A decision support system to manage summer stream temperatures

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Abstract

Warm summer stream temperatures are a critical water quality problem in many western U.S. river basins because of the impact on threatened fish species’ habitat. To alleviate this problem, local and federal organizations are purchasing water rights to be used to increase flows. We present a Decision Support System (DSS) to be used in an operations mode to effectively use this water acquired to mitigate warm stream temperatures. The DSS uses a stream temperature prediction model and a rule-based module to compute reservoir releases. Water releases are calculated to meet a fish habitat temperature target based on the predicted stream temperature and a user specified confidence of the temperature predictions. Strategies that enable effective use of a limited amount of water throughout the season have also been incorporated in the DSS. To display its usefulness, the DSS is applied to the Truckee River in California and Nevada using hypothetical operating policy and 1988 through 1994 inflows. Results indicate that the DSS could substantially reduce the number of temperature violations, i.e., stream temperatures exceeding the target temperature levels.

Key terms


Introduction

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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 summer water quality problems associated with low flows are high stream temperatures—low flows warm up more rapidly than higher flows. High stream temperatures reduce cold water fish populations by inhibiting growth and by fish kills at extremely high temperatures. As fish populations decrease, the federal government is compelled 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). In these studies, the water management agencies need to modify operations to increase habitat and/or improve water quality for fish.

In certain western basins, water rights are being reallocated to ensure adequate supplies are available for fish flows. To implement reallocation and operations changes, water management must incorporate water quality objectives into daily operations and long-term planning. Technically, this is challenging because it requires management of both water quantity and water quality. Managing water quality is much more uncertain than managing quantity because water quality is affected by many factors that change seasonally, daily, and even hourly. Stream temperature varies on an annual cycle, a diurnal cycle, and on an hourly scale based on factors such as cloud cover, air temperature, and wind. There is usually not enough water to meet all water quality objectives with a high degree of certainty. Therefore, decisions must trade off the uncertainties of releasing for water quality objectives and the limited resources available.

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

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 stream temperature objectives into daily operating objectives. A practical DSS for daily use has the following functional requirements:

1. Determination of releases using normal basin operating policy.
2. A stream temperature prediction model that is quick, accurate, easy to use, and spatially and temporally consistent in terms of the DSS.
3. Quantification of confidence associated with the temperature prediction.
4. Operating rules that determine releases that benefit river biota that use the stream temperature prediction and consider the confidence of the prediction.
5. Seasonal strategies incorporated in the operating rules to trade off meeting one day’s targets with the ability to meet seasonal needs.

Neumann et al. (2003) developed an example of a stream temperature prediction model
that accomplishes the second and third items in the above list of requirements. This technical note presents methodology to accomplish the fourth and fifth items in the list. We develop operating rules that recommend releases that are above normal operating releases to lower summer stream temperatures.

To determine the amount of water to release, we predict the stream temperature using normal operating releases and then calculate the additional flow required to meet a temperature target with a desired confidence. We then develop strategies to more effectively use the water based on the stream temperatures over the previous few days.

The paper is organized as follows. First, we present the assumptions used in the model. Next, we develop rules to release additional water to meet stream temperature targets with varying degrees of confidence. We then modify these rules with seasonal use strategies. These rules are applied to the Truckee River in California and Nevada.

Assumptions

To develop operating rules to improve warm summer stream temperatures, we first make some assumptions regarding the layout, hydrology, and operations of the basin. These operating rules were developed for a multipurpose basin that starts high in alpine mountains. Reservoirs store snow and precipitation runoff and release water into a river that flows through a desert region as shown in Figure 1. Below the mountains, the water slows and stream temperatures increase. In general, during the hot summer months of June, July, and August, the reservoirs are operated to meet an instream flow target of approximately 400cfs at location T1. Because of low water supplies, the target cannot always be met.

During these low flow periods, the stream temperature is often above maximum water temperature limits for cold water trout at location T2 which is located within 6-10 hours water
travel time from reservoir A. The preferred maximum target stream temperature is 22°C or less. Below this cutoff, adult trout can live for an extended period of time. At 22°C to 23°C, the chronic range, trout can survive but not for extended periods of time, four or fewer degree-days. The acute temperature range for trout is 23°C to 24°C at which, trout can survive for one day or less. At temperatures greater than 24°C, the absolute maximum, trout begin to die. These targets are hypothetical in nature and should be adjusted for the species in a given river.

