GUNNISON RIVER / ASPINALL UNIT TEMPERATURE STUDY - PHASE II

FINAL REPORT

PREPARED FOR:

UPPER COLORADO RIVER ENDANGERED FISH RECOVERY PROGRAM

PROJECT # 107

(USBR CONTRACT # 01-FC-40-5340)

JANUARY 2004

Jean Marie Boyer

Amy Cutler

HYDROSPHERE
Resource Consultants

BUREAU OF RECLAMATION

This study was funded by the Recovery Implementation Program for Endangered Fish Species in the Upper Colorado River Basin. The Recovery Program is a joint effort of the U.S. Fish and Wildlife Service, U.S. Bureau of Reclamation, National Park Service, Western Area Power Administration, states of Colorado, Utah, and Wyoming, Upper Basin water users, environmental organizations, and the Colorado River Energy Distributors Association.

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1

1. INTRODUCTION...2

2. STATEMENT OF NEED / PROJECT OBJECTIVE..4

3. MODELING OVERVIEW 6

4. RESERVOIR TEMPERATURE MODELING 7

4.1 Overall methodology 7
4.2 Blue Mesa Reservoir...8
4.3 Morrow Point Reservoir 22
4.4 Crystal Reservoir 35

5. RIVER TEMPERATURE MODELING 46

5.1 Model results..48

6. FLOWRATES FOR THE "FLOW RECOMMENDATIONS" SCENARIO ...55

7. ADDRESSING RESERVOIR SCENARIOS USING CE-QUAL-W2................57

7.1 Historical releases 57
7.2 Flow recommendation 57
7.3 TCD Scenarios...58
7.4 Model results using a single-level TCD at Blue Mesa 59
7.5 Model results using a multiple-level TCD at Blue Mesa...............................60
7.6 Low reservoir elevation Scenario 60
7.7 Blue Mesa Reservoir heat budget 62

8. ADDRESSING RIVER SCENARIOS USING QUAL2K...................................66

8.1 Methodology 66
8.2 2K Scenarios results..67
8.3 High-flow scenarios 68
8.4 Average-flow scenarios 69
8.5 Low-flow scenarios..69
8.6 Summary of the River Scenarios 69

9. CONCLUSIONS AND RECOMMENDATIONS...71

10. REFERENCES...74

11. APPENDIX..76

LIST OF TABLES

Table 1: Calibration results for Blue Mesa Reservoir 18

Table 2: Calibration results for Morrow Point Reservoir 31

Table 3: Calibration Results for Crystal Reservoir..................................... 42

Table 4: Minimum and maximum Crystal release temperature based on the use of multi-level TCD in Blue Mesa Reservoir, CO 66

Table 5: Approximate increase in release temperature at Crystal Dam needed to meet temperature target at Delta.................................. 70

LIST OF FIGURES

Figure 1: Gunnison River Basin, CO (adapted from Butler 2000).................. 3
Figure 2: Blue Mesa Reservoir, CO segmentation -- plan view 9
Figure 3: Blue Mesa Reservoir, CO segmentation -- side view of main stem (IOLA = Iola In-Reservoir Sampling Station Location, CEBO = Cebolla In-Reservoir Sampling Station Location, SAPI = Sapinero In-Reservoir Sampling Station Location, B1 = Location of Branch 1, B2 = Location of Branch 2, B3 = Location of Branch 3, and B4 = Location of Branch 4).. 10
Figure 4: Relationship between water surface elevation and capacity of Blue Mesa Reservoir, CO. 11
Figure 5: Relationship between water surface elevation and surface area for Blue Mesa Reservoir, CO. 12
Figure 6: Gunnison River inflow to Blue Mesa Reservoir, CO. 13
Figure 7: Inflow into Blue Mesa Reservoir from the Lake Fork, CO. 13
Figure 8: Distribution of total inflow into Blue Mesa Reservoir................... 14
Figure 9: Inflow temperature into Blue Mesa Reservoir - Gunnison River, CO. 15
Figure 10: Inflow temperature into Blue Mesa Reservoir - Lake Fork, CO.... 16
Figure 11: Inflow temperature into Blue Mesa Reservoir - Cebolla Creek, CO...16
Figure 12: Inflow temperature into Blue Mesa Reservoir - W. Elk Creek, CO...17
Figure 13: Simulated vs. observed water surface elevations for Blue Mesa Reservoir 18
Figure 14: Observed and simulated surface water temperatures at the Sapinero site in Blue Mesa Reservoir, CO...................................... 19
Figure 15: Profiles at the Sapinero site in Blue Mesa Reservoir, CO - 1999 (1 of 2) 20
Figure 15: Profiles at the Sapinero site in Blue Mesa Reservoir, CO - 1999 (2 of 2) 21
Figure 16: Simulated temperatures of Blue Mesa releases and observed inflow temperature of Gunnison River, CO. 22
Figure 17: Morrow Point segmentation -- plan view 23
Figure 18: Morrow Point, CO segmentation -- side view of main stem (MOR1 = Morrow Point In-Reservoir Sampling Station Location #1 and MOR2 = Morrow Point In-Reservoir Sampling Station Location #2) 25

Figure 19:Relationship between water surface elevation and capacity of Morrow Point Reservoir, CO. 26

Figure 20:Relationship between water surface elevation and surface area for Morrow Point Reservoir, CO. 27

Figure 21:Distribution of total inflow into Morrow Point Reservoir, CO. 28

Figure 22:Inflow temperatures from Curecanti Creek, CO. 29

Figure 23:Inflow temperatures from Big Blue Creek, CO. 29

Figure 24:Simulated vs. observed water surface elevations for Morrow Point Reservoir, CO. 30

Figure 25:Observed and simulated surface water temperatures at the Sapinero site in Blue Mesa Reservoir 31

Figure 26:Temperature profiles at MOR1 Site in Morrow Point, CO - 2000 (1 of 2) 33

Figure 26:Temperature profiles at MOR1 Site in Morrow Point, CO - 2000 (2 of 2) 34

Figure 27:Inflow and release water temperatures at Morrow Point, CO. (Tin = inflow water temperatures and Tout = release water temperature) 35

Figure 28:Crystal Reservoir, CO segmentation -- plan view 36

Figure 29:Crystal Reservoir, CO segmentation -- side view (CRYS1 = Crystal In-Reservoir Sampling Station Location #1 and CRYS2 = Crystal In-Reservoir Sampling Station Location #2) 37

Figure 30:Relationship between water surface elevation and capacity of Crystal Reservoir, CO. 38

Figure 31:Relationship between water surface elevation and reservoir surface area for Crystal Reservoir, CO. 39

Figure 32:Distribution of total inflow into Morrow Point Reservoir, CO. 40

Figure 33:Simulated vs. observed water surface elevations for Crystal Reservoir, CO. 41

Figure 34:Observed and Simulated Surface Water Temperatures in Crystal Reservoir, CO. 42

Figure 35:Profiles at CRYS1 Site in Crystal Reservoir, CO - 2000 (1 of 2) 43

Figure 35:Profiles at CRYS1 Site in Crystal Reservoir, CO - 2000 (2 of 2) 44

Figure 36:Observed vs. simulated release temperatures from Crystal Reservoir, CO. 45

Figure 37:River simulation results -- May 23–27, 1997 (The data on the right hand side represent conditions just downstream of Crystal Dam. Data points at 46.7 km are observed data at the FWS site on the

Gunnison River above the confluence with the North Fork. Data points at 79.2 km represent observed temperatures at the FWS temperature site at Delta. The black line is the simulated average steady-state temperature throughout the study area)..................48

Figure 38: River simulation results -- October 17–21, 1997 49

Figure 39: River simulation results -- June 28–30, 1998..................................49

Figure 40: River simulation results -- August 16–20, 1998..............................50

Figure 41: River simulation results -- May 4–6, 2000 50

Figure 42: River simulation results -- June 16–18, 2000..................................51

Figure 43: Diurnal temperature pattern at Delta -- May 23–27, 1997..............51

Figure 44: Diurnal temperature pattern at Delta -- October 17–21, 1997.......52

Figure 45: Diurnal temperature pattern at Delta -- June 28–30, 1998 52

Figure 46: Diurnal temperature pattern at Delta -- August 16–20, 1998 53

Figure 47: Diurnal temperature pattern at Delta -- May 4–6, 2000 53

Figure 48: Diurnal temperature pattern at Delta -- June 16–18, 2000 54

Figure 49: Historical Crystal Reservoir releases compared to flow recommendations...56

Figure 50: Release water temperature at Crystal, CO during 1997 to 2000 (historic) and under scenario if FWS flow recommendations were implemented..57

Figure 51: Release water temperature from Morrow Point reservoir with and without the use of a TCD..59

Figure 52: Release water temperatures below Blue Mesa Reservoir, CO from four different scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition). 61

Figure 53: Water temperature released from Morrow Point Reservoir,CO, based on upstream Blue Mesa reservoir scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition)................................61

Figure 54: Water temperature released from Crystal Reservoir, CO under based on upstream Blue Mesa reservoir scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition)................................62

Figure 55: Water Temperatures, elevations and time series plots from the forebay of Blue Mesa Reservoir, CO (top plot = without TCD scenario and bottom plot = with multi-level TCD scenario).........63

Figure 56: Volume comparison of water temperature ranges from 8 to 10 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD). 63

Figure 57: Volume comparison of water temperature ranges from 10 to 12 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD). 64

Figure 58: Volume comparison of water temperature ranges from 12 to 14 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD). 64

Figure 59: Volume comparison of water temperature ranges from 14 to 16 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD). 65

Figure 60: July high-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C. 67

Figure 61: July average-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C. 68

Figure 62: July low-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C. 68

LIST OF KEY WORDS

Gunnison River, Blue Mesa Reservoir, Morrow Point Reservoir, Crystal Reservoir, water temperature, reservoir temperature, temperature control device

EXECUTIVE SUMMARY

The objective of this study is to determine the feasibility of increasing water temperatures in the Gunnison River at and below Delta, Colorado through structural and/or operational modifications to the Aspinall Unit Reservoirs. Increased river temperatures are needed to enhance growth and survival of the Colorado pikeminnow, an endangered native fish species in Gunnison River reaches designated as critical habitat. The project is being approached in a two-step process. The first phase of the work, which was summarized in a previous report, included data collection and assessment; an overview of factors that may constrain the ability to meet temperature objectives; a preliminary analysis of the data with the intent of gaining insight into the primary physical processes governing water temperature in the basin; and modeling recommendations for the second phase of the work.

The current phase of the project is Phase II. This phase involves 1) the development and application of numerical water quality models of the Gunnison system and 2) a study to quantify the potential impacts of the reoperation of the Aspinall unit and the potential impacts of a temperature control device on downstream Gunnison River temperatures at Delta. CE-QUAL-W2 was used to simulate temperature in Blue Mesa, Morrow Point, and Crystal Reservoirs and QUAL2K was used to simulate river temperatures in the Gunnison River.

Historic reservoir release temperatures were compared to modeled release temperatures resulting from the proposed by the U.S. Fish and Wildlife Service (FWS) “Flow Recommendations” and from two hypothetical selective withdrawal structures at Blue Mesa dam. A final scenario addresses how low reservoir elevations relate to release temperature.

Model results describe the temperature regimes which are probable throughout a given set of years, the effectiveness of incorporating selective withdrawal structures at the Blue Mesa dam, the effect of selective withdrawals on the reservoir’s heat budget, and the range of achievable temperature to meet downstream targets at Delta identified by the FWS (Osmundson 1999). This study indicates that it is possible to meet downstream temperature targets through incorporation of a multiple-level selective withdrawal structure at Blue Mesa Dam. Through model validation, the accuracy of prediction is within +/- 1°C. In the absence of a sensitivity analysis, the magnitude and direction of errors caused by the uncertainties in model inputs are unknown. Ideally a range 4°C to 18°C release temperature is achievable below Crystal Reservoir with selective withdrawal at Blue Mesa. The heat budget at Blue Mesa is affected considerably by selective withdrawal temperature as well as other hydrologic and meteorological factors.

1. INTRODUCTION

Hydrology of the Gunnison River has been significantly altered by the construction and operation of the Aspinall Unit (Blue Mesa, Morrow Point and Crystal Reservoirs), and by diversions and return flows primarily related to irrigation in the areas surrounding Montrose and Delta (Figure 1). Cool river temperatures resulting from dam related changes to the basin hydrology (Stanford 1994) have been identified as a significant impediment to re-establishment of Colorado pikeminnow in the Gunnison River (Osmundson 1999).

Records indicate that Colorado pikeminnow historically were found in the Gunnison River as far upstream as Delta, Colorado (Quarterone 1993), though recent studies indicate that Colorado pikeminnow are largely confined to downstream reaches of the river (Valdez et al. 1982; Burdick 1995). Osmundson (1999) states that the area near Delta provides the "most diverse physical habitat conditions in the Gunnison River" between Hartland Diversion and the mouth. The Hartland Diversion dam is located above the city of Delta, just below the mouth of Tongue Creek.

Results of Osmundson's work indicate that increasing daily mean water temperatures at Delta by 1 ^{o}C in June, September and October, and by 2 ^{o}C in July and August, would increase the mean annual thermal units (ATU) from 32 to 46 units. The ATU are calculated by the sum of the mean daily temperatures in a year, which were converted from values relative to the maximum potential (1.0) for growth at the optimum temperature at 25°C (Kaeding and Osmundson 1988). Such an increase would put stream temperatures at Delta at a level similar to sites on the Yampa and Colorado Rivers that support functioning populations of Colorado pikeminnow.

Stream temperature in reservoir-regulated rivers is a function of several related variables. The "natural" mean water temperature is closely related to mean air temperature (Sinokrot and Stefan 1993). Water released from a reservoir will tend to approach this natural or ambient water temperature as it travels downstream. The rate at which the waters warm and the ability to achieve a specific temperature at a specific location depend on release temperature, flow, and atmospheric conditions. In general, increasing reservoir release temperatures will result in warmer downstream temperatures. The relationship between release temperature and downstream temperature is nonlinear (e.g., a 1 ^{o}C increase in release temperature does not necessarily result in a 1 ^{o}C increase downstream) and is limited by the ambient atmospheric conditions. Reducing reservoir releases typically will also increase downstream temperatures during June to September, depending upon ambient atmospheric conditions. This is the result of the slower rate at which the water travels downstream, thus increasing the time it is exposed to atmospheric heating.

There are potentially two ways that downstream water temperature can be increased in the Gunnison River. These are to 1) *increase* the *temperature* of the water being released from the Aspinall Reservoirs, and/or 2) *decrease* the *amount* of water being released. Analysis of the potential for releasing warmer water is complicated by the physical characteristics of the Aspinall Unit reservoirs. If a temperature control device (TCD) solution is desired, it is not immediately clear which reservoir or reservoirs would need to be modified with such structures.

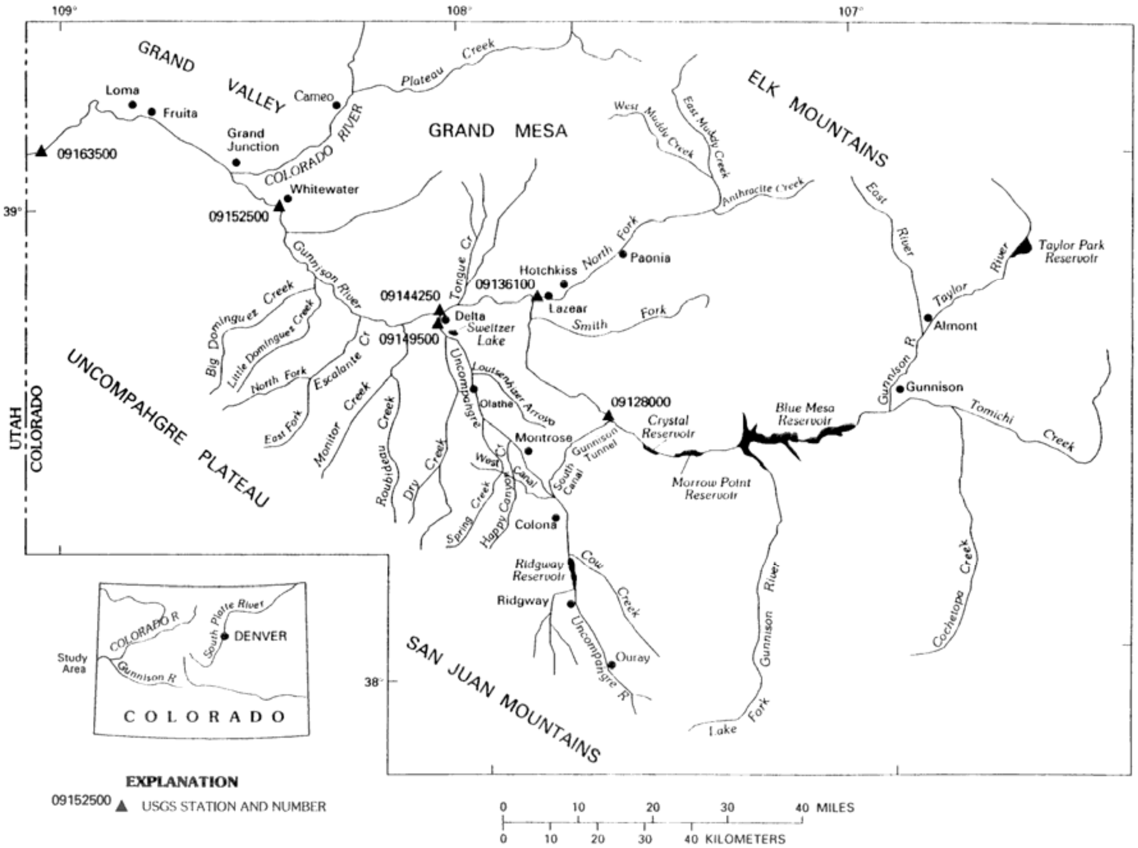


Figure 1: Gunnison River Basin, CO (adapted from Butler 2000).

Additionally, before any decision can be made to modify the system for purposes of temperature management, a whole host of other physical and institutional constraints must be taken into consideration. These constraints may include, but are not limited to, factors such as: water rights administration, hydropower generation, recreational fisheries (river and reservoir), reservoir recreation, flood control, FWS flow recommendations, environmental compliance, and interstate and international compacts.

2. STATEMENT OF NEED / PROJECT OBJECTIVE

The objectives of this study are to determine whether structural modifications to the Aspinall Unit Reservoirs can increase release water temperature below Crystal dam and meet downstream temperature recommendation at Delta, CO in the Gunnison River as described by Osmundson 1999. The project is being approached in a two-step process. The first phase of the work, which was summarized in a previous report (Hydrosphere Resource Consultants 2002), included data collection and assessment; an overview of factors that may constrain the ability to meet temperature objectives; a preliminary analysis of the data with the intent of gaining insight into the primary physical processes governing water temperature in the basin; and modeling recommendations for the second phase of the work.

The deliverables for Phase I of the study were:

- Collection and assessment of existing data and models from the Gunnison Basin, including stream and reservoir temperatures, mainstem and tributary inflows, meteorological data, and any models of the reservoir / river system;

- A work plan outlining additional data collection and field work required to have a "complete" database for future modeling efforts;

- An analysis of non-physical factors that may influence temperature control, such as constraints on reservoir operations or water delivery obligations; and

- An initial assessment of the prospects for obtaining warmer stream temperatures at Delta and what methods are likely to be most effective (e.g., modification of reservoir release hydrograph vs. use of selective withdrawal for releasing warmer water).

The Phase I work concluded with the following:

> "The preliminary results of the reservoir and river data analyses seem to indicate that a temperature control device, most likely located at Blue Mesa Dam, could be used to achieve warmer temperatures in the Gunnison River near Delta. We strongly recommend a rigorous modeling study be conducted on the three Aspinall Unit reservoirs to better understand the implications of a TCD on one or more of the structures. Additionally, we recommend a river temperature modeling exercise, based either on QUAL-2E or on a multivariate statistical model. Our preliminary results indicate that since longer-term average temperatures in the river are more relevant than daily or hourly temperatures, a rigorous mechanistic model of the river system may be unnecessary."

The current phase of the project, Phase II, involves development and application of numerical models of the Gunnison system. The goal is to use the models to answer several questions, including:

- Do the models confirm the Phase I results indicating that a temperature control device at Blue Mesa Dam would result in warmer release temperatures from Crystal Dam?

- Would an increase in release temperatures from Crystal Dam result in a significant increase in stream temperatures in the area around Delta, Colorado?

- If so, how much warmer would the release waters need to be to meet the targets identified in Osmundson's 1999 report?

- How do wet/normal/dry year inflows to the Aspinall Unit affect reservoir releases and how would these variations affect the use of a TCD?

- Can temperature targets be met in a wet/normal/dry year?

- What is the impact of a TCD on reservoir heat budget?

- What are the most feasible TCD options to achieve temperature targets?

- What are reservoir responses to flow recommendations?

This report is structured as follows. A modeling overview is given in Section 3. The development of the three reservoir models is described in Section 4 followed by a description of the river model in Section 5. The development of the flow rates for the "flow recommendations" scenario is described in Section 6. The Flow Recommendations were developed by FWS to aid the recovery of native endangered fishes for the Gunnison River. Section 7 provides an overview of the results from the "flow recommendations" scenario. Sections 8 and 9 contain a discussion of the results, conclusions and recommendations.

3. MODELING OVERVIEW

In order to predict the impacts of modified operations of Blue Mesa Reservoir on stream temperatures at Delta, the system between these points needed to be simulated. The system was divided into the following components: Blue Mesa Reservoir, Morrow Point Reservoir, Crystal Reservoir, and the Gunnison River between Blue Mesa Dam and Delta.

The CE-QUAL-W2 model was chosen to simulate each of the three reservoirs. The simulated outflows from the upstream reservoirs were used to provide input into the downstream reservoirs. The simulated release from Crystal Reservoir was then used as input to the river model. The details of the reservoir modeling are described in Section 4.

The initial plan for the river model was to use a multivariate statistical model. Due to the inability to use this approach during the critical months of July through September an alternative approach was needed. The final river modeling was conducted using the QUAL2K model. The details of the river modeling are described in Section 5.

After the four models were calibrated, new flow files were developed to reflect operations according to the flow recommendations put forth by FWS (McAda 2003). These flow recommendations were developed to provide the annual and seasonal patterns of flow in the Gunnison River to enhance the population of the Colorado pikeminnow. The development of specific flow files for this project and the results from running those flow files are discussed in Sections 6 and 7.

4. RESERVOIR TEMPERATURE MODELING

4.1 Overall methodology

Three two-dimensional reservoir models were developed for this project -- one for each of the three reservoirs of the Aspinall Unit (Blue Mesa Reservoir, Morrow Point Reservoir, and Crystal Reservoir). Temperature was simulated over several years and the models were calibrated using observed data.

The modeling framework chosen for this effort is CE-QUAL-W2 (or "W2"). W2 (Cole and Wells 2002) was developed by the U.S. Army Corps of Engineers and has been under continuous development since the 1970s. It has been successfully applied to over 400 systems in the United States and worldwide. It is a two-dimensional, laterally averaged hydrodynamic model. Input data vary with time and the results are produced as a time series. The W2 model is well known for its ability to accurately simulate reservoir hydrodynamics and temperature. Although W2 can be used to simulate a suite of water quality constituents, only temperature was simulated for this application. Impacts on reservoir fisheries and specific dynamics such as zooplankton production, fish distribution and feeding behavior, and predator-prey interactions were beyond the scope of Phase II.

The version of W2 used for this project is 3.1. The specific file used was downloaded from the W2 website (www.ce.pdx.edu/w2/) on September 25, 2002. Note that the model is continuously being modified, so the copy of CE-QUAL-W2 v3.1 on the website today may not be exactly the same as the copy available on September 25, 2002. (The version number changes only after significant upgrades have been made.)

Although W2 has been designed to simulate a system of reservoirs and rivers in one model, three separate models were developed due to run-time constraints. For calibration purposes, each reservoir was simulated starting with the first day in 1997 that reservoir profiles were available. This was done in order to start with a good initial condition for each model. Simulations were then run for the period through September 30, 2001. This period of time encompasses wet, dry, and average years.

Two metrics were used to assess how well each model matched the observed data. The first is the Absolute Mean Error (AME) which is computed as:

$$AME = \frac{\sum |Computed - Observed|}{NumberofObservations}$$

An AME of 0.5 ^{o}C means that the model is, on average, within ± 0.5 ^{o}C of the observed data. An AME less than 1.0 ^{o}C is considered to be reasonably well calibrated.

The other metric is called the Root Mean Square Error (RMSE). It is an indicator of the spread of how far computed values deviate from the observed values. The RMSE is computed as:

$$RMSE = \sqrt{\frac{\sum (Computed - Observed)^2}{NumberofObservations}}$$

An RMSE of 0.5 ^{o}C means that the simulated temperatures are within 0.5 ^{o}C of the measured temperatures about 67% of the time (Green et al. 2003).

The characterization for each reservoir is described below. Basic information for the three reservoirs (morphometry, residence time, hydrology, etc.) is described in the Phase I report (Hydrosphere 2002).

4.2 Blue Mesa Reservoir

Simulation period

For Blue Mesa Reservoir, the simulation period was from June 3, 1997, through September 30, 2001. The start date was the date of the first temperature profile in 1997.

Computational grid

A plan view of Blue Mesa Reservoir is shown in Figure 2. The reservoir was divided into 53 segments longitudinally along the main branch (Gunnison River) and four tributary branches. Segments varied in length from 500 to 1,500 meters. The reservoir was also divided into 37 layers (Figure 3). Layer depths varied from 1 to 5 meters. The reservoir outlet is at 2,245.5 meters (7,367 feet) above mean sea level (MSL), and the spillway is at elevation 2,282.3 meters (7,487.9 feet) above MSL.

In addition to the Gunnison River (designated as Branch 1), the following branches were represented:

Branch 2:	Cebolla Creek Arm
Branch 3:	W. Elk Creek Arm
Branch 4:	Soap Creek Arm
Branch 5:	Lake Fork of the Gunnison Arm

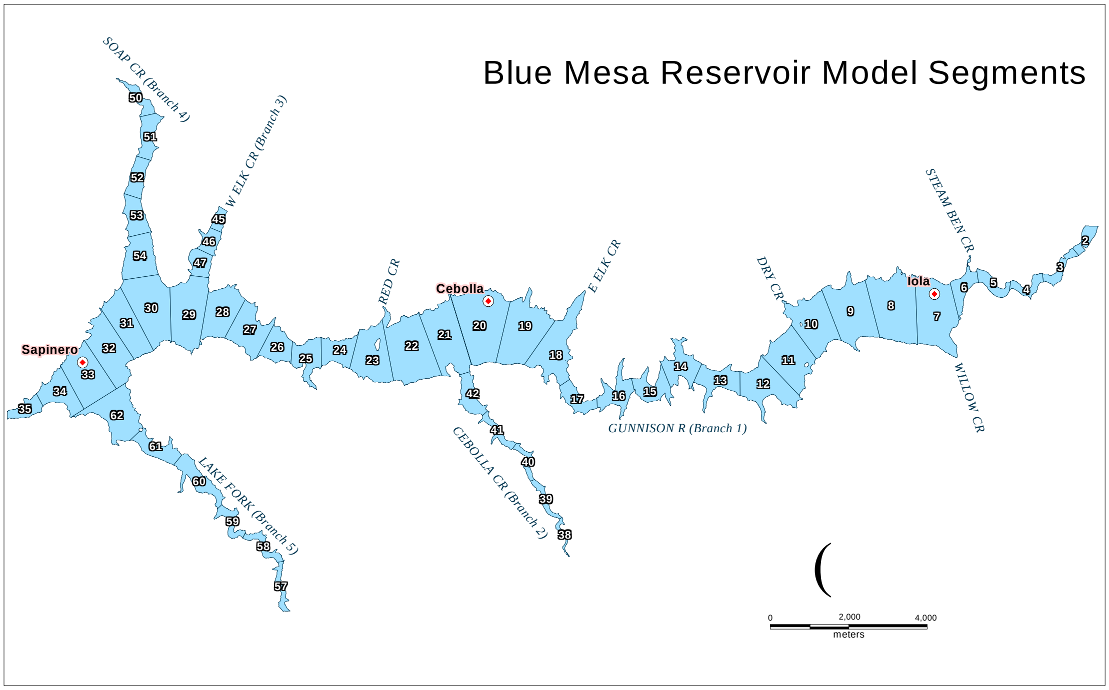


Figure 2: Blue Mesa Reservoir, CO segmentation -- plan view

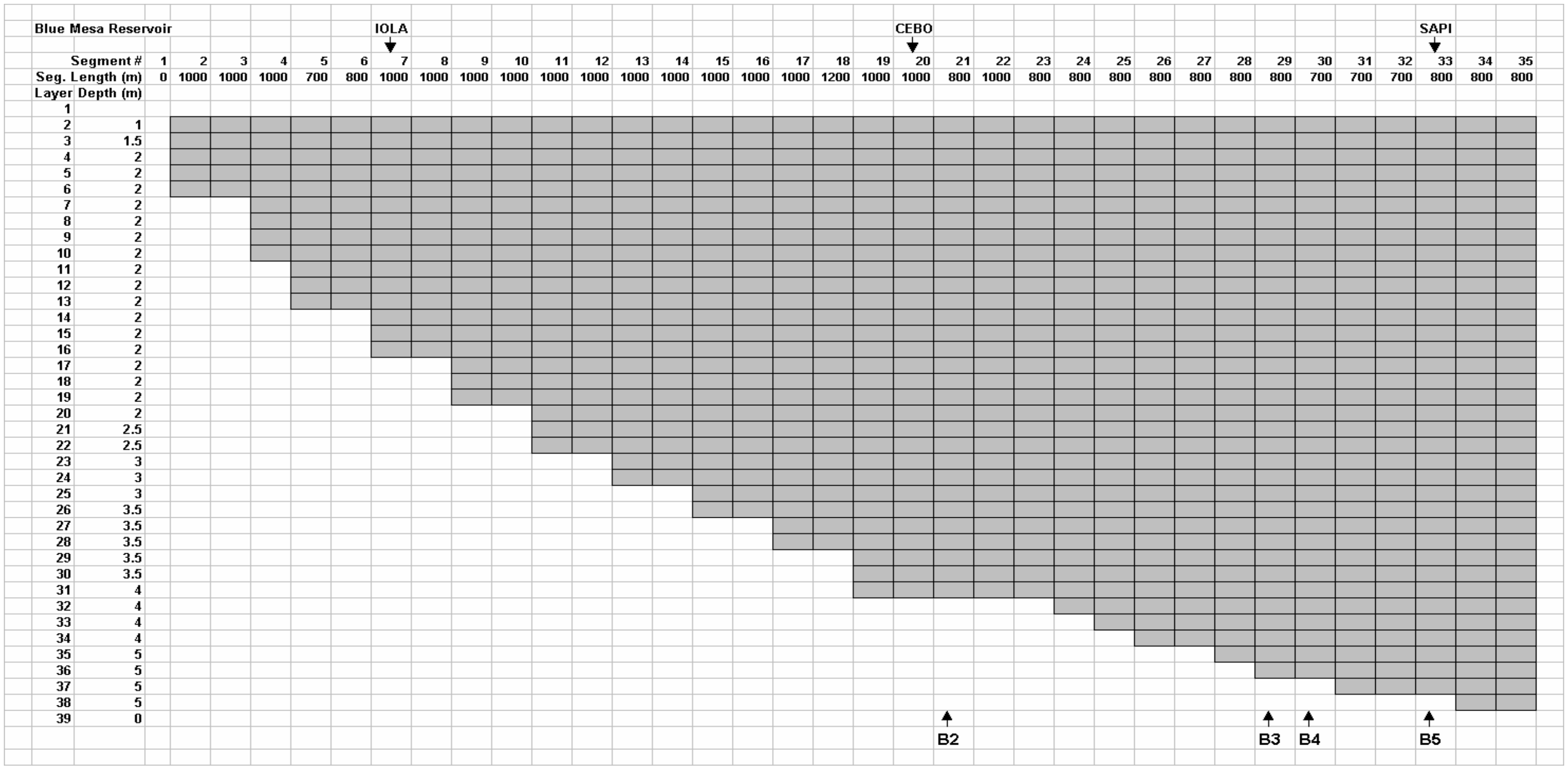


Figure 3: **Blue Mesa Reservoir, CO segmentation -- side view of main stem (IOLA = Iola In-Reservoir Sampling Station Location, CEBO = Cebolla In-Reservoir Sampling Station Location, SAPI = Sapinero In-Reservoir Sampling Station Location, B1 = Location of Branch 1, B2 = Location of Branch 2, B3 = Location of Branch 3, and B4 = Location of Branch 4)**

An input file describing the bathymetry of the reservoir was set up for the model. Actual versus simulated relationships between water surface elevation and reservoir contents and between water surface elevation and reservoir surface area are shown in Figures 4 and 5.

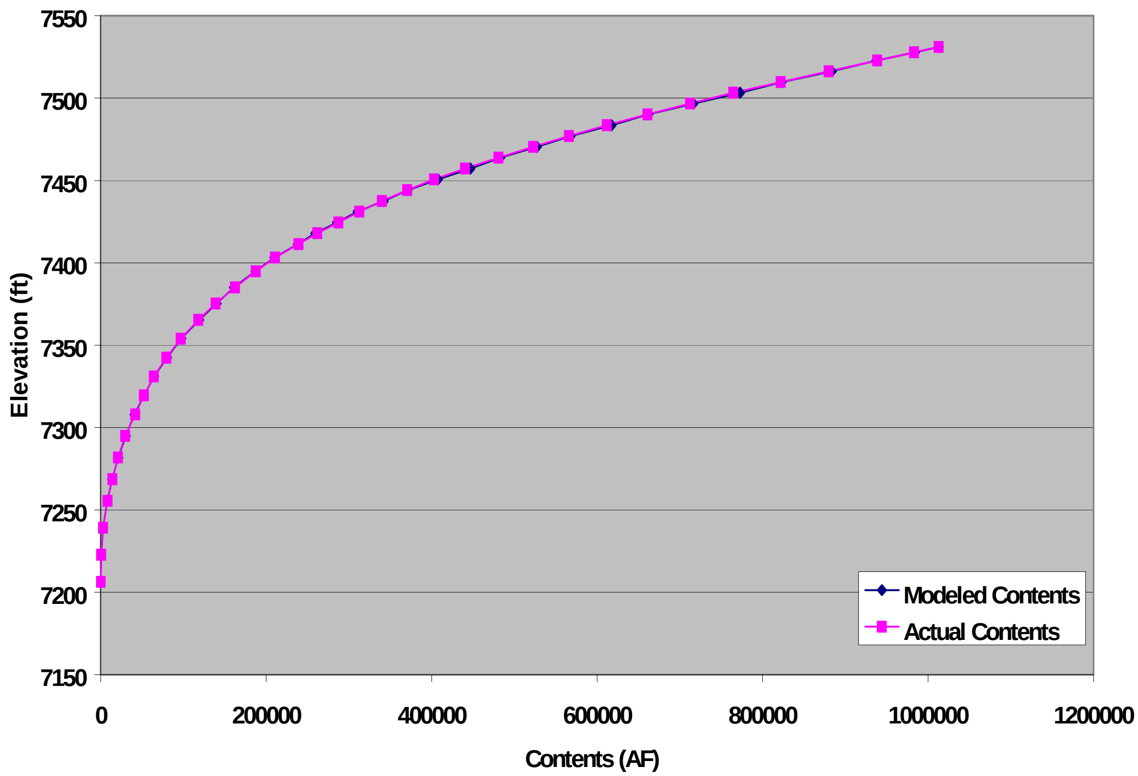


Figure 4: Relationship between water surface elevation and capacity of Blue Mesa Reservoir, CO.

