A Decision Support System to Manage Summer Stream Temperatures

By David W. Neumann[1], Edith A. Zagona[2], Balaji Rajagopalan[3]

Abstract

Warm summer stream temperatures due to low flows and high air temperatures are a critical water quality problem in many western U.S. river basins because they impact threatened fish species' habitat. One way to alleviate this problem is for local and federal organizations to purchase water rights to be used to increase flows, hence decrease temperatures. Presented is a Decision Support System (DSS) that can be used in an operations mode to effectively use water acquired to mitigate warm stream temperatures. The DSS uses a statistical model for predicting daily stream temperatures and a rule-based module to compute reservoir releases. Water releases are calculated to meet fish habitat temperature targets based on the predicted stream temperature and a user specified confidence of the temperature predictions. Strategies that enable effective use of a limited amount of water throughout the season have also been incorporated in the DSS. The utility of the DSS is demonstrated by an example application to the Truckee River near Reno, Nevada, using hypothetical operating policy and 1988 through 1994 inflows. Results indicate that the DSS could substantially reduce the number of target temperature violations, i.e., stream temperatures exceeding the target temperature levels detrimental to fish habitat.

Key terms

Decision Support Systems, Stream Temperature, Simulation, Water Quality, Planning, Water Allocation, Rivers/Streams

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Introduction

An increasingly common river management problem is that water storage and use for municipal, industrial, agricultural and power production purposes leave insufficient flow to maintain fish populations. Low flows threaten fish by deteriorating habitat and/or water quality. One of the most common summer water quality problems associated with low flows is high stream temperatures—low flows warm up due to warm air temperatures more rapidly than higher flows. High stream temperatures reduce cold water fish populations by inhibiting growth and extremely high temperatures can result in fish kills. Excessive or prolonged low flows can threaten or endanger fish species, necessitating modified management practices. Hence, many National Environmental Policy Act (NEPA) studies of reservoir operations have as an objective to provide additional flows to increase habitat and/or improve water quality for fish. In some western basins this problem is addressed by transferring water rights from other uses to supplies reserved for fish flows.

To effectively use these water rights to protect fish, water managers must modify operational strategies by incorporating water quality objectives into daily operations and long-term planning. The operational objectives involve management of water quantity, i.e., streamflows, to control water quality characteristics such as temperature. Meeting the water quality objective is more challenging than meeting other water use objectives because it requires understanding the relationship between water quantity and water quality. Furthermore, managing water quality is subject to greater uncertainty than managing quantity, as water quality is affected by many factors that change seasonally, daily, and even hourly, such as air temperature, solar radiation, point and non-point pollutants, biological and chemical reactions, etc.

Researchers have attempted to address the problem of jointly managing water quantity and quality in multi-purpose basins. de Azevedo et al. (2000) coupled a water allocations model to a water quality model and the results of the water quality model are evaluated in terms of meeting the planning objectives and other performance measures. Adjustments are then made to the water quantity model and the process iterates until satisfactory performance measures are obtained. Carron and Rajaram (2001) examined the use of diurnally varied reservoir releases to control stream temperatures below a dam. They found that short term adjustments to the reservoir releases based on local meteorological conditions can meet stream temperature objectives with minimal water use.

Often it is not practical for real-world operational decision support systems (DSSs) for large river and reservoir systems to include detailed physical process water quality models, so decisions about how to most effectively use dedicated water quality water must be based on simplified predictive models that can easily be incorporated into the operational decision-making logic. Since the supply of water for water quality control is limited and the predictions are uncertain, decisions must trade off the risk of not meeting the quality objectives with the risk of using up the dedicated water too quickly. Such a DSS is particulary promising for the objective of mitigating high stream temperatures with additional reservoir releases because the temperature prediction models are relatively simple and depend on a small number of variables.

This paper describes the development of a predictive model-based DSS for stream temperature management and demonstrates the effective use of it within a simulation model-based DSS for operation of a multi-objective, multi-reservoir, river system. The water temperature DSS is demonstrated by an example application on the Truckee River near Reno, Nevada.

DSS Objectives

The Truckee River flows 187 km from Lake Tahoe in California’s Sierra Nevada mountains through an arid desert near Reno before terminating in Nevada’s Pyramid Lake. Tributary reservoirs, shown in Figure 1, are operated to meet a legal flow target measured at the Farad gage near the California and Nevada state line. The target flow, which dictates many of the release decisions in the basin, varies between 8.5 and 14.2 m^3/s (300 and 500 cfs) depending on the time of year and reservoir levels. In dry years, the target is not always met because there is insufficient natural inflow to the system. Figure 2 shows a schemtic of the DSS layout.