Because of the warm stream temperatures and other water quality issues, government bodies have recently purchased rights to water that can be stored in the upstream reservoirs and released to mitigate these temperatures. We will call this Water Quality Credit Water (WQCW).

Temperature Prediction Model

To improve stream temperatures during the summer, it is first necessary to be able to predict the stream temperature at the target location given normal operations. In addition, it is necessary to quantify the uncertainty of this prediction.

There are many different types of models that can be used to accomplish this goal. For example, Neumann et al. (2003) developed a regression model that found that maximum daily stream temperatures at a downstream target location can be predicted as a linear function of stream flow and air temperature for the warm summer period. This type of model is consistent with the above DSS requirements in that it is quick, accurate, and the timestep of the data is consistent with a daily operations DSS. In addition, from linear regression theory, a quantification of the uncertainty is developed. From this uncertainty calculation, a procedure is presented to determine the additional flow required to meet a temperature target with a given probability of exceeding the target. Assuming that increased flow has an impact on stream temperature, this type of procedure could, in theory, be developed for other types of stream
temperature prediction models.

Decision Support System

A model-based DSS is developed that meets the requirements set forth in the introduction. The DSS includes the daily timestep simulation model and the temperature prediction model, as well as operating rules to determine reservoir releases each day. The DSS works as follows. On each day of the simulation, first, the normal operating policy sets reservoir releases and diversions. The model then routes these flows downstream to predict the flows that would occur under normal operations. At this point, the DSS predicts the maximum daily stream temperature at T2. A rule checks if this predicted stream temperature is above the preferred target level of 22°C and sets additional releases to alleviate the problem. In this study, we develop and evaluate two different rules that set additional releases of WQCW to improve the stream temperature. The first rule releases water to meet a fixed temperature target, the second rule releases water to meet a varying temperature target based on the previous days’ stream temperatures. The second rule strives to make better use of limited water supplies by releasing WQCW only when necessary.

Rule to release additional flow to meet a fixed target temperature

The first WQCW release rule is designed so that when the predicted stream temperature is above the target, additional releases will be calculated to meet a fixed target temperature of 22°C with the desired probability of exceedance. This means that on any given day, if the predicted stream temperature is above 22°C, releases will be made to return the stream temperature to 22°C, no matter how large the release. These rules do not look at the previous days’ stream temperatures or the volume of WQCW available.
Rule to release additional flow to meet a varying target temperature using the degree-days approach

The second WQCW rule is designed to make use of additional stream temperature information to decrease the number of stream temperature violations. We modified the above rule to look at the previous stream temperature and, using the concept of degree-days, determine the target temperature. The degree-days concept is used in prediction techniques in biology, agriculture, and energy fields. Wood et al. (1996) used the number of degree-days above freezing as a predictor to the timing of algal blooms. Also, the number of cumulative degree-days have been shown to help predict the growth of certain fish (Cyterski and Spangler 1996 and Lukas and Orth 1995).

In our model, the “degree-day” at each daily timestep is calculated as the number of degrees above the preferred target for the current day plus the previous day’s degree-days. Because of lack of historical record, the stream temperature used in the degree-day calculation is predicted by the regression, using flows that include WQCW corrected releases. If the stream temperature dips below the preferred target temperature, the degree-day counter resets to zero. The calculation of degree-days is a useful way to keep track of variations in temperature over time. Using this concept, we modify the above rules by changing the desired temperature target for the DSS. Instead of always releasing enough water to reach the preferred target of 22°C, we may be able to use a higher target such that we do not cause a violation. The policy to determine the target temperature to use on any given timestep of the simulation is shown in Table where DD is the previous timestep’s degree-days and T is the predicted temperature at the current day. This set of logic allows the stream temperature to exceed the preferred target as long as the number of degree days is not very large. If the number of degree-days is large, the logic will set the target to the preferred level to try to reset the degree-days. Even though this logic determines
the target temperature, releases may not be able to meet it.

