NAVAJO RESERVOIR AND SAN JUAN RIVER TEMPERATURE STUDY

NAVAJO RESERVOIR

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NAVAJO RESERVOIR AND SAN JUAN RIVER TEMPERATURE STUDY

PREPARED FOR:

SAN JUAN RIVER ENDANGERED FISH RECOVERY PROGRAM

BY:

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LIST OF KEY WORDS

San Juan River, Navajo Reservoir, San Juan River system, water temperature, reservoir temperature, temperature control device

EXECUTIVE SUMMARY

Navajo Reservoir on the San Juan River serves as a water storage, flood control and power generation project for the San Juan River Basin. Because of deep hypolimnetic release from the dam, water temperatures are cooler than natural pre-dam conditions. Post-dam release water temperatures during the summer months are 4-8 °C (39-46 °F) as compared to pre-dam temperatures of 20-25 °C (68-77 °F). Colder water temperatures from the dam to Shiprock (~80 mile; 129 km downstream of the dam) may negatively impact survival of native fish species living below the dam but benefit the tail-water trout fishery (Vanicek, 1967; Holden, 1973; USBR, 2003). Colorado pikeminnow and razorback sucker are endangered fish species native to the San Juan River. Previous research suggests that their optimum temperature range is 20 °C to 28 °C (68-82 °F). The objectives of this study were to model water temperature in the San Juan River system and determine whether structural modifications of the Navajo Dam outlet can increase water temperatures in the San Juan River below the dam to Shiprock, NM.

The project was approached in a two-step process. The first step was the selection and application of water quality models for the San Juan River system. The second step was to quantify the potential warming of water temperature with the use of a temperature control device (TCD) downstream from Navajo Dam to Shiprock, NM.

I used the CE-QUAL-W2 numerical 2-D water quality model to characterize Navajo Reservoir, which in turn provided release temperatures for use in the downstream model. To characterize the San Juan River below Navajo Dam I used the 1-D steady-state model QUAL-2K and the numerical 1-D water quality model GEMSS. A selected period of hydrology was used to analyze release temperatures with and without a TCD at Navajo Dam. This period of 1995 to 2000 encompassed years with hydrologic regimes of wet, average, and dry conditions. Release temperatures for this period varied from 4 °C to 10 °C (39-50 °F) and increased or decreased depending on the time of year, release volume, and distance from the dam as the water traveled downstream. By the time the water reached Farmington, NM (~43 miles; ~70 km downstream from the dam) the temperatures on average varied from 0 °C to 23 °C (32-73 °F) and 0 °C to 25 °C (32-77 °F) at Shiprock, NM (~76 miles; ~123 km).

The reservoir and river models were validated with field data and the accuracy were all +/- 1 °C (2 °F). A sensitivity analysis of the models input data was not performed for this study, therefore the magnitude of errors caused by uncertainties from the inputs were not analyzed. The reservoir and river models were then coupled together to address varying hydrology and TCD scenarios. The combined models described the range of possible release temperatures from Navajo Reservoir with the use of TCD and the effect these would have on the long-term heat budget of the reservoir.

The two TCD configurations analyzed in this report were a fixed-level and a multiple-level TCD. The fixed-level TCD had one elevation for withdrawal beside the remaining outlets. The multiple-level TCD was modeled to select water from any elevation in the water column above the penstock.

Model results indicated that a single fixed-level TCD could increase release temperature to 21 °C (70 °F) and a multiple-level TCD configuration could release water as warm as 23 °C (73 °F). These increases were as much as 16 °C (29 °F) higher than current conditions; however, this temperature increase diminished as the water traveled downstream. With a fixed-level TCD, the water temperature at Farmington from May to October could increase as much as 8 °C (14 °F), but the average increase would only be 1.4 °C (2.5 °F). For the same location and time period a multi-level TCD could increase water temperature as much as 8.4 °C (15 °F), but on average it was 2 °C (4 °F). At Shiprock the water temperature from May to October could increase as much as 7 °C (13 °F) from a fixed-level TCD, but the average increase would only be 1 °C (2 °F). At the same location and time period a multi-level TCD could increase water temperature as much as 7.6°C (14 °F), but only 1.4 °C (2.5 °F) on average.

The heat budget at Navajo Reservoir was affected considerably by both configurations of a TCD. By releasing water from higher in the water column of a reservoir the heat budget within that body of water is reduced. My model showed an average temperature decrease of 1.1° C (2° F) for the water between the surface and 100 ft (~30 m), resulting in a decrease in epilimnion thickness. Surface water temperatures during the winter would be colder by an average of 1° C (2° F).

1. INTRODUCTION

The Navajo Dam on the San Juan River is an earth and rock-fill structure completed in 1963 to store water as part of the Colorado River Storage Project (Figure 1). With a total storage capacity of 1,709,000 acre-feet (2108 Mm^3) Navajo Reservoir was one of the key components in the development of the Colorado River Storage Project for water storage, flood control and power generation. Navajo Dam presently releases deep hypolimnetic water. Post dam release temperatures during the months of summer are generally cooler than the pre-dam temperatures (4-8 °C vs. 20- 25°C [39-46 °F vs. 68-77 °F]). Colder water temperatures may negatively impact survival of native fish species living below the dam but benefit the tail-water trout fishery (Vanicek, 1967; Holden, 1973; USBR, 2003). Colorado pikeminnow and razorback sucker are endangered fish species native to the San Juan River and their optimum temperature range is thought to be 20 °C to 25 °C (68-77 °F; as reviewed by Lamarra 2006). Researchers postulate that changes in hydrology and water temperature that more closely mimic pre-dam conditions might provide certain benefits to native fish (Vanicek, 1967; Holden, 1973; USBR, 2003). Increasing the temperature of water released into the San Juan River below Navajo Dam has been hypothesized to improve growth and reproduction for the razorback sucker and Colorado pikeminnow (Vanicek, 1967; Vanicek et al., 1970; Holden, 1973; Seethaler, et al., 1976).

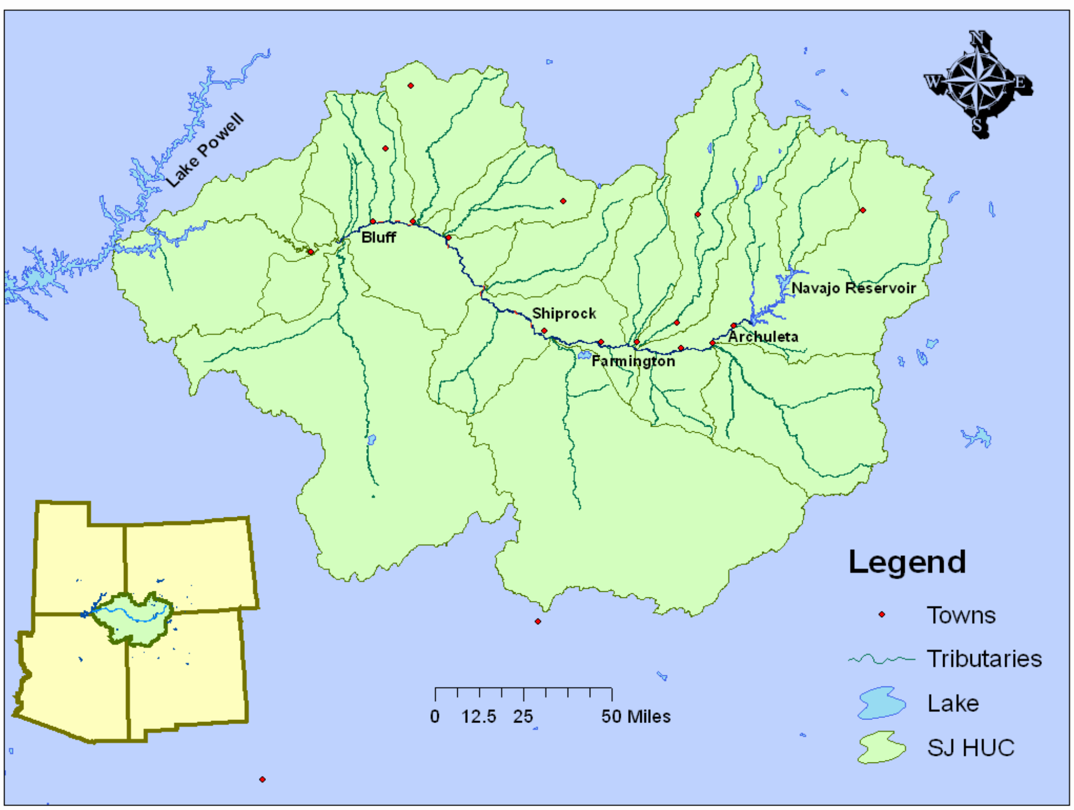


Figure 1. San Juan River Basin, NM.

Water released from a reservoir approaches ambient water temperature as it travels downstream. The rate at which the water warms depends on release temperature, flow volume, and atmospheric conditions. In general, increasing reservoir release temperatures will result in warmer downstream temperatures. However, 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). One method for increasing water temperatures is reducing reservoir releases, which typically increases downstream temperatures during June to September depending upon ambient atmospheric conditions. Warmer water temperatures result from a smaller volume with a slower travel rate, thus increasing exposure to atmospheric heating. Another method to increase water temperature is through modification of the dam by delivering water from shallower, warmer thermal layers within a reservoir. A selective withdrawal structure, or temperature control device (TCD), can release impounded water from select elevations, permitting release of water from warmer layers of the reservoir.

This study used physical models to characterize the potential of release temperatures from Navajo Reservoir with structural modification scenarios. However, this study did not address whether a TCD is feasible with respect to other factors including: water rights administration, hydropower generation, recreational fisheries (river and reservoir), reservoir recreation, flood control, political feasibility, Fish and Wildlife Service flow recommendations, environmental compliance, and interstate and international compacts. Determining the effect of warmer releases and the appropriate timing of specific releases for the endangered fish was also beyond the scope of this study, and specific temperature targets for the San Juan River will be developed in a subsequent study.

2. OBJECTIVES

The objectives of this study were to determine whether structural modifications to Navajo Dam can increase release and downstream water temperatures. To accomplish these objectives existing data were used for the inputs to physical models in the San Juan River. These models were used to also address the following questions and objectives:

- To determine potential temperature regimes in the San Juan River down to approximately River Mile 150 that would result from the two TCD options.

- Compare and contrast release water temperature for a historic period with and without TCD modifications.

- Determine the times of year in which water temperature ranges can be met.

- Determine the effect of TCD on the heat budget of the reservoir.

Specific questions related to these objectives were addressed.

- Would increasing release temperatures from Navajo Dam result in increasing in water temperatures at Farmington and Shiprock, NM?

- How do wet, normal, and dry year inflows affect release temperatures and how could these variations affect the use of a TCD?

- What is the best TCD option to achieve downstream warming?

This report is structured as follows. A modeling overview is provided in Section 3. The development of the reservoir and river models is described in Section 4, followed by a description of the river model in Section 5 and 6. Sections 7 through 11 contain a discussion of the results, conclusions and recommendations.

3. MODELING OVERVIEW

A two-component approach was used to determine potential temperature regimes downstream of Navajo Dam. First, a reservoir model was constructed to determine release temperatures based on release patterns and location of a TCD. The second component was using river model to determine the resulting range of temperatures in the river from Navajo Dam to Shiprock, NM.

The model used to characterize Navajo Reservoir was the U.S. Army Corps of Engineer's CE-QUAL-W2 (W2; Cole 1995). The W2 model was selected because of its successful applications at > 400 reservoir systems worldwide and its ability to effectively characterize reservoir dynamics with high accuracy. Navajo Reservoir is a good candidate for the W2 model application because of its narrow geometry (Cole 1995). The W2 model provided a platform to analyze release temperatures with various flow and TCD scenarios. Release volumes and temperatures predicted from the W2 model were then used as input to the river models.

The initial plan for the river model was to use the EPA's QUAL2E (Brown 1987) one-dimensional steady-state model, but an advanced version was selected, QUAL2K (Chapra 2003), due to software incompatibilities. The nature of steady-state models was limited to analyzing one flow condition at a time. While QUAL2K was very efficient in predicting water temperature with associated flows, the SJRIP Biology Committee required information that exceeded steady conditions. Therefore a non-steady-state model, GEMSS Model (Kolluru and Fichera 2003), was also used to predict downstream temperatures. I included the steady state QUAL2K analysis in this report because it was easy to use and can be a useful tool for managers in working with stakeholders to portray flow and temperature scenarios. The use of two river models also helped to corroborate each models' results.

The modeling details are described in Sections 4 through 6.

4. RESERVOIR TEMPERATURE MODELING

I used the two-dimensional CE-QUAL-W2 (W2) water quality model developed by the U.S. Army Corps of Engineers to characterize Navajo Reservoir. This model has been under continuous development since 1975 with over 400 reservoir systems worldwide modeled successfully using the W2 model. W2 is well known for its ability to accurately simulate reservoir hydrodynamics and temperature.

The W2 model predicts water surface elevations, velocities, and water temperature using longitudinal-vertical hydrodynamic calculations to route water though an array of control volumes that define the geometry of the water body being modeled, leaving the lateral dimension of the control volumes to be averaged (homogenous). The fundamental structure of the model was derived from theories of hydrodynamics, aquatic biology, aquatic chemistry, and statistical equations for water behavior. In particular, the hydrodynamic portion of the model was composed of the governing equations for continuity and conservation of momentum. Water temperature was included in this calculation because of its effect on water density. The timestep in this model was variable to ensure numerical stability. The model accepts time-varying inputs at the frequency they occur independent of model timestep. The model uses numerical solutions to calculate constituents between boundaries of control volumes within the system. Variables defined at the boundary include velocities, dispersion coefficients, and internal shear stress. The other variables such as density, constituent concentration, cell width, and pressure were defined at the cell center (Cole 1995).

The main constituent modeled in my application was temperature; the effects on reservoir fisheries and specific dynamics such as zooplankton production, fish distribution and feeding behavior, and predator-prey interactions were beyond the scope of this study.

The information required to set up the W2 model consisted of reservoir geometry, hydrologic data, water quality data, meteorological data, and the selection of a model period. To assess the accuracy of the model I used absolute mean errors. This was calculated as the sum of the absolute difference between observed and modeled values divided by the number of samples.

<u>**Simulation Period**</u>

For this study I used the period of 1995 to 2000 to represent the diversity of reservoir elevations and inflows (Table 1 and Figure 2). This period also included a year of intensive reservoir water quality sampling that was used for model calibration.

Table 1. Inflows, percent of average, and average reservoir elevations for the model period of 1995 to 2000.

Year	1995	1996	1997	1998	1999	2000
Total inflow (10^3 Ac-ft)	1,467	414	1,382	859	1,112	440
% of Average inflow	150%	40%	140%	90%	110%	40%
Average Water Surface Elevation in feet	6071.3 (1851 m)	6059.0 (1847 m)	6064.5 (1848 m)	6069.1 (1850 m)	6071.4 (1851 m)	6066.9 (1849 m)

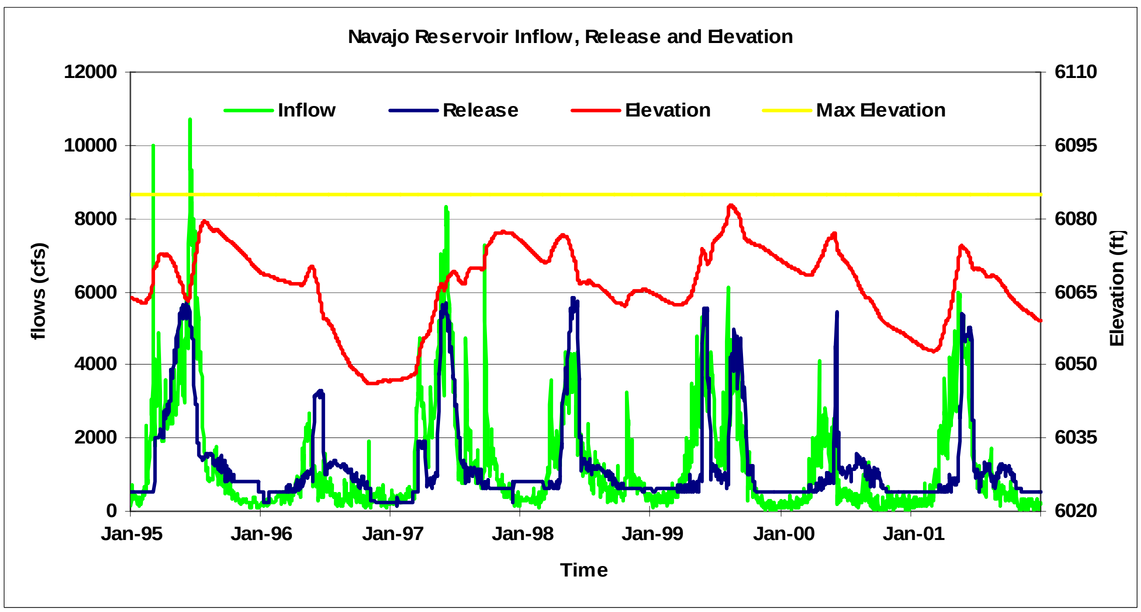


Figure 2. Total inflow, release, reservoir elevation and max elevation at Navajo Reservoir, NM from January 1995 to December 2001.

Model Geometry

For the W2 model, reservoir geometry was simplified into two dimensions--length and depth--leaving the lateral dimension to be averaged. This technique divided the reservoir into model segments and layers (Figure 3). Navajo Reservoir was characterized with four branches, including 52 model segments that were approximately 7,000 ft (2134 m) long, and 64 vertical layers set at 6.5 ft (2 m) depth intervals. In addition to the San Juan River branch the other three branches were:

Branch 2: Piedra River

Branch 3: Los Pinos River

Branch 4: Francis Creek

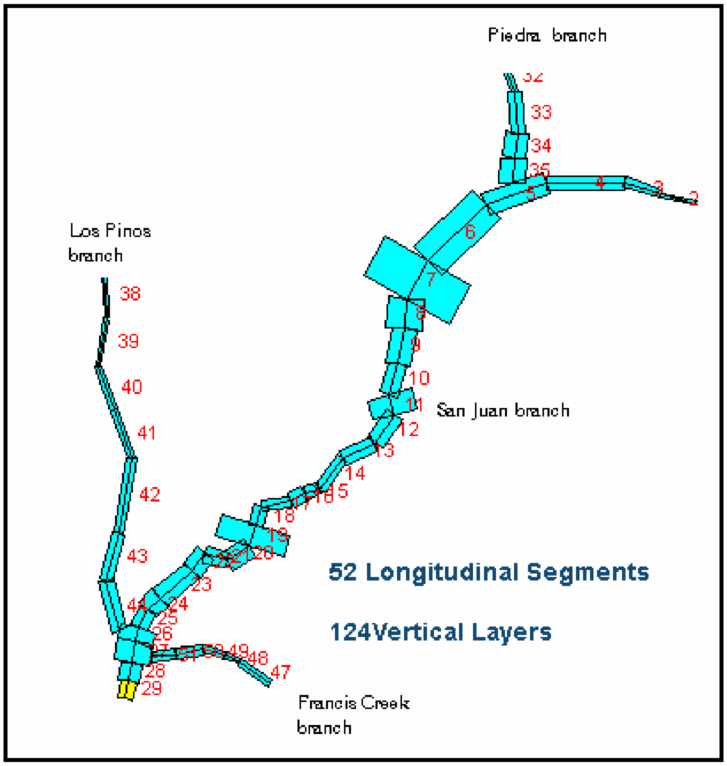


Figure 3. W2 model input geometry with longitudinal segments and vertical layers for Navajo Reservoir, NM.

Model Data

The Navajo Reservoir W2 model used inflow and outflow data from the U.S. Geological Survey (USGS) and Bureau of Reclamation (USBR) databases. Daily inflow and outflow quantities were available at the following stream gages: San Juan River near Carracas, CO; Piedra River near Arboles, CO; Los Pinos River near Boca, CO, and San Juan River below Navajo Dam, NM.

Hourly meteorological data were required for the model and the data used was from the Farmington, NM station. There were meteorological data available at the Navajo Dam station; however it was not used because of the coarseness of daily timesteps; the timesteps at Navajo Dam would not allow the model to reproduce the diurnal temperature variation required for this study. In comparing the two meteorological datasets, the dew point and air temperature data were closely correlated; however, wind speed near the dam was consistently 67% lower in value. Because of this, a wind sheltering coefficient was applied to the hourly data from Farmington. Inflow water temperature data for each branch was also required as model input. Measured water temperatures from each of the inflow stations listed above were limited. On average there were 12 samples taken per year from each of the stations with the data collection ending September, 1996. Missing water temperature data for the period 1995--2000 were generated as equilibrium temperatures with meteorological data to produce complete daily inputs. Figures 4-6 illustrate the comparison of observed versus model inflow water temperature for each of the stations.

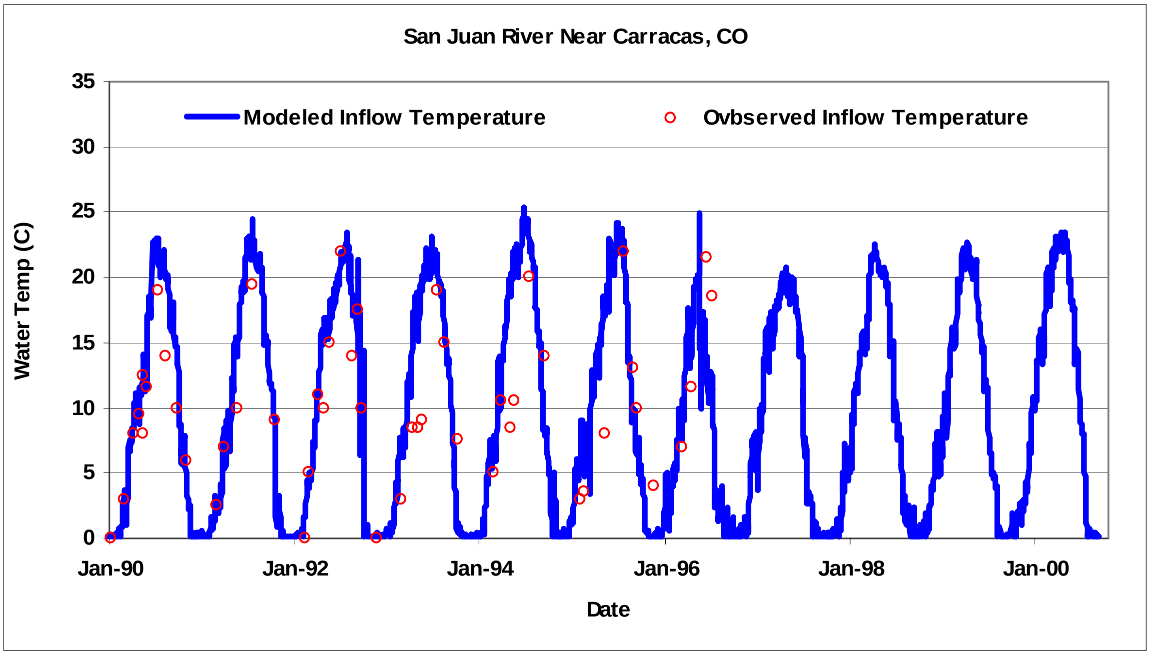


Figure 4. Comparison of observed water temperature at San Juan River Near Carracas, CO to modeled temperature.

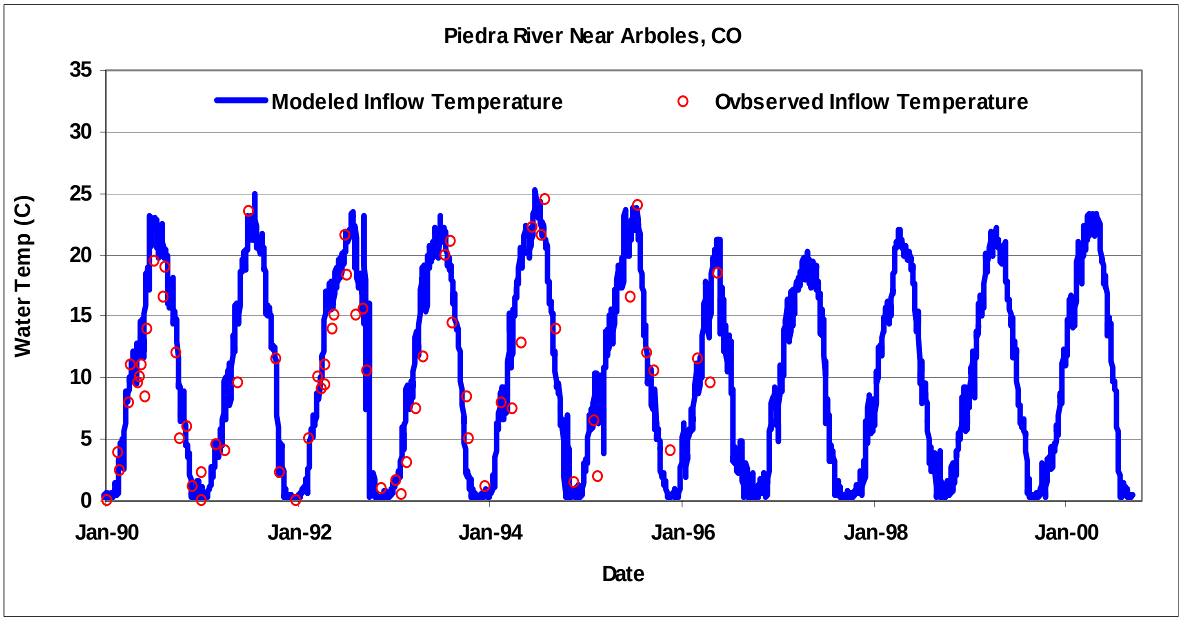


Figure 5. Comparison of observed water temperature at Piedra River Near Arboles, CO to modeled temperature.

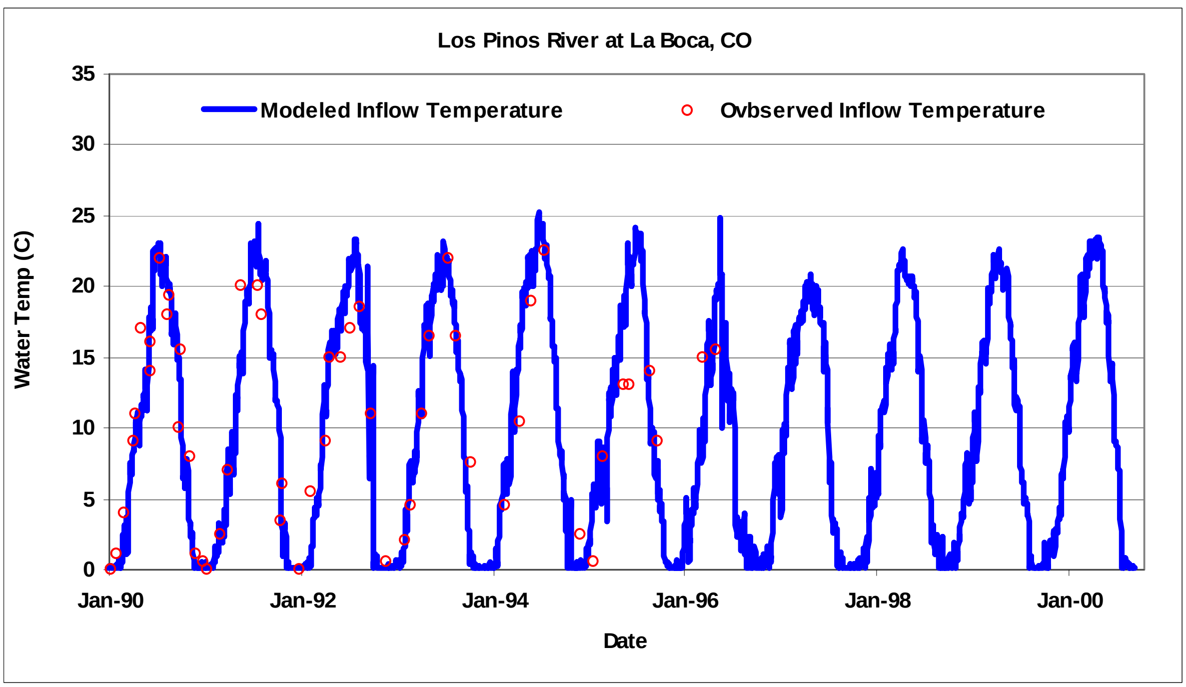


Figure 6. Comparison of observed water temperature at Los Pinos River at La Boca, CO to modeled temperature.

Water Balance and Temperature Calibrations

A water balance for each day of the simulation was prepared. Inflow into the reservoir was represented as the San Juan River, Piedra River and Los Pinos River. These inflows accounted for 94% of the total inflow to the reservoir. The water balance was completed using average gains, losses, and evaporation so the model could predict the observed water surface elevation. Elevation data for the period from 1995 to 2000 were available from USBR's hydrologic database. Figure 7 illustrates the water surface elevations compared with the field measurements. The absolute mean error between the model reservoir elevation output and field data was within 1.3 ft (0.4 m). This error was less 1% of the total capacity. The error was attributable to the simplified reservoir geometry and evaporation assumption.

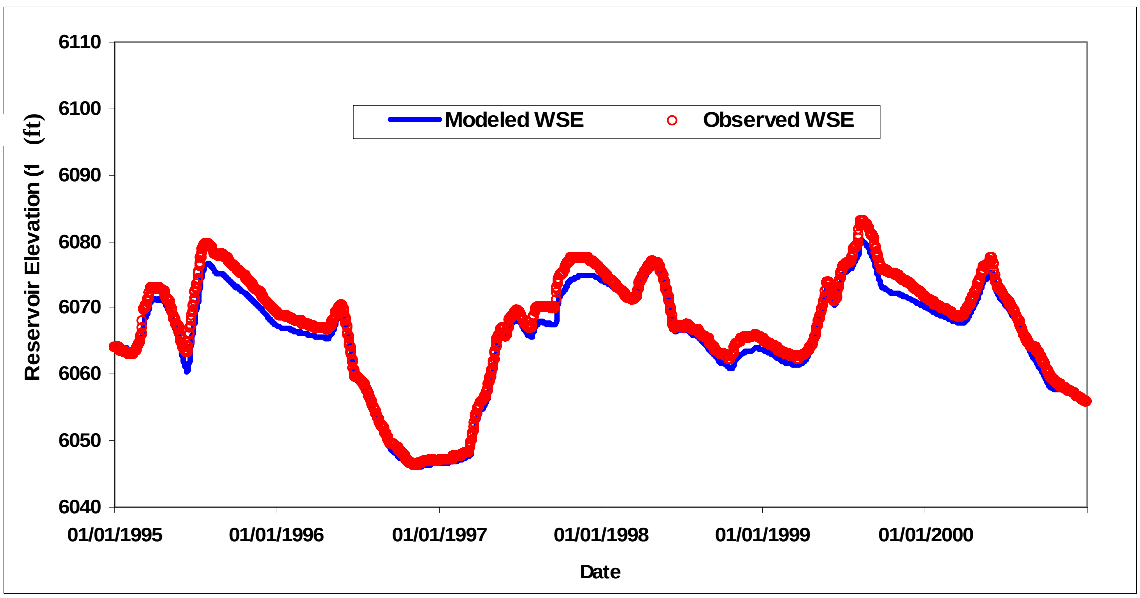


Figure 7. Comparison of W2 model output and actual observed reservoir elevations on Navajo Reservoir, NM. (WSE = water surface elevation)

Water temperature calibration was done by comparing reservoir temperature profiles and release water temperatures. The temperature profiles were measured near the dam (V. Lamarra, unpublished data). The temperature profiles were collected on a continuous basis from 3/30/1998 to 2/17/1999. Due to the large number of profiles, a selected set of profiles were used to calibrate the model every thirty days at noon. The model was calibrated to actual release temperatures using data provided by R. Bliesner (unpublished data) for July 1999 to June 2001. The temperature profiles in this dataset only captured the top 100 ft (30 m) of the reservoir. With a full reservoir, combined with above-average inflows during this period, these profiles did not capture the entire epilimnion and the transition of the thermocline to the hypolimnion because it could be > 100 ft (30m) deep. The calibration for this model was therefore limited to the quality of the available temperature profiles. The absolute mean error between modeled temperature profiles and observed temperature profiles was 1.35 °C (2.34 °F). An absolute mean error of less than 1.0 ^{o}C (2 °F) was reported by Cole (1995) as a well calibrated model. Appendix B lists water temperature profile calibration plots for the reservoir. While the calibration of reservoir temperatures was important, a more important calibration was release water temperature. The absolute mean error between the modeled release water temperature and the observed release water temperature averaged 0.43 °C (0.8 °F). Observed release water temperatures were only available from July 1999 to December 2000.