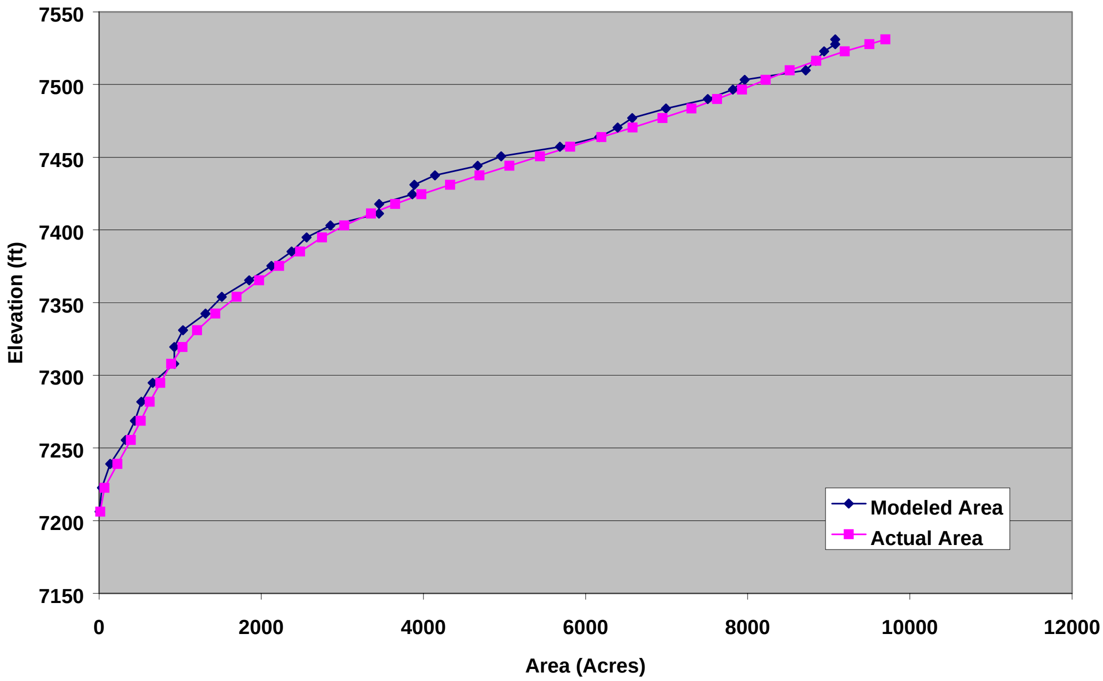


Figure 5: Relationship between water surface elevation and surface area for Blue Mesa Reservoir, CO.

Water balance / hydrology

A water balance for each day of the simulation was prepared. Inflow into the reservoir was represented as the Gunnison River, Cebolla Creek, W. Elk Creek, Soap Creek, and the Lake Fork. To complete the water balance, miscellaneous gains and losses including evaporation were also represented so that the model predicted the observed water surface elevation of the reservoir.

Daily contents, total inflow, releases, and evaporation data for Blue Mesa Reservoir were obtained electronically from the U.S. Bureau of Reclamation (Thatcher 2002). Flows for the inflow from the Gunnison River were approximated using U.S. Geological Survey (USGS) data from gage 09114500 Gunnison River Near Gunnison, CO (0.7 miles downstream of Antelope Creek) (Figure 6). Flows from the Lake Fork were approximated using data from the USGS gage 09124500 Lake Fork at Gateview, CO (0.2 miles upstream of Indian Creek) (Figure 7).

Flows from Soap, W. Elk and Cebolla creeks were estimated based on historical daily data (Malick 2002) and watershed area. The flow from Soap Creek was assumed to approximate the inflow from the Lake Fork. The flow from W. Elk Creek also was assumed to be 48% of the flow from Soap Creek, and the flow from Cebolla Creek was assumed to be 42% of the flow from Soap Creek.

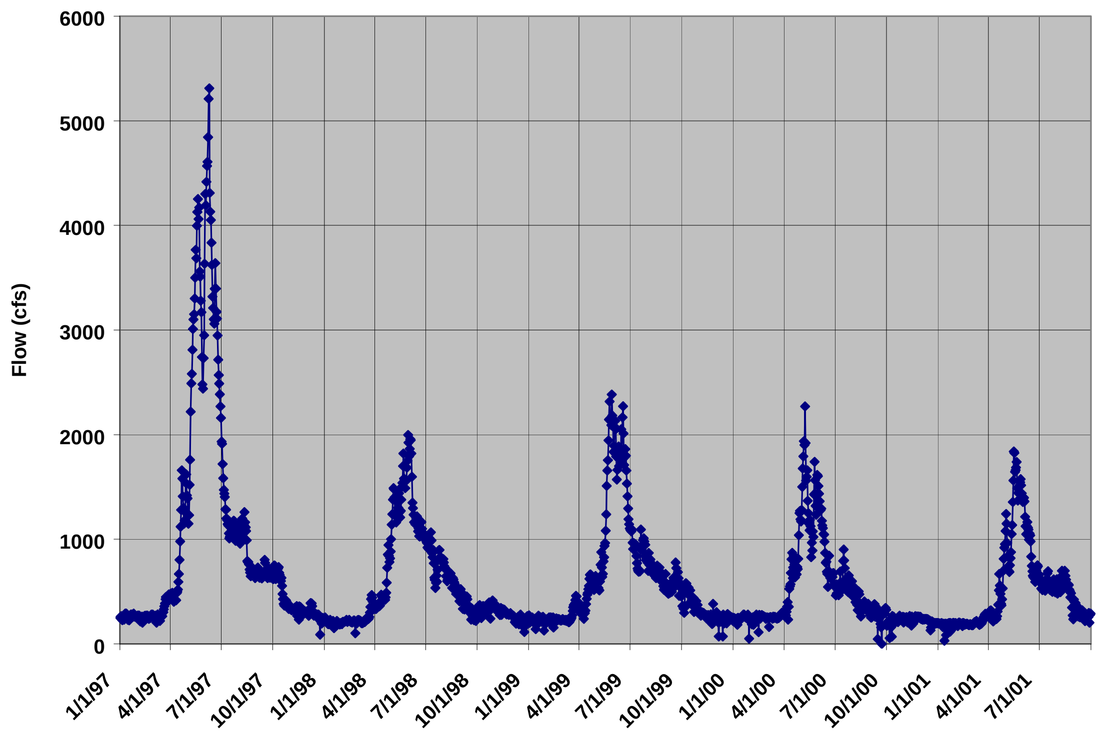


Figure 6: Gunnison River inflow to Blue Mesa Reservoir, CO.

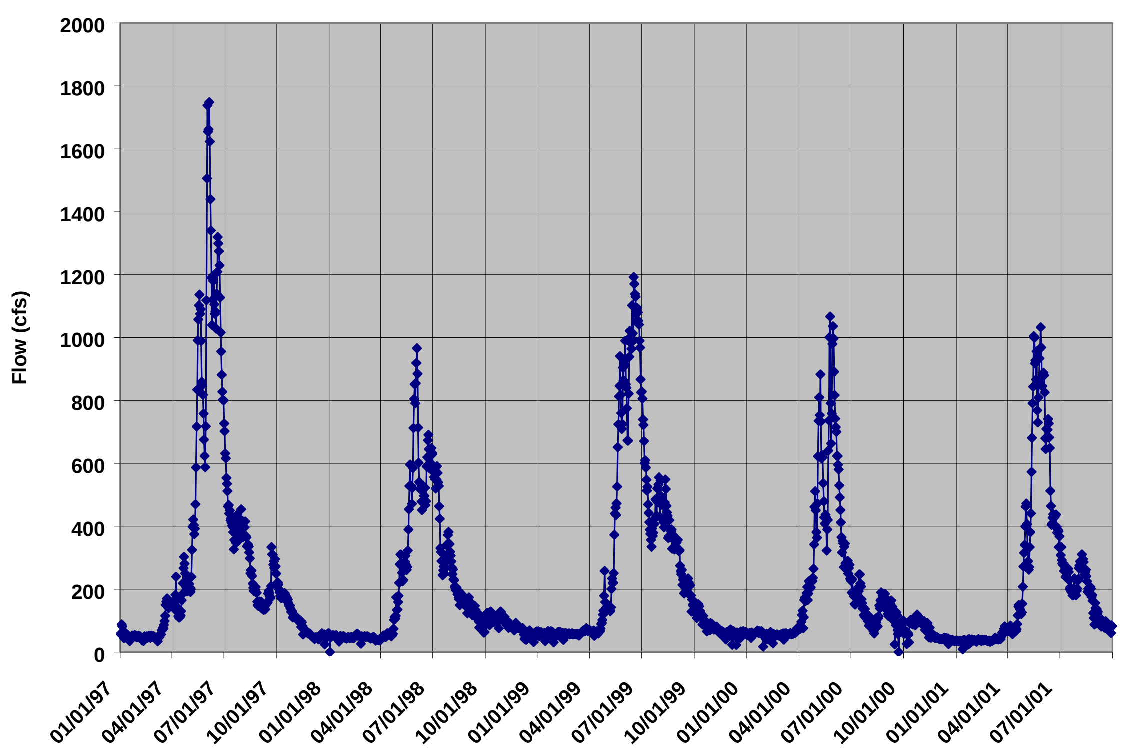


Figure 7: Inflow into Blue Mesa Reservoir from the Lake Fork, CO.

Figure 8 shows the distribution of the various inflows by source over the period of simulation. Almost half of the inflows to Blue Mesa Reservoir come from the Gunnison River. Outflows from the reservoir predominantly occur through the outlet works and spillway. Outlet works refers to outlets where releases generate hydropower. Evaporation was accounted for but was insignificant compared to the other outflows.

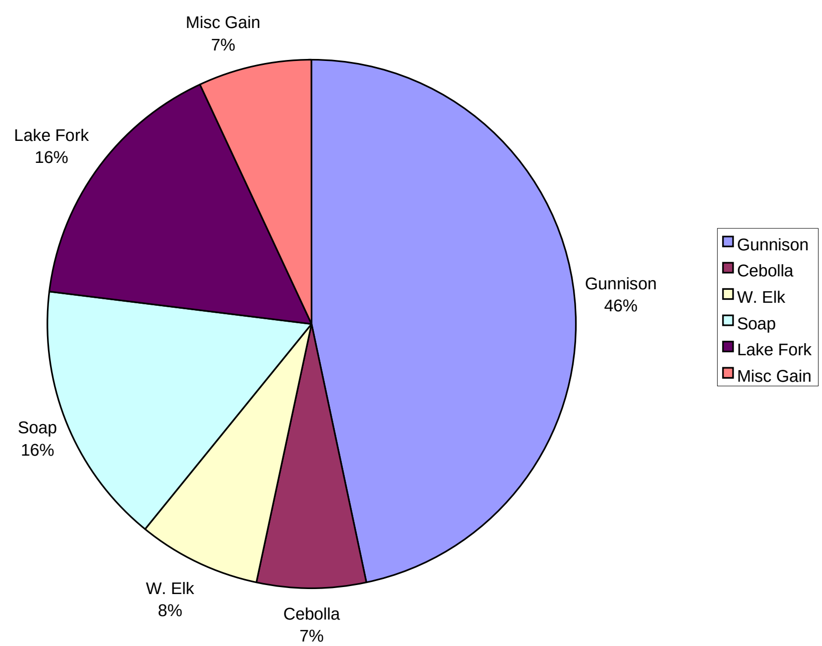


Figure 8: Distribution of total inflow into Blue Mesa Reservoir

<u>Inflow temperatures</u>

The model requires temperature data for the incoming tributaries. Temperature data were available for each of the tributaries, but data gaps needed to be filled using data either from other similar years or from similar tributaries. Data were provided by the U.S. Fish and Wildlife Service (FWS) (Malick 2002) for the following sites:

Inflow Name	*FWS Site ID*	*FWS Site Name*
Gunnison River	GR07	Gunnison River - Riverway
Lake Fork	LF1	Lake Fork
Cebolla Creek	CB1A	Cebolla Creek
W. Elk Creek	WEC1	West Elk Creek
Soap Creek	SOAP	Soap Creek - Ponderosa Campground

Since there were few data available for Soap Creek, a comparison of temperatures was made between the data provided for Soap Creek and for other tributaries. Temperatures for Soap Creek and W. Elk were similar; therefore, the temperature time series for W. Elk was also used for Soap Creek. Time series graphs of inflow temperatures are shown in Figures 9 through 12.

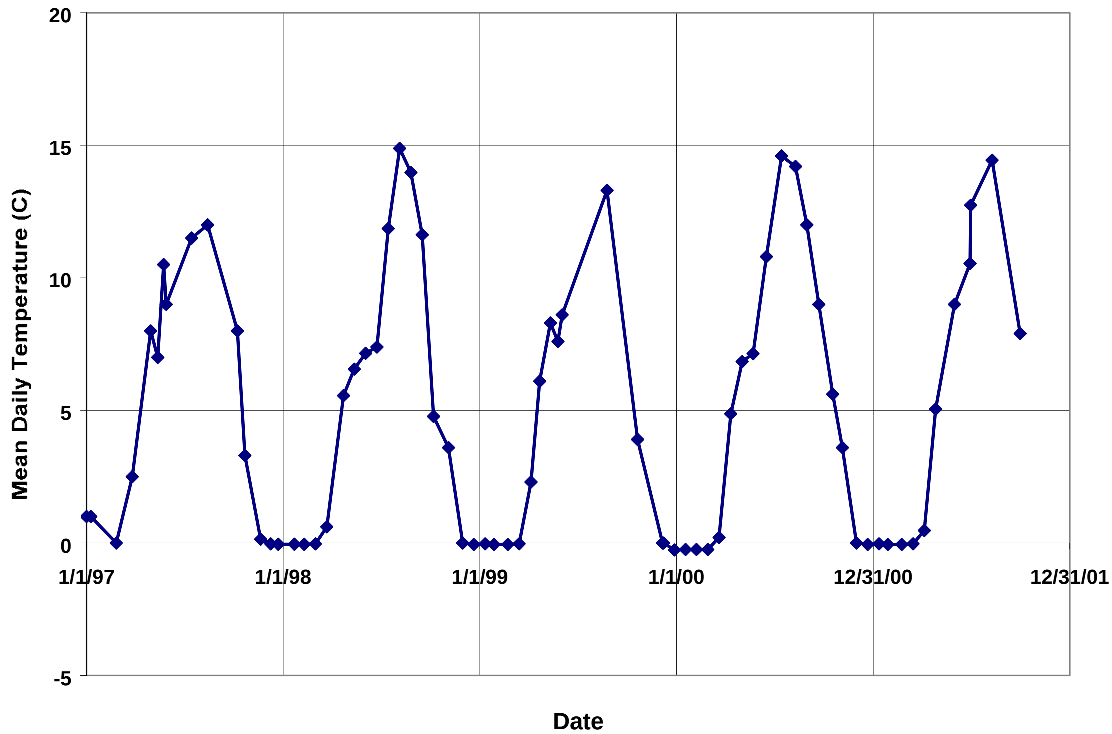


Figure 9: Inflow temperature into Blue Mesa Reservoir - Gunnison River, CO.

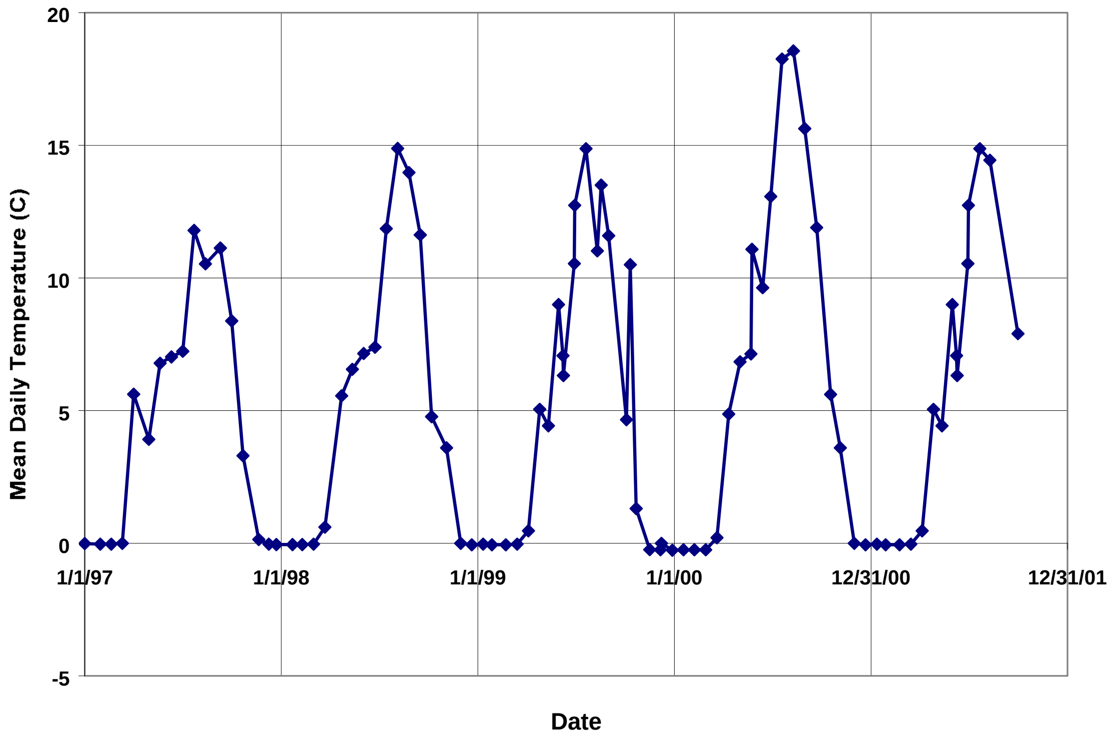


Figure 10: Inflow temperature into Blue Mesa Reservoir - Lake Fork, CO.

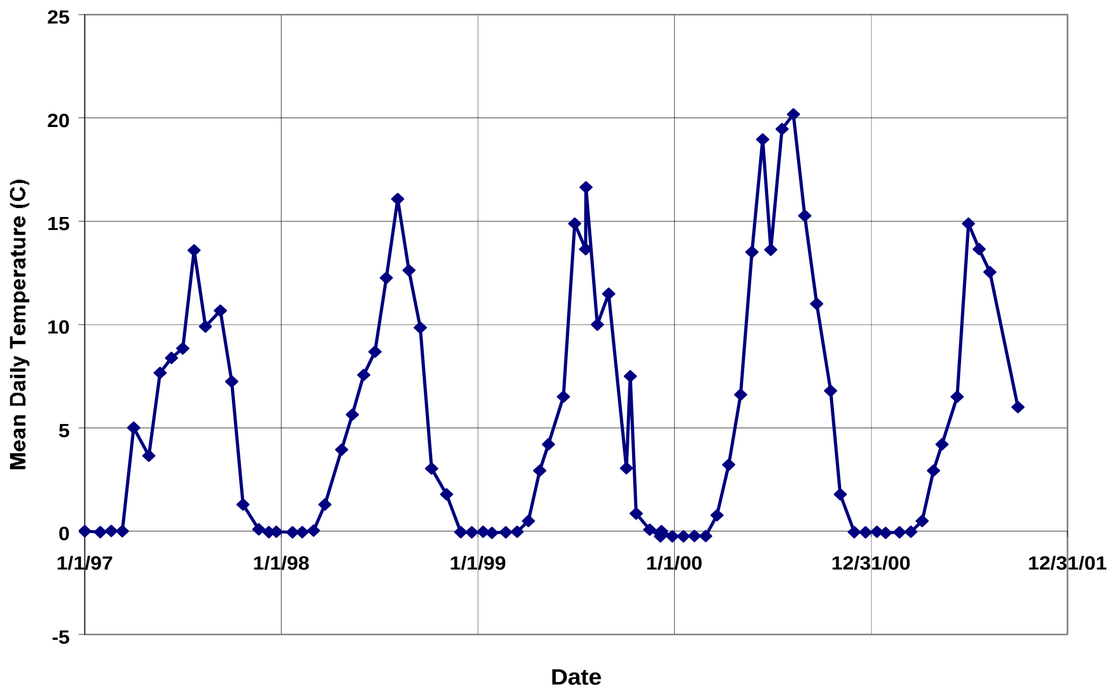


Figure 11: Inflow temperature into Blue Mesa Reservoir - Cebolla Creek, CO.

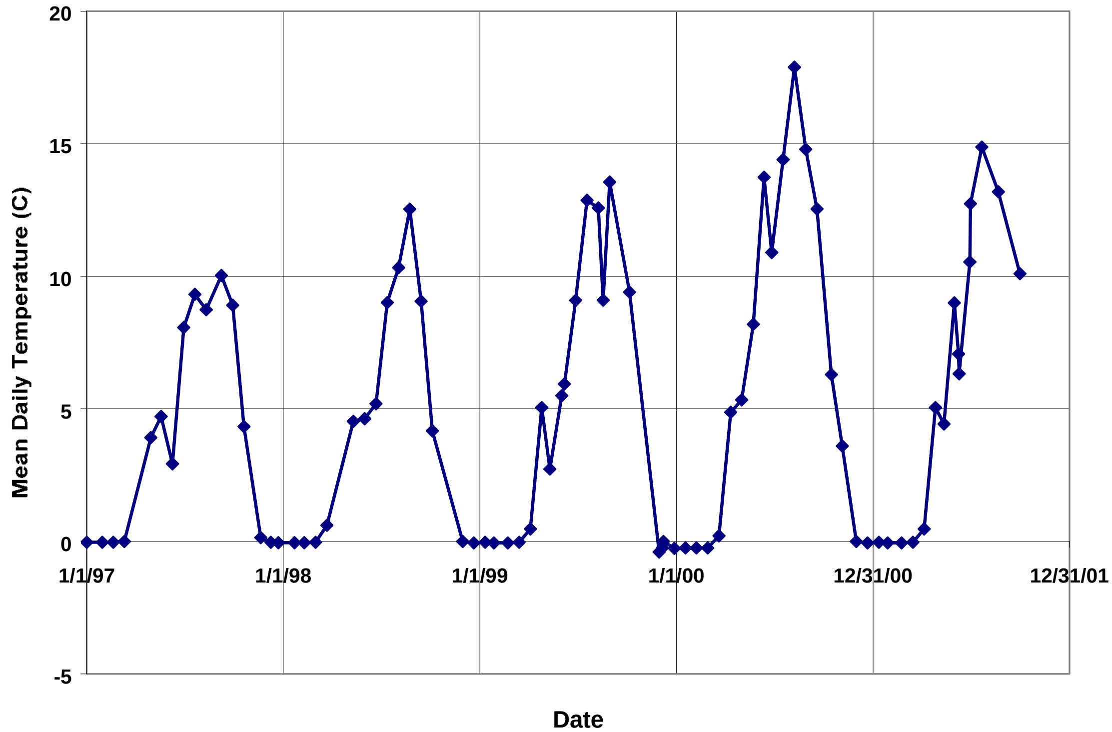


Figure 12: Inflow temperature into Blue Mesa Reservoir - W. Elk Creek, CO.

Meteorological data

Meteorological data from the Gunnison Airport were used for the simulation: air temperature, wind speed, wind direction, dew point, and cloud cover data. The data were obtained through the Western Regional Climate Center, Desert Research Institute, Reno, Nevada and were taken, in general, every 20 minutes.

Calibration and results

Input data files were assembled using the information described above, and the model was run from June 3, 1997, through September 30, 2001. The calibration parameters were initially set at default values. The wind sheltering coefficient was adjusted during the calibration process. The final wind sheltering coefficients varied from 0.5 to 0.95, which is in the range of values used for other applications (Cole and Wells 2002). Simulation results are described below.

Reservoir Contents:

Daily reservoir elevations were obtained from the U.S. Bureau of Reclamation for Blue Mesa Reservoir. These data are graphed along with simulated results in Figure 13.

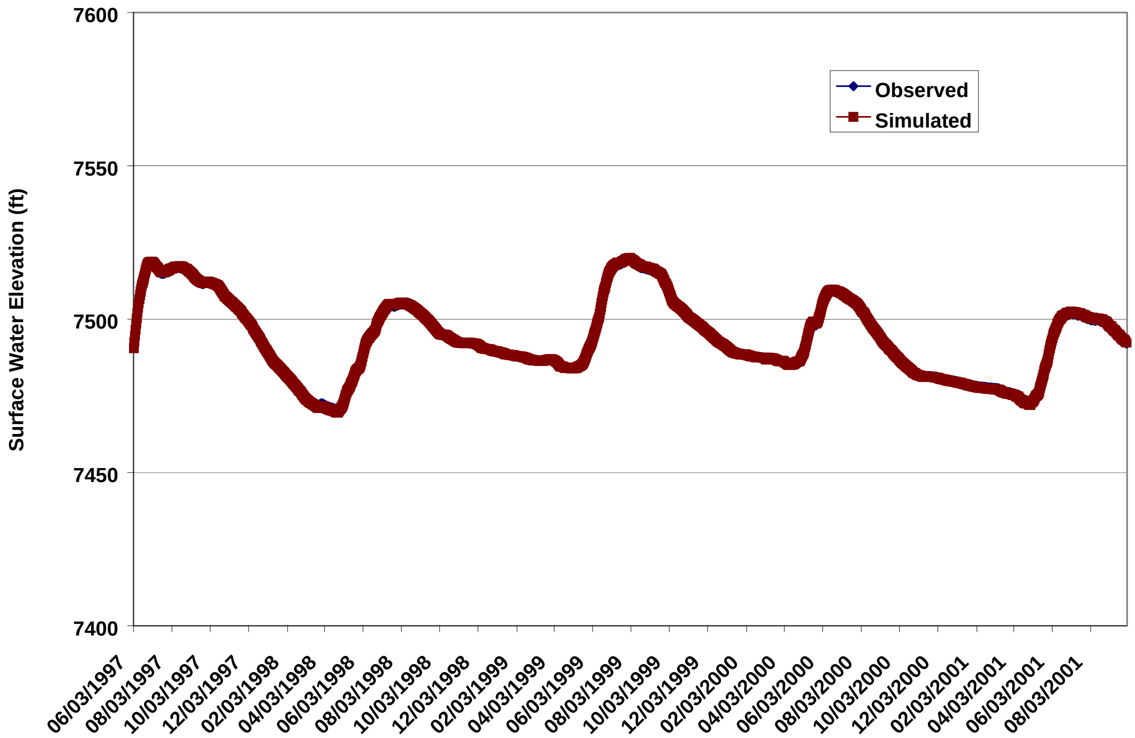


Figure 13: Simulated vs. observed water surface elevations for Blue Mesa Reservoir

Reservoir temperature:

There are three locations in Blue Mesa Reservoir where temperature profiles have been taken over the period of simulation. They are noted in Figure 2 as Iola (in the upper reservoir), Cebolla (mid-reservoir), and Sapinero (near the dam). A total of 116 profiles were taken, representing 2920 data points, during the period of simulation. The overall calibration statistics are displayed in Table 1.

Table 1: Calibration results for Blue Mesa Reservoir

Reservoir	Time Period	Sites	AME	RSME	Number of Profiles	Number of Data Points
Blue Mesa	1997 - 2001	All sites	0.85	1.08	116	2920
	1997 - 2001	Iola	0.88	1.15	38	692
	1997 - 2001	Cebolla	0.91	1.12	39	1042
	1997 - 2001	Sapinero	0.78	1.00	39	1186
	1997	All sites	0.76	1.00	27	670
	1998	All sites	0.80	1.03	21	488
	1999	All sites	0.72	0.91	27	677
	2000	All sites	1.09	1.30	23	601
	2001	All sites	0.89	1.16	18	484

The model calibrated well for all sites and for all years. Except for 2000 for which the AME is 1.09, the AME values are less than 1.0. A graph of observed vs. simulated surface water temperatures at the Sapinero station is shown in Figure 14. Profiles at the Sapinero Site during 1999 are shown in Figure 15 (2 pages).

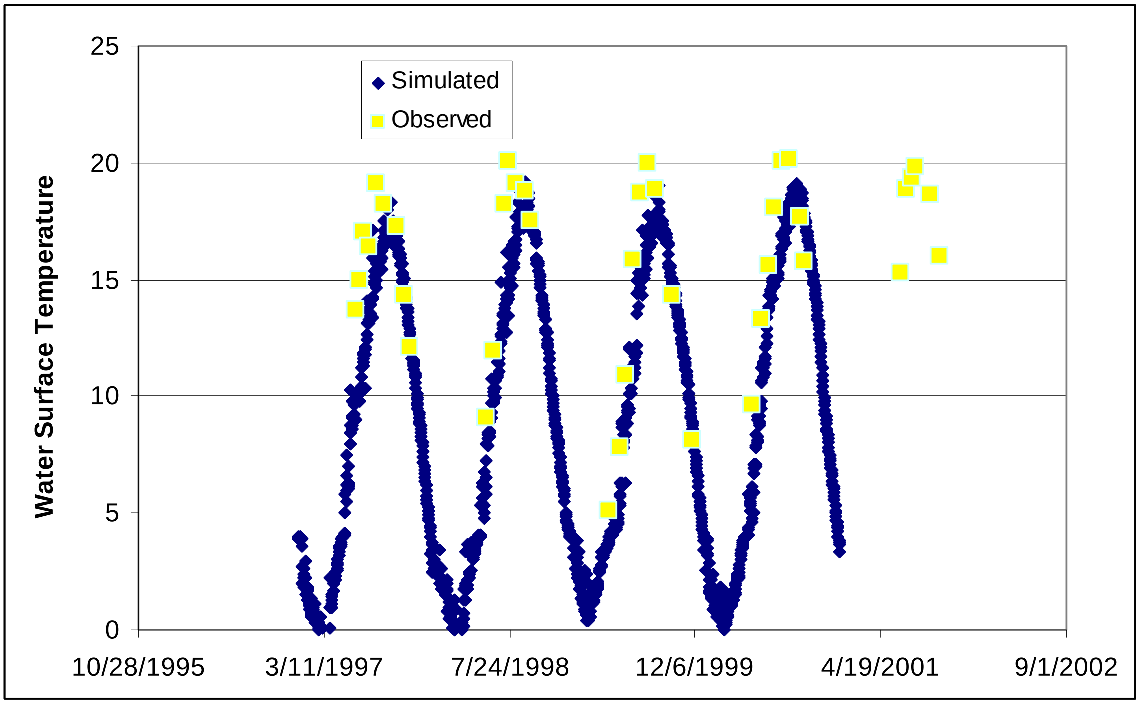


Figure 14: Observed and simulated surface water temperatures at the Sapinero site in Blue Mesa Reservoir, CO.

