AN OPERATIONS MODEL FOR TEMPERATURE MANAGEMENT OF THE TRUCKEE RIVER ABOVE RENO, NEVADA

by

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This thesis entitled:

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An Operations Model for Temperature Management of the Truckee River above Reno, NV

Thesis directed by Edith Zagona and Assistant Professor Rajagopalan Balaji

This thesis develops and presents a decision support system (DSS) to manage the temperature of the Truckee River at Reno, Nevada. Warm summer river temperatures adversely affect threatened and endangered fish. Water rights are anticipated to be purchased by the federal government and local entities as part of the Water Quality Settlement Agreement (WQSA). The acquired water will be stored in upstream reservoirs and released to improve downstream water quality.

The DSS implements an empirical model to predict maximum daily Truckee River water temperatures in June, July and August given predicted maximum daily air temperature and modeled average daily flow. The empirical model ($R^2 = 0.9$) is created using a step-wise linear regression selection process using 1993 and 1994 data. The model is shown to work in a predictive mode by validation using three years of historical data and by using cross-validation. The predictive model includes a prediction confidence interval to quantify the uncertainty. A target minimum water surface elevation for the primary reservoir is determined to prevent warm releases.

The U.S. Bureau of Reclamation is developing an operations model of the Truckee River using RiverWare that uses prioritized operating rules to calculate reservoir releases. The model is under development and does not yet represent current or historical operations. This research develops additional rules that calculate higher releases using stored WQSA water if the predicted water temperature at Reno is above the target value. Releases are determined from the temperature prediction relationship and a user-specified confidence level for meeting the target. Strategies are develop to effectively use the WQSA water throughout the season. These strategies are based on seasonal climate forecasts, the temperature of the river over the previous few days, and the amount of available WQSA water.

The DSS model is tested using historical inflows for a dry hydrology from 1990 to 1994. Various scenarios are explored that show the effect of changing the confidence level and using seasonal strategies. Results from this study show that there is not enough water to avoid all temperature violations in a drought, but most of the early violations can be avoided with a high degree of certainty.

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Chapter 1

Introduction

An increasingly common problem in western U.S. river basins and elsewhere in the world is that water storage and use for municipal, industrial, agricultural, and power production purposes leave fish with insufficient flow to maintain populations. Low flows threaten fish by deteriorating habitat and/or water quality. One of the most common water quality problems associated with low flows is temperature—low flows warm up more rapidly than higher flows. High river temperatures reduce cold water fish populations by inhibiting growth and by fish kills at extreme high temperatures. As fish populations decrease, the federal government is forced to list species as threatened or endangered. For this reason, the impact of low flows on fish is the central focus of many operations studies and National Environmental Policy Act (NEPA) Environmental Impact Statement (EIS) analyses such as those on the Rio Grande, Colorado, and Columbia basins (Rio Grande, 2000; Operation, 1995; Columbia, 1995). In each of these basins, the water management agencies need to modify operations to increase habitat and/or improve water quality for fish. In some basins, water rights are being reallocated to insure adequate supplies for fish flows. To implement reallocation and operations changes, water management must incorporate fish objectives into their daily operations and long term planning tools. Technically, this is more challenging because it requires management of both water quantity and water quality. Also, managing water quality is much more uncertain than managing quantity. Water quality is affected by many factors that change seasonally, daily, and even hourly. There is usually not enough water to meet all water quality and fish objectives with a high degree of certainty. Therefore, decisions must trade off the uncertainties of releasing for fish and water quality objectives and the limited resources available.

1.1 Problem statement

Management of water temperature by controlling flow in a large, multi-purpose, multi-reservoir basin can effectively be accomplished with the assistance of a model-based decision support system (DSS) that can predict temperature and incorporate temperature objectives into daily operations objectives. A practical DSS for daily use has the following functional requirements:

1. A water temperature prediction model that is quick, accurate, and easy to use in terms of the DSS. It must be spatially and temporally consistent with the operations decision model.
2. Quantification of confidence associated with the temperature prediction.
3. Operations rules for releases that benefit river biota that use the water temperature prediction and consider the confidence of the prediction.
4. Integration of other operating releases.
5. Seasonal strategies incorporated in the operations to trade off meeting one day's targets with the ability to meet seasonal needs.

1.2 Study Area

The Truckee River, like other basins in the western U.S., does not have the water resources to meet agricultural, municipal, and industrial purposes and still provide adequate habitat for fish. The Truckee River starts high in the California Sierra Nevada mountains and flows through an arid desert before terminating in Nevada's Lake Pyramid. Because of low flows exacerbated by human uses, temperatures in the lower river are too warm during the summer months for endangered and threatened cold water fish. Water rights will be acquired by the Water Quality Settlement Agreement (WQSA) to be used to improve the water quality of the Truckee River. The U.S. Bureau of Reclamation has been charged to help manage the system. They are developing a current operations decision support tool using the general-purpose river and reservoir modeling software RiverWare (Zagona et al., 1998 and 2001). The USBR's intention is to develop a DSS for current conditions and then modify it to simulate the Truckee River Operating Agreement (TROA). The TROA—which is still under negotiation—modifies legal operating policy for the basin. The current conditions DSS is under development and does not represent all policies in the basin. As a result, this thesis refers to the operating policies reflected in that DSS as the *baseline operations*. The baseline operations DSS is not complete nor is it tested against actual operations. The results produced are hypothetical in nature. In the future, the framework developed in this thesis can be used with actual operations to produce more realistic results.

The USBR funded this thesis as part of an overall request for research guidance to their implementation of the WQSA in terms of operations of the federally controlled reservoirs in the Truckee basin. Although other water quality concerns exist, including dissolved oxygen, nutrient loading, and dissolved solids, this research is intended to be a proof of concept that specifically addresses water management for temperature control.

1.3 Outline of approach

This thesis approaches the problem as shown in the flowchart in Figure 1.1. A description of each step in this process follows:

1. Develop an empirically based predictive river temperature model that can be used by the DSS. Standard statistical methods are used to identify significant model variables. The prediction model is verified. This is presented in Chapter 4, “Temperature Prediction Model.”

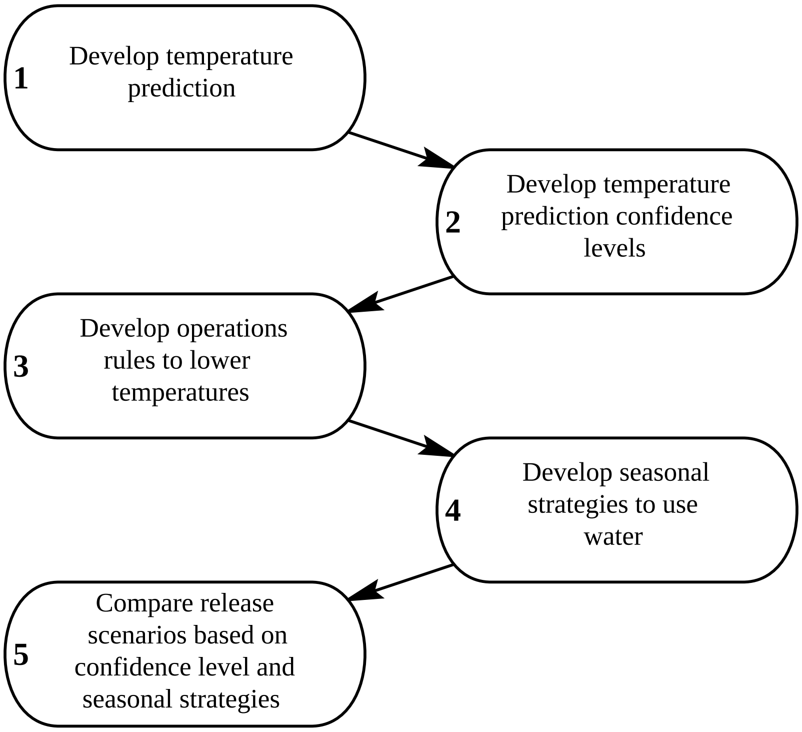


Figure 1.1: DSS development flowchart

2. Develop confidence levels for the predictive model using standard statistical techniques. This is also presented in Chapter 4, “Temperature Prediction Model.”

3. Develop operations rules to release water acquired by the WQSA to improve temperatures for fish. The rules are based on the USBR’s baseline operations DSS. The temperature prediction and the associated uncertainty is incorporated into the DSS so that operations rules can be developed to release water for water quality purposes. The new rules are checked to ensure they do not affect other operations and that they, in fact, lower river temperatures for fish. This is presented in Chapter 5, “Decision Support System.”

4. Develop seasonal strategy rules that incorporate long-term climate forecasts and predictions of the available water. This is also presented in Chapter 5, “Decision Support System.”

5. Use the DSS with and without seasonal strategies in historic low-flow peri-

ods to demonstrate the effectiveness of the DSS and the benefits of seasonal strategies. Also, the DSS will be used with different confidence levels to show the impact of user-specified confidence levels. The results are presented in Chapter 6, “Testing and Results.”

1.4 Contribution of this research

This research shows how temperature objectives can be integrated into a daily operations decision support systems to help make decisions that lower river temperatures. To accomplish this, a simple empirical predictive model that includes the uncertainty of the prediction is developed and tested. The prediction and the uncertainty are incorporated into the operations DSS through the use of rules that model reservoir releases. Results show that seasonal use strategies are necessary to maximize the benefit of an allocation of water. Finally, this research exposes additional areas that warrant more research.

Chapter 2

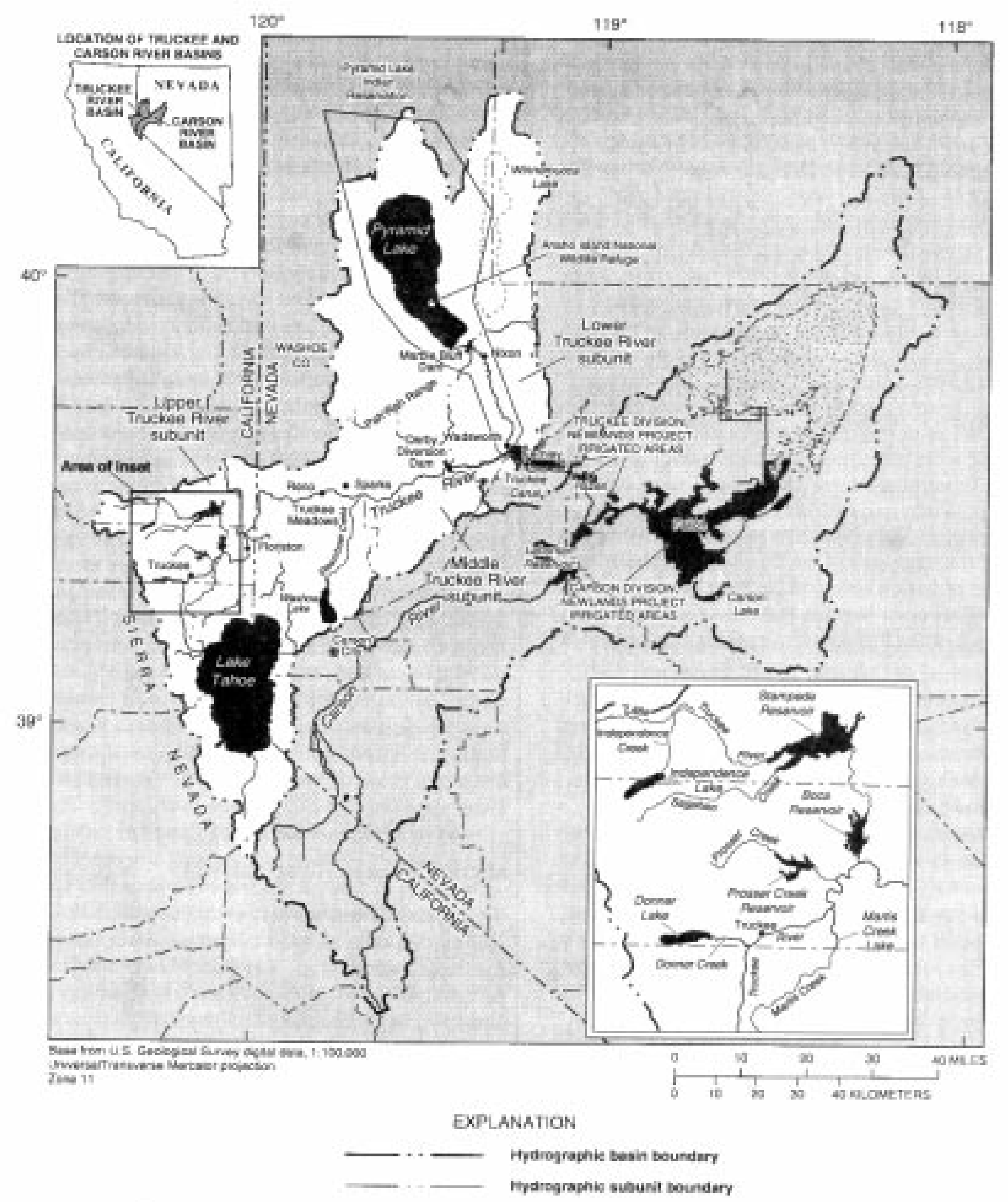
Background

2.1 Description of the Truckee basin

The Truckee River flows from Lake Tahoe high in the California Sierra Nevada Mountains, past Reno, Nevada, into Pyramid Lake. A map of the basin is shown in Figure 2.1. The river basin includes three general areas: the upper basin downstream of Lake Tahoe, the middle basin near the Truckee Meadows, and the lower basin downstream of Reno and Sparks.

Upper basin downstream of Lake Tahoe.

The upper basin is steep, high alpine or forested land and the clear, cool river flows through steep canyons. This area receives the greatest precipitation all in the basin: 30 - 60 inches a year mostly in the form of snow (Taylor, 1998). Seven major storage reservoirs exist in the upper part of the basin. Three are natural lakes with outlet control structures: Lake Tahoe, Donner Lake, and Independence Lake, and four are artificial reservoirs: Martis Creek Lake, Prosser Creek Reservoir, Stampede Reservoir, and Boca Reservoir. These reservoirs provide a large amount of flood control storage and store for downstream uses. Development in the upper basin includes ski resort and tourist activity. Housing communities also exist on the shores of Lake Tahoe.

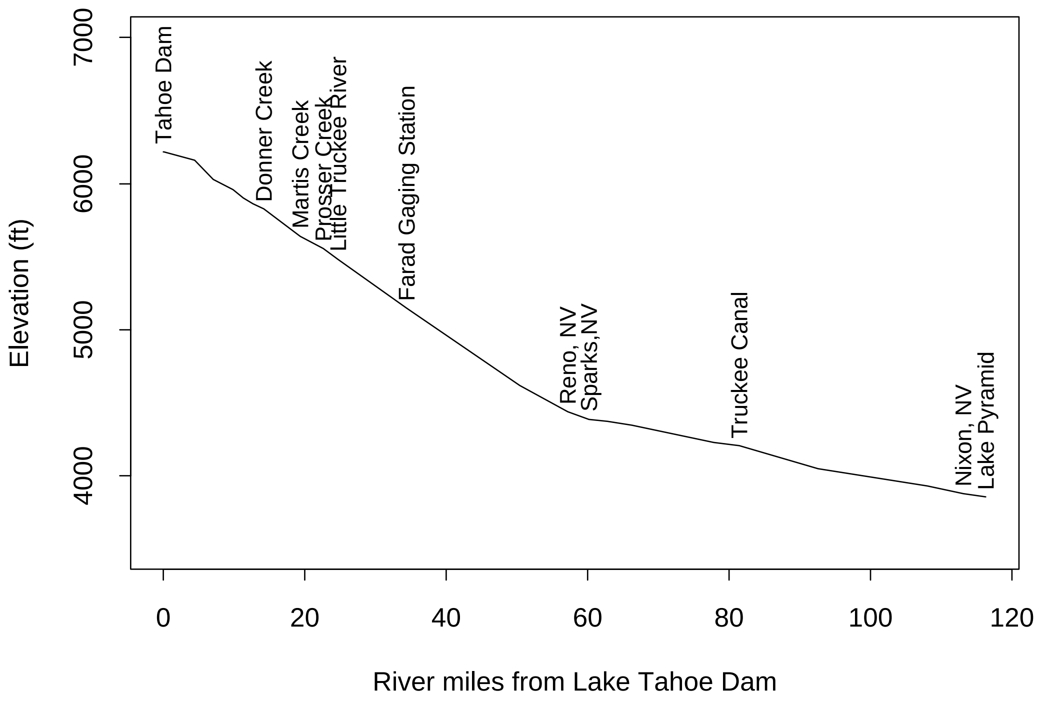


(Taylor, 1998)

Figure 2.1: Map of the Truckee/Carson Basin

Middle basin near Truckee Meadows.

After joining the Little Truckee River near Boca, California, the Truckee River flows in a steep canyon before it reaches the Truckee Meadows that encompass the cities of Reno and Sparks, Nevada. Near Reno, the river gradient decreases as shown in Figure 2.2, leading to slower stream velocities and higher water temperatures.



Created from data in Brown & Krygier (1986)

Figure 2.2: Truckee River elevation profile

Slower stream velocities lead to higher water temperatures because the water has longer contact with warm air temperatures and solar radiation. Figure 2.3 shows representative maximum daily Truckee River temperatures between the Little Truckee River and Reno for 1994. It shows how this reach of river warms during low flow summer periods.

The Truckee Meadows is in the rain shadow of the Sierra Nevada Mountains and receives less than 8 inches of precipitation a year (Taylor, 1998). Although the Truckee Meadows was once an agricultural area, the expanding cities of Reno and Sparks have converted much of the land to urban uses. Consequently, water use has changed from agriculture to municipal and industrial (M&I). Used M&I water, treated at the Truckee Meadows Wastewater Reclamation Facility (TMWRF), is released into Steamboat Ditch near its return to the Truckee River. When the river is low, a large portion of the flow is treated wastewater, which degrades water quality.

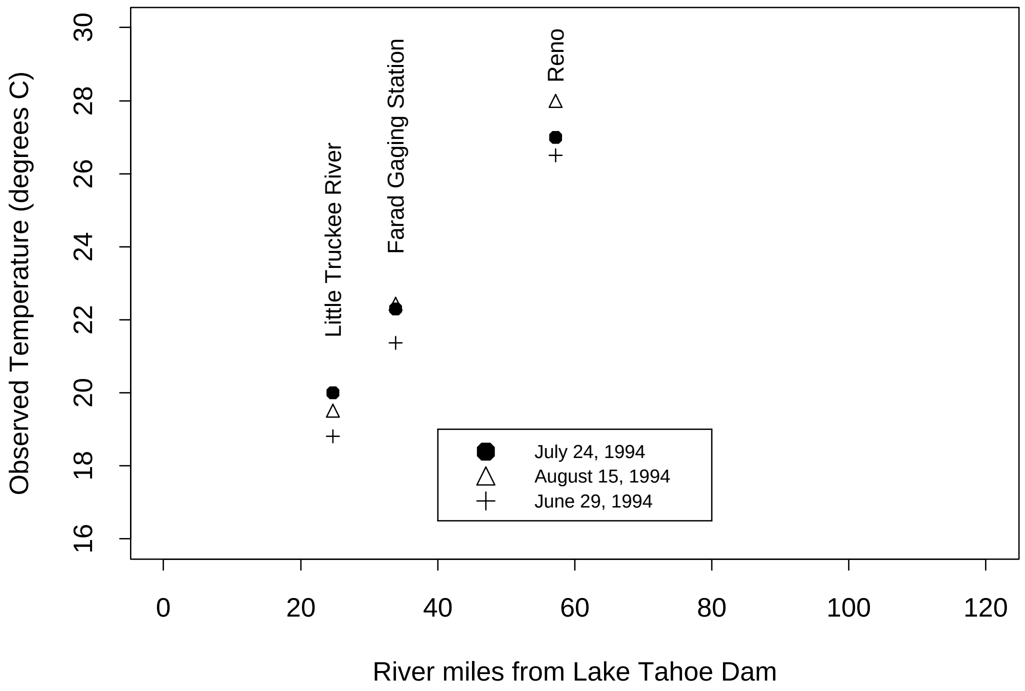


Figure 2.3: Representative observed Truckee River temperatures

Studies have shown temperature problems in the Truckee River upstream of Reno. Between the state line and Reno, historic temperatures exceed instantaneous and prolonged exposure limits for trout during July and August (Bender, 1995). Cold water from Prosser and Boca can be released to mitigate these problems. If the reservoirs are low, however, released water may be too warm for trout, resulting in fish kills, as happened in the summer of 1994 (Truckee River Operating Agreement Draft EIS/EIR, 1998). Because the U.S. Fish and Wildlife Service maintains the river upstream of Reno as a trophy fishery and the river within Reno/Sparks as an urban fishery (Tisdale, 2001), the temperature of the river is important for fisheries.

Lower basin downstream of Reno/Sparks

Downstream of Reno/Sparks, the river flows across a large flat plateau and water is diverted to the Truckee Canal. Diverted water is stored in Lahontan Reservoir, located in the Carson River basin, and used to irrigate lands in the Newlands Project. The portion of the river that is not diverted to the Truckee Canal continues in a desert canyon before pouring into Pyramid Lake, a terminal desert lake, within the Pyramid Lake Indian Reservation. Two culturally and economically important fish to the Pyramid Lake Indian Tribe live in Pyramid Lake—the endangered cui-ui and the threatened Lahontan cutthroat trout—which migrate upstream to spawn. Sediment, reduced flow, and diversion dams have made it increasingly difficult for these fish to move upstream to spawn. Also, low flow and shallow depths can lead to unfavorable stream temperatures for spawning, egg incubation, and survival (Taylor, 1998). Brock and Caupp (1996) performed a study of the Truckee River between Reno/Sparks and Pyramid Lake to model temperature using physical processes. They showed that many river temperature violations occur in dry years and that in wet years and during spring before irrigation releases start, fish temperature standards are also exceeded on many days.

2.2 Water temperature management location

In terms of operations, it is not practical to predict river temperature everywhere because the number of computations and the required inputs is too great, therefore the water temperature prediction location must be selected carefully to give results that are accurate and useful to affect operations changes. Most of the temperature problems in the Truckee River are downstream of Reno where the river flattens out in the arid desert. But, downstream of Reno, wastewater effluent and irrigation return flows enter the river. Thus, accurately predicting temperatures is much more complex. To simplify the problem and to prove the concept, this thesis predicts and manages the temperature at Reno. Although the WQSA specifically states that water allocated by WQSA water rights is to be used to improve water quality downstream of Reno, a simplified tool to predict and manage temperatures at Reno is useful as a starting point. Setting Reno as the main temperature prediction and improvement point ensures that the river reach from Reno upstream to the confluence with the Little Truckee River is cool enough. In addition, temperature targets at Reno can be set low enough that a realistic probability exists that temperatures at downstream locations are also acceptable. Figure 2.4 shows a map of the study area. Future studies should extend the temperature prediction downstream of Reno.

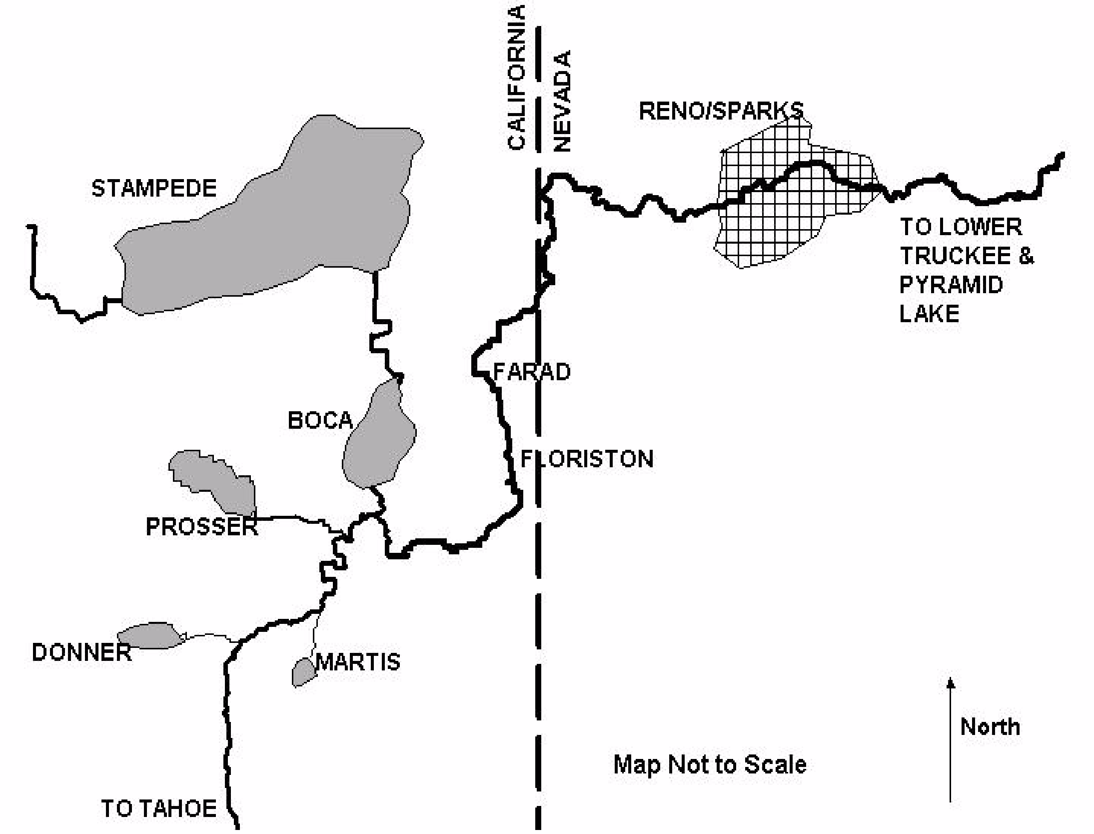


Figure 2.4: Map of the study section

2.3 Ongoing policy negotiations

Two types of policy are defined in this study. *Legal policy* refers to water rights and operational criteria as established by agreements, legislation, and court decisions such as Public Law 101-618, the Truckee River Operating Agreement (TROA), and the Water Quality Settlement Agreement (WQSA). Operators have little control over these policies. *Implementation policy* is the procedure project operators use to meet legal policy. Implementation policy is how operators decide how much water to release each day or month—within legal policy—based on scheduled demands, forecasts and physical constraints. Operators and water managers have more control over the implementation procedures than the legal policies. In fact, the water management agencies must develop implementation policies.