Navajo Reservoir was particularly difficult to calibrate because of the limited input and calibration data, and the input and calibration data were temporally out of sync. Navajo Reservoir releases water from its hypolimnion where limited data were available for calibration. Figure 8 illustrates the comparison of modeled versus observed dam release water temperatures. The lack of data and temporal shift in calibration and input data leads to a model that predicts water warming later in the year when compared to observed temperatures.

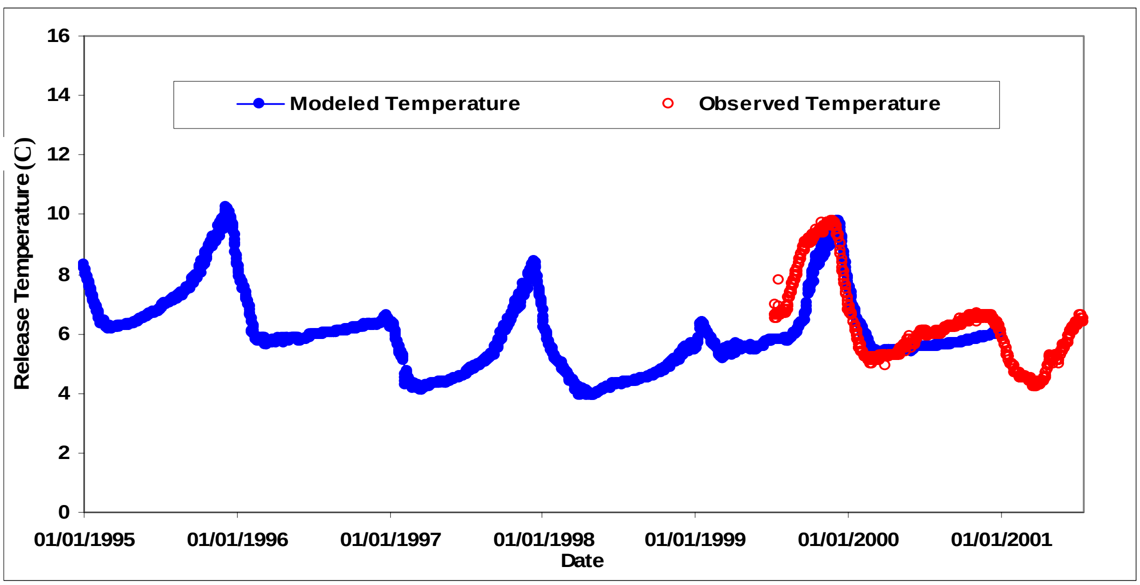


Figure 8. Comparison of W2 model output and actual observed release water temperature from Navajo Reservoir, NM.

A peer-review of the W2 model development, calibration, and outputs was performed by J. E. Edinger Associates, Inc (Wayne, PA). The review included a detailed analysis of the input data sets, the geometry of Navajo Reservoir, and verification of the model results to field data. The peer-review concluded that with the given date set this was the best calibration that could be expected.

5. RIVER TEMPERATURE MODELING

The original scope of work anticipated that the QUAL2E model (Brown and Barnwell 1987) would be used to route the water from Navajo Dam to Shiprock. However, during model development the enhanced version, QUAL2K (Chapra 2003), became available, and based on recommendations from the Biology Committee the newer version was used in its place. Both models were one-dimensional and assume steady-state hydraulics. The QUAL2K model operates in the Microsoft (MS) Windows environment with an easy-to-use Excel graphical user interface. Unlike QUAL2E, QUAL2K can be segmented unequally which provides additional flexibility. Both models can be used to represent a variety of water quality parameters. In this study, water temperature for the San Juan River was the sole parameter modeled using QUAL2K. The model calculated water temperatures through surface heat fluxes from solar radiation and substrate/water interface. The solar radiation heat fluxes included shortwave radiation, atmospheric longwave radiation, water longwave radiation, conduction, convection, evaporation, and condensation.

The QUAL2K model also required the geometric, hydrologic, meteorologic, and water temperature data; however, as a steady-state model, time-series data were not required. To build the geometry dataset, I used the14 measured cross sections (Reclamation 1998) and the stage relationships at the three gauging locations (Archuleta, Farmington, and Shiprock, NM). Based on the above information the San Juan River geometry was simplified to have 25 longitudinal segments, with each being approximately 16,000 ft (~5000 m) long.

The hydrologic data used in the QUAL2K model included water release data from Navajo Dam, tributary inflows, and diversions. These data came from USGS gauging stations, USBR's San Juan Riverware model, and the State of Colorado's Department of Environmental Quality (CDEQ) databases. Hydrologic data from the San Juan River's two main tributaries, the Animas and La Plata rivers were also included (USGS gauging stations "Animas near Farmington" and "La Plata River at Hesperus"). The miscellaneous gains and losses from irrigation, power, and M&I withdrawal between Navajo Dam and Shiprock were taken from the USBR's Riverware model as monthly volumes from 1929 to 1993.

I used the same metrological data from Farmington, NM as I used with the W2 model. The primary meteorological data required by the model were air temperature, dew point temperature, wind speed, and cloud cover.

Water temperature data were provided by R. Bliesner (Logan, UT, unpublished data). This dataset was a time series (July, 1999 to April, 2003) of water temperature data at four stations: Archuleta, Farmington, Animas River near Farmington, and Shiprock, NM. I selected two years (1999 and 2000) that were consistent with the W2 model period (1995-2000) for calibration and for results of downstream temperature. I selected data from the fifteenth day of every month for calibration. Rather than selecting a time series period, these days were selected because of steady-state model limitations. This once-a-month selection approach also provided an opportunity to test the model with different flow conditions, meteorological conditions and water temperature conditions.

Water Temperature Calibrations

The model was built using release water temperatures, release volumes, and meteorological data for the 15th day of every month; however, the tributary inflows and temperature were from the 16th day of the month to account for travel time. Each of the days was calibrated to water temperature at three locations (Archuleta, Farmington and Shiprock, NM). Figure 6 illustrates the longitudinal river temperature profile of predicted average, minimum and maximum water temperatures on a given day by matching the observed water temperature at four locations (Figure 6). The remaining 11 longitudinal calibration plots for the other periods are illustrated in Appendix B.

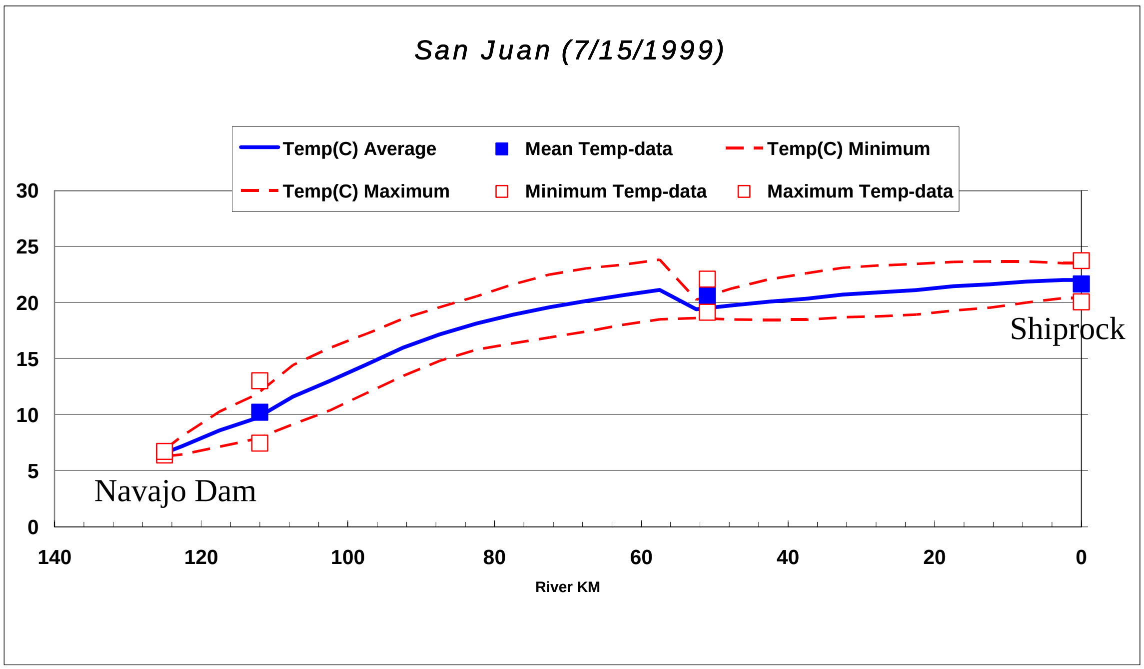


Figure 6. Longitudinal river profile of water temperatures. The points represent observed water temperature data locations (from left to right: below Navajo Dam, Archuleta, Farmington and Shiprock, NM) in the San Juan River, NM.

A specific calibration was also performed by request of the Biology Committee to determine how accurate QUAL2K was at predicting water temperatures during the descending hydrograph. This period refers to releases from the dam returning to average flow following a spring peak release. The period selected for this test was the 2000 descending hydrograph which started on June 5th and ended on June 13th (Figure 7).

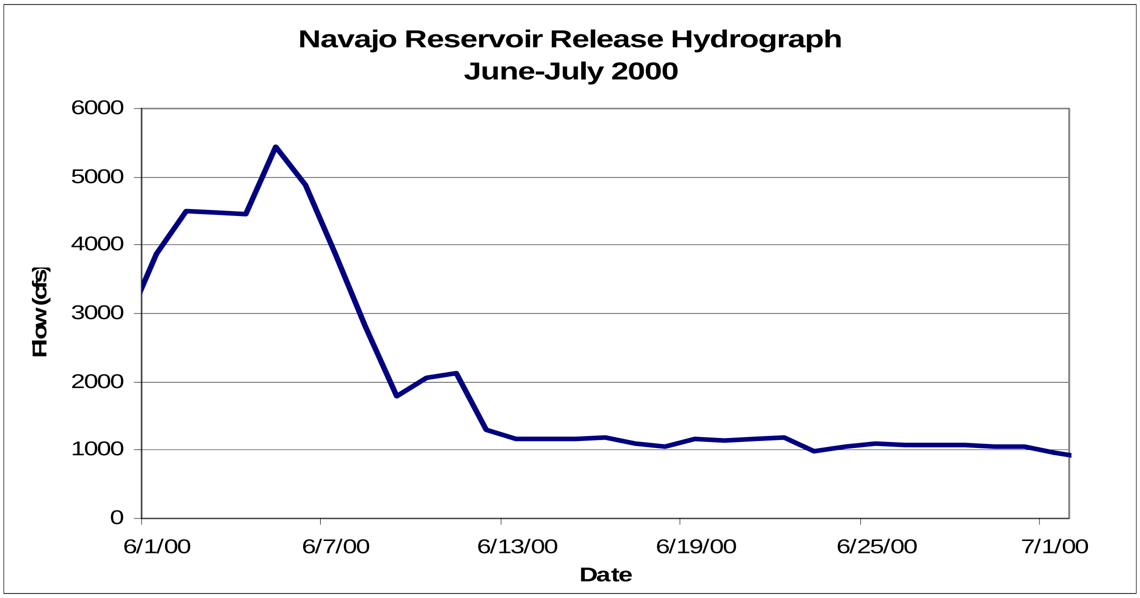


Figure 7. The 2000 observed release hydrograph from Navajo Reservoir, NM.

There were 192 temperature values observed at Shiprock during this eight-day period which were used to verify model output. The mean error over the 8-day period was 0.658 °C (1.2 °F; Figure 8). Graphs showing the comparison between observed hourly temperatures at Shiprock and model temperatures for June 6th to June 13th can be found in Appendix B.

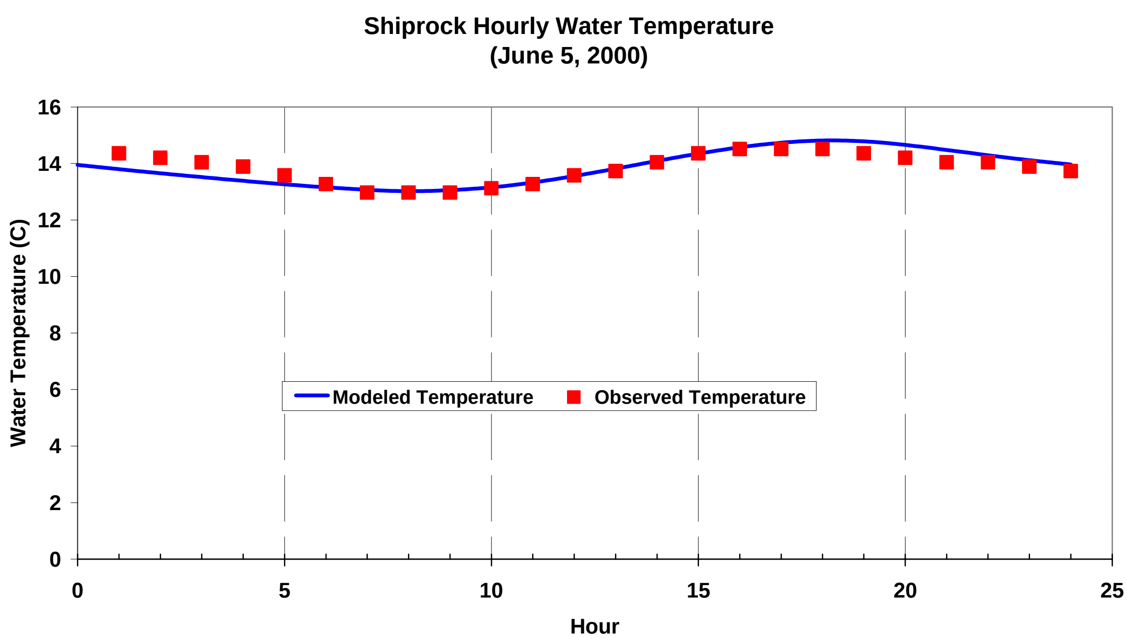


Figure 8. Observed and modeled diurnal water temperature on June 5, 2000 at Shiprock, NM.

The modeled travel time from Navajo Dam to Shiprock ranged from 1.3 days to 2.8 days at releases of 5000 cfs and 250 cfs (142 cms and 7 cms), respectively. These travel times were not calibrated because there was no data available for validation. Justine Barker of ERI (Logan, UT; personal communication), who collected data on the river and was familiar with this system, indicated that it takes about eight hours to travel 20 miles. This value closely matched the modeled travel time.

Steady-state models were a useful tool for analyzing a particular flow condition at a given time. They quickly address certain questions, e.g., with a given flow what was the downstream water quality. However, the SJRIP program felt an unsteady model would be better suited to address the program needs of more specific temperature predictions. I included the steady-state QUAL2K analysis because I felt that this was a useful tool for future reference and could complement other studies. The next section contains a discussion of the application of the 1-D unsteady state GEMSS model.

6. UNSTEADY RIVER TEMPERATURE MODELING

The 1-D hydrodynamic and water quality model GEMSS was developed by J. E. Edinger Associates, Inc. (Wayne, PA). The transport equations for this model were similar to W2 which was based on the Generalized Longitudinal Hydrodynamic and Transport (GLHT) computation derived from the three-dimensional equations of fluid motion and continuity (Edinger and Buchak 1980). This model was selected because of its successful applications of the 1-D water quality/hydrodynamic module in TMDL studies. Like the other two models it can model numerous water quality parameters; however, only water temperature was modeled for this study.

I used the San Juan River GIS shape files (Bliesner 2000) to generate the geometry for the GEMSS model. The simplified geometry was characterized by 59 segments and each segment length averaged 4,000 ft (1219 m). The boundary hydrology included daily average release data from Navajo Dam and daily inflows from the Animas and La Plata Rivers. These data came from USGS gauging stations, the State of Colorado's Department of Environmental Quality (CDEQ), and USBR databases. The water temperature boundary conditions included hourly measured temperatures below Navajo Dam and at the Animas River near Farmington provided by Keller-Bliesner Inc. (Logan, UT). The La Plata River temperature was assumed to be similar to the Animas River. Meteorological data from Farmington, NM was required to compute surface wind shear and heat exchange and consisted of hourly air and dew point temperature, wind speed, wind direction, cloud cover, solar radiation, and atmospheric pressure.

The GEMSS model was calibrated to observed Shiprock hydrology and observed water temperature at four locations (Archuleta, Farmington, Animas near Farmington, and Shiprock, NM) that were provided by Keller-Bliesner (Logan, UT). The calibration period was based on the period for which data were available from July, 1999 to April, 2003.

Water Balance and Temperature Calibrations

To verify the mass balance calculation of the model, the modeled flows were compared with actual flows at Shiprock (Figure 9). The modeled flows at Shiprock were consistently higher than observed flows due to lack of withdrawl data upstream of Shiprock. The average errors for comparison between modeled and observed hourly water temperatures were 0.35 °C (0.6 °F) at Archuleta, 0.81 °C (1.5 °F) at Farmington, and -0.96 °C (-1.7 °F) at Shiprock (Figures 10, 12, and 14 respectively). The modeled water temperatures at the Shiprock station were consistently lower than the observed data. This was likely caused by the higher modeled flows due to a lack of withdrawal data upstream.

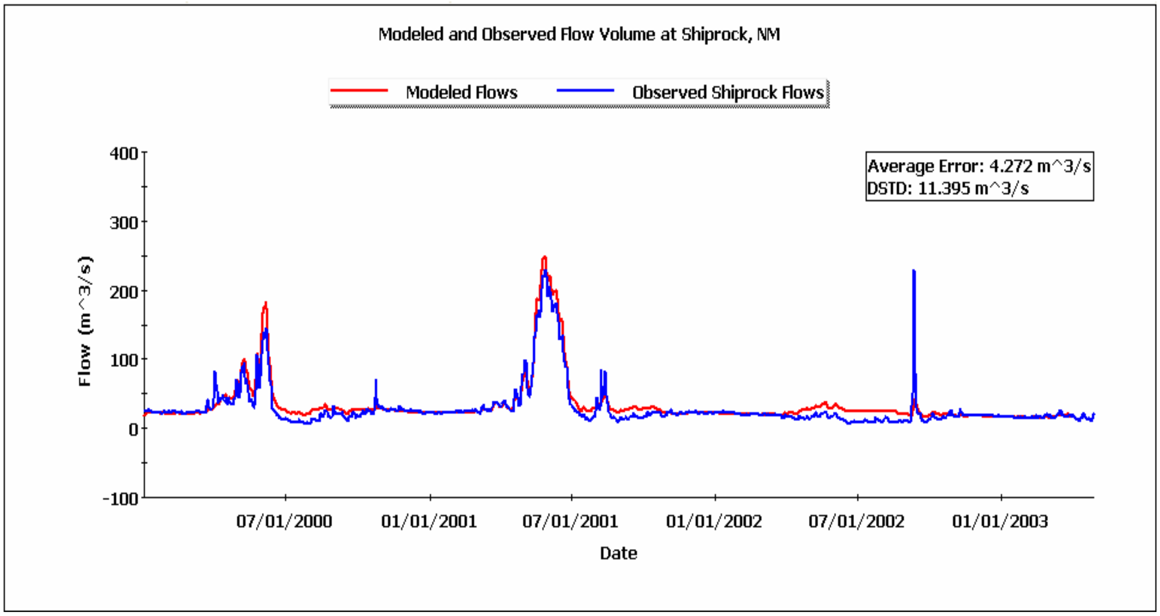


Figure 9. Comparison of GEMSS model estimate and actual observed flows on the San Juan River at Shiprock, NM (USGS, gauging station).

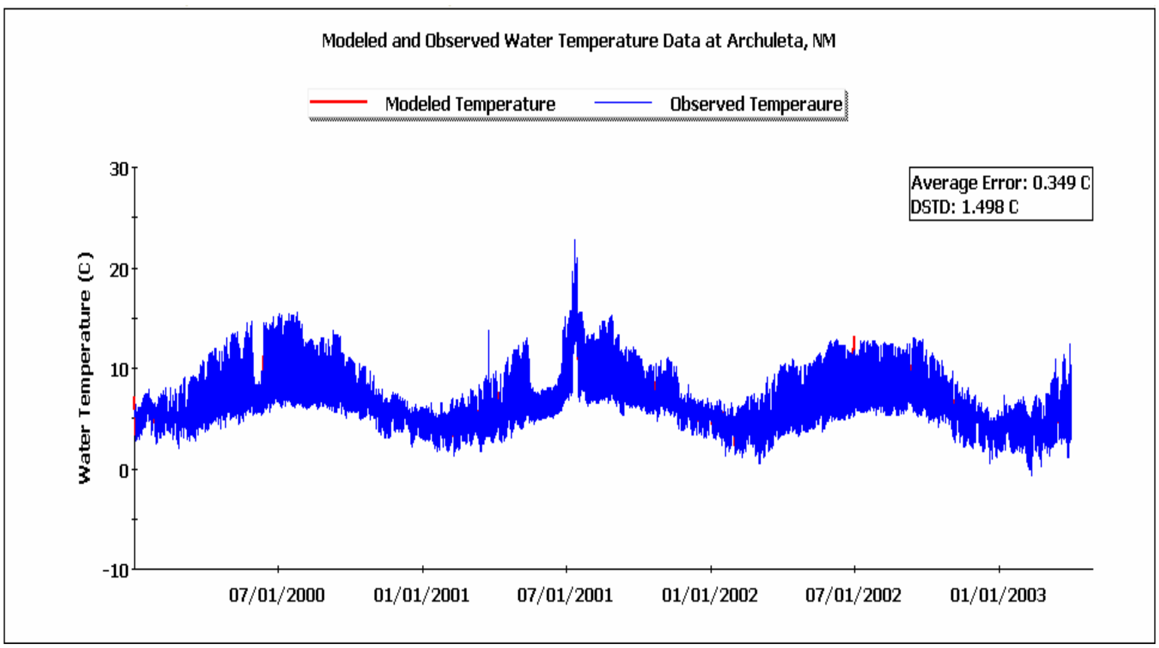


Figure 10. Comparison of GEMSS model's hourly estimate and actual observed water temperatures on the San Juan River at Archuleta, NM.

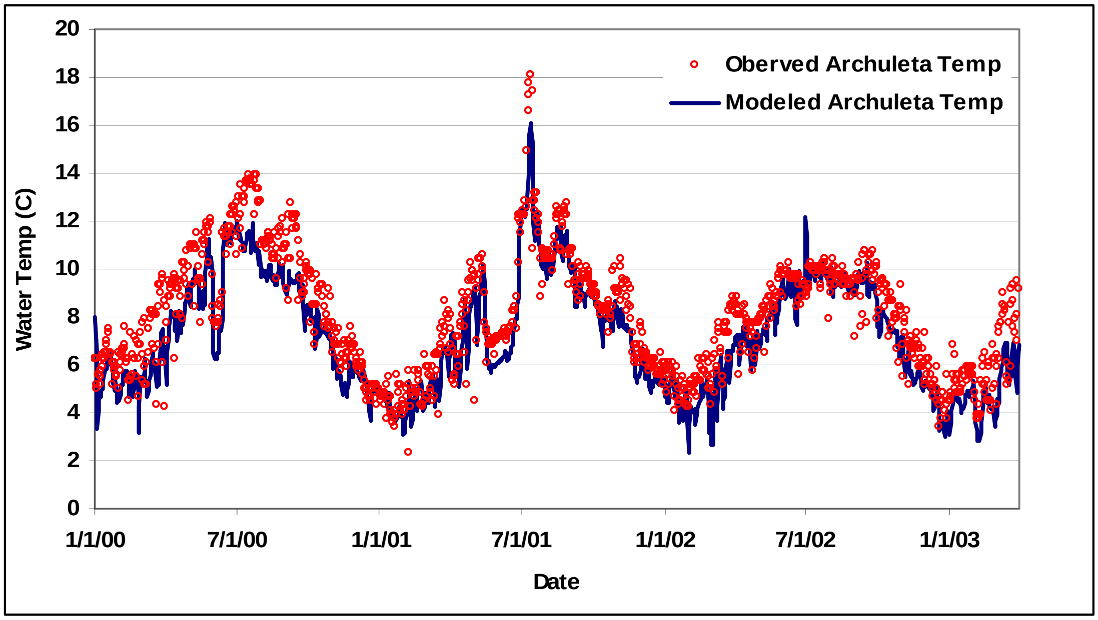


Figure 11. Comparison of GEMSS model's daily average estimate and actual observed water temperatures on the San Juan River at Archuleta, NM.

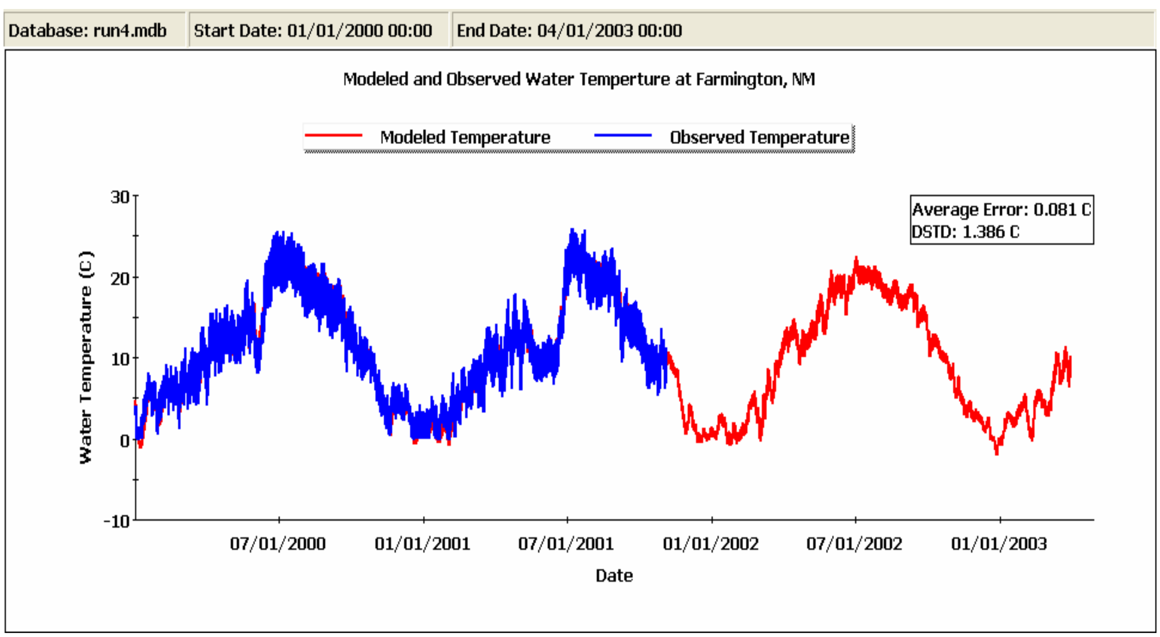


Figure 12. Comparison of GEMSS model's hourly estimate and actual observed water temperatures on the San Juan River at Farmington, NM. Hourly observed data from Farmington were unavailable after September, 2001.

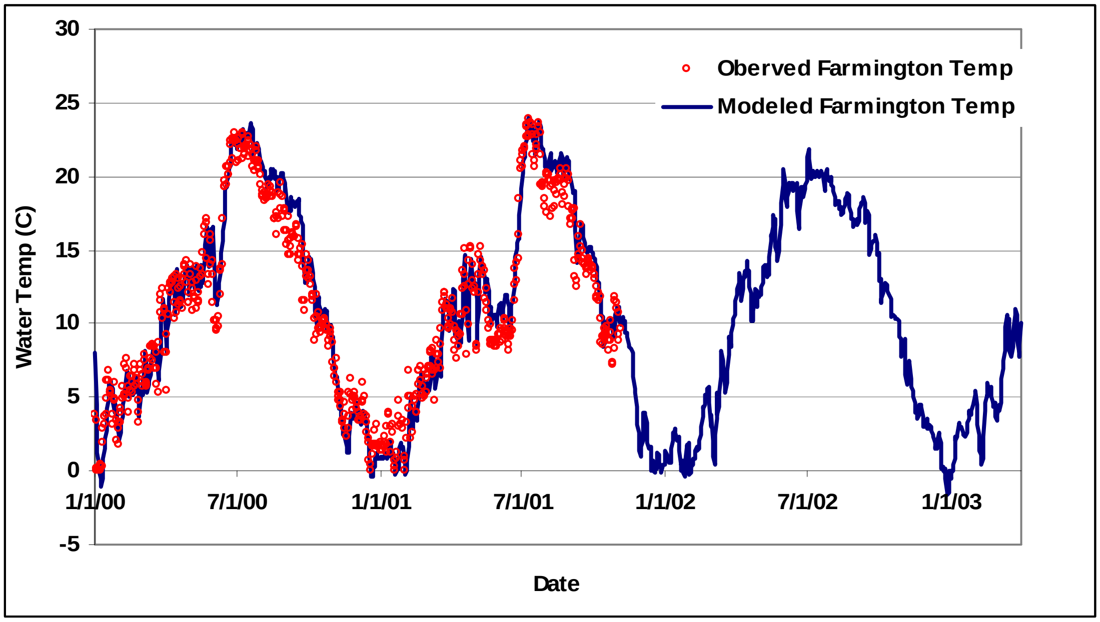


Figure 13. Comparison of GEMSS model's daily average estimate and actual observed water temperatures on the San Juan River at Farmington, NM. Observed data from Farmington were unavailable after September, 2001.

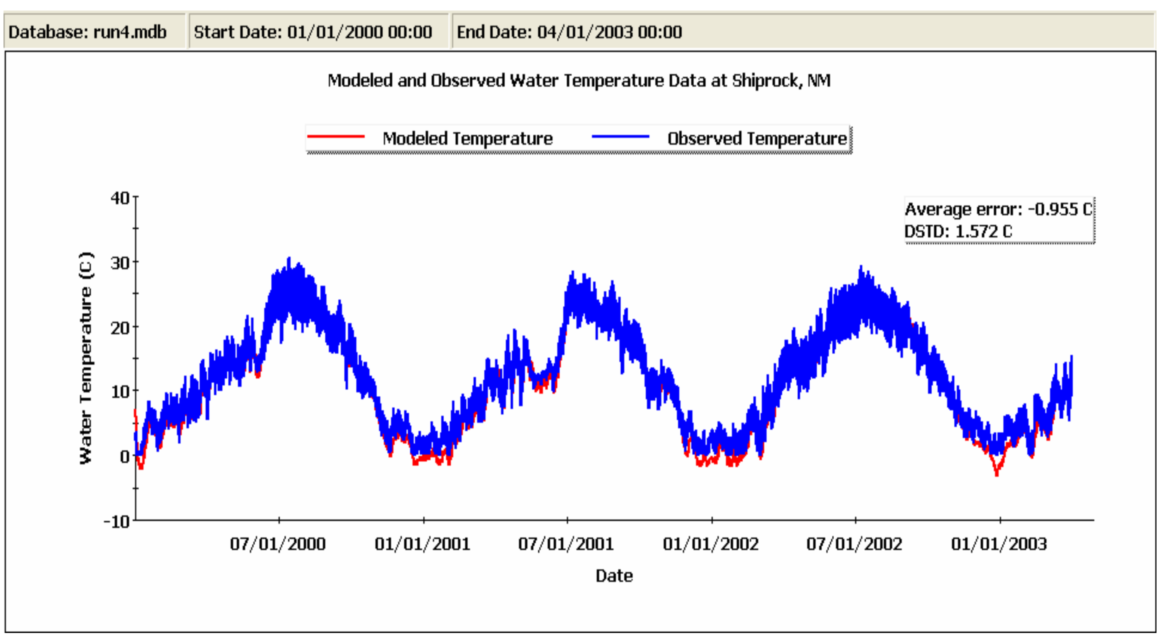


Figure 14. Comparison of GEMSS model's hourly estimate and actual observed water temperatures on the San Juan River at Shiprock, NM.