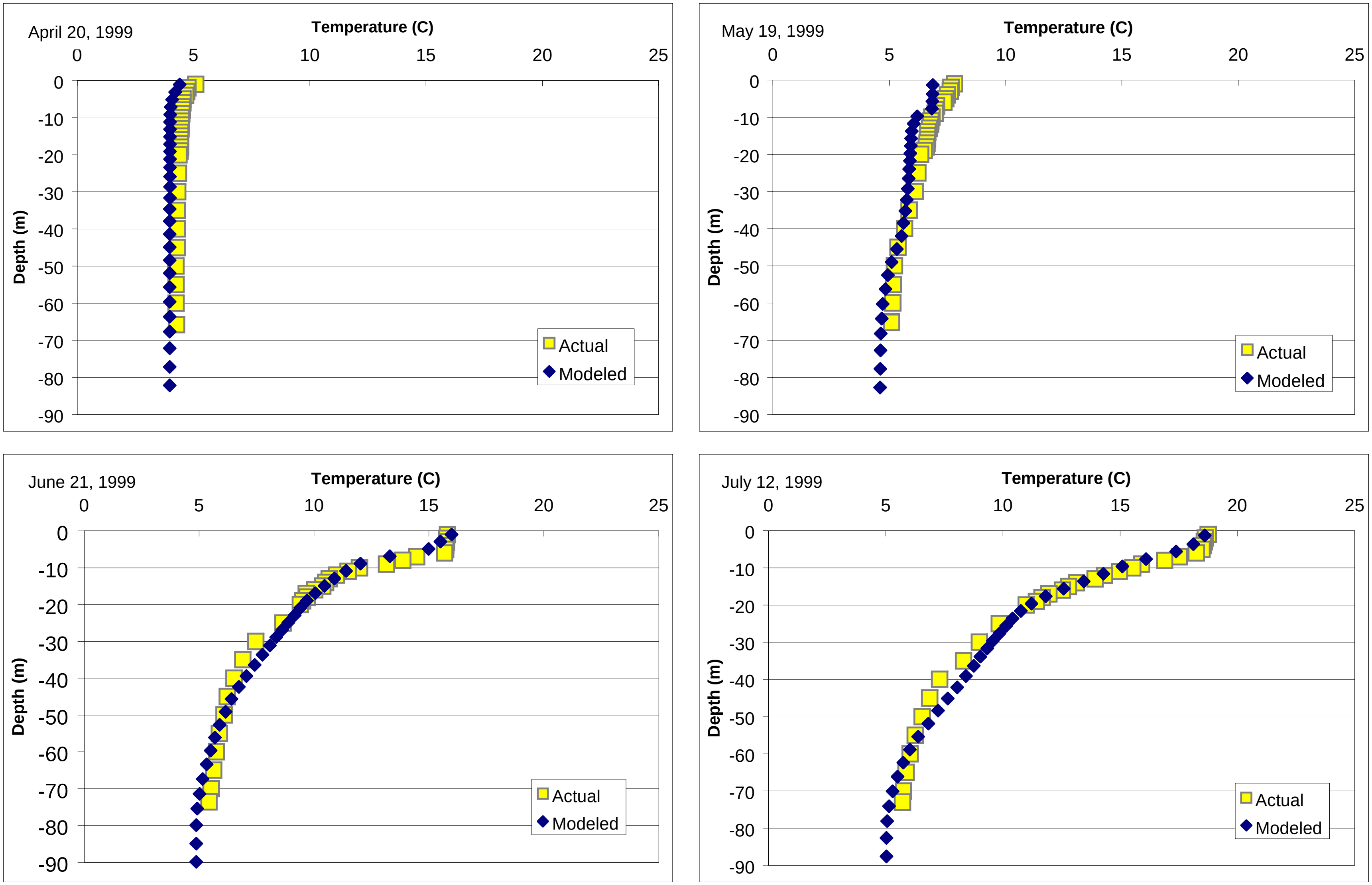


Figure 15: Profiles at the Sapinero site in Blue Mesa Reservoir, CO - 1999 (1 of 2)

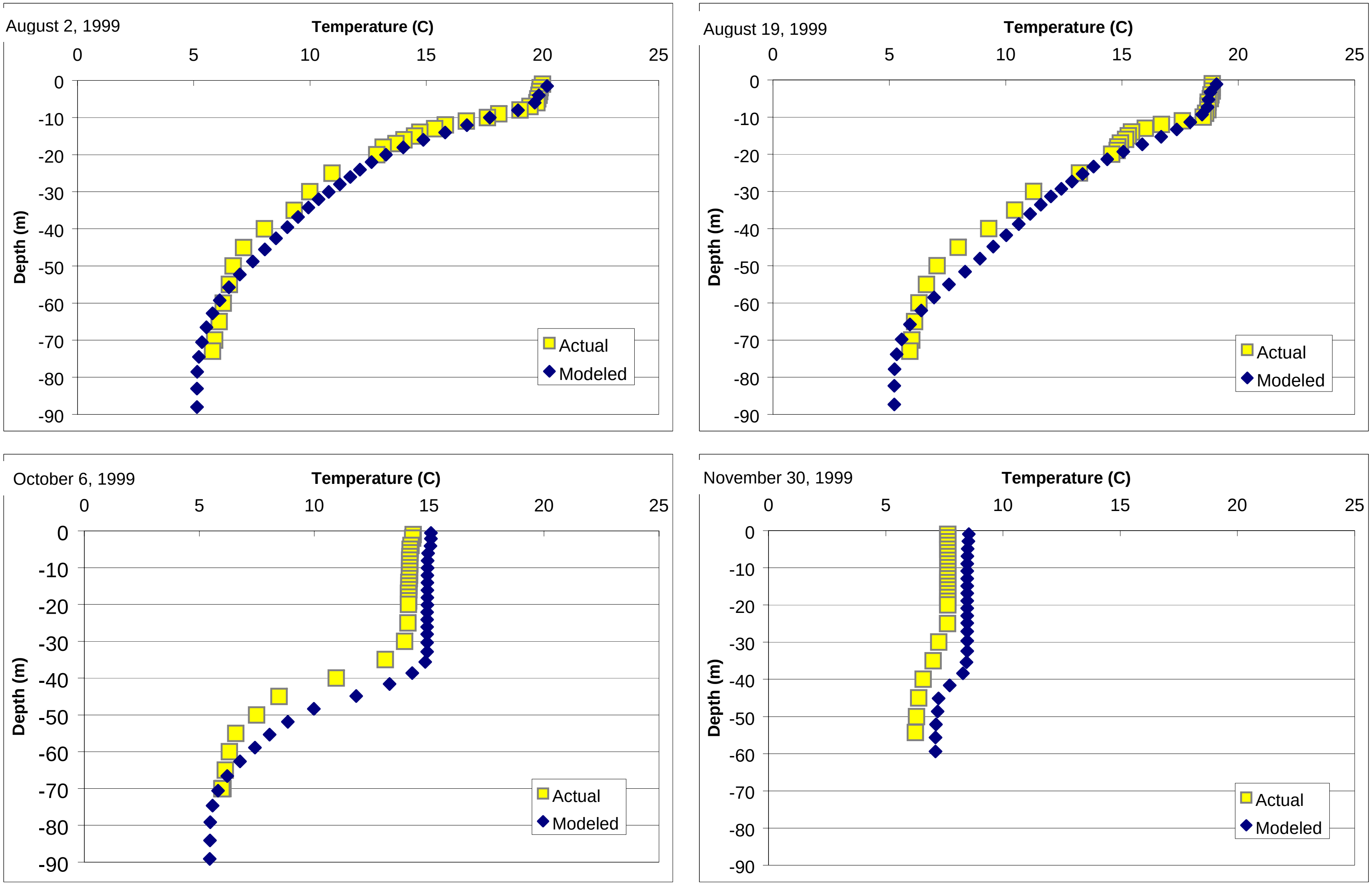


Figure 15: Profiles at the Sapinero site in Blue Mesa Reservoir, CO - 1999 (2 of 2)

There were no observed Blue Mesa Reservoir release water temperature data to compare to the simulated results. Simulated Blue Mesa Reservoir release water temperatures are displayed in Figure 16 along with the Gunnison River temperatures upstream of the reservoir. Release temperatures rise from about 4 ºC up to 12–13 ºC from April to October, after which the reservoir turns over and the release temperatures drop. Throughout the summer months, the release temperature of the reservoir is lower than the temperature of the incoming Gunnison River.

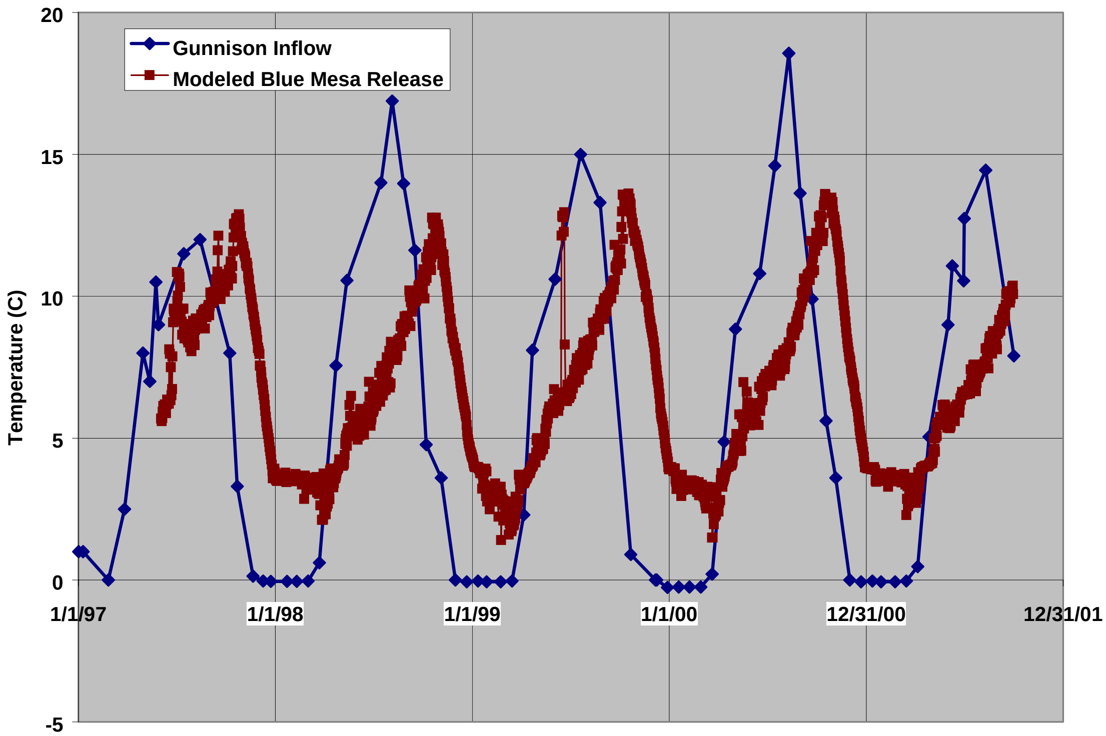


Figure 16: Simulated temperatures of Blue Mesa releases and observed inflow temperature of Gunnison River, CO.

4.3 Morrow Point Reservoir

Simulation period

For Morrow Point Reservoir, the simulation period was from June 5, 1997 through September 30, 2001. The start date was the date of the first temperature profile in 1997.

Computational grid

A plan view of Morrow Point Reservoir is shown in Figure 17. The reservoir was divided into 42 segments longitudinally along the main branch. All segments were set to a length of 450 meters. The reservoir was also divided into 39 layers (Figure 18). Layer depths varied from 1.5 to 6 meters. The outlet is 2,158 meters (7,080 feet) above MSL and the spillway is 2,171.1 meters (7,122.9 feet) above MSL.

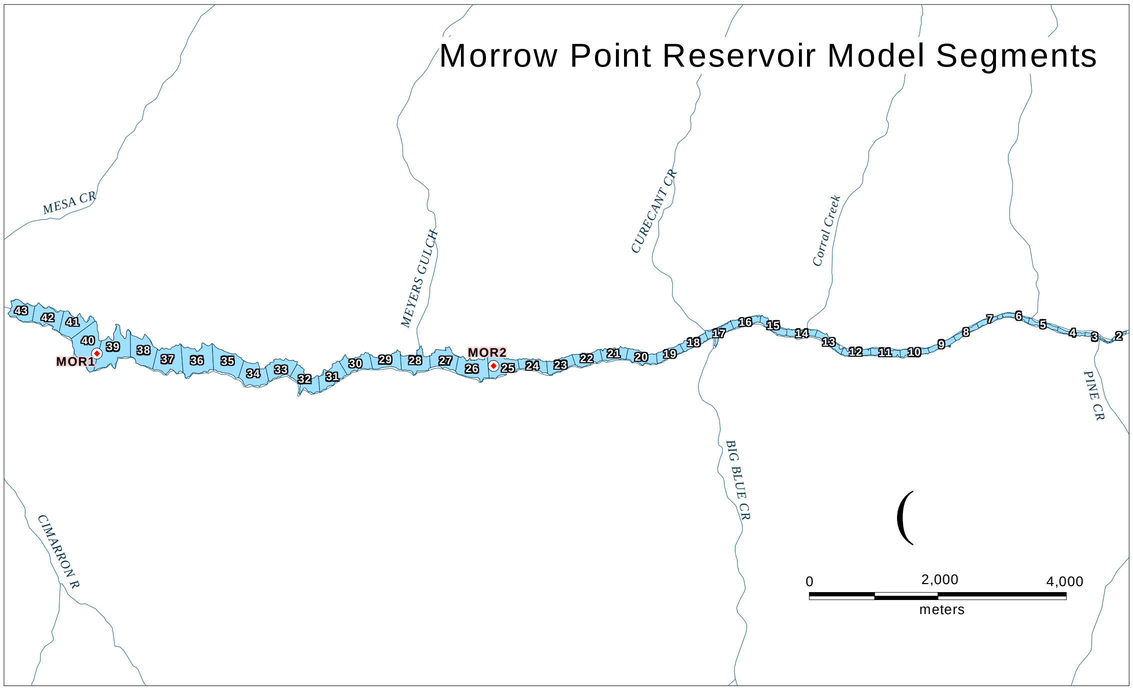


Figure 17: Morrow Point segmentation -- plan view

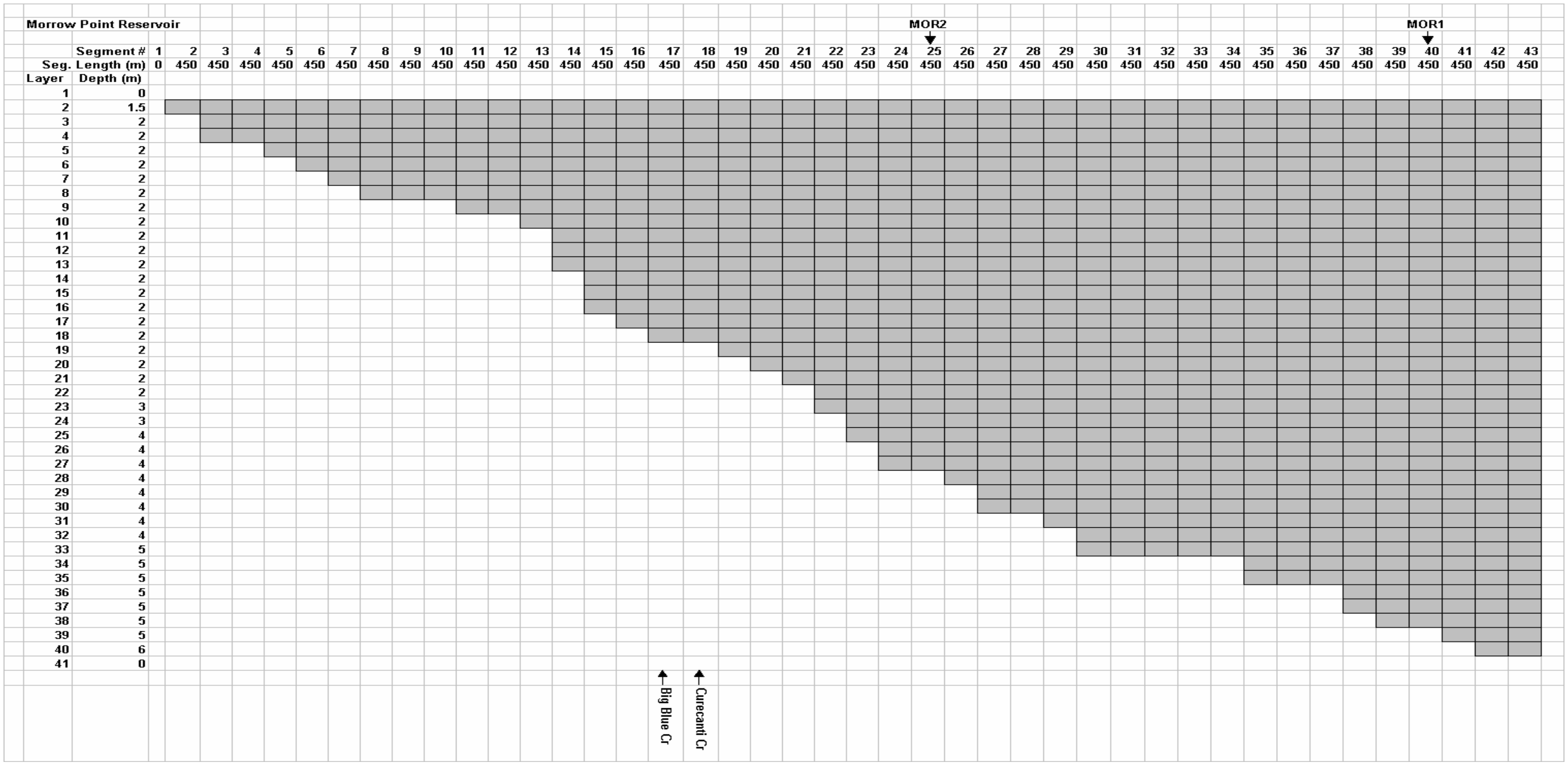


Figure 18: Morrow Point, CO segmentation -- side view of main stem (MOR1 = Morrow Point In-Reservoir Sampling Station Location #1 and MOR2 = Morrow Point In-Reservoir Sampling Station Location #2)

An input file describing the bathymetry of the reservoir was set up for the model. Actual versus simulated relationships between water surface elevation and reservoir contents and between water surface elevation and reservoir surface area are shown in Figures 19 and 20.

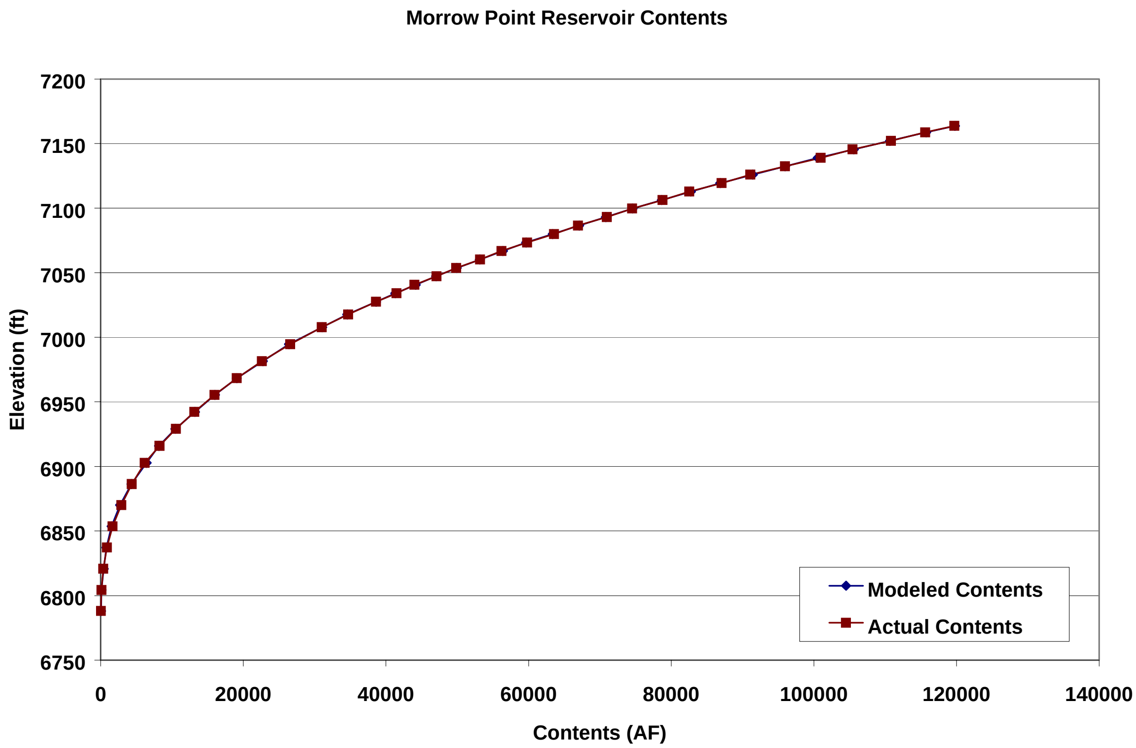


Figure 19: Relationship between water surface elevation and capacity of Morrow Point Reservoir, CO.

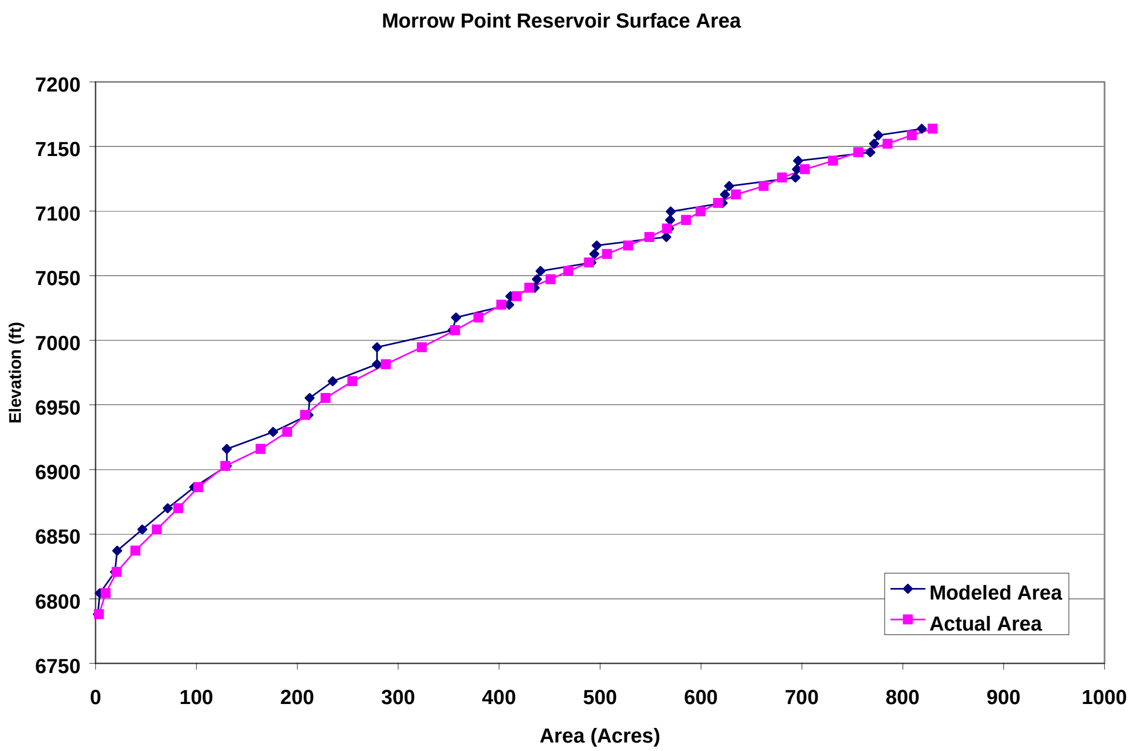


Figure 20: Relationship between water surface elevation and surface area for Morrow Point Reservoir, CO.

Water balance / hydrology

A water balance was prepared for each day of the simulation. Inflow into the reservoir was represented as 1) the releases from Blue Mesa Reservoir, 2) the inflows from Pine Creek, 3) the inflows from Big Blue Creek, and 4) the inflows from Curecanti Creek. To complete the water balance, miscellaneous gains and losses including evaporation were also represented so that the model predicted the observed water surface elevation of the reservoir.

Since Pine Creek flows into the main stem above the active storage elevation of the reservoir, the flow from Pine Creek was added to the releases from Blue Mesa Reservoir as inflow into the main stem of Morrow Point. The inflow temperature was set at the simulated release temperature from Blue Mesa.

Daily contents, upstream inflow, side inflow, releases, and evaporation data for Morrow Point Reservoir were obtained electronically from the U.S. Bureau of Reclamation (Thatcher 2002). The side inflow data were distributed among Pine Creek, Big Blue Creek, and Curecanti Creek based on watershed area.

Figure 21 shows the distribution of the various inflows by source over the period of simulation. Ninety-two percent of the inflow into Morrow Point comes from Blue Mesa Reservoir. Outflow from the reservoir occurs predominantly through the outlet works and spillway. Evaporation was accounted for but was insignificant compared to the other inflows.

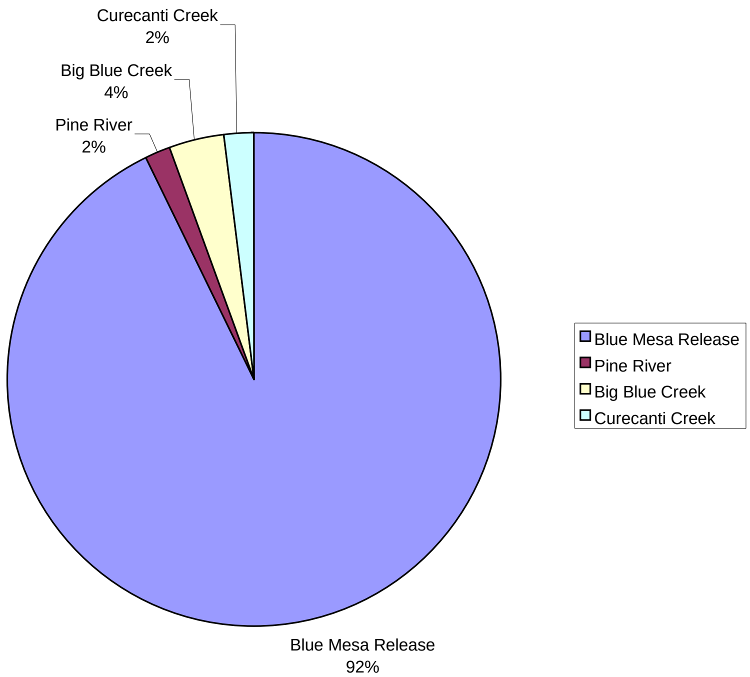


Figure 21: Distribution of total inflow into Morrow Point Reservoir, CO.

Inflow temperatures

The model requires temperature data for the inflowing tributaries. Temperature data were available for each of the tributaries, but data gaps needed to be filled using data from similar years. These data were provided by the FWS (Malick 2002) for the following sites:

Inflow Name	***FWS Site ID***	***FWS Site Name***
Curecanti Creek	CUR2	Curecanti Creek
Big Blue Creek	BC01	Blue Creek

Time series graphs of inflow temperatures are shown in Figures 22 and 23.

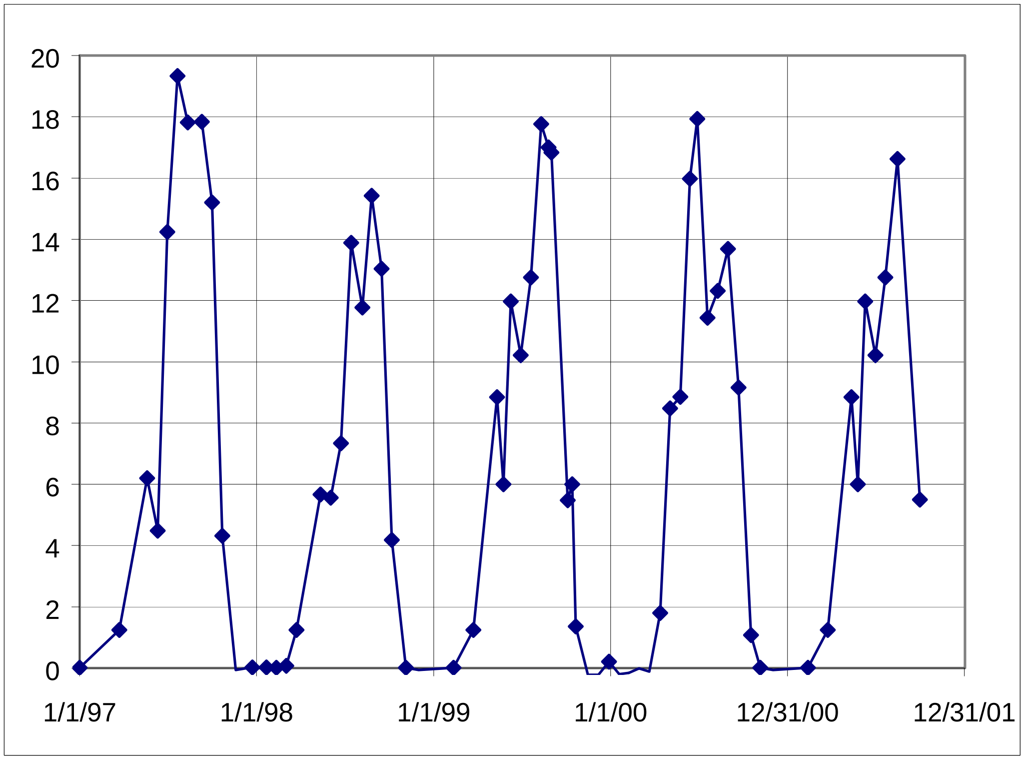


Figure 22: Inflow temperatures from Curecanti Creek, CO.

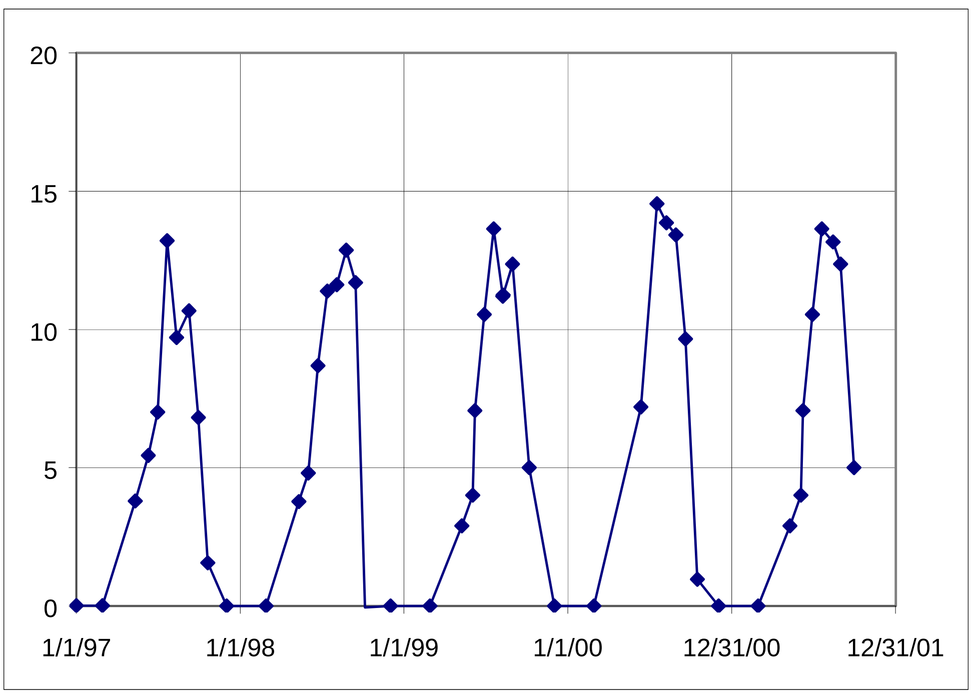


Figure 23: Inflow temperatures from Big Blue Creek, CO.

Meteorological data

Meteorological data from the Gunnison Airport were used for the simulation: air temperature, wind speed, wind direction, dew point, and cloud cover. The data were obtained through the Western Regional Climate Center, Desert Research Institute, Reno, Nevada, and were taken, in general, every 20 minutes.

Calibration and results

Input data files were assembled using the information described above and the model was run from June 5, 1997 through September 30, 2001. The calibration parameters were initially set at default values. The wind sheltering coefficient was adjusted during the calibration process. The final wind sheltering coefficients varied from 0.6 to 0.7, which is in the range of values used for other applications (Cole and Wells 2002). Simulation results are described below.

Reservoir contents:

Daily reservoir elevations were obtained from the U.S. Bureau of Reclamation for Morrow Point Reservoir. These data are graphed along with simulated results in Figure 24.

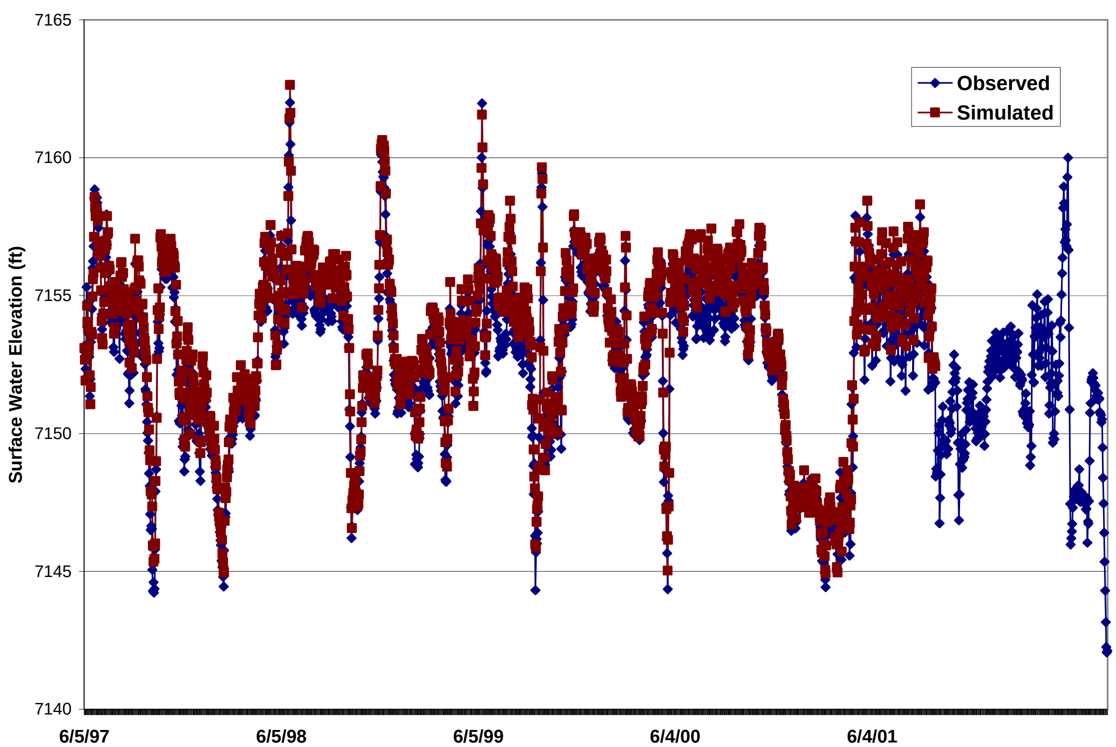


Figure 24: Simulated vs. observed water surface elevations for Morrow Point Reservoir, CO.

Reservoir temperature:

There are two locations in Morrow Point Reservoir where temperature profiles have been taken over the period of simulation. They are noted in Figure 17 as MOR2 (in the upper reservoir) and MOR1 (near the dam). Sixty-one profiles were taken, representing 1,730 data points, during the period of simulation. The overall calibration statistics are displayed in Table 2.

Table 2: Calibration results for Morrow Point Reservoir

Reservoir	Time Period	Sites	AME	RSME	Number of Profiles	Number of Data Points
Morrow Point	1997 - 2001	All sites	0.755	1.08	61	1730
	1997 - 2001	MOR2	0.760	0.984	31	765
	1997 - 2001	MOR1	0.752	1.15	30	965
	1997	All sites	0.707	0.992	10	269
	1998	All sites	0.82	1.11	12	330
	1999	All sites	0.771	0.994	14	388
	2000	All sites	0.738	1.09	16	484
	2001	All sites	0.731	1.20	9	259

The model calibrated well for all sites and for all years. A graph of observed vs. simulated surface water temperatures at the MOR1 station is shown in Figure 25. As an example, profiles at the MOR1 Site during 1999 are shown in Figure 26 (2 pages).

