison of the simulated temperature record from the unimpounded river (above) and current conditions (below) scenarios at the location of Ice Harbor dam.

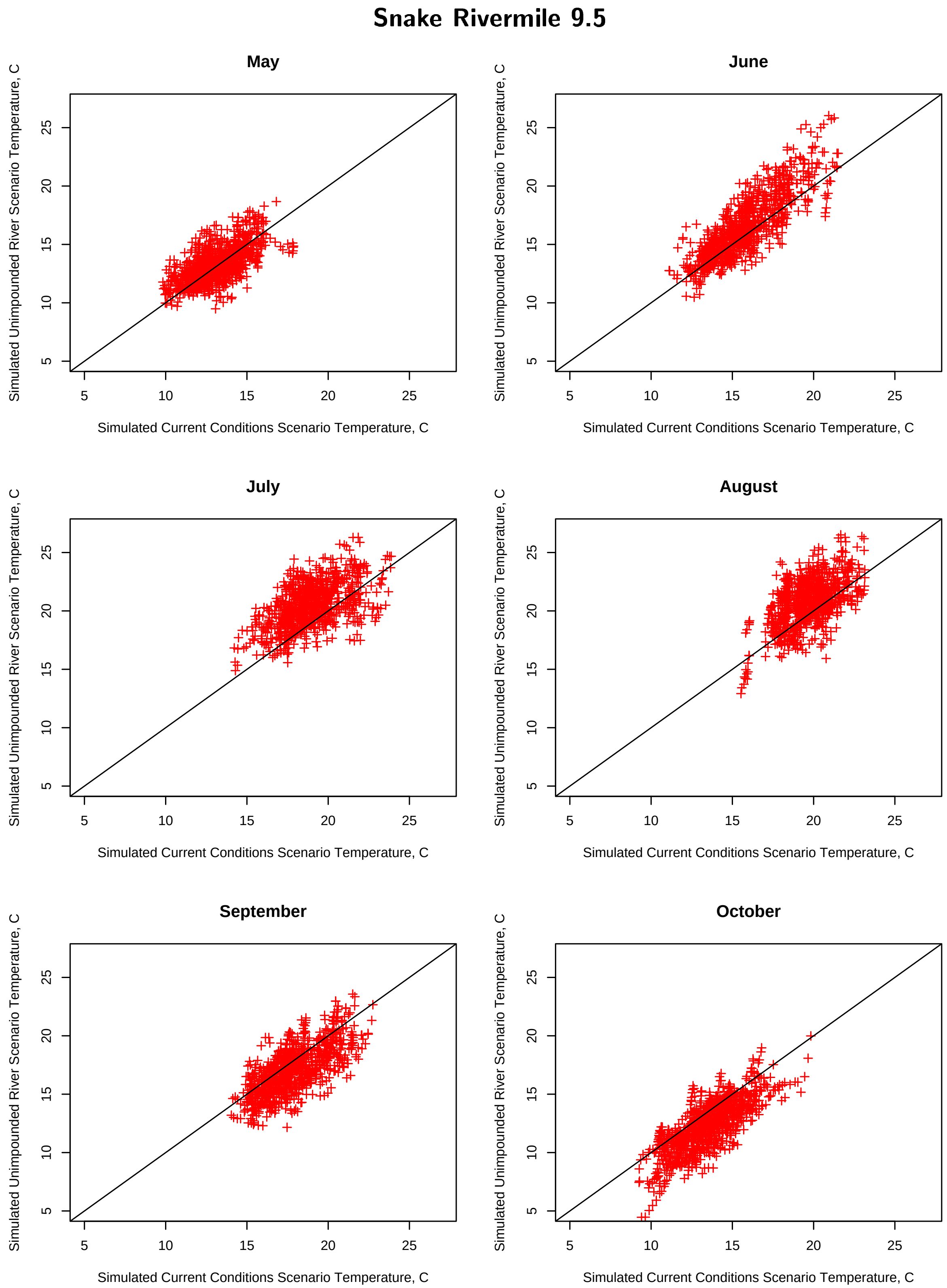

Figure 5.14: Scatter plot comparison, by month, of simulated temperature from unimpounded river and current conditions at the location of Ice Harbor dam.

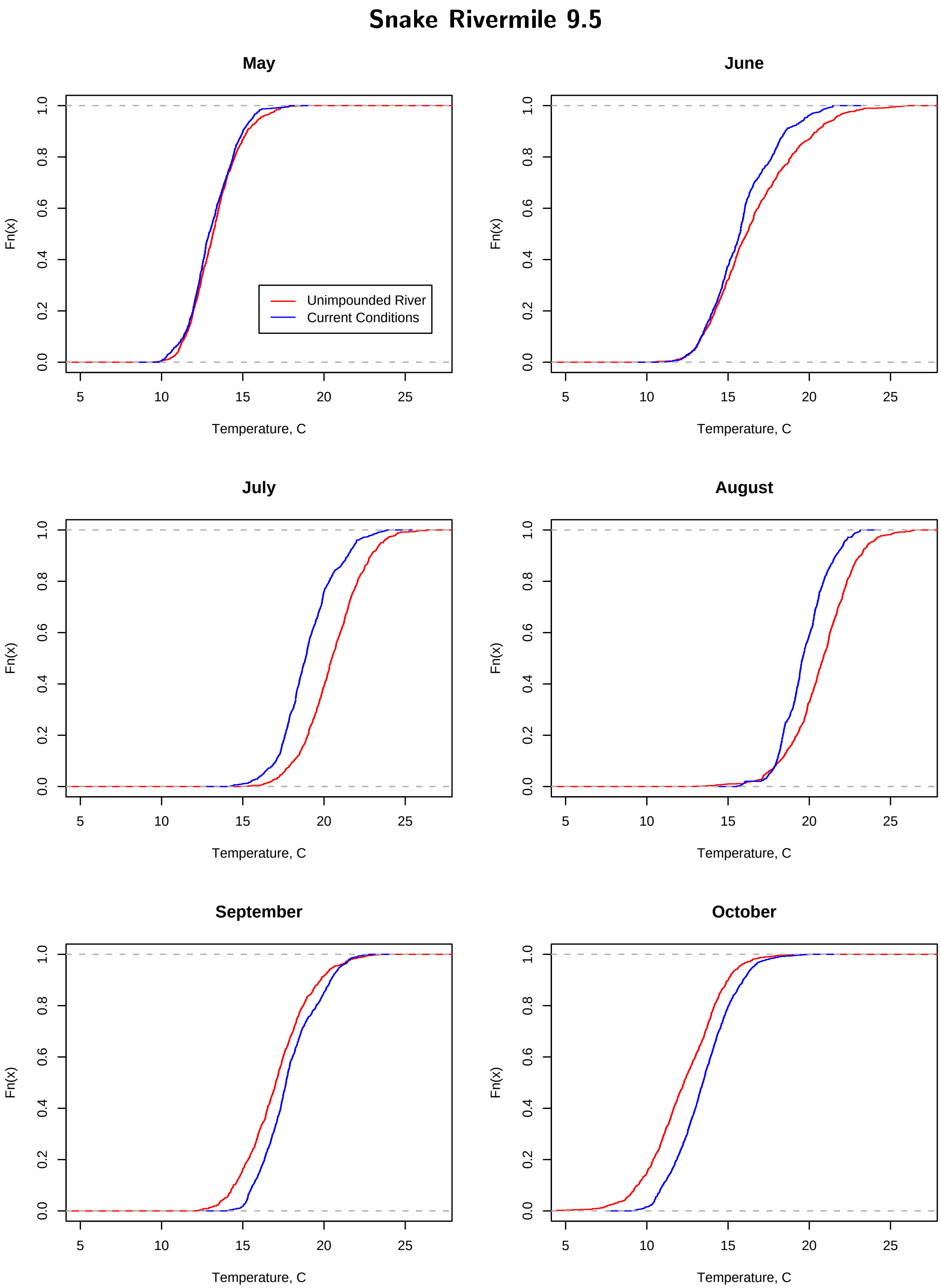

Figure 5.15: Cumulative frequency comparison, by month, of temperature at the location of Ice Harbor dam from the unimpounded river and current conditions simulations.