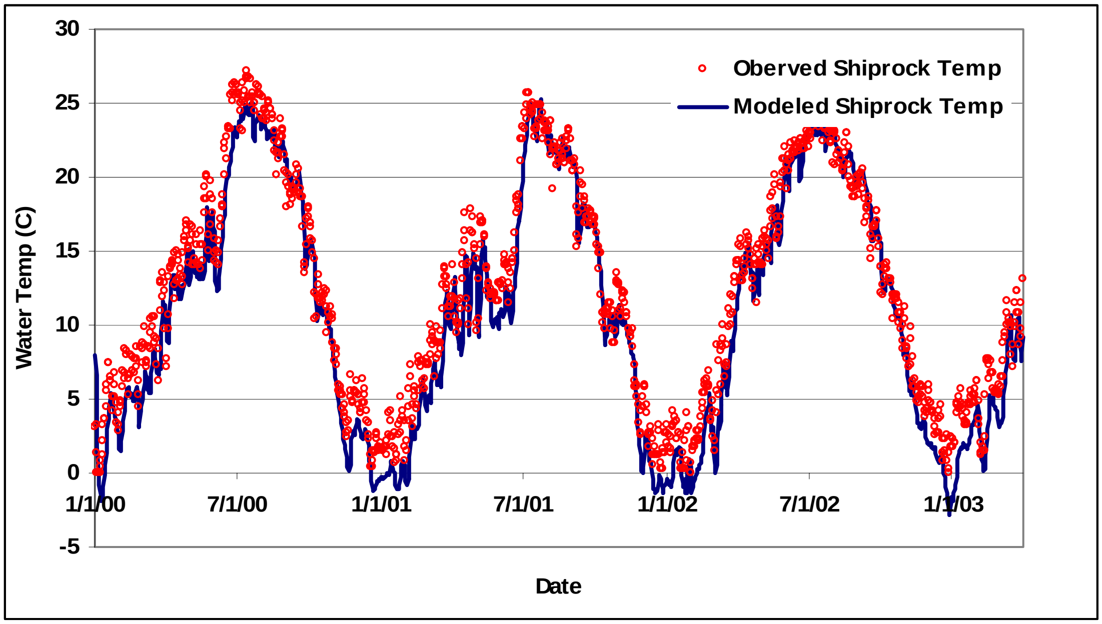


Figure 15. Comparison of GEMSS model's daily average estimate and actual observed water temperatures on the San Juan River at Shiprock, NM.

7. ADDRESSING RESERVOIR SCENARIOS USING CE-QUAL-W2

The W2 reservoir model was used to analyze release water temperatures for the following scenarios over the 1995–2000 period:

1) Historical release temperatures (1995–2000) as a base case

2) Fixed-level TCD scenario

3) Multiple-level TCD scenario

7.1 Base Case Scenario

The historical dam condition referred to modeled historical release temperatures and were used as the basis for TCD comparisons. The modeled historical release tempertures are referenced in graphs as “1995–2000”. The water tempertures released from the dam under the historical dam conditions fluctuated between 4°C to 10 °C (39-50 °F) and flow varied from 250 to 5,050 cfs (7-143 cms), depending on time of year and ambient conditions.

7.2 TCD Scenarios

Assumptions

Six assumptions were necessary to address TCD scenarios:

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

2) The TCD outlet passed only the releases from the 1995–2000 historical record and did not include bypasses through the spillway.

3) There was a 20-foot (6 m) buffering zone above all TCD release elevations to avoid formation of vortices which can damage the outlet structures.

4) Boundary conditions (meteorological data, tributary inflows and temperature, etc.) were the same as the 1995–2000 conditions.

5) There were two TCD configurations: 1) fixed-level outlet and 2) multiple-level outlets. A fixed-level TCD outlet operates at a fixed elevation relative to the water surface elevation and was based on one selected elevation for this study. The multiple-level TCD can select unique layers of water in the water column within ten-foot intervals and operates at different elevations relative to the surface water elevation.

6) The TCD scenarios were based on ideal conditions without leakage.

Single-level TCD

Navajo Reservoir was analyzed with a fixed-level TCD configuration using a TCD intake elevation of 6026 ft (1837 m; Figure 16). The TCD elevation was selected based upon the lowest reservoir elevation for the period of 1995 to 2000 and dropping an additional 20 ft (6 m) for a buffering zone to avoid formation of vortices. This added depth was an assumption based upon experience with other facilities, and may be higher or lower based on the requirements of the design configuration.

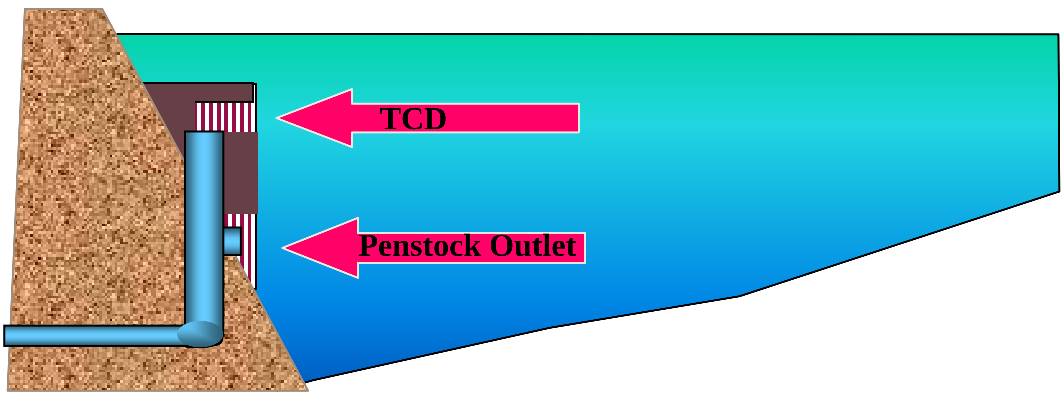


Figure 16. Conceptual diagram of fixed-level TCD (top arrow) on Navajo Reservoir, NM. The upper arrow represents the location of the inlet for the TCD and the bottom arrow indicates the current penstock outlet.

The successful operation of a fixed-level TCD is highly dependent upon the water surface elevation. As the reservoir stratifies seasonally, the outlet location can withdraw water that is warmer than would be possible without TCD if the outlet is in a position where it can withdraw warmer water. But a fixed withdrawl location limits the ability to achieve desirable temperature ranges throughout a range of water elevations since you cannot optimize the specific water depth for withdrawls. Any operation at or below a reservoir water surface elevation of 6046 ft (1843 m) requires that releases be taken from the penstock elevation of 5882 ft (1793 m) and negates any advantages of the TCD. The release water temperature generated by the W2 model for this scenario ranged from 3 to 21 °C (37-70 °F).

Multiple-level TCD

The uppermost TCD withdrawal elevation for this alternative starts 20 ft (6 m) below the highest water surface elevation (6085 ft; 1855 m), and continues to the penstock elevation in ten-foot intervals. The multiple-level TCD configuration ensured that the largest possible range of release water temperatures were exploited through systematic operations. Results from the modeled inflow hydrology during the period of 1995–2000 indicated that water release temperatures below Navajo Reservoir can range from 3 to 23 °C (37-73 °F).

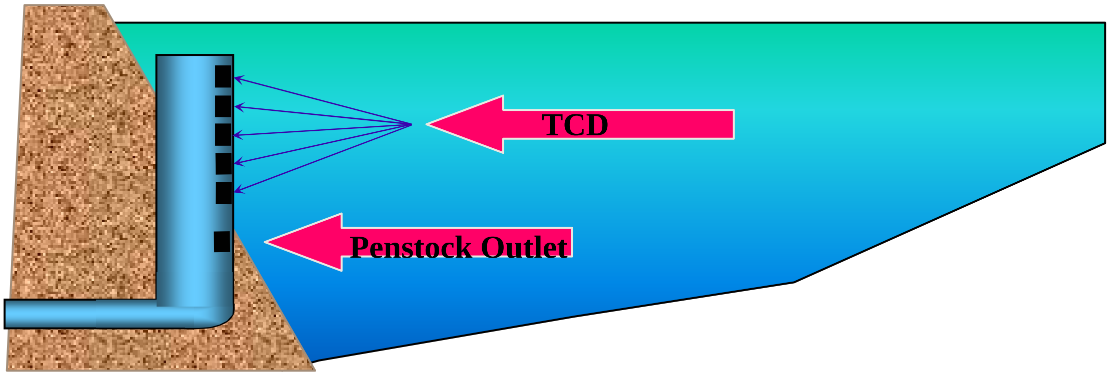


Figure 17. Conceptual diagram of multiple-level TCD (top arrow) on Navajo Reservoir, NM. multi-level TCD (upper arrow); the bottom arrow was the current penstock outlet.

A summary of release water temperatures from Navajo Reservoir for three scenarios (1995 to 2000, fixed-level TCD and multiple-level TCD) are presented in the following graph (Figure 18)).

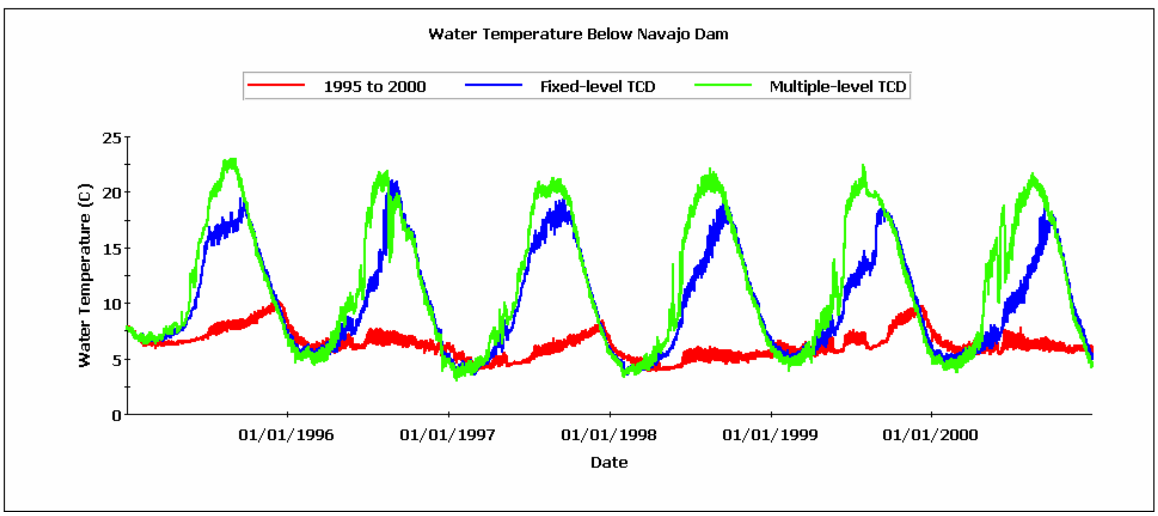


Figure 18. Water temperature released from Navajo Reservoir with three scenarios 1995 to 2000, fixed-level TCD and multiple-level TCD.

The highest release water temperature from Navajo Reservoir without TCD was 10 °C (50 °F) and occurred in December. With a fixed-level TCD 21 °C (70 °F) was reached by September, and with a multiple-level TCD 23°C (73 °F) was reached in August. Based on the optimum temperature range of 20 °C to 25 °C (68-77 °F) indicated in Lamarra's (2006) report, both TCD configurations increased water temperatures to the optimum by mid July or August. In general, the more control of the outlet elevation that was available the earlier higher release temperatures were achievable base on the models.

7.3 Navajo Reservoir Heat Budget

The in-reservoir temperature patterns were important components in determining the effect of TCD operations on the heat budget of the reservoir. Two model runs were completed to determine if there were any major or long-lasting effects on the temperature of the reservoir itself. Figure 14 illustrates the six-year comparison of the reservoir water temperature resulting from the use of the multi-level TCDs compared to the historic condition at one-hundred feet (~30 m) below the water surface elevation near the dam. The TCD could lower in-reservoir temperatures by an average of 1.1 °C (2 °F) and a maximum of 5.3 °C (10 °F).

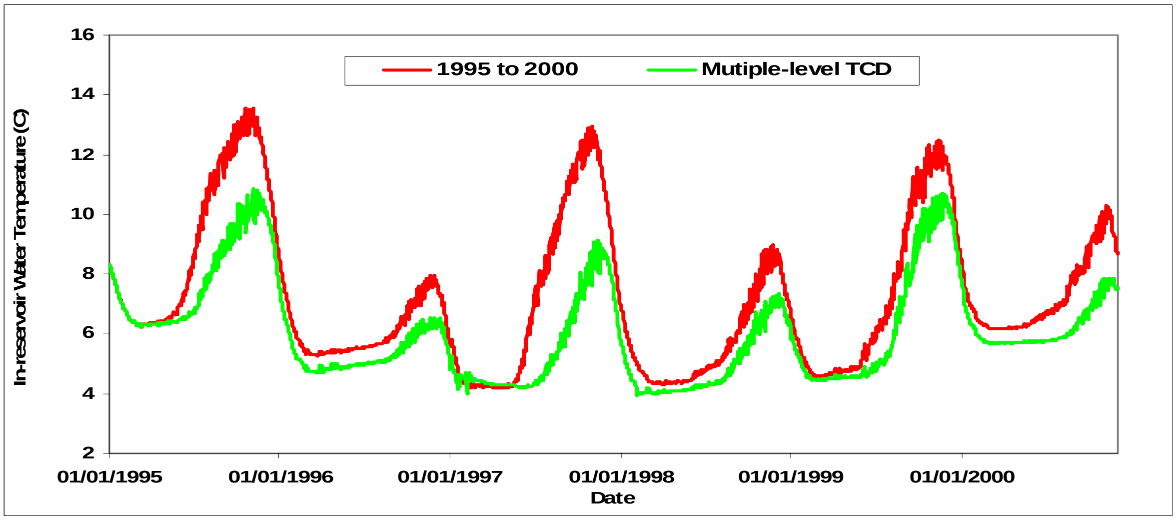


Figure 19. The comparison of in-reservoir water temperature of normal operations and the use of a multiple-level TCD at 100 ft (30.5m) below water surface elevation at Navajo Reservoir, NM.

A TCD could lower temperatures by an average of 0.4 °C at 30 ft, 0.9 °C at 60 ft, 1.0 °C at 130 ft, 0.8 °C at 160 ft, 0.6 °C at 200 ft and 0.3 °C between 200 ft to the bottom (0.7 °F at 9 m; 1.6 °F at 18 m; 1.8 °F at 40 m; 1.4 °F at 49 m; 1 °F at 61 m; and 0.5 °F below 61 m). The volume of water in the reservoir most influenced by the multiple-level TCD was the 10 °C to 18 °C (50-64 °F) temperature water (Figure 20).

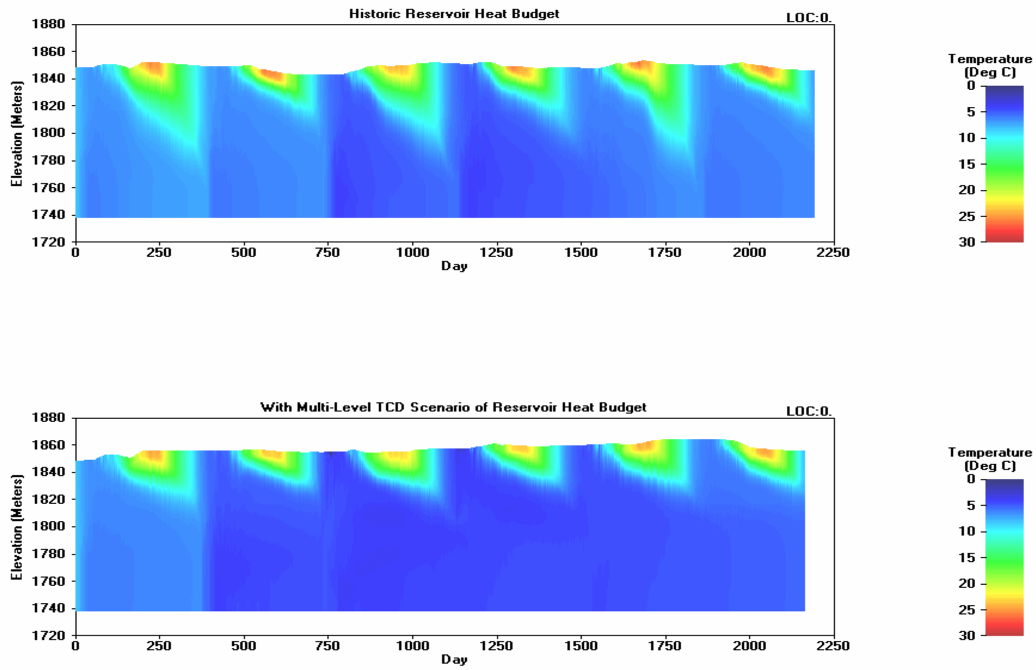


Figure 20. The comparison of time-series water temperature profiles for normal operations and with a multiple-level TCD at Navajo Reservoir, NM.

8. ADDRESSING RIVER SCENARIOS USING QUAL2K

Using W2 model release temperatures for 1995 to 2000, fixed-level and multiple-level TCDs scenarios, the QUAL2K model was used to model water tempertures in the San Juan River from below Navajo Dam to Shiprock. I used the calibrated event-based runs from section 5 to predict downstream temperature. The runs were based on releases for the fifteenth of each month from July, 1999 to June, 2000. I also added 1996's monthly data to have a larger, more representative, dataset. 1996 had cooler release temperatures compared with 1995 and 1997 to 2000, therefore it was a good addition to the analysis. Each of the monthly events was routed from the dam to Shiprock using temperatures from the W2 model. The temperatures for an event would consist of with and without each TCD configuration. Figure 21 shows the event on July 15, 1999 with longitudinal San Juan River temperatures with and without a TCD. A similar set of graphs for the years of 1999, 2000, and 1996 is presented in appendix A.

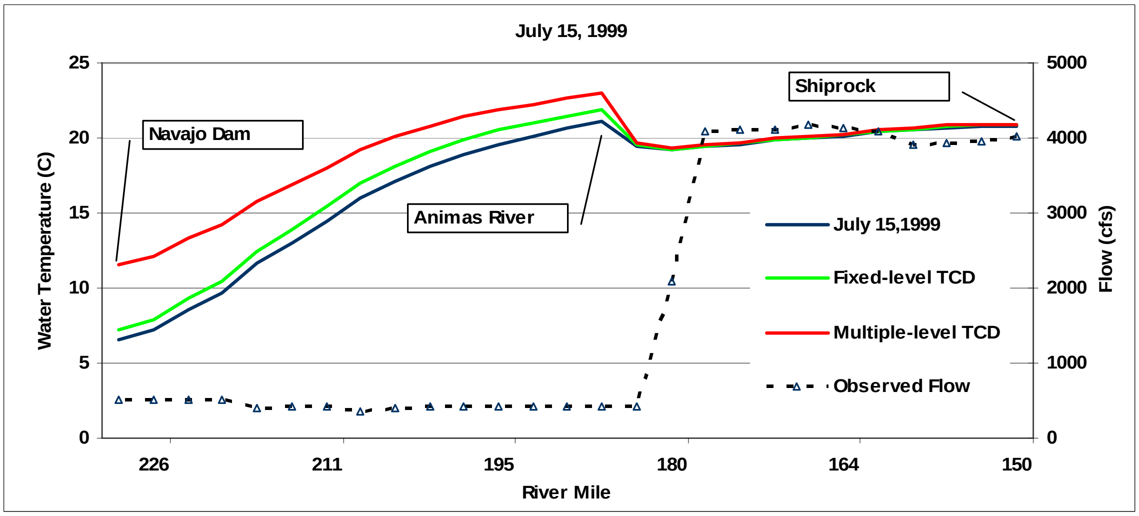


Figure 21. A scenario representing longitudinal water temperature in the San Juan River downstream of Navajo Reservoir, NM with normal releases and both fixed-level and multiple-level TCDs.

Water released from Navajo Dam will approach mean ambient temperature the further downstream it travels. The rate at which water warms depends on release temperature, flow, and atmospheric conditions. Even though the multiple-level TCD scenario increased water temperatures as much as 16 °C (29 °F) at the dam, the increase in water temperature did not transfer completely to Shiprock. Using limited monthly analysis, my results indicate that the greatest warming occurs between the Navajo Dam to just above the Animas River inflow. Downstream of the Animas and the La Plata Rivers the average increase in temperature from a TCD was 1 °C (2 °F). This relationship varies with releases from the dam and tributary inflows, with a TCD providing greater downstream warming under increased release situations. A multiple-level TCD can provide a 2.25 °C (3.8 °F) average increase compared to observed water temperatures above the Animas River inflow, but this effect diminishes due to the overwhelming influence of these tributaries. A separate set of analyses were also performed to give a different perspective on downstream warming. Using average release patterns and the set of assumptions below, these analyses give a sense of what the average condition could be with and without a TCD.

Assumptions:

1. All tributary inflow and withdrawal volumes were averaged monthly.

2. The water temperatures of tributary inflows were averaged monthly.

3. All meteorological data were averaged hourly for each month.

4. Monthly release volumes were average from 1967 to 2002.

5. Release water temperatures were based on the ranges of low and high water temperatures with and without the use of a TCD.

6. For the purpose of this study, the maximum water temperature release was set at 16 °C (61 °F). Even though higher release temperatures were possible, I assumed that proper operation of a TCD would permit 16 °C (61 °F) to be an achievable maximum target.

Based upon the above assumptions, and release water temperatures available from Navajo Reservoir (Table 2), a set of monthly runs were made. Figure 22 illustrates different release temperatures using average flows from Navajo Dam in July. Additional plots of average flow conditions for May through October are included in Appendix A.

Table 2. Ranges of available Navajo Reservoir release water temperatures from May to October.

	Navajo Release Water Temperature	
	Min Temperature	Max Temperature
May	4	10
June	4	17
July	4	20
August	4	22
September	4	21
October	5	19

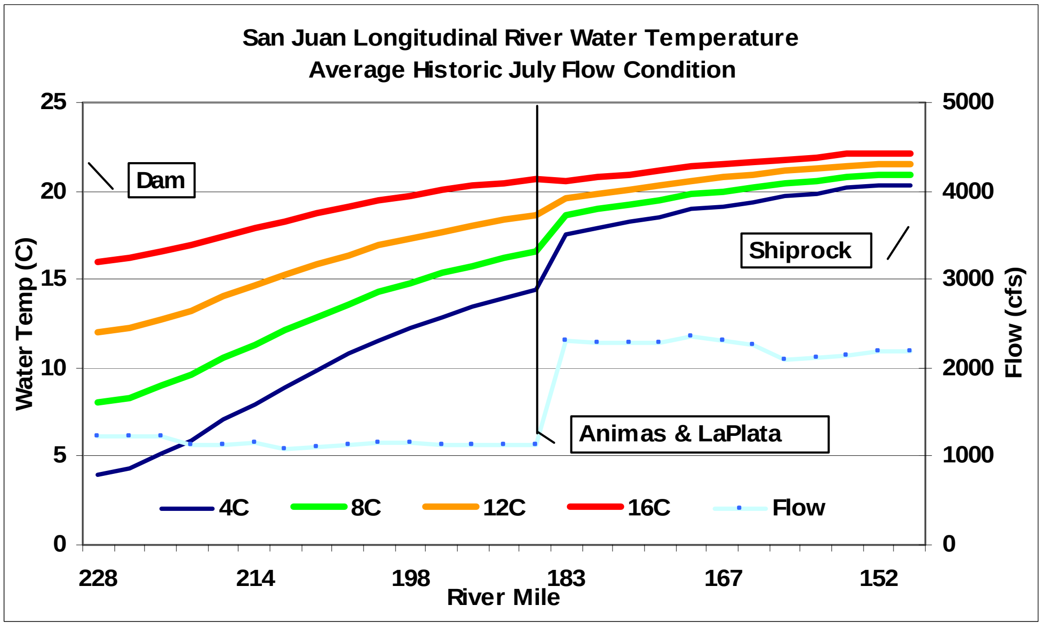


Figure 22. Longitudinal temperature profile in the San Juan River downstream of Navajo Reservoir, NM using average flow and meteorological conditions. This scenario shows potential water temperatures for the month of July with and without the use of a TCD. Colored lines show four release temperature scenarios and the respected increase downstream from the dam. Doted line show flow volume from the dam to Shiprock.

The July example provides an estimate of how this system interacts with flow, temperature, and meteorology. Average historical releases from Navajo Reservoir in May and June were generally lower than those of the Animas. From July to October the releases from Navajo Reservoir were generally higher than the Animas River. Water temperatures from the Animas River were generally cooler than the mean ambient temperatures. Therefore, under low volume releases, where the Animas had a higher or similar volume, the TCD warming at the dam disappeared as the water reached Shiprock, NM. During average flow conditions without a TCD water temperature can increase as much as 4 °C to 7 °C (7-13 °F) at Shiprock, NM over the temperature above the confluence with the Animas River. This illustrates that a TCD would likely have little effect on water temperatures below the confluence of the Animas River in most years.

9. ADDRESSING RIVER SCENARIOS USING GEMSS

I used the GEMSS model to also determine downstream temperature regimes in the San Juan River from below Navajo Dam to Shiprock. Unlike the QUAL2K model, this model can address time-series release scenarios and was not event-based. The calibrated GEMSS model was used to analyze three scenarios during the 1995–2000 period:

1) Historical release temperatures (1995–2000) as a base case
2) Fixed-level TCD
3) Multiple-level TCD

Release water temperature outputs from the W2 reservoir model for 1995 to 2000 were used as inputs to the GEMSS model. Animas River inflow temperatures for 1995 to 2000 were generated using an equilibrium temperature model. The results of the equilibrium model were calibrated for the period when observed water temperature data were available (Figure 23).

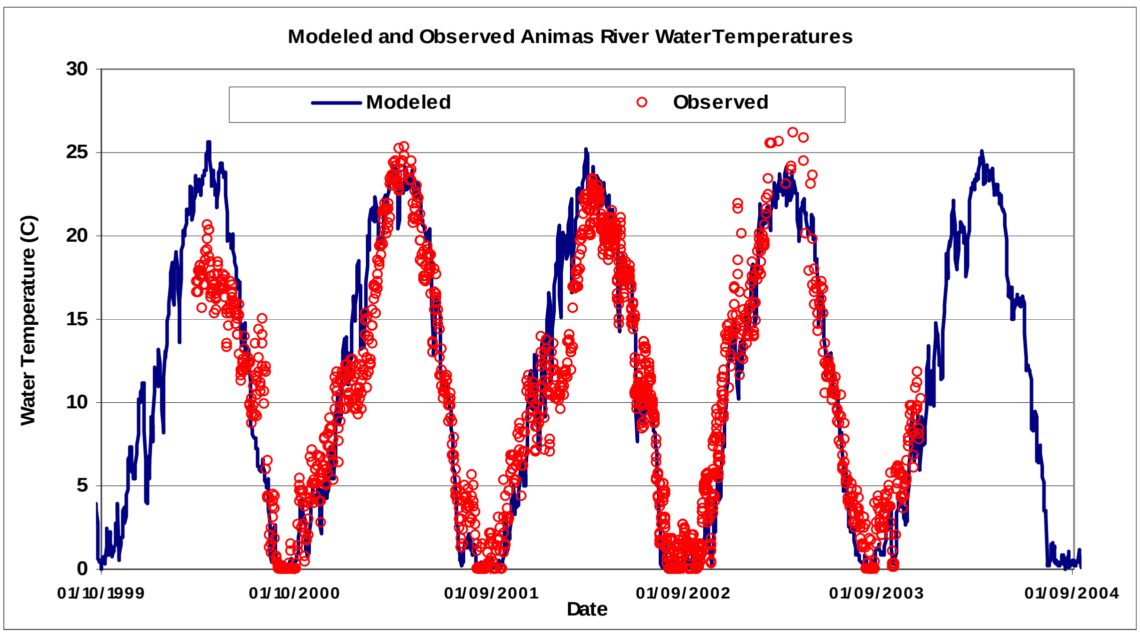


Figure 23. Comparison of equilibrium temperature model output and observed water temperatures on the Animas River near Farmington, NM.

The GEMSS model results suggested that, from May through October, average water temperatures with a fixed and multi-level TCD increased 7 °C and 10 °C (13-18 °F) downstream of Navajo Dam, 6 °C and 8.5 °C (11-16 °F) near Archuleta, 3 °C and 4.5 °C (5-8 °F) above the Animas River, 1.4 °C and 2.0 °C (3-4 °F) at Farmington, and 1 °C and 1.4 °C (2-3 °F) at Shiprock (Figures 24-28). My results also indicated that the maximum temperature increases with the fixed- and multiple-level TCDs could be as high as 14 °C and 16 °C (25-29 °F) below Navajo Dam, 11.8 °C and 13.5 °C (21-near Archuleta, 10.5 °C and 12 °C (19-22 °F) above the Animas River, 8 °C and 8.4 °C (14-15 °F) at Farmington, and 7.1 °C and 7.6 °C (13-14 °F) at Shiprock.

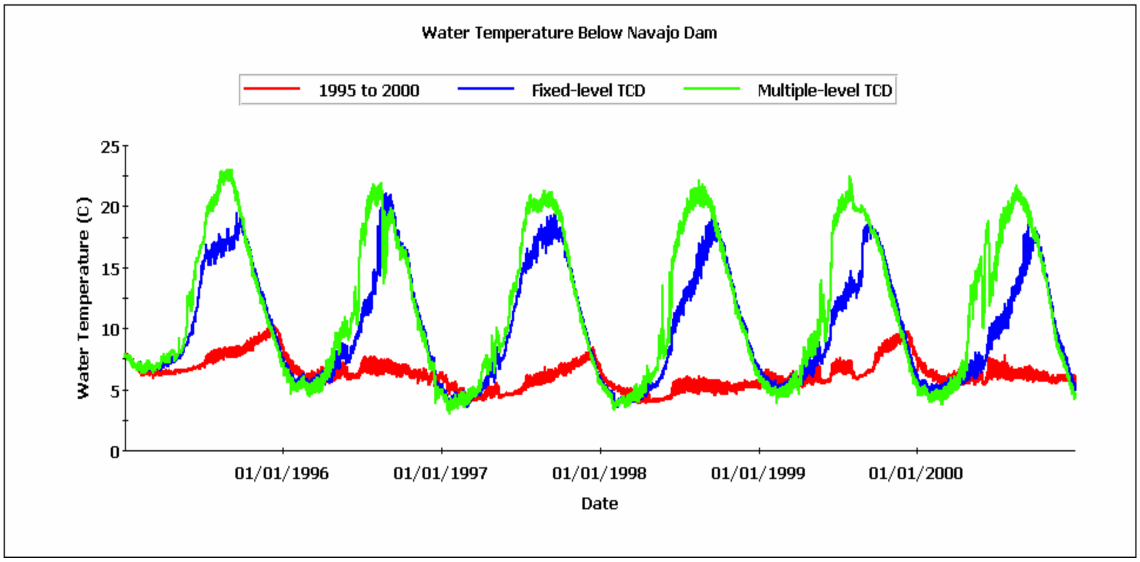


Figure 24. Water temperatures below Navajo Reservoir with three scenarios: 1995 to 2000, fixed-level TCD, and multiple-level TCD.