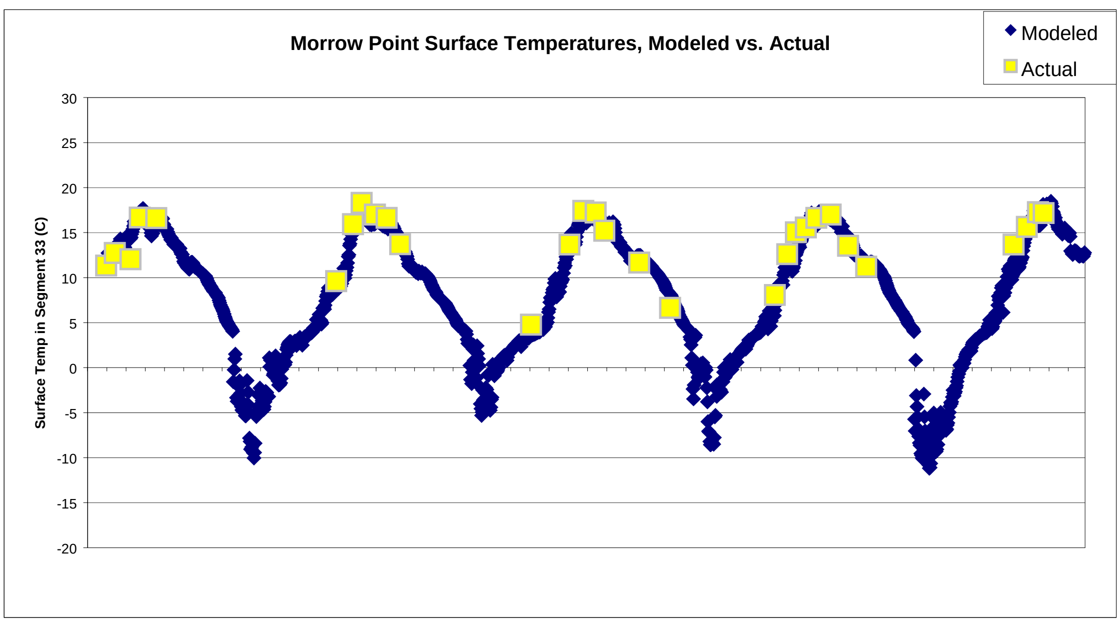


Figure 25: Observed and simulated surface water temperatures at the Sapinero site in Blue Mesa Reservoir

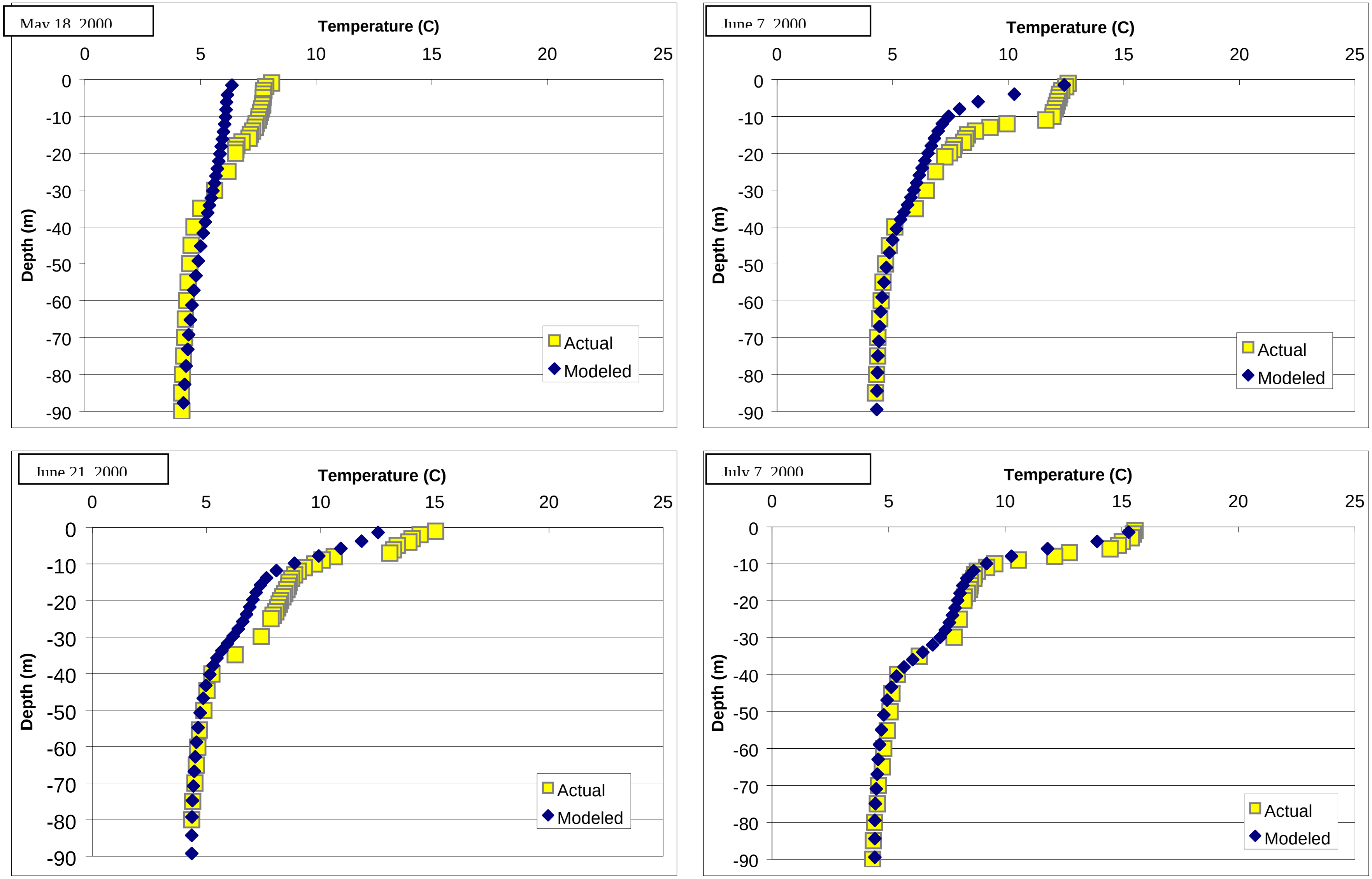


Figure 26: Temperature profiles at MOR1 Site in Morrow Point, CO - 2000 (1 of 2)

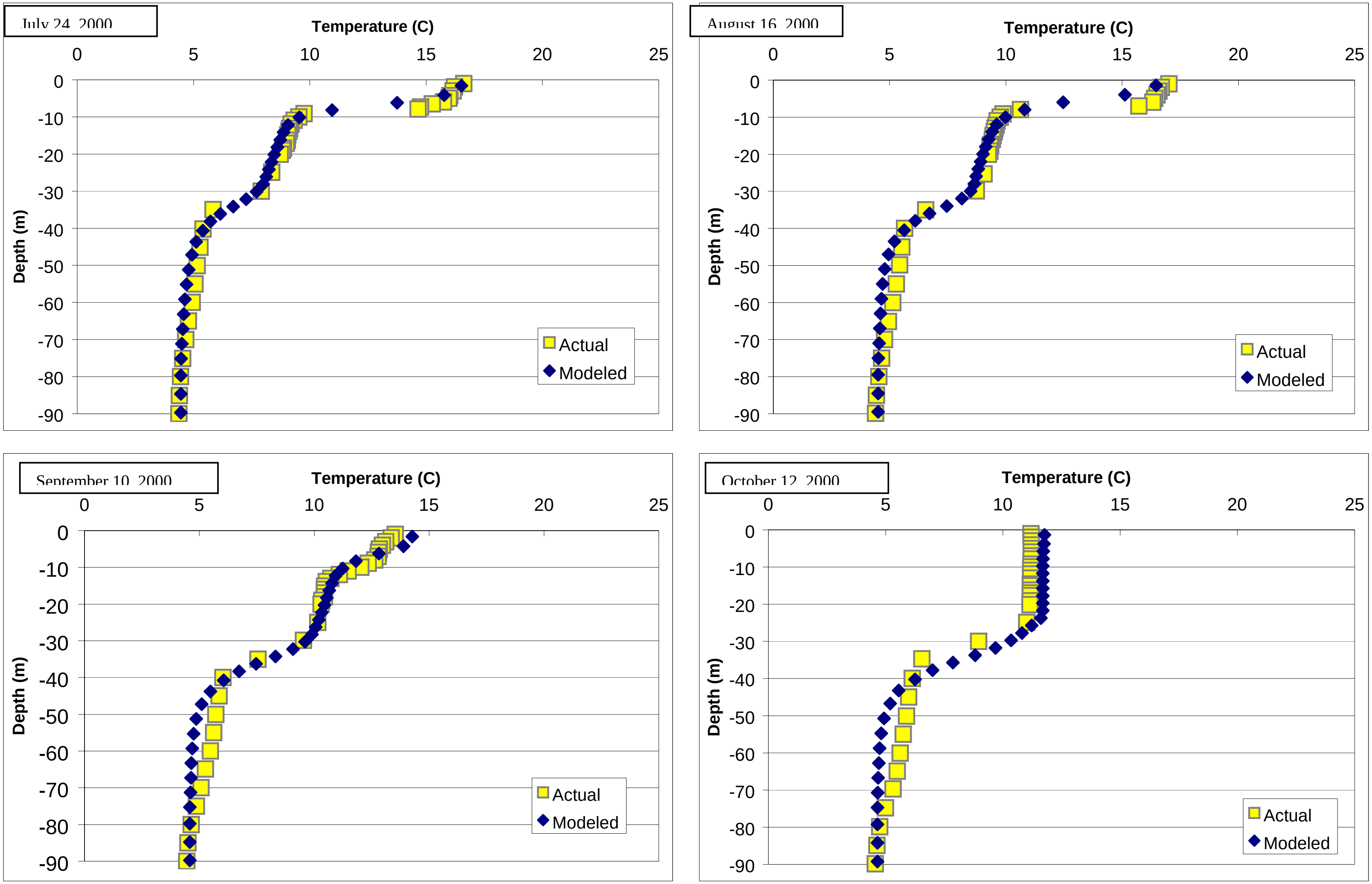


Figure 26: Temperature profiles at MOR1 Site in Morrow Point, CO - 2000 (2 of 2)

There were no observed Morrow Point Reservoir water release temperature data to compare to the simulated results. Simulated Morrow Point Reservoir water release temperatures are displayed in Figure 27 along with incoming temperatures from Blue Mesa Reservoir. Since the residence time is so short in Morrow Point, there is no lag in temperature, as seen in Blue Mesa. The peak temperatures from the inflow are attenuated.

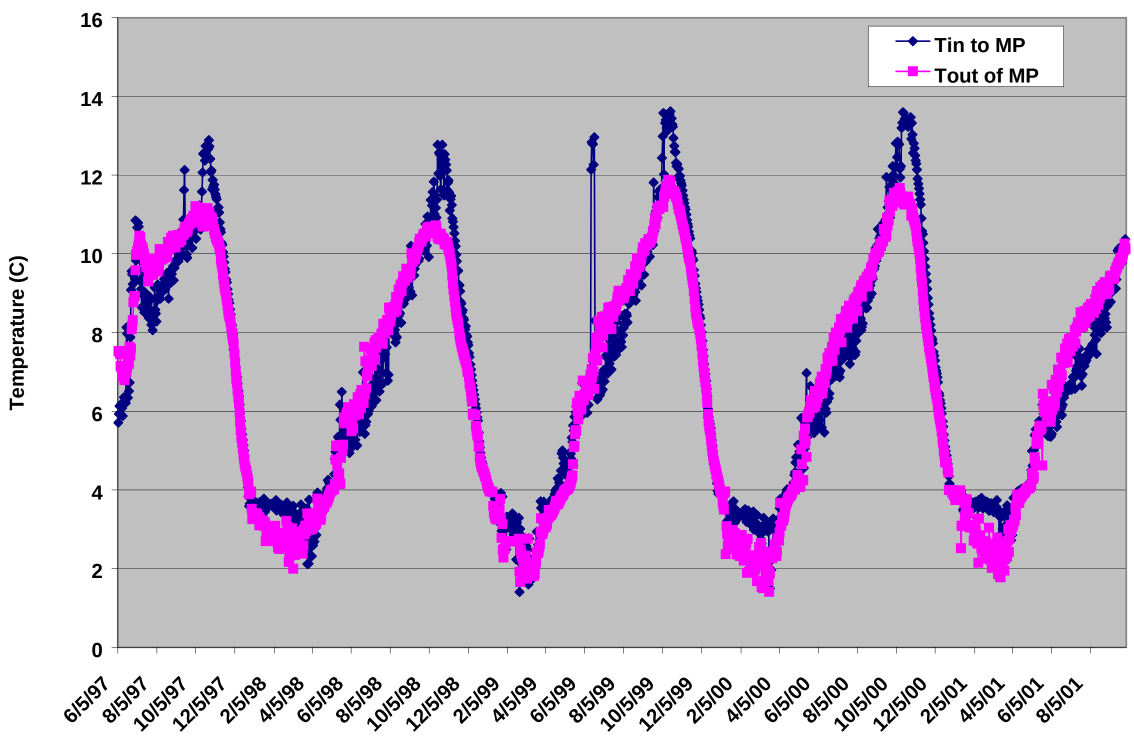


Figure 27: Inflow and release water temperatures at Morrow Point, CO. (Tin = inflow water temperatures and Tout = release water temperature)

4.4 Crystal Reservoir

Simulation period

For Crystal Reservoir, the simulation period was from July 23, 1998 through September 30, 2001. The start date was the date the first temperature profile was available in 1998. No profiles were available for 1997.

Computational grid

A plan view of Crystal Reservoir is shown in Figure 28. The reservoir was divided into 30 segments longitudinally along the main branch. Segment lengths varied from 350 to 400 meters. The reservoir was also divided into 34 layers (Figure 29). Layer depths were set at 2 meters. The penstock outlet is 2,042.2 meters (6,700 feet) above MSL, the river outlet is 2,033 meters (6,670 feet) above MSL and the spillway is 2,059.2 meters (6,755.8 feet) above MSL.

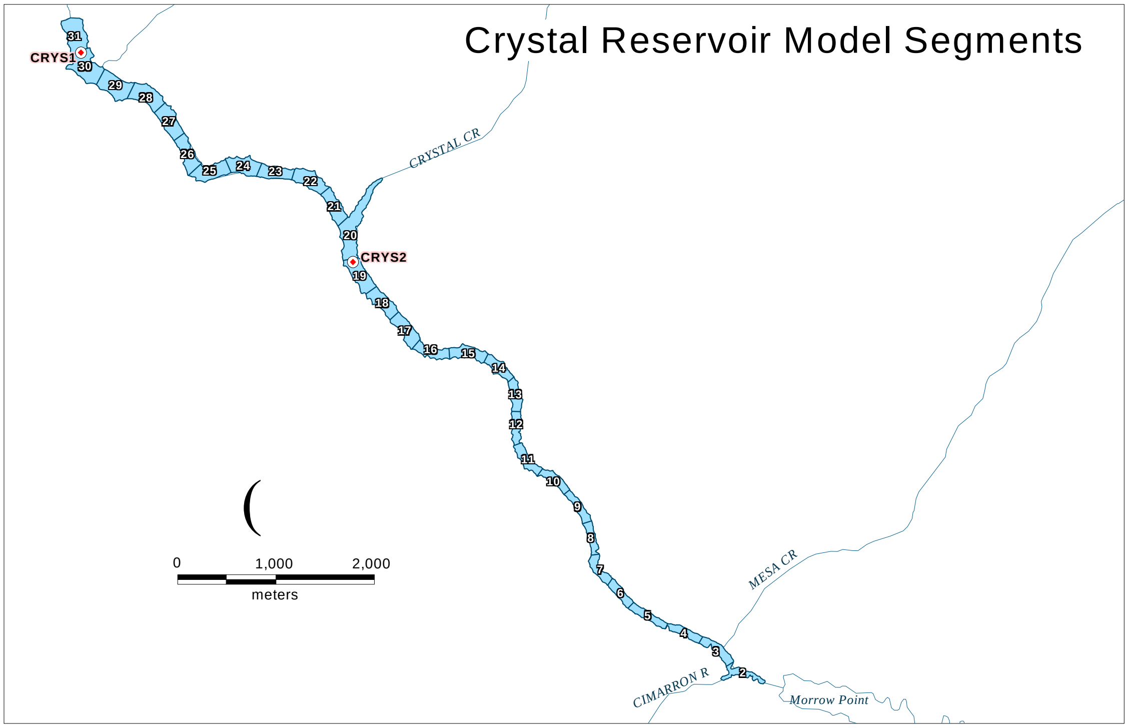


Figure 28: Crystal Reservoir, CO segmentation -- plan view

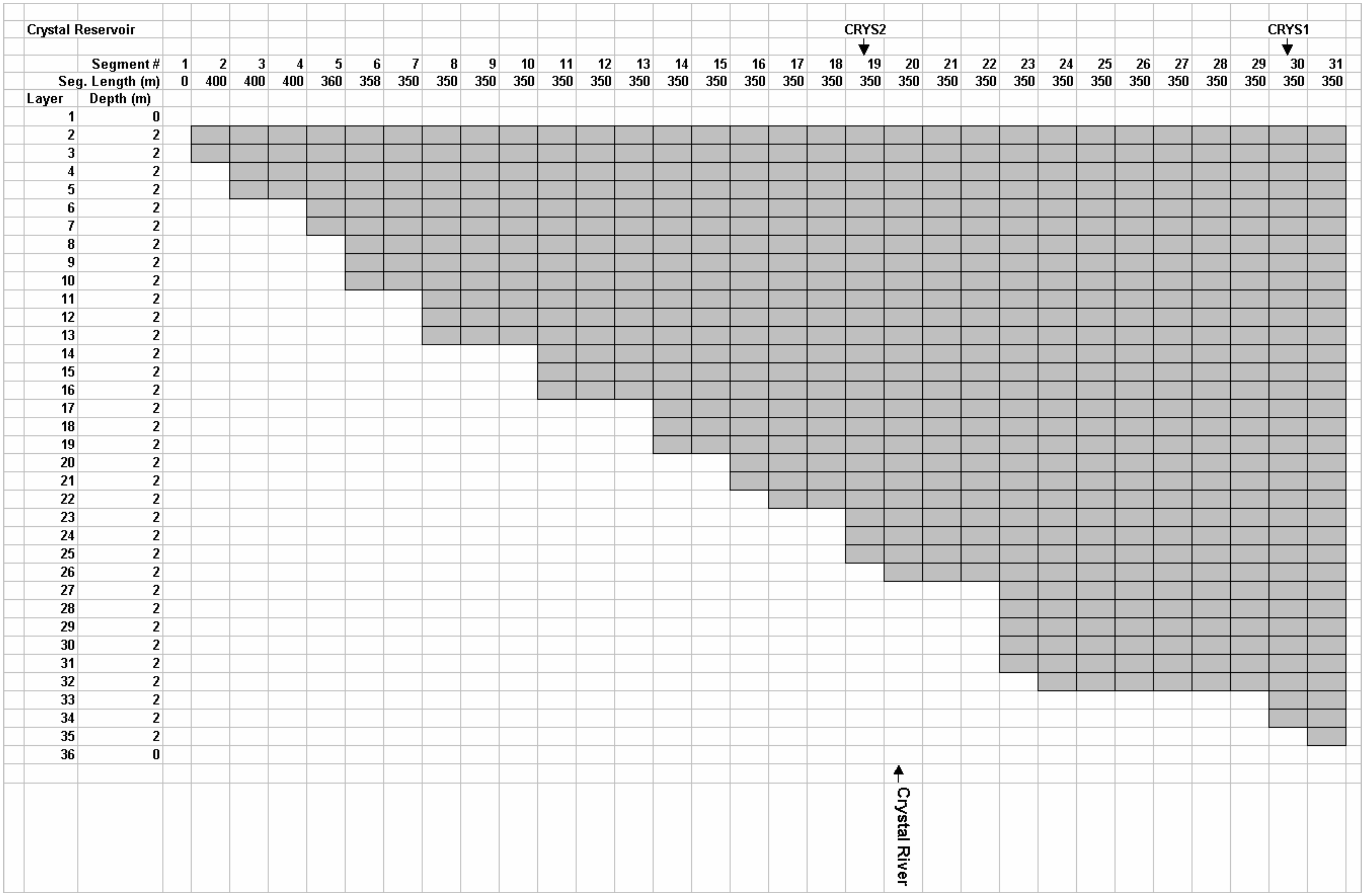


Figure 29: Crystal Reservoir, CO segmentation -- side view (CRYS1 = Crystal In-Reservoir Sampling Station Location #1 and CRYS2 = Crystal In-Reservoir Sampling Station Location #2)

An input file describing the bathymetry of the reservoir was set up for the model. Actual versus simulated relationships between water surface elevation and reservoir contents and between water surface elevation and reservoir surface area are shown in Figures 30 and 31.

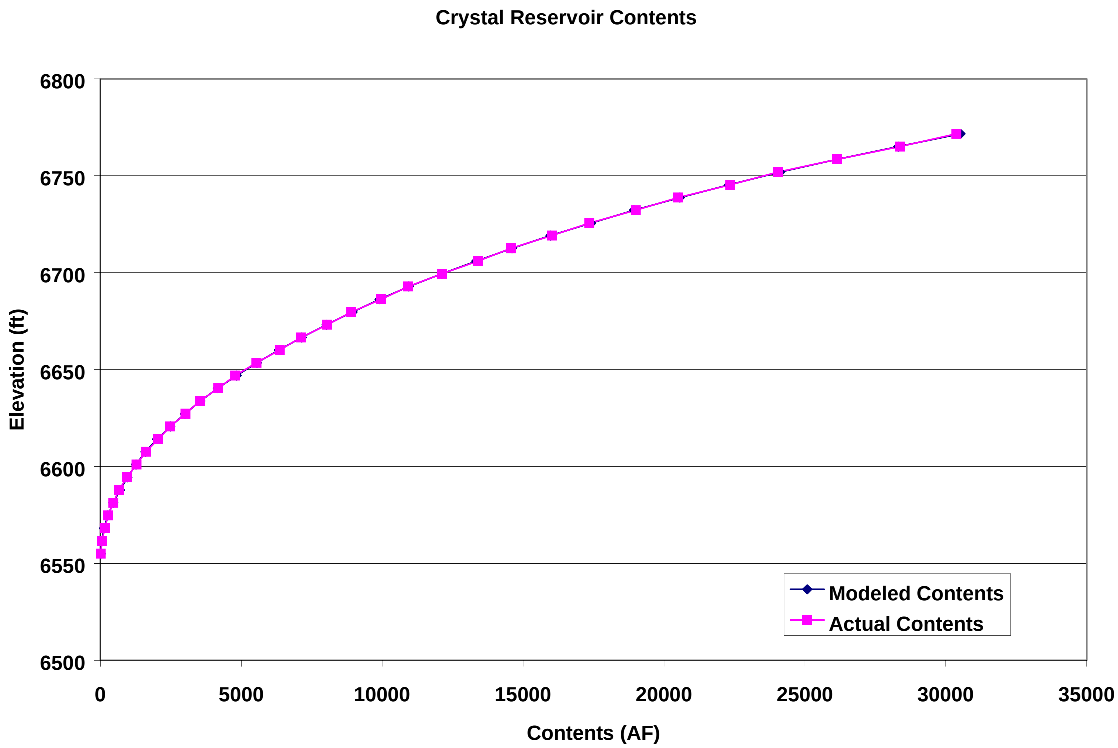


Figure 30: Relationship between water surface elevation and capacity of Crystal Reservoir, CO.

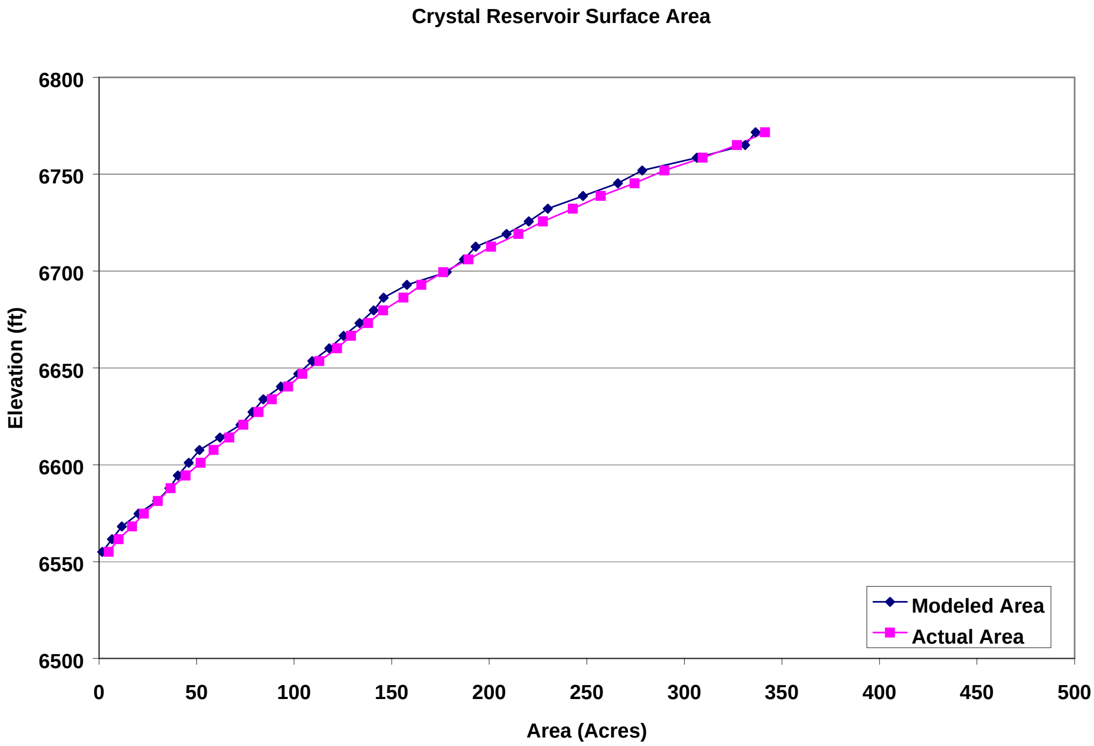


Figure 31: Relationship between water surface elevation and reservoir surface area for Crystal Reservoir, CO.

Water balance / hydrology

A water balance for each day of the simulation was prepared. Inflow into the reservoir was represented as 1) the releases from Morrow Point Reservoir, 2) the inflows from Cimarron River, and 3) the inflows from Crystal Creek. To complete the water balance, miscellaneous gains and losses including evaporation were also represented so that the model predicted the observed water surface elevation of the reservoir.

Since the Cimarron River flows into the main stem at or above the active storage elevation of the reservoir, the flow from the Cimarron River was added to the releases from Morrow Point Reservoir as inflow into the main stem of Crystal Reservoir. The inflow temperature was set at the simulated release temperature from Morrow Point for October through February. An adjustment was necessary during the March through September timeframe to provide enough heat to Crystal Reservoir to simulate observed temperatures. This adjustment was applied consistently each year.

The adjustment involved adding 1°C to the simulated release temperatures in March through May and July through September. In June, 2°C were added to the simulated temperatures. Much, if not all, of this increase in temperature can be explained by the inflows from Cimarron River and Mesa Creek, which enter the main stem at or above the simulated reservoir. The temperatures of both of these creeks are higher than the simulated releases from Morrow Point during the affected time period (4–5 °C in some cases) and can thus impact the "effective" temperature entering the reservoir.

Daily contents, upstream inflow, side inflow, releases, and evaporation data for Crystal Reservoir were obtained electronically from the U.S. Bureau of Reclamation (Thatcher 2002).

Figure 32 shows the distribution of the various inflows by source over the period of simulation. Ninety percent of the inflow into Crystal Reservoir comes from Morrow Point Reservoir. Outflow from the reservoir is through the outlet works and spillway. Evaporation was accounted for but was insignificant compared to the other inflows.

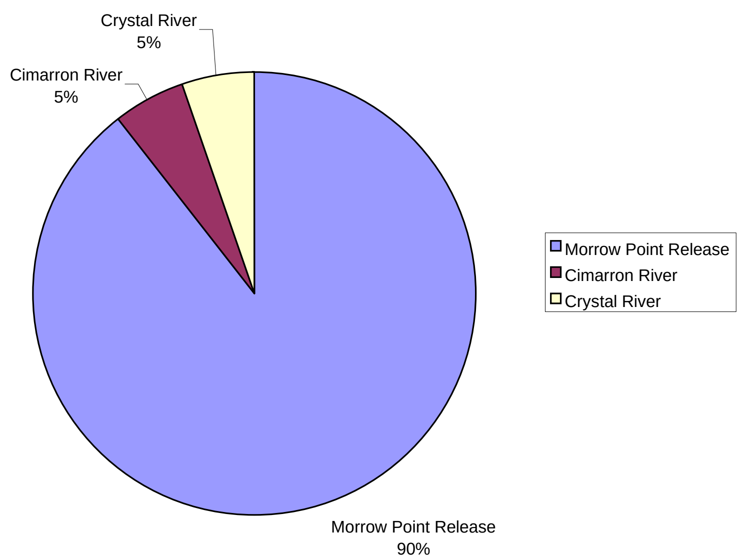


Figure 32: Distribution of total inflow into Morrow Point Reservoir, CO.

The model requires temperature data for the incoming tributaries. Temperature data were available for Cimarron River, but data gaps needed to be filled using data from similar years. There were few data points for Crystal Creek. The temperatures for Crystal Creek were assumed to approximate the temperatures from Curecanti Creek.

Meteorological Data

Meteorological data from the Montrose Airport were used for the simulation. Data used include air temperature, wind speed, wind direction, dew point, and cloud cover. The data were obtained through the Western Regional Climate Center, Desert Research Institute, Reno, Nevada, and were taken, in general, every hour.

Calibration and Results

Input data files were assembled using the information described above and the model was run from July 23, 1998, through September 30, 2001. The calibration parameters were initially set at default values. The wind sheltering coefficient was adjusted during the calibration process. The final wind sheltering coefficients varied from 0.5 to 2.0. Although wind sheltering coefficients are normally less than 1.0, values greater than 1.0 are sometimes necessary to simulate a tunneling effect (Cole and Wells 2002). Simulation results are described below.

Reservoir Contents:

Daily reservoir elevations were obtained from the U.S. Bureau of Reclamation for Crystal Reservoir. These data are graphed along with simulated results in Figure 33.

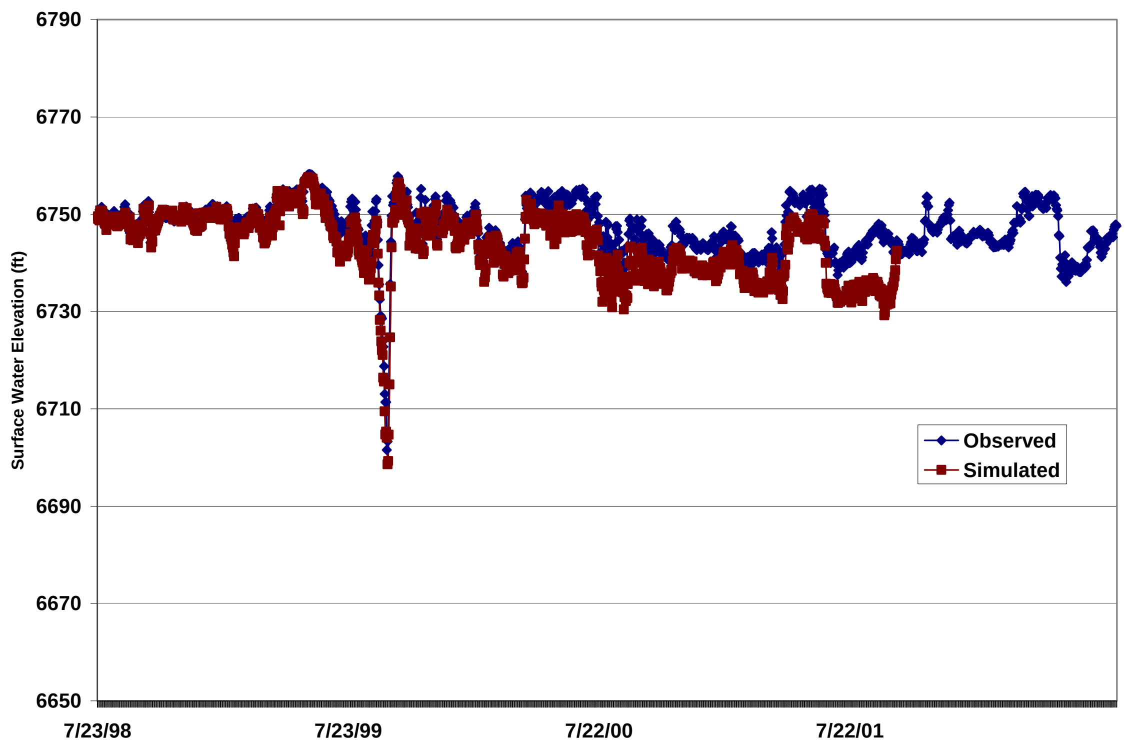


Figure 33: Simulated vs. observed water surface elevations for Crystal Reservoir, CO.

Reservoir temperature:

There are two locations in Crystal Reservoir where temperature profiles have been taken over the period of simulation. They are noted in Figure 29 as CRYS2 (in the upper reservoir) and CRYS1 (near the dam). Thirty-seven profiles were taken, representing 864 data points, during the period of simulation. The overall calibration statistics are displayed in Table 3.

Table 3: Calibration Results for Crystal Reservoir

Reservoir	*Time Period*	*Sites*	*AME*	*RSME*	*Number of Profiles*	*Number of Data Points*
Crystal	1998 - 2001	All sites	0.681	1.054	37	874
	1998 - 2001	CRYS2	0.599	0.872	17	353
	1998 - 2001	CRYS1	0.737	1.16	20	521
	1998	All sites	0.622	1.11	4	95
	1999	All sites	0.676	1.02	10	253
	2000	All sites	0.579	0.878	13	297
	2001	All sites	0.843	1.26	10	229

The model calibrated well for all sites and for all years. A graph of observed vs. simulated surface water temperatures at the CRYS1 station is shown in Figure 34. As an example, profiles at the CRYS1 Site during 2000 are shown in Figure 35 (2 pages).