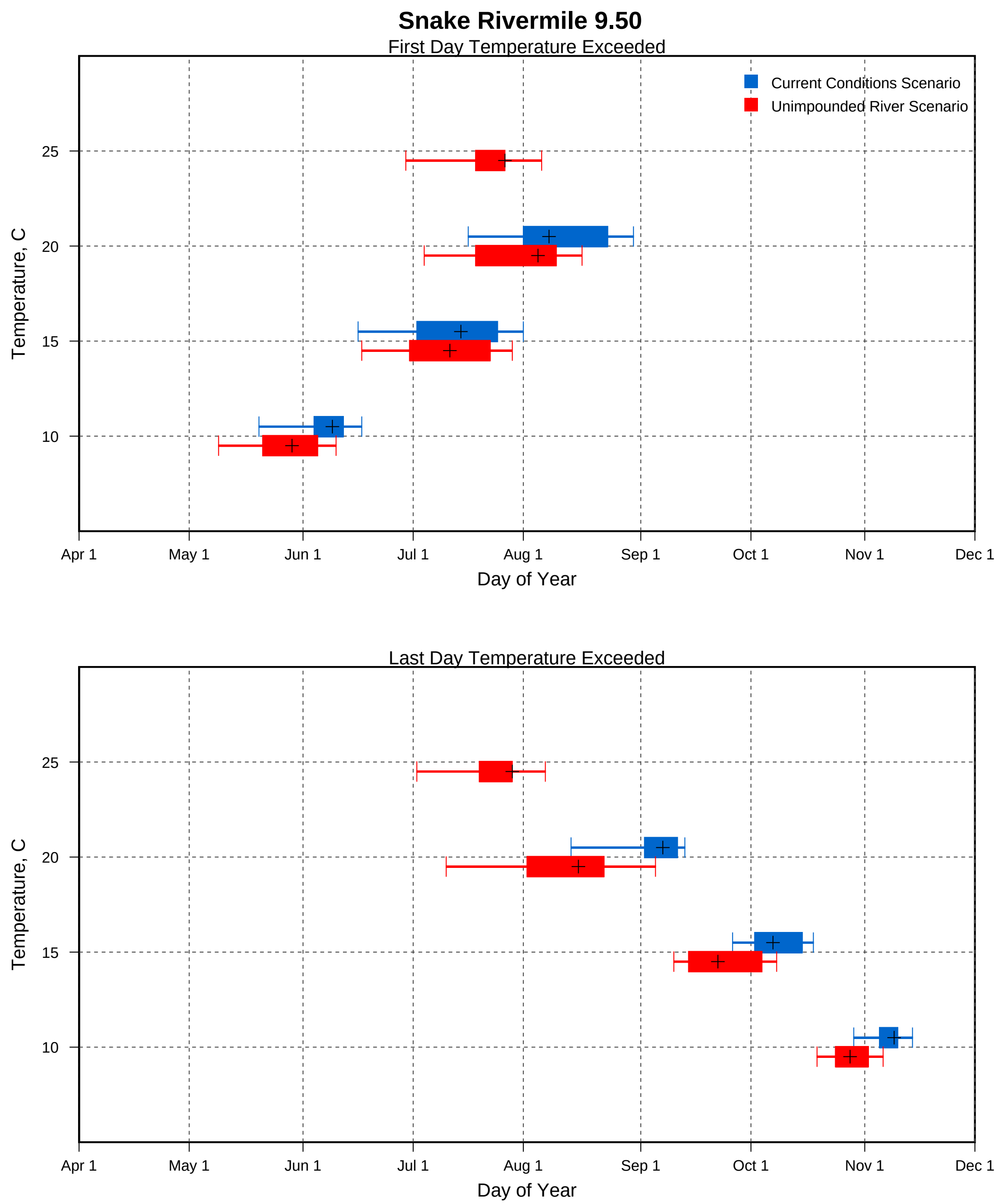

Figure 5.16: Comparison of when, during the year, simulated water temperature rose above (top) and fell below (bottom) various levels at the location of Ice Harbor dam during the unimpounded and current conditions scenarios.

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A Snake River Dissolved Gas Field Study Summaries

During 1996 and 1997, a series of field studies were performed by the U.S. Corps of Engineers in the Snake and Columbia Rivers as part of the Dissolved Gas Abatement Study (DGAS). The purpose of these studies was to measure the production and movement of dissolved gas during the spill season. During the studies, several water quality parameters, including temperature, were measured at various of locations and times.

This appendix summarizes the field studies from which data was used for MASS1 temperature model verification in Section 2, but only to the extent of presenting monitor station location and deployment duration. A more complete summary of the studies can be found in Carroll et al. (1998). A general description of the field work and of the DGAS program can be found in USACE (1999). In the following sections, the studies are presented by reservoir and simulated temperatures are compared to those observed during the studies.

A.1 Ice Harbor Pool

Two field studies were performed in Ice Harbor pool; one in the spring of 1996 and another in the spring of 1997. Table A.1 lists the monitoring stations and their deployment period. Figure A.1 shows the monitoring locations. Figures A.2 and A.3 show temperatures measured during the Spring 1996 and Spring 1997 studies, respectively, and compares simulated values from MASS1.

A.2 Lower Monumental Pool

Three field studies were performed in Lower Monumental pool during the spring of 1996, the spring of 1997, and the summer of 1997. Table A.2 lists the stations and their deployment period. Figure A.4 shows the monitor locations. Figures A.5, A.6, and A.7 show, respectively, temperatures observed during the Spring 1996, Spring 1997, and Summer 1997 study periods and compares them to simulated temperatures.

A.3 Little Goose Pool

Two field studies were performed in the Little Goose pool during the spring and summer of 1997. Table A.3 shows a list of the monitoring stations used and their deployment durations. Figure A.8 shows the monitor locations during the studies. Figures A.9 and A.10 show temperatures observed during the Spring 1997 and Summer 1997 study periods and compares them to simulated temperatures.

A.4 Lower Granite Pool

A single study was performed in Lower Granite pool during the spring of 1997. The monitoring stations used during the study are listed in Table A.4. Their locations are shown in Figure A.11.

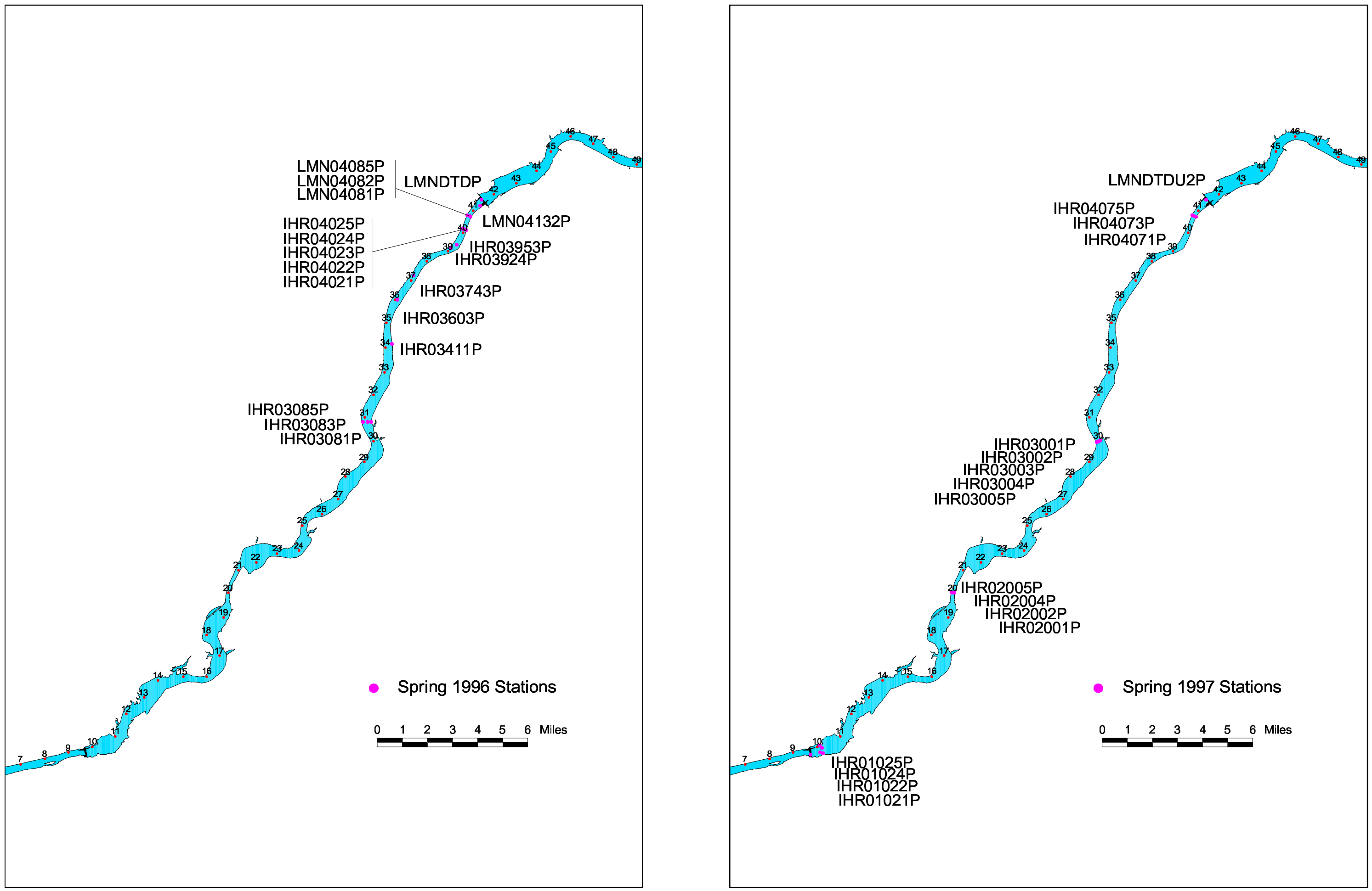

Figure A.1: Water quality monitoring stations used during the Spring 1996 (left) and Spring 1997 (right) DGAS study in Ice Harbor Pool.