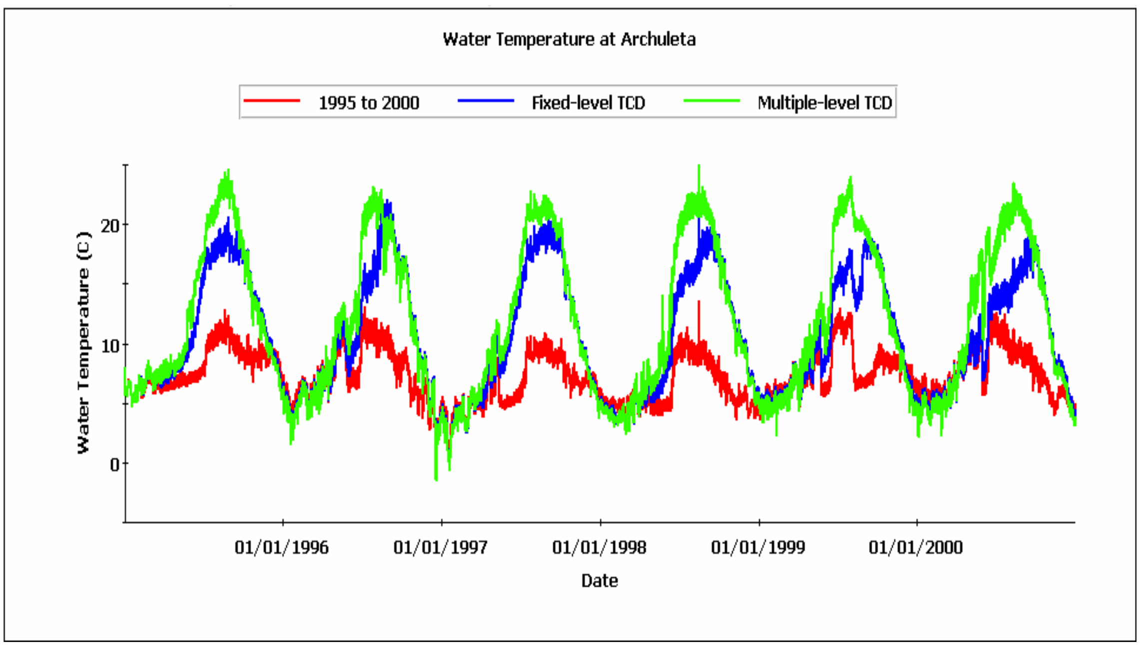


Figure 25. Water temperatures at Archuleta, NM with three scenarios: 1995 to 2000, fixed-level TCD and multiple-level TCD.

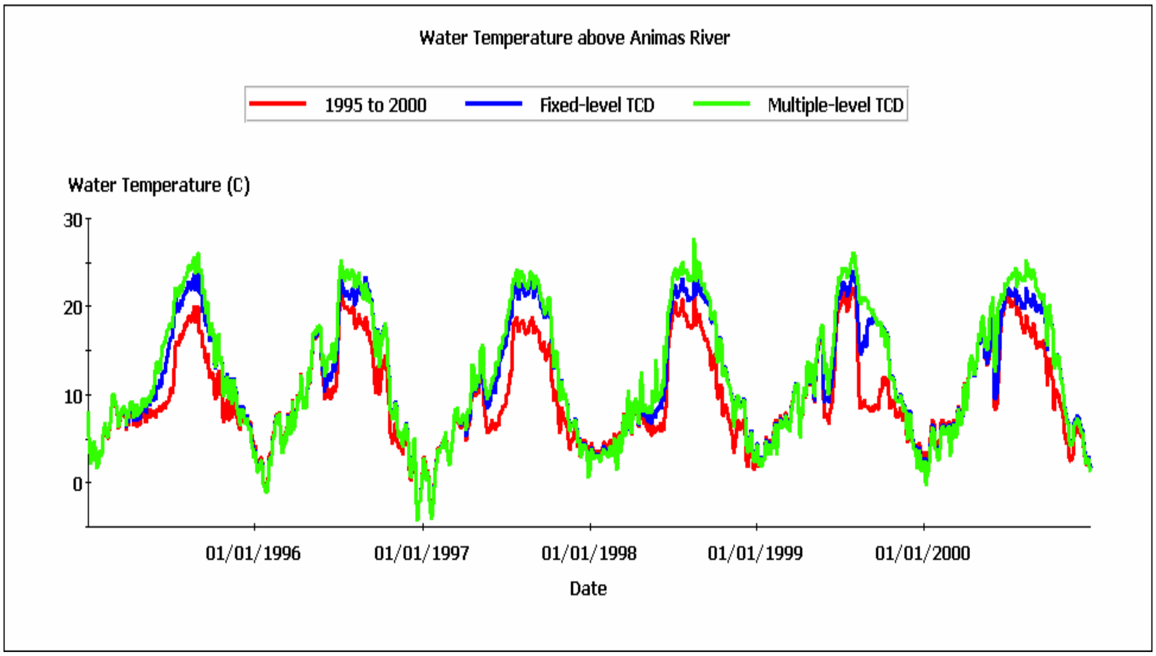


Figure 26. Water temperatures above the Animas River with three scenarios: 1995 to 2000, fixed-level TCD, and multiple-level TCD.

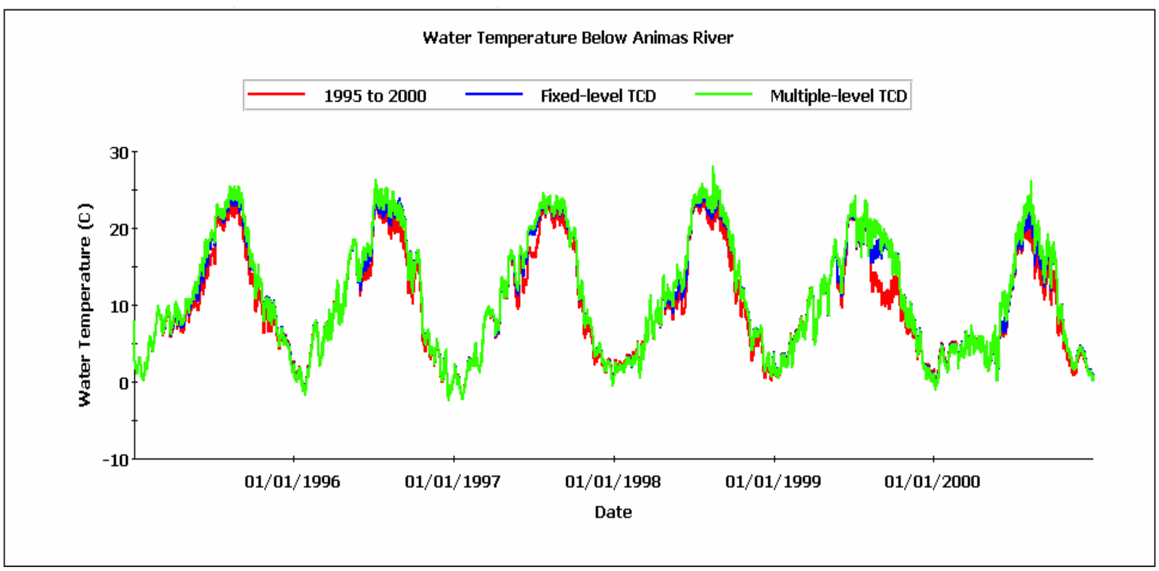


Figure 27. Water temperatures below the Animas River with three scenarios: 1995 to 2000, fixed-level TCD, and multiple-level TCD.

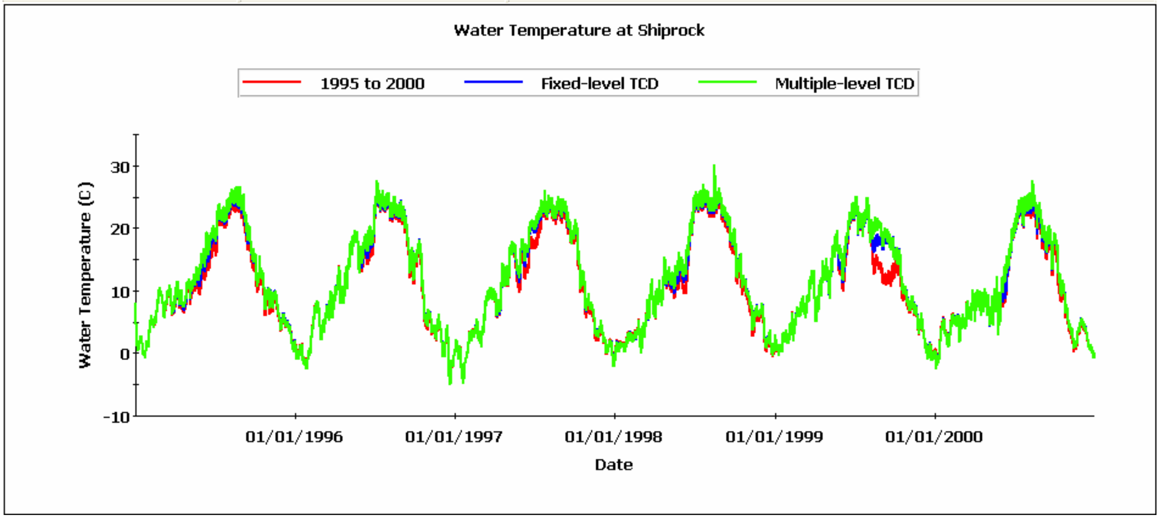


Figure 28. Water temperatures at Shiprock, NM with three scenarios: 1995 to 2000, fixed-level TCD, and multiple-level TCD.

Both TCD scenarios suggest a larger increase in water temperature at Farmington and Shiprock, NM during the period of high flow. The descending hydrographs of 1997 and 2000 were good examples of high flows transitioning to low flow, a multiple-level TCD could increase water temperatures at Farmington by 3.8 °C (7 °F) and at Shiprock by 3 °C (5 °F) (Figures 29-32). However, a fixed-level TCD was less consistent than a multiple-level TCD in achieving higher temperatures (Figures 29-32).

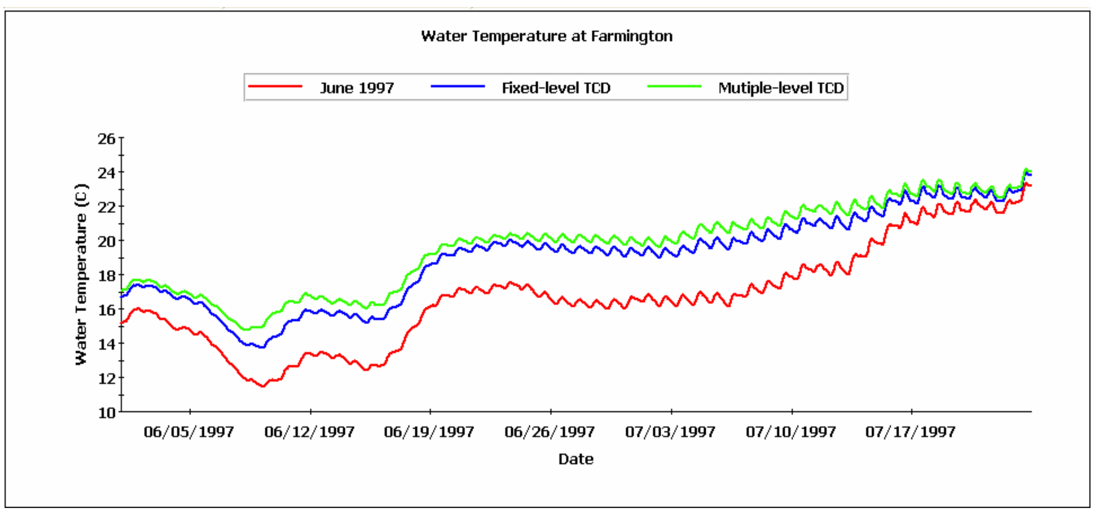


Figure 29: Water temperatures comparisons at Farmington, NM during 1997 descending hydrograph with three scenarios: June 5th through July 17th, fixed-level TCD, and multiple-level TCD.

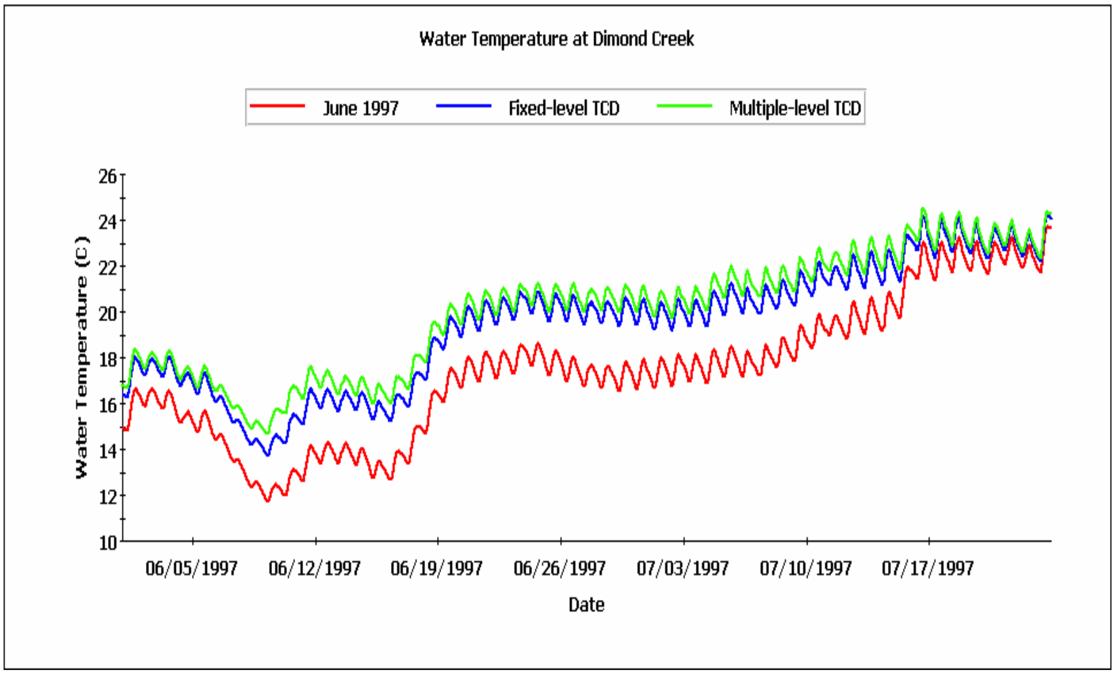


Figure 30: Water temperatures comparisons at Shiprock, NM during 1997 descending hydrograph with three scenarios: June 5th through July 17th, fixed-level TCD, and multiple-level TCD.

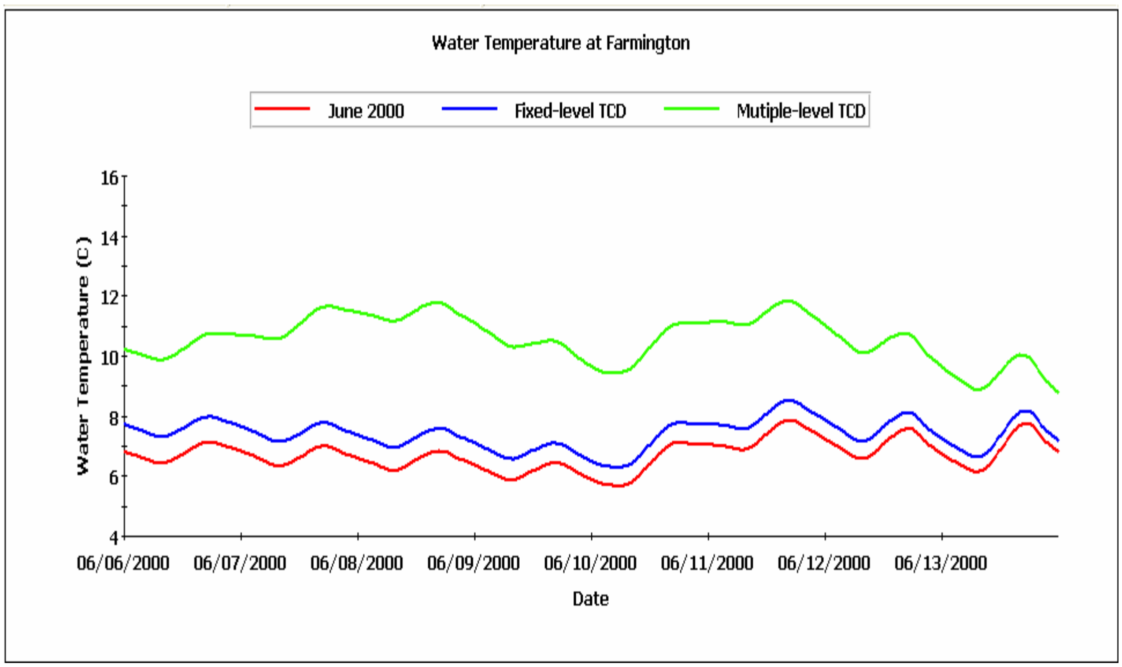


Figure 31. Water temperatures comparisons at Farmington, NM during 2000 descending hydrograph with three scenarios: June 5th through 13th, fixed-level TCD, and multiple-level TCD.

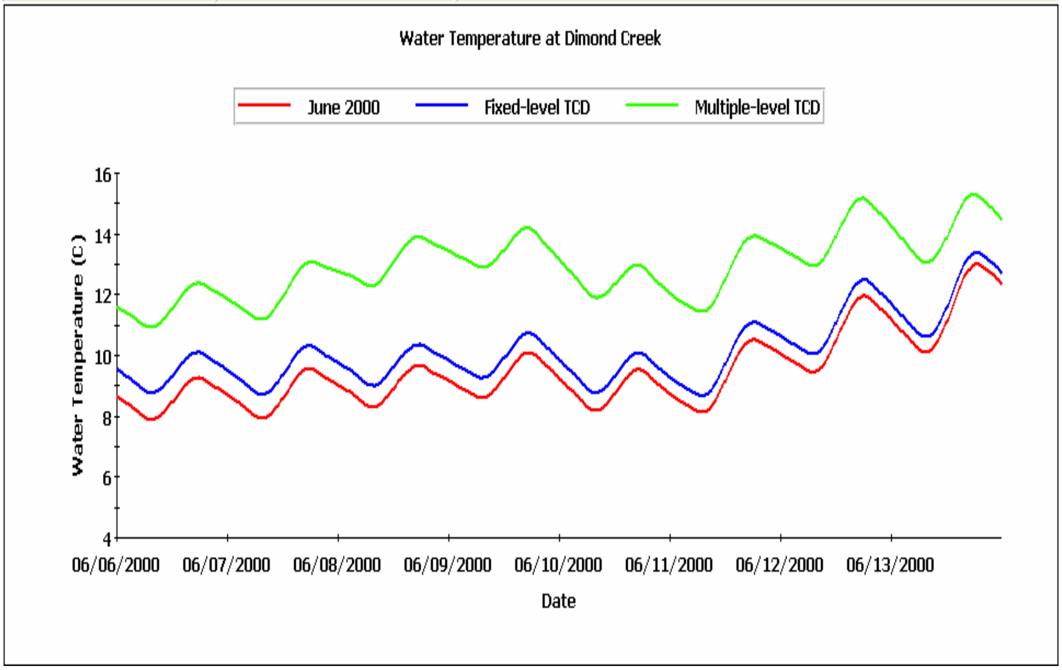


Figure 32. Water temperatures comparisons at Shiprock, NM during 2000 descending hydrograph with three scenarios: June 5th through 13th, fixed-level TCD, and multiple-level TCD.

The periods of 1997 and 2000 were good examples of how the fixed-level and multiple-level TCDs would have responded to reservoir elevations. In 1997, the reservoir elevation on June 5th was 6066 ft (1849 m) which was 9 ft (3 m) lower than June 5th of 2000. The lower elevation in 1997 created temperatures similar to those with a fixed-level and multiple-level TCD at Farmington and Shiprock. In 2000, with higher reservoir elevations and a fixed-level TCD, the temperatures at Farmington and Shiprock were closer to the temperatures without a TCD. These examples illustrate that during the periods of a descending hydrograph a TCD could increase temperatures at Farmington and Shiprock anywhere from 0.5 C to 4.5 °C (1-8 °F).

In summary, at Farmington the water temperature from May to October could increase as much as 8 °C (14 °F) with a fixed-level TCD, but the average increase would be 1.4 °C (2.5 °F). At the same location and time period a multi-level TCD could increase water temperature as high as 8.4 °C (15 °F) but on average only 2 °C (4 °F). At Shiprock the water temperature from May to October could increase as much as 7 °C (13 °F) with a one-level TCD, but the average increase would be 1 °C (2 °F). At the same location and time period a multi-level TCD could increase water temperature as high as 7.6°C (14 °F) with an average of 1.4 °C (2.5 °F).

10. DISCUSSION

This two-phased approach provided information addressing the effects of two types of TCDs on both the reservoir and the San Juan River downstream of Navajo dam. The W2 model provided a platform to predict the effects on Navajo Reservoir and provided release temperatures for various flow and TCD scenarios. Release volumes and temperatures predicted from the W2 model were then used as input to the river models.

Both river models suggested an average increase in water tempertures of 2 °C (4 °F) at Farmington and 1.4 °C (2.5 °F) at Shiprock with the multiple-level TCD option. My results showed that a TCD could increase release temperatures in the summer months, however it would not have much affect on temperatures below Farmington due to lower flows in the San Juan River and the relatively larger inputs from the Animas River. A TCD would have the most significant increase in temperature below Farmington during high flow periods.

Lamarra (2006) reported an optimal temperature range of 20 °C to 25 °C (68-77 °F) for the Colorado pikeminnow and razorback sucker in the San Juan River. Based on my models with the fixed-level TCD configuration, 20 °C temperatures were achievable in mid August in only 20% of the years. However my models suggested that a multiple-level TCD configuration could release 20 °C water in mid-July during all years. At Farmington, 20 °C is usually present during late June without a TCD. A fixed-level TCD would achieve 20 °C at Farmington approximately one week earlier than with no TCD, and two weeks earlier with a multiple-level TCD. 20 °C was available with and without a TCD by July at Shiprock.

11. CONCLUSIONS AND RECOMMENDATIONS

My results suggest that with a TCD there could be measurable increases in water temperature at Shiprock compared to current conditions. This study demonstrates that a fixed-level TCD would be less flexible across variable reservoir levels, but would provide some level of warming depending on the reservoir elevation and release volume. At reservoir elevations of 6,085 to 6,046 ft (1855-1843 m) a fixed-level TCD is predicted to work well. However, if reservoir elevations drop below 6,046 ft (1843 m), the fixed-level TCD scenario would not be operational. Furthermore, even if the reservoir is full, the water temperature from a fixed-level TCD may not fall within the optimal range of desired temperatures. The elevation selected for the fixed-level TCD was based upon a short period of hydrology and will likely not represent future elevations. A multiple-level TCD option would provide the most flexibility to operate under different reservoir elevations, but this scenario would involve higher capital costs.

Based on the reservoir model, more consistent water temperature monitoring locations should be added in Navajo Reservoir and below the dam to refine the calibration of the reservoir model. The reservoir profile data set used for the calibration of W2 model does not extend all the way to the reservoir floor; in fact these profiles do not extend low enough to capture the transition of the thermocline. Therefore a significant portion of the environment was not included in this study. Poor data reduces the quality of the calibration process. An ideal value for the mean error should be less than 1.0 °C (2 °F). Reduction of the mean error term for the river model requires better bathymetric data including travel times, roughness factors, and diversion data. This can be accomplished with dye tests and placement of gages at withdrawal locations. The water quality data set for the reservoir and for the river should be continuous (i.e. daily) and of a longer period to provide a complete analysis.

Model assumptions and uncertainties included average monthly tributary inflows and temperatures. For the TCD scenarios, my assumptions included the TCD designs, buffer elevation levels, and an absence of leakage; these assumptions influenced the modeled TCD release temperatures. Reservoir and river system modeling relies on boundary-inputs to characterize downstream conditions. In this case where boundary data were incomplete, I used interpolated data and this contributed to uncertainty. The uncertainties in downstream river models also include lack of withdrawal data in the San Juan River.

In summary the goal of this project was to answer several questions:

- Would an increase in release temperature from Navajo Dam result in increased water temperatures at Farmington and Shiprock, NM?

In summary, at Farmington the water temperature from May to October could increase as much as 8 °C (14 °F) from a fixed-level TCD, but the average increase would be 1.4 °C (2.5 °F). At the same location and time period a multi-level TCD could increase water temperature as high as 8.4 °C (15 °F) but on average only 2 °C (4 °F). At Shiprock the water temperature from May to October could increase as much as 7 °C (13 °F) from a fixed-level TCD, but the average increase would be 1 °C (2 °F). At the same location and time period a multi-level TCD could increase water temperature as high as 7.6°C (14 °F) and an average of 1.4 °C (2.5 °F).

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

In general, large inflow years (wet) deepen reservoir stratification and increase the released water temperature in the late summer. With a TCD during wet years, warmer temperatures would occur earlier in the year than during dry years.

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

The W2 model indicated the volume of water in the reservoir most influenced by a TCD was the 10 °C to 18 ^{o}C (50-64 ° F) zones of water temperatures. But year-to-year carry-over effects on temperatures does not appear to be a significant factor. Instead, temperatures seem to be most dominated by inflow and meteorological effects.

- What were the best TCD options to achieve downstream warming?

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

The tools and analysis addressed in this report were a great starting point for future analyses as deemed necessary by the committee. Below was a list of the recommendations:

- More temperature monitoring locations should be added in the reservoir and below the dam to facilitate future reservoir model calibration.
- More information is needed on river travel-time to improve river model calibration.
- The committee should identify the level of uncertainty in model predictions that they were willing to accept.

11. REFERENCES

Barker, J. 2003, phone conversation on San Juan River travel time, Ecosystems Research Institute, Logan, UT.

Bliesner, R., Lamarra, V. 2000. "Hydrology Geomorphology and Habitat Studies", San Juan River Basin Recovery Implementation Program, Keller-Bliesner Engineering, Logan, UT.

Brown, L. C. and T.O. Barnwell. 1987. "The Enhanced Stream Water Quality Models QUAL2E and QUAL2E-UNCAS: Documentation and User Manual", EPA-600/3-87/007. U.S. Environmental Protection Agency, GA.

Brown, L. C. 1987. "Uncertainty Analysis in Water Quality Modeling Using QUAL2E" Tufts University, Medford, MA.

Chapra, S. C. 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. M. 1995. "A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 2.0", Final Report E-86-5, U.S. Army Corps of Engineers.

Edinger, J. E. and D. K. Brady. 1974. "Heat Exchange and Transport in the Environment. Cooling Water Discharge Research Project (RP-49)", Electric Power Research Institute, CA.

Edinger, J. E. and E. M. Buchak. 1980. "Numerical Hydrodynamics of Estuaries in Estuarine and Wetland Processes with Emphasis on Modeling", Plenum Press, New York, New York.

Environmental Resources Management. 2006. GEMSS-1D: User Guide. GEMSS Development Team, ERM, Exton, PA.

Holden, P. B. 1973. "Distribution, Abundance, and Life History of the Fishes of the Upper Colorado Riverbasin". Ph.D. dissertation, Utah State University, Logan, UT.

Holden, P. B. (Ed.). 1999. "Flow Recommendations for San Juan River", San Juan River Basin Recovery Implementation Program, U.S. Fish and Wildlife Service, Albuquerque, NM.

Kolluru S. V. and M. Fichera 2003. "Development and Application of Combined 1-D and 3-D Modeling System for TMDL Studies", Reprinted from Estuarine and Coastal Modeling Proceedings of the Eighth International Conference American Society of Civil Engineers, Monterey, California, pp 108-127.

Lamarra, V. A. 2006. "San Juan River Fishery Response to Thermal Modification—DRAFT", San Juan River Recovery Implementation Program Biology Committee, Ecosystems Research Institute, Logan, UT.

Seethalar, K. H., C. W. McAda, and R. S. Wydoski. 1976. "Endangered and Threatened Fish in the Yampa and Green Rivers of Dinosaur National Monument". Utah Cooperative Fisheries Research Unit, Utah State University. Logan, UT.

Simons, J. 2003, phone conversation on San Juan Riverware model inputs, U.S Department of the Interior Bureau of Reclamation, Upper Colorado Region Western Colorado Area Office, Durango, CO.

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.

USBR. 2003. "Draft Environmental Impact Statement, Navajo Reservoir Operations", Navajo Unit-San Juan River, Volumes I and II, U.S Department of the Interior Bureau of Reclamation, Upper Colorado Region Western Colorado Area Office, Grand Junction – Durango, CO.

USBR. 1998. "Summary Report San Juan River Winter Flow Test", Navajo Unit, U.S Department of the Interior Bureau of Reclamation, Upper Colorado Region Western Colorado Area Office, Southern Division, CO.

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.

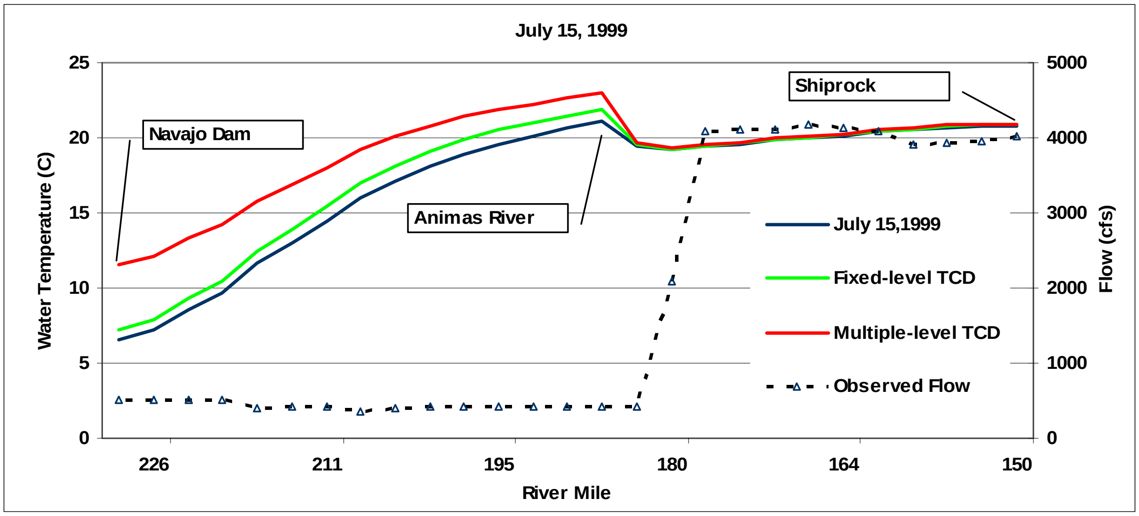
Vanicek, C. D., R. A. Kramer, and D. R. Franklin. 1970. "Distribution of Green River Fishes in Utah and Colorado Following Closure of Flaming Gorge Dam". Southwest Naturalist 14(3): 294-315.

Vanicek, C. D. 1967. "Ecological Studies of Green River Fishes Below Flaming Gorge Dam, 1964-1966. PhD Dissertation. Utah State University, Logan, UT.

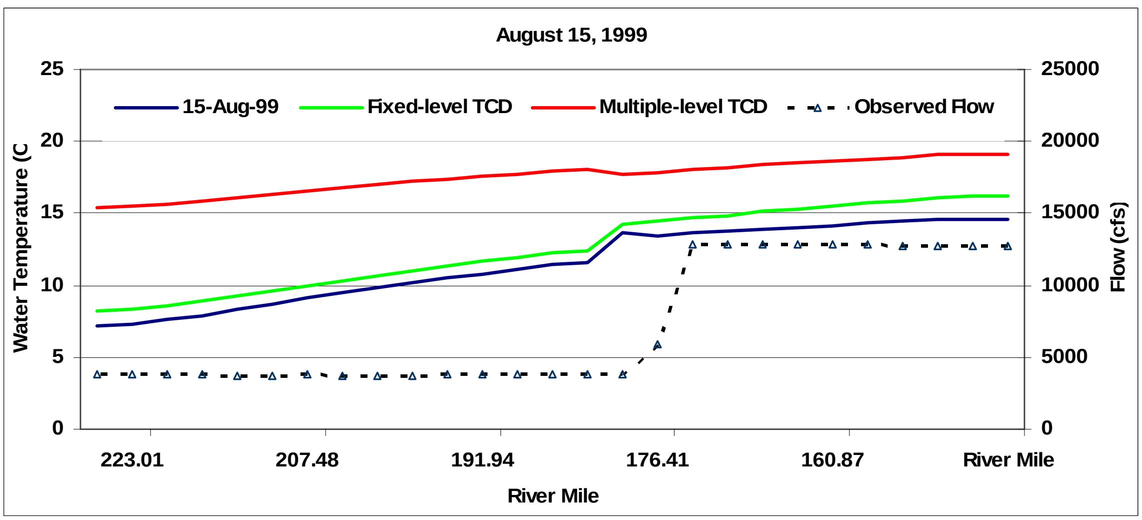
Westfall, B. 2003, phone conversation on San Juan River cross section data, Keller-Bliesner Engineering, Logan, UT.