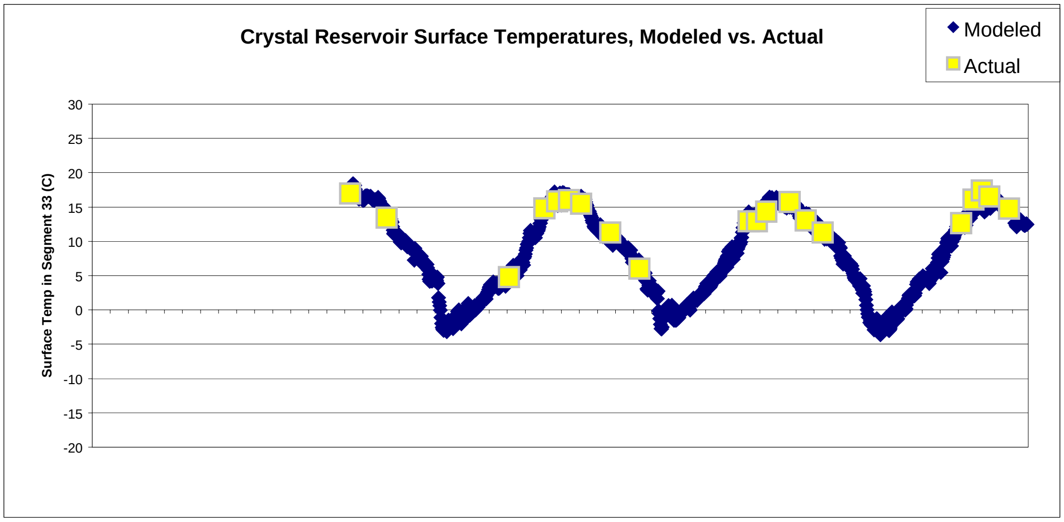


Figure 34: Observed and Simulated Surface Water Temperatures in Crystal Reservoir, CO

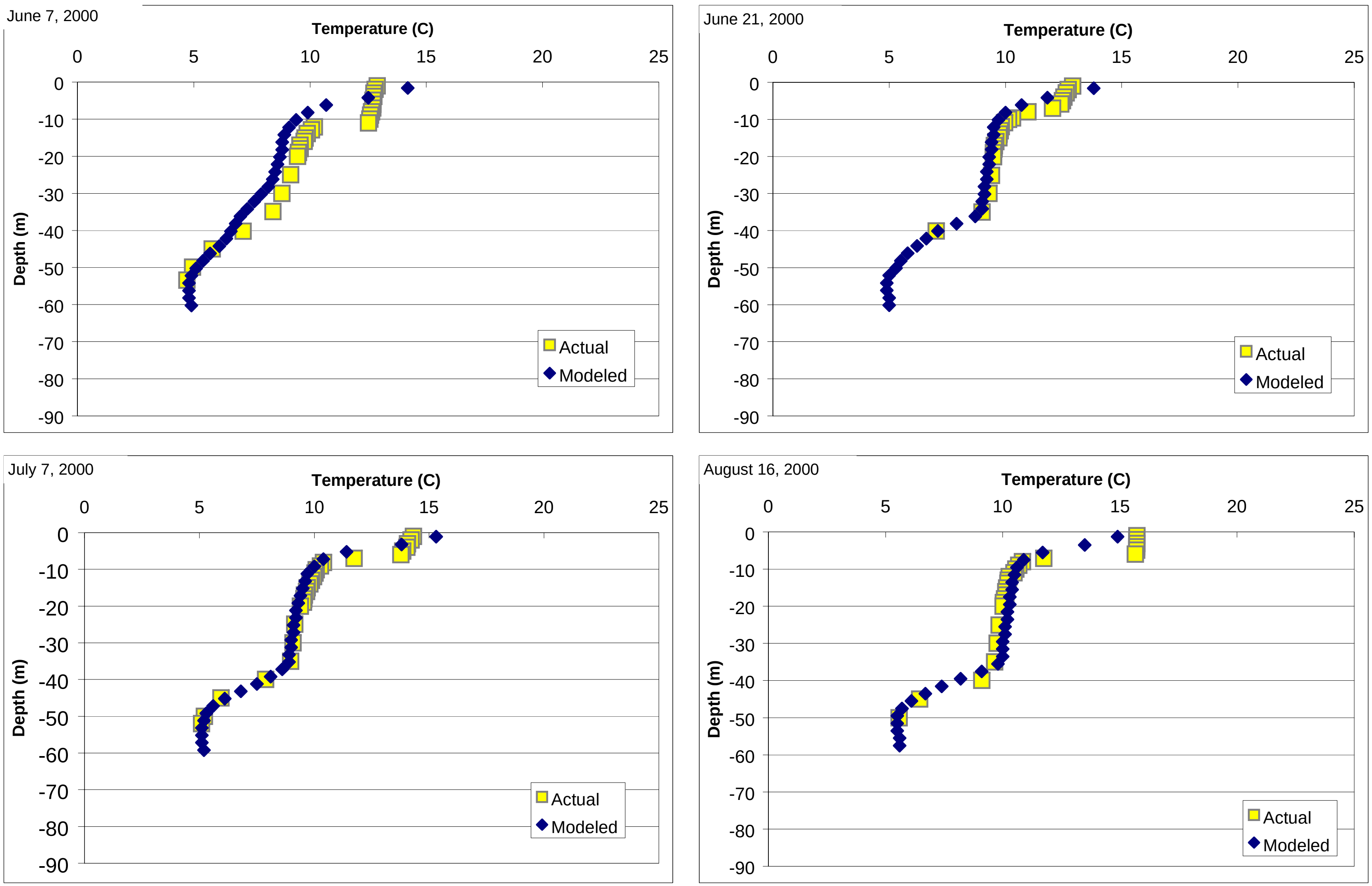
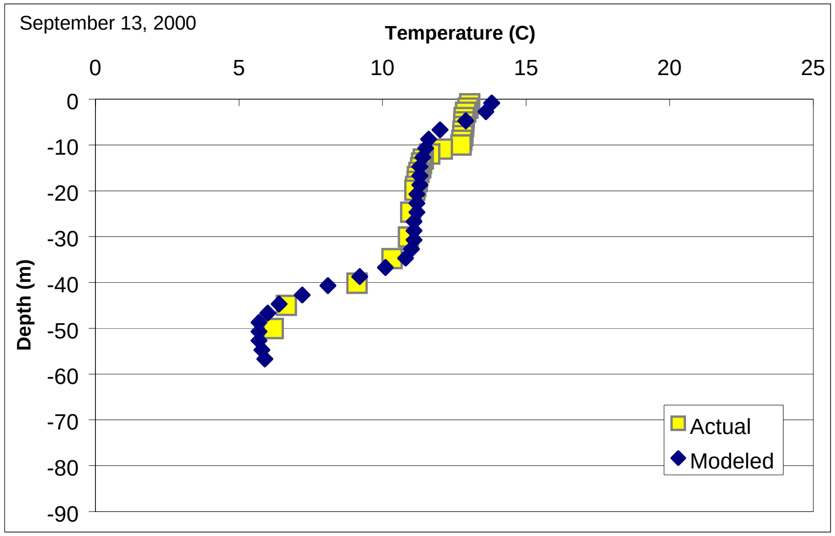


Figure 35: Profiles at CRYS1 Site in Crystal Reservoir, CO - 2000 (1 of 2)



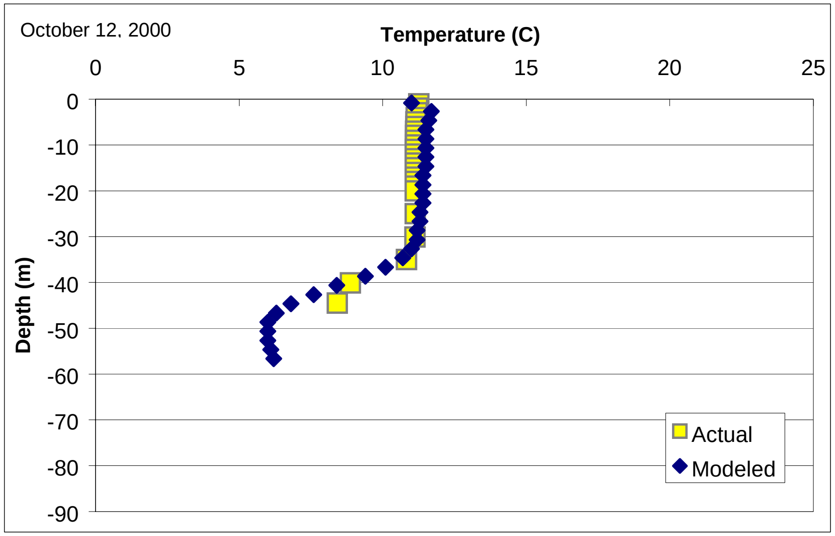


Figure 35: Profiles at CRYS1 Site in Crystal Reservoir, CO - 2000 (2 of 2)

There are observed Crystal Reservoir release temperatures to compare to the simulated results. Observed and simulated release temperatures for 1998-2001 from Crystal Reservoir were in close agreement (Figure 36); N = 962, AME = 0.658, RSME = 0.664.

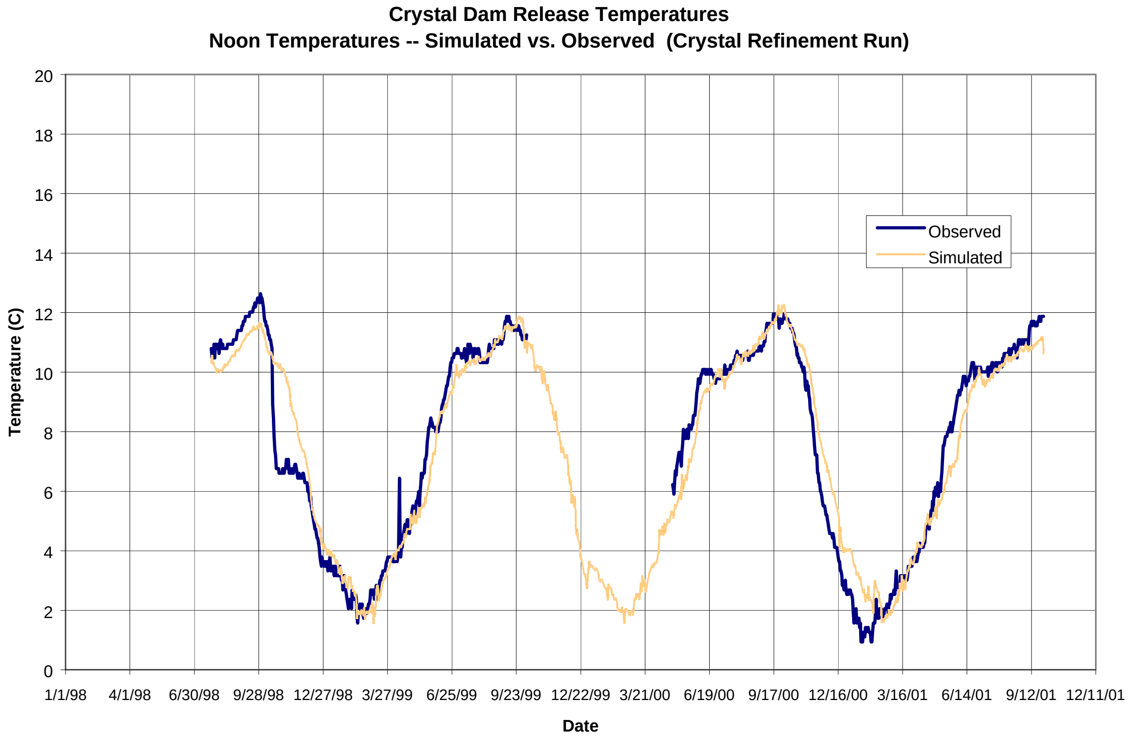


Figure 36: Observed vs. simulated release temperatures from Crystal Reservoir, CO.

5. RIVER TEMPERATURE MODELING

The original scope of work for the river model in Phase II anticipated the development of an empirical (statistical) model of mean daily water temperatures in the reaches between Crystal Dam and the City of Delta, Colorado. The critical months for the analysis, based on the Colorado pikeminnow growing season, are late May/early June through October. These are the months during which river temperatures are most reduced (i.e., cooler water) by the Aspinall Unit reservoirs.

The approach to developing this empirical model was to use a multivariate, stepwise regression, using air temperature, Crystal Reservoir release volumes and temperature, and flows from the North Fork and Uncompahgre River as the independent variables. Several variations on this theme, including the use of hourly and daily average and maximum data sets, were investigated. Aggregating the daily average data by month has produced reasonably good results in the "shoulder" months of interest, i.e., May, June, and October. However, the July through September results are less encouraging. The primary issue appears to be that once the reservoirs have stratified, there is almost no variation in release temperatures for these months. Because the historical data reflect very little variation in release temperatures for these months, the statistical model is unable to discern a relationship between release temperatures and river temperatures at Delta.

Due to the inability of this model to predict water temperatures during this critical time period, other temperature modeling approaches were investigated. An attempt was made to simulate the river using CE-QUAL-W2 -- the same model used for the reservoirs. Although this model has the advantage of being dynamic (or time-varying), it also was not a viable option for modeling the Gunnison River. This was due to the steep profile of the river channel and the need to divide the river into very small segments (in order to avoid numerical instabilities). Although the model would execute, run times were too long to be practical for simulating the river with this tool. Finally, the QUAL2K model was employed to model the Gunnison River.

QUAL2K (Chapra and Pelletier 2003) is an enhanced version of QUAL2E (Brown and Barnwell 1987). Both models are one-dimensional and assume steady-state hydraulics. The heat budget and temperature are simulated as a function of meteorology on a diurnal time scale. QUAL2K also has several other new features, most of which are associated with water quality variables other than temperature. The model is programmed using Visual Basic for Application (VBA) for Microsoft EXCEL® and has an easy-to-use user interface which is a significant improvement over QUAL2E.

Although the model is set up to simulate a host of water-quality constituents, it was used solely for temperature in this application. The heat budget includes surface heat fluxes in the form of solar shortwave radiation, atmospheric longwave radiation, water longwave radiation, conduction and convection, and evaporation and condensation. It also includes fluxes at the substrate-water interface.

The Gunnison River was divided into 89 segments along the approximately 80-km (49-mile) reach between Crystal dam and the FWS temperature monitoring site at Delta. Most segments were 1 km in length but a few deviated from this, having the range of 0.5 to 1.18 km in length. Inflows from the North Fork of the Gunnison and the Uncompahgre River, as well as diversions at the Gunnison Tunnel, were taken into account. Data for the Gunnison Tunnel diversions and for the two tributaries were obtained from the USGS. Two USGS flow gages exist on the Gunnison River in the modeled area -- one below the Gunnison Tunnel (USGS 09128000 GUNNISON RIVER BELOW GUNNISON TUNNEL, CO.) and one at Delta (USGS 09144250 GUNNISON RIVER AT DELTA, CO.). Temperature data in the modeled area were obtained from the FWS at three locations on the Gunnison River -- one below Crystal Dam, one above the confluence with the North Fork, and one below the confluence with the Uncompahgre River.

Monthly temperature data were obtained from the North Fork volunteer water-quality monitoring program for the North Fork River. These data were used for guidance in estimating inflow temperatures from the North Fork. Uncompahgre River inflow temperatures were obtained from the USGS at site 09149500 UNCOMPAHGRE RIVER AT DELTA, CO.

To calibrate the QUAL2K, it was necessary to determine appropriate calibration periods. Data during the period January 1, 1997, through September 30, 2001, were analyzed for periods where flows and meteorological conditions were relatively stable over a period of days. Six periods were identified that met those criteria:

May 23–27, 1997	Aug 16–20, 1998
Oct 17–21, 1997	May 4–6, 2000
June 28–30, 1998	June 16–18, 2000

Model input data were assembled for each of these periods and the model was run.

The solar radiation term in the model is a function of effective shade. This factor accounts for the fraction of solar radiation blocked by vegetation and topography and is entered on an hourly basis for each segment. A separate program named SHADE - version 29 (Pelletier 2003) was used to determine these factors by segment on an hourly basis. This model accounts for both topographic shade and vegetative shade. Due to the steep canyon walls and the significant amount of topographic shade in the study area, vegetative shade was assumed to be negligible. Topographic shade angles were estimated for each reach of the study area and shade factors were computed for the days in which the model was calibrated.

Meteorological data from the Montrose Airport were used for the river simulations: air temperature, dew point temperature, wind speed, and cloud cover.

Distributed gains and losses were accounted for in the model to ensure that observed Gunnison River flows above the North Fork and at Delta were simulated. The model was calibrated to fit the observed stage data using reasonable values of Manning's n.

5.1 Model results

Predicted mean temperatures for the six periods used for calibration were graphed (Figures 37–42).

For all six model runs, the average temperatures were very closely predicted. The predicted diurnal temperature patterns at the Delta site are shown in Figures 43–48. Maximum and minimum daily temperatures were also closely predicted.

Goodness-of-fit statistics were not computed for the river model. Since there are temperature data at three locations in the simulated reach of the river and the model is simulating the steady-state average temperature, most goodness-of-fit techniques are not applicable to this situation.

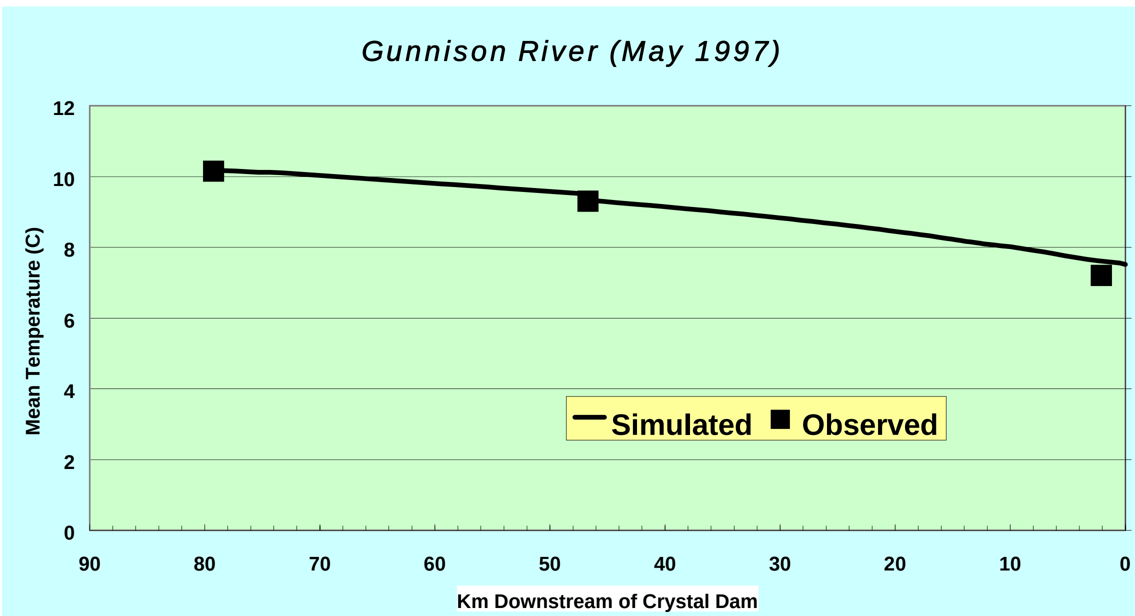


Figure 37: River simulation results -- May 23–27, 1997 (The data on the right hand side represent conditions just downstream of Crystal Dam. Data points at 46.7 km are observed data at the FWS site on the Gunnison River above the confluence with the North Fork. Data points at 79.2 km represent observed temperatures at the FWS temperature site at Delta. The black line is the simulated average steady-state temperature throughout the study area).