Figure 1 First Mentioned

Figure 2 First Mentioned

During low flows that occur in the summer, stream temperatures can get too warm for cold water fish in the reach between Farad and Reno. This has led to stress on fish populations in the area on occasion. To address this, a specified volume of storage rights in the the upstream reservoirs for dedicated fish water have been proposed (Notice 2002, p.63446). Additional releases of fish water are proposed to prevent downstream temperatures from reaching levels that harm the fish. Flow travel time between Boca and Reno ranges from 6 to10 hours, so water released early in the morning arrives at Reno during the hottest part of the day. Operational decisions about the use of the fish water would be based on prediction of expected temperatures without the extra releases to identify the need for a fish release, as well as determination of quantity of additional releases needed to keep temperatures under critical limits many miles downstream.

The DSS must consider the fact that critical water temperature for fish is not a single value, but rather a set of critical temperature ranges at which the species at various life stages could thrive, survive or reproduce (Armour, 1991). To demonstrate decision-making to meet realistic fish temperature objectives, our DSS uses the following typical temperature limits for cold water fish in this basin.

The preferred maximum target stream temperature is 22ºC, below which the fish can live and thrive for an extended period of time. In the range from 22ºC to 23ºC, the fish can survive but not for extended periods of time. The acute temperature range is 23ºC to 24ºC, at which, the fish can survive for one day or less. At temperatures greater than 24ºC, the absolute maximum, fish begin to die.

The DSS makes a daily release decision and implements the release in the simulation model. It first makes reservoir releases based on Farad gage flow objectives, then uses the predictive model to determine whether the temperature at Reno meets the fish targets. If not, the water quality decision logic tries to meet the temperature objective by computing selective releases of dedicated fish water at specified confidence levels, and considering the tradeoff of risk to the fish with risk of using up the fish water prematurely.

The DSS includes the following components:

1. Logic for determination of reservoir releases for other (non water quality) operating objectives such as agriculture and M&I deliveries. For the Truckee River example, this objective is met by meeting the target flow at the Farad Gage, constrained by supply.
2. A stream temperature prediction model for a critical fish habitat reach that is quick, relatively accurate and easy to use. The model provides a prediction at the same computational timestep as the DSS simulation model and is integrated into the the comprehensive DSS logic.
3. Quantification of confidence associated with the temperature prediction.
4. Operating rules that determine reservoir releases for a downstream, critical fish reach based on the stream temperature prediction and its associated confidence.

5. Strategies incorporated in the operating rules to trade off meeting one day's targets with the ability to meet longer term needs.

Statistical Temperature Prediction Model with Confidence

One of the key components of the DSS is the simple stream temperature prediction module that can provide stream temperature forecasts with quantified uncertainty. The DSS employs a statistical stream temperature prediction model developed and tested for the Truckee River near Reno, Nevada, and described in detail in Neumann et al. (2003). It predicts the maximum daily stream temperature at Reno $\hat{T}$ as follows:

$$\hat{T} = a_0 + a_1 T_{Air} + a_2 Q \qquad \textbf{(1)}$$

Where, T_{Air} is the maximum daily air temperature at Reno and Q is the average daily flow at Farad. The regression coefficients are $a_0 = 14.4$ ºC, $a_1 = 0.40$, and $a_2 = -0.49$ ºC/m^3/s, estimated from the observed data with an adjusted $r^2 = 0.91$. This relatively accurate and simple model is easily utilized in the execution of DSS logic.

The statistical model has the added advantage that uncertainty is easy to quantify and can be used in decision-making. From linear regression theory a quantification of the model's uncertainty was developed by Neumann et al. (2003) and summarized here. Helsel and Hirsch (1992, p. 300) define the *confidence interval* as the range (+/- the mean) of values in which the mean of regression estimate will lie. For example, the 95% confidence interval indicates that 95% of the time, the mean estimated response variable will be within the interval. In predictive mode, a similar concept called the *prediction interval* is defined as "the confidence interval for prediction of an estimate of an individual response variable." Linear regression theory provides the upper prediction interval to be approximated by (Helsel and Hirsch 1992, p. 300):

$$\text{Prediction Interval} = \hat{y} + t(\alpha, n-p)\sigma \qquad \textbf{(2)}$$

where $t(\alpha, n-p)$ is the quantile given by the 100(α) percentile on the student's t-distribution having *n-p* degrees of freedom (Ang and Tang, 1975, p. 237). At large degrees of freedom, (n-p), the students t-distribution is identical to a Gaussian distribution. The desired confidence level is 1-α and the data has a standard deviation σ. There are *n* observations used to create the regression and *p* explanatory variables plus one (for the intercept term). Thus, with 100(α) percent confidence, Equation 2 is the upper limit for the predicted value.