12. APPENDIX A

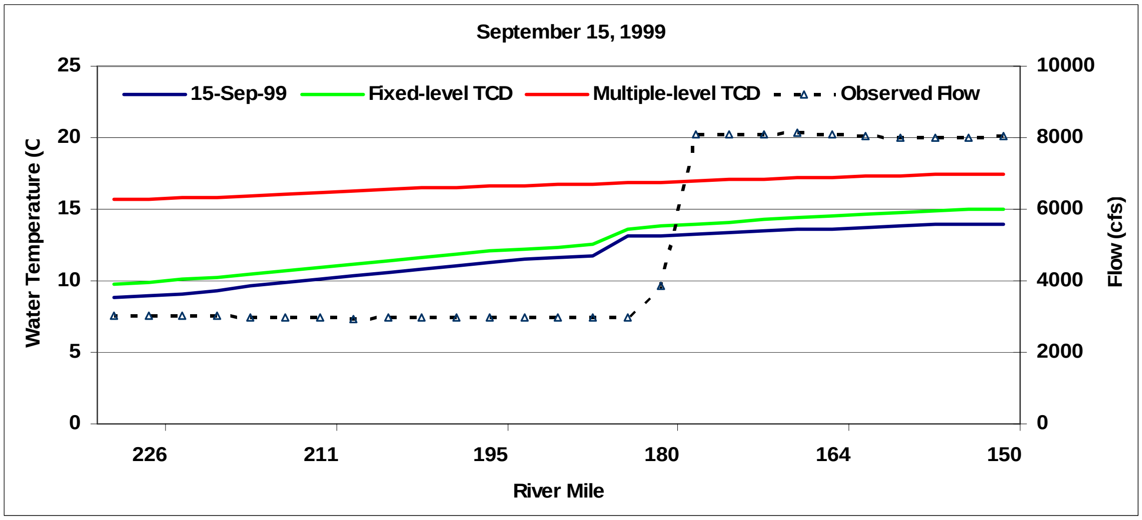
QUAL2K Results

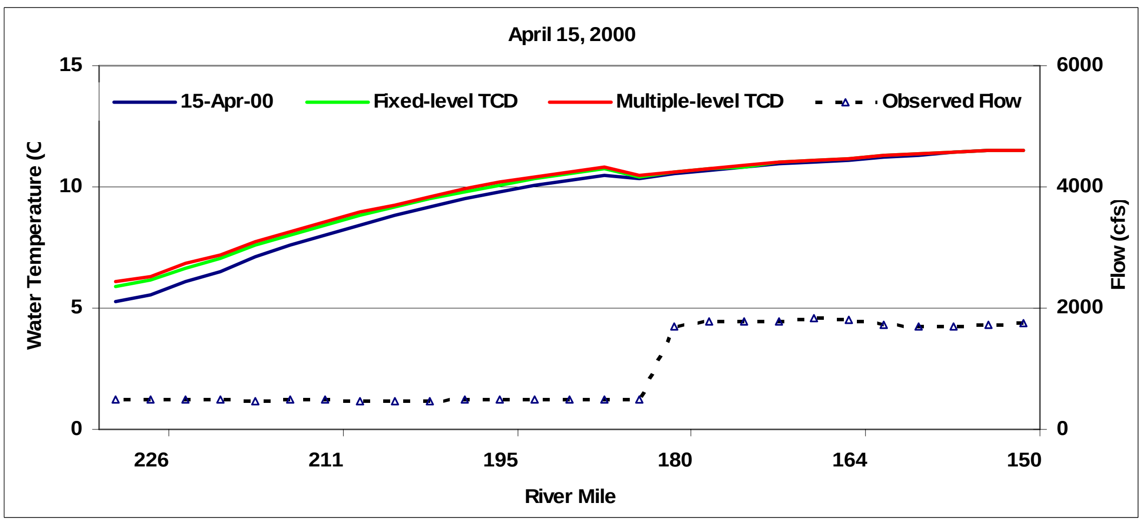


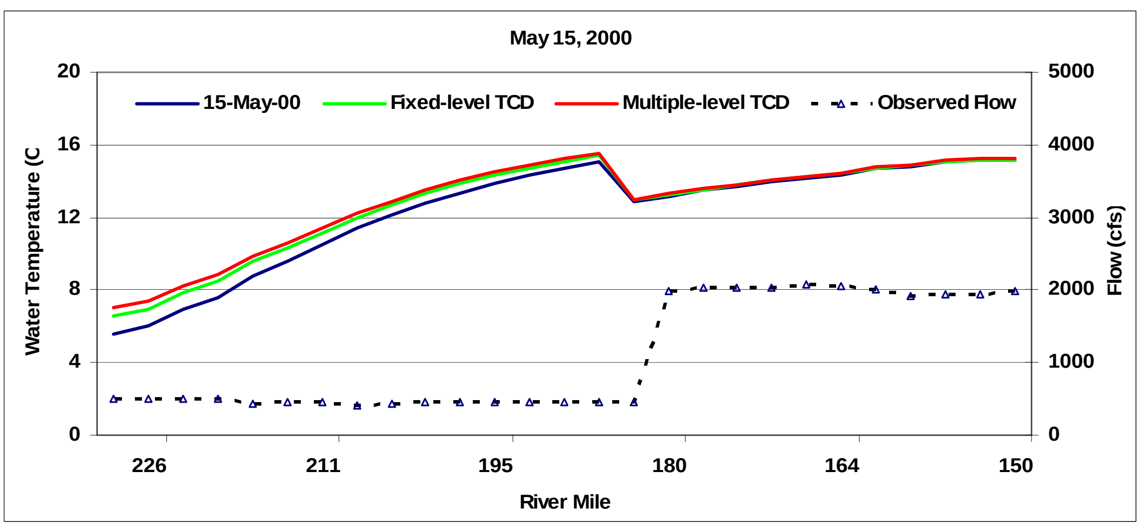
This scenario represents longitudinal water temperature in the San Juan River down stream of Navajo Reservoir, NM with normal release and the use of a fixed-level and multiple-level TCD on July 15.

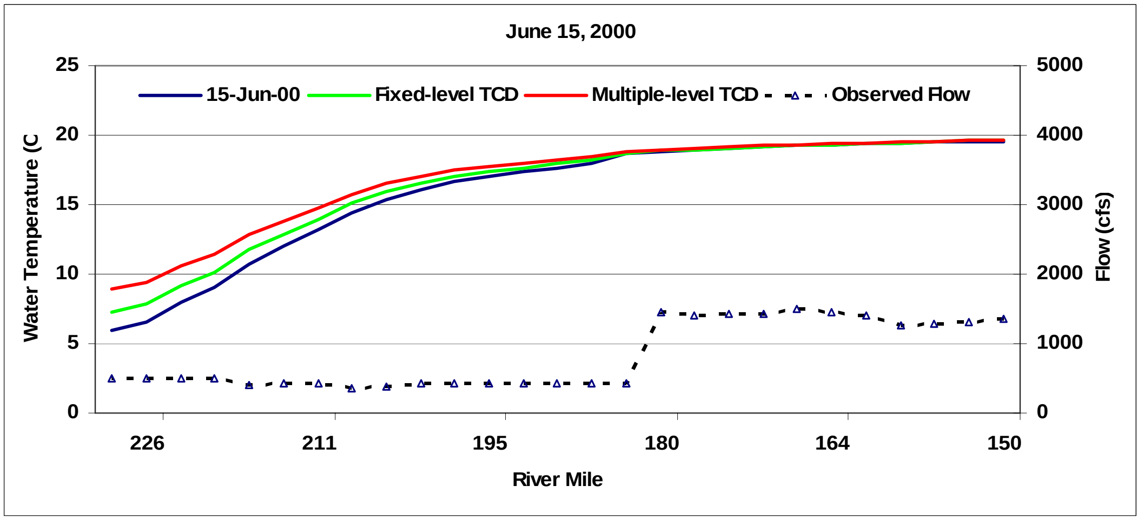


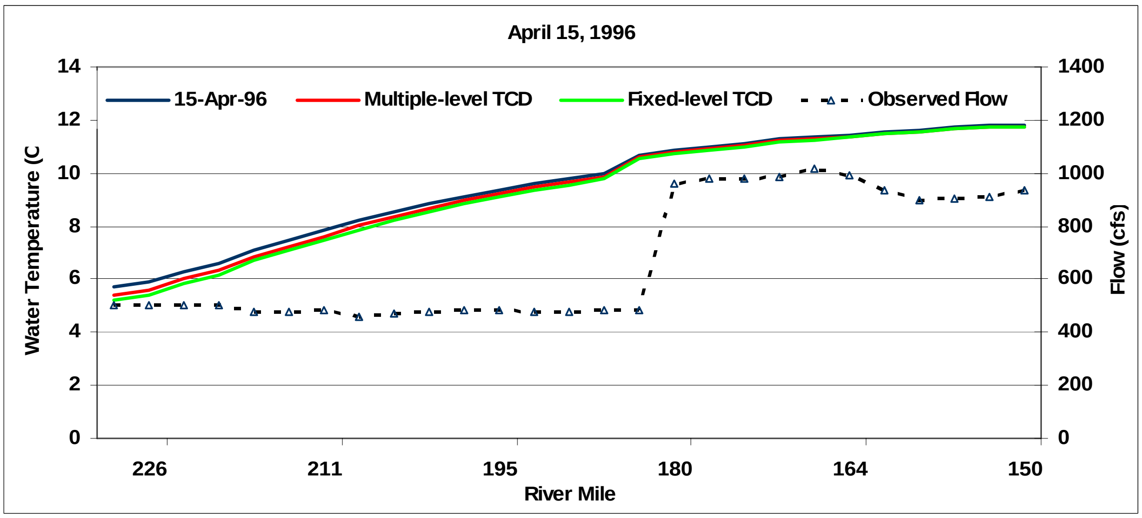
This scenario represents longitudinal water temperature in the San Juan River down stream of Navajo Reservoir, NM with normal release and the use of a fixed-level and multiple-level TCD on August 15.

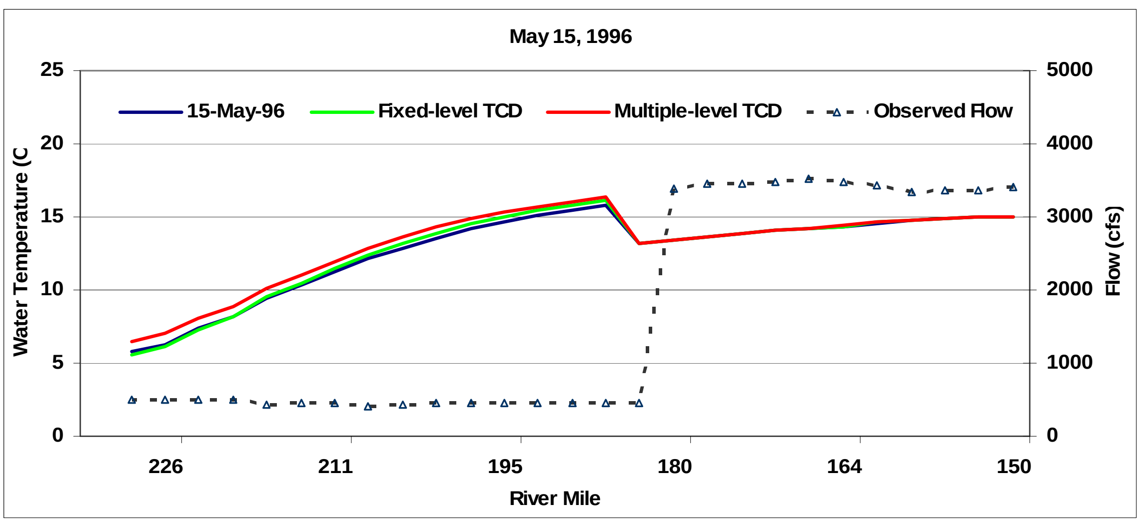

September 15, 1999
15-Sep-99
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
25
20
15
10
5
0
10000
8000
6000
4000
2000
0
226
211
195
180
164
150

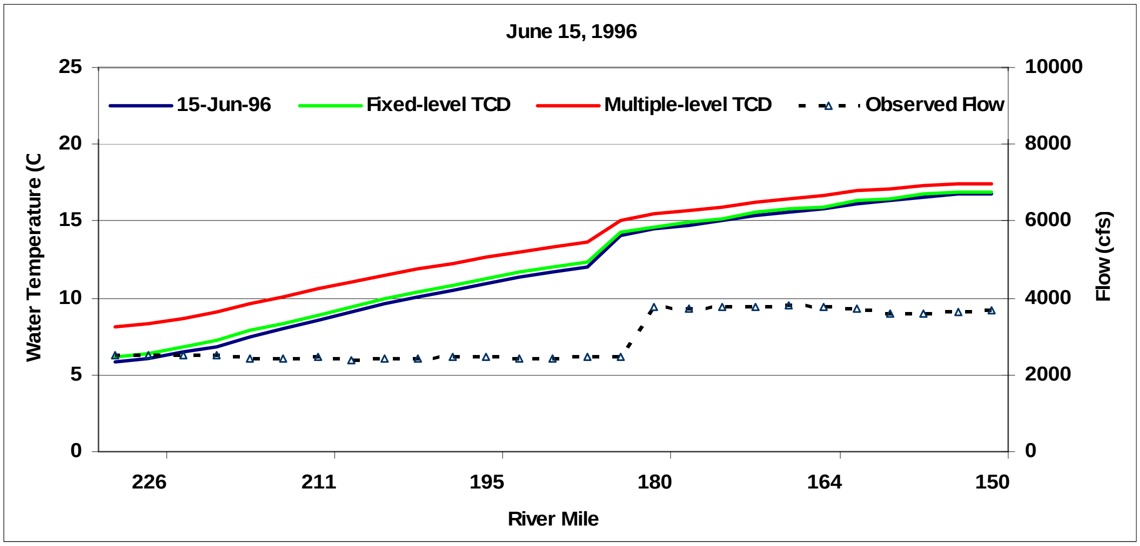

April 15, 2000
15-Apr-00
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
15
10
5
0
6000
4000
2000
0
226
211
195
180
164
150

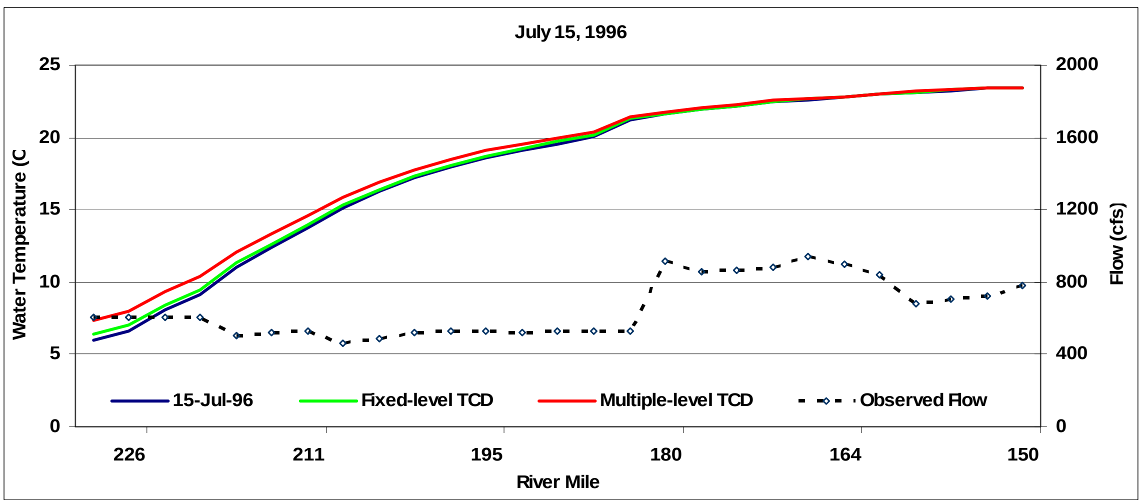

May 15, 2000
15-May-00
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
20
16
12
8
4
0
5000
4000
3000
2000
1000
0
226
211
195
180
164
150

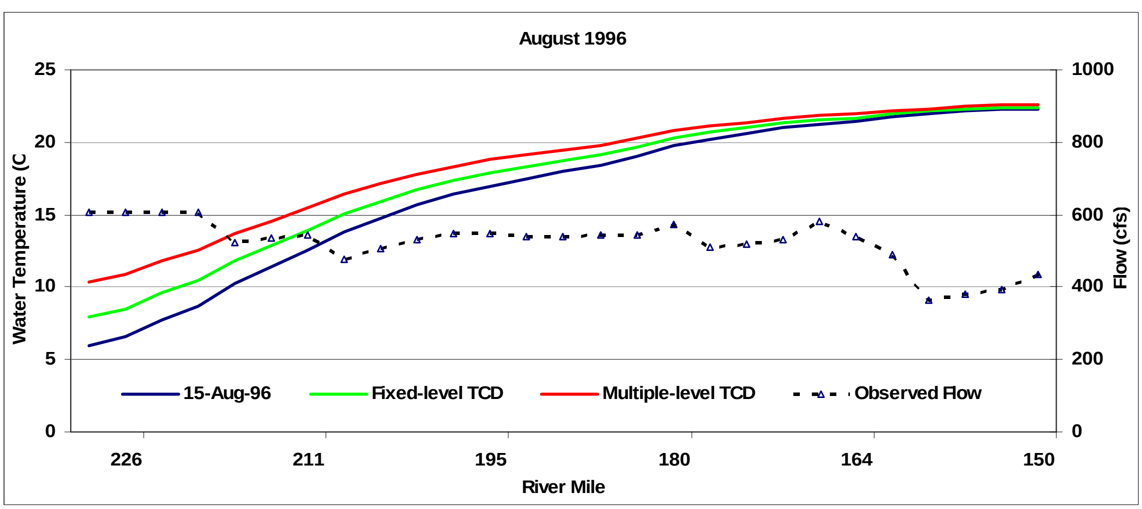

June 15, 2000
15-Jun-00
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
25
20
15
10
5
0
5000
4000
3000
2000
1000
0
226
211
195
180
164
150

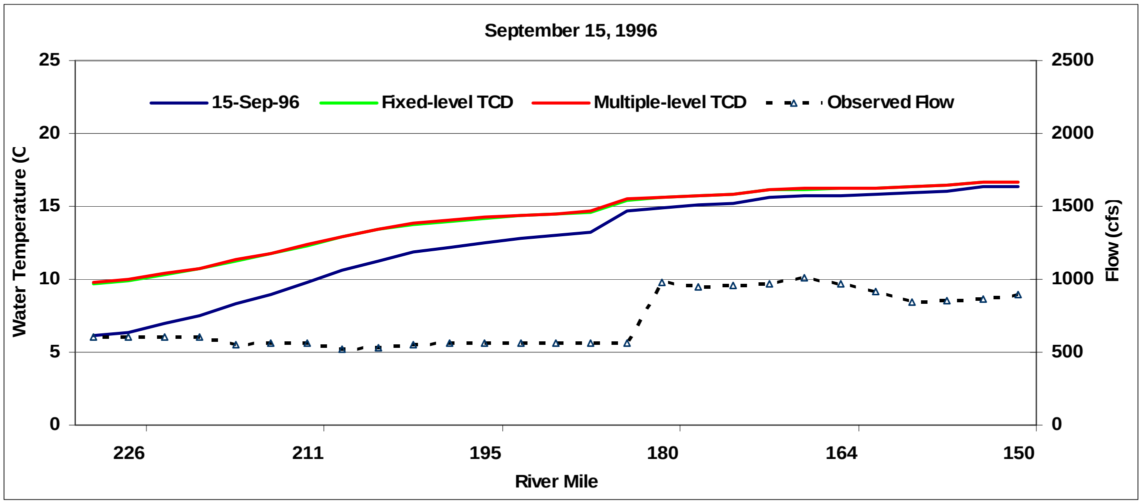

April 15, 1996
15-Apr-96
Multiple-level TCD
Fixed-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
14
12
10
8
6
4
2
0
1400
1200
1000
800
600
400
200
0
226
211
195
180
164
150

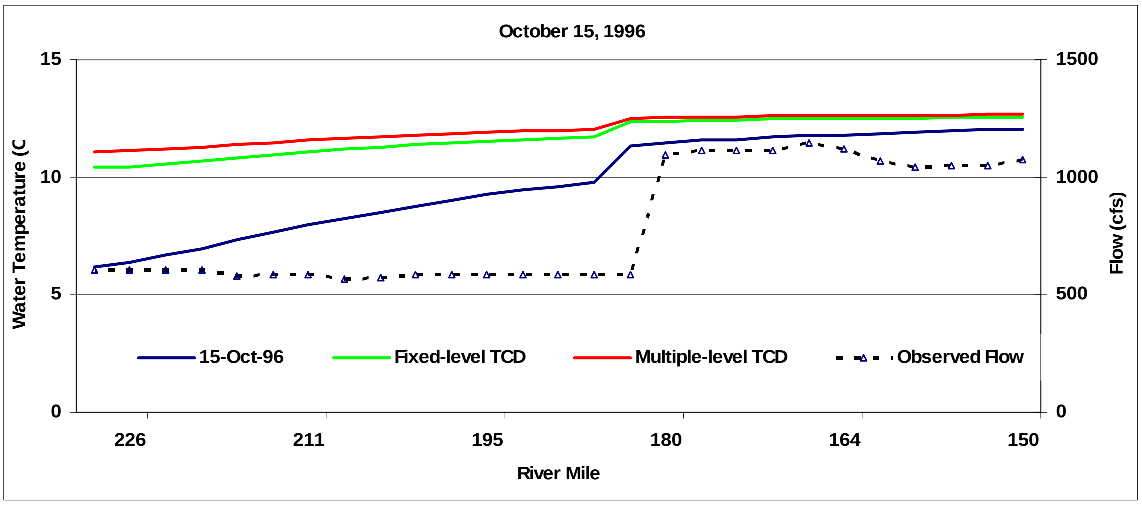

May 15, 1996
15-May-96
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
25
20
15
10
5
0
5000
4000
3000
2000
1000
0
226
211
195
180
164
150


June 15, 1996
15-Jun-96
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
0
5
10
15
20
25
0
2000
4000
6000
8000
10000
226
211
195
180
164
150

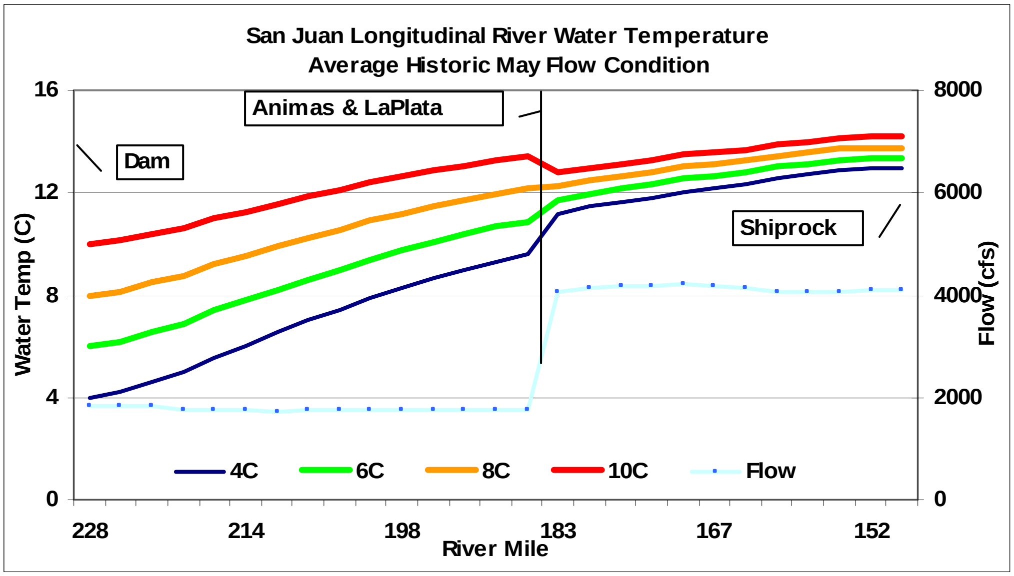

July 15, 1996
15-Jul-96
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
0
5
10
15
20
25
0
400
800
1200
1600
2000
226
211
195
180
164
150

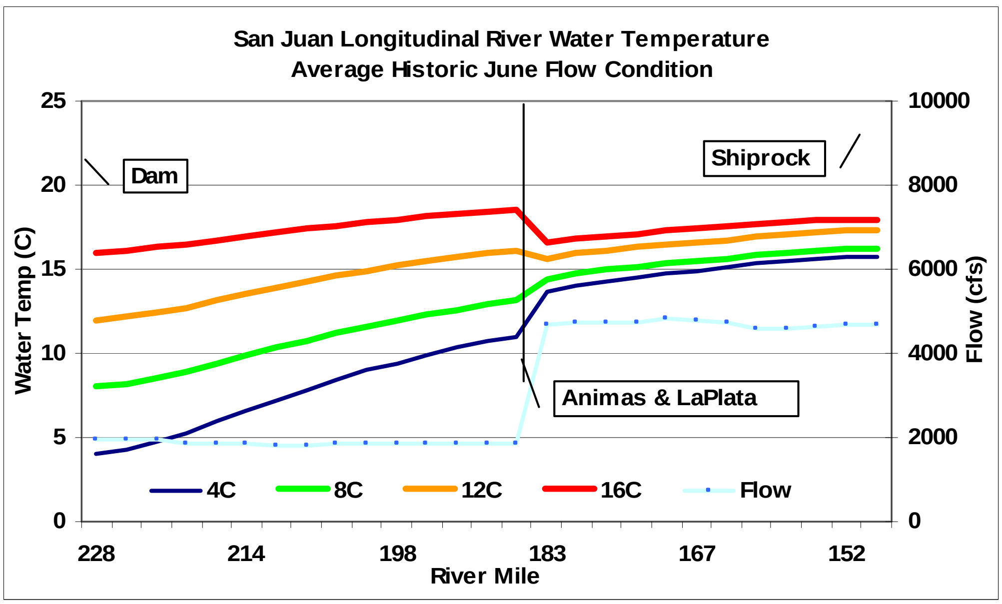

August 1996
15-Aug-96
Fixed-level TCD
Multiple-level TCD
Observed Flow
Water Temperature (C
Flow (cfs)
River Mile
0
5
10
15
20
25
0
200
400
600
800
1000
226
211
195
180
164
150

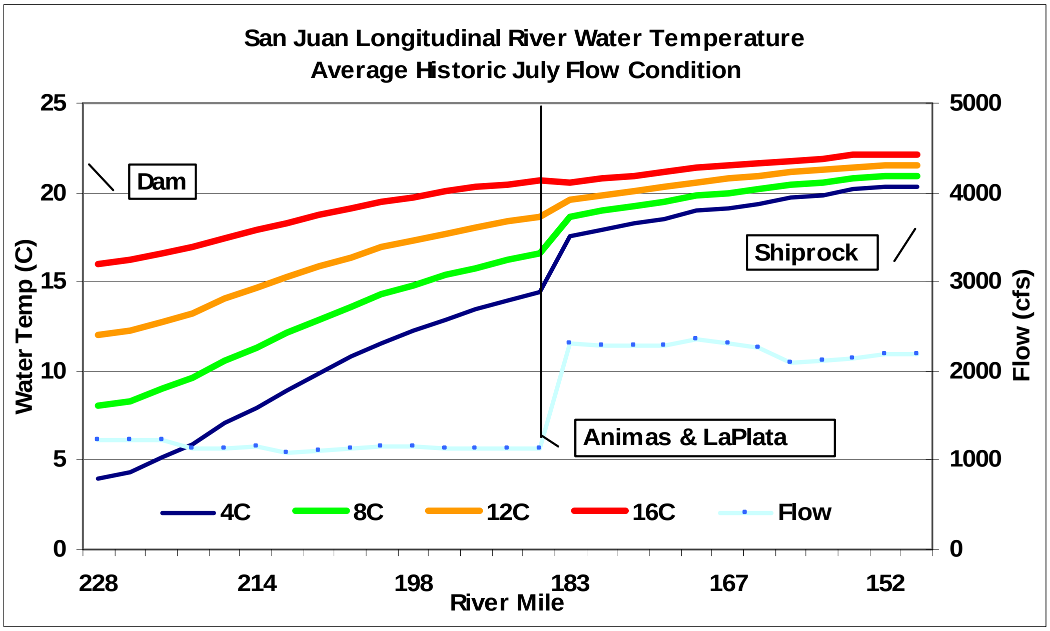


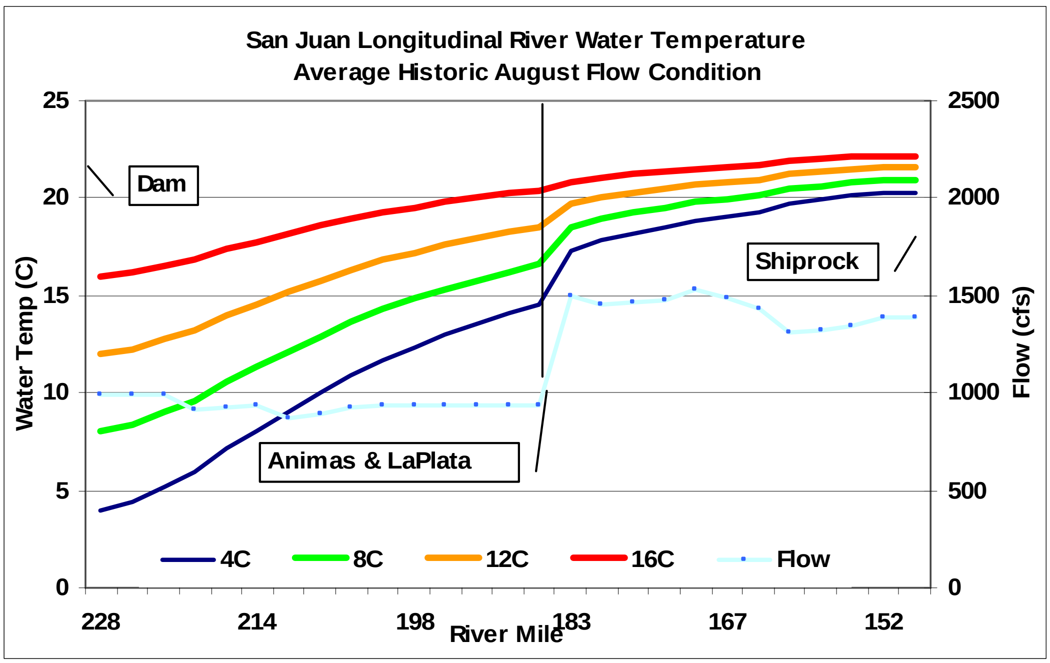


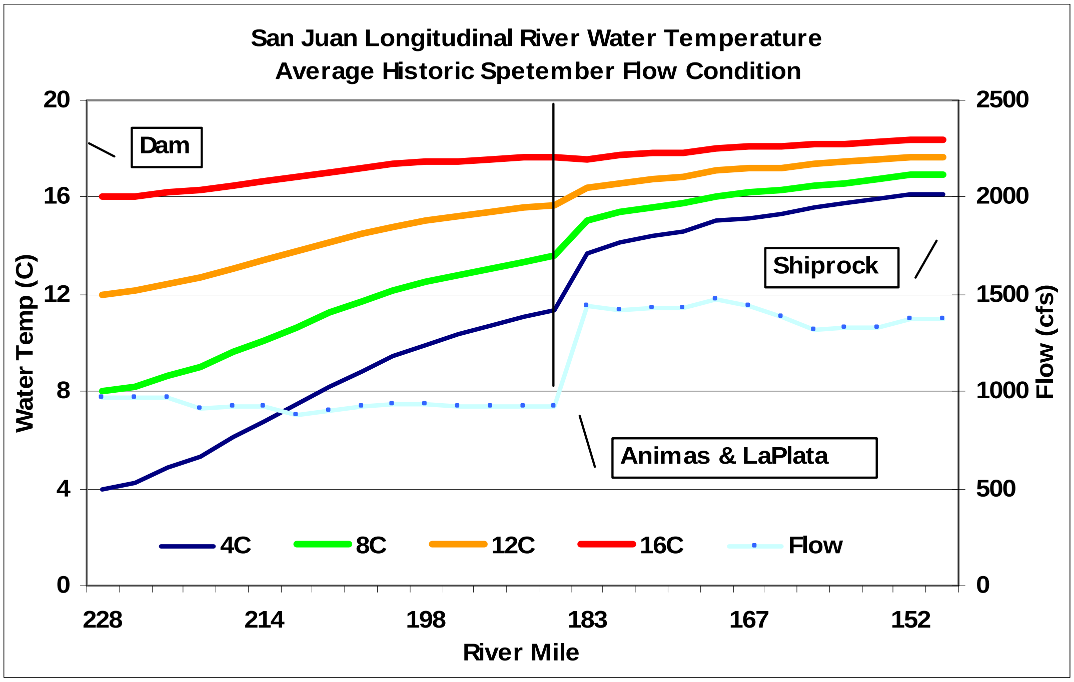
Average Flow Conditions (May to October)