Negotiations continue over the legal policy to operate the river. In 1990, negotiations began on the Truckee River Operating Agreement (TROA), as dictated by Public Law 101-618. This law states that the U.S. Secretary of the Interior must negotiate an agreement on how to operate the Truckee River with the states of California and Nevada, the Sierra Pacific Power Company, and the Pyramid Lake Indian Tribe. Other negotiating parties include the cities of Reno and Sparks, Washoe County, and the Truckee Carson Irrigation District. P.L.101-618 requires that the TROA specify reservoir operations such that terms, conditions and contingencies of the Preliminary Settlement Agreement (PSA) are fulfilled. The PSA of 1989, between Sierra Pacific Power Company and the Pyramid Lake Tribe, changes the operations of federally controlled reservoirs to improve spawning conditions for endangered fish in the Truckee River and to increase municipal and industrial water for the Truckee Meadows during drought conditions. Because of the large number of interested parties, negotiations over acceptable legal policies have been delayed. As of November 2001, TROA has not been approved. This delayed negotiation procedure shows the complicated nature of the problem.

2.4 WQSA

In 1996, the Water Quality Settlement Agreement (WQSA) was reached among the U.S. Federal Government, the Nevada Department of Environmental Protection, Washoe County, Reno, Sparks, and the Pyramid Lake Paiute Tribe to enhance flows in the Truckee River explicitly to improve water quality between Reno and Pyramid Lake. Washoe County, in conjunction with the cities of Reno and Sparks, and the federal government each agreed to purchase half of $24 million worth of water rights to help meet water quality standards downstream of Reno/Sparks during the low flow summer period. The WQSA (1996) states that the water rights shall be used

> primarily to augment instream flows in the Truckee River from the Reno/Sparks area to Pyramid Lake to assist in the compliance with water quality standards, and also to improve water quality and to maintain and preserve the lower Truckee River and Pyramid Lake for purposes of fish and wildlife, including threatened and endangered species, and recreation.

The water rights are expected to be purchased in the Truckee Meadows and in the Truckee Division off of the Truckee Canal. Instead of diverting water for irrigation, water, from the purchased water rights, is left in the river for water quality purposes. In other words, the irrigation water is converted to the purchased water in near real time and left to flow to Pyramid. Under certain conditions, the purchased water in the river can be exchanged with fish spawning water and stored in Stampede and Prosser as Water Quality Credit Water (WQCW). As part of the WQSA, the federal government agreed to provide storage space in Stampede and Prosser for WQCW. Whereas the WQSA is the agreement to purchase water rights for water quality purposes, WQCW is the stored water accumulated from water purchased by the WQSA. WQCW storage in the federally controlled Stampede and Prosser reservoirs are junior to storage of water addressed in the PSA, P.L. 101-618 and TROA. At the time of negotiations, the WQSA negotiations estimated that $24 million could purchase 24,000 acre-feet of water rights (Scott, 2001). As of early 2000, the USBR estimated that 17,000 acre-feet of water could be purchased (Scott, 2001).   Although the process and methods of acquiring the water rights and storage space are nearly in place, the criteria for releasing the WQCW is to be determined by a committee with no specified guidance. The WQSA (1996) says that in determining when and how much water to release or store, the program parties must take into consideration:

> the amount of water available, the need to maintain carryover storage, the potential for spill loss, estimates of incremental evaporation loss, the benefits of releasing the water, the need to meet existing or revised National Pollution Discharge Elimination System permit conditions, and future water augmentation needs.

Whether or not a TROA is signed, the WQSA will be implemented. Decisions will need to be made as to how to use the WQCW.

2.5 Fish tolerance levels

Fish temperature tolerance levels indicate the maximum water temperature the fish can tolerate and for how long. Gaining information on temperature tolerance levels is fairly difficult. Fishery biologists are reluctant to give numbers because of the many variables involved. The levels used in this thesis are based on a summary of Nevada standards given by Brock and Caupp (1996) in which the maximum temperature for juvenile Lahontan cutthroat trout in summer is 24 ºC. Bender (2001) suggested modifying the targets to include four-day maximum limits and allowable one-day maximum temperatures. The resulting standards, shown in Table 2.1 and used in this study, are realistic but not official.

Table 2.1: Truckee River target temperatures

Target (ºC)	Description	Time Period
T ≤ 22	Preferred Maximum	> 4days
22 < T ≤ 23	Chronic Maximum	≤ 4days
23 <T ≤ 24	Acute Maximum	≤ 1day
24 < T	Absolute Maximum	0 days

The temperature standards and targets include: preferred maximum, acute maximums, chronic maximums, and absolute maximums. The preferred maximum target temperature in the Truckee River above Reno, NV is 22 ºC. At this temperature, adult trout can live for an extended period of time. Although this temperature may be too high for juvenile fish and for rearing, it is a comfortable upper limit for adult fish. At 23 ºC, trout can survive but not for extended periods of time. Thus, in this thesis, 23 ºC is an allowable temperature for four or fewer days. The acute maximum temperature for trout in the Truckee River is 24 ºC. At this temperature, trout can survive for one day or less. We assume that 24 ºC is the allowable one-day maximum temperature. At temperatures greater 24 ºC, trout in the Truckee River are adversely affected. If this temperature is exceeded for more than a few hours, trout begin to die. The rules developed in this thesis strive to always make the maximum daily Truckee River temperature at Reno less than 24 ºC. This thesis assumes that the daily maximum occurs for only a few hours. That is, even if the temperature reaches 23.9 ºC, it is for only a few hours, and fish are not greatly affected. Finally, if the temperature on any given day is in any temperature range for more than the specified number of days, the fish are adversely affected. In this thesis, this is defined as a *violation*. It does not correspond directly to legal violations but is a way to quantify the results of the study.

There are additional water quality standards in the Truckee River that deal with dissolved oxygen, dissolved solids, turbidity, and other water quality parameters. Other water quality parameters (dissolved oxygen in particular) are dependent on water temperature. Because of the complexity of quantifying and predicting other parameters and the importance of temperature, this thesis only deals with temperature. Historically, the standards—including temperature—only had to be met 90% of the time (Bender, 2001). The water quality standards, in low flow periods, were often not met.

2.6 Baseline operations model using RiverWare

The USBR is currently creating a daily time-step model of the Truckee and Carson Rivers using RiverWare, a general purpose river and reservoir operations policy modeling software (Zagona et al., 1998 and 2001). The movement of water through objects representing reservoirs, reaches, and diversions are controlled by user-defined, prioritized logic based on legal and implementation policy called rules. The model also includes an accounting network to track water as it moves through the system. Consequently, it is possible to track whether water was released to meet flow targets or for irrigation demands. The rules dictate how much water is released from each reservoir, what account the water came from, and where the water goes. The Truckee River RiverWare model simulates implementation policy—reservoir releases, forecasts, and diversion schedules. By using different rules to move water through the system, it is possible to simulate flow patterns using different policies. The rules attempt to model the current operations in the basin and are still under development. Currently they do not represent all of the policies in the basin. We refer to this set of rules as the *baseline operations*. The baseline operations differ from both historical and actual current operations; therefore, the model cannot be calibrated or verified against historical observations.

An instream flow target at Farad, called the Floriston rates, is the main basin operating goal modeled. Floriston rates are met by unregulated inflow and releases from storage. The water released for Floriston rates is used for irrigation and municipal purposes. Boca reservoir was created to store and release water to meet Floriston rates. As a result, Boca is drawn down completely in dry times to meet Floriston rates. Other major policies and laws simulated include flood control, instream flows, Tahoe-Prosser Exchange, Operating Criteria and Procedures for the Newlands Project, and fish spawning releases (see Appendix A, “Operating Policy in the Basin” and Appendix B, “Description of select laws”).

Chapter 3

Literature Review

Researchers have conducted extensive studies to predict water quality parameters in rivers and streams. Much of the work has involved modeling the physical processes that affect temperature in a stream. Researchers have also tried to use empirical relationships and historical data to predict how temperature will vary in the future. Both of these techniques have been used in the Truckee River basin. In some studies, the uncertainty of water quality prediction has been analyzed. The following is a review of previous research.

3.1 Physical process stream temperature models and studies

A great deal of research has been conducted using mechanistic approaches to model temperature in a river. This effort usually consists of solving the one (or two)-dimensional advection and dispersion equations for flow and heat transfer. This approach uses numerical methods to solve a partial differential equation. With this approach, various processes need to be included, such as heat transfer between the air/water and bed/water interface, solar radiation, evaporation, and heat inputs from other sources like thermal power plants. Each of these processes can be as complex or as simple as desired. For example, Carron and Rajaram (2001) used atmospheric and streambed heat transfer in a coupled unsteady flow and heat transport model to simulate river temperatures below a dam. For a good description of the processes involved and the governing equations see Carron and Rajaram (2001), Sinokrot and Stefan(1993), Gu et al. (1998), and Hockey et al. (1982).

3.2 Physical process models of the Truckee Basin

Researchers have conducted many studies and projects on the quality of Truckee River water.

Rowell performed an equilibrium temperature modeling study for the USBR (1975). This study predicted temperatures in the Truckee River at Marble Bluff Dam given hydrologic and meteorological conditions. It set the minimum flow required to meet a given temperature objective. Rowell used empirical equations to model the physical processes affecting the river. Temperature modeling was based on an empirical exponential temperature equation throughout the reach with heat exchanges based on coefficients and empirical relationships. This study is significant because it set up minimum flows to achieve a desired temperature goal. U.S. Fish and Wildlife Service (USFWS) still uses charts and tables based on this study to determine the flows necessary for the endangered fish spawning runs.

Taylor (1998) performed a study that modeled temperature of the Truckee River on an hourly scale using physical processes. The model was verified and calibrated using hourly data for 1993 and 1994. The most significant contribution to our research was the observed data. Hourly temperature was sampled at several sites on the Truckee River and has provided some of the data for our study.

Hoffman & Scoppettone (1988) studied the survival of Lahontan cutthroat trout eggs in the Truckee River. They found that the trout eggs survive best in gravel that is between 8.7 ºC and 13.3 ºC.

Chiatovich (1977) looked at total dissolved solids and chloride in the Truckee River above the California-Nevada state line. This study used a monthly deterministic dynamic programming model to simulate reservoir operation and a conservative transport model to simulate the water quality parameters.

In the process of negotiating the TROA, a draft environmental impact statement (TROA DEIS/DEIR, 1998) was prepared to look at the impacts of the proposed legal operating policy. The water quality of the current conditions, the No Action Alternative, and the TROA Alternative are compared in the Water Quality Appendix. This analysis is based on modeling done by Brock and Caupp (1996) using the Dynamic Stream Simulation and Assessment Model with temperature (DSSAMt) that builds on the Truckee River geometry and assumptions developed by Nowlin (1987). Nowlin developed a one-dimensional nutrient and dissolved oxygen transport model of the Truckee River from Reno to Pyramid Lake. Brock and Caupp (1996) used steady state flow with a dynamic representation of water quality parameters. River temperature is modeled using hourly meteorological data and a mechanistic representation of equilibrium temperature and heat exchange. In addition, these model runs have been calibrated and verified for wet, average, and dry years. Both the No Action and TROA Alternatives include the WQSA and are, therefore, relevant even if TROA is not signed. For the No Action and TROA Alternatives, Brock has shown that temperatures for fish will be above standard and preferred levels for wet, average, and dry years and will be particularly warm in dry and extreme drought conditions. This shows the need to explore the use of the WQCW.

The Truckee River is much warmer in summer and fall than in winter and spring. As a result, it may not be necessary to spend time and resources modeling winter conditions when the temperature does not exceed the standards. Brock and Caupp (1996) showed this to be the case. They compiled data on fish in the Truckee River and the preferred temperatures for various life stages. The DSSAMt model showed that river temperatures would predominantly exceed the standards in the lower Truckee River from April through September.

The Watershed Analysis Risk Management Framework (WARMF) is a watershed modeling framework that uses EPA's watershed approach of looking at water quality management. WARMF guides stakeholders and decision-makers through development of water quality management approaches. In the engineering module, WARMF calculates the daily runoff, groundwater flow, hydrology, and water quality of river segments. It uses meteorological, hydrological, and point load data. WARMF can model the following processes: canopy interception, snow pack accumulation, snow melt, infiltration, evapotranspiration, stream routing among others. WARMF does not encompass other operations objectives or enable managers to test prioritized implementation policy. The cities of Reno and Sparks have created a WARMF model for the Truckee River.

3.3 Empirical stream temperature models

A few articles have been published that discuss a similar approach to our proposed temperature prediction.

Hockey et al. (1982) used regression of historical data to model temperature in a river in New Zealand. The regression model used 20 years of spot mid-day river temperatures at one location. Although solar radiation is the most significant process affecting river temperature, they used maximum air temperature because other meteorological data is lacking. They fit regressions between river temperature and discharge and between river temperature and air temperature and develop a formula that relates the three variables, explaining 62% of the variance. They concluded that their technique is unsatisfactory because it does not account for diurnal variations, does not consider enough meteorological conditions, and the prediction site is not where the proposed operations changes will occur. They then used a physical process model that produced more satisfactory results. Although Hockey and others used a regression analysis, they admit that they did not have the continuous data necessary to produce the desired results.

Gu et al. (1999) looked at creating weather dependent minimum flows through correlation and regression of historical data and an analytical solution of the heat equation to quantify the impacts of flow on temperature. The minimum flow requirements were derived from the relationship between maximum daily river temperature and flow for different weather conditions. They treated weather as a reference to decouple weather from the relationship between discharge and water temperature. They grouped air temperature, solar radiation, wind and humidity into the equilibrium water temperature. They use the equilibrium water temperature to calculate the maximum heat flux, which they used as the sole weather parameter.

Where no data were available, they used a numerical unsteady heat transport and hydrodynamic model to generate the data. Heat exchange through the air-water interface is the most important and governing process for temperature in the river. Gu et al. (1998) did a similar analysis in a previous study and solved the heat equations with various heat inputs and removals.

Where data were available, they used correlation and temperature flow regressions. To perform the regression, they compared maximum and minimum daily water temperature with flow and compared maximum daily water temperature with maximum daily heat flux. They divided the sorted hourly maximum heat flux values into classes that were then considered a “weather condition.” They determined regression equations for each class and calculated a minimum flow to meet a temperature standard.

They applied their method on the Platte River in Nebraska and found a strong relationship between flow and maximum water temperature but a weak relationship between flow and minimum water temperature. This article is significant because Gu and others found that correlation of flow to river temperature is possible and useful when weather parameters are accounted for but decoupled from the model.

Mohseni, et al. (1998) developed a nonlinear regression model for weekly stream temperatures over the annual cycle. They found that a logistic function fitted the S-shaped data between weekly air temperature and weekly river temperature for

584 gaging stations in the U.S. To account for hysteresis, they fit different curves for the rising and falling limbs. This article is significant because it presents a nonlinear relationship between air temperature and river temperature that accounts for hysteresis in the annual heating and cooling cycle.

3.4 Uncertainty of water quality modeling

Our purpose is to develop an operations model to predict and help manage temperature in the Truckee River. As a part of this, we quantify the uncertainty of the temperature prediction and use this in the DSS. Three articles deal with different aspects of uncertainty of water quality modeling. The articles describe the problems, issues and approaches to quantifying uncertainty. Following is a brief summary of each article and how it applies to our research.

Beck (1987) assessed the role of uncertainty in model development to explain past-observed behavior and predict future behavior. He emphasized the need to consider uncertainty in models and not to depend on large deterministic models. He notes that larger water quality models may give highly uncertain results that must be quantified to understand the accuracy of the prediction and the resulting decisions. Also, he stressed that a model used to explain historical behavior may not necessarily be able to predict the future with the same degree of certainty. He reviewed the methods to analyze four problem areas: uncertainty of model structure, uncertainty of parameter values, uncertainty of prediction, and the design of experiments and monitoring to reduce uncertainty.

Reckhow (1994) examined various kinds of uncertainty and risk in surface water transport and fate modeling and provided examples of how to identify and quantify this uncertainty. He offered a proposal for model selection in ecological risk assessment with uncertainty. The main contribution of this paper is showing that highly detailed model structure is incompatible with “limited observational data and scientific knowledge.” He discusses the need for the public and decision-makers to know the uncertainty of a decision option so it can be fully evaluated. He also discussed the differences between empirical and mechanistic model parameter determination and suggested that managers and decision-makers come up with desired endpoints and uncertainties. If an endpoint cannot be obtained with the desired accuracy, a new endpoint or surrogate should be chosen.

Tung (1996) analyzed uncertainty in various aspects of water resources engineering. He described two main areas of uncertainty: (1) uncertainty due to inherent randomness of physical processes and (2) uncertainty due to lack of complete knowledge about parameters, processes, data, models, etc. Natural variability always occurs in real systems and can be called random or stochastic uncertainty. It is difficult to reduce natural variability because of the inherent randomness. On the other hand, uncertainty due to lack of information is called knowledge uncertainty. Knowledge uncertainty often includes model uncertainty, parameter uncertainty, data uncertainty, and operational uncertainty. Knowledge uncertainty can be improved by increasing sampling and by improving the mathematical representation of natural processes.

Tung named three types of measures of uncertainty. A probability density function (PDF) shows the most complete and ideal set of information, although it is often hard to develop precisely. A confidence interval is a “numerical interval that would capture the quantity subject to uncertainty with a specific probabilistic confidence” (Tung, 1996). Finally, a statistical moment (variance and standard deviation) captures the dispersion and spread of a random variable subject to uncertainty.

Tung described two types of techniques to quantify uncertainty: analytic and approximate. Analytic techniques are best suited to simple models where the PDF is known. Approximate techniques are useful in complex models where the PDF cannot be found or dealt with analytically. These techniques are useful to combine the uncertainty of given variables to quantify the uncertainty of the entire system. Tung described the first-order variance estimation technique, first-order second moment technique, the probabilistic point estimation technique, and the Monte Carlo techniques.

According to Tung, uncertainty and sensitivity are closely related but different in concept. Sensitivity analysis is used to investigate the mathematical response of outputs to changes in inputs. Uncertainty analysis is used to “analyze the stochasticity of the model” through the internal mathematical relationships.

In general, Tung presented various methods and philosophies related to uncertainty in water resources engineering. The techniques to analyze uncertainty should be selected based on the model structure that is used.

Chapter 4

Temperature Prediction Model

This chapter develops the predictive temperature model and quantification of the confidence level of prediction. This model is needed to predict water temperatures at Reno assuming baseline operations, and to then make decisions to release additional WQCW to improve predicted temperatures that are unacceptably warm. The model must be practical in terms of daily river operations, therefore, it must be simple and easy to implement. It should use widely available near real time inputs. Finally, the predictive model must be able to quantify the prediction uncertainty so water managers know the dependability of the prediction. This chapter describes the available historic data, and the development of the predictive temperature model and its associated uncertainty, and the development of reservoir pool elevation thresholds.

4.1 Type of predictive temperature model

A number of types of water temperature prediction models are possible, including deterministic and empirical models. The temperature of the Truckee River downstream of Reno, for example, has been modeled effectively using a physical process model (Brock and Caupp, 1996). They assumed the river flow was steady for 16 time ranges (e.g., January 1 to January 31) distributed throughout the year. In addition, the model requires large amounts of input data to effectively account for hourly boundary conditions and physical processes. Such a model is appropriate for small temporal and spatial ranges but cannot be linked to daily operations. Although an hourly mechanistic temperature model could, in theory, give very accurate results, this type of model requires numerous detailed inputs and intensive computations and is, therefore, difficult to link directly to an operations model. An empirical model can be computationally less intensive, therefore quick to implement and easy to validate. Therefore, a simplified empirical tool to predict temperature is more practical to couple with a DSS for daily operations decisions. Development of a reliable empirical model depends on adequate historical data; fortunately, that data is available for the Truckee River.

4.2 Data availability

A large amount of data have been collected on the Truckee River. Following is a description of the general types and frequencies of flow and temperature data that are potentially useful in predicting water temperature at Reno. Presented also are the data available at key locations and the reasons particular data were used.

The USGS has collected daily flows and reservoir elevations at a number of sites along the Truckee River and its tributaries. In general, these appear to be the only daily flow data that are available. Reservoir storage can be calculated using USGS pool elevations and USGS reservoir tables that relate storage to pool elevation.

Additional water quality monitoring was performed for the TROA DEIS/DEIR (1998) and Taylor’s temperature study (1998). In particular, hourly temperature data were collected at various stations on the Truckee River from Truckee, CA to Pyramid Lake from 1993-1995. In addition, reservoir temperature profiles and release temperatures were collected at Boca, Stampede, and Prosser once a month during the summer and fall of 1994. Although it would have been desirable to have sampled these profiles more frequently, they are useful to establish the correlation between water temperature and water depth in the reservoir.

Figure 4.1 shows a schematic of the study section with gaging locations that may be relevant to a prediction of temperature at Reno. These include reservoir release temperatures and flows, upstream river temperatures and flows, and air temperatures.

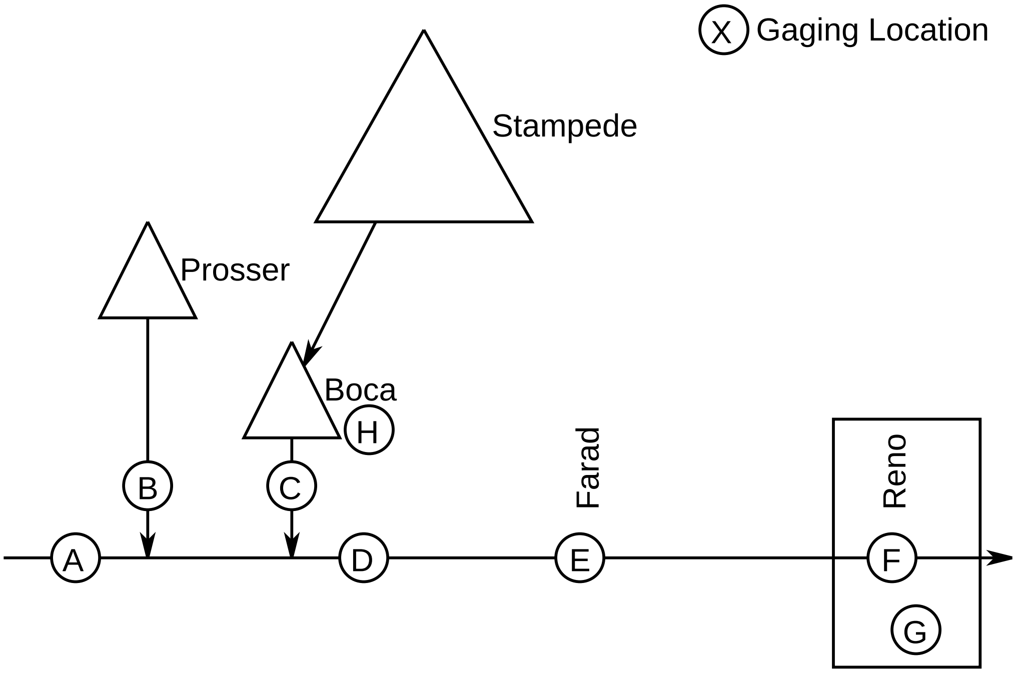


Figure 4.1: Schematic of the study section

Table 4.1 describes the availability of data at each of the gaging locations in Figure 4.1. In addition, daily reservoir elevations are known for every reservoir for the entire time period. We used average daily flow data from the USGS and maximum daily river temperatures collected from both the USGS and from the TROA DEIS/DEIR monitoring. Most of the temperature data was collected after 1993. Since 1993 and 1994 were dry years with low flows and high river temperatures, these are the most appropriate years to use in the empirical relationships. In addition, only data from June, July, and August will be used. We did not include September because the river cools in the latter half of the month. It is likely that the model developed will be applicable to the first half of September.

Table 4.1: Available relevant data

Schematic Locator	Location	Data Collected	Collection Period
A	Truckee River above Prosser Creek	Average daily flow Maximum daily river temperature Hourly river temperature	3/1993-9/1998 3/1993-9/1998 6/1993-10/1994
B	Prosser Creek below Prosser	Average daily flow Maximum daily river temperature Hourly river temperature	1/1942-current 3/1993-9/1998 6/1993-10/1994
C	Little Truckee River below Boca	Average daily flow Maximum daily river temperature Hourly river temperature	6/1980-current 4/1993-9/1998 6/1993-10/1994
D	Truckee River below Little Truckee River confluence	Average daily flow Hourly river temperature	6/1993-10/1994 6/1993-10/1994
E	Truckee River at Farad	Average daily flow Maximum daily river temperature Hourly river temperature	1/1909-current 4/1980-9/1998 7/1993-10/1994
F	Truckee River at Reno	Average daily flow Maximum daily river temperature Hourly river temperature	7/1906-current 8/1989-9/1998 1/1994-11/1994
G	Reno Airport	Maximum daily air temperature	1/1986-12/1996
H	Near Boca Reservoir	Maximum daily air temperature	1/1986-12/1996

We chose to look at data for which the flow at Farad is less than 500 cfs because at flows above 500 cfs, there is rarely a temperature problem in the study reach. Also, 500 cfs is a logical cutoff because, according to USBR water managers

(Scott, 2001), WQCW will not be released when the legal flow target of 500 cfs at Farad (Floriston rates) is met. When flows are less than 500 cfs, most of the water at Farad comes from the Little Truckee River. For example, in July of 1994, 65% of the water passing the Farad gage came from the Little Truckee River sub-basin via Boca.