Calculation of Fish Water Releases

Figure 3 First Mentioned

When the predicted stream temperature is higher than the target, the regression model and the prediction upper interval can be used to determine how much additional water to release. The regression model, Equation 1, predicts a stream temperature and its associated Gaussian distribution denoted by curve A in Figure 3. By releasing more water, the distribution is shifted to the left. If the expected value of the distribution is shifted to the target temperature, T_{Target}, as shown by curve B, the probability of exceeding that target is 0.5. Shifting the distribution to the left of the target temperature by the prediction confidence distance (PCD) gives a specified probability of exceeding the target temperature. Curve C shows the distribution that results by shifting the distribution to $T_{\text{Necessary}}$, which is the target minus the PCD such that the distribution gives 0.05 probability of exceeding T_{Target}. The PCD is defined as:

$$\text{PCD} = t(\alpha, n-p)\sigma \tag{3}$$

The PCD combined with Equation 1 gives the additional fish release. By evaluating Equation 1 with $T_{\text{Necessary}}$ as $\hat{T}$ and rearranging to solve for Q, the required flow at Farad is:

$$Q_{\text{Required}} = \frac{T_{\text{Necessary}} - a_1 T_{Air} - a_0}{a_2} \tag{4}$$

Subtracting Equation 1 from Equation 4 and rearranging, the additional flow required becomes:

$$\left(Q_{\text{Required}} - Q\right) = \frac{\hat{T} - T_{\text{Necessary}}}{-a_2} \qquad \textbf{(5)}$$

To generalize, $T_{\text{Necessary}}$ in Figure 3 can also be defined as:

$$T_{\text{Necessary}} = T_{\text{Target}} - PCD \qquad \textbf{(6)}$$

Replacing $T_{\text{Necessary}}$ in Equation 5 with Equation 6:

$$\Delta Q = \frac{\hat{T} - T_{\text{Target}} + PCD}{-a_2} \qquad \textbf{(7)}$$

ΔQ is the additional flow that must be released to meet the target stream temperature with the desired level of confidence.

Fixed Target Fish Release Rule

The DSS fish release rule logic predicts the stream temperature using Equation 1. If the predicted temperature is above the preferred maximum target, Equation 7 is used to calculate the additional release to meet the target with a specified probability of exceedance. The additional release is executed in the model as long as the supply of fish water is available. When the fish water supply is exhausted, no further temperature mitigation measures are possible.

Degree-Day Fish Release Rule

With limited fish water allocation, in dry years the supply of fish water may be expended, leaving the fish at risk. Noting that the fish can survive for limited periods of time in temperatures exceeding the preferred target, an alternative fish rule attempts to conserve fish water by allowing temperatures to exceed the preferred target for limited periods, but never allowing the temperature to exceed the absolute maximum as long as fish water is available.

The logic of this rule limits temperatures to a number of “degree-days,” where degree-days is calculated as the sum of the degrees above a target on consecutive days. The degree-days concept is used in prediction techniques in biology, agriculture, and energy fields. Wood et al.(1996) used the number of degree-days above freezing as a predictor to the timing of algal blooms. Also, the number of cumulative degree-days has been shown to help predict the growth of certain fish (Cyterski and Spangler 1996 and Lukas and Orth 1995).

The degree-day rule at each daily timestep computes the predicted temperature, $\hat{T}$, and the number of degree-days, DD, where DD is defined as the number of degrees the predicted stream temperature is above the preferred target for the current day plus the previous day's degree-days. When the stream temperature dips below the preferred target temperature, the degree-day counter resets to zero. Based on DD and $\hat{T}$, the rule selects a target temperature for the day by matching one of the mutually exclusive conditions shown in Table 1, then executes the rule using the adjusted target. If $\hat{T}$ is less than the preferred temperature of 22ºC, then no target is selected and the rule does not execute to release more water.

Table 1 First Mentioned

In a real-time application of the DSS, the degree-day rule could access actual recorded stream temperatures for previous days if that data were available. Otherwise, the DSS uses the previous day's predicted temperature based on modeled releases, including fish release adjustments.

DSS Application

The fish release rules were integrated in a daily model-based DSS of the Truckee system. The DSS includes the daily time step simulation model of the reservoirs and rivers, the temperature prediction model, and operating rules to determine reservoir releases each day. On each day of the simulation, the first rules that execute determine reservoir releases that meet the target flows at Farad as well as possible with the current water in storage. The system simulation model then routes the releases downstream to simulate the modeled stream flow at Reno for the current day. Next, the DSS predicts the maximum stream temperature for the day at Reno by applying the regression model, Equation 1. Then, the fish release rule checks if this predicted stream temperature is above the preferred target level of 22ºC and if so, computes an additional release of dedicated fish water from Boca Reservoir to reduce the stream temperature at Reno to an acceptable level. The additional release is simulated and the DSS proceeds to the next day. The DSS keeps track of the fish water in storage and makes additional releases only as long as there is fish water available.