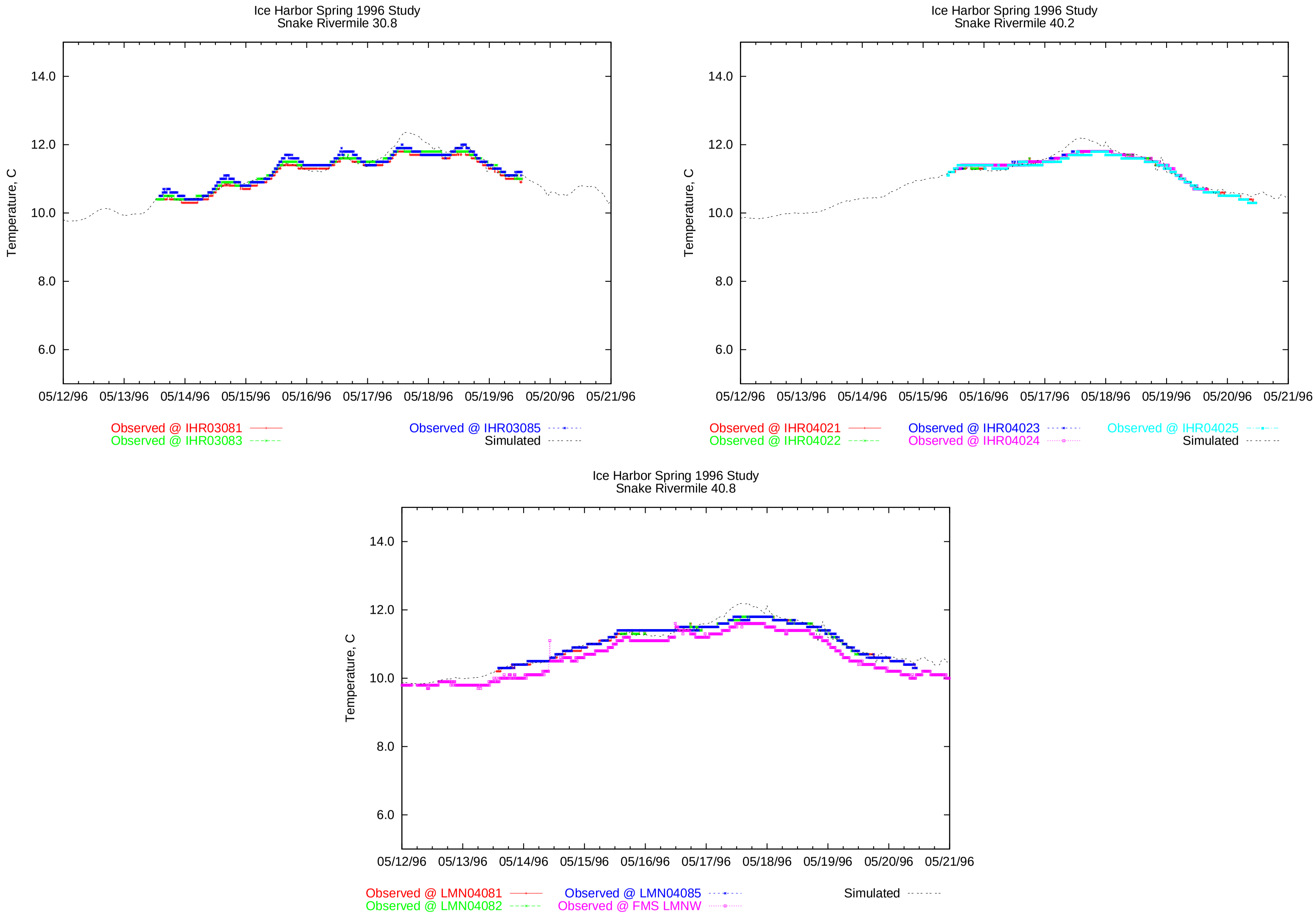

Figure A.2: Comparison of MASS1 simulated temperature with observed temperature during the Spring 1996 DGAS study in Ice Harbor pool.

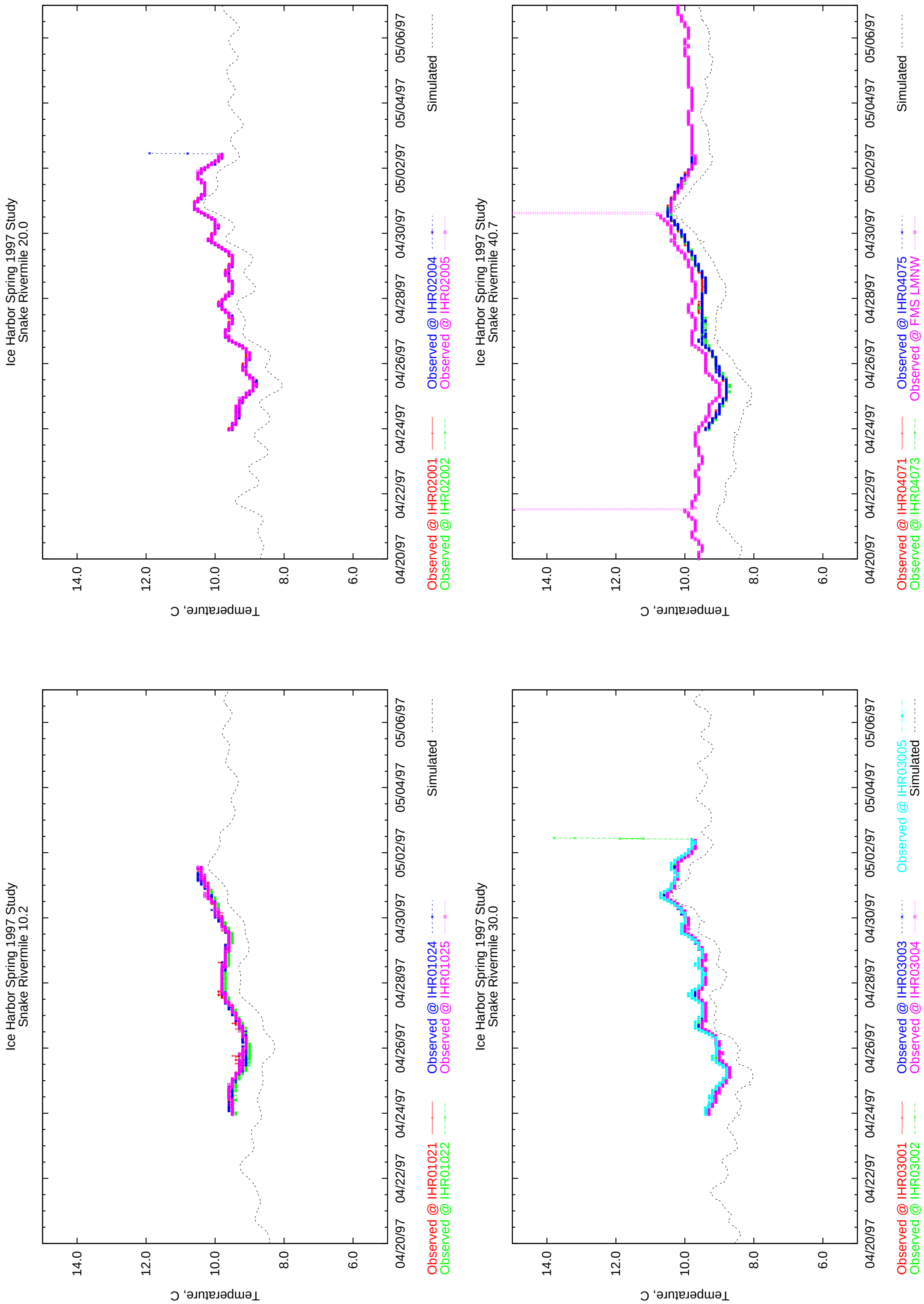

Figure A.3: Comparison of MASS1 simulated temperature with observed temperature during the Spring 1997 DGAS study in Ice Harbor pool.