None of the gaging sites upstream of Farad is currently recording water temperature. If upstream water temperature is a key predictor, a recommendation could be made to establish permanent temperature monitoring. For a DSS to be useful in the near future, the predictive model will have to use other variables to predict water temperature. Readily available data include air temperatures and flows. This information is often telemetered from the gaging site to the water managers office meaning the data can be used immediately.

4.3 Development of an empirical model to predict daily maximum temperature of Truckee River at Reno, Nevada

The available historical data were used to develop empirical relationships to predict maximum daily water temperature at Reno. A multiple linear regression (MLR) statistical technique was used to predict the dependent variable (daily maximum water temperature) based on independent predictor variables. The fitted value, $\hat{y}$, is the predicted river temperature expressed as

$$\hat{y} = a_0 + a_1x_1 + a_2x_2 + \ldots + a_nx_n \qquad \text{Eq. 4.1}$$

where, a_0, a_1, a_2, ... ,a_n are coefficients, and x_1,x_2, ... , x_n are independent predictor variables.

Candidate predictor variables to predict the river temperature at Reno include:

1. Previous day’s maximum daily river temperature at Reno
2. Maximum daily river temperature at the Truckee River below the confluence with the Little Truckee River (Location D)

3. Maximum daily air temperature at Reno
4. Maximum daily air temperature at Boca
5. Average daily flow at Reno
6. Average daily flow at Farad
7. Maximum daily release temperature from Boca

The first predictor variable is not practical for the DSS purpose. Although historically the river temperature on any day is closely related to the river temperature on the previous day, once water is released to affect the temperature, that relationship will be changed. For example, the previous day’s temperature may be below the target but only because additional water was released. This corrected temperature is not related to the current day’s temperature unless an equivalent flow is released. Therefore, the previous day’s river temperature cannot be used in the predictive model.

The second predictor variable, maximum daily river temperature at location D, was observed for June 29, 1994 to August 31, 1994 and estimated from observed upstream temperatures for the remaining days in June, July, and August 1993 and 1994. To estimate the temperature at location D, we used a flow-weighted average of historical temperature observations at A, B, and C. The mixed temperature downstream of a confluence can be calculated as a flow-weighted sum of the incoming temperatures:

$$T_{mixed} = \frac{T_1 Q_1 \times T_2 Q_2}{Q_1 + Q_2} \qquad \text{Eq. 4.2}$$

where T_1 and T_2 are the temperatures of the incoming water and Q_1 and Q_2 are the incoming respective flows. Equation 4.2 is a conservation of heat assuming there are no additional heat sources or sinks. This process was performed using observed flows and temperatures at locations A and B and then again with that result and the observed flow and temperature at location C to estimate the temperature at location D.

For variables 3 through 7, sufficient data exist and no adjustments had to be made. Figure 4.2 shows various predictor variables plotted against the maximum daily river temperature at Reno and a non-parametric locally weighted regression (Loader, 1999) curve on each plot.

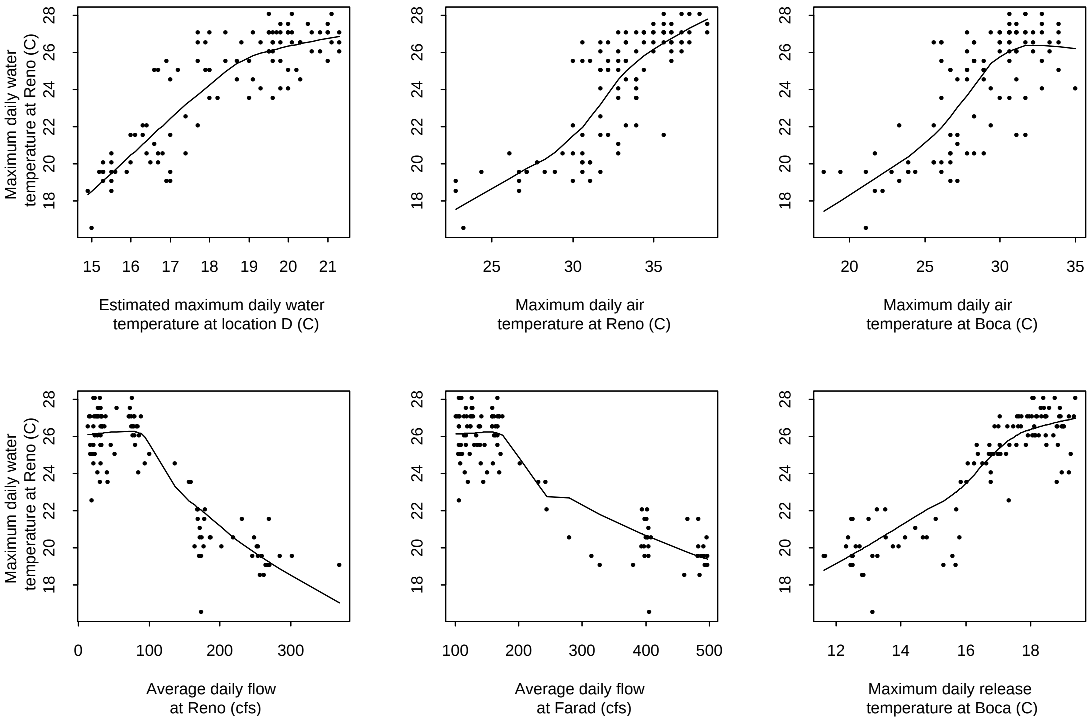


Figure 4.2: Data used in regression relationships

Figure 4.2 shows a strong positive correlation between air temperature and river temperature, and a negative correlation between flow and river temperature. These results are as expected. Higher flow leads to lower river temperatures and warm air temperatures lead to warmer water temperatures. Also, there is a strong correlation between upstream (Boca release and location D) river temperatures and river temperatures at Reno. Since it appears that all of these predictor variables are related to Reno water temperatures, a stepwise procedure is necessary to determine which subset of predictor variables lead to the best prediction.

A stepwise regression procedure is used to select the best subset of predictor variables from candidate predictor variables. The stepwise procedure selects the subset of predictor variables that optimizes Mallow's Cp statistic, Akaike's Information Criteria (AIC), R^2, or adjusted R^2. The AIC and Cp statistics are widely used because they try to achieve a good compromise between the desire to explain as much variance in the predictor variable as possible (minimize bias) by including all relevant predictor variables, and to minimize the variance of the resulting estimates (minimize the standard error) by keeping the number of coefficients small. The AIC statistic, the likelihood version of the Cp statistic (MathSoft, 1998, *S-Plus 5 for UNIX Guide to Statistics, p. 153*), is calculated as:

$$AIC = \hat{\sigma}^2(Cp + n) \qquad \text{Eq. 4.3}$$

and the Cp statistic is:

$$Cp = p + \frac{(n-p) \bullet (s_p^2 - \hat{\sigma}^2)}{\hat{\sigma}^2} \qquad \text{Eq. 4.4}$$

where n is the number of observations, p is the number of explanatory variables plus one, s_p^2 is the mean square error of this p coefficient model, and $\hat{\sigma}^2$ is the best estimate of the true error (Helsel and Hirsch, 1992, p. 312). The AIC statistic is used because it further rewards for having a low mean square error while penalizing for including too many variables.

The stepwise regression procedure starts with a linear regression based on the predictor that gives the highest correlation between the predictor variable and the river temperature at Reno. New predictor variables are added if they result in a lower AIC statistic than the previous model.

We performed a stepwise procedure on the set of predictor variable listed above. Table 4.2 shows the numerical results of the steps of the procedure.

Table 4.2: Stepwise selection to find maximum daily water temperature at Reno

	AIC Value		
Water temperature at Reno =	f(variable in column 1)	f(flow at Farad, variable in column 1)	f(flow at Farad, Reno air T, variable in column 1)
constant	1016	239	140
Water temperature at location D	309	198	153
Air temperature at Reno	379	**140**	
Air temperature at Boca	500	190	159
Flow at Reno	278	250	158
Flow at Farad	**239**		
Boca release temperature	244	225	155

The second column shows the AIC values for a regression model for each variable in column 1, e.g., water temperature at Reno as a function of air temperature at Reno, water temperature at Reno as a function of air temperature at Boca, etc. The lowest AIC value is selected: flow at Farad. Then the AIC value is calculated for this new model and each of the variables in the first column. Now, the air temperature at Reno has a lower AIC so it is added to the model. This process is repeated. In the fourth column, no AIC values are lower than those in the third column meaning that adding additional variables is not necessary. Figure 4.3 shows that the lowest AIC statistic occurs with two parameters. Increasing or decreasing the number of parameters result in higher AIC statistics.

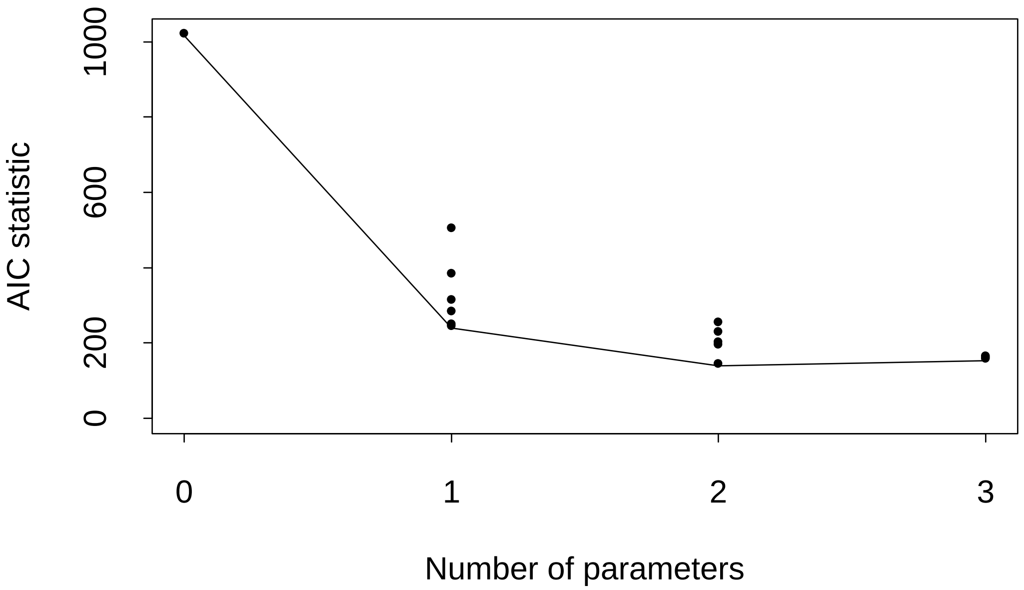


Figure 4.3: AIC versus number of parameters

The stepwise procedure performed on the set of predictor variables listed above and the water temperature at Reno resulted in the following regression equation with an adjusted R^2 of 0.915:

$$\hat{T} = a_0 + a_1 T_{Air} + a_2 Q \qquad \text{Eq. 4.5}$$

where T_{Air} is the air temperature at Reno, Q is the flow at Farad. The regression coefficients are a_0 = 14.4 ºC, a_1 = 0.40, and a_2 = 0.014 ºC/cfs. We also performed a stepwise selection procedure using the adjusted R^2 and Cp statistic instead of the AIC statistic. In addition to flow at Farad and air temperature at Reno, the stepwise procedure using Cp and adjusted R^2 selected the flow at Reno and the river temperature at the Truckee River below the Little Truckee River confluence (location D). This model has an adjusted R^2 of 0.924 which is not significantly different than the R^2 in the regression described by Equation 4.5. Because the R^2 values are nearly identical, it is more efficient to use the model with the smallest number of predictor variables. Therefore, the predictive temperature model described in Equation 4.5 is selected.

The regression is consistent with earlier work by Brock and Caupp (1996) in which they found that air temperature and river flow were the significant variables for predicting river temperature. Brock and Caupp used a similar approach to get the upstream boundary condition at Reno for their DSSAMt model.

Although Boca's release temperature does have an impact on the Truckee River, the stepwise regression did not select this variable. It is possible that the prediction site at Reno is far enough downstream from the reservoir that air temperature and flow are the dominating factors.

In addition to the linear regression, we investigated non-linear techniques because they have the ability to model arbitrary dependence structure. We tried local polynomial methods (Loader, 1999) and found improvements to be insignificant since the relationships were strongly linear.

Figure 4.4 shows the predicted values of maximum daily Truckee River temperature at Reno from the regression equation plotted against the actual historical observations. A visual inspection shows that most of the points fall within two degrees of the 45 degree line indicating the regression equation is a good model.

Auto-correlation is a measure of the strength of successive predictions. It is another statistic that shows that the model fits the data well. Figure 4.5 shows the autocorrelation function (ACF) plot of the residuals. The dotted lines are the 95% confidence lines. If no ACF estimates fall outside the 95% confidence limit, one can safely assume there is no serial correlation. The auto-correlation plot in Figure 4.5 shows that there is some serial correlation between the residuals at lag 1 but shows no clear trends.

Linear regression theory assumes residuals are normally distributed and symmetric about the mean. Figure 4.6 shows that the residuals of the Reno water tempera-

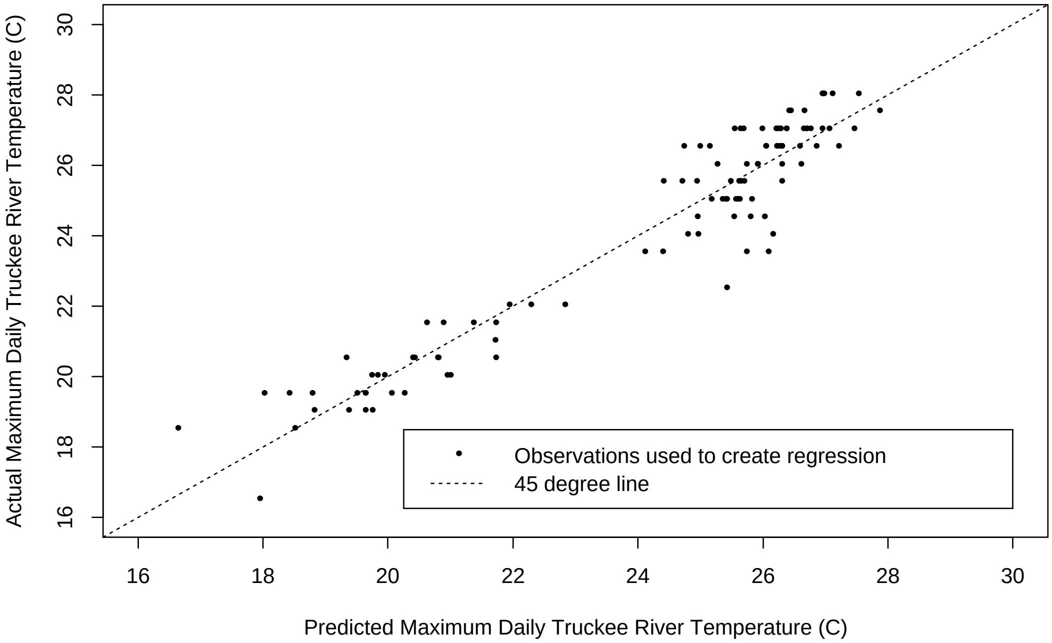


Figure 4.4: Fitted Reno water temperature regression line

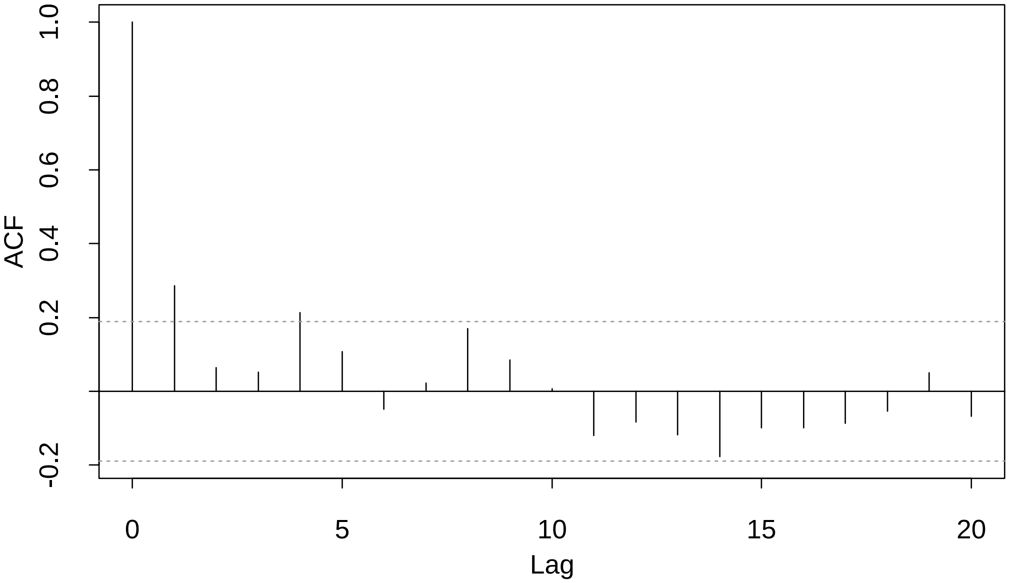


Figure 4.5: Reno water temperature regression residuals auto correlation

ture estimates appear to be normally distributed, centered around zero. We can quantify whether or not this distribution is gaussian by looking at Figure 4.7 which shows the quantiles of the residuals versus the quantiles of a normal distribution. If the

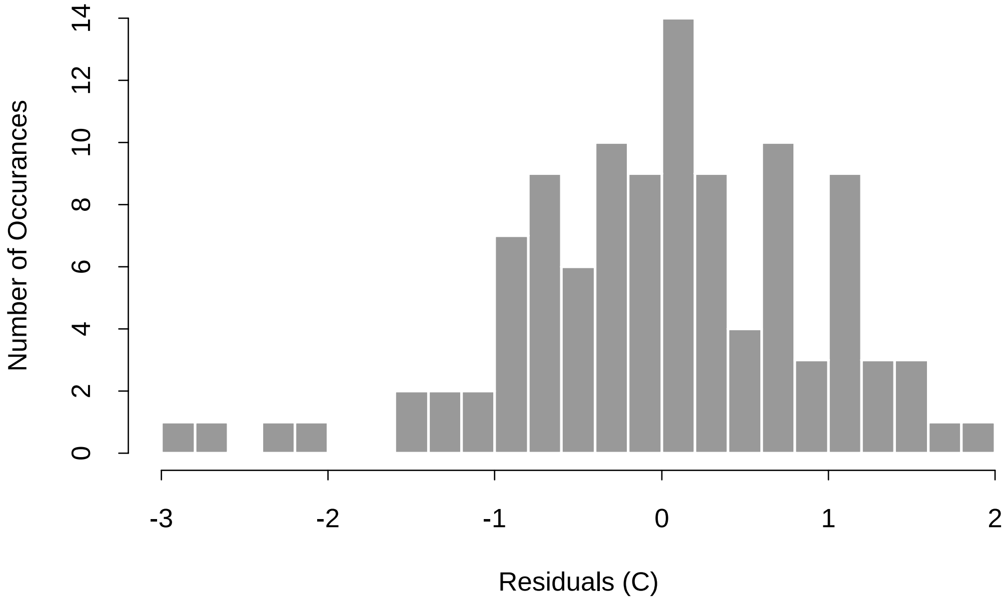


Figure 4.6: Reno water temperature regression residuals histogram

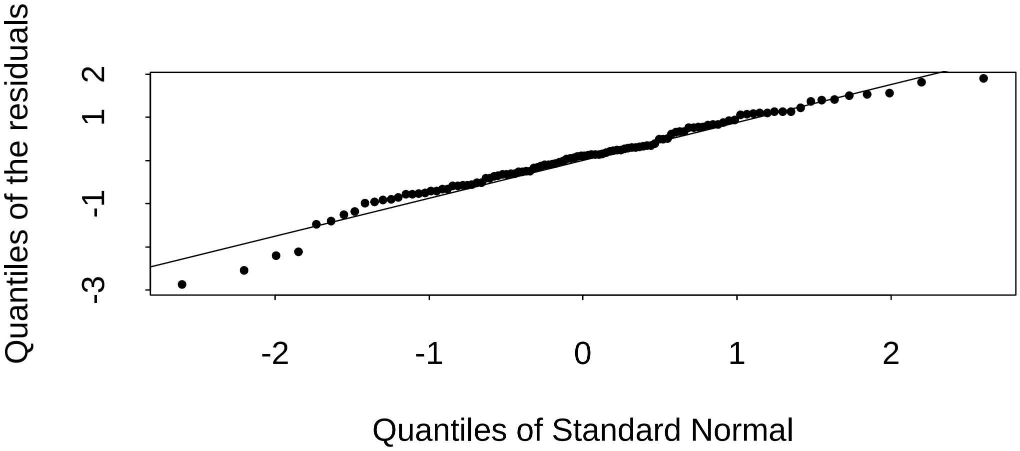


Figure 4.7: Quantile vs. quantile plot to test for normality

points fall on the line, the distribution is normal. To formally test for normality, a correlation is computed between the residual and normal quantiles. For the distribution to be normal, the correlation must be greater than or equal to the 95% confidence level, critical probability plot correlation coefficient in Helsel and Hirsch (1992). The correlation for our data is 0.987 and the critical value for a 95% confidence level and 108 observations is 0.987. Therefore, the residuals are significantly normal.

4.4 Model verification

An empirically developed multiple linear regression model may fit the data used to estimate the regression coefficients very well, but its performance on new data is not certain. Three methods are used to assess the ability of the model to predict future events: (i) validating the model with observations not used in the regression, (ii) cross validation, and (iii) withholding some data used in the fitting process and validating the model with the withheld data.

Figure 4.8 shows the modeled and observed maximum daily river temperature at Reno for June, July, and August of 1990-1992. The modeled temperatures were predicted using observed flow and air temperatures in regression Equation 4.5. Missing predictions indicate that the Farad flow was greater than 500 cfs. A linear regression between the observed and modeled temperatures produces an R^2 of 0.52, indicating that the regression performs decently in a predictive mode for 1990-1992. As expected, this R^2 is lower than the R^2 in the fitting process. The R^2 value for each year is also shown in Figure 4.8. The R^2 values found in this validation process are lower than the fitting procedure because of the skill in different ranges. Figure 4.4 shows that there are two regions in the fitting procedure. The range above 23 ºC has more scatter than the range below 23 ºC. In other words, the regression is better at explaining variance below 23 ºC than above. As a result, the skill in predicting temperatures above 23 ºC is not as good. Most of the observations in 1990-1992 are above 23 ºC, meaning the prediction is less accurate then if they were below 23 ºC.

By grouping occurrences into categories defined in Table 2.1, we can look at the distribution of temperatures. Figure 4.9 shows pie charts of the observed temperatures and the fitted temperature values for the 276 days in June, July and August of 1990-1992.

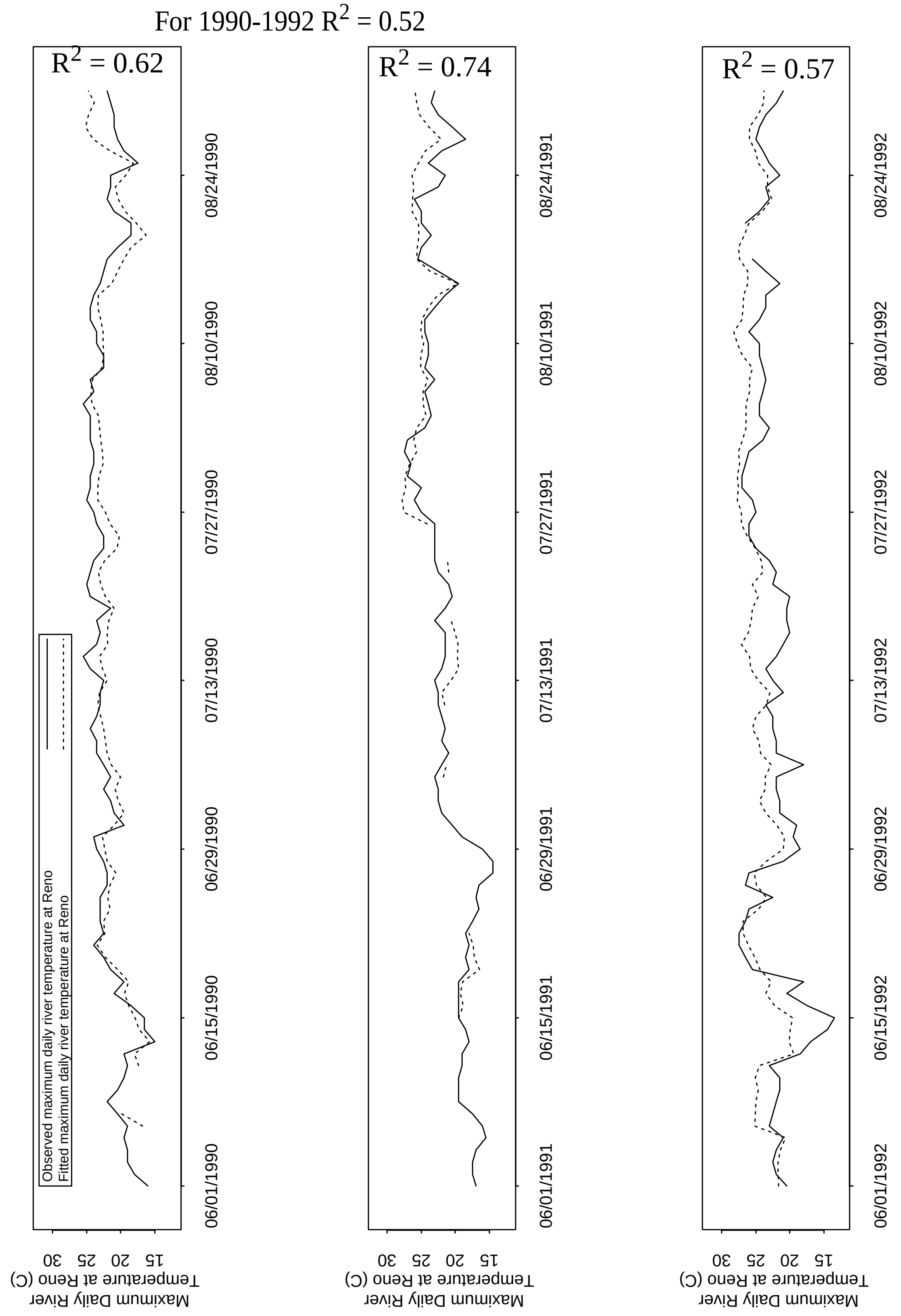
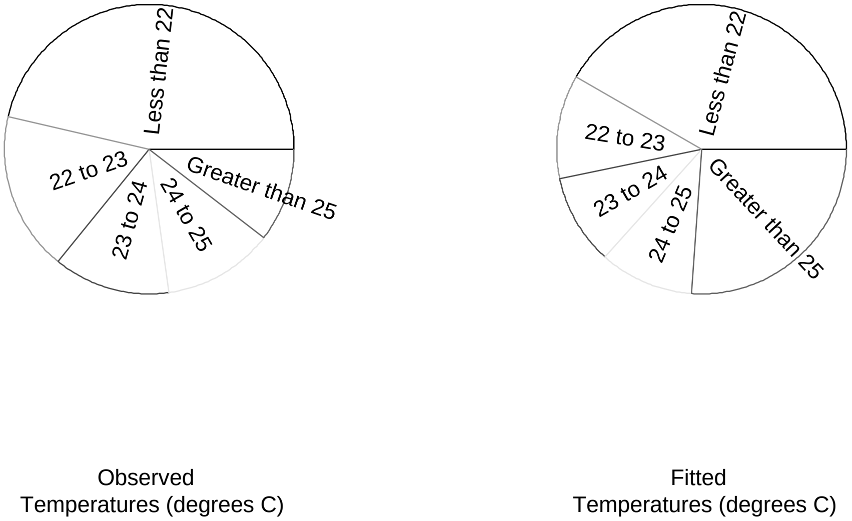


Figure 4.8: June, July, and August 1990-1992, validation of maximum daily river temperatures



Observed
Temperatures (degrees C)

Fitted
Temperatures (degrees C)

Figure 4.9: Temperature occurrences

There are 43 more occurrences of temperatures that are greater than 25 ºC in the fitted values than in the observed. That indicates that the predictive model predicts temperatures that are higher than reality. This is likely because the time range used to create the regression model was from an extremely dry year where there was not much water in the system. Otherwise, the distributions of temperatures in the two cases are similar.