Most of the runoff in the Truckee basin starts as snow in the winter. The April 1st Snow Water Equivalent (SWE) obtained from the Natural Resources Conservation Service is a very good indicator of the streamflow runoff resulting from the winter snowpack. To compare the hydrology of a given year, the SWE was averaged over 17 snow measurement stations in the upper Truckee basin and compared to the long-term average. To test the fish release rules in a relatively dry period with consecutive low-flow years, the DSS used unregulated reservoir and local inflows from 1988 to 1994. Years 1988 (33% SWE of long-term average), 1989 (103%), 1990 (54%), 1991 (64%), and 1992 (51%) were dry, followed by an above average year in 1993 (149%), and then another dry year in 1994 (51%).

Table 2 First Mentioned

The DSS was run with the scenarios defined in Table 2. Scenario I is the DSS without fish releases. In this case the DSS rules operate the reservoirs to meet the normal operating objectives. Scenario II executes the fixed target fish release rule and scenario III executes the degree-day fish release rule. Scenarios II and III use a probablity of exceedance value that is constant throughout the run. To evaluate the effect of this variable, scenarios II and III were run with a range of probability of exceedances between 0.05 and 0.5. The comparative runs use the probability of exceedance for each scenario that gives the fewest number of temperature violations.

In this study, operations with fish release rules are compared with identical normal operations without fish release rules in order to quantify the potential benefit of the fish release rules and to compare the simple target rule with the degree day rule. The DSS normal operating policies are a simplified version of the actual operating policies, but reflect the basic objectives of those policies. Comparisons with historical streamflow temperatures would not be useful in assessing the value of the fish release rules because historic operations have varied over the years and are not well documented. The test scenarios presented indicate the potential benefits of a DSS coupled with a stream temperature forecast model and fish release rules, in terms of minimizing water quality violations with minimum water use.

Test Results

To determine the optimal probability of exceedance for scenarios II and III, each scenario was run with a range of probabilities of exceedance. A plot of the number of temperature violations from 1988 to 1994 for each scenario over the range is shown in Figure 4. A violation is defined identically for the three scenarios: it is any day on which the temperature and number of degree-days violate the constraints in Table 1. For scenario I, the rules do not include a probability of exceedance, thus the number of violations is always the same. For the other two scenarios, as the probability of exceedance increases, the number of violations decrease until a low point is reached; then the number of violations increases.

Figure 4 First Mentioned

For scenario II, the fish target rule, the fewest number of violations, 84 days, occurs at a probability of exceedance of 0.45. At lower probabilities of exceedance (higher confidence in meeting the target on each day), the fish water is used up too early in the summer, and there is no protection against violations later in the season. At probabilities greater than 0.45 (smaller fish releases with lower confidence in meeting the targets on any given day), the violations increase because the rule is not meeting the targets often enough.

Scenario III, the degree-day fish release rule, calculates smaller fish releases at lower probabilities of exceedance, thus does not use the fish water as quickly as scenario II and hence has fewer overall violations. Scenario III has an optimal probability of exccedance of 0.2 with 72 violations. Like scenario II, the scenario III violations decrease as the probability of exceedance increases up to the optimal probability, then increase slightly because at low confidence levels, the lower releases do not meet the targets on enough total days.

At lower probability of exceedances the degree-day rule outperforms the target rule because it saves more water for later in the season, while preventing the early season violations with high level of confidence. At higher probability of exceedances, both rules release less water, but the the target rule is more successful because it is a more conservative rule by definition, aiming to meet the perferred target every day. An additional risk in saving too much for later in the season is that, in dry years, late-season low reservoir pools can reduce the outlet capacities so that fish releases are not possible. This effect is seen in the sharp increase in violations for scenario III at probability of exceedances greater than 0.4. At a probability of exceedance of 0.45, scenario II uses more fish water with fewer violations early in the season when total reservoir storage is higher. The combination of more conservative logic with larger earlier releases make the target rule more effective when late season low reservoir elevations impede fish releases. However, the most effective combination of rule logic and probability of exceedance is at higher confidence levels, where the degree-day rule provides the fewest violations.

Figure 5 First Mentioned

Figure 5 shows the stream temperatures for June, July, and August of 1988 through 1994 under all three scenarios using the optimal probabilities of exceedance for scenarios II and III. From 1988 through 1991, fish releases are either not needed at all or are not needed until August. Because there is sufficient fish water available and released, there are few violations in these years. 1992 was the end of five consecutive years of drought and there was little water remaining in storage for fish or other purposes. This, coupled with the lack of precipitation in 1992, leads to stream temperatures that are above the violation threshold by the end of June in Scenario II and the middle of July in Scenario III. Because the hydrology in 1993 is relatively wet, water can be stored and released for fish and other purposes. There are few occurrences of fish water releases and almost no violations.

1994 is again a relatively dry year. The 1994 plot shows that meeting a constant target temperature of 22ºC (scenario II) results in the reservoir running out of fish water in the middle of August. The degree-day approach (scenario III) allows the target temperature to vary, saving enough water for a few more days in August. The day after the temperature goes below the preferred target, the temperature is in the 23ºC to 24ºC range because the target was set to 24ºC. Then, a larger volume is released to aim for a target of 23ºC. The temperature is fairly constant in this range between 22ºC and 23ºC until the number of degree-days is above the threshold. At this point, a larger volume of water is released to reset the degree-day counter to zero and the process repeats. In a dry year like 1994, the degree-day scenario exhibits an up-and-down pattern due to the changing targets. However, all of the fish water is used with both fish release rules.