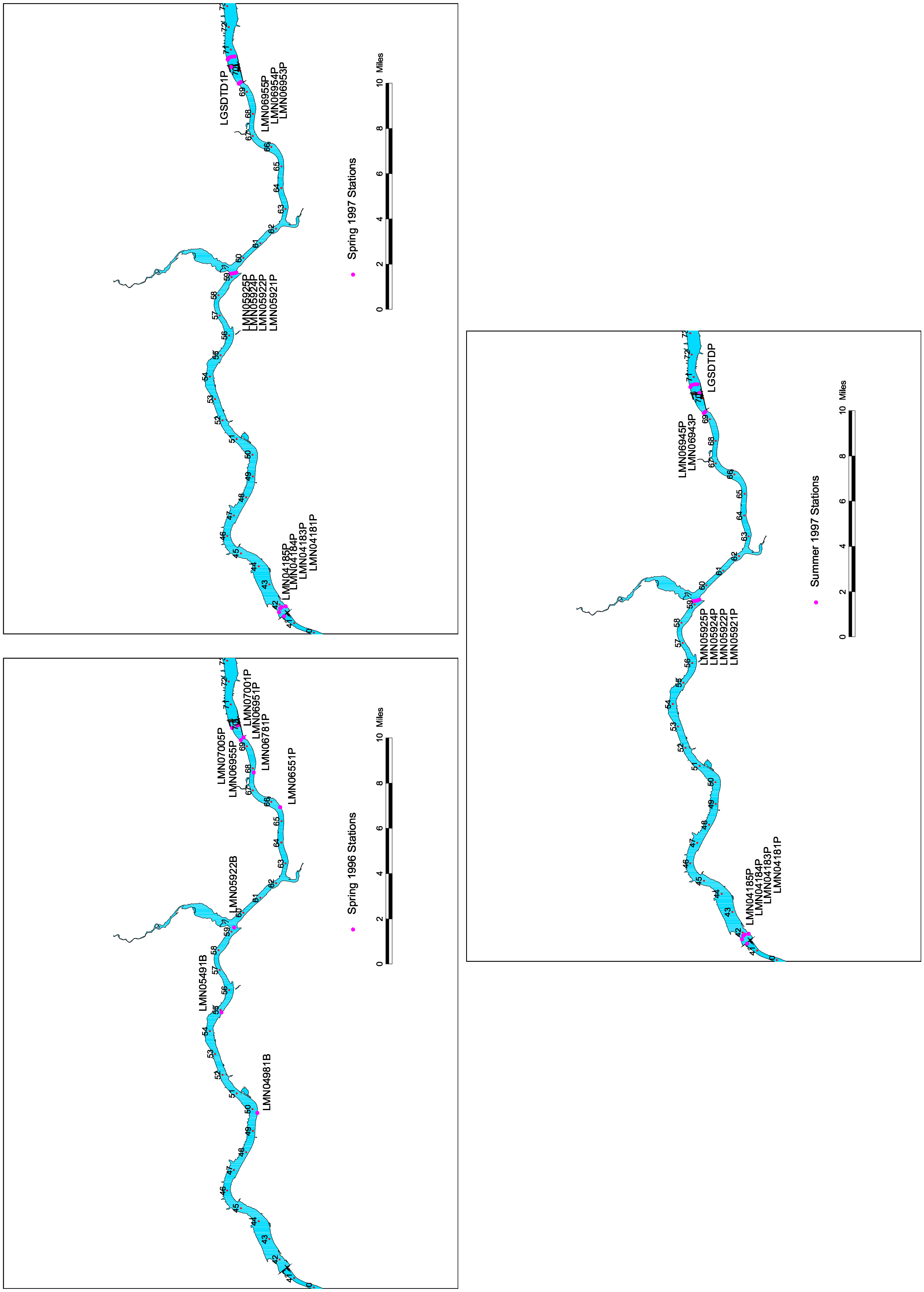

Figure A.4: Water quality monitoring stations used during the Spring 1996 DGAS study in Lower Monumental Pool.

Table A.1: Ice Harbor pool DGAS monitoring stations.

Study	Station	Start Date	End Date	Records
Spring 1996	IHR03081P	5/13/96 1:27:00 PM	5/19/96 12:57:00 PM	574
	IHR03083P	5/13/96 12:49:00 PM	5/19/96 12:49:00 PM	577
	IHR03085P	5/13/96 1:59:00 PM	5/19/96 12:44:00 PM	572
	IHR04021P	5/15/96 10:54:00 AM	5/20/96 11:24:00 AM	483
	IHR04022P	5/15/96 1:39:00 PM	5/19/96 3:09:00 PM	390
	IHR04023P	5/15/96 12:58:00 PM	5/19/96 3:43:00 PM	374
	IHR04024P	5/15/96 12:58:00 PM	5/19/96 3:43:00 PM	389
	IHR04025P	5/15/96 9:45:00 AM	5/20/96 11:15:00 AM	486
	LMN04081P	5/13/96 1:13:00 PM	5/20/96 10:28:00 AM	662
	LMN04082P	5/15/96 2:14:00 PM	5/19/96 3:44:00 PM	391
	LMN04085P	5/13/96 2:01:00 PM	5/20/96 11:01:00 AM	661
Spring 1997	IHR01021P	4/23/97 11:00:00 PM	5/1/97 1:00:00 PM	729
	IHR01022P	4/23/97 11:00:00 PM	5/1/97 1:15:00 PM	730
	IHR01024P	4/23/97 11:00:00 PM	5/1/97 1:15:00 PM	730
	IHR01025P	4/23/97 11:00:00 PM	5/1/97 1:30:00 PM	731
	IHR02001P	4/23/97 11:00:00 PM	5/2/97 10:30:00 AM	815
	IHR02004P	4/23/97 11:00:00 PM	5/2/97 11:00:00 AM	817
	IHR02005P	4/23/97 11:00:00 PM	5/2/97 10:15:00 AM	814
	IHR03001P	4/23/97 11:00:00 PM	5/2/97 11:00:00 AM	817
	IHR03002P	4/23/97 11:00:00 PM	5/2/97 11:00:00 AM	817
	IHR03003P	4/23/97 11:00:00 PM	5/2/97 9:30:00 AM	811
	IHR03004P	4/23/97 11:00:00 PM	5/2/97 9:30:00 AM	811
	IHR03005P	4/23/97 11:00:00 PM	5/2/97 9:15:00 AM	810
	IHR04071P	4/23/97 11:00:00 PM	5/2/97 8:00:00 AM	805
	IHR04073P	4/23/97 11:00:00 PM	5/2/97 8:00:00 AM	801
	IHR04075P	4/23/97 11:00:00 PM	5/2/97 8:15:00 AM	806

Snake River temperatures observed during the study are shown in Figure A.12; those for the Clearwater River are shown in Figure A.13. MASS1 simulated values are shown in both Figures A.12 and A.13 for comparison.

Table A.2: Lower Monumental pool DGAS monitoring stations.

Study	Station	Start Date	End Date	Records
Spring 1996	LMN06951P	4/23/96 2:52:00 PM	4/28/96 1:02:00 PM	468
	LMN06955P	4/23/96 2:33:00 PM	4/28/96 12:58:00 PM	469
Spring 1997	LMN04181P	4/4/97 3:30:00 PM	4/15/97 8:00:00 AM	514
	LMN04183P	4/4/97 3:30:00 PM	4/15/97 7:30:00 AM	257
	LMN04184P	4/4/97 4:30:00 PM	4/15/97 8:00:00 AM	512
	LMN04185P	4/4/97 4:00:00 PM	4/15/97 8:00:00 AM	513
	LMN05921P	4/3/97 4:00:00 PM	4/9/97 9:00:00 AM	137
	LMN05922P	4/4/97 9:30:00 AM	4/9/97 12:30:00 PM	124
	LMN05924P	4/4/97 9:30:00 AM	4/9/97 6:30:00 AM	118
	LMN05925P	4/4/97 9:30:00 AM	4/9/97 4:30:00 PM	119
	LMN06953P	4/4/97 11:38:00 AM	4/15/97 7:08:00 AM	514
	LMN06954P	4/4/97 12:13:00 PM	4/15/97 6:43:00 AM	512
	LMN06955P	4/4/97 11:30:00 AM	4/8/97 5:30:00 AM	91
Summer 1997	LMN04181P	6/6/97 12:00:00 PM	6/10/97 8:15:00 AM	368
	LMN04183P	6/6/97 12:00:00 PM	6/14/97 12:30:00 PM	771
	LMN04184P	6/6/97 12:00:00 PM	6/14/97 12:30:00 PM	771
	LMN04185P	6/6/97 12:00:00 PM	6/14/97 12:30:00 PM	771
	LMN05921P	6/6/97 12:00:00 PM	6/14/97 9:00:00 AM	757
	LMN05922P	6/6/97 12:00:00 PM	6/14/97 9:00:00 AM	757
	LMN05924P	6/6/97 12:00:00 PM	6/14/97 9:00:00 AM	757
	LMN05925P	6/6/97 12:00:00 PM	6/14/97 8:45:00 AM	755
	LMN06943P	6/6/97 12:00:00 PM	6/14/97 10:00:00 AM	761
	LMN06945P	6/6/97 12:00:00 PM	6/14/97 9:30:00 AM	759

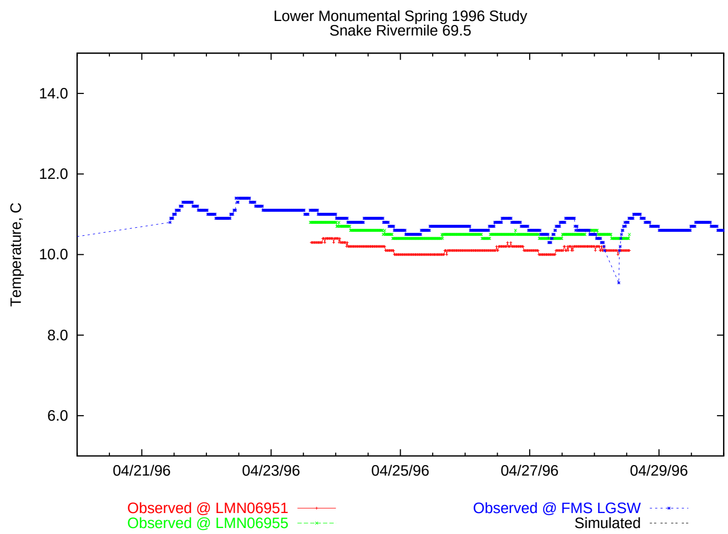

Figure A.5: Comparison of MASS1 simulated temperature with observed temperature during the Spring 1996 DGAS study in Lower Monumental pool.