**Test Scenarios**

The DSS was applied to the Truckee River to improve stream temperatures at Reno, Nevada using WQCW stored in Stampede and Boca Reservoir. The basin closely meets all of the assumptions described above. We used the linear regression based stream temperature model that we developed in Neumann et. al. (2003). The regression provides stream temperature forecasts with uncertainty, assuming a Gaussian distribution. For operation purpose we could chose the mean forecast from the regression (which would correspond to an exceedence probability of 0.5); or a value at any other exceedence probability. The smaller the exceedence probability, the forecast value is picked from the right hand tail - i.e. a higher temperature. Because this model also has a quantification of the prediction confidence, we included logic to allow the releases to try to meet the target with varying degrees of confidence.

We ran the model with historic inflow data to examine the effects different inputs have on the stream temperature and the amount of water used. We applied the DSS to the period from 1988 to 1994 because these years were relatively dry; target flows were not always met. To summarize the hydrology, there was a five year dry spell from 1988 to 1992 followed by one average year in 1993 and then a dry year in 1994. 1992 was the driest year in that period and 1993 was the wettest year.

The DSS was run with the scenarios defined in Table 1. In each case, a desired probability of exceedance was input to the DSS that was constant throughout the run. To evaluate the effect of this variable, we ran scenario II and scenario III with different probability of exceedances between 0.05 and 0.5. The comparative runs use the probability of exceedance for each scenario that gives the fewest number of violations.
The results presented are not compared to observed river temperatures because the policies modeled in the DSS are not the same as historic operations. The policies in the DSS reflect simplified reservoir operations. As a result, it would not be meaningful to compare the model results to historical operations. However, these test scenarios will indicate the potential benefits from a DSS coupled with a stream temperature forecast model, in terms of minimizing water quality violations with minimum water use.

**Results and Discussion**

A plot of the number of total violations from 1988 to 1994 for each scenario over a range of probability of exceedances is shown in Figure 2. Again, a violation is any day that the temperature and number of degree-days are as defined above. With no WQCW releases, there are 216 days in violation; the probability of exceedance has no effect. For the other two scenarios, as the probability of exceedance increases, the number of violations decrease until a low point is reached; then the number of violations increases. At low probability of exceedances, large volumes of water are released to ensure that there are cool stream temperatures, but the WQCW is quickly used and violations occur. At a probability of exceedance near 0.5, a smaller amount of water is released but the stream temperatures are often slightly above the target because the reservoir can only release so much water due to outlet constraints. This also results in a larger number of violations.

Figure 2 shows that the fewest number of violations, 83 days, for scenario II occurs at a probability of exceedance of 0.45. One would think that using a probability of exceedance of 0.45 and scenario III would result in fewer violations, but because of reservoir outlet capacity constraints, this is not the case. The number of violations can only be reduced in scenario III by decreasing the probability of exceedance to 0.2 which leads to 73 days in violation. This is
strong evidence to use the degree-day approach. Fewer violations are achieved with much lower probability of exceeding the target temperature. It is better to use a lower probability of exceedance if it does not result in significantly more violations because there is higher confidence that the actual stream temperature will be less than or equal to the target.

Figure 3 shows a plot of the stream temperature for June, July, and August of 1993 and 1994 under scenarios I through III using the best probability of exceedance for each scenario as shown in the legend. Because the hydrology in 1993 is relatively wet, there are few occurrences where WQCW is released. The 1994 plot shows that meeting a constant target temperature of 22°C, Scenario II, results in the reservoir running out of WQCW in the middle of August. The degree-day approach, shown in scenario III, allows the target temperature to vary, saving enough water for a few more days in August. The day after the temperature goes below the preferred target, the temperature is in the 23°C to 24°C range because the target was set to 24°C. Then, a larger volume is released to aim for a target of 23°C. The temperature is fairly constant in this range between 22°C and 23°C until the number of degree-days is above the threshold. At this point, a larger volume of water is released to reset the degree-day counter to zero and the process repeats. The results from 1994 are shown to exhibit the sawtooth pattern in scenario III and that all of the water is used regardless of the scenario.