In the second method, cross validation, one historical observation is dropped from the fitting process and is predicted using the regression fit based on the remaining observations. This is repeated for all observation points. The predictions are plotted against the actual observations in Figure 4.10. The points fall on the straight line indicating that the regression is able to perform well in predictions. The R^2 value between the predicted and observed values is 0.91, which is quite good.

In the third method, we withheld August 1993 data in the fitting process and then used the fitted regression to predict the values for the withheld period. Figure 4.11 shows the predicted and observed water temperatures at Reno for August 1993. Plot-

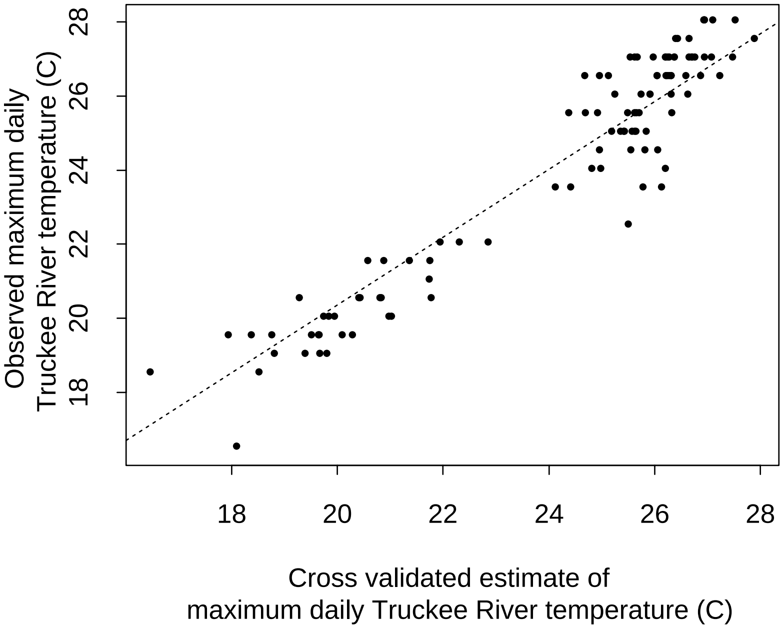


Figure 4.10: Cross validation of water temperature regression at Reno

ted also is the 90% upper prediction interval from the regression. The predicted values fall below the prediction interval line indicating a good performance of the regression model in a predictive mode.

4.5 Uncertainty of predicted temperatures

Uncertainty exists in water temperature predictions due to modeling errors. Processes that add uncertainty to temperature prediction include evaporation, solar radiation, cloud cover, wind, changes to channel geometry, flow rate, and unregulated inflows. As Tung (1996) describes, this uncertainty is due to inherent randomness of physical processes. These processes all act to influence the temperature of the river but are complex to model and difficult to predict. Even if we could model each of these processes, we may not be able to predict how each process affects the river temperature. This is the uncertainty Tung describes as the lack of complete knowledge about parameters, processes, data, and model structure.

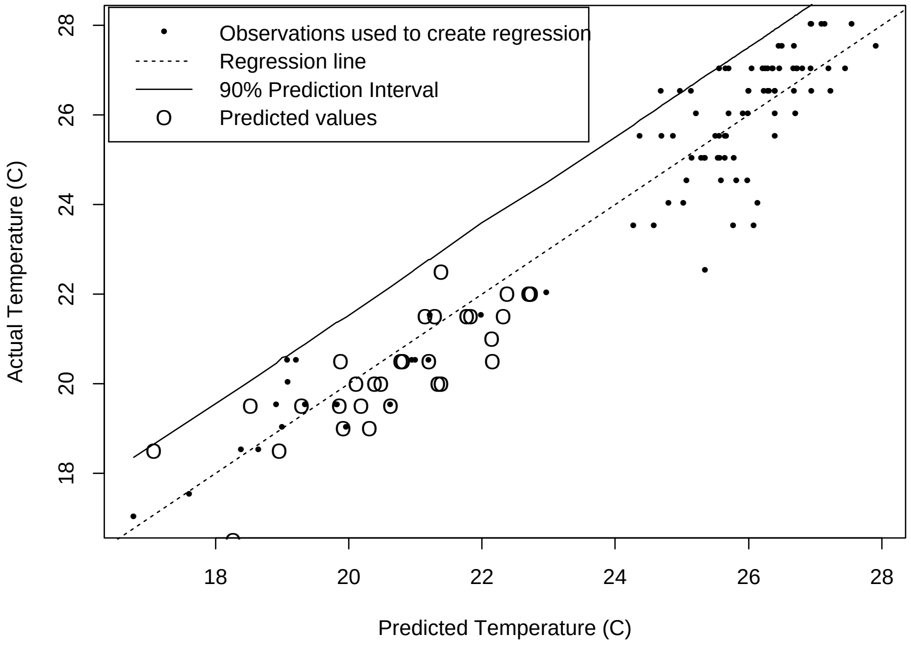


Figure 4.11: Prediction validation using withheld 1993 data

For our model, Equation 4.5, we will assume that all of the variability in the river temperature prediction comes from the air temperature forecast. In other words, we assume that we know the flow in the river with 100% confidence. This assumption is reasonable because the target flows at Farad are the basis of policy in the entire basin. These flow rates are met with a high degree of confidence through the use of gages and releases.

How much water must be released to ensure that the probability of exceeding a given temperature target is acceptable? The regression equation and resulting prediction intervals can answer this question. Helsel and Hirsch (1992, p. 300) define the *confidence interval* as the range (+/- the mean) of values in which the mean of estimates by regression will lie. For example, the 95% confidence interval indicates that 95% of the time, the mean estimated response variable will be within the interval. A similar concept called the *prediction interval* is used in a predictive mode. The prediction interval is defined as “the confidence interval for prediction of an estimate of an individual response variable." For example, the 95% prediction interval indicates that 95% of the time the predicted value will be within the interval.

The formula for the prediction interval is:

$$\text{Prediction Interval} = \left(\hat{y} - t(\alpha/2, n-p)\sigma\sqrt{1 + x_0' X' X^{-1} x_0}\ ,\ \hat{y} + t(\alpha/2, n-p)\sigma\sqrt{1 + x_0' X' X^{-1} x_0} \right) \qquad \text{Eq. 4.6}$$

where $t(\alpha/2, n-p)$ is the quantile given by the $100\left(\frac{\alpha}{2}\right)$ 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. There are n observations used to create the regression and p explanatory variables plus one (for the intercept term). The standard deviation of the residuals is σ and x_0 is a vector of 1 and the predictor variables ({1, x_1,x_2}). The matrix X is a column of ones and each new observation of predictor variables:

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} \\ 1 & x_{21} & x_{22} \\ \cdots & \cdots & \cdots \\ 1 & x_{n1} & x_{n2} \end{bmatrix} \qquad \text{Eq. 4.7}$$

This prediction interval gives the confidence that the prediction is within an upper and lower value. By evaluating the student's t-distribution at α instead of α/2, we get the confidence that the prediction is below a certain value. The formula becomes:

$$\text{Prediction Upper Limit} = \hat{y} + t(\alpha, n-p)\sigma\sqrt{1 + x_0'(X'X)^{-1} x_0} \qquad \text{Eq. 4.8}$$

Using historical data, an upper prediction interval can be constructed for the full range of predictor variables. Figure 4.12 shows the regression line and the upper prediction interval line. Most of the observations are below the upper prediction inter-

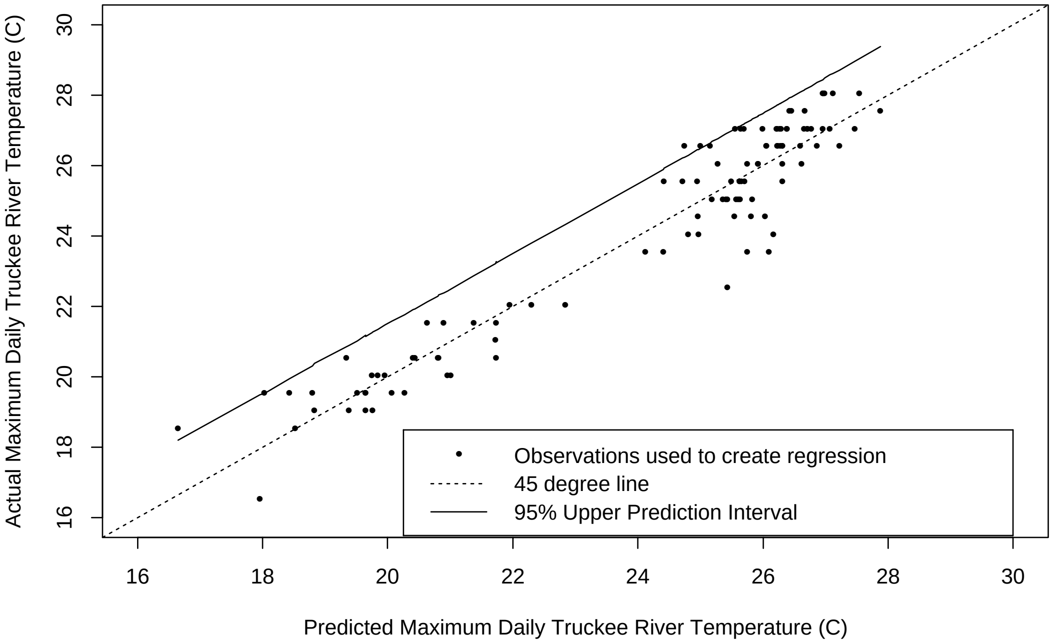


Figure 4.12: Reno water temperature regression with prediction interval

val line as expected. Lowering the prediction confidence below 95% would move the upper prediction interval closer to the 45 degree line.

Like a confidence interval, the prediction interval is smaller near the center of the data and larger toward the edges. We assume that the prediction interval is linear for implementation purposes. This assumption is valid because the second term under the square root, $x_0'X'X^{-1}x_0$, in Equation 4.5 is small compared to the first term, 1, provided the sample size is large (Helsel and Hirsch, 1992, p. 242). This leads to the approximation of the prediction interval to be:

$$\text{Prediction Interval} = (\hat{y} - t(\alpha, n-p)\sigma \ , \ \hat{y} + t(\alpha, n-p)\sigma) \qquad \text{Eq. 4.9}$$

Another related variable is the prediction confidence distance (PCD), which is the average distance from the regression line to the upper prediction interval defined as:

$$PCD = Mean(t(\alpha, n - p)\sigma\sqrt{1 + x_0'(X'X)^{-1}x_0}) \qquad \text{Eq. 4.10}$$

The PCD will be used in the DSS that will be develop in the next chapter.

4.6 Reservoir release temperature threshold

In the model, the temperature at Reno is a function of flow and air temperature only. The model is not accurate when reservoir releases are above a certain threshold. In addition, any corrective action taken by rules to meet temperature targets assumes that water released is cold. If it is not cold enough, releasing additional water will have no effect on downstream water temperatures.

Boca’s release temperature was chosen because WQCW stored in Stampede must pass through Boca to reach the Truckee River. Because Stampede is much larger and often has more water, Stampede’s release temperature does not influence downstream temperatures as greatly as Boca’s release temperature. If Boca is too low, releasing more warm water intensifies the temperature problem for trout. By predicting the reservoir release temperature, we may be able to prevent fish kills upstream of Reno caused by low reservoirs and high release temperatures from Boca. Water released from the bottom of a reservoir—Boca, Prosser, and Stampede all have bottom outlet works—has less diurnal temperature fluctuation than water in other parts of the river. Water temperature affects water density, and cold water (from winter chilling) sinks to the bottom of the reservoir. Thus, in summer, it is possible to release colder water because it has been stored throughout the winter. But, there are complications to this process. The amount of cold water in storage depends on the amount of water in the reservoir, the corresponding depth, when the reservoir filled, and, to a lessor degree, meteorology. An emptier, shallower reservoir warms up faster and does not have as much cold water at the bottom. In this way, the temperature of water released depends on the depth of the reservoir (measured as water surface elevation). The water temperature is also affected by air temperatures and solar radiation that act to warm the cold release water, leading to a diurnal oscillation of release temperature.

The purpose of investigating the variation in Boca's release temperature is to develop a threshold pool elevation at which lower pool elevations release warm water. Figure 4.13 compares Boca's release temperature with the maximum daily river temperature at Reno. Although this plot does not account for air temperature or flow, it

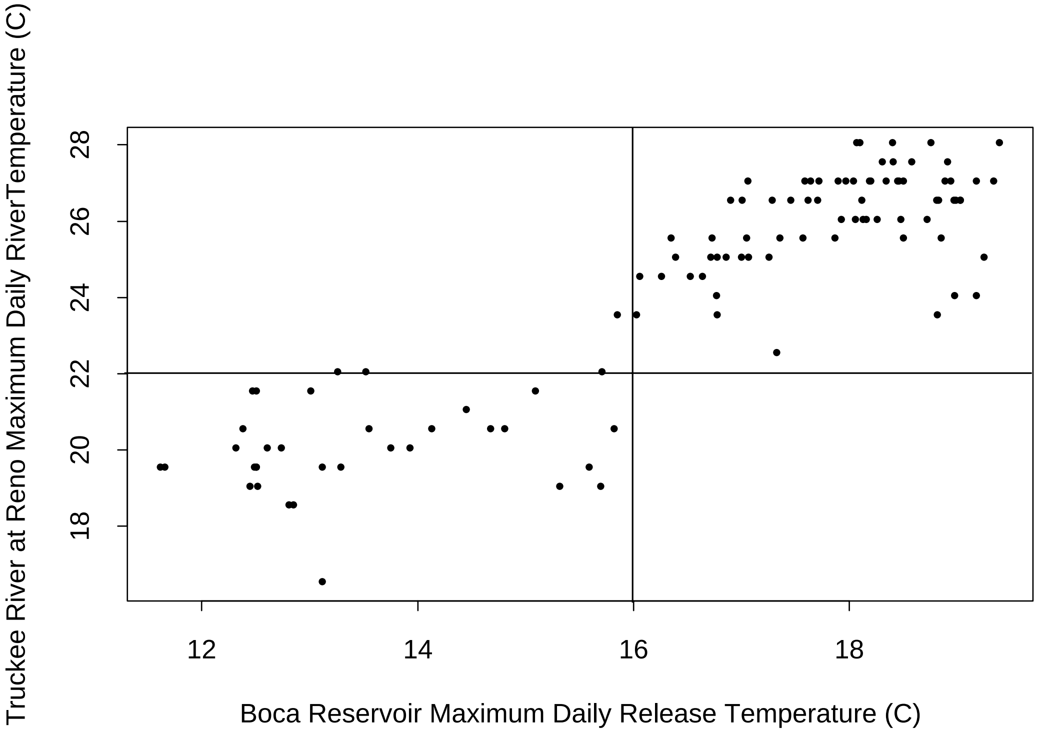


Figure 4.13: Boca maximum daily release temperature vs. maximum daily river temperature at Reno

does show that only when Boca's release temperature is greater than 16 ºC is the water temperature at Reno greater than the 22 ºC temperature target. The data are from June, July, and August of 1993 and 1994.

This simplification is appropriate because the desired result of this prediction is a Boca target elevation. By analyzing and predicting Boca's release temperature, we can develop a Boca target elevation that is high enough to ensure cold releases. With the RiverWare rules, we can operate the system to keep Boca above the target elevation. This is necessary as it is impossible to modify meteorological factors. Monitoring the release temperature is one way to ensure that cold water is released. But, if the temperature is too warm, there may not be any way to fix temperature problems.

The scatter plot of Boca's pool elevation versus Boca's release temperature along with a fitted line is shown in Figure 4.14. From Figure 4.13 and Figure 4.14, we can infer that when Boca's water surface elevation is below 5565 ft., warm water will be released. This target elevation is adequate to help plan operations. In daily operations, actual release temperatures could feed into the DSS to tell when the release temperature is above the threshold.

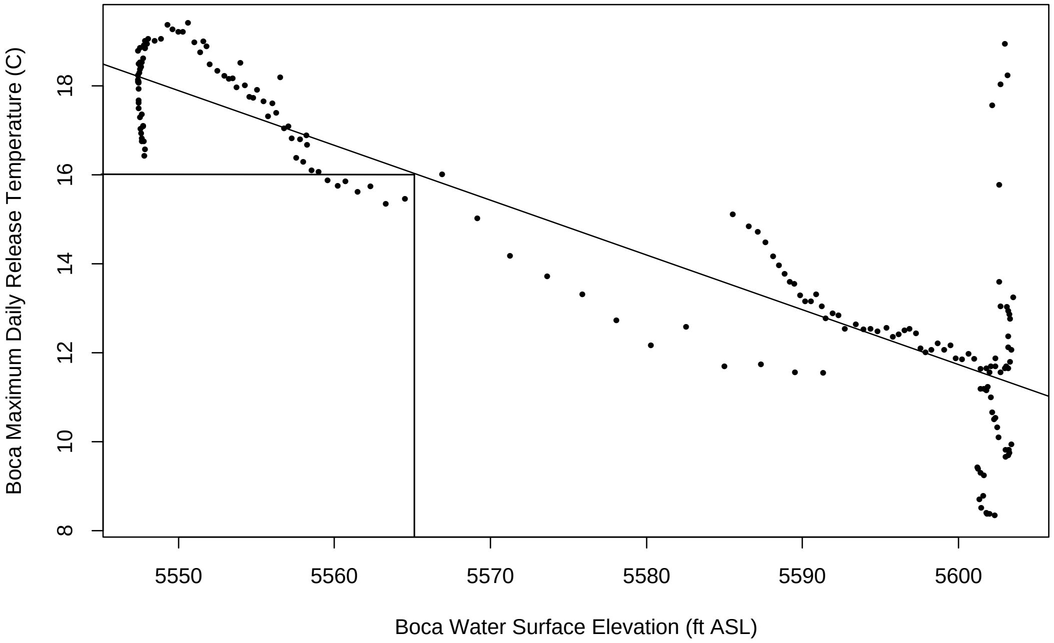


Figure 4.14: Boca pool elevation vs. release temperature

It can be seen in the upper right corner of Figure 4.14 that there are a number of outliers that have high release temperatures and high water surface elevation. These are a result of extremely low flows. Boca was drawn down, resulting in the observations that have very low water surface elevations and a high release temperatures. In addition, the release temperature of one day correlates to the release temperature on the following day. More data would be necessary to create better relationships. In addition, profile monitoring would help to show the depths of thermoclines for various filling and hydrologic scenarios.

Chapter 5

Decision Support System

In this chapter, a model-based DSS is developed that meets the requirements set forth in Section 1.1. Several specific operating rules are developed to meet specific system requirements. These include:

1. Rules to store WQCW as specified by the WQSA.
2. Rules that predict water temperatures at Reno without WQCW releases and determines flow increases needed to meet target temperatures for a given confidence level.
3. Rules to manage reservoir releases given constraints and release temperature thresholds
4. Rules to use seasonal strategies to more effectively use WQCW.

These rules are added to the existing RiverWare model ruleset as described in Section 2.6, that operates the system according to baseline operating policies.

At the end of this chapter, the logic of the entire policy for temperature management is presented along with a summary of the input requirements and possibilities for alternative scenarios.

5.1 Rules to store WQCW

The WQSA allows storage as WQCW of some portion of the water provided by the purchased water rights. The amount that can be stored on an ongoing basis depends on whether or not Floriston rates are met and whether fish spawning releases are being made.

The WQSA proposes to purchase Orr Ditch Decree water rights in the Truckee Division of the Truckee Canal. Previous to the WQSA, this water is delivered as part of the Floriston rates. With the WQSA, the consumptive use fraction of this purchased water will remain in the river and flow to Pyramid Lake. During fish spawning runs, this water supplements fish water released from Stampede or Prosser. Due to this additional WQSA water in the lower Truckee River, less fish spawning water needs to be released from Stampede and Prosser; the amount by which these releases are decreased is converted by exchange to WQCW stored in these reservoirs.

The WQSA, also provides for an additional 6,700 acre-feet of water per year to be stored in Stampede as WQCW because downstream irrigators have changed from using river water to wastewater effluent. The Truckee Meadows Water Association (TMWA), that provides municipal and industrial (M&I) water pumps some groundwater instead of diverting all their water from the Truckee River. The effluent that is produced proportional to the groundwater component does not have to return to the river. Instead, it can be used as irrigation water to offset irrigation withdrawals from the river. These irrigation rights that are not diverted can be exchanged to store WQCW in Stampede and Prosser, limited to 6700 acre-feet per year.

Figure 5.1 shows the logic of these rules. The WQCW storage rules check to see that Floriston rates are met and then converts the fish spawning water in Stampede to WQCW based on the amount of the groundwater component of the effluent used. If there is a fish spawning water release, irrigation water used to meet Floriston rates is converted to fish spawning water according to the amount of water rights purchased. An equal amount of fish spawning water is withheld in Stampede and exchanged to WQCW.

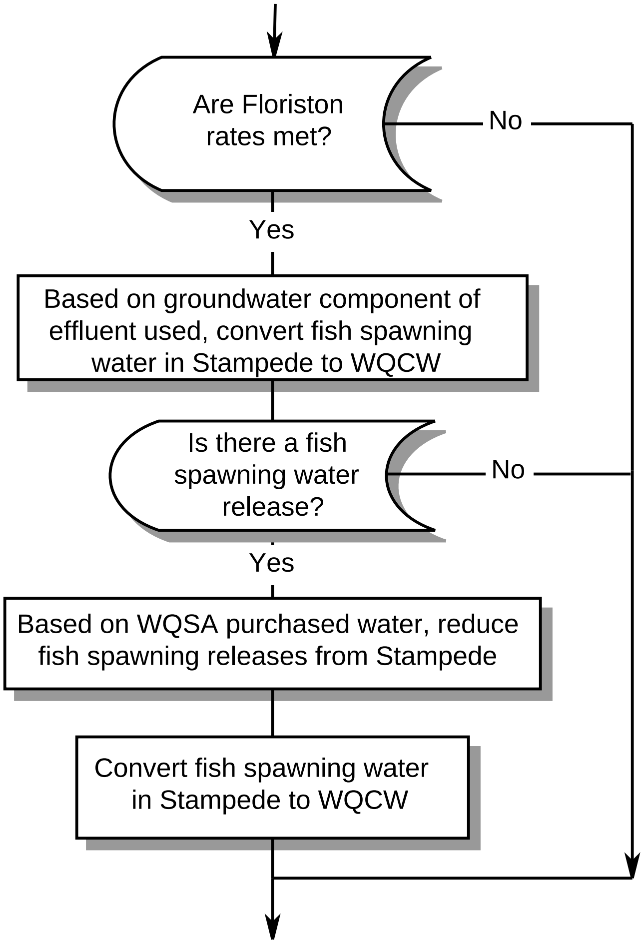


Figure 5.1: WQCW storage flowchart

5.2 Rules to predict water predict water temperature at Reno and release additional flow to meet target temperatures

If the predicted river temperature exceeds the target, the DSS recommends a WQCW release to lower the temperatures. The empirical regression formula to predict river temperature from flow and air temperature, Equation 4.5, is used to determine how much additional water is required to lower the temperature such that the probability of exceeding the target is as specified. The predicted maximum daily air temperature is given; thus, the only controlling variable that can influence Truckee River temperature is flow. Rearranging Equation 4.5 to solve for flow gives:

$$Q = \frac{\hat{T} - a_1 T_{Air} - a_3}{a_2} \qquad \text{Eq. 5.1}$$

where T_{Air} is the predicted air temperature at Reno, Q is the flow at Farad, and $\hat{T}$ is the target water temperature at Reno. By subtracting the PCD for a specified probability of exceedance, as calculated in Equation 4.10, from the target temperature, we get the necessary temperature—the temperature at which the probability of exceedance is the specified value:

$$T_{Necessary} = T_{\mathrm{Target}} - PCD \qquad \text{Eq. 5.2}$$

Evaluating Equation 5.1 with $T_{Necessary}$ as $\hat{T}$, we get the required flow at Farad:

$$Q_{Required} = \frac{T_{Necessary} - a_1 T_{Air} - a_3}{a_2} \qquad \text{Eq. 5.3}$$

Figure 5.2 illustrates the relationship between the predicted temperature, $\hat{T}$, the target temperature, T_{Target}, and $T_{Necessary}$, the temperature required to provide a specified probability of exceedance. Curve A represents the distribution of predicted values (recall from Section 4.5 the assumption of gaussian distribution). The expected value of the prediction is $\hat{T}$. To lower river temperatures, we shift the temperature distribution to the left by adding more flow. If the expected value of the distribution is shifted to the target temperature as shown by curve B, the probability of exceeding the target is 0.5. Shifting the distribution to the left of the target temperature gives a higher probability that the temperature will be below the standard. Curve C shows the expected value reduced by the PCD value that gives 0.05 probability of exceeding T_{Target}.