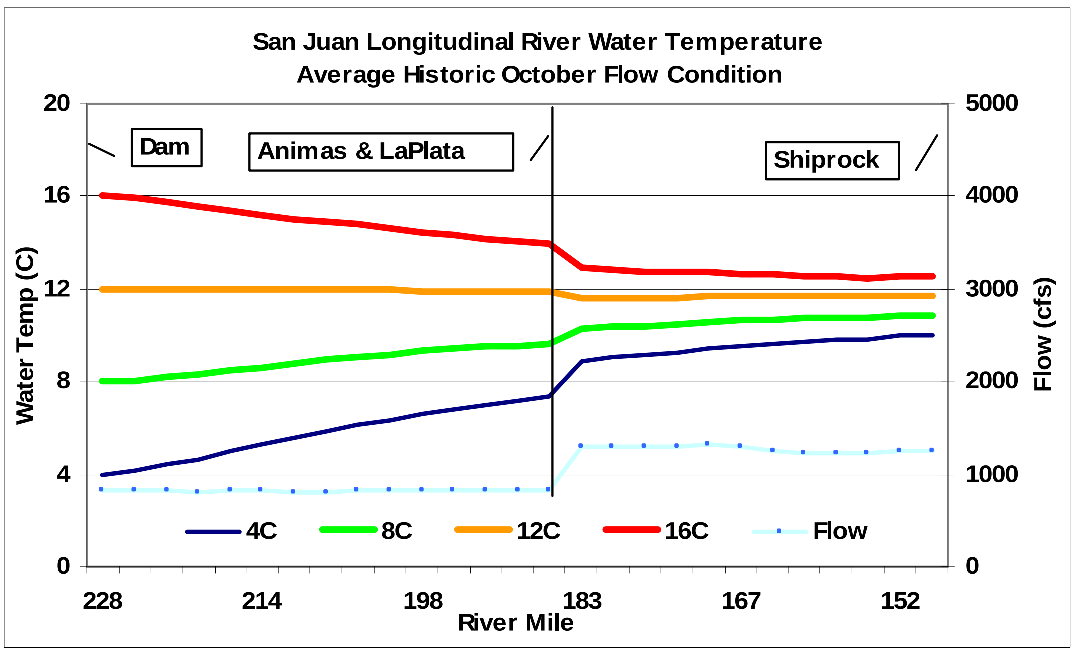

San Juan Longitudinal River Water Temperature
Average Historic May Flow Condition
Animas & LaPlata
Dam
Shiprock
Water Temp (C)
Flow (cfs)
16
12
8
4
0
8000
6000
4000
2000
0
4C
6C
8C
10C
Flow
228
214
198
183
167
152
River Mile


San Juan Longitudinal River Water Temperature
Average Historic June Flow Condition
Dam
Shiprock
Animas & LaPlata
Water Temp (C)
Flow (cfs)
25
20
15
10
5
0
10000
8000
6000
4000
2000
0
4C
8C
12C
16C
Flow
228
214
198
183
167
152
River Mile


San Juan Longitudinal River Water Temperature
Average Historic July Flow Condition
Water Temp (C)
Flow (cfs)
River Mile
Dam
Shiprock
Animas & LaPlata
4C
8C
12C
16C
Flow
25
20
15
10
5
0
5000
4000
3000
2000
1000
0
228
214
198
183
167
152

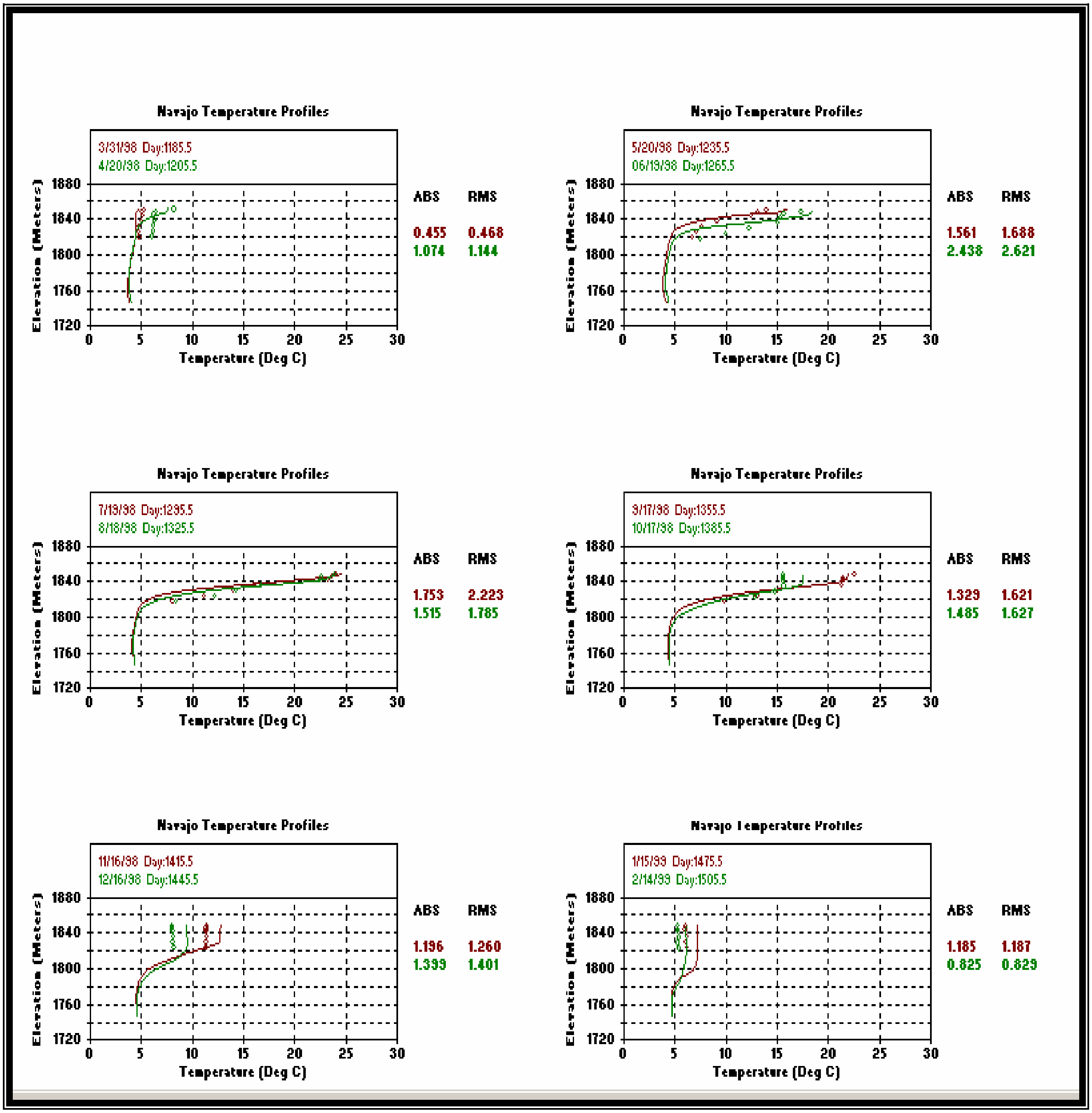

San Juan Longitudinal River Water Temperature
Average Historic August Flow Condition
Water Temp (C)
Flow (cfs)
River Mile
Dam
Shiprock
Animas & LaPlata
4C
8C
12C
16C
Flow
25
20
15
10
5
0
2500
2000
1500
1000
500
0
228
214
198
183
167
152


San Juan Longitudinal River Water Temperature
Average Historic Spetember Flow Condition
Dam
Shiprock
Animas & LaPlata
Water Temp (C)
Flow (cfs)
River Mile
4C
8C
12C
16C
Flow
228
214
198
183
167
152
0
4
8
12
16
20
0
500
1000
1500
2000
2500

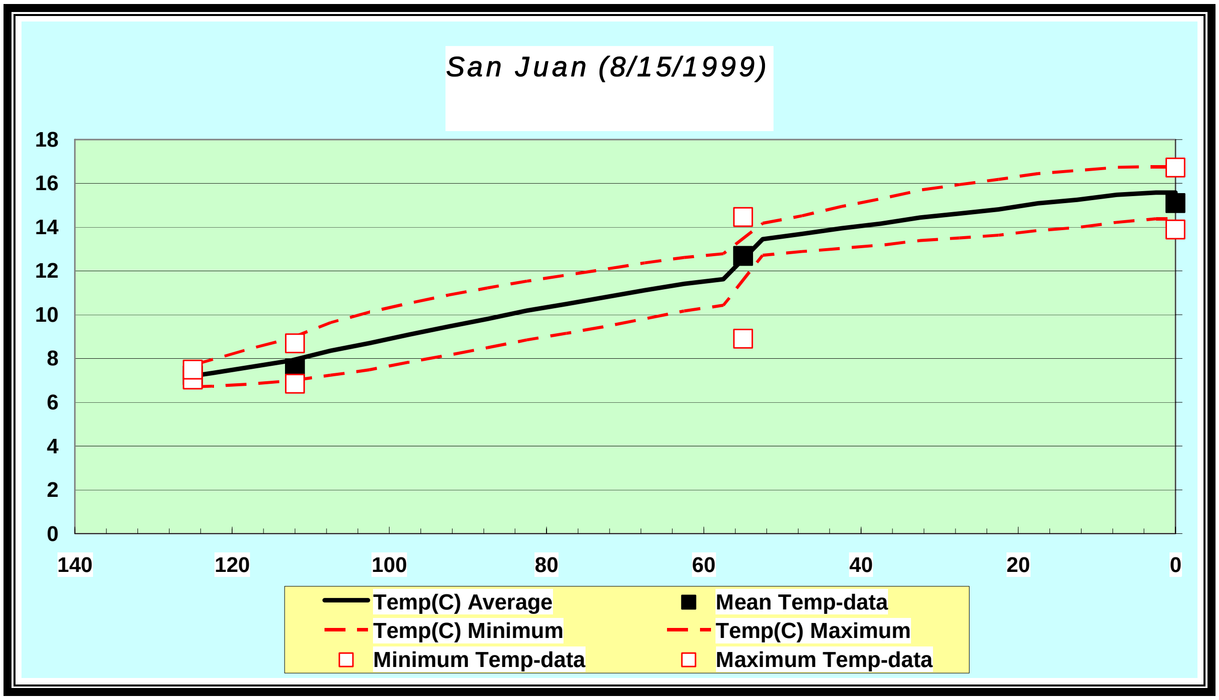

San Juan Longitudinal River Water Temperature
Average Historic October Flow Condition
Dam
Animas & LaPlata
Shiprock
Water Temp (C)
Flow (cfs)
River Mile
4C
8C
12C
16C
Flow
228
214
198
183
167
152
0
4
8
12
16
20
0
1000
2000
3000
4000
5000

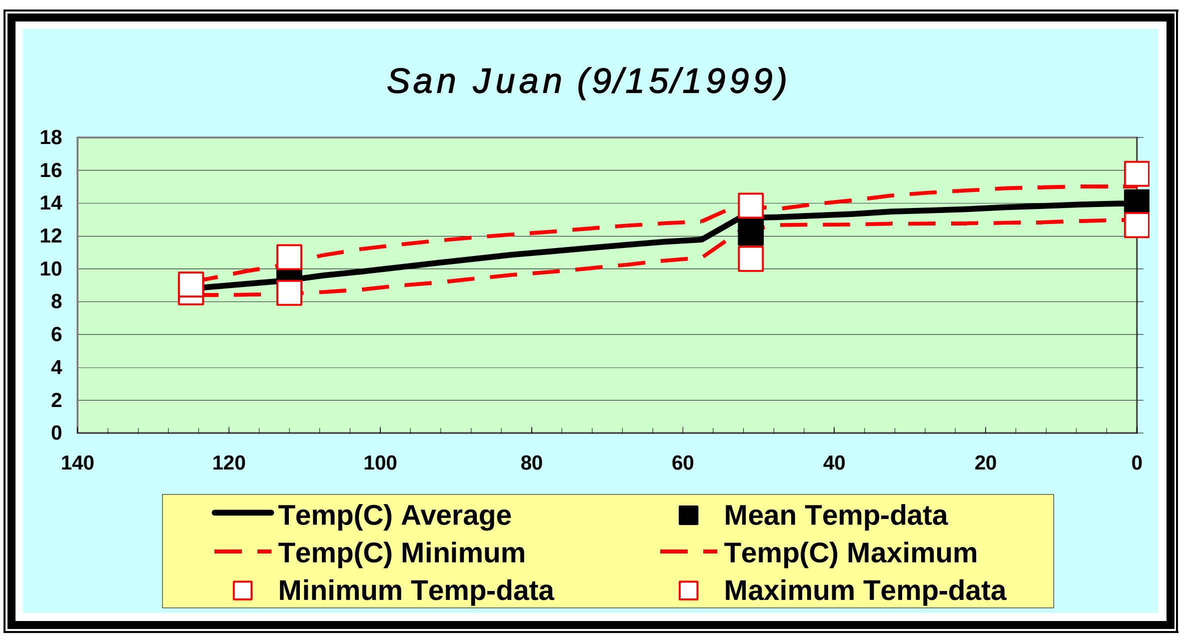
13. APPENDIX B

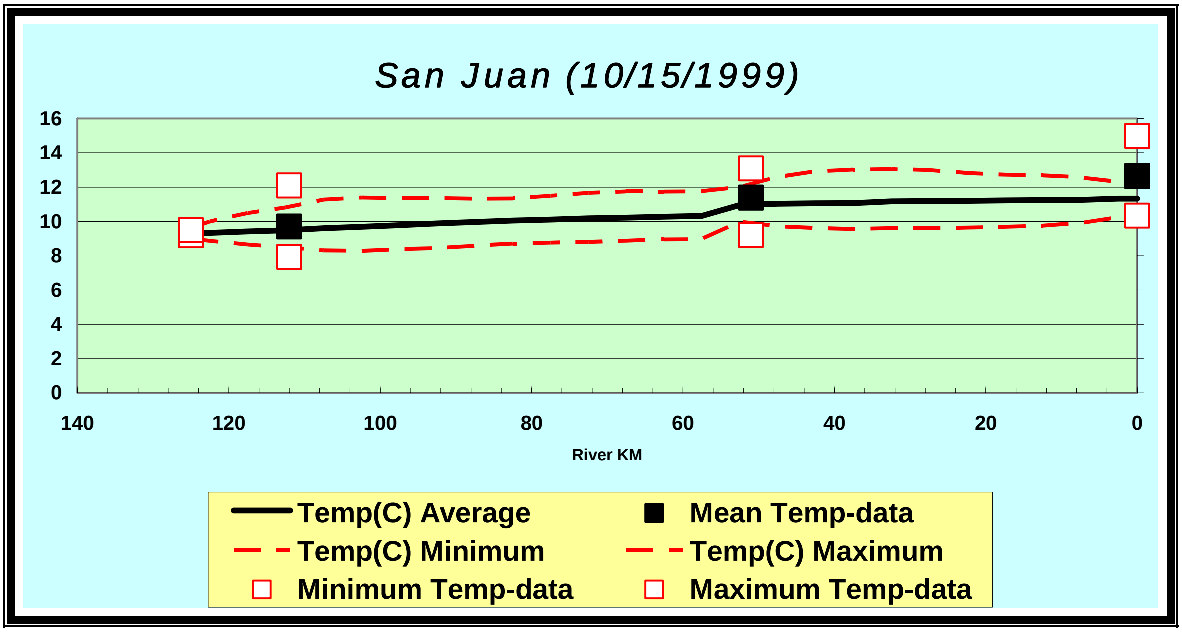
W2 Profile Calibration Plots

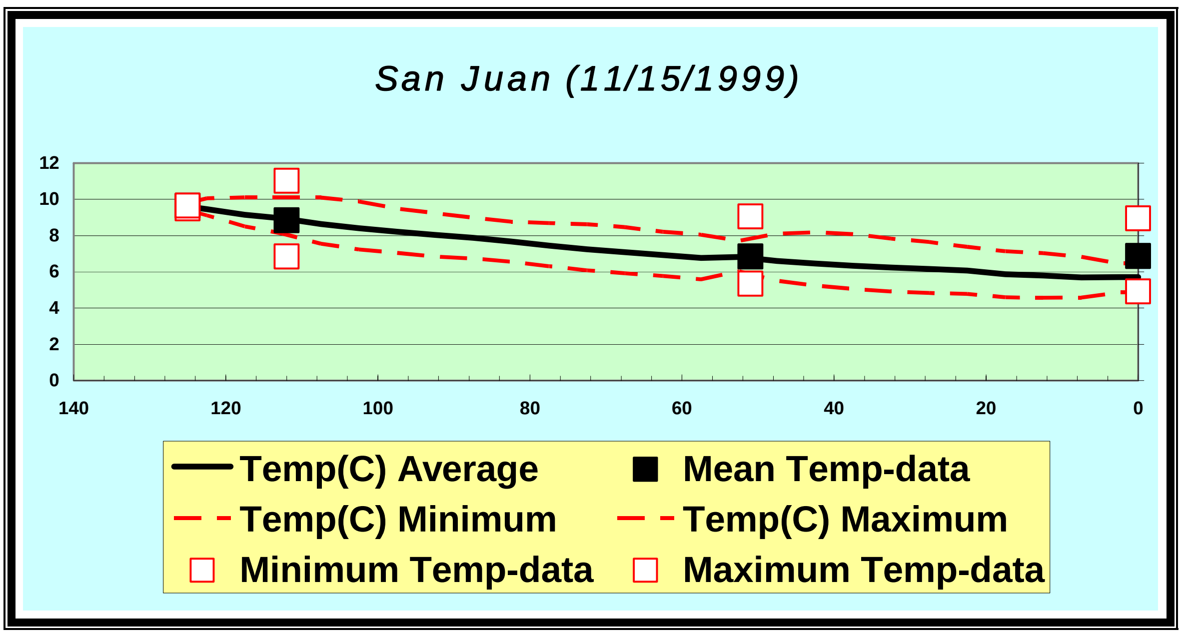


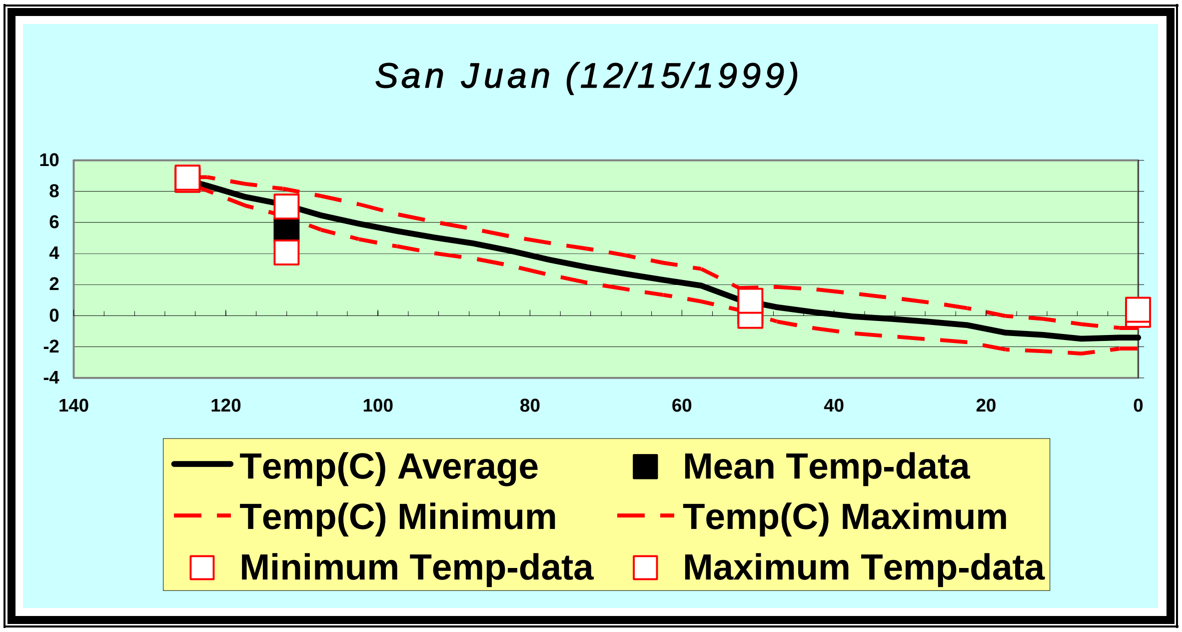
2K Calibration Plots

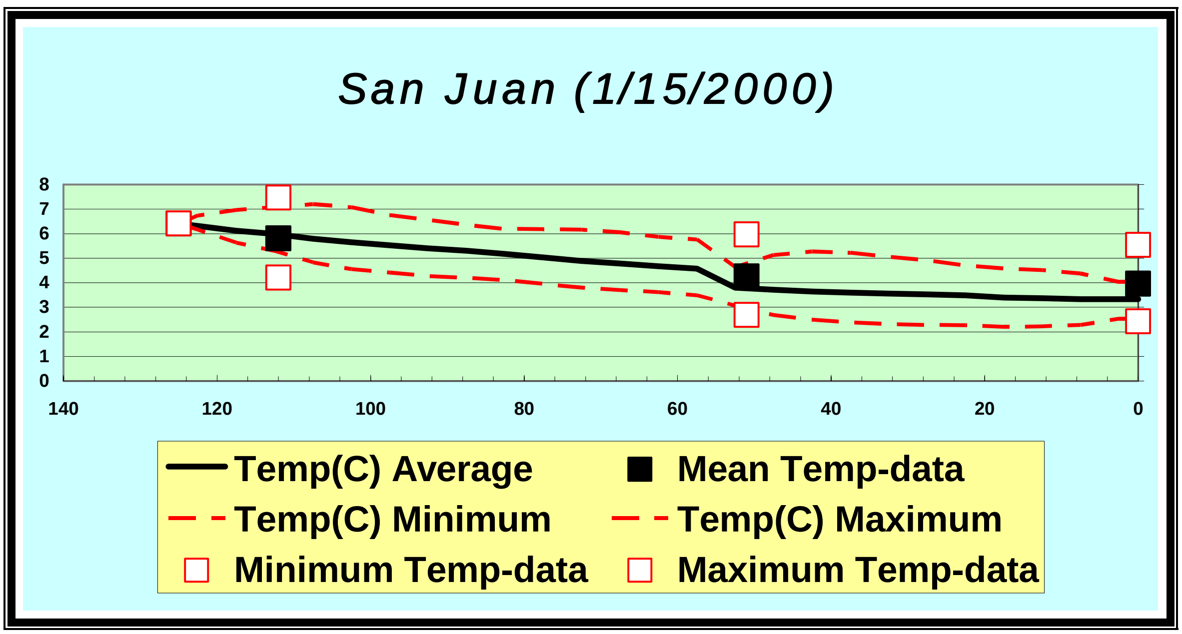


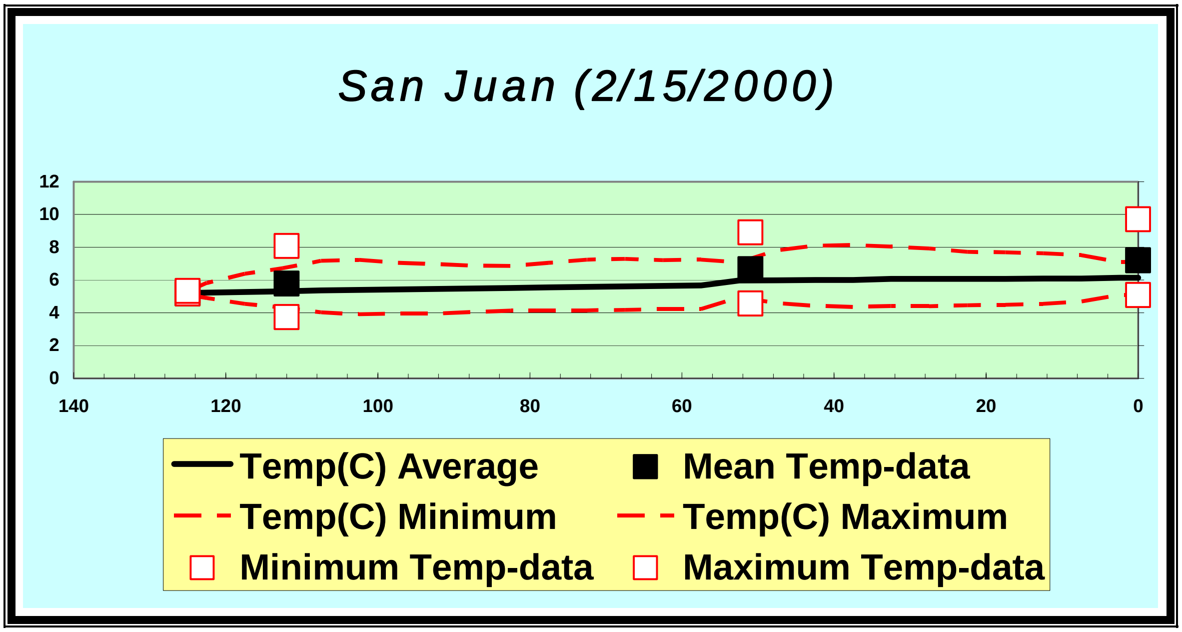


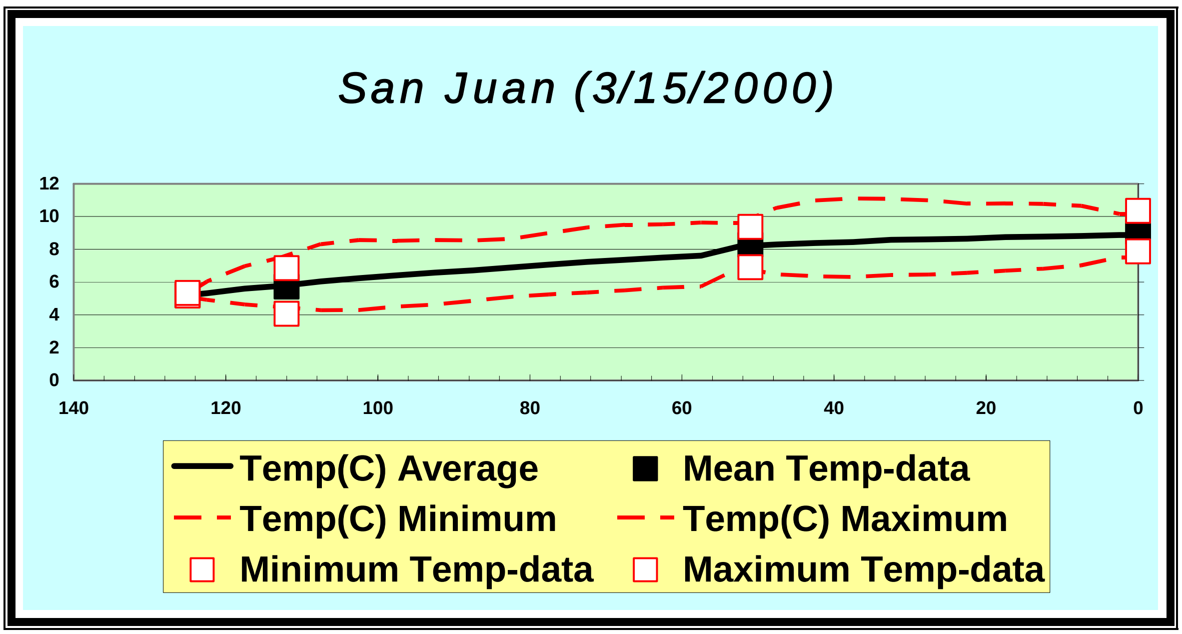

San Juan (10/15/1999)
16
14
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
River KM
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

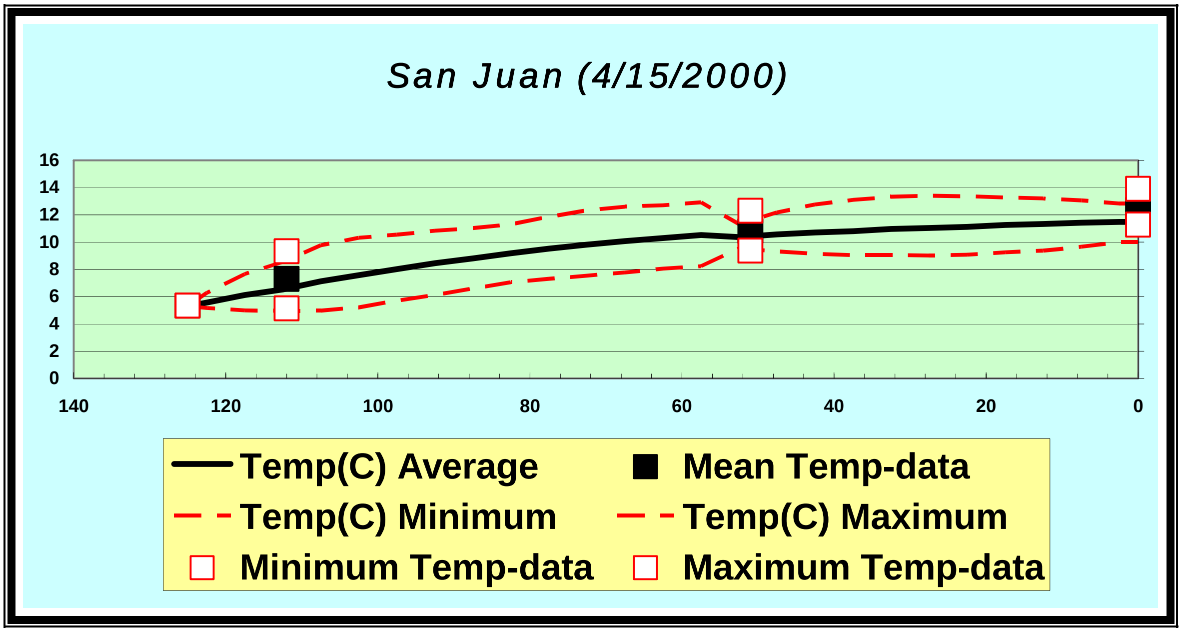

San Juan (11/15/1999)
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

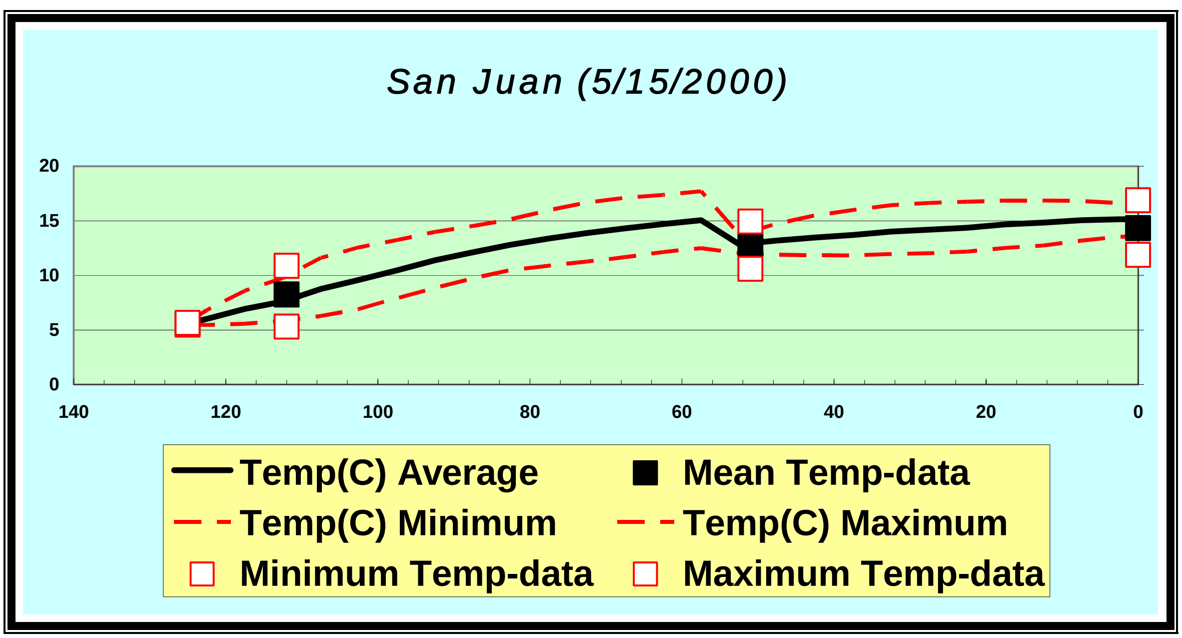

San Juan (12/15/1999)
10
8
6
4
2
0
-2
-4
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data