Table 3 First Mentioned

Table 3 shows the volume of fish water released for each scenario. In scenario I, there is no fish water stored or released. In the other two scenarios, the volume of fish water released is almost identical; the degree-day rule achieves fewer violations and uses only slightly more water in doing so. For the example application, the quantity of fish water was adequate to avoid temperature violations in a single dry year. But during an extended five year drought, there was not enough fish water to avoid violations regardless of the fish release rule selected.

To summarize, the results demonstrate that the fish release rules in this DSS reduce the number of temperature violations at Reno by using a statistical model-based prediction of the stream temperature based on scheduled flow and forecasted air temperatures. The target release rule reduces violations by determining the necessary additional flow required to meet a temperature target with a specified confidence level. The degree-day rule further decreases the number of violations using less water by taking advantage of more flexible targets.

The flexibility provided by the degree-day approach and the uncertainty threshold is a unique and important feature of the DSS. Furthermore, each component can be modified based on new information and techniques. For example, the temperature prediction model can be calibrated to new or different data and the operational rules can be modified to tailor the DSS to a different basin.

In this basin, the effect of the releases for stream temperature does not continue significantly past Reno. Downstream of Reno, the stream temperature is typically at the equilibrium temperature and additional releases of a reasonable magnitude do not lower the stream temperature. Although temperature is not affected downstream of Reno, the fish water is beneficial to dilute wastewater treatment plant effluent that is discharged into the stream.

The DSS framework developed in this paper is likely to perform better in daily operations than with historic data because observed temperature data from the previous day can be used to predict current day temperatures. The previous day’s water temperature can be monitored and used in the degree-day calculation, thus, improving the use of the limited supply of the fish water.

Summary

This paper presents a DSS to help make decisions about how to most beneficially use allocated fish water to avoid stream temperature violations in the summer season. The main objective of the DSS is to minimize temperature violations with limited available water. Included in the DSS framework is a statistical stream temperature prediction module with associated confidence levels for meeting a temperature target. The DSS components can be tailored to use on any basins with allocated fish water in which temperature downstream of the controlled release of the fish water can be predicted with a statistical model.

A simple example application to the Truckee River near Reno, Nevada, shows that large volumes of water are necessary to meet a temperature target with a high degree of certainty and violations may still occur if all of the stored water is depleted. A lower degree of certainty uses less water but there is a higher probability that the temperature targets will be exceeded. In a further refinement of the target concept, a release rule, based on degree-days considers the previous days' stream temperatures and allows temperatures to exceed the preferred targets for a limited number of days that can be tolerated by the fish. These rules resulted in a reduction of the number of temperature violations without increasing the amount of water used. With a limited supply of fish water, each fish release rule has an optimal probability of exceedance level that balances confidence in achieving target temperatures with the risk of running out of fish water later in the season. For the test case, the volume of fish water was adequate to avoid temperature violations in a dry year but during an extended drought, there was insufficient fish water to avoid violations regardless of the fish release rule selected.

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Tables

Table 1. Temperature target determination, degree-day approach

	June	July	August
22ºC < $\hat{T}$ and 4 ≤ DD	22ºC		
25ºC ≤ $\hat{T}$ and DD ≤ 4	23ºC		
24ºC ≤ $\hat{T}$ ≤ 25ºC and 1 ≤ DD < 4	23ºC		22ºC
24ºC ≤ $\hat{T}$ ≤ 25ºC and DD < 1	24ºC		23ºC
22ºC ≤ $\hat{T}$ ≤ 24ºC and DD < 4	23ºC		

Table 2. Scenarios for DSS model results

Scenario Number	Description of Scenario
I. Normal operations	Normal Operations: Releases to meet Farad target flows and other normal operations, constrained by hydrology
II. Fixed target fish water release rule	Normal Operations with: Fish water storage in Boca and Stampede, Fish water releases to meet temperature target of 22ºC, and Constant probability of exceedance throughout run.
III. Degree-day fish water release rule	Normal Operations with: Fish water storage in Boca and Stampede, Constant probability of exceedance throughout run, and Includes degree-day approach.