In the example illustrated in Figure 5.2, the predicted river temperature, $\hat{T}$, at Reno is 28 ºC. We want to lower the temperature to a target, T_{Target}, of 22 ºC with probability of exceedance of 0.05. To find the flow required at Farad to give $T_{Necessary}$ at Reno, we subtract the PCD given by Equation 4.10 for 5% exceedance. In this case, PCD equals 1.4 ºC. From Equation 5.2, $T_{Necessary} = T_{Target}$ - PCD = 22 ºC - 1.4 ºC =

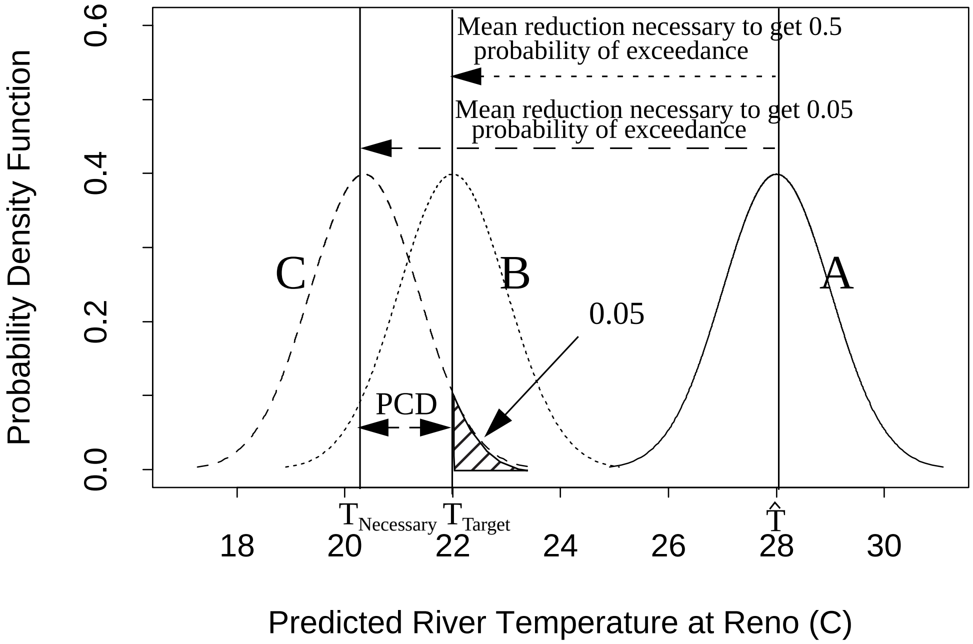


Figure 5.2: Temperature reduction to meet desired exceedance probability

20.6 ºC. Thus, 20.6 ºC is $T_{Necessary}$ for the given probability of exceeding, 0.05, the target water temperature. We enter the necessary temperature, 20.6 ºC, into Equation 5.3 and solve for a flow. This is the flow necessary to reduce the mean to the target with the specified 5% probability of exceeding the target river temperature of 22 ºC.

This procedure is used in the DSS to calculate the necessary flows at Farad to meet specified targets with specified exceedance probabilities. To ease implementation, a set of lookup tables was developed containing the necessary additional flows for a given T_{Target}, $\hat{T}$, and probability of exceedance. The temperature at Reno for normal operations, without using WQCW, is predicted using Equation 4.5 repeated here:

$$\hat{T} = a_0 + a_1 T_{Air} + a_2 Q \qquad \text{Eq. 5.4}$$

where T_{Air} is the predicted air temperature at Reno, Q is the flow at Farad. The regression coefficients are $a_0 = 14.4$ ºC, $a_1 = 0.40$, and $a_2 = 0.014$ ºC/cfs. From Equation 5.3, the necessary temperature at Reno, can be expressed as:

$$T_{Necessary} = a_0 + a_1 T_{Air} + a_2 Q_{Required} \qquad \text{Eq. 5.5}$$

Subtracting Equation 5.5 from Equation 5.4 gives:

$$\hat{T} - T_{Necessary} = a_2(Q - Q_{Required}) \qquad \text{Eq. 5.6}$$

Rearranging to get the additional flow required at Farad:

$$(Q_{Required} - Q) = \frac{\hat{T} - T_{Necessary}}{-a_2} \qquad \text{Eq. 5.7}$$

We can replace $T_{\text{Necessary}}$ with Equation 5.2 to get:

$$\Delta Q = \frac{\hat{T} - T_{\text{Target}} + PCD}{-a_2} \qquad \text{Eq. 5.8}$$

The PCD is calculated by Equation 4.10 for a specified exceedance probability.

A lookup table was developed for each target temperature. For that target temperature, the table has the initial predicted temperature on one axis and the probability of exceedance on the other axis. The values in the table are the additional flow necessary to reduce the temperature to the target as calculated by Equation 5.8. Table 5.1 shows additional flows needed for a target temperature of 22 ºC.

Table 5.1: Additional flow required at Farad to reduce maximum daily river temperature to a target of 22º C

		Probability of Exceedance								
		0.05	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80
Predicted Temperature (º C)	20	-40	-65	-96	-118	-137	-154	-171	-190	-212
	21	37	12	-19	-41	-60	-77	-94	-113	-135
	22	114	89	58	36	17	0	-17	-36	-58
	23	191	166	135	113	94	77	60	41	19
	24	268	243	212	190	171	154	137	118	96
	25	345	320	289	267	249	231	214	195	173
	26	422	397	366	344	326	308	291	272	250
	27	499	474	443	421	403	385	368	349	327
	28	576	551	520	498	480	462	445	426	404
	29	653	628	597	575	557	539	522	503	481
	30	730	705	674	652	634	616	599	580	558
	31	807	782	751	729	711	693	676	657	635
	32	884	859	828	806	788	770	753	734	712
Values in table are additional flow required (cfs)										

The table works as follows. The expected water temperature at Reno is predicted using the regression Equation 4.5. This value is found in the first column, and the additional flow needed is found in the desired probability of exceedance column. Linear interpolation can be performed between rows if necessary.

The negative numbers in the table indicate that when the predicted temperature is lower than the target, flow would have to be reduced to get to the standard. However, in the operations model, rules prevent reductions in flow. The additional flow required for a probability of exceedance of 0.5 at the predicted value equal to the target value of the table is zero. This occurs because the mean predicted value is the target value. But, additional flow is required if a more confident prediction is required.

The logic to release WQCW to lower river temperatures is shown in Figure 5.3. The rule checks to see that Floriston rates are not met. Then the rule predicts the river temperature at Reno and Boca's release temperature. If conditions warrant, additional flow is released, within physical constraints. The temperature at Reno is predicted again. Also shown on the left side of Figure 5.3 are the user specified inputs to the DSS.

5.3 Rules to manage reservoir release constraints

Because releases from Stampede flow into Boca as shown in Figure 4.1, WQCW released from Stampede must pass through Boca. Both reservoirs have physical constraints on the amount of water that can be released, based on inflows and water surface elevations. RiverWare has the functionality to calculate the maximum possible release. The rules must check to see that water released from Stampede can also be released from Boca. Figure 5.4 shows the logic used to determine if the desired amount of water can be released from both reservoirs.

Water released from Boca must be below a certain temperature. The rules stop releasing water if the pool elevation is too low. In this situation, it is more beneficial to save the water instead of releasing warm water that may kill fish. A better approach is to make sure that Boca is always full enough. As a result, a rule releases WQCW from Stampede that is re-stored in Boca to keep Boca's water surface elevation at a target level above 5565 ft. Figure 5.5 shows the logic for this Stampede to Boca exchange.

The stored WQCW in Boca will be exchanged with fish water in Stampede so that the WQCW is paid back to Stampede. Figure 5.6 shows how this is done. This is necessary as there are no legal provisions to permanently store WQCW in Boca.

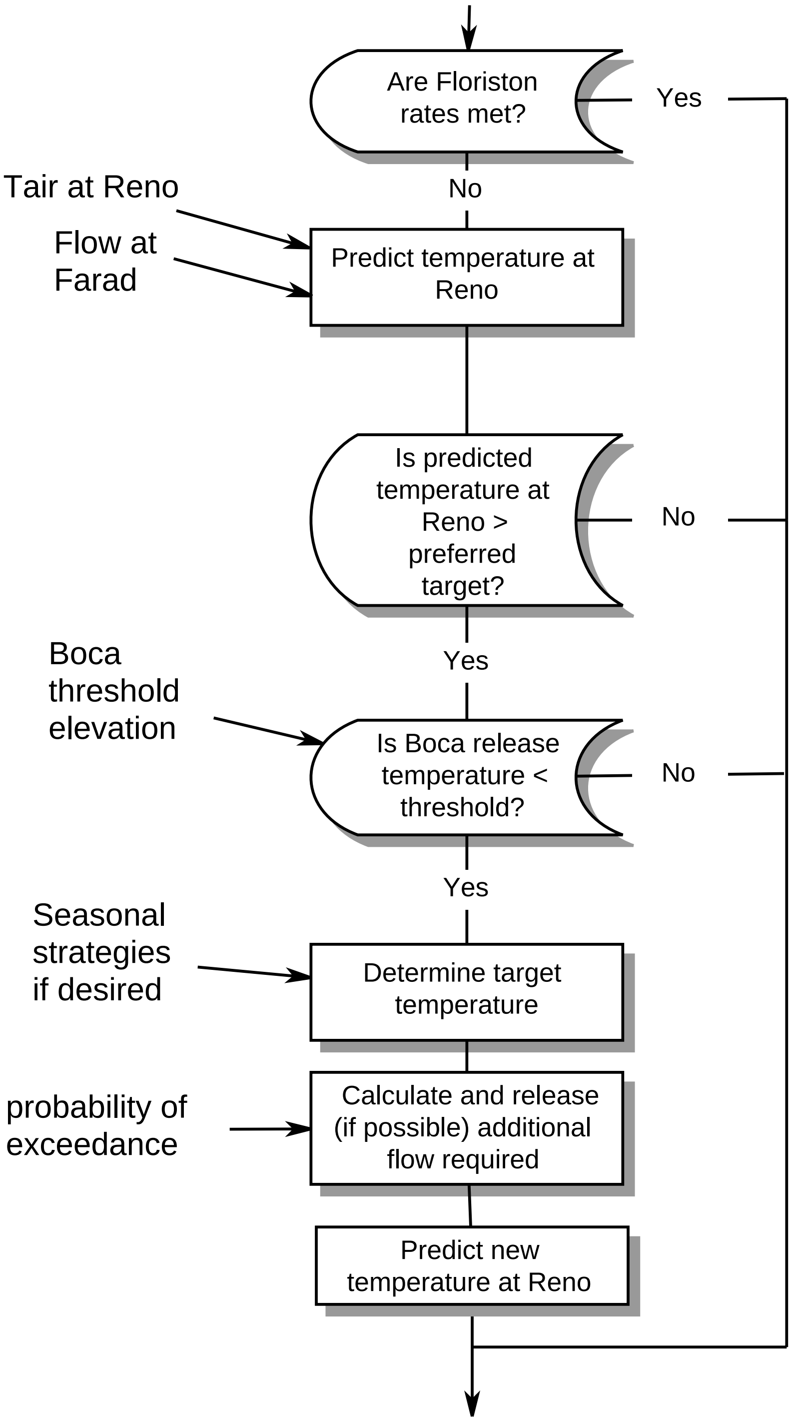


Figure 5.3: WQCW release logic

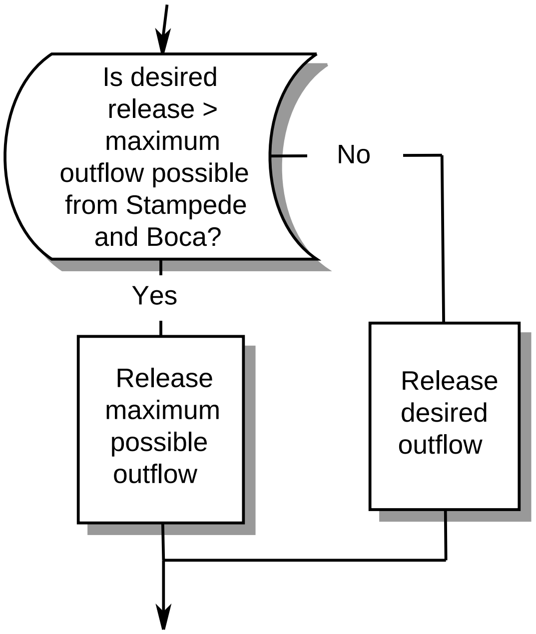


Figure 5.4: Physical constraints logic

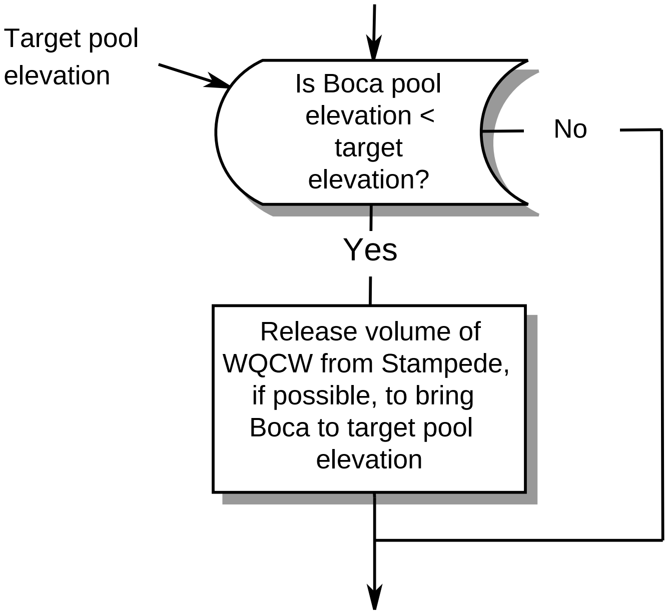


Figure 5.5: Stampede to Boca exchange rules

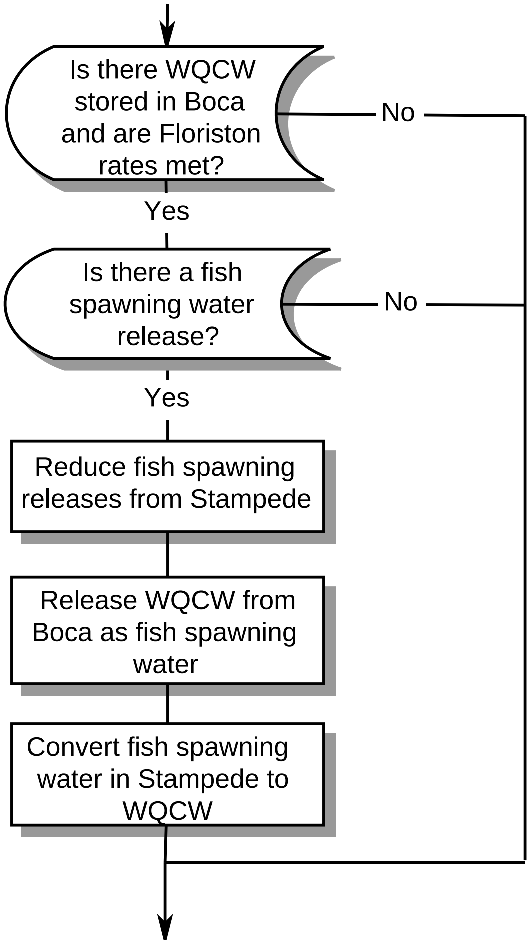


Figure 5.6: Logic to payback WQCW from Boca to Stampede

5.4 Rules to release additional flow to meet target temperatures with seasonal use strategies

The final rules to guide the use of WQCW employ strategies to ensure a set amount of water is available to meet temperature goals throughout a summer based on the seasonal climate forecast. The strategy uses the concept of degree-days which is similar to the concept widely used in agriculture and the energy industries.

Each day of the simulation a variable called a “degree-day” is calculated as the number of degrees above the target for that given day. Degree-days are summed over time; each day has a cumulative sum which is the current day’s degree-days plus the previous day’s cumulative degree-days. If the temperature target is T_{Target} and the actual temperature for that day is T_{Target} +T, then there are T degree-days for that day.

If on day one, there is a cumulative degree-days of T, and day two there is an actual temperature of T_{Target} - T, then there are -T degree-days for day two, and zero total cumulative degree-days. It is possible to have a degree-days threshold for which temperatures below the threshold reset the cumulative degree-days to zero. This will be a user input to the DSS as another method to control the policy. Having this as a user-specified input allows temperatures that are near the target to also reset the cumulative degree-days.

The calculation of degree-days is a useful way to keep track of variations in temperature over time. Using this concept, we create implementation policy that looks at the degree-days to make releases. We can use this policy to determine the severity of a temperature violation and how much water must be released. If the temperature does not exceed the standard by very much and there were cold temperatures the day before, additional water may not be released. However, if the standard has been violated for the last four days, a large release may be necessary to reset the system to zero degree-days.

Incorporating seasonal climate forecasts into WQCW release rules

To effectively conserve water throughout a summer, we need a climate forecast of the summer and modify policies based on the forecast. We use the forecast from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (Climate, 2001). Figure 5.7 is a sample temperature forecast map for October 2001. The CPC produces forecasts for both 30 and 90 day periods. The forecast is created in the middle of the month for the next period (30 or 90 days) and for each subsequent period beginning on each month. For example, a forecast is made in May for the 30 and 90 day period beginning June 1 Also, they make a 30 day and 90 day forecast that begins July 1, August 1, and so forth. We use the 90 day forecast beginning on June 1 that was created in the middle of May. The climate forecasts give the probability that

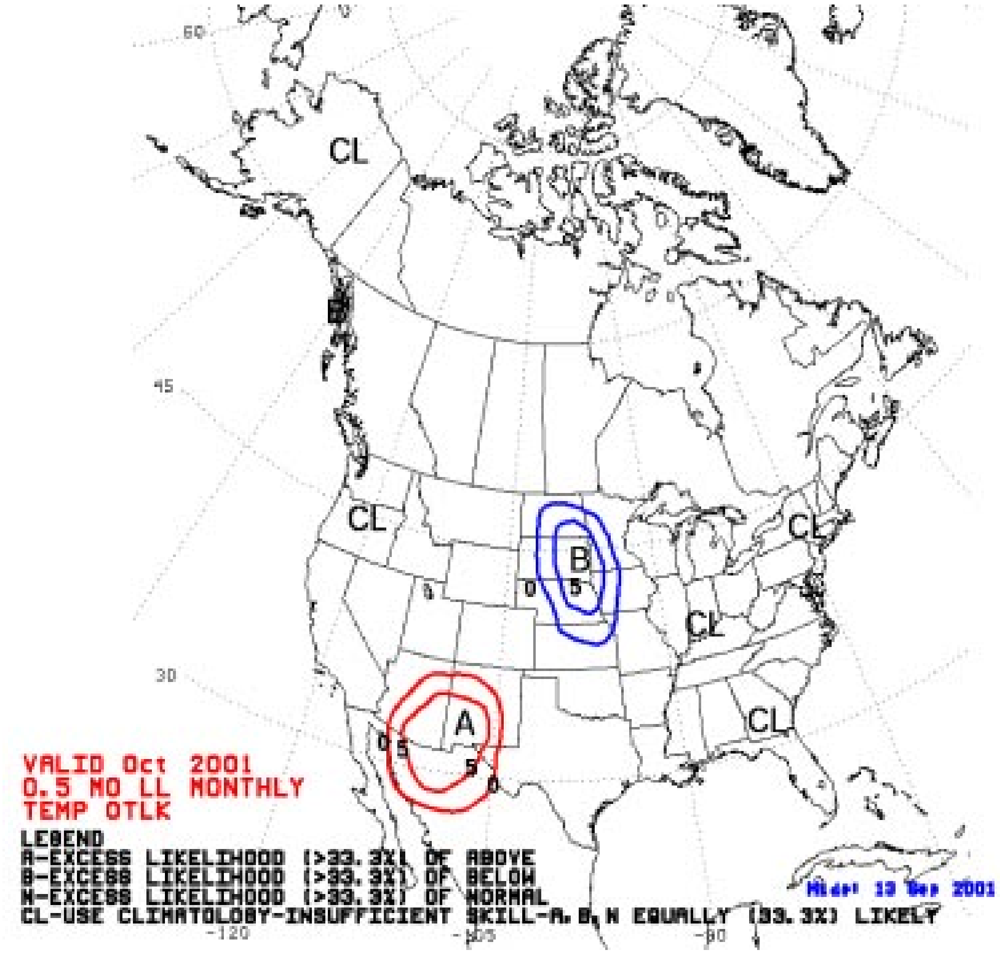


Figure 5.7: Sample 1-month temperature outlook from the CPC

the temperature will be above, near, or below normal. For an average year, the following probabilities are predicted: 33.3% above normal, 33.3% near normal, and 33.3% below normal. This thesis uses the probability that the temperature will be above normal as the indicator variable. The anomaly probability can be read off the prediction map, Figure 5.7, and the probability that it is above normal can be found in Table 5.2 (Climate 2001).

For example, if the temperature is predicted to be warmer than average, a probability anomaly, region A on the map, is shown as having a 20%-30% above normal anomaly meaning there is the following probabilities: 53.3%-63.3% above normal, 33.3% near normal, and 13.3%-3.3% below normal. In the absence of a forecast map,

Table 5.2: Probability table for climate forecasts

Probability anomaly as shown on map	Above, Below, or Normal on Map	Probability of Occurrence for each class		
40%-50%	Above	73.3%-83.3%	23.3%-13.3%	3.3%
30%-40%	Above	63.3%-73.3%	33.3%-23.3%	3.3%
20%-30%	Above	53.3%-63.3%	33.3%	13.3%-3.3%
10%-20%	Above	43.3%-53.3%	33.3%	23.3%-13.3%
5%-10%	Above	38.3%-43.3%	33.3%	28.3%-23.3%
0%-5%	Above	33.3%-38.3%	33.3%	33.3%-28.3%
0%-5%	Normal	30.8%-33.3%	33.3%-38.3%	30.8%-33.3%
5%-10%	Normal	28.3%-30.8%	38.3%-43.3%	28.3%-30.8%
0%-5%	Below	33.3%-28.3%	33.3%	33.3%-38.3%
5%-10%	Below	28.3%-23.3%	33.3%	38.3%-43.3%
10%-20%	Below	23.3%-13.3%	33.3%	43.3%-53.3%
20%-30%	Below	13.3%-3.3%	33.3%	53.3%-63.3%
30%-40%	Below	3.3%	33.3%-23.3%	63.3%-73.3%
40%-50%	Below	3.3%	23.3%-13.3%	73.3%-83.3%
0%	“Climatology”	33.3%	33.3%	33.3%

estimates of the probability anomaly may be provided from other sources. This probability of above normal occurrence is a user input to the DSS. Because the CPC does not publish the forecasts for years before 1994, we had to determine an estimate for the forecast. We selected the driest year as 1994 and estimated its forecast as 44% above normal. We then gave 1990-1993 forecast estimates between 33% and 37% as all of the years were fairly dry. Table 5.3 shows the values used in the DSS for 1990-1994.

Because we know how much WQCW is stored at any given time, we can create a variable called *Storage and Forecast Factor* (SAFF) that combines the available water and the climate forecast.

Table 5.3: Forecast used in DSS

Year	June, 90 day forecast: probability of above average occurrence
1990	37%
1991	37%
1992	36%
1993	33%
1994	44%

$$\text{SAFF} = \frac{\text{Volume of WQCW}}{\text{Probability of above normal occurance}} \qquad \text{Eq. 5.9}$$

A low SAFF indicates little water is available and hot weather is predicted. A high SAFF indicates plenty of WQCW is available and cool weather is forecasted. We estimate an average SAFF as a base condition as the average volume of storage divided by the average probability of above normal occurrence.

$$\text{SAFF}_{Avg} = \frac{\text{Average volume of WQCW}}{\text{Average probability of above normal occurance}} \qquad \text{Eq. 5.10}$$

. The SAFF_{Avg} is an input to the DSS and can be changed by the water manager. In this thesis, we will assume the average volume is 24,000 acre-feet. This is the maximum amount of water that could be stored each year. In addition, WQCW can be carried over from wet years to dry years; more than 24,000 acre-feet can be stored. Therefore, 24,000 acre-feet is a reasonable number to use as an average. The average probability of above normal occurrence is 33.3%. Combining these two, we can determine a SAFF for every day of the summer season. During operations, we will calculate the actual SAFF for each day. If the actual SAFF is above the average SAFF, it is a high SAFF scenario (low need for WQCW); if the actual SAFF is below the average SAFF, it is a low scenario. This set of scenarios is useful because it allows us to quantify the available water and the weather forecast.