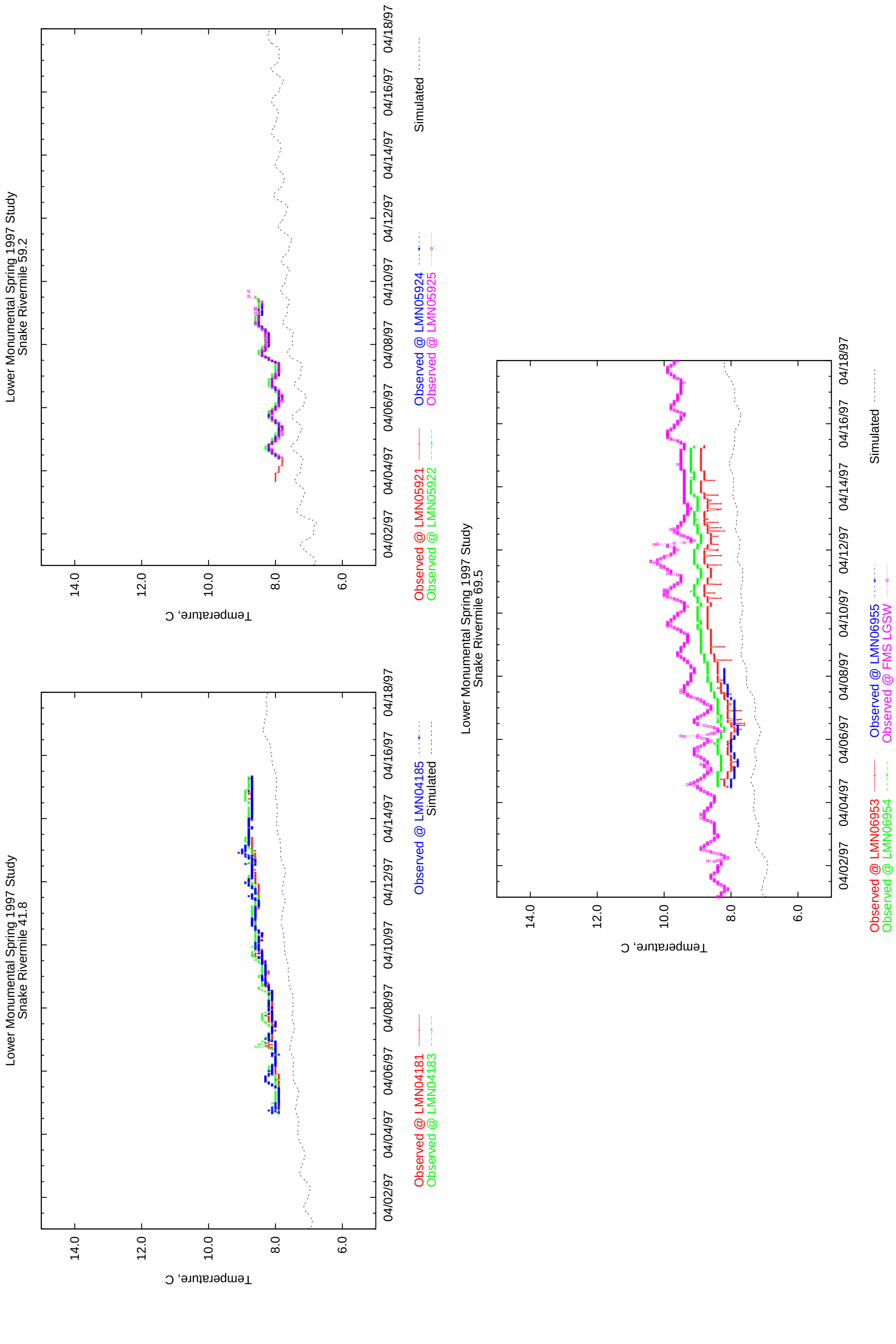

Figure A.6: Comparison of MASS1 simulated temperature with observed temperature during the Spring 1997 DGAS study in Lower Monumental pool.

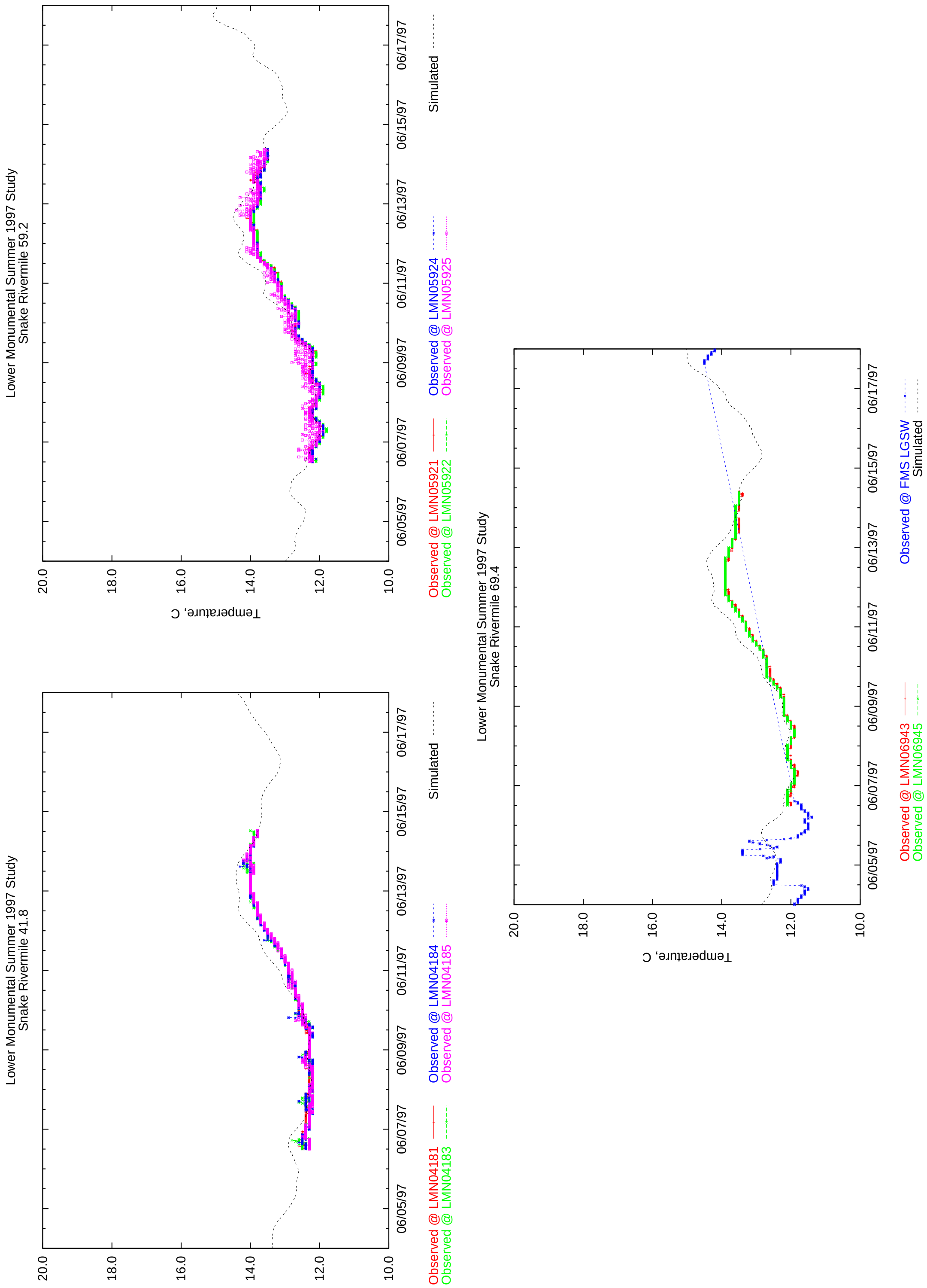

Figure A.7: Comparison of MASS1 simulated temperature with observed temperature during the Summer 1997 DGAS study in Lower Monumental pool.

Table A.3: Little Goose pool DGAS monitoring stations.