San Juan (1/15/2000)
8
7
6
5
4
3
2
1
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

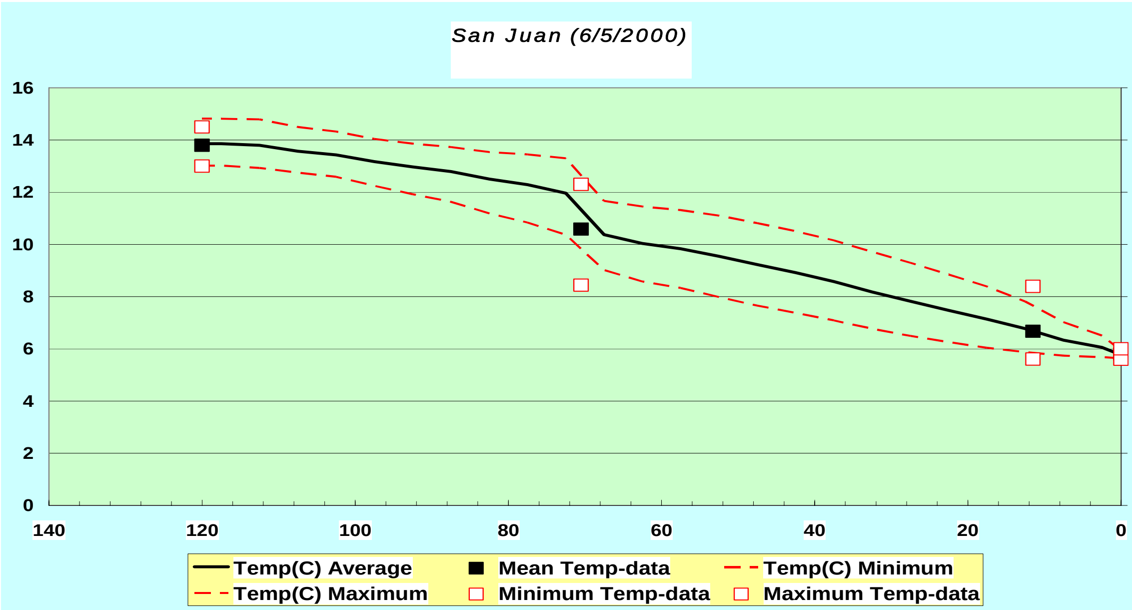

San Juan (2/15/2000)
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

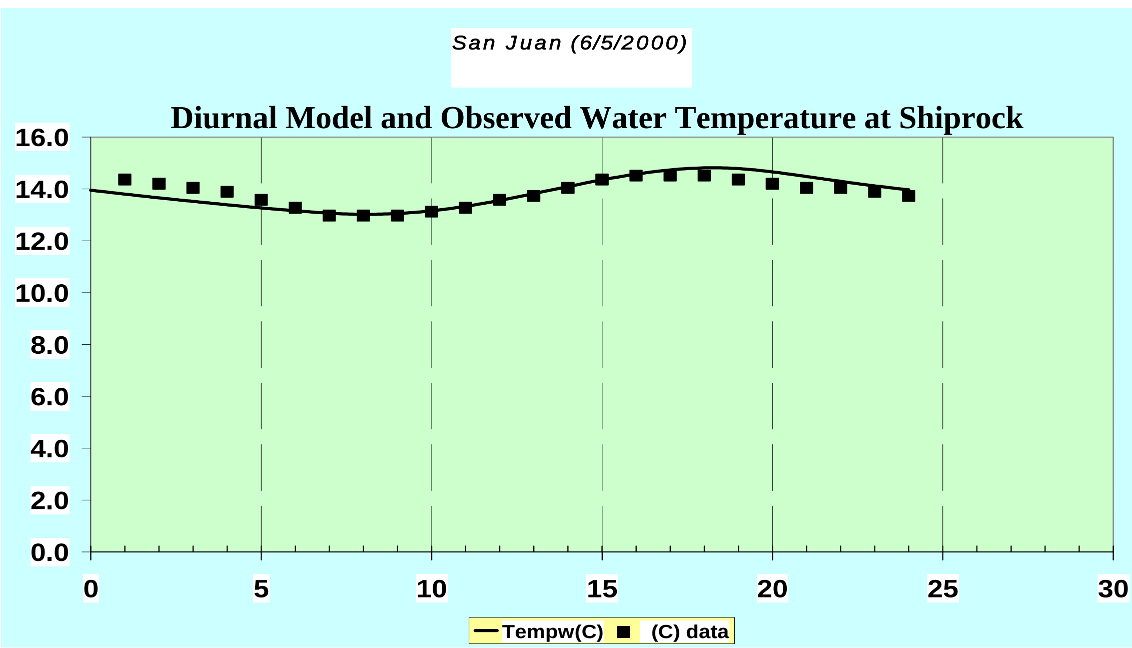

San Juan (3/15/2000)
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

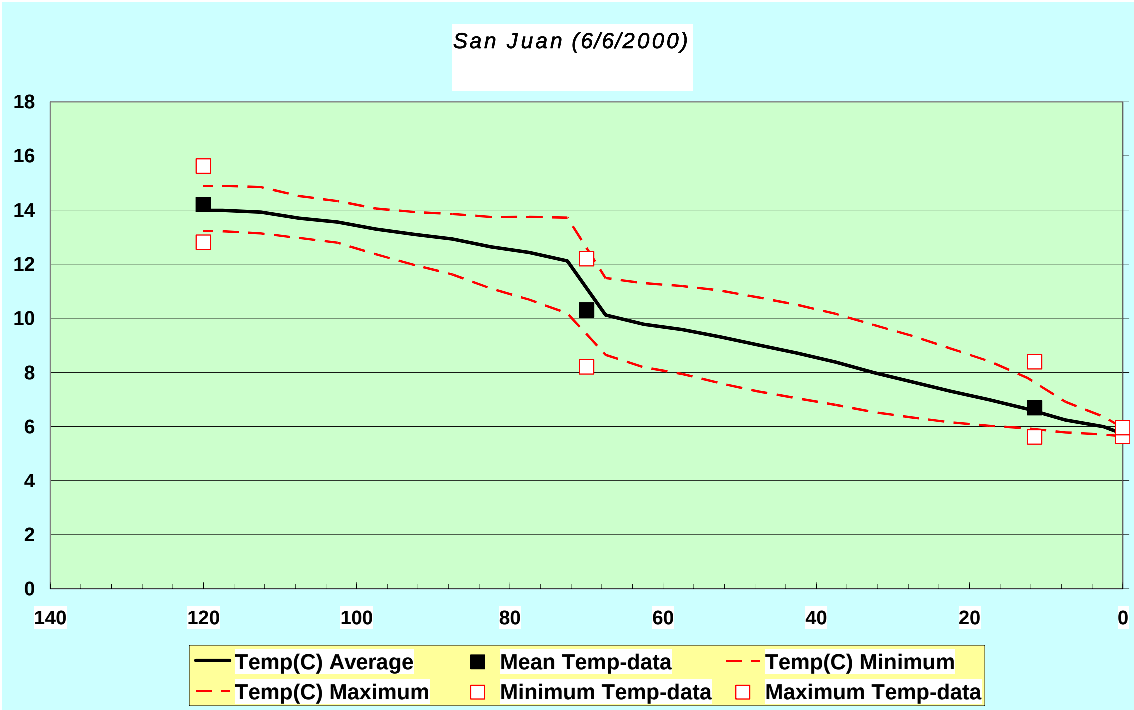

San Juan (4/15/2000)
16
14
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

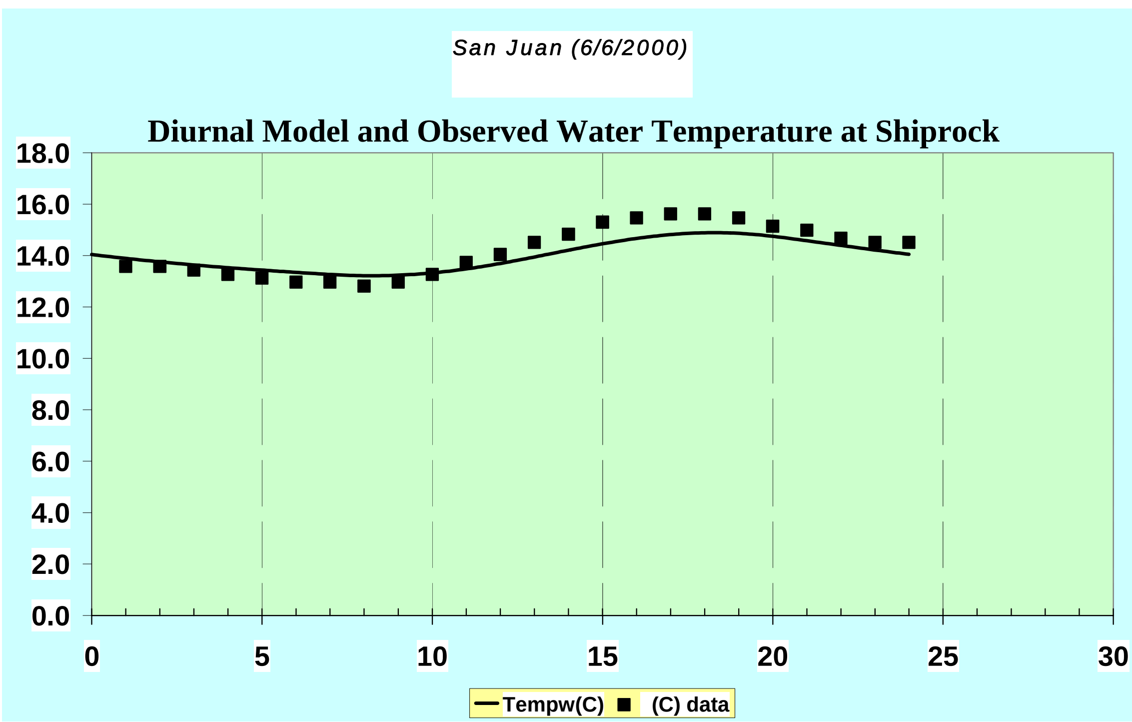

San Juan (5/15/2000)
20
15
10
5
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

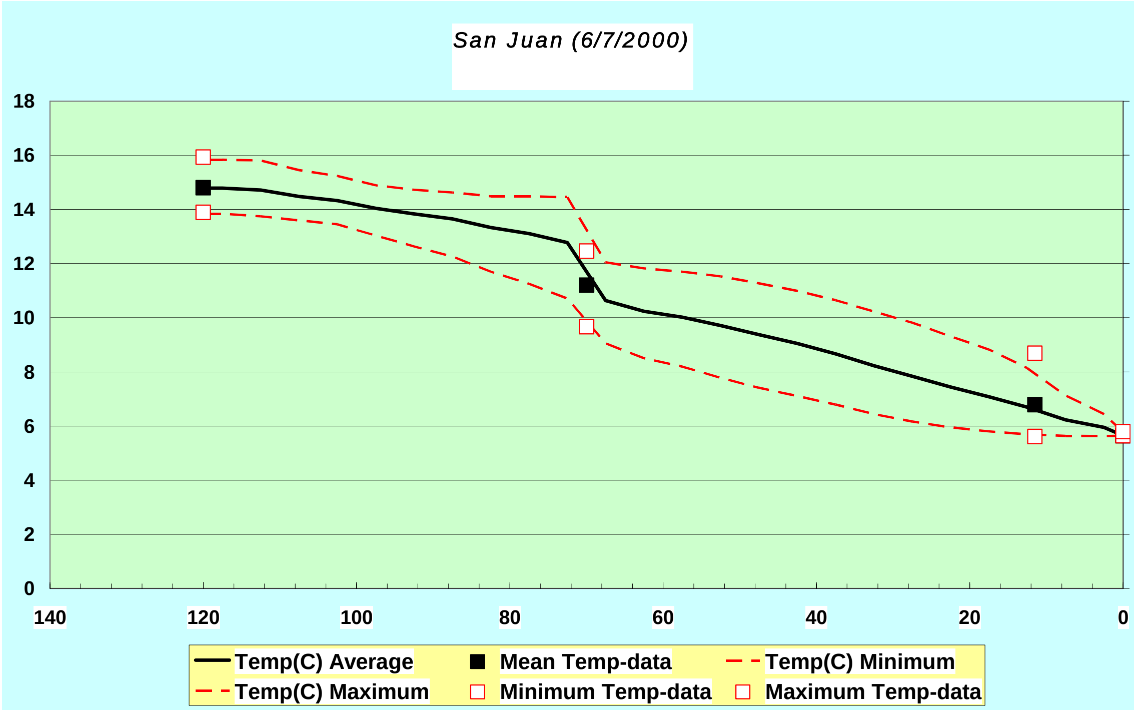
2K calibration plots for the descending hydrograph of 2000

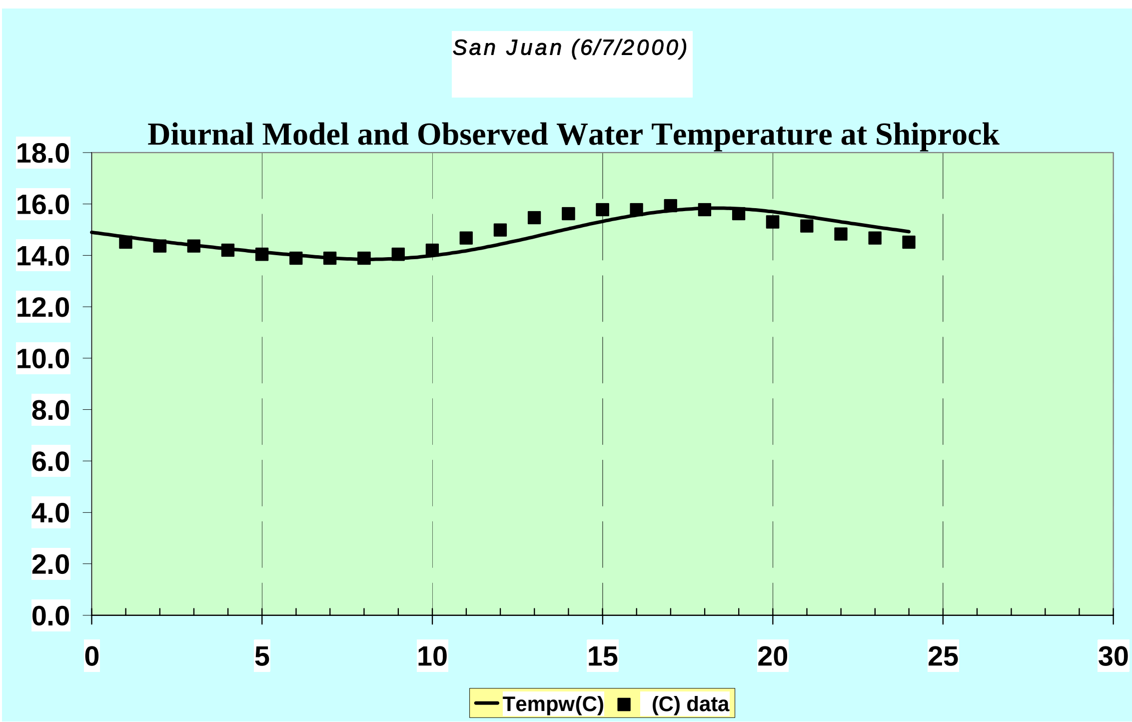


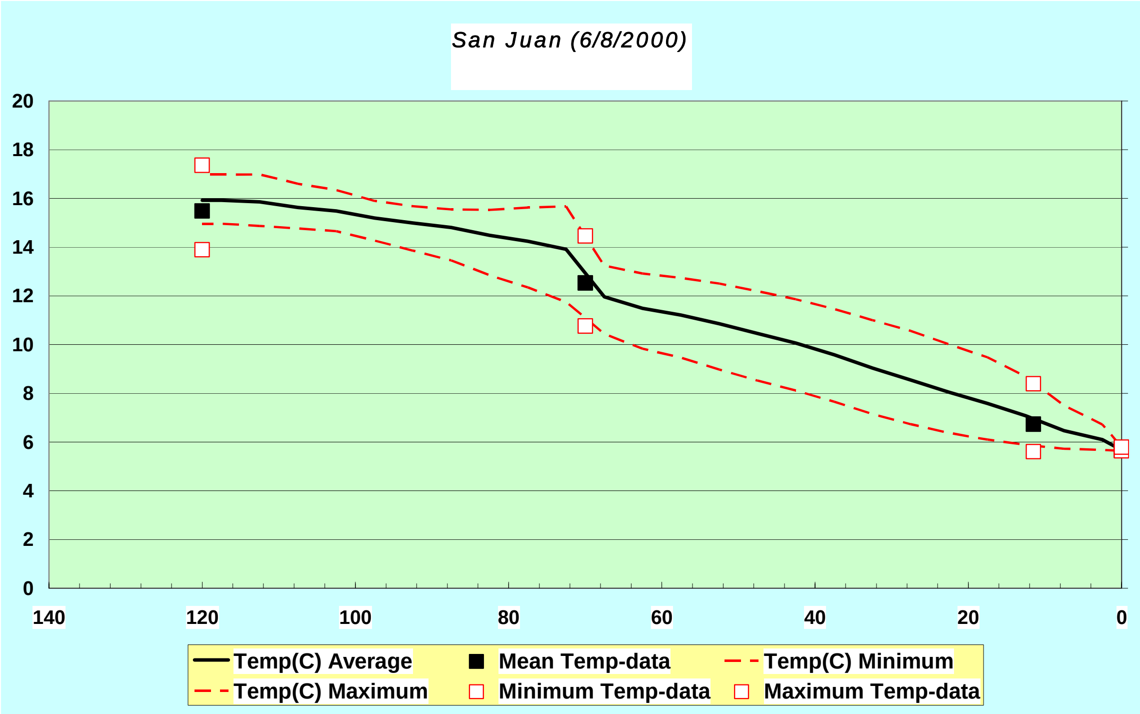


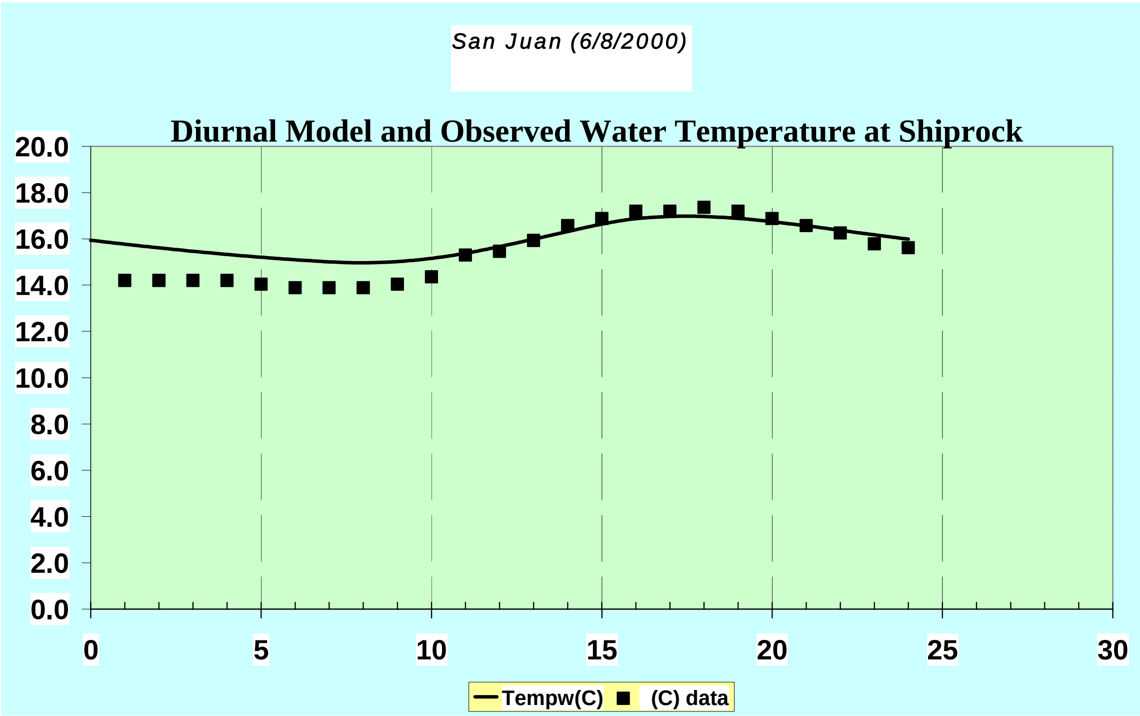

San Juan (6/6/2000)
18
16
14
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data

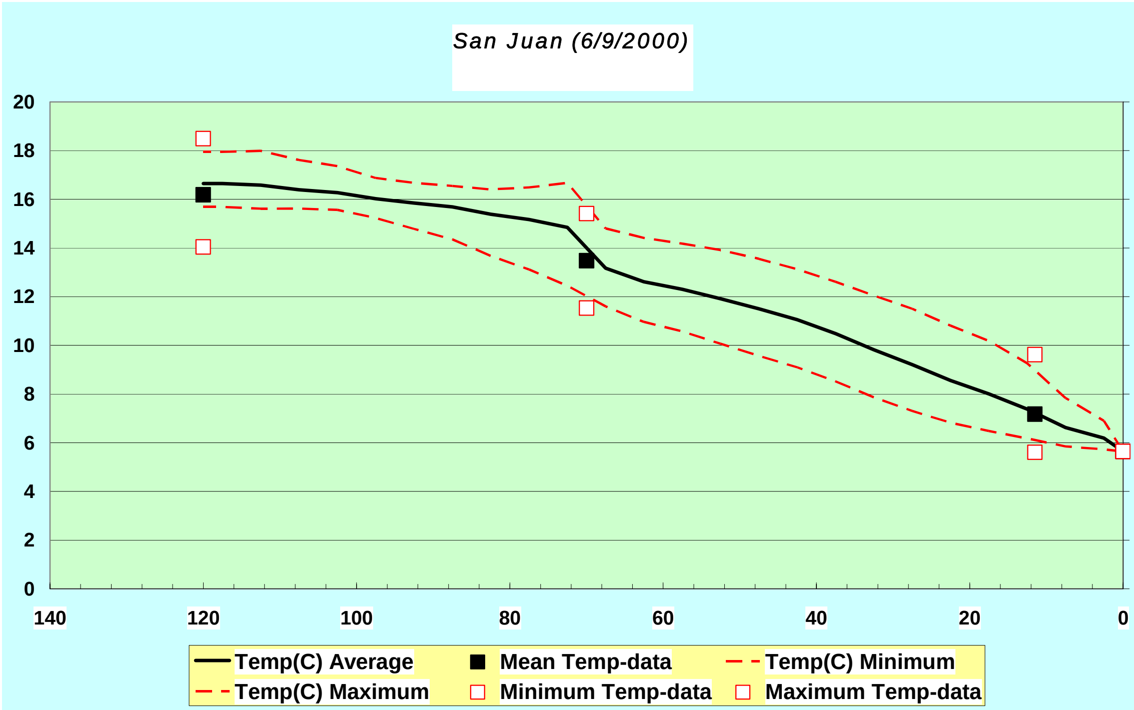

San Juan (6/6/2000)
Diurnal Model and Observed Water Temperature at Shiprock
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5
10
15
20
25
30
Tempw(C)
(C) data


San Juan (6/7/2000)
18
16
14
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data


San Juan (6/7/2000)
Diurnal Model and Observed Water Temperature at Shiprock
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5
10
15
20
25
30
Tempw(C)
(C) data


San Juan (6/8/2000)
20
18
16
14
12
10
8
6
4
2
0
140
120
100
80
60
40
20
0
Temp(C) Average
Mean Temp-data
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data


San Juan (6/8/2000)
Diurnal Model and Observed Water Temperature at Shiprock
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5
10
15
20
25
30
Tempw(C)
(C) data