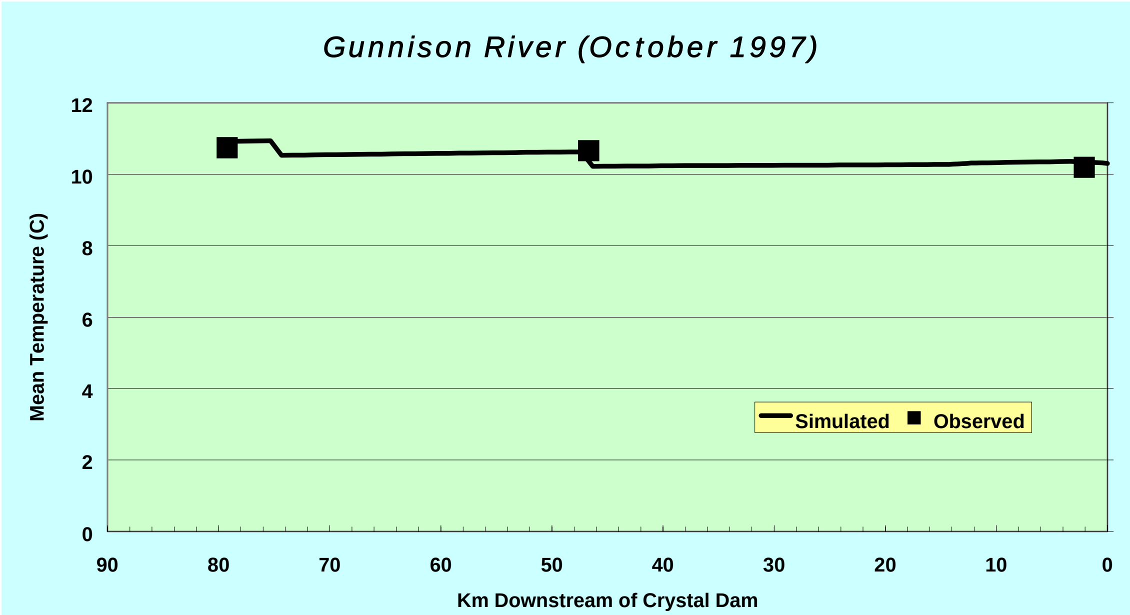


Figure 38: River simulation results -- October 17–21, 1997

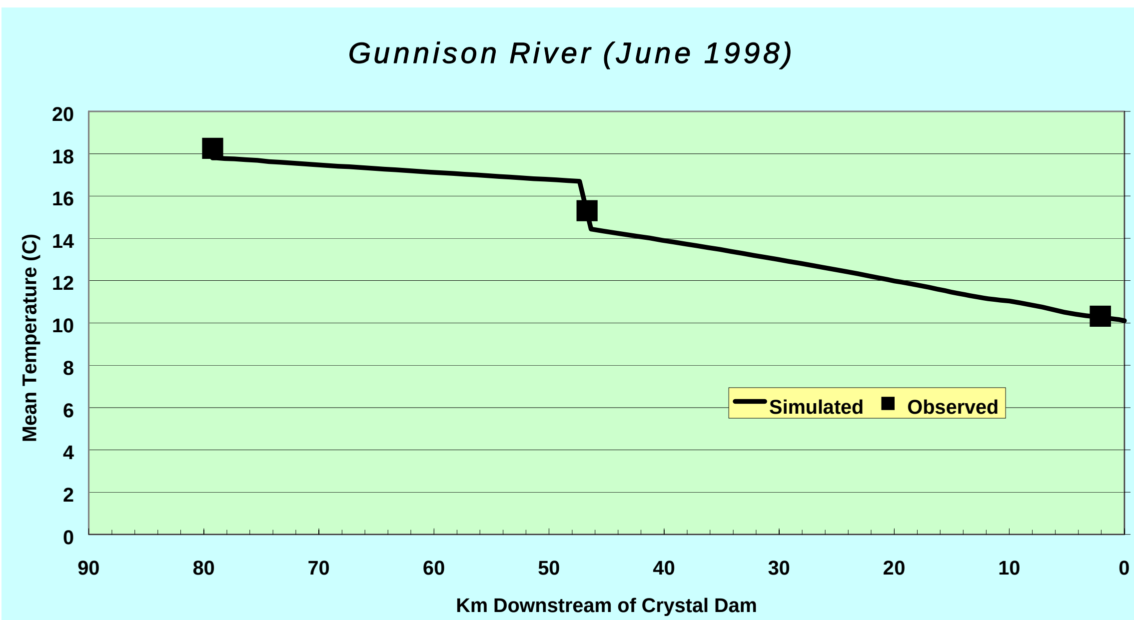


Figure 39: River simulation results -- June 28–30, 1998

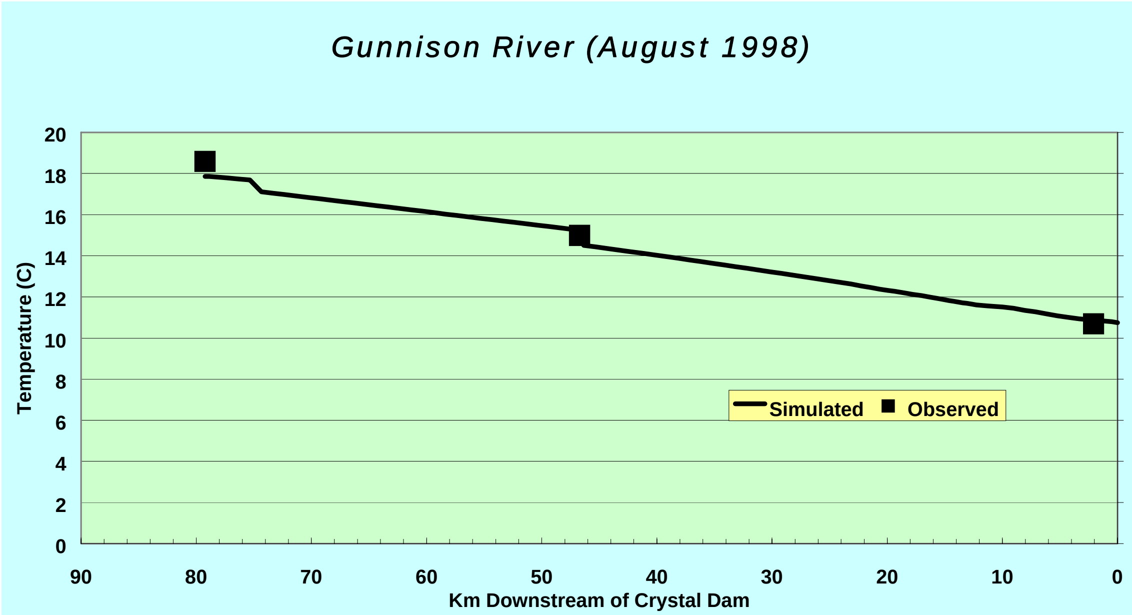


Figure 40: River simulation results -- August 16–20, 1998

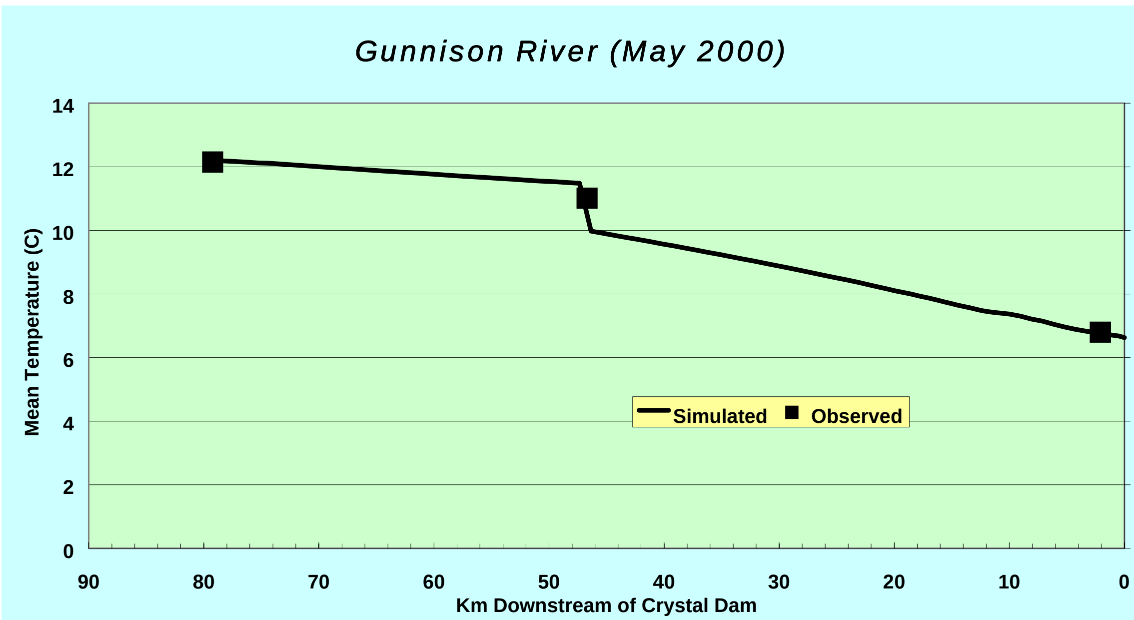


Figure 41: River simulation results -- May 4–6, 2000

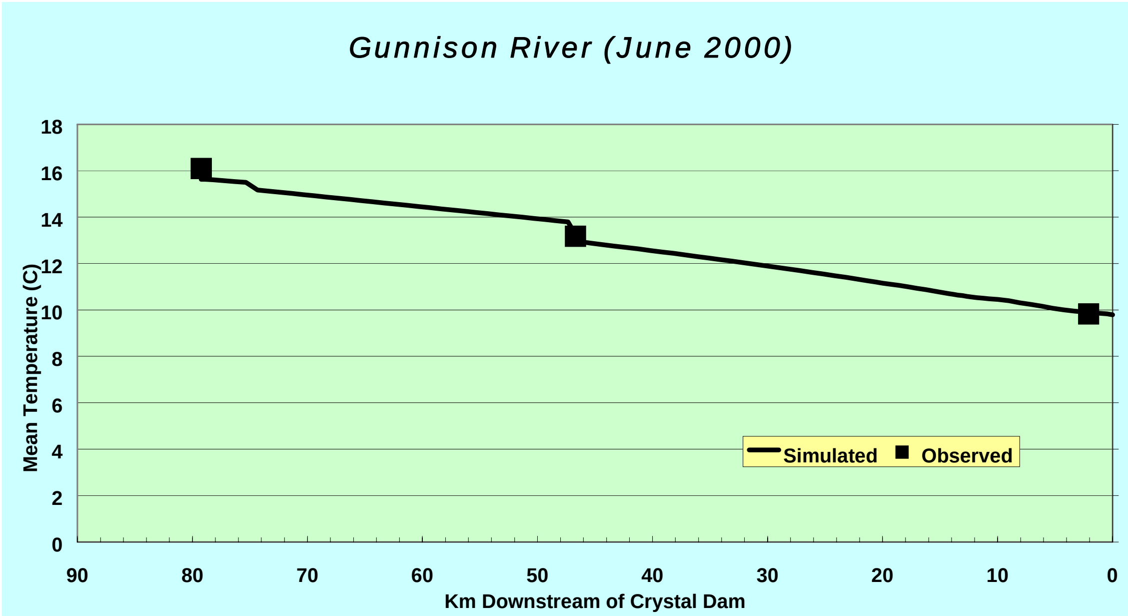


Figure 42: River simulation results -- June 16–18, 2000

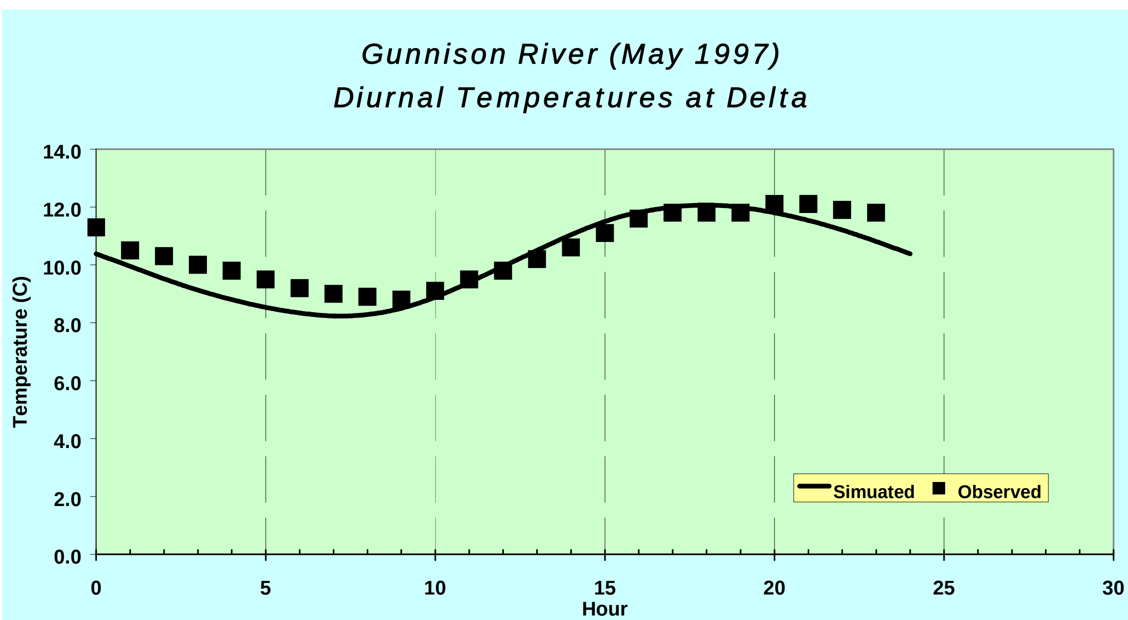


Figure 43: Diurnal temperature pattern at Delta -- May 23–27, 1997

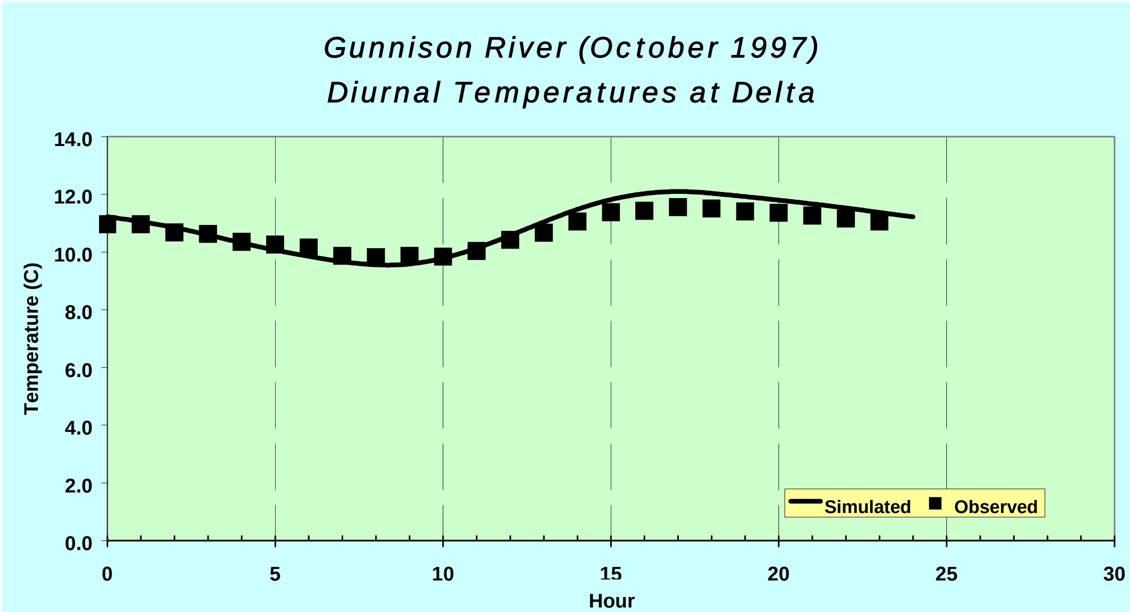


Figure 44: Diurnal temperature pattern at Delta -- October 17–21, 1997

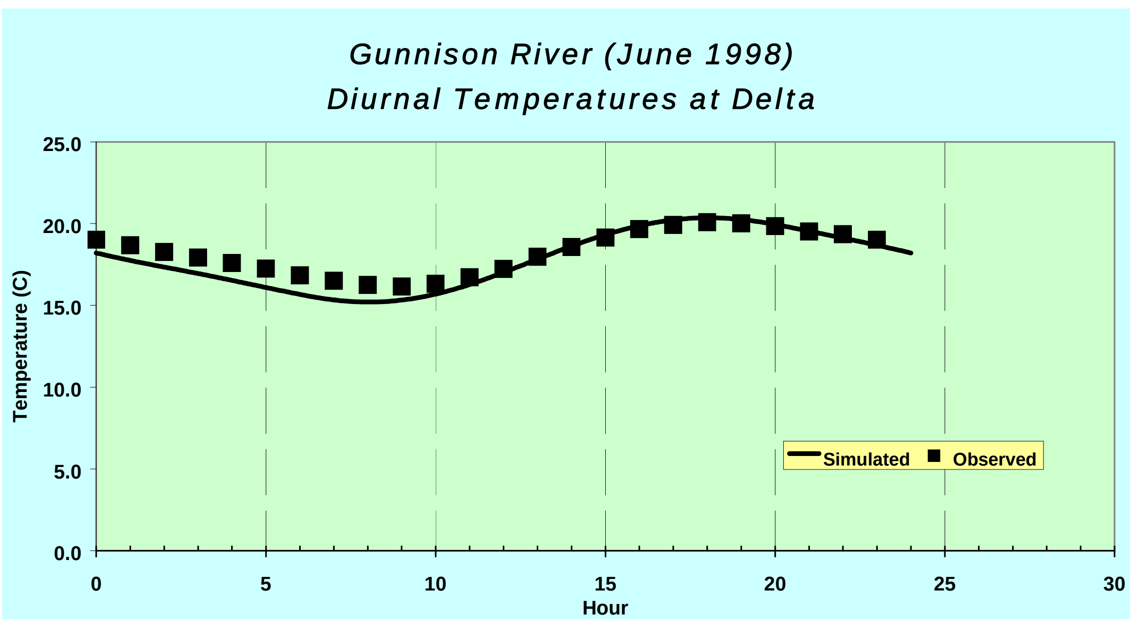


Figure 45: Diurnal temperature pattern at Delta -- June 28–30, 1998

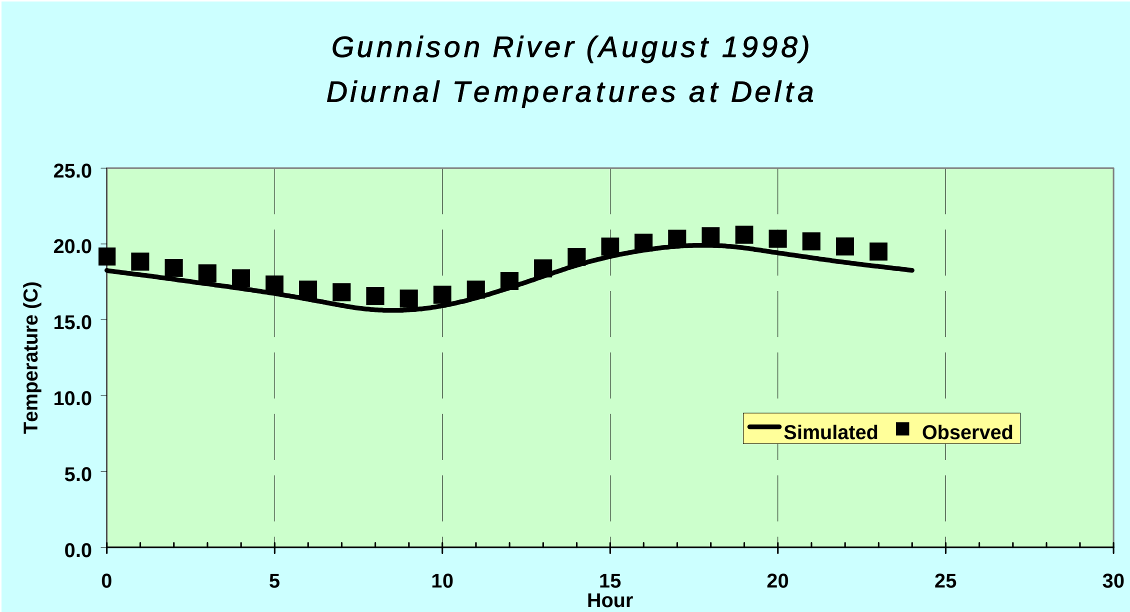


Figure 46: Diurnal temperature pattern at Delta -- August 16–20, 1998

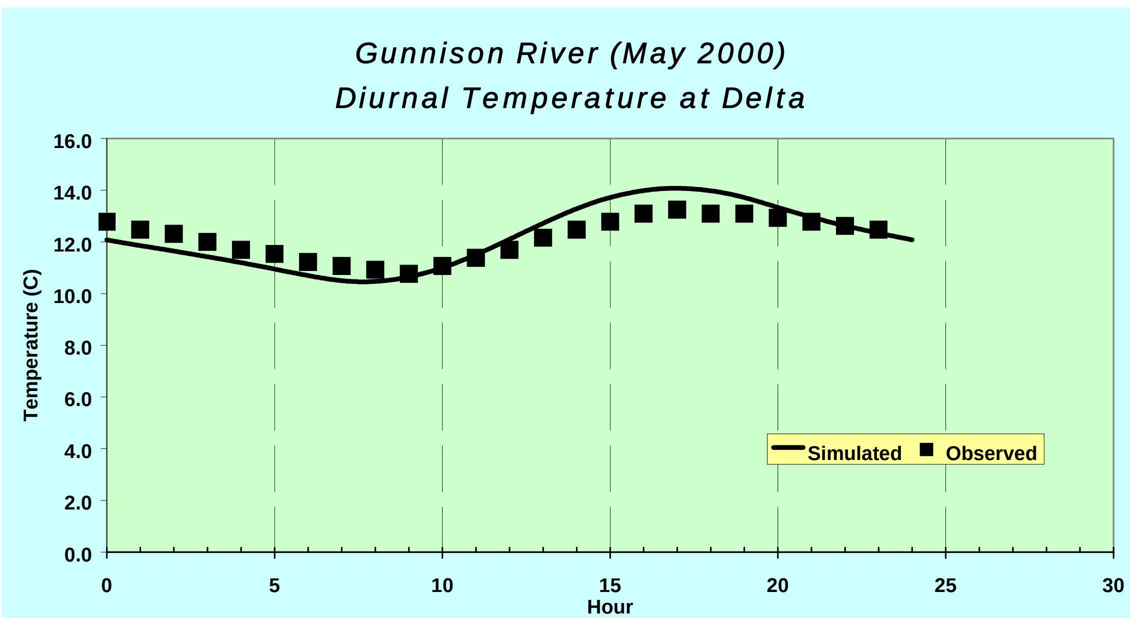


Figure 47: Diurnal temperature pattern at Delta -- May 4–6, 2000

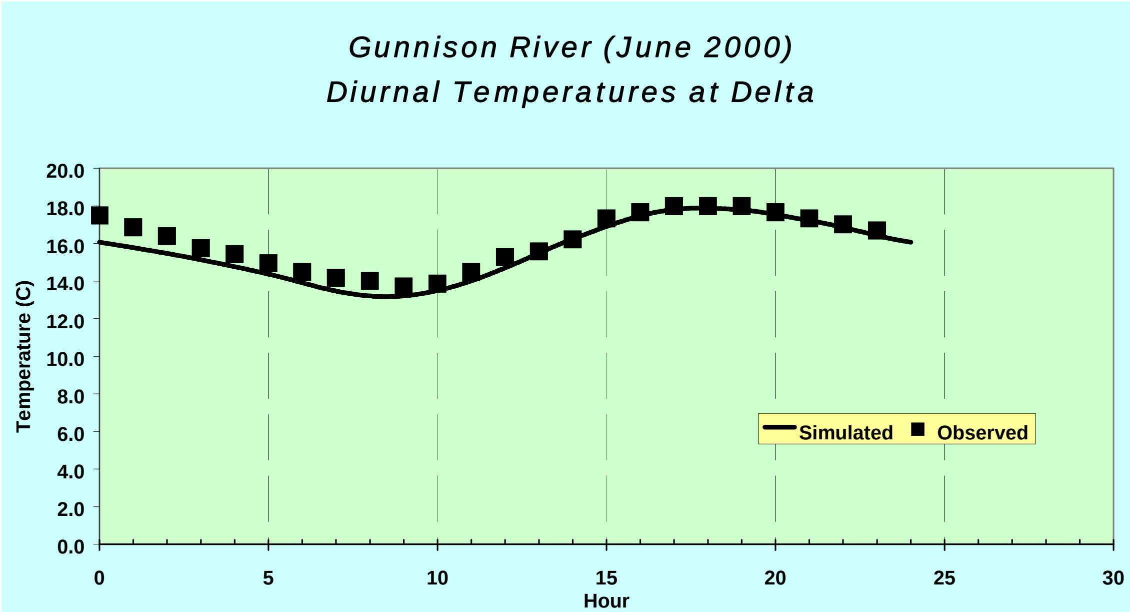


Figure 48: Diurnal temperature pattern at Delta -- June 16–18, 2000

6. FLOWRATES FOR THE "FLOW RECOMMENDATIONS" SCENARIO

In this section, the methodology used to develop the model input flow files for the scenarios described in Section 7 is discussed.

Using historic operational data from 1997–2000, and the FWS flow recommendations (McAda 2003), Crystal Reservoir releases (Figure 49) were developed to reflect the likely operations if the recommendations were to be implemented.

The process of developing the “Flow Recommendation Releases” was as follows:

1) Using unregulated April – July inflows from the Colorado Basin River Forecasting Center, each year was classified as wet, moderately wet, average wet, average dry, moderately dry, or dry.

2) Because the flow recommendations identify target flows at Grand Junction, Crystal releases were determined assuming that the other contributing tributaries below Delta were not impacted by changes in Crystal releases.

3) For each year, it was assumed that the peak flow event under the flow recommendations would begin on May 15. “Shoulder” flows were distributed evenly on either side of the peak event, when appropriate, although no releases for the simulated runoff events were started earlier than May 1.

4) The volume of additional water from Crystal Reservoir needed to meet the target flows identified in the FWS report (McAda 2003) was computed based on the recommended flows and the water already in the river from other contributing streams. It was assumed that the total volume released annually from Crystal Reservoir would remain the same; only the timing would change.

5) Working backward in time from the start of the simulated runoff event, it was assumed that Crystal Reservoir releases would be reduced in order to store water for the runoff event. Curtailment of Crystal releases was conditioned on maintaining the historical Gunnison Tunnel diversion rates, a minimum flow of 300 cfs in the Black Canyon, and a 1000 cfs minimum flow requirement at Grand Junction to meet senior water right demands and provide sufficient water to operate the fish ladder at Redlands Diversion.

The period over which water would need to be stored leading up to a simulated peaking flow event varied significantly from year to year. In 1997, 2 months of modified releases leading up to May 1 would be sufficient to store enough water to meet the flow recommendations, while in 1999, despite the lower peaking target, it would have taken 6 months to store enough excess water to meet the target flows. It is worth noting that this approach to developing new Crystal operations assumes “perfect foreknowledge” of the flows. In reality, it would be impossible to accurately predict hydrologic cycle to meet the flow targets.

After the releases from Crystal Reservoir were computed on a daily basis, the releases from Morrow Point and Blue Mesa were computed along with the corresponding inflows into Morrow Point and Crystal Reservoirs. Again, it was assumed that tributary inflows were not affected by the modified operations. It was also assumed that the water surface elevation of both Crystal and Morrow Point reservoirs remained the same as it actually had been during the 1997 – 2000 period.

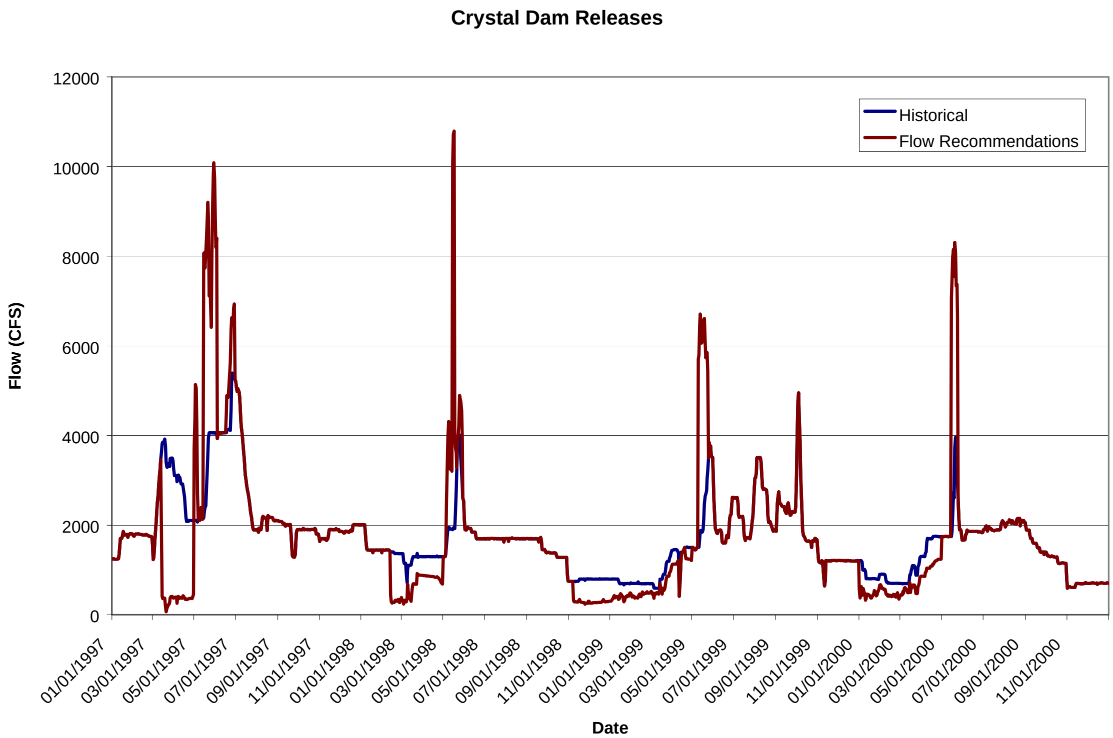


Figure 49: Historical Crystal Reservoir releases compared to flow recommendations

7. ADDRESSING RESERVOIR SCENARIOS USING CE-QUAL-W2

The reservoir W2 model was used to analyze release water temperatures for the following scenarios over the 1997–2000 period:

1) Historical releases
2) Flow Recommendations
3) Temperature control device (TCD) scenarios
4) 2003 low reservoir surface elevation

7.1 Historical releases

Under the 1997–2000 historic condition scenario (97–00), Crystal release water temperature to the Gunnison River fluctuated from 2 °C to 12 °C and flow varied from 0 to 6,015 cfs.

7.2 Flow recommendation

Based on the releases from the Flow Recommendation scenario for Blue Mesa, Morrow Point, and Crystal reservoirs the release water temperature to the Gunnison River ranged from 2 to 13 °C and flow ranged from 0 to 11,785 cfs. Overall release water temperature under historic conditions and flow recommendations were very similar. These values were used as a comparative baseline for the other scenarios described below.

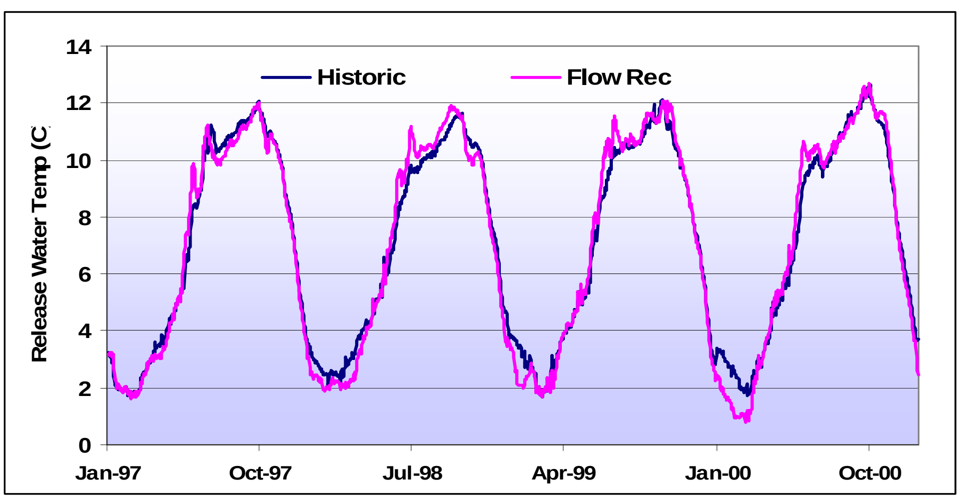


Figure 50: Release water temperature at Crystal, CO during 1997 to 2000 (historic) and under scenario if FWS flow recommendation were implemented.

7.3 TCD Scenarios

Assumptions

Five assumptions were necessary to address TCD scenarios:

1) The TCD configurations are based solely on the physical elevation of the potential releases.

2) The TCD outlet passed only the maximum releases from the historic record that were not bypassed through the spillway.

3) There is a 20-foot buffering zone above all TCD release elevations to avoid formation of vortices.

4) Boundary conditions (meteorological data, tributary inflows and temperature, etc.) were the same as the 1997 to 2000 condition.

5) There were two TCD configurations: 1. fixed-level outlet and 2. multiple-level outlets. A fixed-level TCD outlet operates as a function of reservoir elevation, whereas a multi-level TCD selects unique layers of water in the water column.

Confirm that best location for TCD is at Blue Mesa

Using the above assumptions the first analysis was to determine which reservoir (Blue Mesa, Morrow Point or Crystal) was the best location for a TCD.

To confirm that the best location for a TCD was at Blue Mesa (Hydrosphere 2002), Morrow Point was selected as a logical starting point since it is centrally located in the series of reservoirs. If operating a TCD at Morrow Point resulted in increased release temperatures, the other reservoirs would be analyzed. If there was no discernable positive effect at Morrow Point, then Crystal could be eliminated from the analysis.

Using release valves from the Flow Recommendation scenario and temperature from Blue Mesa, a multi-level TCD configuration was modeled with a starting elevation of 7,142.4 feet, 20 feet below the highest water surface elevation at Morrow Point. The release water temperature with and without the use of a TCD was graphed (Figure 51).

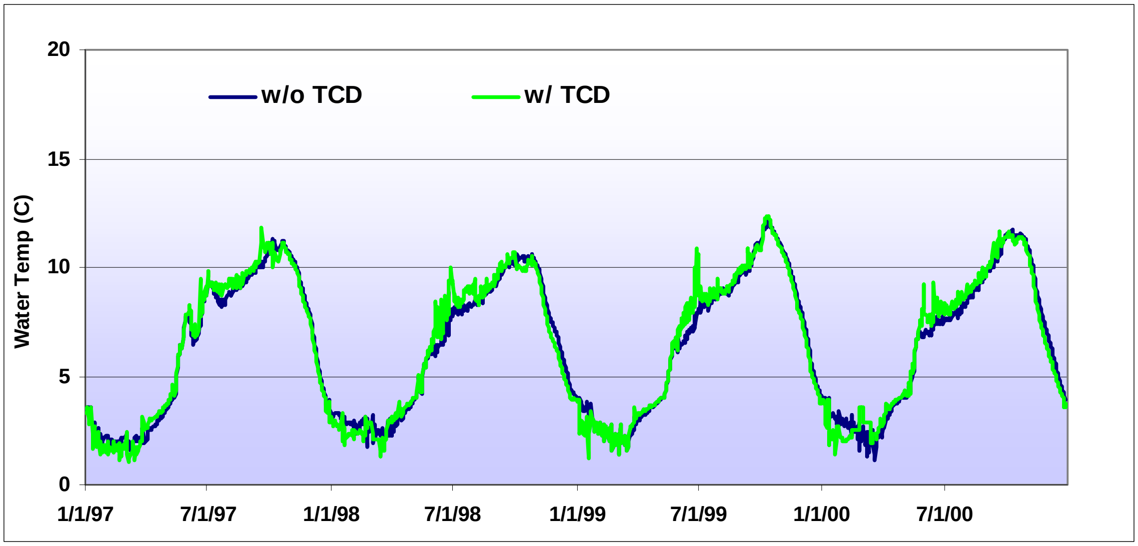


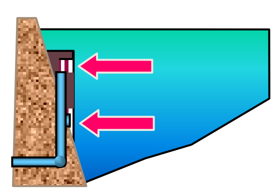
Figure 51: Release water temperature from Morrow Point reservoir with and without the use of a TCD.

The modeling demonstrated that over a 4-year period there was little increase in release water temperature from the addition of a TCD at Morrow Point Reservoir. This makes sense because Blue Mesa is about 8 times larger than Morrow Point and 37 times larger than Crystal; total storage is 940,700 acre-feet, 117,190 acre-feet, and 25,240 acre-feet for Blue Mesa, Morrow Point, and Crystal reservoirs, respectively. The retention time of inflow water through Blue Mesa is about half a year whereas the retention time through Morrow point is about two weeks, and only a few days at Crystal. The release water temperature from both Morrow Point and Crystal reservoirs are similar to the inflow temperature because of the short retention time. Therefore, having a TCD on Morrow Point and Crystal with cold inflow would not increase down stream temperature to the system's potential.

7.4 Model results using a single-level TCD at Blue Mesa

Blue Mesa reservoir was analyzed with a fixed-level TCD configuration under the Flow Recommendation scenario

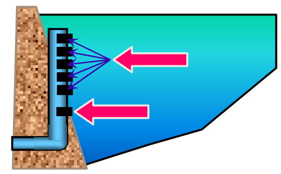
The TCD base elevation of 7,447.2 feet was selected to start 20 feet below the lowest reservoir water surface elevation for the period of 1997 to 2000. For the purpose of this study the TCD elevation was set to ensure that all releases for this period were subject to be released through the TCD outlet. In reality the best location would be based upon detailed forecasts of future reservoir elevations.



The single TCD elevation operated primarily as a function of water surface elevation. As the reservoir stratified seasonally, the outlet location was important to exploit desirable warmer water than would be possible without TCD. A fixed location limited the ability to achieve desirable temperature ranges. Any operation at or below a reservoir water surface elevation of 7,467.2 feet required that releases be taken from the current penstock elevation when operating under these constraints. The release water temperature generated by the W2 model for this scenario ranged from 2 to 17.7 °C.

7.5 Model results using a multiple-level TCD at Blue Mesa

The uppermost elevation of the TCD withdrawal was 7,500 feet, 20 feet below the highest water surface elevation, and continued to the bottom of the TCD in 10-foot intervals.



The multi-level outlet configuration ensured that the largest possible range of release water temperatures was exploited through systematic operations. Results from the modeled inflow hydrology during the period of 1997–2000 indicated the water release temperature pattern below Crystal ranged from 2 to 18 °C.

7.6 Low reservoir elevation Scenario

As Blue Mesa reservoir surface elevation drops, release temperatures increase. In 2003, water surface elevation in Blue Mesa was 62 feet (7,457 feet) below maximum elevation. This scenario addressed possible increases in release temperature below Blue Mesa Reservoir and how the water temperature was routed downstream to below Crystal reservoir based on two assumptions: 1) Blue Mesa reservoir starting elevation was 62 feet below maximum, and 2) reoccurring hydrology of 1997 to 2000.

Results indicated the release temperature from Blue Mesa reservoir during the summer months was tapping into the warmer water column. The release water temperature was as high 16 °C, compared to a historical high release temperature of 13 °C when reservoir elevations were higher.

A summary of release water temperatures below Blue Mesa for four scenarios (flow recommendation, one fixed-level TCD, multi-level TCD and low reservoir condition) are represented on the following graph (Figure 52).

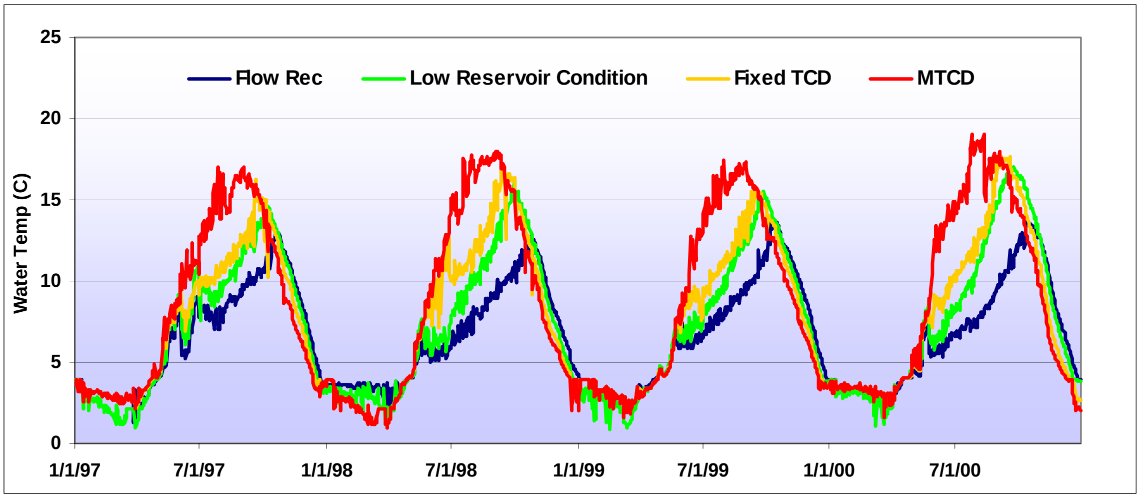


Figure 52: Release water temperatures below Blue Mesa Reservoir, CO from four different scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition).

Release water temperatures below Blue Mesa from the above scenarios were then routed through Morrow Point Reservoir (Figure 53) and Crystal Reservoir (Figure 54).

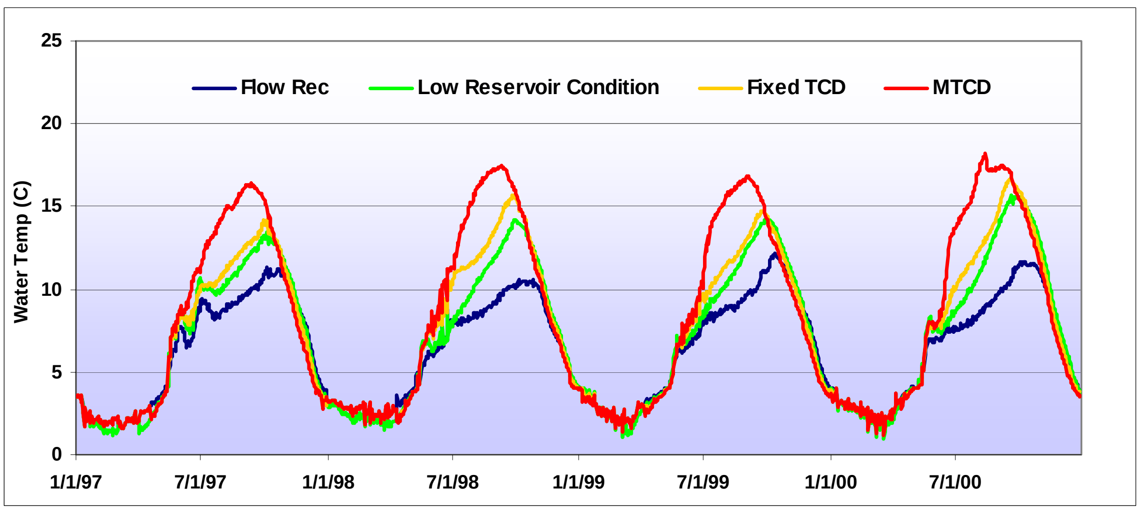


Figure 53: Water temperature released from Morrow Point Reservoir,CO, based on upstream Blue Mesa reservoir scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition).

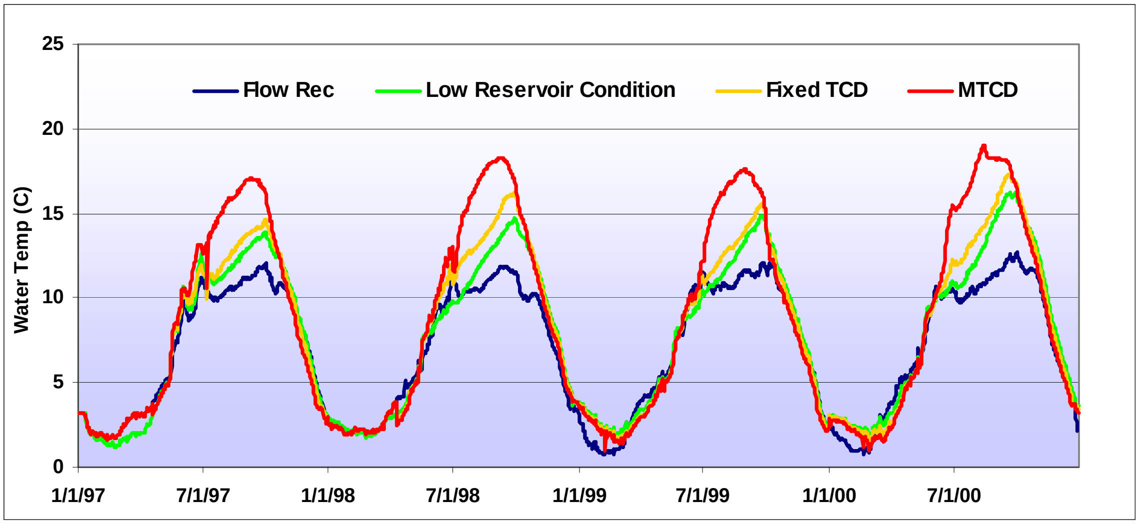


Figure 54: Water temperature released from Crystal Reservoir, CO based on upstream Blue Mesa reservoir scenarios (Flow Rec = flow recommendation, Fixed TCD = one fixed-level TCD, MTCD = multi-level TCD and low reservoir condition).

The released high water temperature from Crystal reservoir was 18°C in August. The release temperatures were used to model downstream Gunnison River temperatures from below Crystal to Delta, CO.

7.7 Blue Mesa Reservoir heat budget

The use of a TCD at Blue Mesa would affect the reservoir's heat budget. The changes were evaluated in comparison with the affected water volume in two model runs. This analysis also looked at long-lasting effects from a TCD to reservoir temperature. Four years of temperatures, elevations, and time series plots for Flow Recommendation, and multi-level TCD scenarios in Blue Mesa are presented below (Figure 55). A comparison of the volume of water with certain temperature ranges was also plotted (Figures 56 to 59).

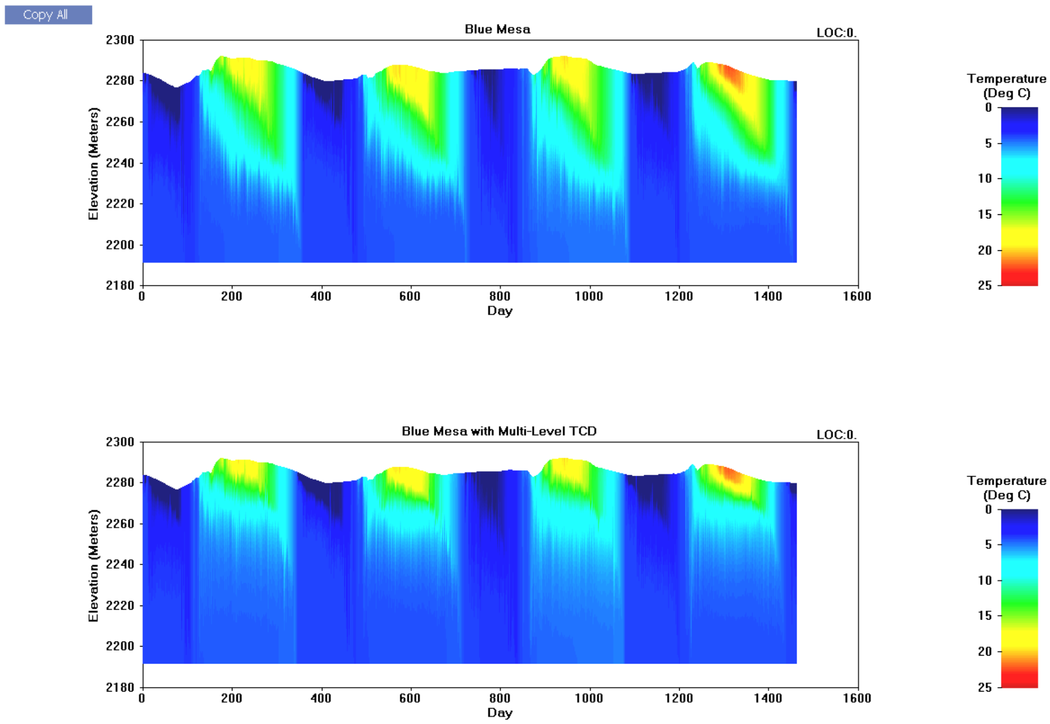


Figure 55: Water Temperatures, elevations and time series plots from the forebay of Blue Mesa Reservoir, CO (top plot = without TCD scenario and bottom plot = with multi-level TCD scenario).