It is necessary to be conservative in terms of water use in the beginning of the season no matter what scenario is used. If the actual temperature does not follow the long-term forecasts, it is critical to ensure water is still available to reduce water temperatures. In the middle or end of the season, if the SAFF is above average, we do not need to conserve water; any temperature violation can be eliminated. If the SAFF is below average, we must conserve as much water as possible, only releasing when absolutely necessary to meet the targets. In general, water must be conserved in the beginning of the season but can be used at the end of the season.

Here is a simple example. The forecast says it will be a cool summer and plenty of WQCW is in storage. During June, water must be conserved. In July, if plenty of water is still available and the climate is reasonably cool, any temperature violations can be mitigated by releasing as much water as necessary. If the same weather continues in August, all temperature violations can be avoided.

In contrast, if the forecast calls for hot weather and only a very small amount of WQCW is available, we must conserve as much water as possible. Standard violations of only one or two degrees are allowed. Violations that meet the acute limit will be mitigated, but they may only be reduced to the chronic (1-2 degrees above the preferred) levels. In July, if little water still remains, it must be conserved. If it happened to be wetter than forecasted, then the release pattern can change to be less conservative in terms of water storage; one to two degree violations can be avoided. If the forecast is correct and it is hot, one to two degree violations are acceptable but only for short periods.

Depending on the month, the predicted river temperature, the SAFF and the number of accumulated degree days, a different target temperature is used in the DSS. Table 5.4 shows the logic to select the target.

Table 5.4: Temperature target determination

	June	July		August	
		Above average SAFF	Below average SAFF	Above average SAFF	Below average SAFF
$\hat{T}$ >25 ºC and DD ≤ 4	Chronic maximum	Chronic maximum	Chronic maximum	Preferred maximum	Chronic maximum
$\hat{T}$ > 25 ºC and DD > 4	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum
24 ºC ≤ $\hat{T}$ ≤ 25 ºC and 1 ≤ DD < 4	Chronic maximum	Preferred maximum	Chronic maximum	Preferred maximum	Preferred maximum
24 ºC ≤ $\hat{T}$ ≤ 25 ºC and DD < 1	Acute maximum	Chronic maximum	Acute maximum	Preferred maximum	Chronic maximum
24 ºC ≤ $\hat{T}$ ≤ 25 ºC and DD > 4	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum
22 ºC ≤ $\hat{T}$ ≤ 24 ºC and DD < 4	Chronic maximum	Preferred maximum	Chronic maximum	Preferred maximum	Chronic maximum
22 ºC ≤ $\hat{T}$ ≤ 24 ºC and DD ≤ 4	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum	Preferred maximum

$\hat{T}$ is the predicted maximum daily river temperature at Reno and DD is the degree-days from the previous day. The actual targets are found in Table 2.1. Since WQCW operations in June should always be conservative in terms of volume used, the SAFF does not appear in the logic. Even though this logic determines the target temperature, releases may not be able to meet it. Physical constraints and available water affect whether there will actually be enough flow at Farad to meet the temperature target.

The seasonal forecasts are modifications to the rules that release additional flow to meet target temperatures. The seasonal strategies are used to determine the target temperature for each day of the simulation as shown in Figure 5.3. As a result, on one day of the simulation, the target may be 22 ºC, while on another day, the target may be 23 ºC.

5.5 Summary of rules

The DSS rules are structured to execute in a specific order as shown in Figure 5.8. The baseline operations policy rules as developed by the USBR execute first. Then rules execute to store WQCW and rules execute to perform the Boca to Stampede WQCW payback. These first rules happen at any time of the year depending on releases and demands as set by the baseline operations policy. But, if the current simulation day is in June, July, or August, additional rules execute to exchange WQCW from Stampede to Boca, and to predict water temperature at Reno and release additional flow if necessary. The actual RiverWare rules and functions are presented in Appendix D, “RiverWare rules and functions.”

5.6 Use of DSS

The DSS is used by water managers to determine how different scenarios will affect operations. Figure 5.9 shows a schematic of the inputs to the DSS. The goal of a water manager is to determine the releases that efficiently meet demands. A model-based DSS is useful because it allows water managers to test the inputs and model parameters that result in effective operations. By changing inputs to the DSS, users can experiment with “what if I tried this” situations. Following is a list of user inputs. The effects of changing some of these will be explored in the scenarios in the following chapter:

1. Probability of exceedance (confidence level)
2. Fish targets
3. Climate forecasts (probability of above normal occurrence)
4. Average volume of WQCW in storage

5. Degree-day threshold
6. Boca target elevation

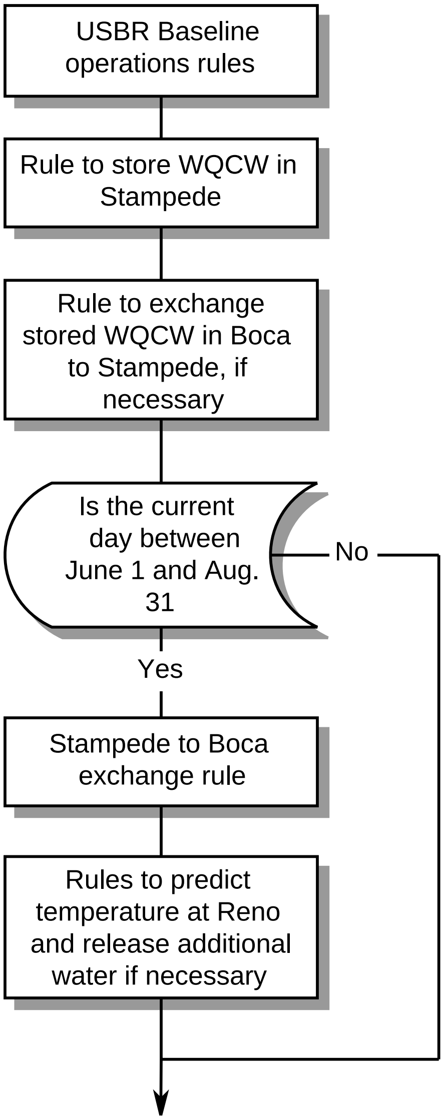


Figure 5.8: Rule execution layout

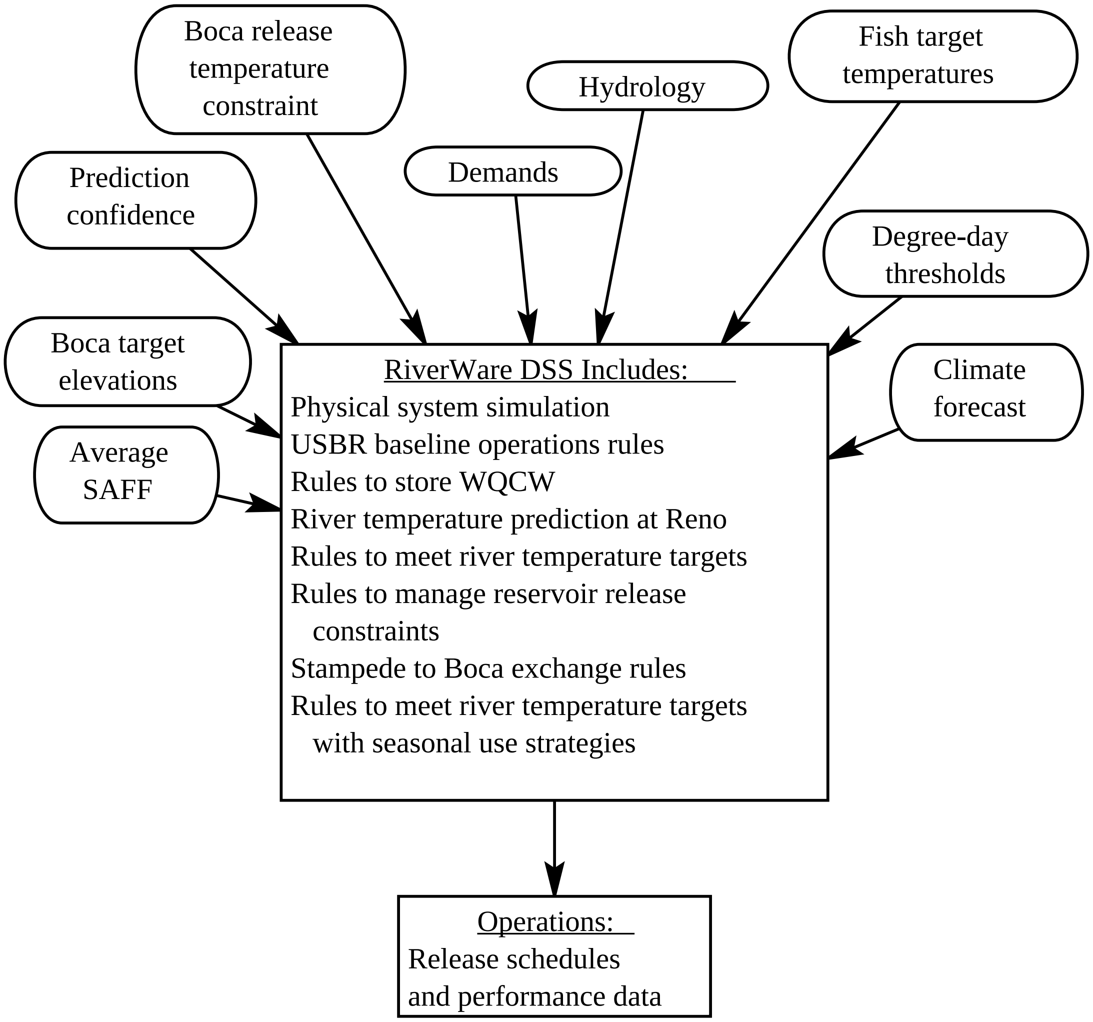


Figure 5.9: Inputs and outputs of the RiverWare DSS

Chapter 6

Testing and Results

The DSS as described in Chapter 5, “Decision Support System,” was run with historic inflow data to examine the effects on operations and the benefits of using the WQCW. We define scenarios simulated by the DSS runs. Each scenario is defined by a particular set of input values and operating policies. Results presented for each run include storages of WQCW in both Stampede and Boca and the maximum daily river temperature at Reno. We summarize the violations for each scenario in tables, show the amount of water that is used for each scenario, and discuss the results.

We applied the DSS to the period from 1980-1997. Of those years, 1988-1994 were dry; Floriston rates were not always met. We selected 1990-1994 as the years in which to focus the investigation. Before 1988, the basin hydrology was wet and there were few days in which Floriston rates were not met. As a result, WQCW would not have been used. 1993 was the wettest year from 1988-1994 and 1992 was the driest year in that period. To summarize the hydrology, There was a five year dry spell from 1988-1992 followed by one average year in 1993 and then a dry year in 1994.

The results presented are not compared to observed river temperatures because the policies modeled in the DSS are not comparable to historical operations. The baseline policies in the DSS reflect the current stage of development of the policy rules by the USBR. These rules reflect most of the legal policies, but omits some policies and operations that influence releases like reservoir maintenance, operating errors, or human judgement. As a result, it would not be meaningful to compare the model results to historical operations.

In Section 5.6, we described the inputs the user can modify. All DSS runs used the fish temperature targets as described in Table 2.1, the climate forecasts presented in Table 5.3, the average WQCW in storage described in Section 5.4, and a Boca target elevation of 5565 ft. We investigated the effects of changing the probability of exceedance, the impact of climate forecasts, and the effects of changing the degree-day thresholds.

We chose to investigate the effects of changing the probability of temperature exceedance from 0.5, the mean value of the predictor, to 0.1. The more confident value, 0.1, was chosen because water quality standards in the Truckee River have to be met only 90% of the time, as described in Section 2.5.

6.1 Stampede to Boca exchange results

The DSS was run with different input scenarios. The first set of scenarios, defined in Table 6.1, are used to show that an exchange from Stampede to Boca is necessary. From this result, we will explore further scenarios.

Figure 6.1 shows the volume of WQCW water in Stampede and Boca for scenarios I, II, and III. There is no WQCW stored in either reservoir for scenario I. Figure 6.1 shows that approximately 7000 acre-feet of WQCW can be stored each year. Of the 7000 acre-feet per year, 6700 acre-feet per year likely comes from the groundwater effluent exchange. Additional water is stored during fish spawning releases but does not result in the full purchased amount of 17,000 acre-feet because fish water either cannot be released because of physical constraints or is not needed because of natural flows. If Stampede did not run out of water, more fish spawning releases could be made. Reducing the fish targets at Pyramid would make the Fish spawning water in Stampede go further and lead to more WQCW creation.

Table 6.1: DSS scenarios for Stampede to Boca exchange

Scenario Number	Description of Scenario
I.	Baseline USBR operations policy: • No WQCW storage or release
II.	Operations with: • WQCW storage rules • WQCW releases to meet Reno Temperature Target of 22º C • Probability of exceedance = 0.5 • **Does NOT include** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • No seasonal strategies
III.	Operations with: • WQCW storage • WQCW releases to meet Reno Temperature Target of 22º C • Probability of exceedance = **0.5** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • No seasonal strategies

Figure 6.2 and Figure 6.3 show the maximum daily river temperature at Reno for scenarios I, II and III for 1990-1994. The plots for scenario II in Figure 6.2 and Figure 6.3 show that, even though there is plenty of WQCW stored in Stampede, temperature violations occur. This is caused by the constraint that prevents warm releases when Boca gets too low. This indicates that the Stampede to Boca exchange is necessary. Scenario III shows that a minimum pool elevation target at Boca gives a more effective way of managing WQCW and allows for the mitigation of temperature violations at Reno. This exchange of water is active in the rest of the scenarios.

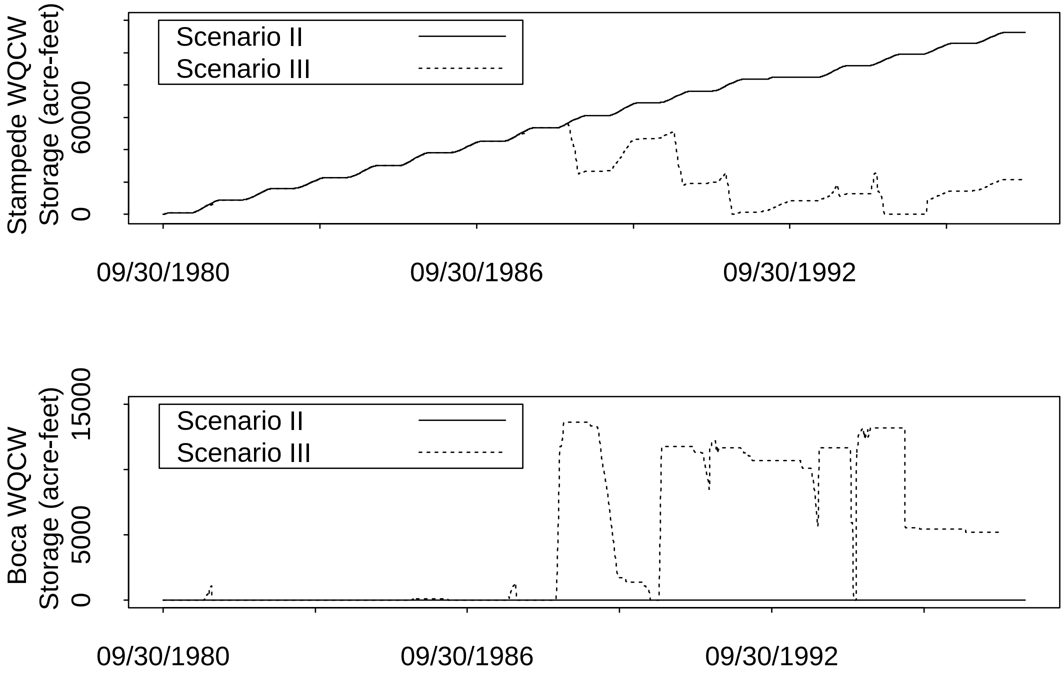


Figure 6.1: Volume of WQCW stored in Stampede and Boca for scenarios II and III

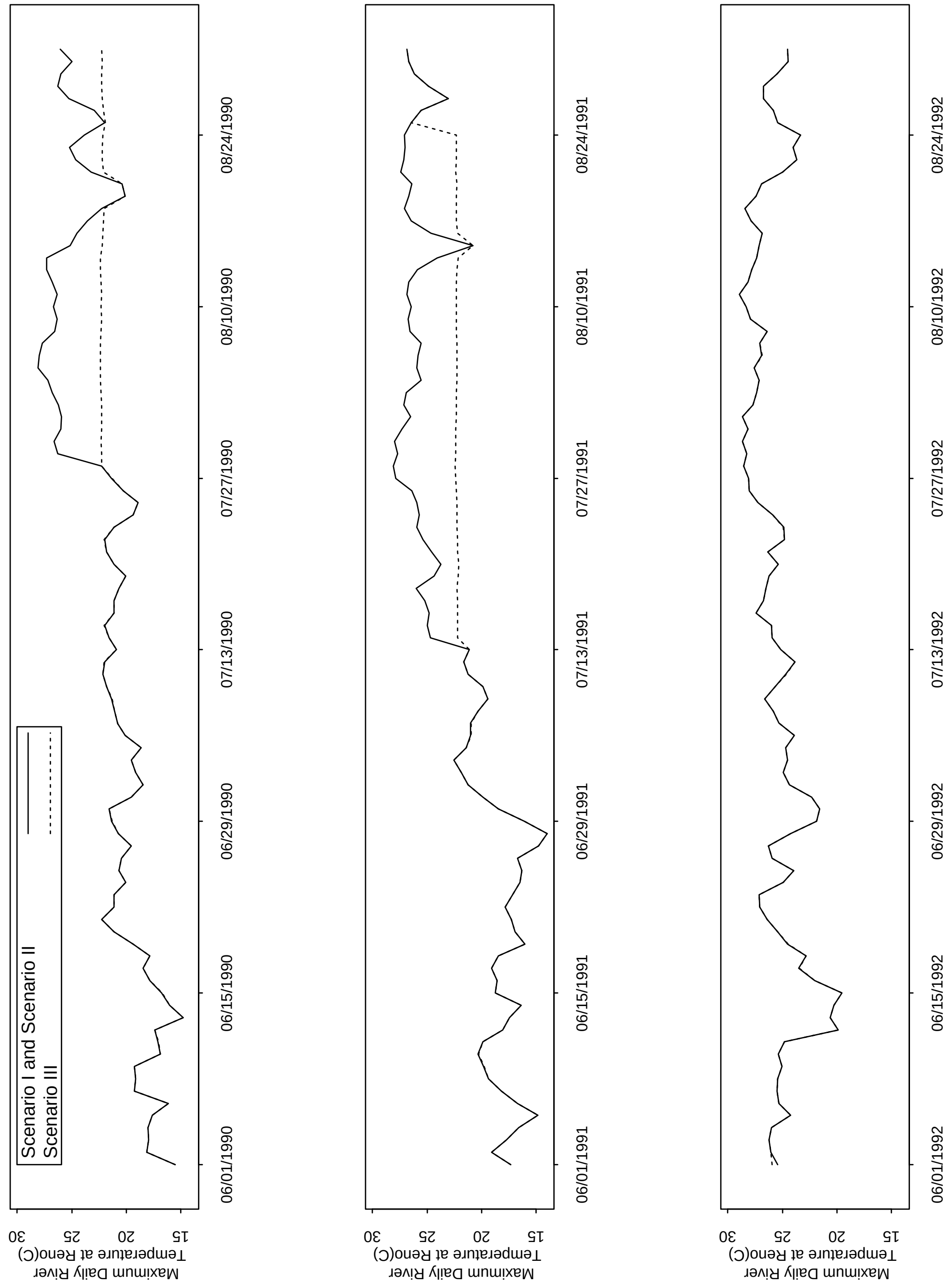


Figure 6.2: Maximum daily river temperature at Reno 1990-1992 for scenarios I-III

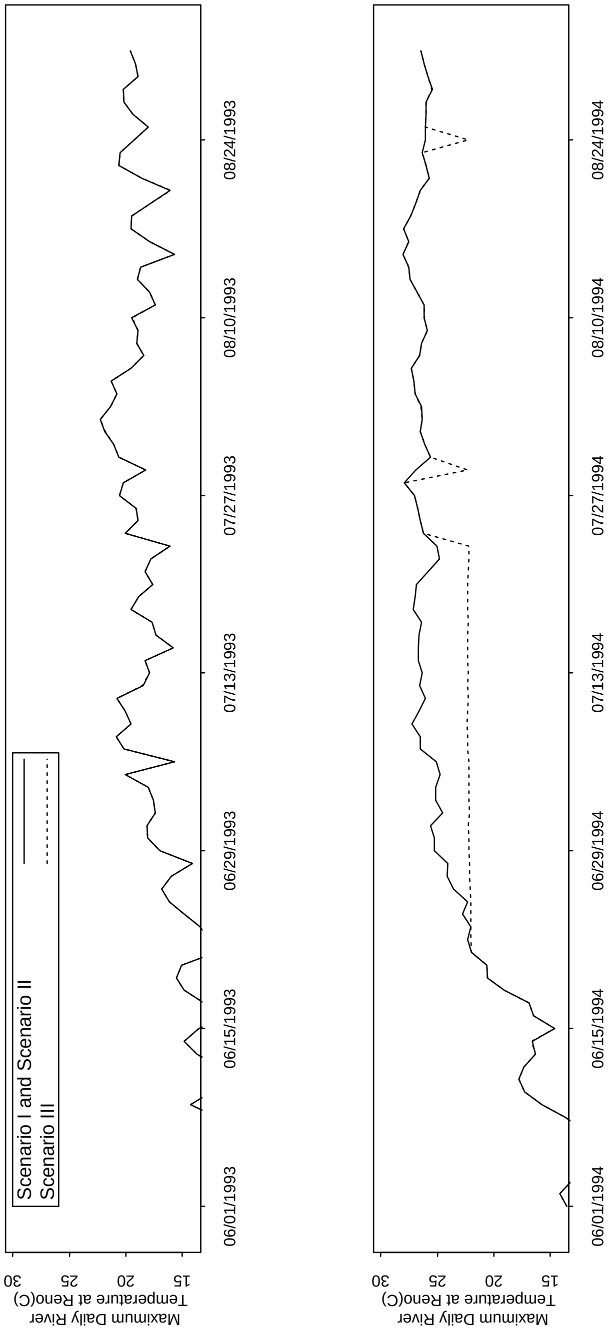


Figure 6.3: Maximum daily river temperature at Reno 1993-1994 for scenarios I-III

6.2 Seasonal strategies and varying probability of exceedance

Additional scenarios are defined in Table 6.2 to compare the effects of different user-specified probability of exceedance and seasonal use strategies.

Table 6.2: Additional scenarios for modified exceedance probability and seasonal strategies

Scenario Number	Description of Scenario
IV.	Operations with: • WQCW storage • WQCW releases to meet Reno Temperature Target of 22º C • Probability of exceedance = **0.1** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • No seasonal strategies
V.	Operations with: • WQCW storage • WQCW releases • Probability of exceedance = **0.5** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target • Includes seasonal use strategies and targets
VI.	Operations with: • WQCW storage • WQCW releases • Probability of exceedance = **0.1** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • Includes seasonal use strategies and targets

Table 6.2: Additional scenarios for modified exceedance probability and seasonal strategies

Scenario Number	Description of Scenario
VII.	Operations with: • WQCW storage • WQCW releases • Probability of exceedance = **0.5** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • Includes seasonal use strategies and targets • Degree-days threshold modified from 22 °C to 22.3 °C
VIII.	Operations with: • WQCW storage • WQCW releases • Probability of exceedance = **0.1** • **Includes** proposed Stampede to Boca exchange rules to keep Boca at target pool elevation • Includes seasonal use strategies and targets • Degree-days threshold modified from 22 °C to 22.3 °C

Figure 6.4 shows the volume of WQCW stored in Stampede and Boca for scenarios II, III, and IV. Decreasing the allowed probability of exceedance from 0.5 to 0.1 increases the amount of water that has to be released leading to lower WQCW storages.

Figure 6.5 and Figure 6.6 show a comparison of maximum daily river temperatures at Reno for scenarios I through IV. Scenarios III and IV both reduce the river temperature in 1990 and 1994 until the reservoirs run out of WQCW. Because scenario IV aims for a much lower probability of exceedance, more water is released to assure

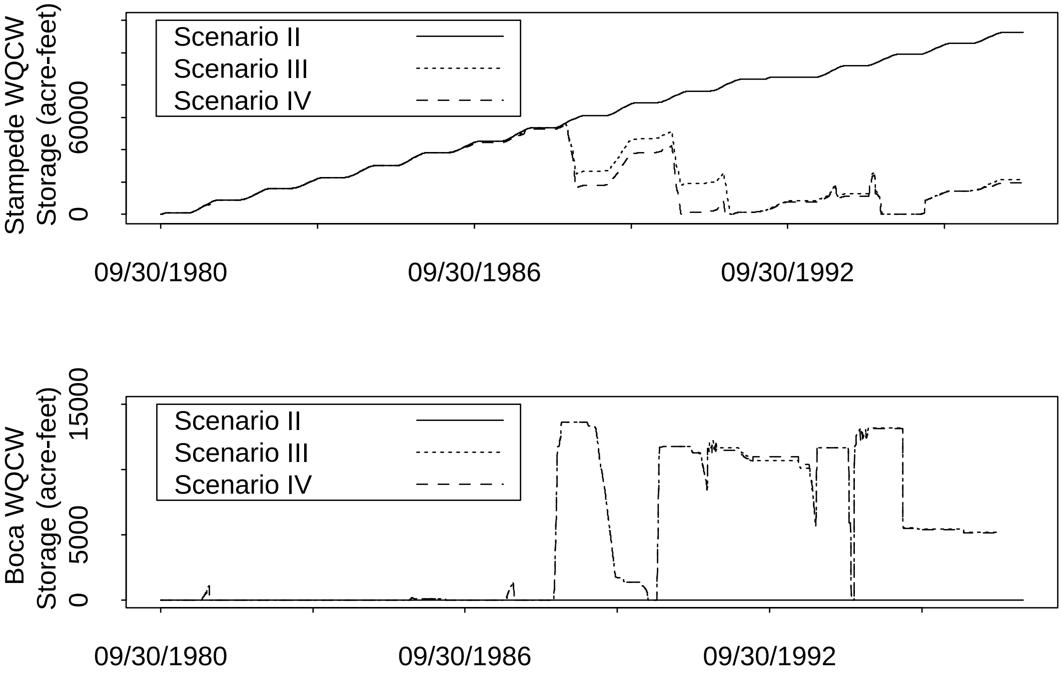


Figure 6.4: Volume of WQCW stored in Stampede and Boca for scenarios II-IV

that the river temperature is below the target. As a result, the WQCW in storage is depleted much sooner. Therefore, a lower probability of exceedance will result in more certainty, but more water is necessary. Also, a lower probability of exceedance will result in a higher confidence that lower river temperatures will occur but may result in more extreme violations once the WQCW is exhausted.