San Juan (6/9/2000)
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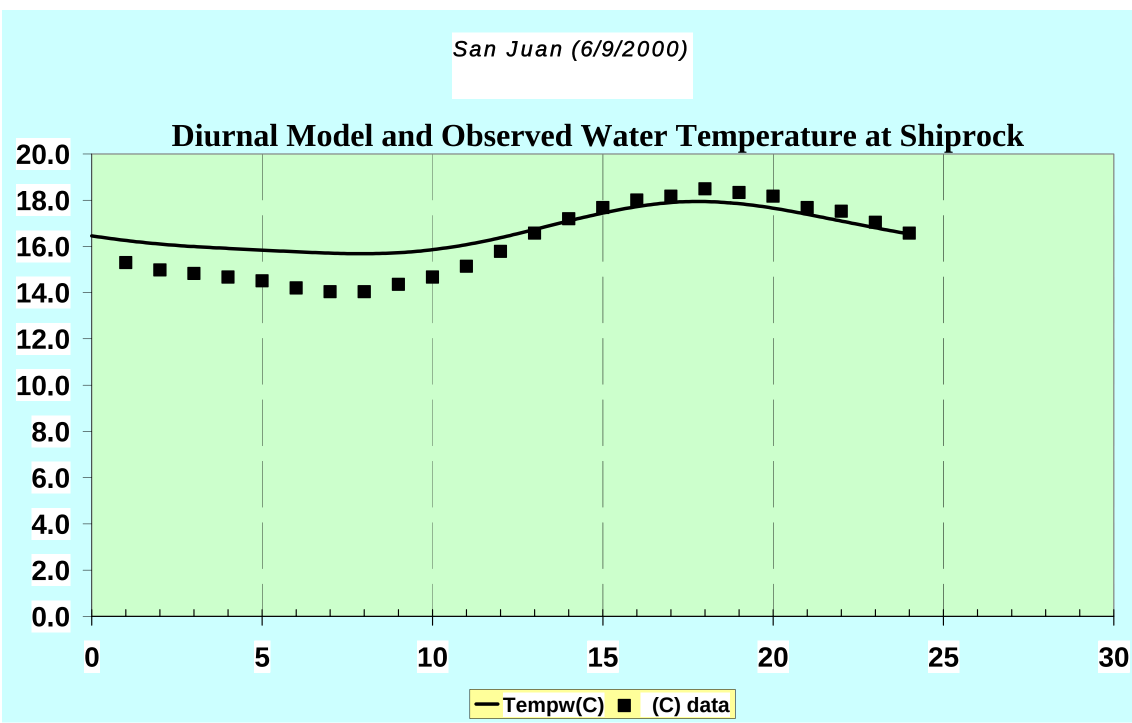
San Juan (6/9/2000)
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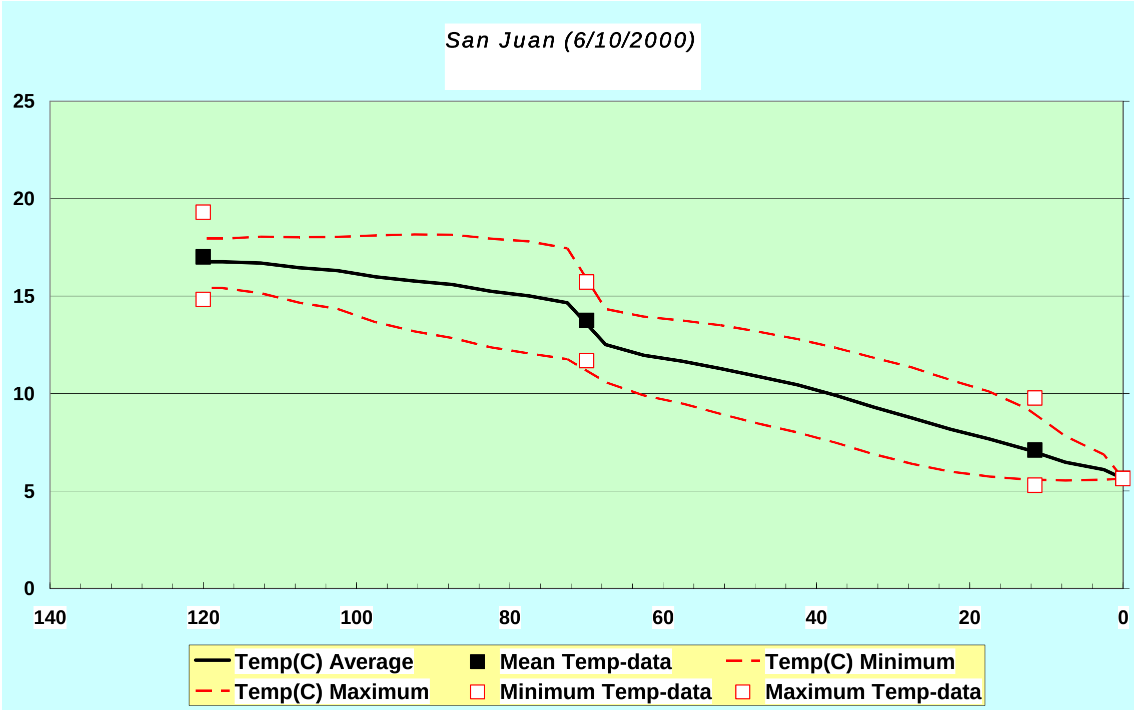
San Juan (6/10/2000)
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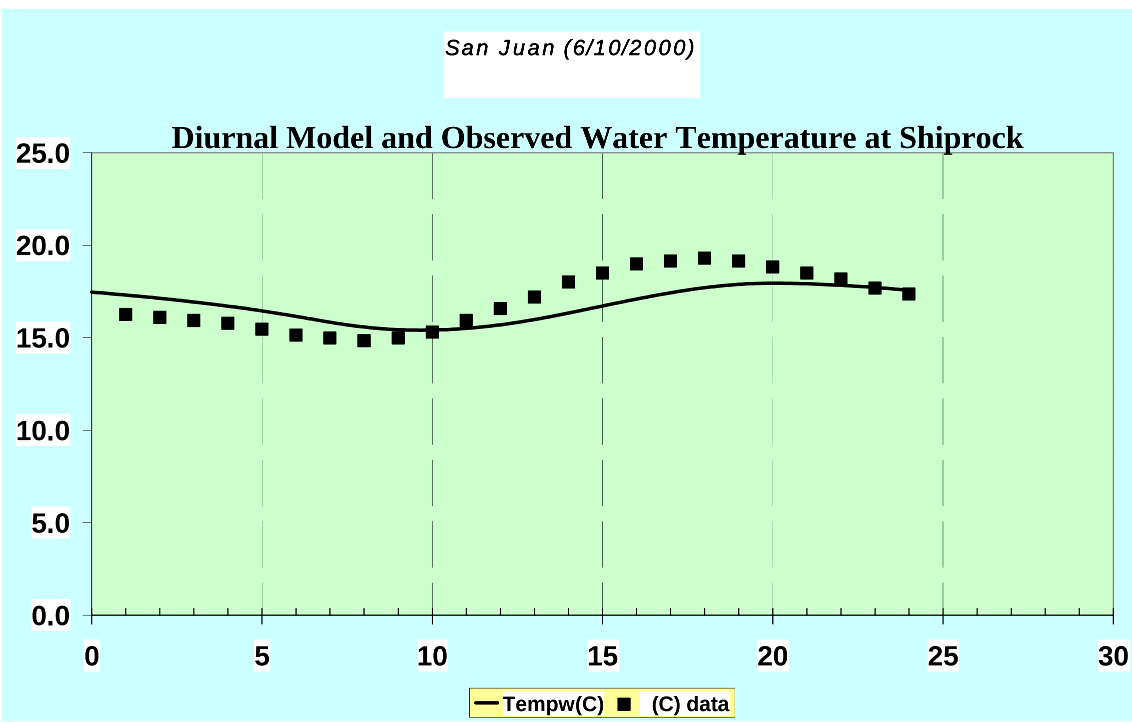
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Diurnal Model and Observed Water Temperature at Shiprock
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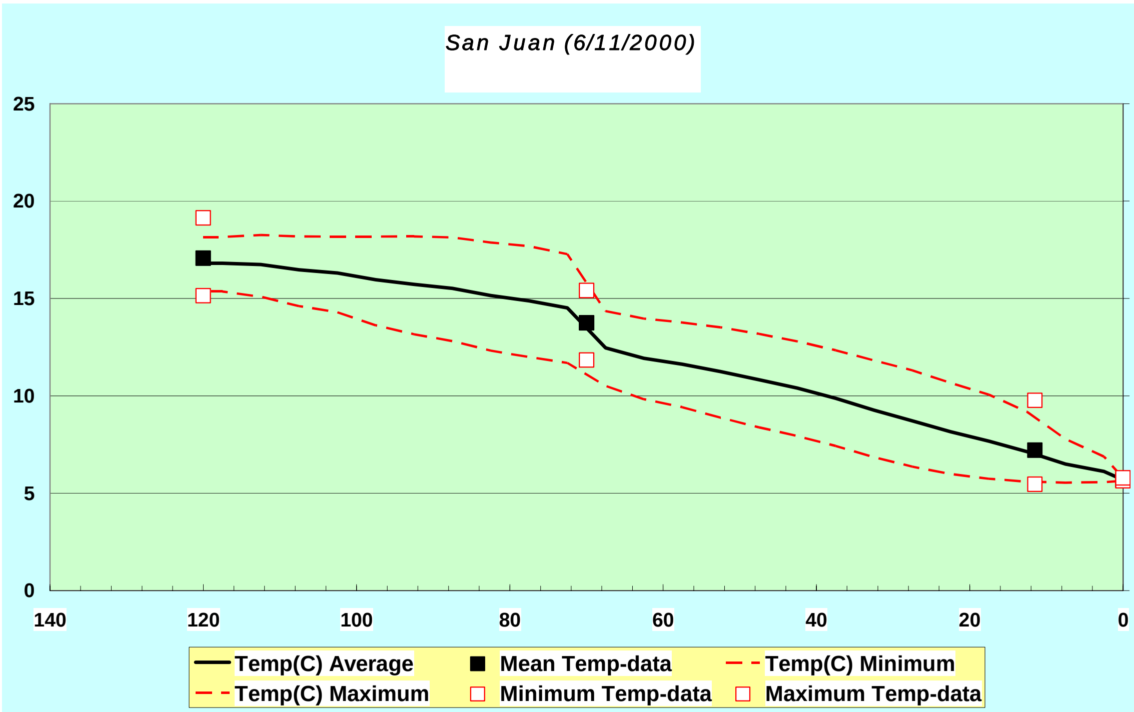
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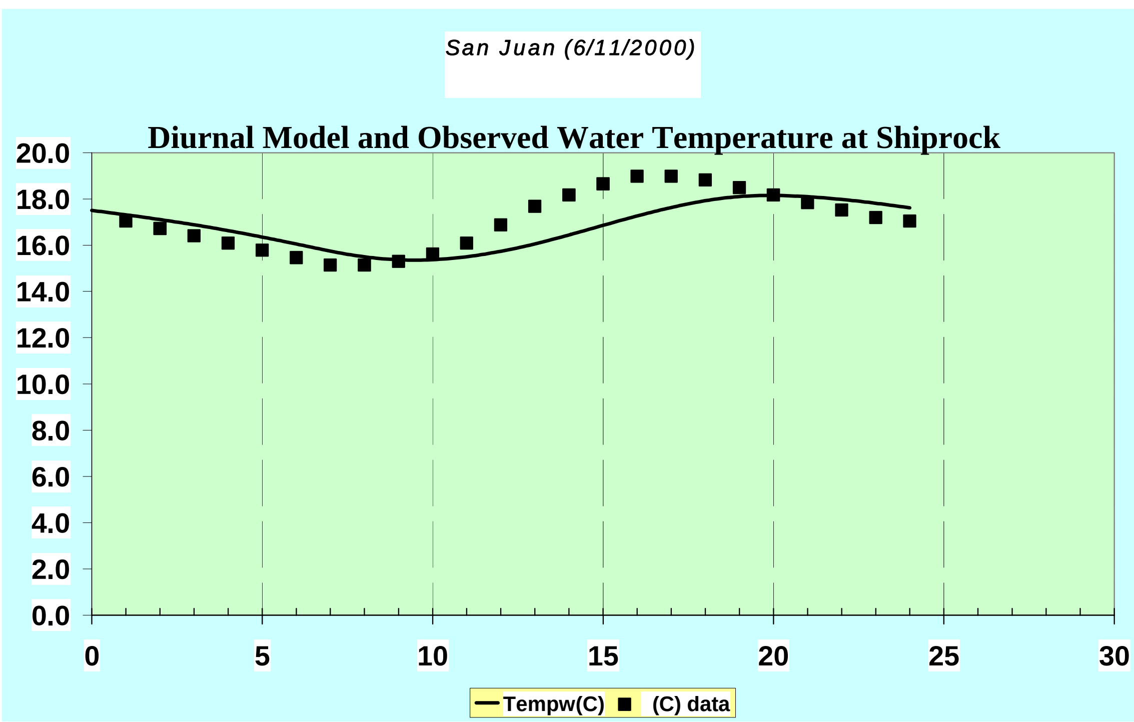
San Juan (6/11/2000)
Diurnal Model and Observed Water Temperature at Shiprock
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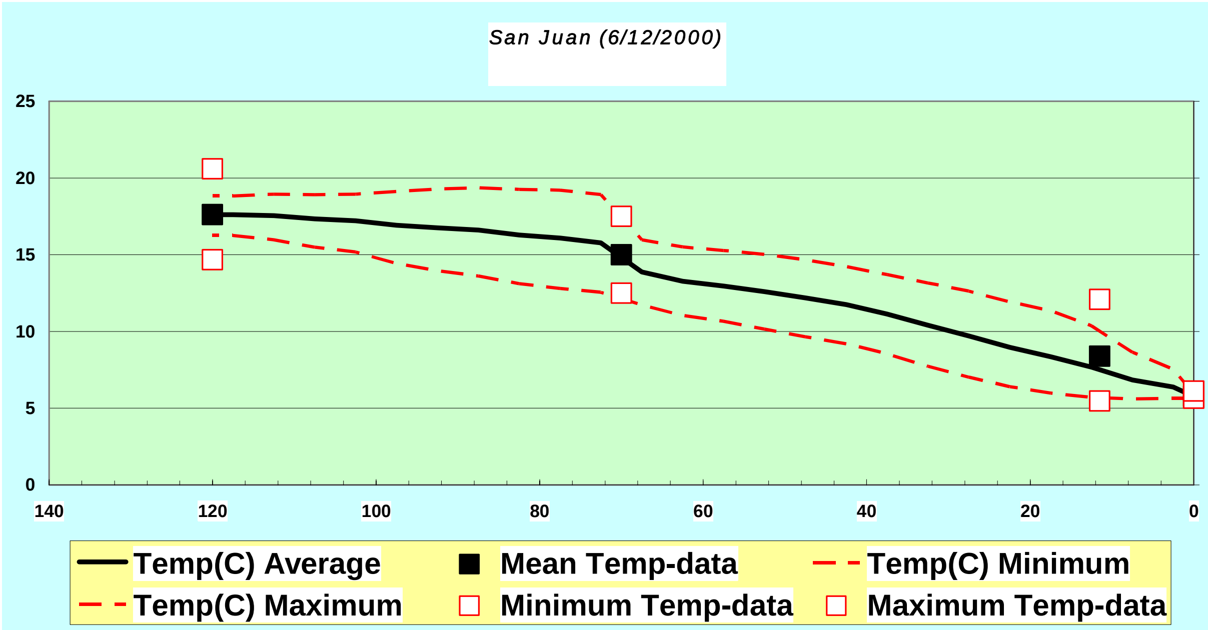
San Juan (6/12/2000)
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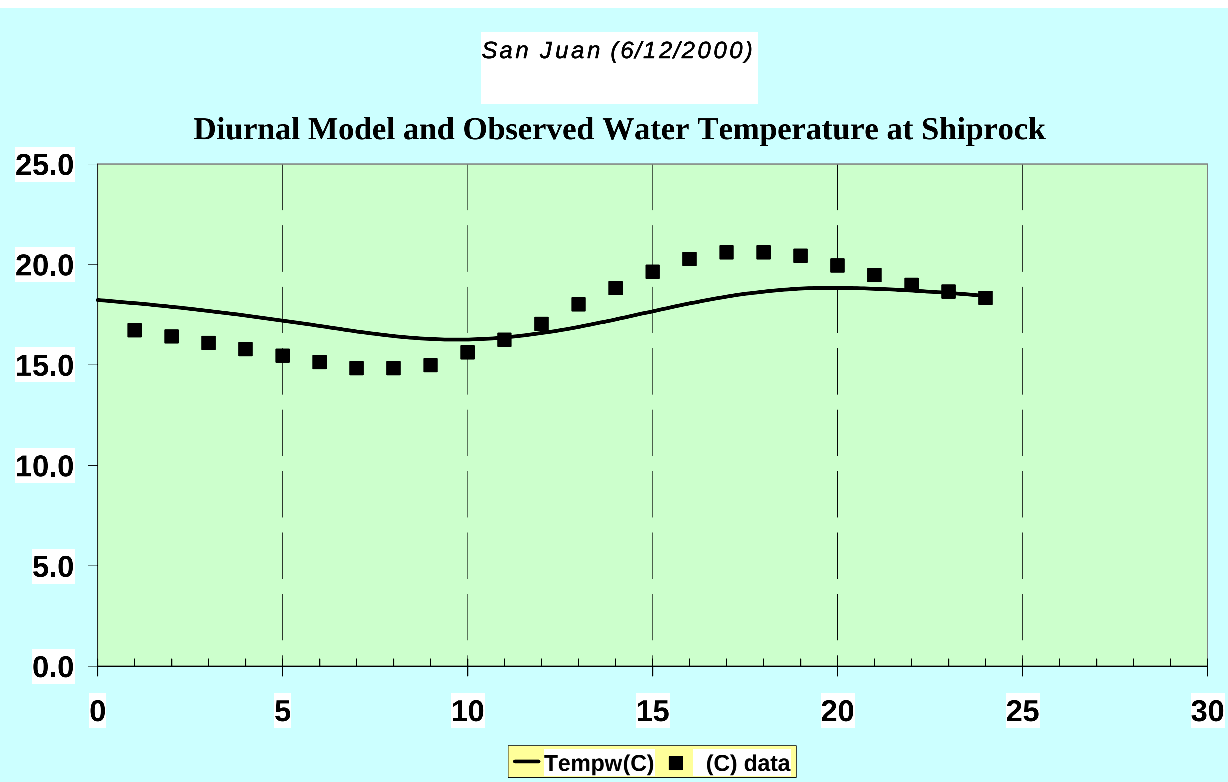
Temp(C) Minimum
Temp(C) Maximum
Minimum Temp-data
Maximum Temp-data


San Juan (6/12/2000)
Diurnal Model and Observed Water Temperature at Shiprock
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Tempw(C)
(C) data

RESPONSE TO COMMENTS ON REPORT

To: San Juan Biology Committee

From: Amy Cutler

Date: November 2006

Subject: Navajo Reservoir and San Juan River Temperature Report

Dear Committee,

Below you will find my responses to your comments regarding the water temperature report for the San Juan River. Most of your editorial comments have been incorporated in the report. Most of you requested that additional information be added to the executive summary and that more detail be included of the three models that were used for predicting water temperatures. I added additional information for both the executive summary and model discussions in the final report. Another consistent comment was that the GEMSS calibration graphs that compared observed to modeled temperature on an hourly basis at three locations (old figures 10-12) were difficult to read because of the large volume of data (52,560 individual values). To improve this I added daily comparison graphs at the same three locations which should allow you to more easily compare the results visually. These general comments as discussed above and the editorial comments will not be addressed again in this memo. If you have questions regarding to my responses to the other comments please feel free to give me a call.

Sincerely,
Amy Cutler
Bureau of Reclamation
801-524-3654

Comments from Dr. Stephen T. Ross:

1. Page 10, par. 1. The sentence in which Fig. 1 is cited leaves the reader looking for a graph of pre- and post-dam water temperatures in the system, not really a map of the system. Figure 1 would be better cited after the first sentence in this paragraph. Also, explain what the red dots mean in the figure. Finally, since the thesis of this report is that there is a problem with lowered water temperatures in the San Juan River following dam construction, it is important that you cite appropriate references or provide appropriate data in support of the apparent problem. If the reader does not understand, at least in an approximate way, how the temperature profile of the river has changed since dam, then it is more difficult to evaluate the modeling output showing increased river temperatures downstream of the dam.

Both Figure 1 and your recommendation of pre-dam condition have been added to the report.

2. Figure 3. It would be helpful to include the labels for the four reservoir branches on the figure. Also in the figure legend indicate that the numbers refer to the longitudinal segments.
I added the branches names and labeled segments on Figure 3.

3. Page 18, last par. Wouldn't it be appropriate to include the outcome of the peer review here?
J. E. Edinger Associates, Inc (Wayne, PA) performed a review of the W2 model development. The review included a detailed analysis of the input data sets, the geometry of Navajo Reservoir, and verification of the model results to field data. The peer-review concluded that with the given data set this was the best calibration.

4. Page 23, last par. & Figure 9. Is it really correct to say that the modeled flows were consistently higher than actual flows when actual flows exceed model flows during various spates?
Yes, it was correct to say modeled flows were consistently higher than measured flows at Shiprock. The higher modeled flows were caused by the limited withdrawal data upstream of Shiprock. The various spates were not captured in the model results because of local rain events.

5. Page 27. Why not be consistent and show the TCD drawings as numbered figures?
Good suggestion, I changed them into figures in the report.

6. Page 27, par. 2. Do you mean a reservoir elevation of 6026 feet rather than the stated 6046 feet?
This statement was correct, the 6046' assumed a 20' buffering zone above 6026' for the avoidance of vortices formation that could damage hydropower turbines.

7. Page 28, par. 1. Wouldn't it be helpful to add that the highest release water temperatures were achieved by the multiple level TCD? In general, you should do more in terms of verbally describing the model output as well as the striking difference between the model predictions and the observed water temperatures. For instance, if someone only had a black and white printed copy, it would be nearly impossible without the accompanying verbal description to understand the results.
Great comment and I incorporated your suggestion in the final report.

8. Page 28, last par. Always make sure when you write about differences that you also indicate the direction of the differences, i.e. that the TCD would lower in-reservoir temperatures by an average of 1.1 C. This makes it much easier for the reader to grasp the significance of the results. These comments apply to the paragraph on page 29 as well.
I incorporated your suggestion in the final report.

9. Figure 17. Wouldn't it be helpful to indicate that the different temperatures shown at the bottom of the figure are release temperatures from the dam?

I added information in the figure caption to the different release temperature scenarios.

10. Page 37. The statement that a fixed-level TCD is less reliable seems misplaced here. Wouldn't it be better to indicate reliability in the section on page 27 where you introduce the fixed and multiple-level TCD's. Also, you could expand on what you mean by reliability. I assume you are referring to operation at variable pool levels.
Reliability here means more control of release temperature from Navajo Reservoir. The fixed-level TCD configuration had one TCD outlet, therefore it had less control as compared to the multiple-level TCD. When water elevation drops below a fixed-level outlet, TCD release temperatures in the summer would be cold again.

11. Page 38. The topic sentence of this paragraph seems confusing because this entire section, rather than what follows in the paragraph, is based on the GEMSS model. As I understand it, this paragraph is describing how the year 2000 data during the recession period are modeled, in contrast to the preceding paragraph which dealt with data from 1997. I realize that you are also comparing the results to the QUAL2K model, but it would be helpful to state this comparison clearly (actually such a comparison would be more appropriate to a discussion section). Also state in this paragraph how the fixed-level TCD performed.
The two periods were selected to show greater detail of the GEMSS's time-series output and were also selected for comparison to QUAL2K analysis of these periods, as suggested in your comments. I have re-written the paragraph to clarify these descriptions.

12. Page 39. I would find it useful to have a short Discussion section prior to the Conclusions and Recommendations sections. In the Discussion, among other things, you could compare the outcome of the competing river models. This would flow nicely from your statement on page 13 that the uses of the two river models help to corroborate results. As it now stands, there isn't really anywhere in the report where the GEMSS and QUAL2K models are compared. Do you think it would be useful to do this?
Yes, I added a Discussion section to compare the models.

Comments from Dr. John Pitlick

13. Executive summary: I suggest adding a few lines summarizing present conditions; what are the temperatures at Shiprock now, during periods of spawning? what is the target temperature? Is there a problem with the timing of warm-water flows?
Later in the executive summary there is a comment regarding sensitivity analysis, and a statement to the effect that the magnitude of errors caused by uncertainty in model input variables is unknown. Could this be reworded? The report stresses differences between modeled and observed values elsewhere, but I wouldn't want someone getting the impression that there's a lot of uncertainty in the models and the results.
I added answers to your questions and more information to the Executive summary. I also reworded the statement on errors and thanks for the good suggestion.

14. Introduction, 2nd para: I suggest adding more details on factors that affect water temperature downstream of a reservoir. In addition to the temperature at the point of release, temperatures are affected by the discharge, which affects not only the volume of water released, but also the speed that the water moves downstream. Atmospheric conditions, including air temperature, relative humidity, wind velocity, solar radiation, and cloud cover, control energy input and output. There's quite a bit that goes into estimating the driving variables, so I suggest adding some details here and later in the modeling section. The author and biology committee members might be interested in seeing a 2001 paper by John Carron and Hari Rajaram, which models downstream changes in temperature for various flow-release scenarios at Flaming Gorge Dam: Carron, J.C. and H. Rajaram, 2001, Impact of variable reservoir releases on management of downstream water temperatures, *Water Resources Research*, v. 37, p. 1733-1743.
I added more detail to the introduction. There is no question that water temperature increases with atmospheric conditions when the air temperature is higher than water temperature. All the atmospheric conditions you mentioned, air temperature, wind speed, wind direction, solar radiation, and cloud cover, were used in all three models to calculate the heat budget. In term of flow rate, this effects the travel time which determines how much time the water spends interfacing with the atmosphere from point A to point B.

15. Figures 4 and 5 on p. 17 provide some of the main results of the reservoir model; however, these results are discussed primarily in the context of calibrating the model. I suggest separating the process of calibration from the process of generating results. You could consider presenting a figure before Fig. 4 showing the effect of tuning one of the model parameters, for a shorter time period, say a single year. Present Figs. 4 and 5 on p. 18 after the 1st paragraph, and add some discussion about what the figure shows. It looks like the model does a very good job of predicting reservoir temperatures, so it is worth highlighting what it took to get the results.
I added more detail on the development of the CE-QUAL model. I added four sections for data selection, geometry development, model inputs and the calibration process in the final report.

16. pp. 27-28: I suggest expanding the discussion of Fig. 13. This is an important figure, however, the comments here are very brief. It would also be helpful to split the figure into several panels (shorter time intervals) to show more detail. Both TCD options appear to have a large effect, but it is evident that there is a lag in the timing of the peak temperature with the fixed-level TCD.
I added more detail discussion for this figure. The lag in the timing of the peak temperature with the fixed-level TCD scenario was caused by not drawing from the surface as the reservoir changed in elevation. On the other hand, the multiple-level TCD scenario can follow the water surface and, therefore, releases the highest temperature in the earliest time of year.

17. p. 29, add some explanation of Fig. 14. p. 30, split Fig. 15 into separate panels to show more detail.
Figure 14 depicts that, at a given elevation in the reservoir near the surface, water temperature decreases with the use of a TCD as compared to the current hypolimnetic withdrawl. Together, figures 14 and 15 illustrate the effects of a TCD on the epilimnion water temperature. A TCD should increase release temperature at the expense of decreasing the heat budget in the reservoir water surface and also decreasing the thickness of the epilimnion.

18. p. 31: I'm a little confused by the wording of the last sentence on this page. By 'increased release situations', do you mean with respect to present operating conditions?
In general, a TCD would have the greatest affect on downstream water temperature during large flow periods or the summer peak flows. In high flow periods the travel time decreases from Navajo Dam to Shiprock, meaning the water has less time to reach ambient temperature and the thermal mass is greater, which means the water requires more time to reach equilibrium. At present, temperatures at Farmington and Shiprock do not reach ambient temperature during peak summer flows, but by increasing release temperatures during these high-flow periods the water should achieve equilibrium temperature at these two locations.

19. p. 32, assumptions: Are the changes in temp. modeled at hourly time steps, then averaged over the month? Is the flow rate assumed to be constant over the month? Figure 17 suggests there is not much change in average monthly water temperature at Shiprock, but I'm wondering if that's due to averaging in the input variables, or simple the average of 30 (or 31) daily values, which vary about the colored lines.
The answers to your questions are yes. QUAL2K is a steady-state model therefore you can only use one flow and one release temperature value for each run. The colored lines represented runs with a single monthly flow in combination with different release temperatures to observed downstream responses

20. The results shown in Figs. 19-23 and the comments at the bottom of page 34 indicate that a TCD will not produce very large changes in temperature downstream of Farmington, although again, this is a little hard to see. Figure 24 shows the differences much more clearly, and this is a very useful and important figure. I am somewhat surprised that the increase in temperature at Shiprock is so small, only about 2-4 °C. Clearly, that's not much of a difference. Perhaps the author can offer some comments on the conditions within the system (or the model) that limit the range in temperature changes one can expect with a TCD. If the program is interested in going forward with additional studies, then it would be useful to include some discussion of the system limitations or modeling limitations, so that we may sharpen the focus of future work.
Your comment was well received; I added a discussion section in the report that talks about some of these issues.

Comments from Tom Wesche:

21. Overall, I found the report to be in pretty rough condition and in need of a thorough editing. Numerous pages are only half-filled, graphs on figure axes are unlabelled, metric and english units are frequently interchanged, page numbering begins with "9" on the Executive Summary and continues from there through the end of the appendices. It needs a real going-over! Regarding content, it is apparent a lot of good work has been accomplished to get to this point.
Several useful additions would be to 1) provide additional background information for the reader to explain why the study is being done, 2) expand the Ex Summary to more thoroughly summarize the results, 3) link this effort to the companion work being done by Vince in the White Paper relating temperature modification to possible biological ramifications, 4) describe the various models used in considerably more detail, 5) where possible, provide sensitivity analysis to indicate the degree to which various model parameters control the predicted outcomes (e.g. in the river models, how much variability is due to flow, release temperature, air temperature, channel geometry.....), and 6) before the Conclusions and Recommendations section, it would be helpful to bring it all together in a Discussion section which also includes consideration of what other options, if any, there may be to modify the river's temperature regime.
Your editorial comments have been incorporated in the final report. For your specific comments 1 and 2) I added background information in the executive summary and more thoroughly summarized my results as suggested. 3) Linking Vince's work to my project was never in the SOW however I did add some of the key temperatures identified in Vince's report and referenced them through out the report. 4) I added more description for each of the models used in the study, 5) Sensitivity analyses are very time consuming tasks that were not in the original SOW, however with that said I did look at some sensitivity from atmospheric and flow relationship. 6) I added a discussion section in the final report.

Comments from Ron Bliesner:

This report is much improved from the previous version with the addition of the non-steady state model analysis. The new model may have utility in future analyses if the program decides we need to proceed. Although the results presented do not allow us to integrate in a detailed way with Vince Lamara's report San Juan River Fishery Response to Thermal Modification, the data are there to do so. It will be very useful. If corrections were to be made to respond to all of the following comments, additional analysis may be required. Amy has already done more in this study than she originally intended, so I don't recommend additional analysis, especially with the Qual2K model, where many of the comments are. Simply acknowledging the limitations in the text will be adequate. However, doing a couple of extra graphs in the calibration areas as indicated below would be very helpful.
22. There are a few issues that need to be cleaned up concerning who the study was completed for and who the participants in the program are. On the title page, it should indicate "San Juan River Basin Recovery Implementation Program" in place of the wording that is there. In page iii, the reference is correct, but then it goes on to describe the participants in the upper basin program with the addition of the San Juan Water users. None of the tribes are mentioned, BIA and BLM are not mentioned and

several entities that are not involved in the San Juan program are listed. This should be corrected to the official list or simply omitted. It is really not needed.
I fixed the tile page as requested.

23. Page 11, sentenced Water temperature change in the system responds not only to travel time, but total mass related to surface area of the flow. At high flow travel timers shorter, but the thermal mass is much greater relative to the atmospheric exchange interface (deeper flow, but not much change in surface area). Thus, the change in temperature will be less than at low flow due both to change in travel time and decrease in mass relative to surface area.
Your comment is right on the mark, however, I feel that I sufficiently addressed the volume of water as it relates to the warming rate throughout the report.

24. Page 12. Objective 1 targets Shiprock. Of key interest is the reach between Farmington and Shiprock. This has been repeated a number of times in previous meetings. While the models report temperatures at other locations, Shiprock is used for major analysis and conclusions. Both Farmington and Shiprock are important as they bracket the range of critical need. Since the data are available, I suggest reporting the response at Farmington any time you report the response at Shiprock. This will add a couple of graphs, but should not be too difficult. It is very important. The objectives from your work plan are: To determine potential temperature regimes in the San Juan River down to approximately River Mile 150 that would result from various TCD options. Compare and contrast release water temperature for a historic period with and without TCD modifications. Determine the times of year in which water temperature targets can be met. Determine the effect of TCD on the heat budgets in the reservoir. Determining impacts to RM 150 include Farmington. You have met the objective but more narrowly define the conclusions to be at Shiprock. Expanding the discussion to include Farmington would satisfy our need, along with the other data you present.
I added the results for Farmington throughout the document.

25. Page 17, Figure 4. I'm puzzled as to why the modeled elevations are different than the actual. Is there error in the inflow, outflow or evaporation data? It's not a big deal because it does not affect the results much, but seems strange and should be explained.
The main cause of this difference between modeled actual elevations was the simplified bathymetry data representing the reservoir. The absolute mean error between the model reservoir elevation output and field data was within 1.3 ft (0.4 m). This error was less than1% of the total capacity. The error was attributable to the simple reservoir geometry and evaporation assumptions.

26. Page 17, Figure 5. The absolute magnitude of the error is not large, but given the small variation in temperature (about6 °C), the error is as large as 30% of the range. The absolute mean error may not be the best metric for calibration. It likely is not a huge deal, given your limited reservoir data for calibration, but it should be/discussed.
Navajo Reservoir was particularly difficult to calibrate because of the limited input and calibration data, and the input and calibration data were temporally out of sync. Figure 8 illustrates the comparison of modeled versus observed dam release water temperatures. Navajo Reservoir releases water from its hypolimnion where limited data were available for calibration. The lack of data and temporal shift in calibration and input data leads to a model that predicts the water warming later in the year when compared to observed temperatures.

27. Page 31. Read the first paragraph. The discussion on time periods does not make sense. I see later what you did, but this paragraph does not describe it.
This paragraph was modified in the final report.

28. Page 31, Figure 16. This is not a very good date to pick to demonstrate the impact of a TCD. Any time Navajo release is so much smaller than Animas flows you are not going to get a difference. If you draw your conclusions from the set of graphs you display, then you will get a distorted response. As we have discussed before, the critical times are during peak releases, typically in June. Your non-steady state analysis gets this addressed, but you should qualify your conclusions in this section because you are not addressing the critical period. Alternately, show the graph for June 7 or 8, 1999 when the release is large. When looking at the graphs in the appendix, you happened to have selected a number of atypical conditions to analyze. It is not worth redoing the analysis, but you should qualify the conclusions and use this as the reason to do the non-steady state model.
This is a very good comment, however at the very beginning of this analysis I did not know which flow condition to analyze therefore I used both low and high flows. One of my goals in the report was to be able to show the difference between extreme flow conditions. I discussed this in the modeling and Discussion section as requested.

29. Page 34. It is unclear what you mean by "historical temperatures" in the three scenarios. Is it actually the historical temperature from the recorders or is it the simulated temperature without TCD? If it is the actual temperature, then I'm quite concerned about the simulation of Animas temperatures given the very large disagreement during the ascending limb in 1999, 2000 and 2001. There are typical errors of over 5°C during thess-times. If "historical" in the discussion is actually "simulated without TCD" then there is less concern. You should clarify this point and you should discuss the implication of the error in the Animas simulation to your results.
To clarify, the "historical temperatures" in this section does refer to the simulated temperature without TCD. In the final report I added not only this clarification but also a discussion of temperature in the Animas.

30. Page 37, Figure 24. Good figure. We need the same figure and discussion for Farmington to bookend the range we are interested, in.
I added figures and discussion for Farmington as requested.

31. Page 39. Conclusions and Recommendations. This is a good discussion one thing to be considered in recommending the type of TCD are the operating rules— of the reservoir. The most critical time for the TCD is during peak release. It has the most effect below the Animas confluence during this time. When the reservoir is low, we do not make peak releases. Therefore, the selection of the elevation may appropriately be set based on reservoir content during release conditions. The report does not need to be modified to address this, but the possibility could be acknowledged in this section. We need to clearly consider this if a TCD is needed, because of the potential cost savings.
I am unclear with your comment on "selection of the elevation may appropriately be set based on reservoir content during release conditions" are you referring to the multiple-level TCD configuration or one-level TCD? This is only true for the multiple-level TCD but not the other one.

32. Appendix A, Page 44, second figure. Something is wrong with the discharge curve in this chart. The August lst, 1999 flow below the Animas River confluence was 6,940, not 13,000 as plotted. Page 45, first figure. Flow is also wrong on this graph. It was 4,280 on this date at Farmington.
The reason why the flows were different was because I used the flow at Animas a day later. This is to account for the travel time to Animas. Please refer to the method section of the river model on page 16 for the discussion.

33. Page 45, second figure. The results are in error here. The Multiple level TCD shows a decreasing temperature downstream and the other two show increasing trends. This cannot be.
Good catch. Thanks!