Study	Station	Start Date	End Date	Records
Spring 1997	LGS07071P	4/3/97 10:00:00 AM	4/16/97 8:00:00 AM	620
	LGS07072P	4/3/97 12:00:00 PM	4/16/97 10:00:00 AM	620
	LGS07074P	4/3/97 10:30:00 AM	4/16/97 8:30:00 AM	620
	LGS07075P	4/3/97 12:00:00 PM	4/16/97 8:00:00 AM	216
	LGS08321P	4/2/97 11:00:00 AM	4/16/97 9:00:00 AM	669
	LGS08322P	4/2/97 11:00:00 AM	4/16/97 9:00:00 AM	667
	LGS08324P	4/2/97 11:00:00 AM	4/16/97 9:00:00 AM	668
	LGS08325P	4/2/97 11:00:00 AM	4/16/97 9:00:00 AM	669
	LGS09841P	4/2/97 6:00:00 PM	4/16/97 11:00:00 AM	659
	LGS09842P	4/2/97 6:30:00 PM	4/16/97 11:00:00 AM	658
	LGS09843P	4/2/97 6:00:00 PM	4/16/97 11:00:00 AM	659
	LGS09844P	4/2/97 6:00:00 PM	4/16/97 11:00:00 AM	659
	LGS09845P	4/2/97 6:00:00 PM	4/16/97 11:00:00 AM	659
	LGS10671P	4/2/97 4:00:00 PM	4/16/97 10:00:00 AM	661
	LGS10672P	4/2/97 4:00:00 PM	4/15/97 7:00:00 AM	607
	LGS10673P	4/2/97 4:00:00 PM	4/16/97 10:00:00 AM	661
	LGS10674P	4/2/97 4:30:00 PM	4/16/97 10:00:00 AM	660
	LGS10675P	4/12/97 10:00:00 AM	4/16/97 10:00:00 AM	193
Summer 1997	LGS07071P	6/6/97 12:00:00 PM	6/13/97 3:30:00 PM	687
	LGS07072P	6/6/97 12:00:00 PM	6/13/97 3:30:00 PM	687
	LGS07074P	6/6/97 12:00:00 PM	6/13/97 3:45:00 PM	688
	LGS07075P	6/6/97 12:00:00 PM	6/13/97 4:00:00 PM	689
	LGS08321P	6/6/97 12:00:00 PM	6/10/97 5:45:00 PM	408
	LGS08322P	6/6/97 12:00:00 PM	6/13/97 1:30:00 PM	679
	LGS08324P	6/6/97 12:00:00 PM	6/13/97 1:45:00 PM	680
	LGS08325P	6/6/97 12:00:00 PM	6/13/97 1:45:00 PM	680
	LGS09841P	6/6/97 12:00:00 PM	6/13/97 11:30:00 AM	671
	LGS09842P	6/6/97 12:00:00 PM	6/13/97 11:30:00 AM	671
	LGS09843P	6/6/97 12:00:00 PM	6/13/97 11:30:00 AM	671
	LGS09844P	6/6/97 12:00:00 PM	6/13/97 11:30:00 AM	671
	LGS09845P	6/6/97 12:00:00 PM	6/13/97 11:00:00 AM	669
	LGS10671P	6/6/97 12:00:00 PM	6/13/97 10:00:00 AM	665
	LGS10672P	6/6/97 12:00:00 PM	6/13/97 10:30:00 AM	667
	LGS10673P	6/6/97 12:00:00 PM	6/13/97 10:15:00 AM	666
	LGS10674P	6/6/97 12:00:00 PM	6/13/97 10:45:00 AM	668
	LGS10675P	6/6/97 12:00:00 PM	6/13/97 9:45:00 AM	664

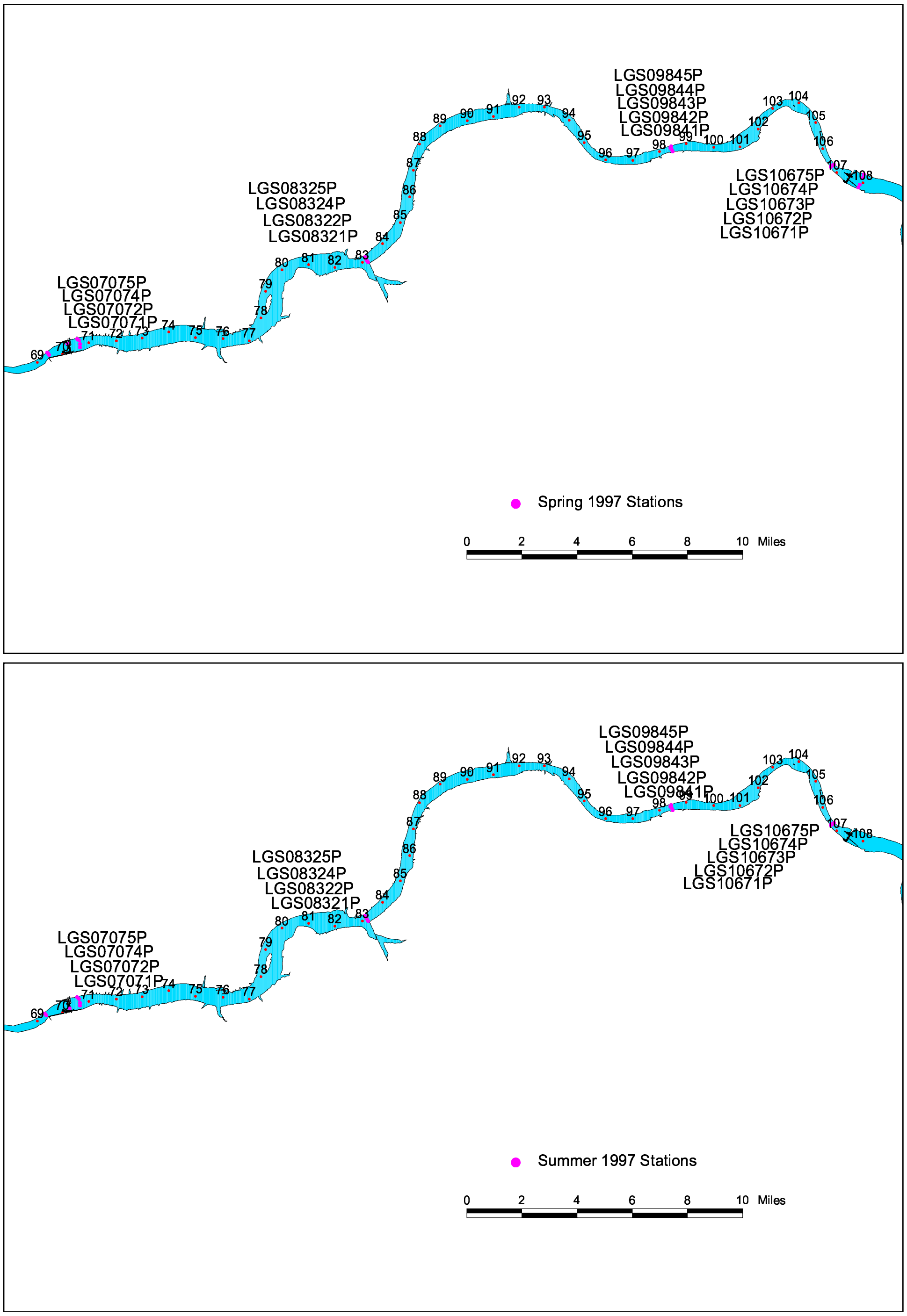

Figure A.8: Water quality monitoring stations used during the Spring 1997 (above) and Summer 1997 (below) DGAS study in Little Goose Pool.

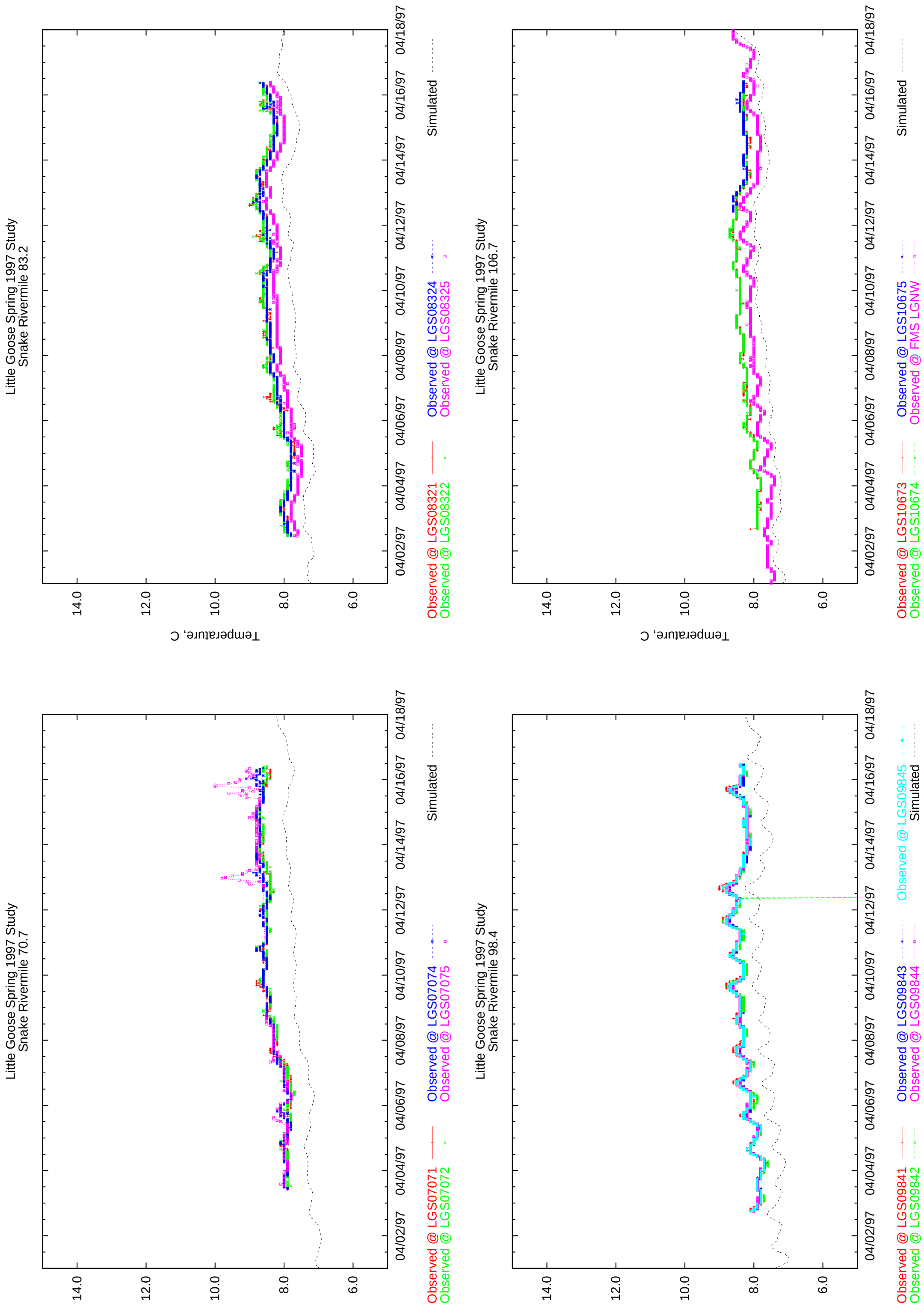

Figure A.9: Comparison of MASS1 simulated temperature with observed temperature during the Spring 1997 DGAS study in Little Goose pool.