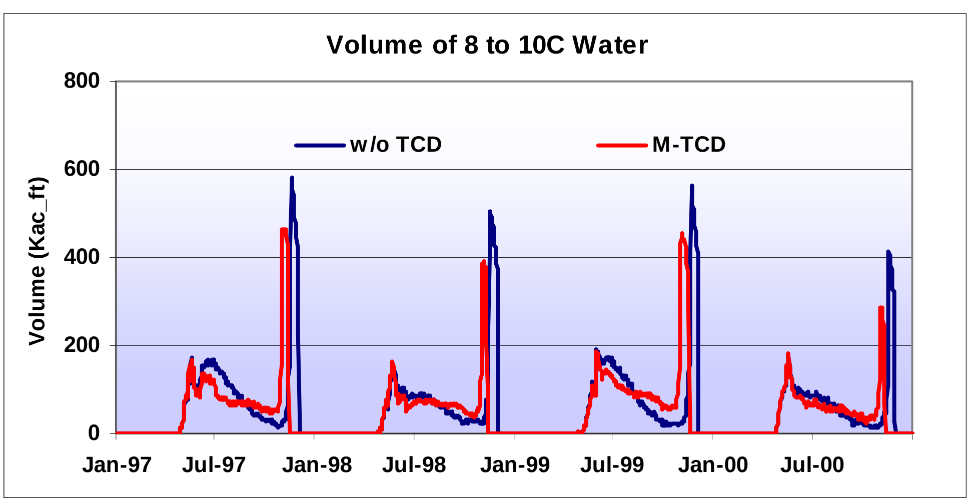


Figure 56: Volume comparison of water temperature ranges from 8 to 10 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD).

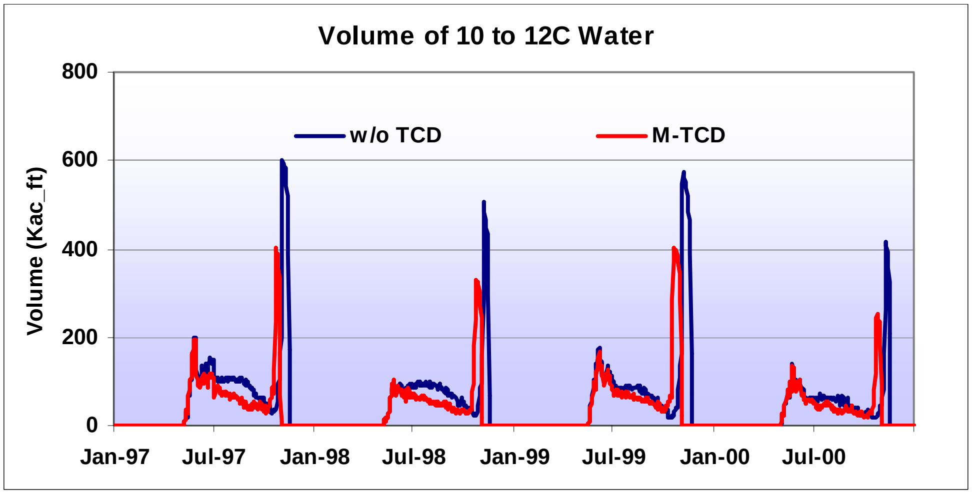


Figure 57: Volume comparison of water temperature ranges from 10 to 12 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD).

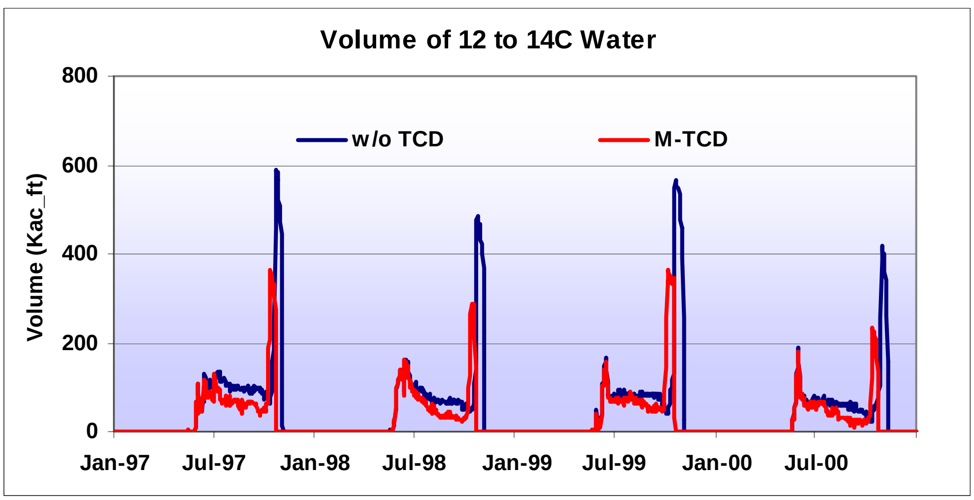


Figure 58: Volume comparison of water temperature ranges from 12 to 14 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD).

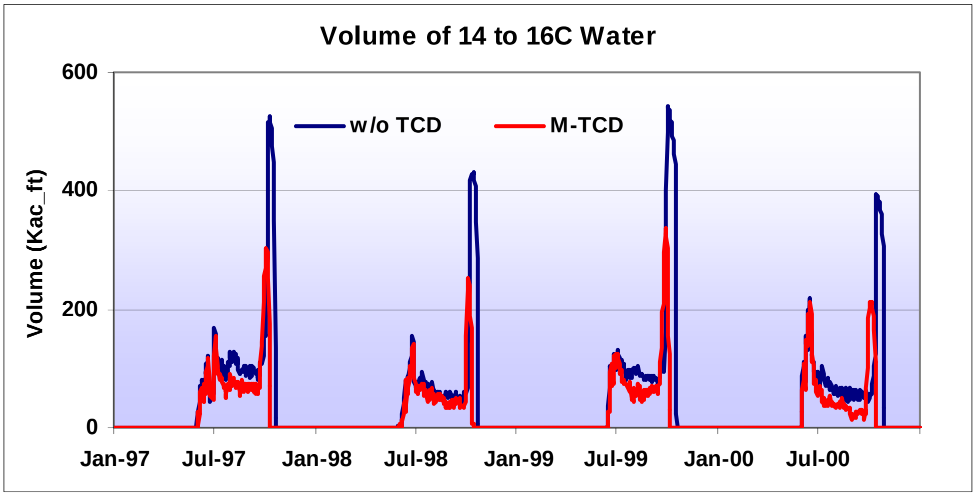


Figure 59: Volume comparison of water temperature ranges from 14 to 16 °C in Blue Mesa, CO with two scenarios (w/o TCD = without a TCD and M-TCD = with a multi-level TCD).

By using a multi-level TCD at Blue Mesa Reservoir, the volume of water ranging from 8 to 16 °C would be decreased by 28%.

The heat budget in the downstream reservoirs would increase. The most considerable increases were 60% within the range of 12 to 16°C water in Morrow Point and 63% in Crystal.

8. ADDRESSING RIVER SCENARIOS USING QUAL2K

8.1 Methodology

The next step was an analysis with QUAL2K to determine potential temperature regimes in the Gunnison River from below Crystal Dam to Delta. Unlike the reservoir W2 models, where time-series release water temperature data were generated, the steady-state 2K model was event-based. The scenarios analyzed wet, average and dry events as addressed for each month from May through October. With this event-based model a set of new assumptions had to be made to make the analysis manageable:

1) All tributary inflows and withdrawals were monthly averaged.

2) The water temperature of tributary inflows was monthly averaged.

3) All meteorological data were hourly averaged each month.

4) The wet, average, and dry hydrology was based on maximum, average and minimum monthly flows from Crystal.

5) A range of Crystal release water temperature was based on the use of multi-level TCD in Blue Mesa Reservoir (Table 6).

Table 4: Minimum and maximum Crystal release temperature with and without TCD at Blue Mesa Reservoir, CO

	With TCD		Without TCD	
	Min Temperature	Max Temperature	Min Temperature	Max Temperature
May	4	10	4	8
June	9	15	7	11
July	11	17	9	11
August	15	18	10	12
September	15	18	11	13
October	10	17	10	13

Historically the average pre-dam high temperature below Crystal Reservoir was about 16°C. By increasing in retention time with post-dam conditions, a TCD could exploit water temperature greater than 16°C. For the purpose of this study the maximum water temperature routed downstream was limited to 16°C.

8.2 2K Scenarios results

Based upon the above assumptions and release water temperatures available from Crystal Reservoir (Table 6), a set of monthly runs was analyzed. Figures 60 to 62 indicate different release temperatures at Crystal with three different flow scenarios for the month of July. Plots for May through October are found in the Appendix.

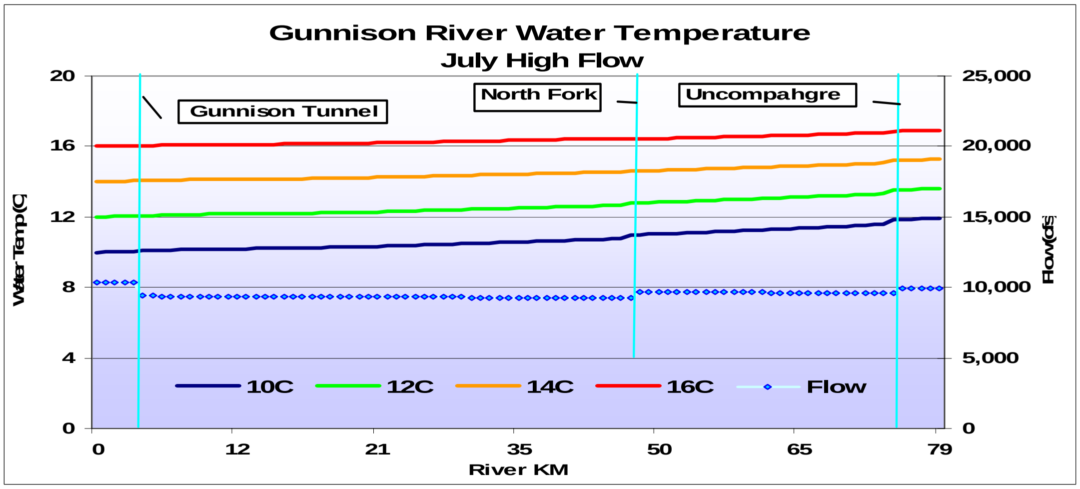


Figure 60: July high-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C.

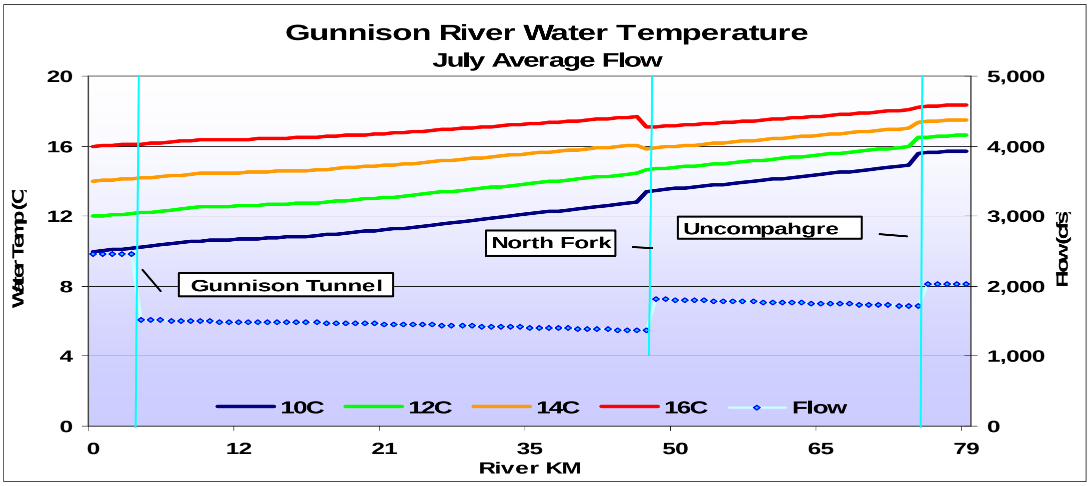


Figure 61: July average-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C.

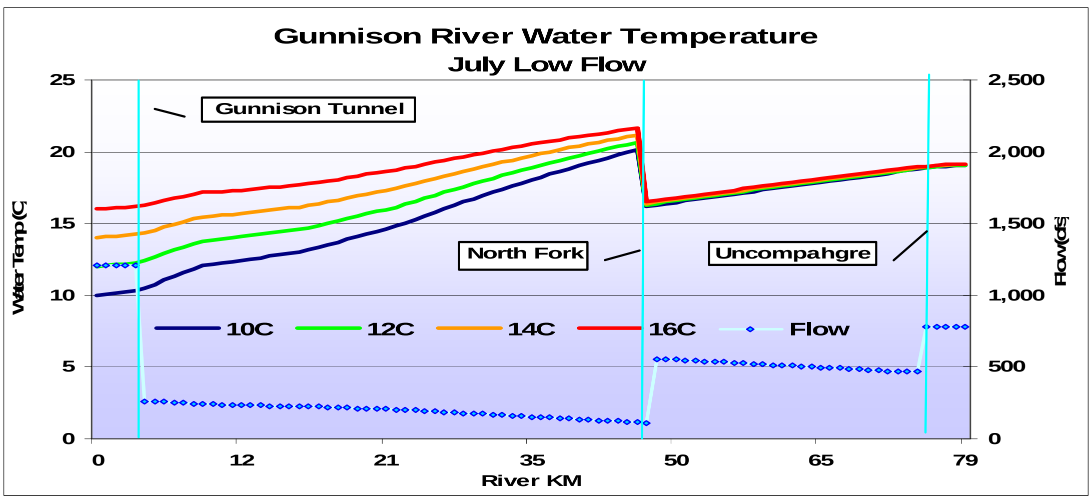


Figure 62: July low-flow scenario for Gunnison River below Crystal Dam to Delta, CO. Release water temperatures from Crystal Dam were 10, 12, 14 and 16 °C.

8.3 High-flow scenarios

Results indicate the high-flow scenario provided the most increase in downstream temperature with the use of a TCD. In the scenario, releases from Crystal dominated tributary inflows such that TCD release temperatures had the greatest impact at Delta. With May flows of 11,000 cfs, there was a 4 °C increase from Crystal to Delta. For example, if released water temperature was 6 °C below Crystal Dam, it would be 10 °C at Delta 80 km downstream from the dam. If flows were 8,500 and 10,000 cfs in June and July respectively, expected increase was 5 °C at Delta. In August and September, when flows drop to 5,000 cfs or below, there would be a 4 ^{o}C increase at Delta. In October, air temperatures started to drop to the extent that release water temperatures from a TCD were often higher than the mean ambient air temperatures, thereby reducing and even reversing the warming effect as water traveled downstream.

8.4 Average-flow scenarios

The average-flow condition scenario provided the best estimate of what a TCD could achieve. The main tributary between Crystal Dam and the City of Delta is the North Fork. In May and June the average flow from the North Fork was similar in magnitude to that of the Gunnison River, and the water temperature from the North Fork was cooler than the mean ambient air temperature. The smaller volume of water in the Gunnison River (compared to the high-flow scenario) caused the water to warm more quickly in response to the warmer air mass. The cooler temperature from the tributary of the North Fork drives the warming in the Gunnison River down. May and June releases from Crystal ranged from 2,300 to 2,600 cfs, respectively, the expected increase from current mean temperature at Delta is about 2.0^{o}C. During the months of July through October, the North Fork flows were generally much smaller compared to the Gunnison River. In July and August with flows of 2,500 to 1,900 cfs respectively, temperatures at Delta could increase by 2 and 3 °C above the current mean temperature. In September, there was a potential 1°C increase at Delta. October TCD release water temperatures were usually higher than mean air temperatures. As water traveled downstream of Crystal, there was a reverse in warming.

8.5 Low-flow scenarios

A TCD provided little to no increase in water temperature at Delta, CO. This scenario addressed flows below 2,000 cfs from Crystal Dam. With flows this low temperature increased from a TCD was diminished by tributaries' water temperatures.

8.6 Summary of the River Scenarios

TCD release water temperatures at Crystal Dam added the most benefit to downstream temperatures at Delta when releases were high. Even though the temperatures between Crystal Dam and Delta increased relatively little due to shorter travel time, results from these operations had large ranging effects downstream. At high volume flows and release temperatures with a 6 ^{o}C range at Crystal Dam, there was a resulting 5 ^{o}C range observed at Delta. Under average-flow scenarios, this effect was diminished such that the same 6 ^{o}C range at Crystal Dam would result in a 3 ^{o}C range at Delta. In low-flow situations, the observed temperatures at Delta were independent of release temperatures from the dam. Modifying release water temperatures from the dam had an important warming role in lower flows before the North Fork confluence. All these scenarios were based on average flows from tributaries. A sensitivity analysis was applied to large flows from the North Fork to determine how that would affect large flow scenarios for May, June and July. The high flows from the North Fork drove water temperatures down below the confluence, but a 4 ^{o}C range of temperatures remained at Delta. One of the objectives was to determine the release temperatures needed to meet the downstream at Delta targets identified in Osmundson's 1999 report. The models indicated target temperatures were achievable from June to October (Table 7).

Table 5: Approximate Crystal Dam release temperatures and Delta water temperature with and with out TCD at Blue Mesa.

	Flows	*Target Temperature at Delta*	*Current average Release Temperature at Crystal*	*Delta Water Temperature w/o TCD*	*Average TCD Release Temperature at Crystal*	*Delta Water Temperature with TCD*
May	12,000 – 2,400 cfs	1°C increase	7 °C	9.0 °C	8 °C	9.5 °C
May	Below 2,400 cfs	1°C increase	6 °C	10 °C	6 °C	10 °C
June	10,000 – 2,600 cfs	1°C increase	9 °C	12.5 °C	12 °C	14.5 °C
June	Below 2,600 cfs	1°C increase	9 °C	14.5 °C	11 °C	14.5 °C
July	10,300 – 2,500	2°C increase	10 °C	12 °C	13 °C	14.5 °C
July	Below 2,500 cfs	2°C increase	10 °C	16 °C	15 °C	18.5 °C
August	5,000 – 1,900 cfs	2°C increase	11 °C	13.5 °C	17 °C	18 °C
August	Below 1,900 cfs	2°C increase	11 °C	17.5 °C	17 °C	19.5 °C
September	4,000 – 1,600 cfs	1°C increase	12 °C	13.5 °C	17 °C	17.5 °C
September	Below 1,600 cfs	1°C increase	12 °C	15 °C	17 °C	17.5 °C
October	5,500 – 1,300 cfs	1°C increase	11 °C	10.5 °C	13 °C	12.5 °C
October	Below 1,300 cfs	1°C increase	11 °C	10.5 °C	13 °C	12.0 °C

9. CONCLUSIONS AND RECOMMENDATIONS

This analysis of effective control of release temperatures from the Blue Mesa through the use of TCDs indicated measurable temperature increases at Delta over current operations. The fixed-level TCD was less flexible. At reservoir elevations of 7,519.4 to 7,467.2 feet this option worked very well; however, reservoir elevations in 2003 were as low as 7,444.5 feet. Under this configuration, the fixed-level TCD was not operable. When the reservoir is full, the release water temperature may not fall within the optimal range. Under this scenario, a fixed TCD elevation of 7,447.2 feet was found to be inadequate for meeting future temperature control requirements. A fixed elevation TCD set at a lower elevation might work better for lower reservoir elevations, but would not be adequate for higher reservoir elevations. The multi-level TCD option provided more flexibility than the fixed level option, but this benefit involves higher capital costs.

The W2 model indicated a 28 percent reduction in the volume of the reservoir in the 8 to 16^{o}C zone of water temperatures through the use of multi-level TCD. The year to year effect on temperatures does not appear to be a significant factor, instead being dominated by inflowing hydrology and meteorological effects.

Based on the reservoir model development effort, more temperature monitoring locations should be added below Blue Mesa and Morrow Point dam to help clarify additional heat gains in this section of the river. Additional data needs for the river model include travel-time studies, the development of additional stage-discharge, flow, and temperature sites along the river, and additional temperature monitoring on the North Fork and the Uncompahgre River.

Model assumptions and uncertainties included average monthly tributary inflows and temperatures. In the TCD scenarios assumptions included TCD design, buffer elevation level, and an absence of leakage; these assumptions will affect the TCD release temperatures. Reservoir and river system modeling relies on boundary-inputs to characterize downstream conditions. Frequently if the boundary data were incomplete interpolated data were used; this is a source of uncertainties. The uncertainties in downstream water temperature model include the steady-state river model which was unable to characterize the hourly or daily operational changes.

The goal of this phase of the project was to answer several questions. The results are listed below:

- Do the models confirm the Phase I results indicating that a temperature control device at Blue Mesa Dam would result in warmer release temperatures from Crystal Dam?

This study found that the best location for a temperature control device would be at Blue Mesa Dam. This is because Blue Mesa is about 8 times larger than Morrow Point and 37 times larger than Crystal. The retention time of inflow water through Blue Mesa is about half a year whereas the retention time through Morrow point is about 2 weeks and a few days at Crystal. The release water temperatures from both Morrow Point and Crystal reservoirs are similar to the inflow temperatures because of the short retention time. Therefore, having a TCD on Morrow Point and Crystal with cold inflow would not increase downstream temperature to the system's potential.

- Would an increase in release temperatures from Crystal Dam result in a significant (1°C or more) increase in stream temperatures in the area around Delta, Colorado?

Large releases from Crystal Dam combined with increased release temperatures can result in as much as 5°C warming at Delta. Smaller releases can result in 1°C warming at Delta and as much as 3°C warming upstream of the North fork confluence. Large or comparable inputs from the North Fork, if they are cooler than the mean water temperature of the Gunnison River upstream from their confluence, can reduce or eliminate TCD warming at the dam.

- If so, how much warmer would the release waters need to be to meet the targets identified in Osmundson's 1999 report?

The relationship between release temperature and downstream temperature in general is not one-to-one. Downstream temperatures depend on the flow volume, tributary inflow and the meteorological conditions. Table 7 shows the approximate increase in release temperatures needed to meet the target at Delta, and what a TCD could deliver in that regard.
The accuracy of the model is +/- 0.7 °C for the projected incremental increase, release temperatures and the TCD release temperatures. The increase released temperatures listed above are achievable only starting from June to October with the TCD option. This analysis only looked at one portion of the Osmundson's 1999 report and did not address the annual thermal units (ATU) temperature. Further analysis can be addressed using the river model if a standard hydrograph and meteorological condition can be defined. Analyzing the ATU would narrow down the temperature and timing of releases from Crystal Dam.

- How do wet/normal/dry year inflows to the Aspinall Unit affect reservoir releases and how would these variations affect the use of a TCD?

In general, there is not much variation in reservoir stratification and release temperatures for the years 1997 through 2001. Crystal reservoir release temperatures were higher during August and early September for the year with the highest inflows (1997). This is predominantly due to Blue Mesa spills during June and July of that year, bringing warmer surface water to the lower two reservoirs. Generally, TCD operations during wet years produce warmer temperatures earlier in the year than during dry years.

- Can temperature targets be met in a wet/normal/dry year?

Based on the hydrology of 1997 to 2000 which represented moderately wet, dry and average conditions, to meet temperature targets recommended by Osmundson (1999) every year, a multi-level TCD would have to be in place.

- What is the impact of a TCD on reservoir heat budget?

Using a TCD at Blue Mesa Reservoir resulted in an average yearly reduction of 28% in the volume of water in the reservoir with temperatures ranging from 8 to 16 ^{o}C.

- What are the most feasible TCD options to achieve temperature targets?

The most effective TCD option is contingent on how often the target temperature must be met. A fixed-level TCD is effective only under a narrow range of reservoir conditions. To ensure the target is met every year, a multi-level TCD is the most effective option.

- What are the responses to flow recommendations?

Flow Recommendation scenario had no impacts to in-reservoir water temperature nor release water temperature compared to the present condition.

The tools and analysis addressed in this report are a great starting point for future analyses as deemed necessary by the Biology Committee. For instance, a more detailed look at what the ATU could achieve with different flow scenarios and release temperatures would be valuable. Below is a summarized list of the recommendations:

- More temperature monitoring locations should be added below Blue Mesa and Morrow Point dam to help clarify additional heat gains in this section of the river.

- River travel-time study of calibration.

- Additional stage-discharge, flow, and temperature sites along the river, and additional temperature monitoring on the North Fork and the Uncompahgre River.

- Identify standard hydrograph and meteorological conditions needed to analyze the ATU would narrow down the temperature and timing of releases from Crystal Dam.

10. REFERENCES

Brown, L.C. and T.O. Barnwell. 1987. The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS. EPA/600/3-87-007. US Environmental Protection Agency. Athens, GA. 189 pp.

Butler, D.L. 2000. Evaluation of water-quality data, lower Gunnison River Basin and Colorado River downstream from the Aspinall Unit, Colorado. U.S. Geological Survey Administrative Report.

Burdick, B.D. 1995. Ichthyofaunal studies of the Gunnison River, Colorado, 1992–1994. Final Report. Colorado River Fishery Project (USFWS). Grand Junction, Colorado.

Chapra, S.C. and G. Pelletier. 2003. QUAL2K: A Modeling framework for simulating river and stream water quality (beta version): documentation and users manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.

Cole, T. and S. Wells. 2002. "CE-QUAL-W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 3.1." User Manual. Instruction Report EL-02-1. Prepared for the US Army Corps of Engineers, Washington DC. Draft Report. August 2002.

Green, W.R., J.M. Galloway, J.M. Richards, and E.A. Wesolowski. 2003. Simulation of hydrodynamics, temperature, and dissolved oxygen in Table Rock Lake, Missouri, 1996–1997. USGS Water-Resources Investigations Report 03-4237.

Hydrosphere Resource Consultants. 2002. Gunnison River / Aspinall Unit temperature study -- Phase I. Final Report. Prepared for the Upper Colorado River Endangered Fish Recovery Program. Project #107. March 2002.

Malick, M., 2002. National Park Service. Personal Communication.

McAda, C.W. 2003. Flow recommendations to benefit endangered fishes in the Colorado and Gunnison Rivers. Recovery Program Project No. 54. US Fish and Wildlife Service, July 2203, Revised October 2003.

Osmundson, D.B. 1999. Longitudinal variation in fish community structure and water temperature in the upper Colorado River. Final Report, Recovery Action Plan, Project # 48-A. U.S. Fish and Wildlife Service.

Pelletier, G. 2003. Models for TMDLs. Washington State Department of Ecology. Available: http://www.ecy.wa.gov/programs/eap/models/. Accessed May 2003.

Quarterone, F. 1993. Historical accounts of Upper Colorado River Basin endangered fish. Final Report. Colorado Division of Wildlife, Denver.

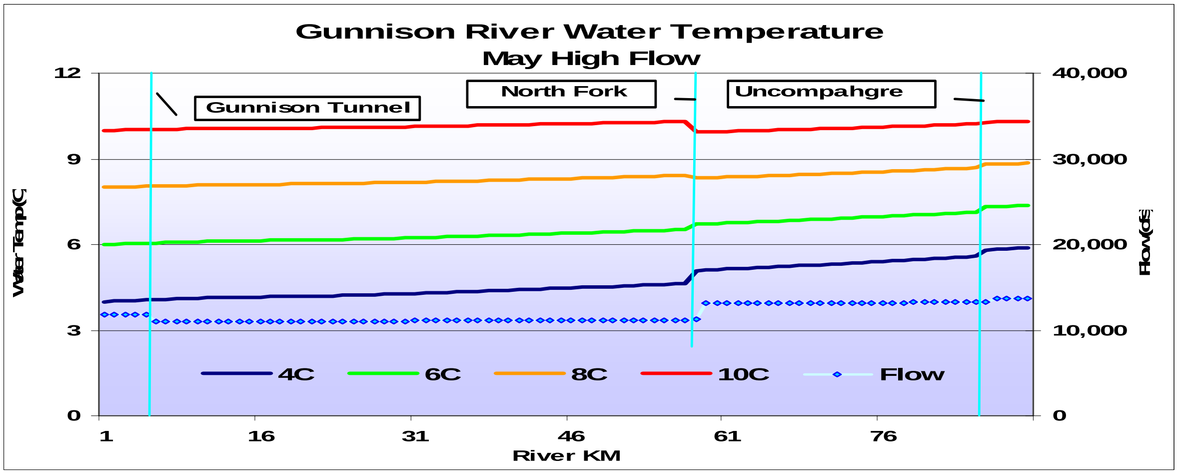
Sinokrot, B.A., and H.G. Stefan. 1993. Stream temperature dynamics: measurement and modeling. Water Resources Research, 29(7), 2299–2312.

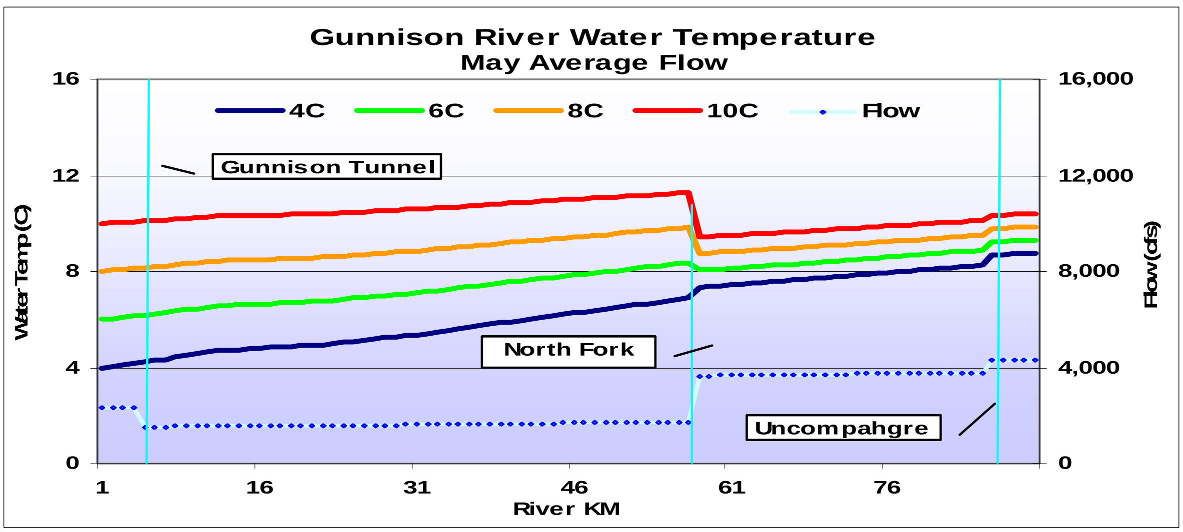
Stanford, J.A. 1994. Instream flows to assist the recovery of endangered fishes of the Upper Colorado River Basin. Biological Report 24. National Biological Survey, U.S. Department of the Interior.

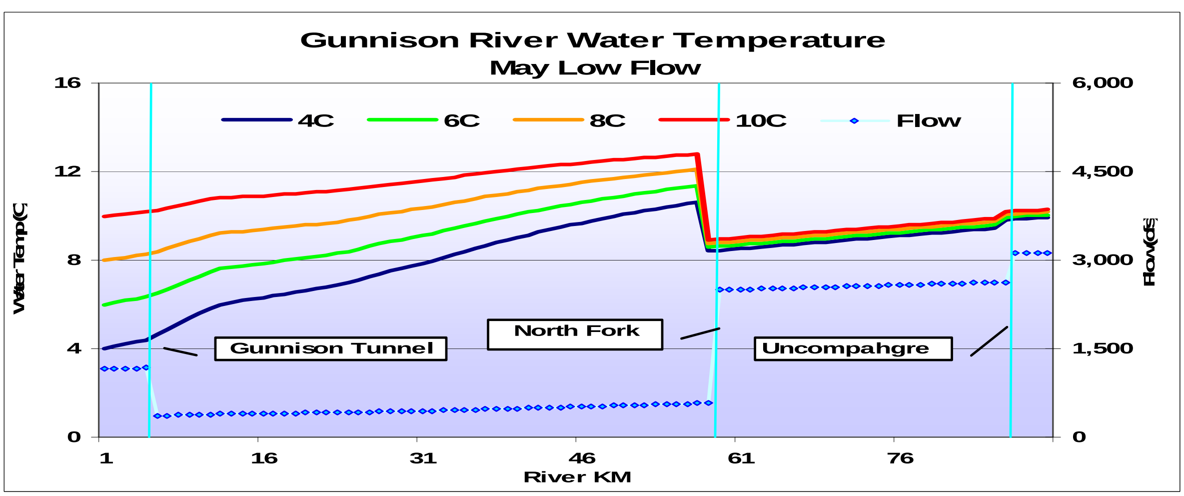
Thatcher, A. 2002. personal communication.

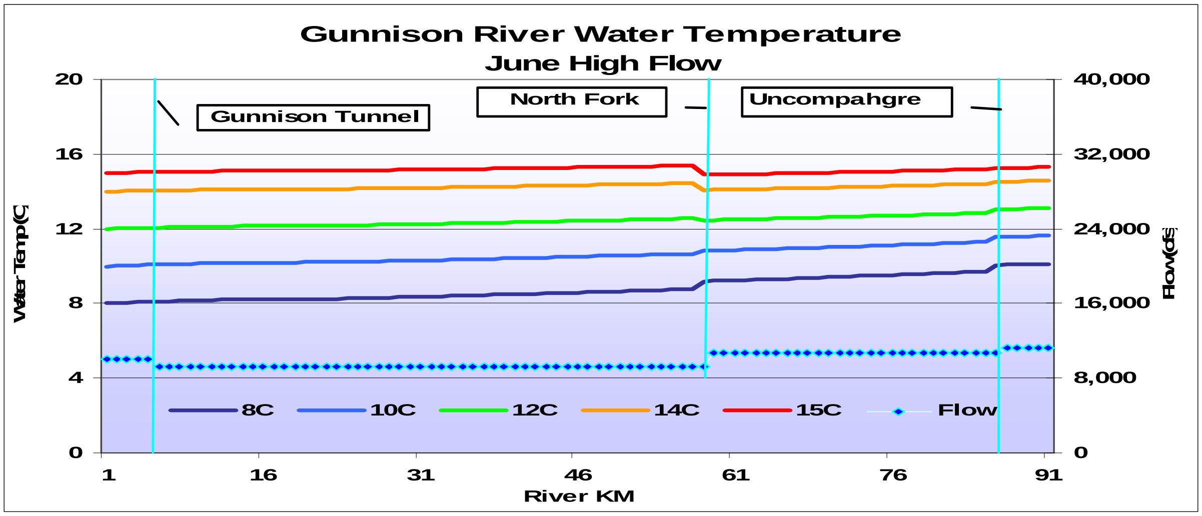
Valdez, R.A., P.G. Mangan, R.P. Smith, and B.C. Nelson. 1982. Upper Colorado River investigation (Rifle, Colorado to Lake Powell, Utah). Colorado River Fishery Project, Part 2; pp 100-279. Salt Lake City, Utah.