Because of the five-year dry period from 1988 to 1992, there was no WQCW stored in Stampede in 1992. As a result, there was no water available to meet temperature targets at Reno. In addition, Boca's pool elevation is below the target and there is no water available to make an exchange from Boca. In this unusual situation, there is nothing water managers can do. But, a DSS tool such as the one created in this thesis gives a tool to managers to predict potential problems such as this. On the other hand,

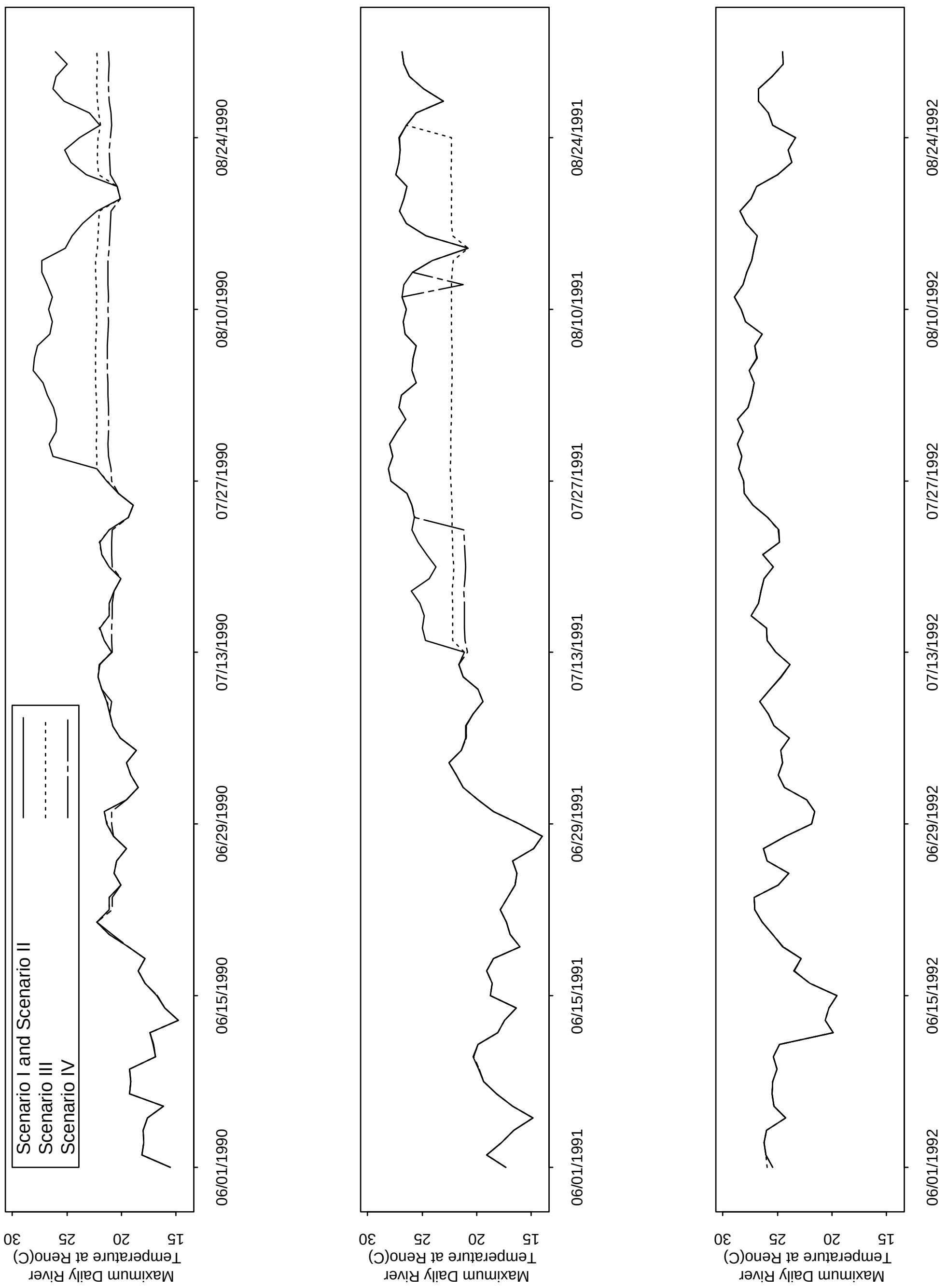


Figure 6.5: Maximum daily river temperature at Reno 1990-1992 for scenarios I-IV

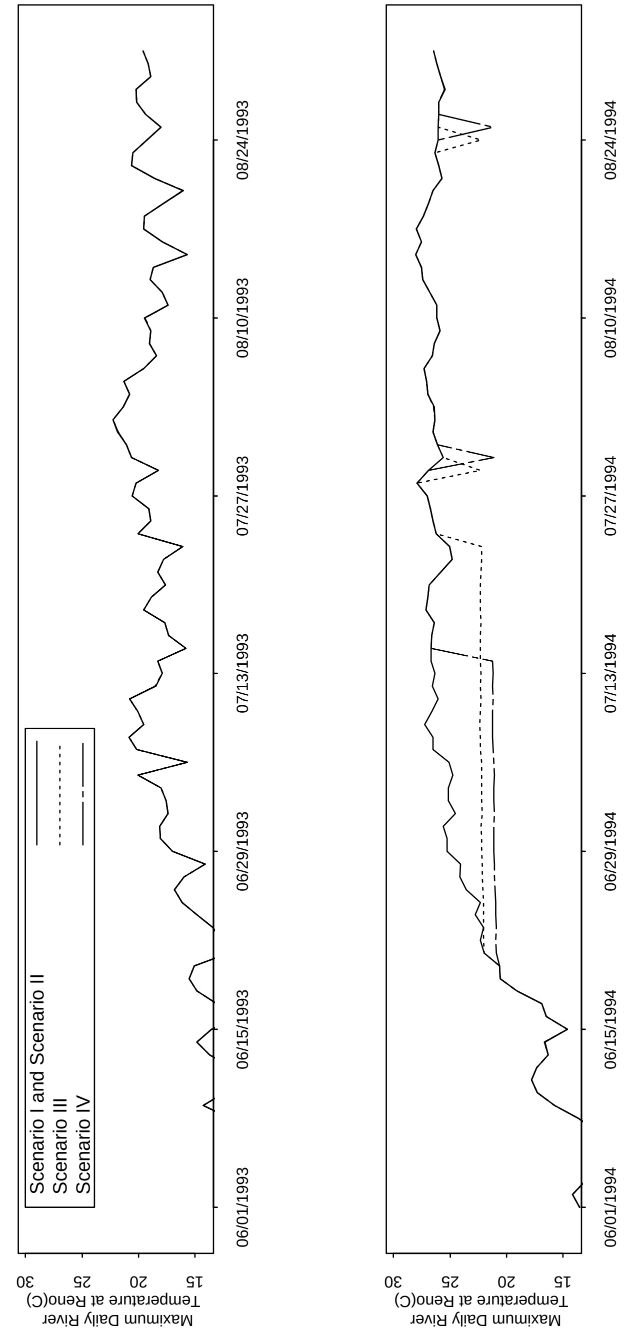


Figure 6.6: Maximum daily river temperature at Reno 1993-1994 for scenarios I-IV

1993 was relatively wet and there was no need for WQCW. In this case, the air temperature was cool and there was enough flow to avoid nearly all river temperature violations.

When a river temperature exceeds the target value for more than the specified time limit, a violation occurs. Table 6.3 shows the violations for scenarios I-IV based on the temperature targets described in Table 2.1.

Table 6.3: Temperature violations 1990-1994 for scenarios I-IV

		T ≤ 22 ºC or NO violation	22 ºC < T≤ 23 ºC for > 4 days	23 ºC < T ≤ 24 ºC for > 1day	24 ºC < T	Total violations
Scenario I No WQCW	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario II, No Stampede to Boca exchange	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario III, Exchange Prob = 0.5	June	129	0	1	20	21
	July	104	14	2	35	51
	August	63	24	3	65	92
	Total	296	38	6	120	164
Scenario IV, Prob = 0.1	June	129	0	1	20	21
	July	101	0	2	52	54
	August	65	0	3	87	90
	Total	295	0	6	159	165

Scenario III has fewer violations over 24 ºC than scenario I and II but more violations in the 22 ºC to 23 ºC range. Because scenario III aims for 22 ºC with 0.5

probability of exceedance, the temperature is just above 22 ºC. Physical constraints often prevent enough water from being released to bring the temperature below 22 ºC.

In scenario IV there are more occurrences of less than 22 ºC and more violations of greater than 24 ºC than in scenario III. The target for scenario IV is 22 ºC minus the PCD calculated based on the probability of exceedance. This leads to the large number of occurrences less than 22 ºC. Then, the reservoir runs out of WQCW and there are a large number of above 25 ºC violations.

The WQCW is depleted before the hottest parts of the year in both scenario III and IV, in 1991 and 1994. These results indicate that seasonal strategies that allow minor violations may be able to help conserve water throughout the summer.

Figure 6.7 and Figure 6.8 show the maximum daily river temperature at Reno for scenarios V and VI, which use seasonal strategies to conserve water. These strategies select higher target temperatures based on the amount of available water and the degree-days.

Even with strategies to conserve water for later season violations, there still is not enough water to avoid all of the temperature problems during very dry periods. In 1991 and 1994 the reservoir still runs out of WQCW in scenario VI. But, the WQCW lasts longer through the season. In 1994, scenario IV runs out of WQCW in the middle of July. But in scenario VI, the WQCW is not depleted until the end of July 1994.

Table 6.4 shows the number of violations for scenarios I-VI. The total violations in scenario V are more than in scenario III but the violations are shifted from violations above 24 ºC in scenario III to violations between 22 ºC and 23 ºC in scenario V. Although these are still violations, they are not as severe as violations above 24 ºC which likely kill fish. Scenario VI shows that seasonal strategies result in fewer violations.

Table 6.5 shows the total amount of water that passes Farad and the total volume of WQCW released. The volume released for scenario I and II are similar and

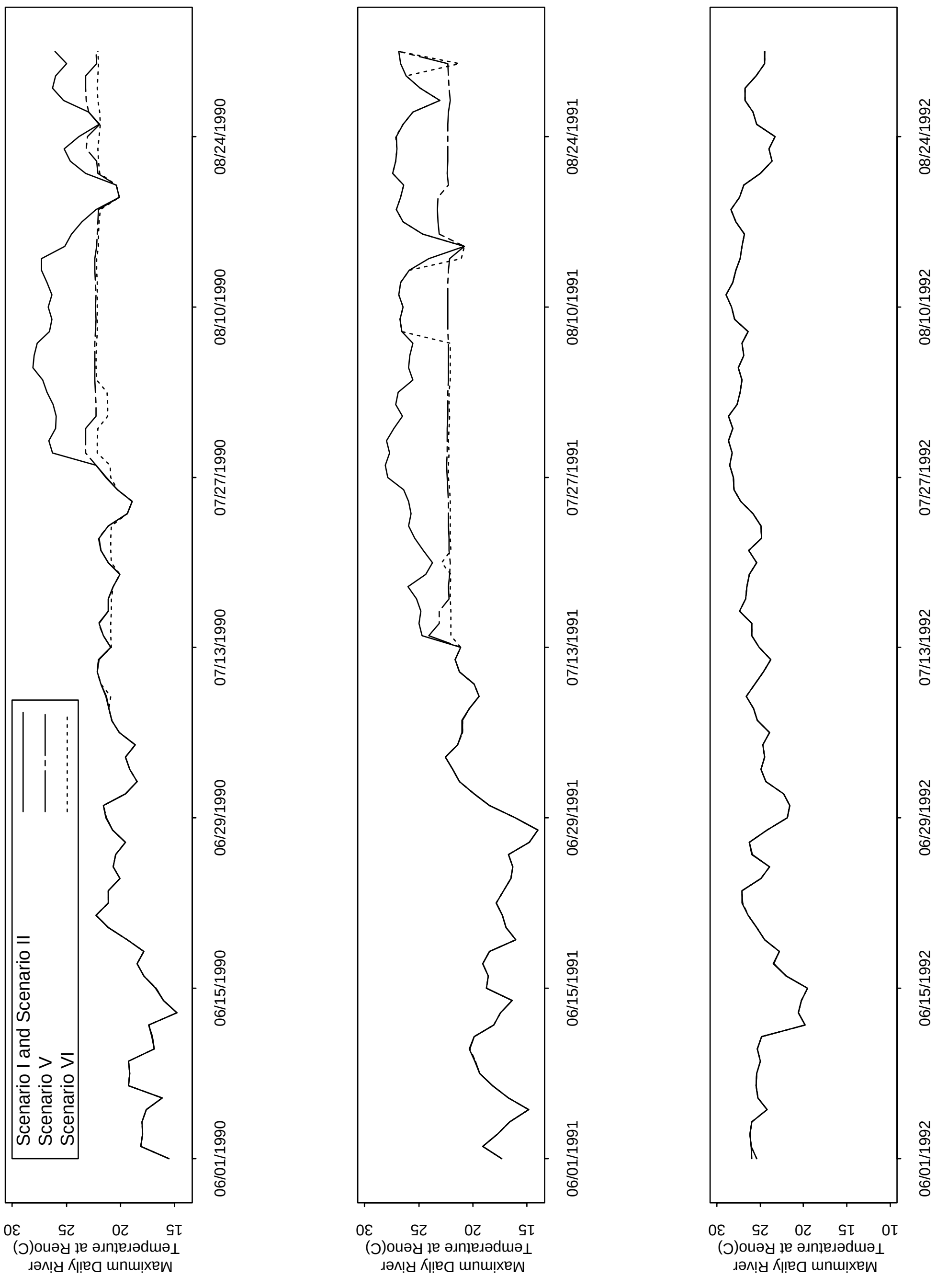


Figure 6.7: Maximum daily river temperature at Reno 1990-1992 for scenarios I-II, V-VI

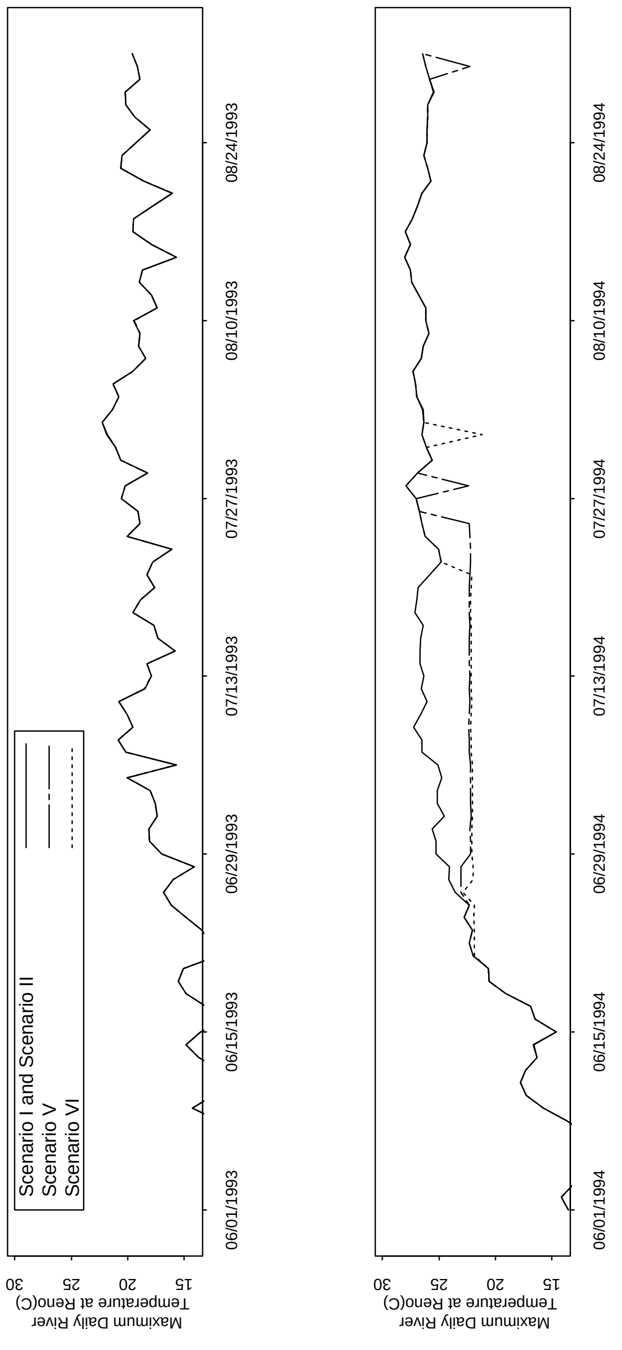


Figure 6.8: Maximum daily river temperature at Reno 1993-1994 for scenarios I-II, V-VI

Table 6.4: Temperature violations 1990-1994 for scenarios I-VI

		T ≤ 22 ºC or no violation	22º C < T≤ 23º C for > 4 days	23º C < T ≤ 24º C for > 1day	24º C < T	Total violations
Scenario I No WQCW	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario II, No Stampede to Boca exchange	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario III, Exchange Prob = 0.5	June	129	0	1	20	21
	July	104	14	2	35	51
	August	63	24	3	65	92
	Total	296	38	6	120	164
Scenario IV, Prob = 0.1	June	129	0	1	20	21
	July	101	0	2	52	54
	August	65	0	3	87	90
	Total	295	0	6	159	165
Scenario V, Prob = 0.5, seasonal strategies	June	124	2	4	20	26
	July	74	41	6	34	81
	August	40	46	9	60	115
	Total	238	89	19	114	222
Scenario VI, Prob = 0.1, seasonal strategies	June	129	0	1	20	21
	July	115	0	2	38	40
	August	73	0	3	79	82
	Total	317	0	6	137	143

Table 6.5: Volume of water used June, July, August 1990-1994, scenarios I-VI

Scenario	Total volume of water passing Farad (acre-feet)	Total volume of WQCW released (acre-feet)
I	289000	0
II	287000	0
III	369000	58000
IV	357000	45000
V	371000	59000
VI	363000	51000

there is no WQCW released. Scenario III and IV release a large volume of WQCW which results in fewer violations. The amount of water used in scenarios V and VI is more than III and IV with the same exceedance probabilities, respectively. Likely, the seasonal strategies used in V and VI keep more water in the reservoirs early in the season which allows more water to be released because of higher operating head.

Intuitively, one would think that the volume of water passing Farad in scenario III minus the volume of WQCW released in scenario III would equal the amount of water passing Farad in scenario II. But this is not the case. Changing operations, even in a small way, often has the effect of completely modifying basin operations. In this case, the Stampede to Boca exchange provides more operating head at Boca allowing more fish spawning and Floriston rate water to be released.

The volume of WQCW released in scenario III is more than in scenario IV because the initial WQCW volume in 1990 was different. WQCW releases in 1988 and 1989 depleted the storage differently in scenario III and IV. As of June 1, 1990, Stampede held 50,000 acre-feet of WQCW in scenario III and 41,000 acre-feet in scenario IV.

The seasonal strategies will be more effective in actual operations because real data can be used to calculate the degree-days. In the DSS, we used the predicted temperature to calculate the current day’s degree-day. In operations, we can use the observed temperature at the end of the current day to calculate the degree-day. As a result, we use actual information to make decisions about the next day’s operations, improving the operations.

In scenarios VII and VIII, we adjusted the threshold at which the degree-day resets to zero. When a river temperature is 22.3 ºC instead of 22 ºC, the degree day cumulative counter is reset to zero. This tests the sensitivity to the resetting of the degree-days. Scenarios VII and VIII are scenarios VI and VII, respectively, with modified degree day thresholds. Figure 6.9 and Figure 6.10 show the maximum daily river temperature at Reno for scenarios VII and VIII.

The degree day modification appears to have an effect on the temperatures in scenario VII but little affect in scenario VIII. In scenario VII, the temperature in 1991 and 1994 has a saw-tooth pattern. The temperature is lowered to 22 ºC one day but is only lowered to 23 ºC for the next few days. Once the degree-days counter goes above four, the target is reset to 22 ºC and the sawtooth starts over. Scenario VIII appears to have little improvement. Because the probability of exceedance is 0.1, the target temperature is the target from Table 5.4 minus the PCD. As a result, the temperature is often less than 23 ºC for fewer than four days and no additional violations occur in this range. Table 6.6 shows the violations of all scenarios.

The volume of WQCW used is presented in Table 6.7 for all scenarios. The volume of water used in scenario V is only slightly more than the volume of water used in scenario III but the number of total violations increases. But, the violations above 24 ºC are reduced. The seasonal strategies changed the distribution of the violations. Changing the degree-day threshold in scenario VII decreases the number of violations to a level near that in scenario III but uses less water.