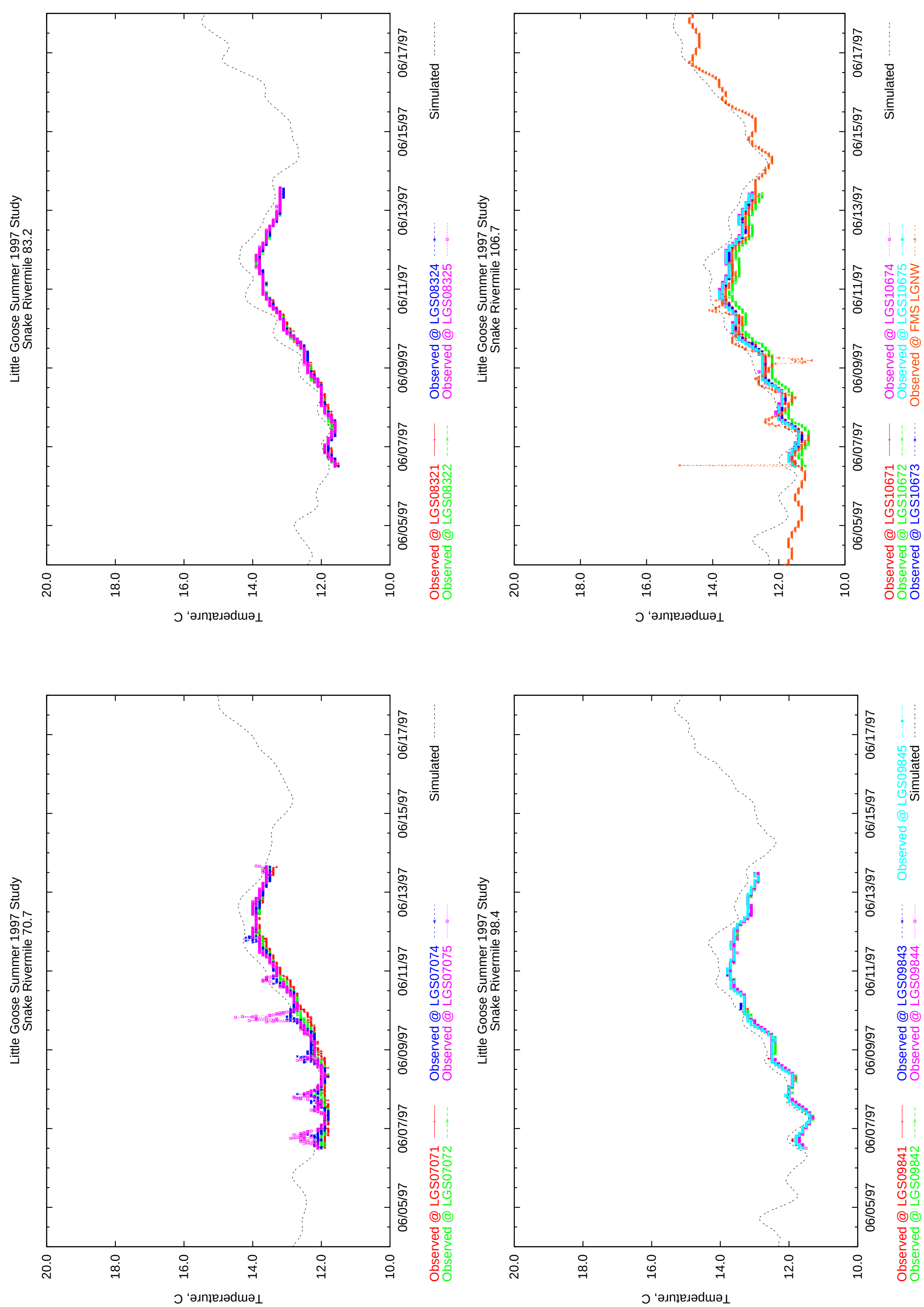

Figure A.10: Comparison of MASS1 simulated temperature with observed temperature during the Summer 1997 DGAS study in Little Goose pool.

Table A.4: Lower Granite pool DGAS monitoring stations.

Study	Station	Start Date	End Date	Records
Spring 1997	LWG00182P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG00184P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG10791P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG10792P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG10794P	4/2/97 11:00:00 PM	4/14/97 11:30:00 AM	554
	LWG10795P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG12371P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG12372P	4/2/97 11:00:00 PM	4/16/97 9:00:00 AM	645
	LWG12374P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG12375P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13741P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13742B	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13742P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13744B	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13744P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13972P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555
	LWG13974P	4/2/97 11:00:00 PM	4/14/97 12:00:00 PM	555

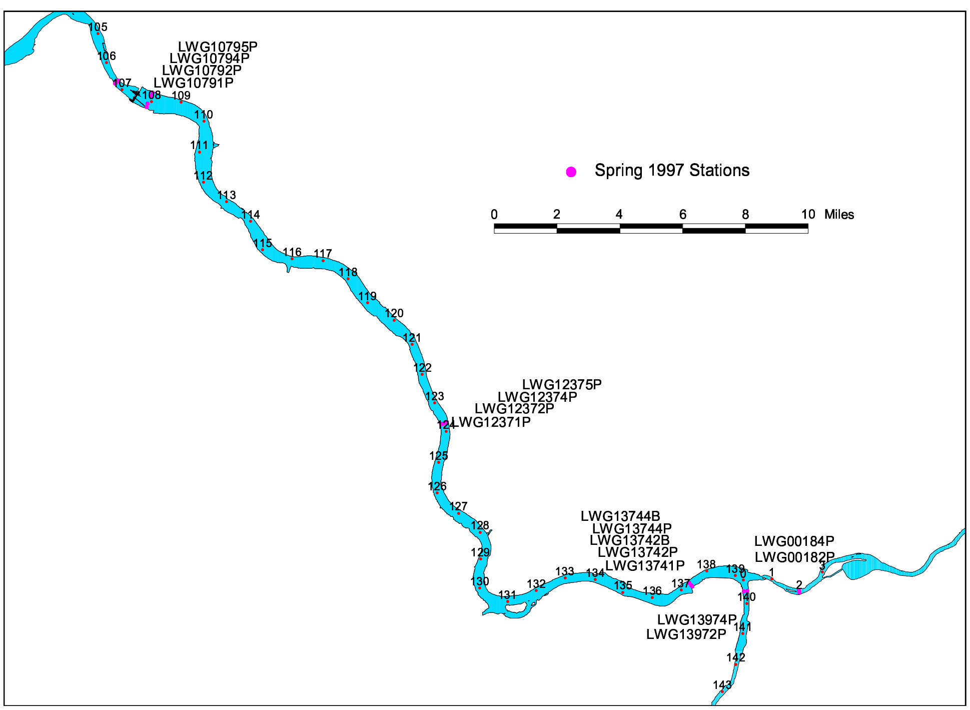

Figure A.11: Water quality monitoring stations used during the Spring 1997 DGAS study in Lower Granite pool.