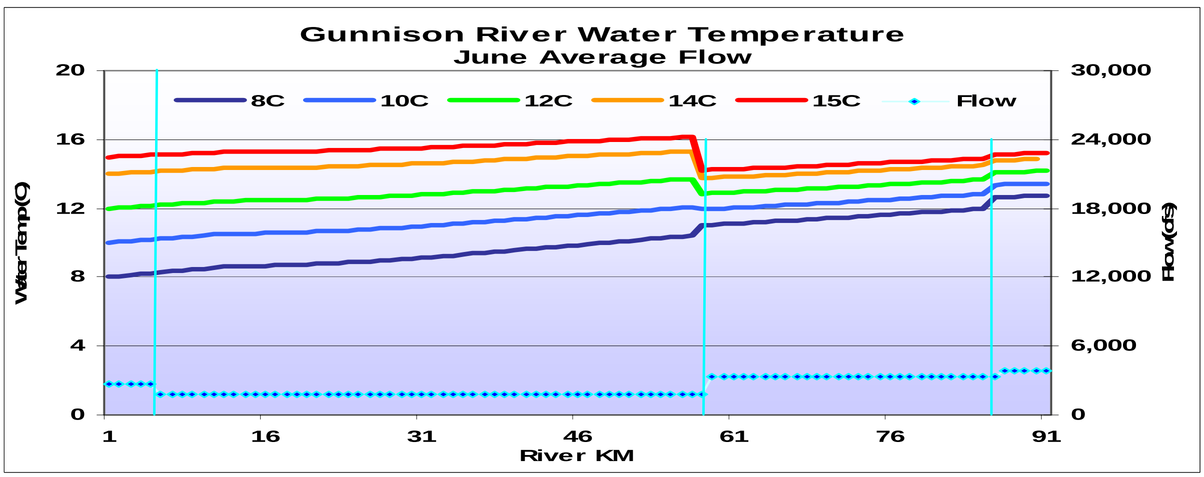
11. APPENDIX

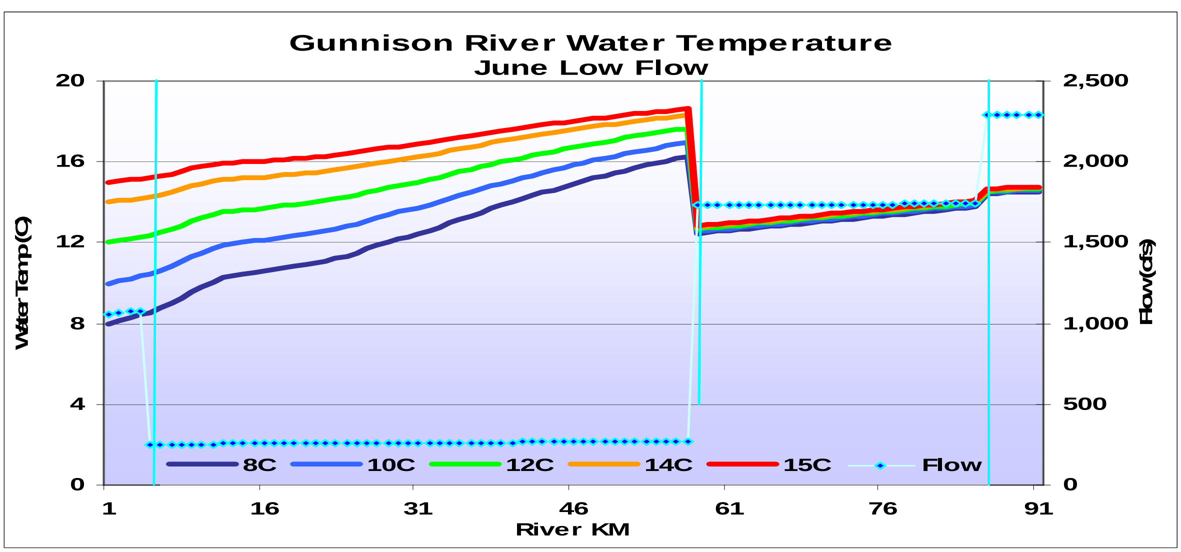

Gunnison River Water Temperature
May High Flow
Gunnison Tunnel
North Fork
Uncompahgre
4C
6C
8C
10C
Flow
Water Temp(C)
Flow(cfs)
River KM
12
9
6
3
0
40,000
30,000
20,000
10,000
0
1
16
31
46
61
76

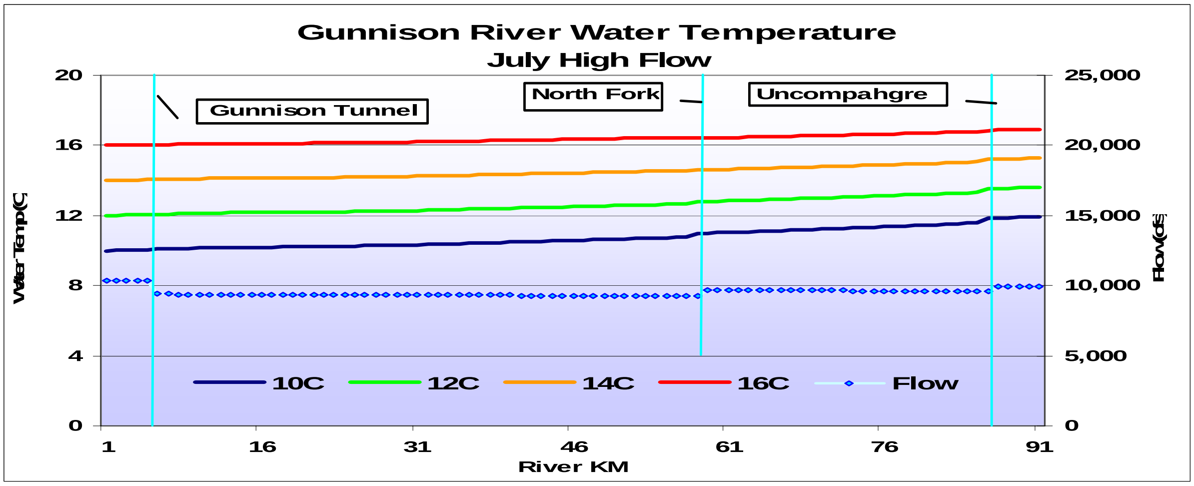

Gunnison River Water Temperature
May Average Flow
4C
6C
8C
10C
Flow
Gunnison Tunnel
North Fork
Uncompahgre
Water Temp (C)
Flow (cfs)
River KM
16
12
8
4
0
16,000
12,000
8,000
4,000
0
1
16
31
46
61
76

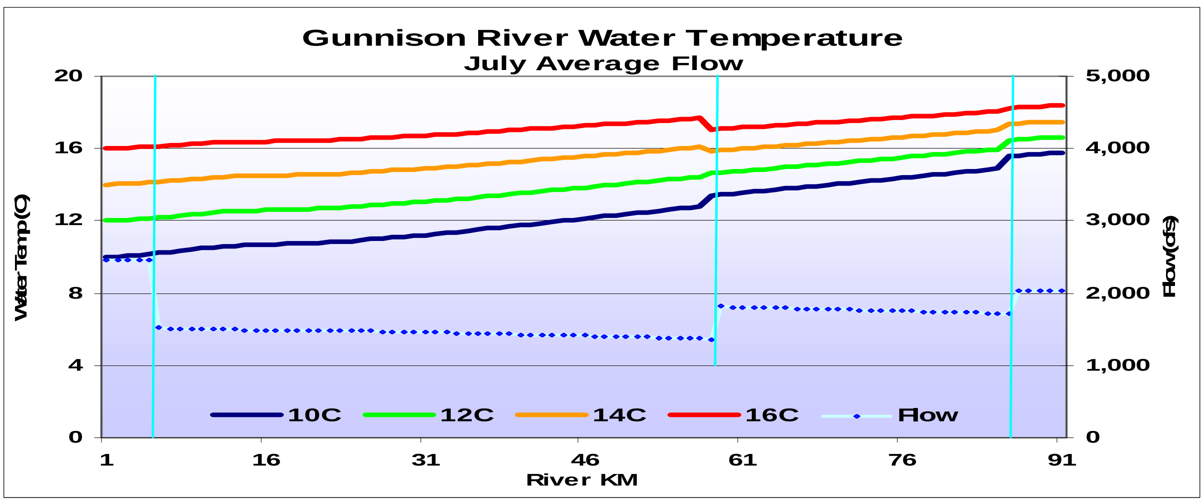

Gunnison River Water Temperature
May Low Flow
4C
6C
8C
10C
Flow
Gunnison Tunnel
North Fork
Uncompahgre
Water Temp(C)
Flow(cfs)
River KM
16
12
8
4
0
6,000
4,500
3,000
1,500
0
1
16
31
46
61
76

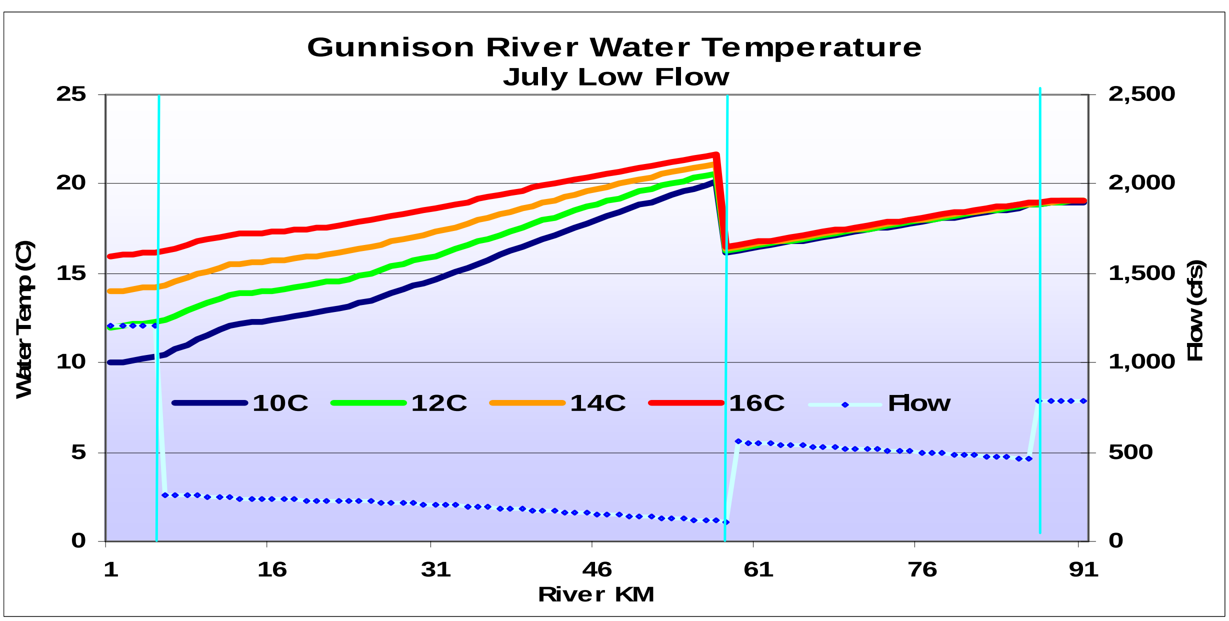

Gunnison River Water Temperature
June High Flow
Gunnison Tunnel
North Fork
Uncompahgre
Water Temp(C)
Flow(cfs)
8C
10C
12C
14C
15C
Flow
River KM
20
16
12
8
4
0
40,000
32,000
24,000
16,000
8,000
0
1
16
31
46
61
76
91

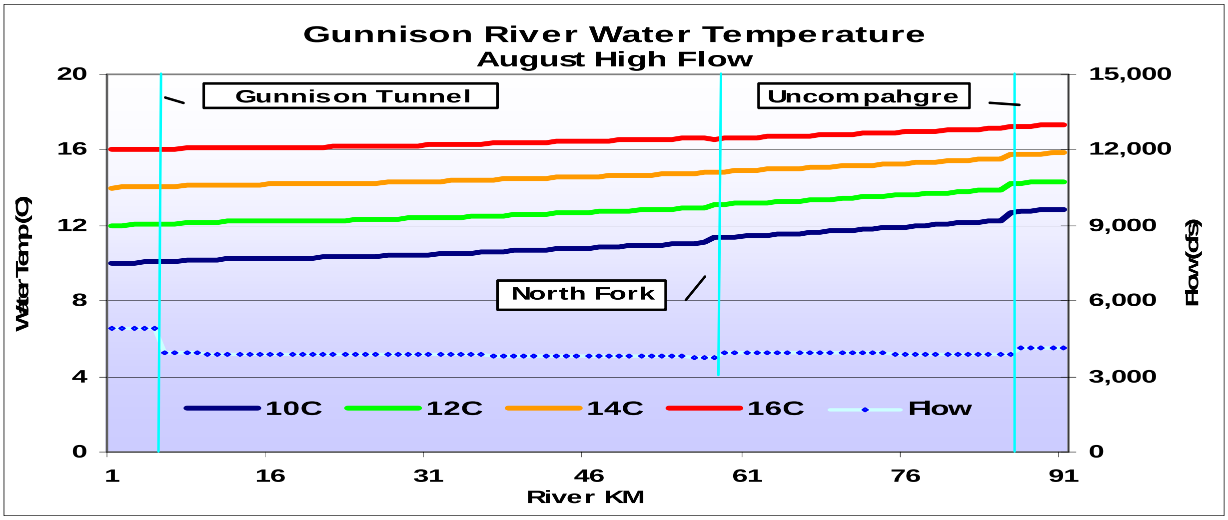

Gunnison River Water Temperature
June Average Flow
Water Temp(C)
Flow(cfs)
8C
10C
12C
14C
15C
Flow
River KM
20
16
12
8
4
0
30,000
24,000
18,000
12,000
6,000
0
1
16
31
46
61
76
91

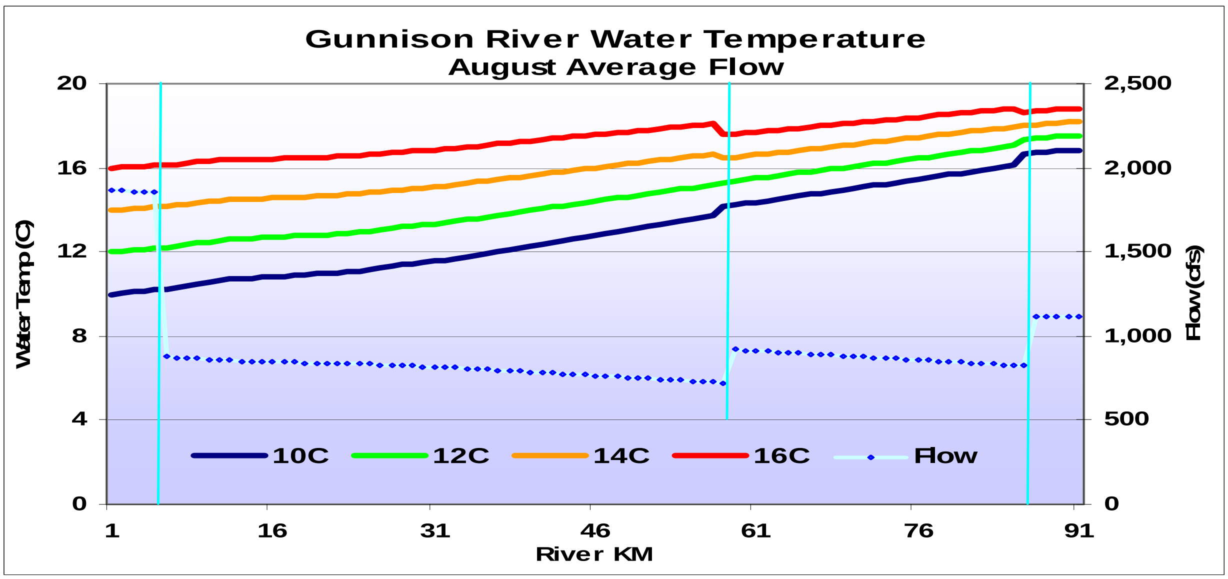

Gunnison River Water Temperature
June Low Flow
Water Temp(C)
Flow(cfs)
8C
10C
12C
14C
15C
Flow
River KM
20
16
12
8
4
0
2,500
2,000
1,500
1,000
500
0
1
16
31
46
61
76
91

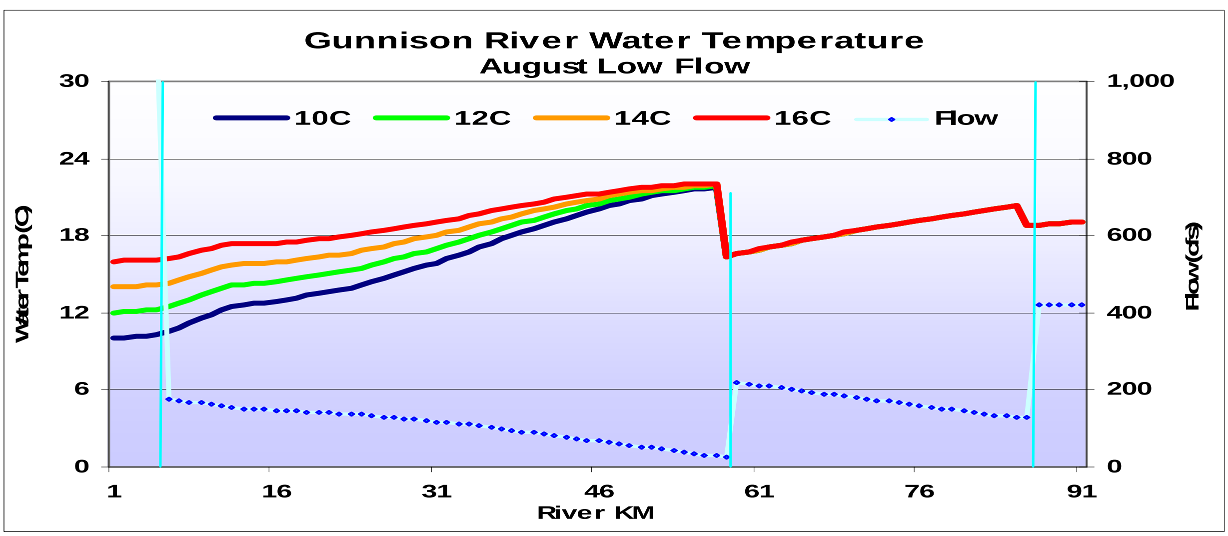

Gunnison River Water Temperature
July High Flow
Gunnison Tunnel
North Fork
Uncompahgre
Water Temp(C)
Flow(cfs)
10C
12C
14C
16C
Flow
River KM
20
16
12
8
4
0
25,000
20,000
15,000
10,000
5,000
0
1
16
31
46
61
76
91

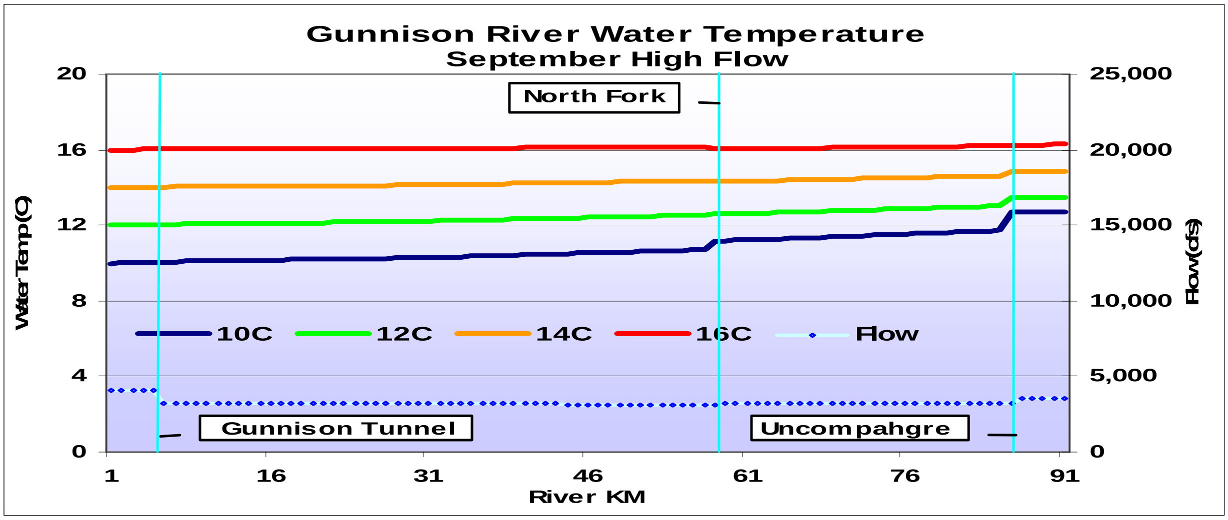

Gunnison River Water Temperature
July Average Flow
Water Temp(C)
Flow(cfs)
10C
12C
14C
16C
Flow
River KM
20
16
12
8
4
0
5,000
4,000
3,000
2,000
1,000
0
1
16
31
46
61
76
91

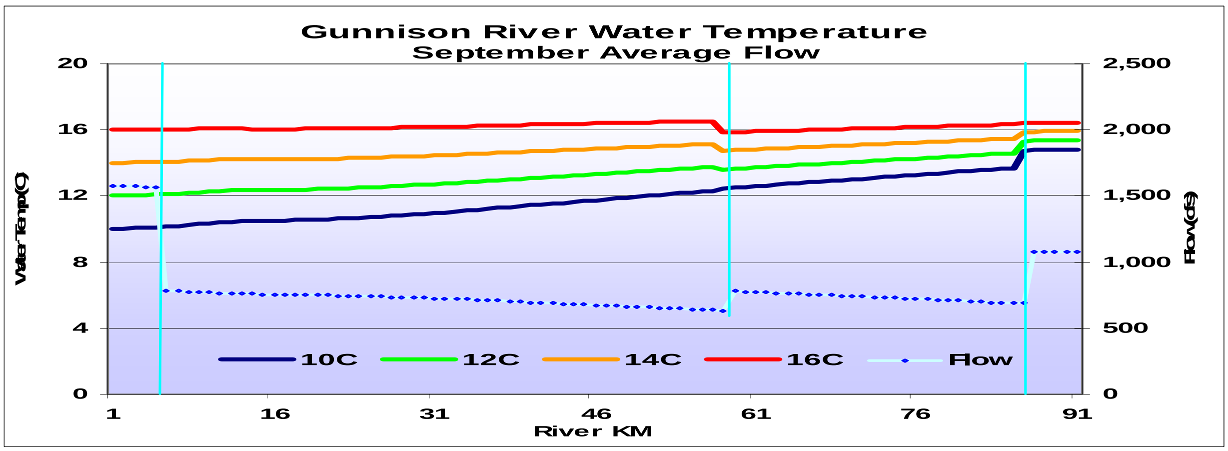

Gunnison River Water Temperature
July Low Flow
Water Temp (C)
Flow (cfs)
10C
12C
14C
16C
Flow
River KM
25
20
15
10
5
0
2,500
2,000
1,500
1,000
500
0
1
16
31
46
61
76
91

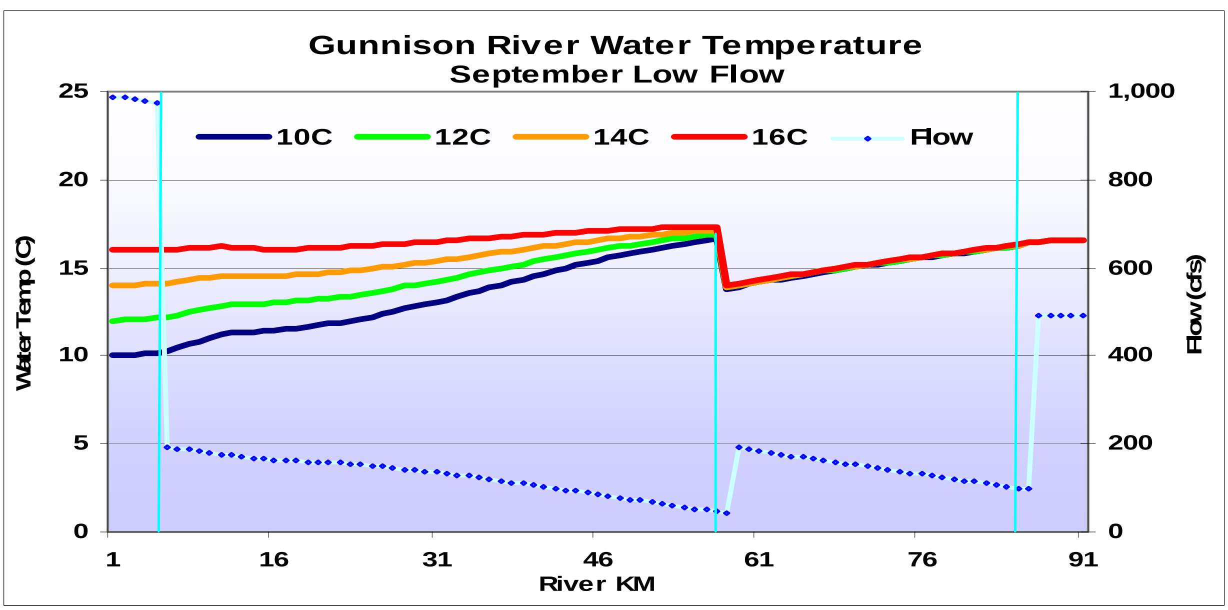

Gunnison River Water Temperature
August High Flow
Gunnison Tunnel
Uncompahgre
North Fork
10C
12C
14C
16C
Flow
Water Temp(C)
Flow(cfs)
River KM
0
4
8
12
16
20
0
3,000
6,000
9,000
12,000
15,000
1
16
31
46
61
76
91

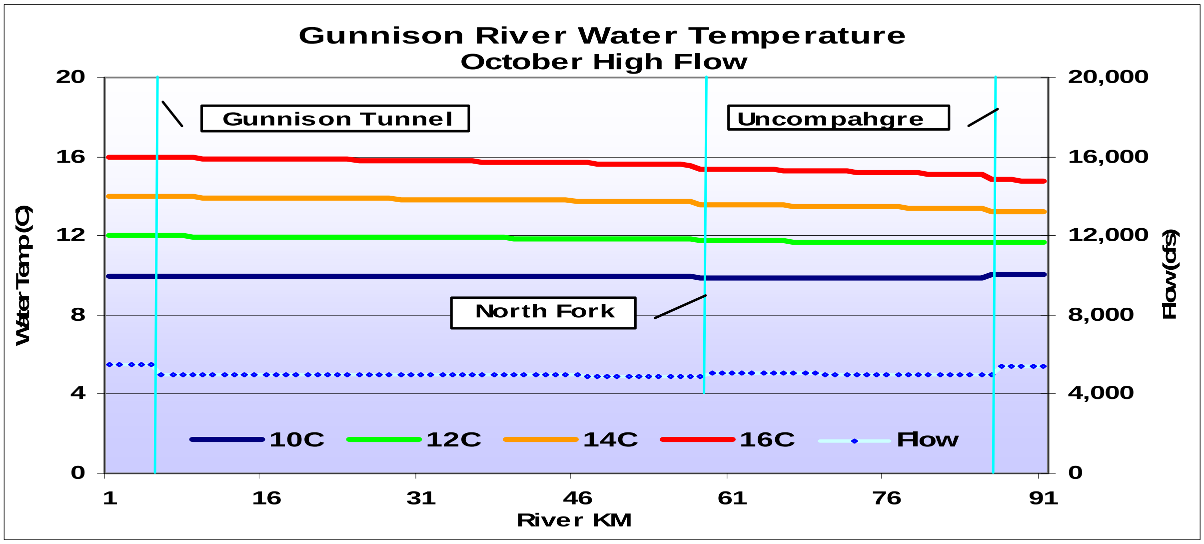

Gunnison River Water Temperature
August Average Flow
10C
12C
14C
16C
Flow
Water Temp(C)
Flow(cfs)
River KM
0
4
8
12
16
20
0
500
1,000
1,500
2,000
2,500
1
16
31
46
61
76
91

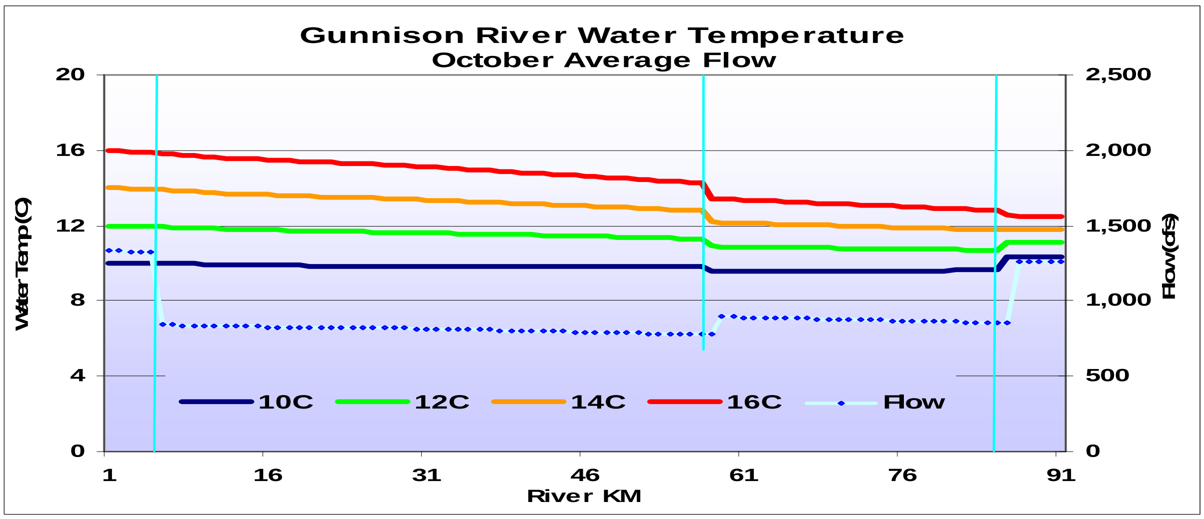

Gunnison River Water Temperature
August Low Flow
10C
12C
14C
16C
Flow
Water Temp(C)
Flow(cfs)
River KM
0
6
12
18
24
30
0
200
400
600
800
1,000
1
16
31
46
61
76
91

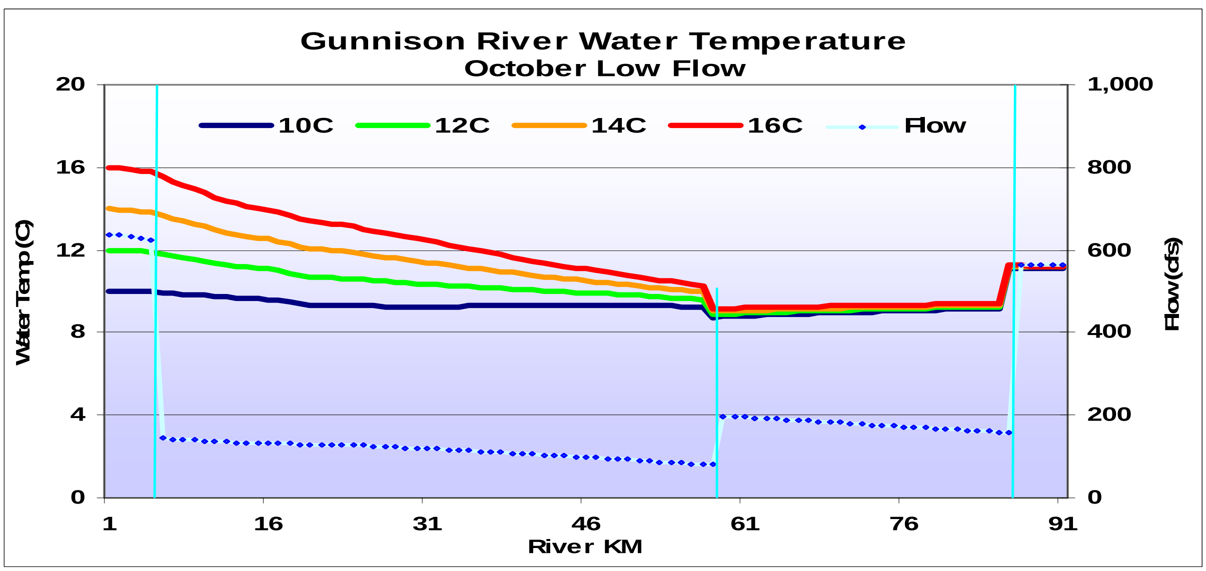

Gunnison River Water Temperature
September High Flow
North Fork
Gunnison Tunnel
Uncompahgre
10C
12C
14C
16C
Flow
Water Temp(C)
Flow(cfs)
River KM
0
4
8
12
16
20
0
5,000
10,000
15,000
20,000
25,000
1
16
31
46
61
76
91


Gunnison River Water Temperature
September Average Flow
10C
12C
14C
16C
Flow
Water Temp(C)
Flow(cfs)
River KM
0
4
8
12
16
20
0
500
1,000
1,500
2,000
2,500
1
16
31
46
61
76
91


Gunnison River Water Temperature
September Low Flow
10C
12C
14C
16C
Flow
Water Temp (C)
Flow(cfs)
River KM
0
5
10
15
20
25
0
200
400
600
800
1,000
1
16
31
46
61
76
91


Gunnison River Water Temperature
October High Flow
Gunnison Tunnel
Uncompahgre
North Fork
Water Temp (C)
Flow (cfs)
River KM
10C
12C
14C
16C
Flow
20
16
12
8
4
0
20,000
16,000
12,000
8,000
4,000
0
1
16
31
46
61
76
91


Gunnison River Water Temperature
October Average Flow
Water Temp (C)
Flow (cfs)
River KM
10C
12C
14C
16C
Flow
20
16
12
8
4
0
2,500
2,000
1,500
1,000
500
0
1
16
31
46
61
76
91


Gunnison River Water Temperature
October Low Flow
Water Temp (C)
Flow (cfs)
River KM
10C
12C
14C
16C
Flow
20
16
12
8
4
0
1,000
800
600
400
200
0
1
16
31
46
61
76
91

North Fork High Flow Sensitivity Analysis