Table 3. Volume of fish water used 1988-1994

Scenario	Fish water used ($10^7 m^3$)
I.	0
II. P = 0.45	7.72
III. P = 0.2	7.80

List of Figures

Figure 1. Map of the Truckee Basin

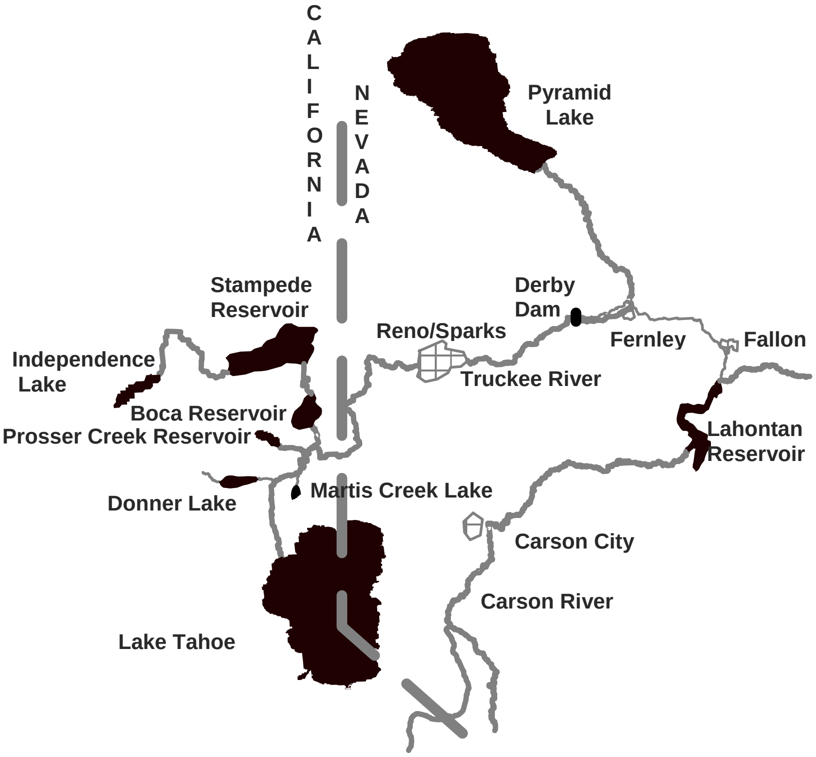


Figure 2. Schematic of DSS Study Area

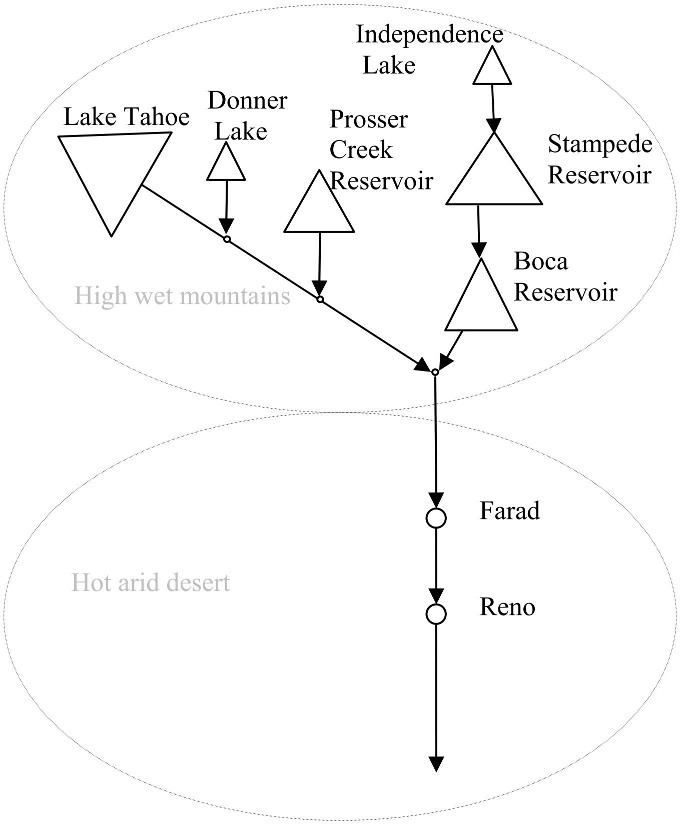


Figure 3. Temperature Reduction To Meet Desired Exceedance Probability

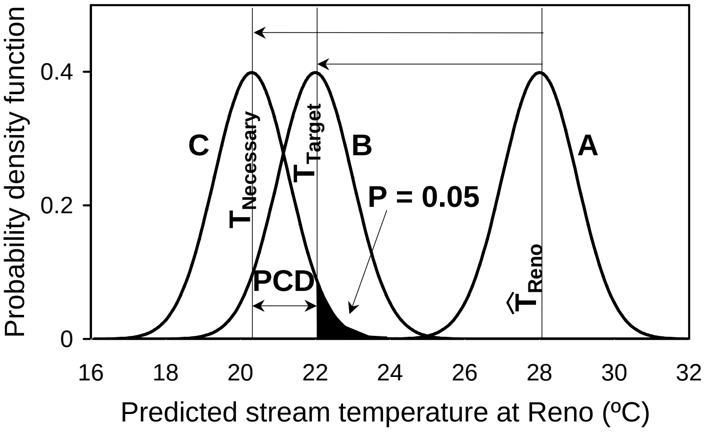


Figure 4. Number of Days in Violation Versus Probability of Exceedance, June, July, and August, 1988 to 1994