Table 3 shows the amount of WQCW used for each of the scenarios. In scenario I, WQCW is released only for flood control releases and other spills. Because of the WQCW’s low priority, it is the first classification of water to spill from the reservoirs. In the other three scenarios, the volume of WQCW is fairly similar. This means that in scenario III, more violations can be avoided without using significantly more water.

To summarize, the results demonstrate that the operating rules created in this DSS reduce
the number of violations by using a prediction of the stream temperature based on scheduled flow and forecasted air temperatures to determine the necessary additional flow required to meet a temperature target with the desired confidence. Using the degree-day approach further decreases the number of violations without using significantly more water.

The flexible structure is an important feature of the DSS. Each component can be modified based on new information and techniques. For example, if a water manager wants to use a different temperature prediction model, that component of the DSS can be changed without impacting the other components. Consequently, the DSS can be applied to different basins and operating policies.

The framework developed in this paper may perform better in daily operations because of additional observed data. To determine the releases on a given day, observed data from previous days is available. The previous day’s water temperature can be monitored and used in the degree-day calculation, possibly improving the use of the limited supply of water.

Summary

This paper presents a DSS to help make decisions about when to release additional water to avoid stream temperature violations. Included in this framework is the ability for 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 violations may still occur if all of the water is used. A lower degree of certainty uses less water but there is a higher probability that the temperature target will be exceeded. By using a degree-day approach that looks at the previous days’ stream temperatures and allows temperatures above the preferred target, water is saved throughout the summer without increasing the number of violations. In fact, the fewest
number of violations can be achieved by using a fairly high level of confidence and the degree-days approach. Even with seasonal use 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.

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

Acknowledgments

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Literature Cited


Table 1. Temperature target determination, degree-day approach

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<tr>
<th>Condition</th>
<th>June</th>
<th>July</th>
<th>August</th>
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<tbody>
<tr>
<td>DD &gt; 4</td>
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<td></td>
<td>22°C</td>
</tr>
<tr>
<td>25°C ≤ $\hat{T}$ and DD ≤ 4</td>
<td></td>
<td></td>
<td>23°C</td>
</tr>
<tr>
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<td>and 1 DD &lt; 4</td>
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<td>and DD &lt; 1</td>
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<tr>
<td>22°C ≤ $\hat{T}$ ≤ 24°C</td>
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<td>and DD ≤ 4</td>
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Table 2. Scenarios for DSS model results

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Description of Scenario</th>
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<tr>
<td>I. Normal operations</td>
<td>Operations with:</td>
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<tr>
<td></td>
<td>• WQCW storage and necessary spills</td>
</tr>
<tr>
<td>II. Constant target temperature</td>
<td>Operations with:</td>
</tr>
<tr>
<td></td>
<td>• WQCW storage and necessary spills</td>
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<tr>
<td></td>
<td>• WQCW releases to meet temperature target of 22ºC</td>
</tr>
<tr>
<td></td>
<td>• Constant probability of exceedance throughout run</td>
</tr>
<tr>
<td></td>
<td>• No degree-days information</td>
</tr>
<tr>
<td>III. Degree-day Analysis</td>
<td>Operations with:</td>
</tr>
<tr>
<td></td>
<td>• WQCW storage and necessary spills</td>
</tr>
<tr>
<td></td>
<td>• WQCW releases to meet temperature target in Table 1</td>
</tr>
<tr>
<td></td>
<td>• Constant probability of exceedance throughout run</td>
</tr>
<tr>
<td></td>
<td>• Includes degree-day approach</td>
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Table 3. Volume of WQCW used 1988-1994

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WQCW used (10^7 m^3)</th>
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<tbody>
<tr>
<td>I.</td>
<td>2.84</td>
</tr>
<tr>
<td>II. P = 0.45</td>
<td>7.75</td>
</tr>
<tr>
<td>III. P = 0.2</td>
<td>7.72</td>
</tr>
</tbody>
</table>
Figure 1. Diagram of study area

High wet mountains

Hot arid desert

Reservoirs A, B, C
Figure 2. Number of days in violation versus probability of exceedance, June, July, and August, 1988 to 1994
Figure 3. Stream temperature at Reno for scenarios defined in Table 2; P is the probability of exceedance.