The scenarios with the lowest violations are scenario VI and VII. In addition, they use the second smallest volume of water. Possibly, there is a scenario between VII and VIII that has a probability of exceedance between 0.1 and 0.5 that would result in

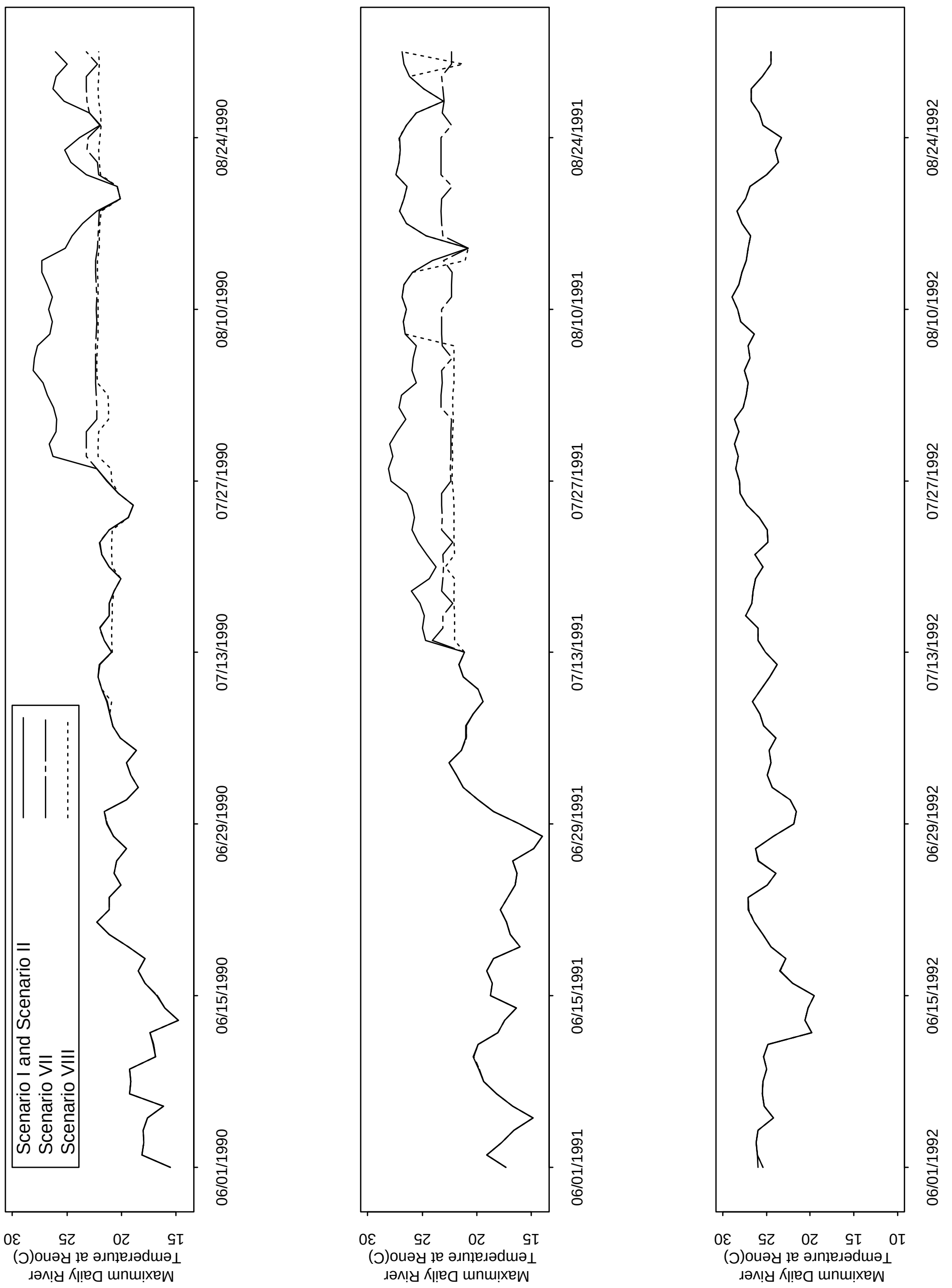


Figure 6.9: Maximum daily river temperature at Reno 1990-1992, scenarios I-II, VII-VIII

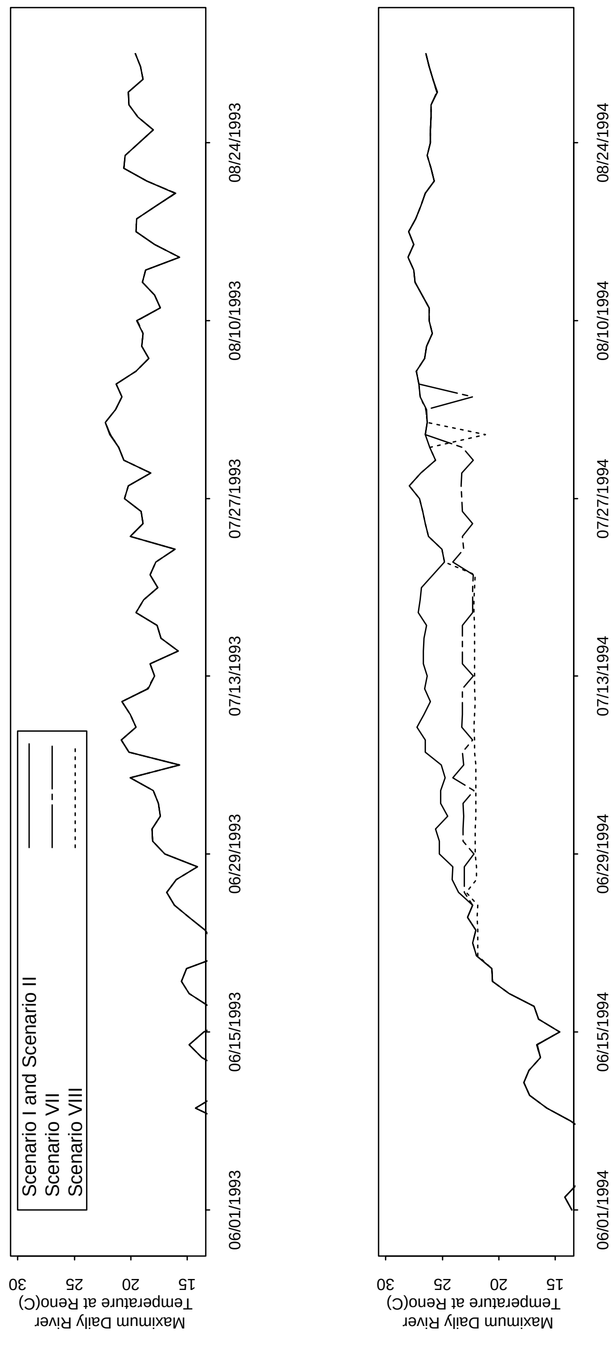


Figure 6.10: Maximum daily river temperature at Reno 1993-1994, scenarios I-II, VI-VIII

Table 6.6: Temperature violations 1990-1994, scenarios I-VIII

		T ≤ 22 ºC or no violation	22º C < T≤ 23º C for > 4 days	23º C < T ≤ 24º C for > 1day	24º C < T	Total violations
Scenario I No WQCW	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario II, No Stampede to Boca exchange	June	116	0	1	33	34
	July	74	0	3	78	81
	August	37	1	5	112	118
	Total	227	1	9	223	233
Scenario III, Exchange Prob = 0.5	June	129	0	1	20	21
	July	104	14	2	35	51
	August	63	24	3	65	92
	Total	296	38	6	120	164
Scenario IV, Prob = 0.1	June	129	0	1	20	21
	July	101	0	2	52	54
	August	65	0	3	87	90
	Total	295	0	6	159	165
Scenario V, Prob = 0.5, seasonal strategies	June	124	2	4	20	26
	July	74	41	6	34	81
	August	40	46	9	60	115
	Total	238	89	19	114	222
Scenario VI, Prob = 0.1, seasonal strategies	June	129	0	1	20	21
	July	115	0	2	38	40
	August	73	0	3	79	82
	Total	317	0	6	137	143

Table 6.6: Temperature violations 1990-1994, scenarios I-VIII

Scenario VII, Prob = 0.5, adjusted DD threshold	June	126	0	4	20	24
	July	88	8	28	31	67
	August	74	2	20	59	81
	Total	288	10	52	110	172
Scenario VIII, Prob = 0.1 adjusted DD threshold	June	129	0	1	20	21
	July	115	0	2	38	40
	August	73	0	3	79	82
	Total	317	0	6	137	143

Table 6.7: Volume of water used, June, July, August 1990-1994, scenarios I-VIII

Scenario	Total volume of water passing Farad (acre-feet)	Total volume of WQCW released (acre-feet)
I	289000	0
II	287000	0
III	369000	58000
IV	357000	45000
V	371000	59000
VI	363000	51000
VII	367000	56000
VIII	363000	51000

fewer violations. Further use of the DSS would be necessary to find the optimum scenario. Because the warm temperatures cannot be corrected in 1992, the violations in 1992 are the same in each scenario. Table 6.8 shows the violations for 1992.

Table 6.8: Temperature violations in 1992

		T ≤ 22 ºC or No Violation	22º C < T≤ 23º C for > 4 days	23º C < T ≤ 24º C for > 1day	24º C < T	Total Violations
1992 only, identical for all scenarios	June	9	0	1	20	21
	July	1	0	2	28	30
	August	0	0	2	29	31
	Total	10	0	5	77	82

By removing 1992 violations from the violations in Table 6.6, we can summarize, for each scenario, the percentage reduction in violations from scenario I. By removing 1992, Table 6.9 shows the percent reduction when WQCW is available.

Table 6.9: Percentage reduction in violation

Scenario	Percent violation reduction from scenario I
I	—
II	0%
III	46%
IV	45%
V	7%
VI	60%
VII	40%
VIII	60%

There are additional scenarios that are beyond the scope of this thesis that could help to meet target temperatures at Reno. The probability of exceeding the target temperature is an input that is constant within each DSS run. To decrease the number of violations, it may be useful to change the probability of exceedance every day based on climate information, available water, and the desired confidence level. For example, in June, it may be necessary to have a low probability of exceedance to help juvenile fish. If there is no fish spawning for that year, this confidence level may not be necessary. As a result, the probability of exceedance is a useful user input that may help to make decisions that result in fewer temperature violations.

Chapter 7

Conclusions and Recommendations

This section summarizes and concludes this thesis. We will make some recommendations for the future and try to explain some interesting features and observations of the system.

7.1 Summary

Like other rivers in the western U.S., the Truckee River suffers from warm summer river temperatures exacerbated by human uses. Water has been reallocated to be used specifically for water quality and temperature purposes. This thesis presents a framework to empirically predict river temperatures and then use the prediction to make decisions about when to release water. Included in this framework is the ability for the water manager to select the desired confidence level with which they wish to meet a temperature target. Results were presented that show that large volumes of water are necessary to meet a temperature target with a high degree of certainty and extreme violations may still occur if all of the WQCW is used. A lower degree of certainty uses less water but there is a higher probability that the temperature target will be exceeded. Seasonal strategies to conserve water throughout the summer were then presented that allow minor violations to occur. Even with seasonal strategies, extreme violations still occur when all of the water is used. No matter what policy or strategy is used, not all of the temperature violations can be avoided without additional water.

This result shows legislatures and water managers the need to allocate additional water for water quality purposes.

It is important to note that this thesis used a hypothetical baseline operating policy that does not reflect historical, current, or future operations. Therefore, the results of this thesis do not reflect the number of violations and the amount of water necessary to minimize those violations in actual operations.

7.2 Conclusions

The temperature prediction model fits the historic data well ($R^2 = 0.9$) and fits the verification data relatively well ($R^2 = 0.5$). A more accurate, less simple model could be developed, particularly for the high temperature range.

The structure of the prediction model lends itself to relatively easy computation of uncertainties of the prediction. These uncertainties provide useful information in deciding how much water to release. The results of the scenarios illustrate that the efficient use of water is highly dependent on the required confidence level to meet the targets. Adopting a decision process that considers quantified uncertainties contributes to the understanding of managing natural systems such as the Truckee River.

The implementation policy created in this thesis successfully reduces the number of violations. The DSS is a success because it uses a prediction of the river temperature based on scheduled flow and forecasted air temperatures, the confidence of that prediction, and reservoir release constraints to determine the necessary additional flow required. Seasonal climate forecast information further decreases the number of violations without using significantly more water and is, therefore, useful in this type of DSS.

The flexible structure of the DSS is a significant contribution of this research. Each component can be modified based on new information and techniques. For example, if a water manager wants to use a different temperature prediction, that component of the DSS can be changed without impacting the other components. Consequently, the DSS structure is flexible to new methods and portable to different basins and operating policies.

The framework developed in this thesis will perform better in daily operations because of additional observed data. To determine how much water to release on a given day, observed data from previous days is available. For example, the previous day's water temperature can be monitored and used in the degree-day calculation. In addition, climate forecasts can be updated monthly. Both of these improve the use of the limited supply of water by including observed information.

The DSS presented is not ready for actual operations. Because we used baseline operating policy, not all of the policies are modeled. Once the baseline operating rules duplicate the current operations and the WQSA water rights are purchased, water managers can incorporate the temperature prediction and WQCW release rules into daily operations. At this point, the number of modeled violations will not be hypothetical in nature. The DSS can be run with historical inputs to see if the implementation policy developed would have reduced the number of violations.

7.3 Recommendations for future work

Further data collection and river temperature monitoring is necessary to improve the temperature prediction. Temperature sensors should be placed in all USGS flow gaging stations to measure hourly temperature. More data helps any modeling study in terms of calibration, verification, and feedback for real time operations. Improved sites need to be created to give operators real time data. The travel time on the Truckee River between the Little Truckee River and Reno is 8-10 hours for low flows (Rowell 1975). Water must be released early in the morning to mitigate temperature problems during the hottest part of the day. Although the prediction site for this study is at Reno, telemetered gaging stations should be created on the Truckee River below the Little Truckee River and at Farad. This will help on hot summer days by giving operators the actual early morning river temperature. If the early morning river temperatures are above a threshold, additional flow can be released and it will have an effect that same day. Using real time data below the Little Truckee River and at Farad gives operators another tool to help mitigate warm Truckee River temperatures.

Improvements to the river temperature prediction will further help to use the WQCW more efficiently. By making the temperature prediction model more certain, less water will be necessary to meet the temperature targets with a desired probability of exceedance. The relationships in this study were strongly linear, therefore linear regression is adequate. In the future or in other studies, non-parametric techniques that can capture any dependence structure are attractive and should be explored. Future studies may need to use mechanistic models to predict river temperatures. Although this is computationally intensive in an operations model, it may become necessary if additional water quality parameters are to be modeled or more accuracy is warranted.

The WQSA specifies that purchased water is to be used to improve water quality downstream of Reno. Future studies should extend the temperature prediction to Pyramid Lake. Coupled with this, dissolved oxygen and nutrient loadings will need to be modeled as specified by the WQSA. This thesis is a small part of an overall goal to improve the water quality in the Truckee River. Future studies will need to be more general to encompass multiple parameter prediction for use in determining operations.

There is another layer of long-term planning that should be added to the WQCW release rules. Since WQCW can be stored during wet times and carried over to dry times, long term planning can ensure that water will be available in droughts. Long-term climate projections on inter-annual to inter-decadal scales, due to large scale climate phenomena (La Nina and El-Nino), can be obtained from global climate models. Such information can be incorporated into the WQCW rules to ensure water availability. Based on the climate prediction, a set amount of water should be reserved for future uses. For example, if a drought is predicted over the next four years, a percentage of the WQCW could be excluded from the available WQCW water and carried over to the next year. By looking at climate information, a method is created to determine how much water is needed to be carried over to future years.

In addition to long term climate predictions, generated weather information can be used to determine the likelihood of water temperature violations. Based on the seasonal climate forecasts, a synthetic weather generator can develop a suite of daily air temperatures for the entire season. Each suite can be used in the DSS to find the number of river temperature violations. The likelihood of violation on a given day can be determined based on the results of the runs from all of the suites.

We assume that water released from Boca is cold enough to lower Truckee River temperatures at Reno, NV. This assumption is only true if Boca is filled in the early spring with cold water and the water surface elevation is kept sufficiently high. Although it is hard to control when the reservoir is filled, it is possible to move water from Stampede to Boca to keep the water surface elevation high. In the summer of 1994, Boca was drawn down because of unusual circumstances. Warm water was released resulting in fish kills downstream of the reservoir. At the same time, Stampede had sufficient water. Operators could have been prevented fish kills had they moved water to Boca. This thesis recommends that Boca’s water surface elevation be kept high enough (by moving WQCW from Stampede) to ensure there is a bottom layer of cold water. The results of this thesis show that a higher Boca pool elevation is necessary; and therefore, the exchange is necessary. Any WQCW moved to Boca can be exchanged back to Stampede. On the other hand, fish spawning water could be exchanged from Stampede to Boca to provide the necessary pool elevation for cold releases. This would allow more releases of the WQCW to reduce river temperatures at Reno. Later, the fish spawning water stored in Boca could be released instead of a scheduled fish spawning water release from Stampede. This policy change is likely controversial but may be necessary to further improve temperature downstream.

WQCW released to meet daily maximum temperature targets is only needed during the middle of the day. If operation of the reservoirs were modified so release changes were made more than once a day, additional water could be saved. Currently, a dam-operator manually adjusts the gates in the morning based on scheduled releases for the day. If the dam gates are adjusted at 8am or earlier—possibly automatically—to release WQCW to meet temperature targets at Reno and then readjusted at 5pm to stop WQCW releases, 50% of the water would be saved. This would allow the WQCW to go further in the season.

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Appendix A

Operating Policy in the Basin

The Truckee Basin is highly regulated and litigated. Over the past 150 years there have been a number of laws, regulations, court cases, and decrees that affect basin operations. Typically, new agreements or laws incorporate the previous policy, so many of the original policies are still in force today. This section tells briefly how the river has been operated in the past, today, and in the future. Description of some of the laws is found in the appendix titled Description of select laws.

A.1 Historic and current policy

Except for Lake Tahoe, Donner Lake, and Independence Lake, reservoirs in the basin are operated according to U.S. Army Corp of Engineers flood control regulations to prevent flooding downstream.

Other than flood control, the main policy that affects the basin is Floriston rates as set in 1908 and reaffirmed in the 1944 Orr Ditch Decree. The Floriston rates are a set of flow rates that must be met at the Farad gage near the town of Floriston on the border of California and Nevada. These rates vary between 300 and 500 cfs based on the level of Lake Tahoe and the time of year. Flow rates are first met using unregulated inflows, then storage water from Boca, Prosser, and Tahoe. The water released for Floriston rates is used downstream for municipal, industrial, and agricultural uses.

Donner Lake and Independence Lake are privately owned. The Sierra Pacific

Power Company owns half of the storage water rights in Donner Lake and all of the storage rights in Independence Lake. The Truckee Carson Irrigation District owns the other half of the storage rights in Donner Lake. These private entities can schedule releases and use water they have in storage. Uses include municipal, agricultural and industrial in the Truckee-Meadows area and on the Truckee Canal. Although these lakes are private, their storage rights do not have higher priority than the Floriston rates; they can only store water when the Floriston rates are met.

Stampede Reservoir, one of the largest (12% of the total available basin storage) federally controlled reservoirs in the basin, was originally constructed to provide supplemental water for agricultural and municipal purposes. In 1982, the Stampede Reservoir Judgement said that all of the water and storage in Stampede are for spawning endangered cui-ui and threatened Lahontan cutthroat trout. Releases are based on schedules set by the U.S. Fish and Wildlife Service (USFWS) and Pyramid Lake Tribe. In general, a decision is made each year whether to have a cui-ui spawning run based on storage values, forecasted precipitation, and time since the last run. If the USFWS and the Pyramid Lake Tribe decide to have a spawning run, the releases from Stampede try to meet the following flow targets at Pyramid Lake: January 90cfs, February 120cfs, March 190cfs, April 570cfs, May 1000cfs, June 50cfs (Berris 2001). Because of its more recent construction and therefore junior water rights, Stampede rarely fills completely.

The Truckee Canal diverts Truckee River water into the Carson River basin for use in the Newlands Project. Diversion criteria are defined in the Truckee River Agreement, the Orr Ditch Decree, and the Newlands Project Operating Criteria and Procedures (OCAP). The Orr Ditch Decree gives a right that up to 1500 cfs can be diverted to the canal. The actual diversion amount is governed by the adjusted OCAP which reduces the divertable amount based on land that is actually irrigated.

Policies have been implemented to keep portions of the upper basin healthy.

The Tahoe-Prosser Exchange Agreement set up procedures to maintain instream flows below Tahoe Dam by allowing exchanges between Tahoe and Prosser reservoirs. A simplified example of an exchange follows. Although Tahoe does not have to release water, Tahoe releases to keep a live stream downstream of Tahoe dam. At the same time, Prosser stores inflows which would otherwise would have been released. In this way, Prosser is storing some of Tahoe's water, which is known as an exchange. Exchanges like this exist in other parts of the basin particularly between Boca and Donner reservoirs. Exchanges allow for more flexibility in scheduling releases.

A.2 Future policy affecting the Basin

Past policies and precedents determine how the river operates in the future. A future operations change is the implementation of the Water Quality Settlement Agreement. The WQSA provides water to meet water quality standards or improve water quality in the river downstream of Reno/Sparks. The methods to store WQCW are described in Section 5.1, "Rules to store WQCW."

The new Truckee River Operating Agreement, if agreed on, will regulate the river in the future while still incorporating many of the past laws and policy. In particular, Floriston rates will still be the main operations goal but those entitled to use Floriston rate water could store some of their water for specific purposes later. The stored water would be classified into categories and could only be released to benefit the purpose for which they were stored. (Truckee River Operating Agreement DEIS/DEIR 1998). Another change in TROA is the condition in which stored water can be exchanged with scheduled releases in other reservoirs. This type of exchange and the necessary accounting make operations more flexible for multiple purposes.

With the addition of TROA, Floriston rates can be reduced so that more water can be stored as WQCW even when cui-ui are not spawning. Before TROA, it would be hard to do this because Floriston rates would have to be reduced and that would be a legally impossible.

Appendix B

Description of select laws

The following is select description of some of the laws in the Truckee Rive basin. See the Truckee River Chronology (Horton 1995) and the Truckee River Atlas (1995) for a full description of history and laws in the basin.

B.1 Floriston Rates

In 1908, an agreement was enacted between the Floriston Paper Company and the Truckee River General Electric Company called the Floriston rates. It established mean instream flows of 500cfs between March 1 and September 30 and 400cfs for the rest of the year measured at Floriston, CA. The Truckee River General Electric Decree of 1915 and the Truckee River Agreement of 1935 amended the Floriston rates to allow for reduced rates based on the level of Lake Tahoe. Between November 1 and March 31, Floriston rates were 350cfs if Lake Tahoe was below 6225.0 ft. AMSL and 300 cfs if Lake Tahoe fell below 6225.25 ft. The rates were to be met through unregulated flow and from Tahoe releases (and Boca once it was built). This is significant because even today the reservoirs must be operated such that the Floriston rates are met. (Horton 1995)

B.2 Truckee River Agreement

The Truckee River Agreement (TRA) of 1935 enacted a contract with the federal government, Sierra Pacific Power Company, TCID, and Washoe County Water Conservation District. This agreement reaffirmed the Floriston rates and set rules as to how Lake Tahoe water could be removed and used. The agreement set the natural rim of Lake Tahoe at 6223.0 ft. AMSL allowing 6.1 feet of storage depth in the lake.

Finally, this agreement, in conjunction with the Truckee Storage Project, paved the way for the construction of Boca Reservoir on the Little Truckee River. (Horton 1995)

B.3 Orr Ditch Decree

The Orr Ditch Decree of 1944 incorporated the provisions of the TRA and delineated Truckee River water rights. In general, the decree said that the Pyramid Lake Paiute Indian Tribe had the most senior water rights to irrigate land. The next most senior right gave up to 1500 cfs to the Truckee Canal. The Sierra Pacific Power Company was given the next water rights for municipal, domestic, and industrial purposes.

B.4 Tahoe -Prosser Exchange Agreement

The Tahoe-Prosser Exchange Agreement maintains flows directly downstream of Lake Tahoe during periods when releases from Lake Tahoe are unnecessary to meet Floriston rates. This 1959 agreement allowed an equal amount of water released from Tahoe to be stored in Prosser thereby exchanging water between the two reservoirs.

B.5 Newlands Project Operating Criteria and Procedures (OCAP)

The Operating Criteria and Procedures regulate the diversions from the Truckee River to the Newlands Project via the Truckee Canal. In 1997, the Secretary of the Interior adjusted the 1988 OCAP to make the Newlands Project less dependent on Truckee River water and to increase the efficiency of water used on the project. Even in 1967 when the original OCAP was issued, the need to conserve water and avoid using Truckee River water was established.

B.6 Stampede Reservoir Judgement

In 1982, the federal Ninth Circuit Court ruled in Carson-Truckee Water Conservation District v. Watt that all water in Stampede Reservoir be used for threatened and endangered fish in Pyramid Lake until such time as those species are not on the

Endangered Species List. This set up the Stampede project water dedicated to the Pyramid Lake fisheries. Schedules to release this water are developed by USFWS and the Pyramid Lake Tribe to encourage cui-ui spawning.

B.7 Preliminary Settlement Act

The Preliminary Settlement Act of 1989, negotiated between Pyramid Lake Paiute Tribe and Sierra Pacific Power Company (SPPCo), provided 39,500 acre-feet of storage rights for SPPCo when not needed for M&I uses. At the same time, excess water in storage would be used for fishery purposes and SPPCo gave up its right to single use hydropower flows. This allowed for storage of fish water to be used for spawning at certain times of the year.

B.8 Negotiated Settlement Act: P.L. 101-618

The Negotiated Settlement Act (P.L. 101-618) provided legislation to settle many of the outstanding court cases and disputes over water rights in the Truckee River basin. It did this by providing for protection of wetlands, recovery of endangered and threatened fish, improved management of the Newlands project, settlement of Fallon Paiute-Shoshone and Pyramid Lake Paiute Tribe water issues, and apportionment of interstate water. The act incorporated the conditions set in the Preliminary Settlement Agreement but stated that the act was not effective until a new operating agreement is negotiated and ratified.

B.9 Water Quality Settlement Agreement

In 1996, the US Department of Justice, Environmental Protection Agency, Department of the Interior, Nevada Department of Environment Protection joined Washoe County, Reno, Sparks and the Pyramid Lake Paiute Tribe in signing the Truckee River Water Quality Settlement Agreement. This agreement set up a program to improve Truckee River water quality downstream of Reno by augmenting river flows during low flow periods. The Federal government and Washoe County have each agreed to purchase $12 million worth of water rights explicitly for water quality purposes. This water is to be stored in the federally controlled reservoirs and released by decision of a committee.

B.10 Truckee River Operating Agreement

The Truckee River Operating Agreement is a negotiated settlement involving all of major entities in the Truckee basin. As of June 2001, the agreement has not been approved and is still under negotiations. In general, the agreement will coordinate reservoir releases and storage, improve exchange of stored water, improve efficiency of water and storage space, improve the accounting procedures to track water, and set up the Interstate Allocation. (Scott 2001)

B.11 Water Rights Acquisition Program (WRAP)

Public Law 101-618 provides for a program to acquire water rights to preserve and enhance wetlands in Lahontan Valley. As a result, the Water Rights Acquisition Program (WRAP) will acquire approximately 75,000 acre-feet of water to help preserve 25,000 acres of wetland in the Stillwater National Wildlife Refuge and Stillwater Wildlife Management Area. Most of this water will come from the Carson Division of the Newlands Project but some of the water could be diverted from the Truckee River via the Truckee Canal.

Appendix C

Glossary

Following is a glossary of acronyms and terms used in this thesis. Appendix B, “Description of select laws” lists an explanation of the major laws that control how the river is operated. These laws are not repeated in this glossary.

Cui-ui

The cui-ui is an endangered lake sucker fish that lives in Pyramid Lake and swims up the Truckee River to spawn.

DSS

Decision Support System (DSS) is a term used to describe tools used by resource managers to evaluate alternatives.

DSSAMt

Dynamic Stream Simulation and Assessment Model with temperature models water quality parameters in the Truckee River.

Lahontan cutthroat trout

The Lahontan cutthroat trout is a threatened fish that live in the Truckee River and Pyramid Lake.

M&I

Municipal and Industrial (M&I) water is a classification of Truckee River water that is treated and used for domestic or industrial uses.

Probability of exceedance

The probability of exceedance of is the likelihood that the observed value will be above a given value.

Pool elevation

Pool Elevation is a term used in RiverWare to represent the water surface elevation of a reservoir.

RiverWare

RiverWare is a general purpose river and reservoir modeling tool created by the Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado, Boulder.

TMWRF

The Truckee Meadows Water Reclamation Facility is the main wastewater treatment plant for Reno and Sparks, NV. It is located on the eastern edge of the two cities and effluent from it is returned to the Truckee River via Steamboat ditch.

TTSA

The Tahoe-Truckee Sanitation Agency treats wastewater from communities surrounding Lake Tahoe and from Truckee, CA. It returns effluent to the Truckee River near Martis Creek.

USBR

U.S. Bureau of Reclamation.

USFWS

U.S. Fish and Wildlife Service.

USGS

U.S. Geological Survey.

WARMF

The Watershed Analysis Risk Management Framework (WARMF) is a watershed modeling framework used by the cities of Reno and Sparks, NV.

WQCW

Water quality credit water (WQCW) is created from water rights purchased as part of the WQSA and stored in federally controlled reservoirs.