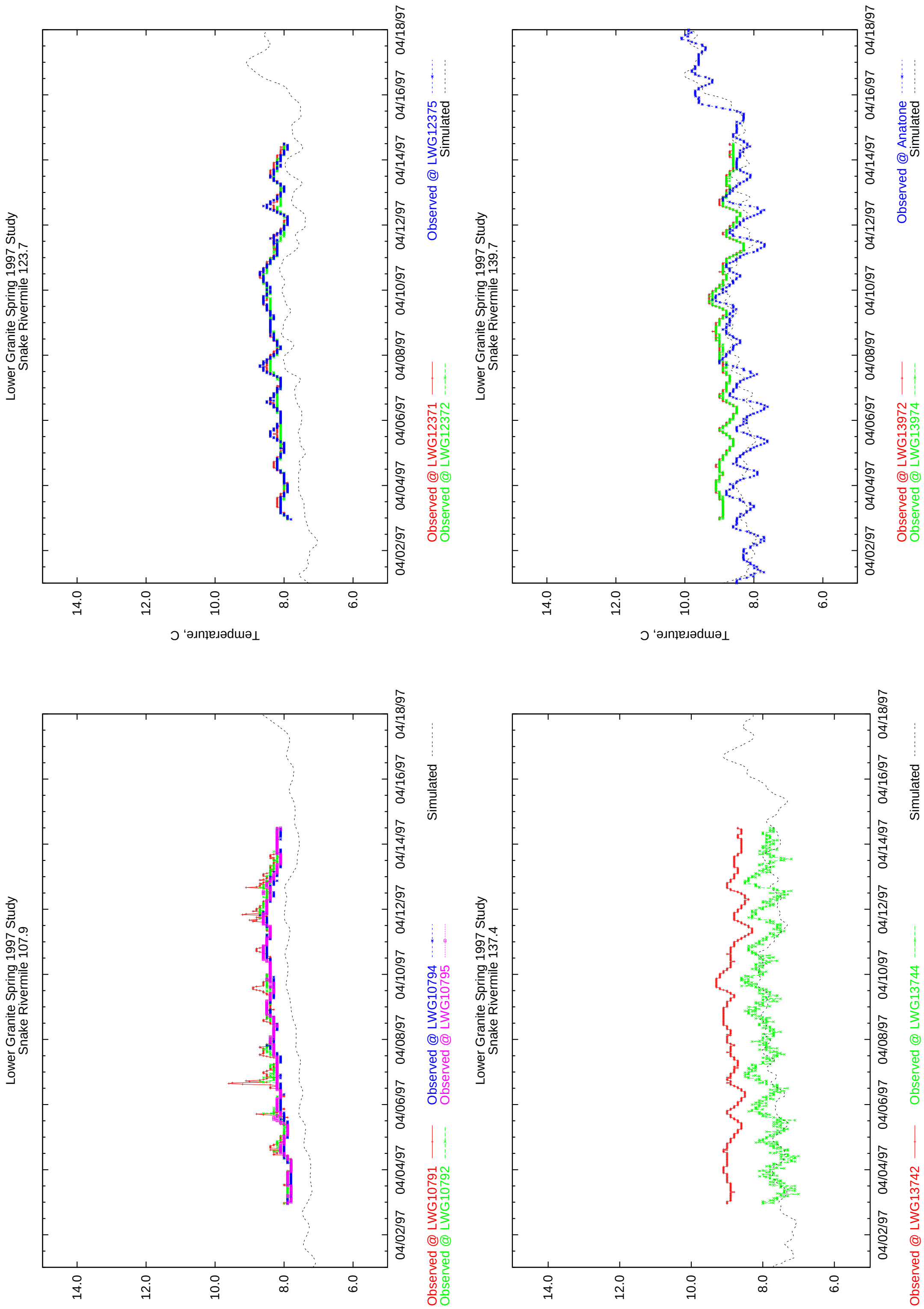

Figure A.12: Comparison of MASS1 simulated Snake River temperature with observed temperature during the Spring 1997 DGAS study in Lower Granite pool.

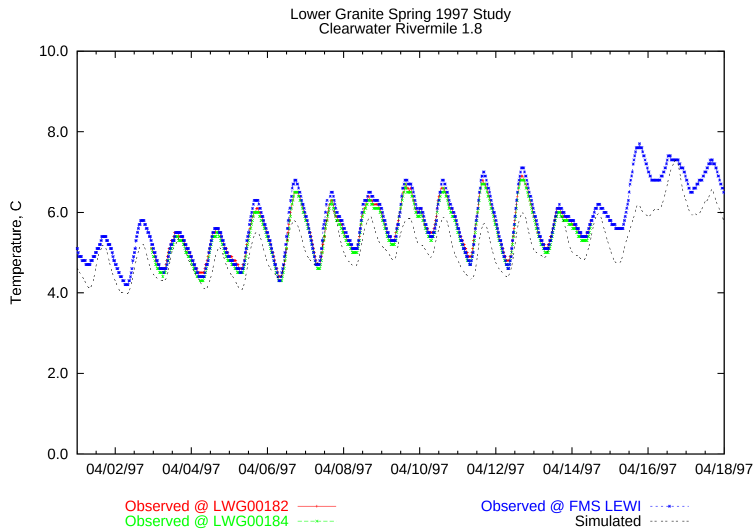

Figure A.13: Comparison of MASS1 simulated Clearwater River temperature with observed temperature during the Spring 1997 DGAS study in Lower Granite pool.

B Surface Heat Exchange

Heat exchange at the water surface is computed as the net heat flux which is represented as

$$\sum H = H_{sn} + H_{an} - (H_b + H_e + H_c) \tag{B.1}$$

where

$\sum H =$ net surface heat flux (W/m^2)
$H_{sn} =$ net solar shortwave radiation (W/m^2)
$H_{an} =$ net atmospheric long wave radiation (W/m^2)
$H_b =$ long wave back radiation (W/m^2)
$H_e =$ heat flux due to evaporation (W/m^2)
$H_c =$ heat flux due to conduction (W/m^2)

If measured radiation is available, the net solar short wave radiation is computed as

$$H_{sn} = H_a (1 - R_s) \tag{B.2}$$

where

$H_{sn} =$ net incoming short-wave solar radiation flux, W/m^2
$H_a =$ measured short-wave solar radiation, W/m^2
$R_s =$ albedo or reflection coefficient

The albedo is computed as Brown and Barnwell (1987)

$$R_s = A \left(\frac{180\alpha}{\pi} \right)^B \tag{B.3}$$

where

$\alpha =$ solar altitude, radians.

$$A = \begin{cases} 1.18 \text{ for } C_L < 0.1 \\ 2.20 \text{ for } 0.1 \le C_L < 0.5 \\ 0.95 \text{ for } 0.5 \le C_L < 0.9 \\ 0.35 \text{ for } C_L > 0.9 \end{cases}$$

and

$$B = \begin{cases} -0.77 \text{ for } C_L < 0.1 \\ -0.97 \text{ for } 0.1 \le C_L < 0.5 \\ -0.75 \text{ for } 0.5 \le C_L \le 0.9 \\ -0.45 \text{ for } C_L > 0.9 \end{cases}$$

When measured radiation is not available, net incoming short-wave solar radiation is estimated using Brown and Barnwell (1987)

$$H_{sn} = H_o a_t (1 - R_s) \left(1 - 0.65 C_L^2\right) \tag{B.4}$$

where

$H_o =$ the radiation flux reaching the earth's atmosphere, W/m^2
$a_t =$ atmospheric transmission coefficient
$C_L =$ cloudiness as a fraction of sky covered

H_o is estimated using ((Wigmosta and Perkins, 1997, Appendix C))

$$H_o = H_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]\sin\alpha \tag{B.5}$$

where

$H_{sc} =$ the solar constant, approximately 1360 W/m^2
$n =$ day of the year

and the solar altitude is calculated using

$$\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos h \tag{B.6}$$

where

$\phi =$ site latitude, radians
$\delta =$ declination of the sun, radians
$= 23.45\frac{\pi}{180d}\sin\left(2\pi\left[\frac{284+n}{365}\right]\right)$
$h =$ hour angle of the sun, radians
$= \frac{\pi}{12}(T_s - 12)$

T_s is the solar time, in hours, given by

$$T_s = T_l + \frac{12}{\pi}(L_{st} - L_{loc}) + E \tag{B.7}$$

where

$T_l =$ local time, hours
$L_{st} =$ standard longitude for the local time zone ($120\pi/180$ for the Pacific time zone), radians
$L_{st} =$ local longitude, radians
$E =$ equation of time, hours
$= (9.87\sin 2B - 7.53\cos B - 1.5\sin B)/60$
$B = \frac{2\pi(n-81)}{364}$

The net atmospheric long wave radiation is computed using formula 2.1.1 in Edinger et al. (1974):

$$H_a = 4.4\times10^{-8}(T_a + 273)^4\left[C_a + 0.031\sqrt{e_a}\right] \tag{B.8}$$

where

$T_a =$ air temperature, C°
$e_a =$ air vapor pressure, mm Hg
$C_a =$ Brunt's coefficient, (average value $= 0.65$)

The long wave back-radiation is computed using formula 2.1.4 in Edinger et al. (1974):

$$H_b = \varepsilon_w \sigma^* (T_s + 273.15)^4 \tag{B.9}$$

where

$T_s =$ water surface temperature, C°
$\varepsilon_a =$ emissivity of water (= 0.97)
$\sigma^* =$ Stephan-Boltzmann constant (= $5.67 \times 10^{-8}\ W/m^2K^4$)

The evaporation heat flux is computed using formula 2.1.5 in Edinger et al. (1974):

$$H_e = f(W)(e_s - e_a) \tag{B.10}$$

where

$f(W) =$ wind speed function = $9.2 + 0.46W^2 (W/(m^2 mmHg))$
$W =$ wind speed (m/s)
$e_a =$ air vapor pressure $(mmHg)$
$e_s =$ saturation vapor pressure of air at the water surface at $T_s(mmHg)$

The conduction heat flux is computed using formula 2.1.11 in Edinger et al. (1974):

$$H_c = 0.47 f(W)(T_s - Ta) \tag{B.11}$$

$f(W) =$ wind speed function = $9.2 + 0.46W^2 (W/(m^2 mmHg))$
$W =$ wind speed (m/s)
$e_a =$ air vapor pressure $(mmHg)$
$e_s =$ saturation vapor pressure of air at the water surface at $T_s(mmHg)$