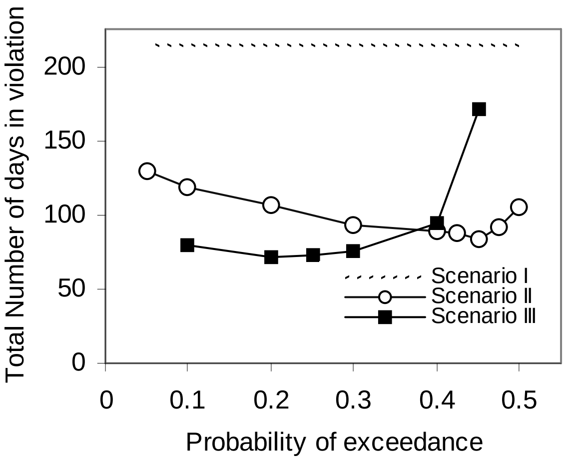
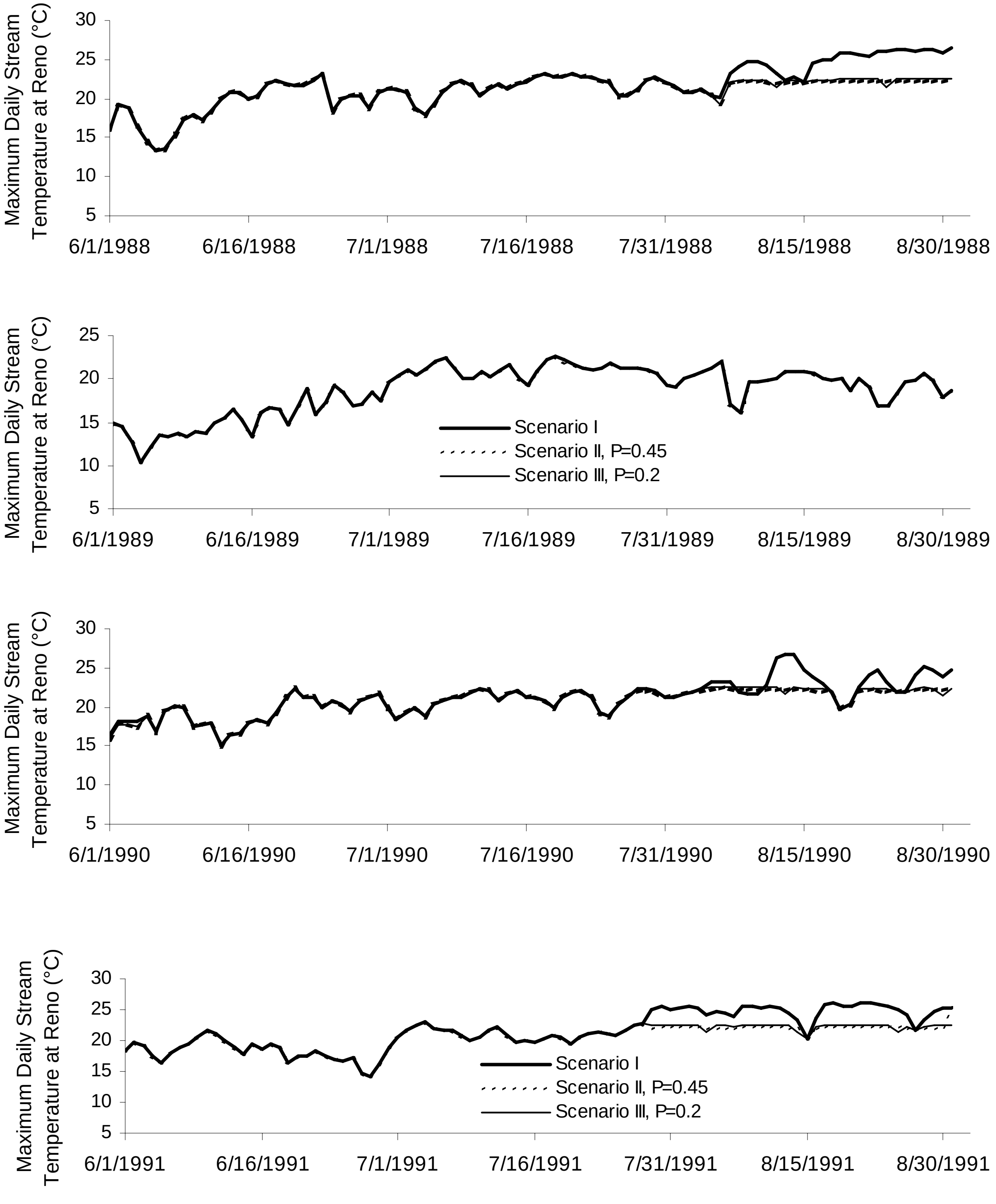
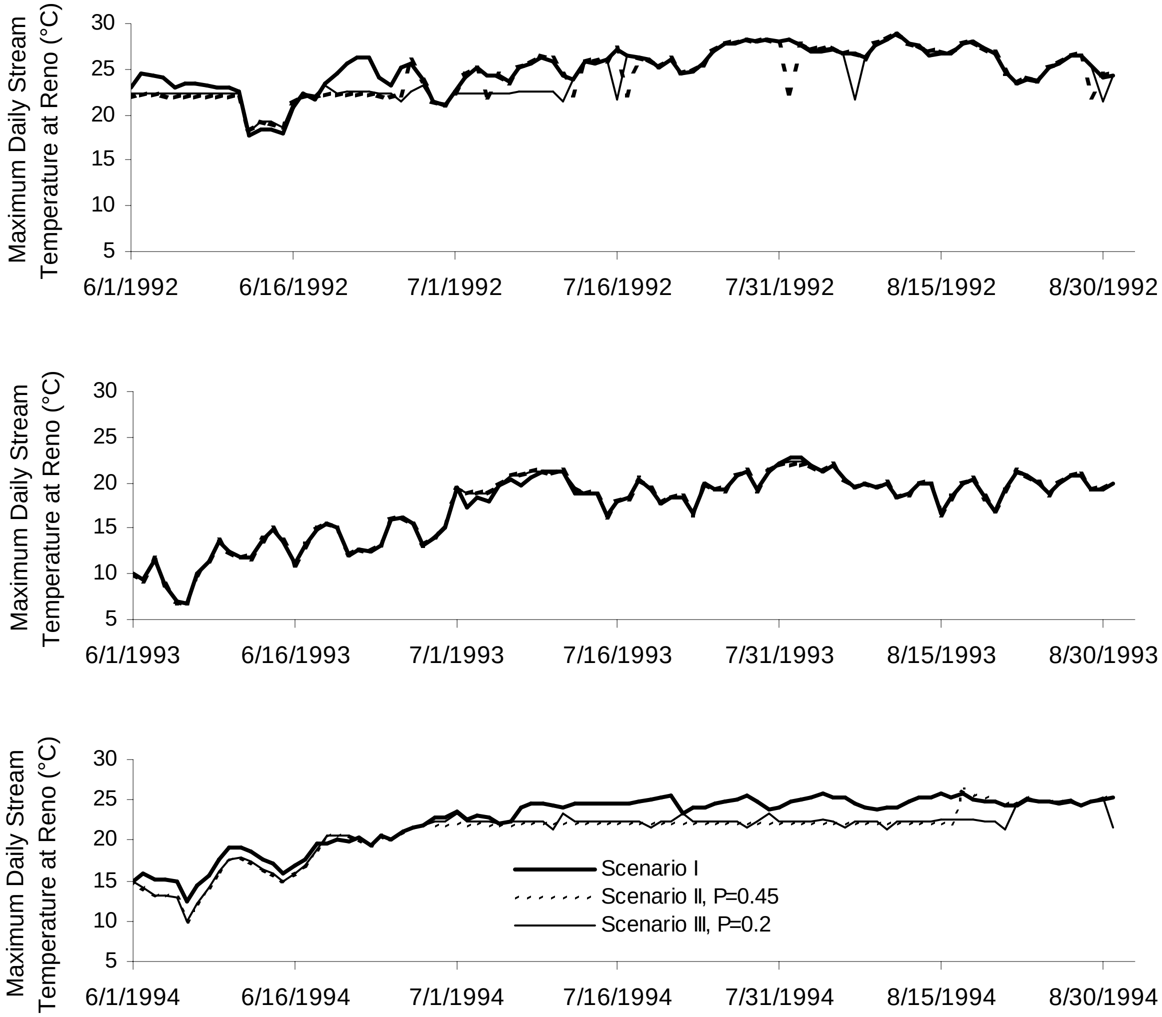


Figure 5. Stream Temperature at Reno for Scenarios I, II, and III; P is the Probability of Exceedance




Maximum Daily Stream Temperature at Reno (°C)
30
25
20
15
10
5
6/1/1992
6/16/1992
7/1/1992
7/16/1992
7/31/1992
8/15/1992
8/30/1992
Maximum Daily Stream Temperature at Reno (°C)
30
25
20
15
10
5
6/1/1993
6/16/1993
7/1/1993
7/16/1993
7/31/1993
8/15/1993
8/30/1993
Maximum Daily Stream Temperature at Reno (°C)
30
25
20
15
10
5
6/1/1994
6/16/1994
7/1/1994
7/16/1994
7/31/1994
8/15/1994
8/30/1994
Scenario I
Scenario II, P=0.45
Scenario III, P=0.2