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Modeling Thermal Effects of Operational and Structural Modifications at a Hydropower Facility on a Premier Trout Stream in Southwestern Montana[1]

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ABSTRACT

We used a one-dimensional hydrodynamic model coupled with a river temperature model to evaluate the relative heating and cooling of the Madison River to evaluate various alternatives proposed to mitigate warm temperatures downstream of the hydropower facility at Madison Dam. The model requires inputs of local meteorological data, stream geometry, flow, and river temperature throughout the 109-mile reach modeled. The simulated alternatives included proposals to remove the dam, increase the height of the dam, and bypass the river around the lake. The model was calibrated to water travel times determined during dye studies and to historical temperature records. A sensitivity analysis of the model indicated that water temperatures in the lower reaches of the river are more sensitive to release temperatures upstream at the powerhouse than to changes in ambient air temperature or flow. Model results indicated that none of the proposed alternatives was likely to produce a significant decrease in water temperature 20 miles below the dam. Due to the river geometry, removal of the dam and restoration of the river to its natural state would actually cause downstream temperatures to be higher than they are with the dam in place. Other alternatives might produce some thermal benefit, but associated economic and ecological costs may not justify the slight thermal improvements.

INTRODUCTION

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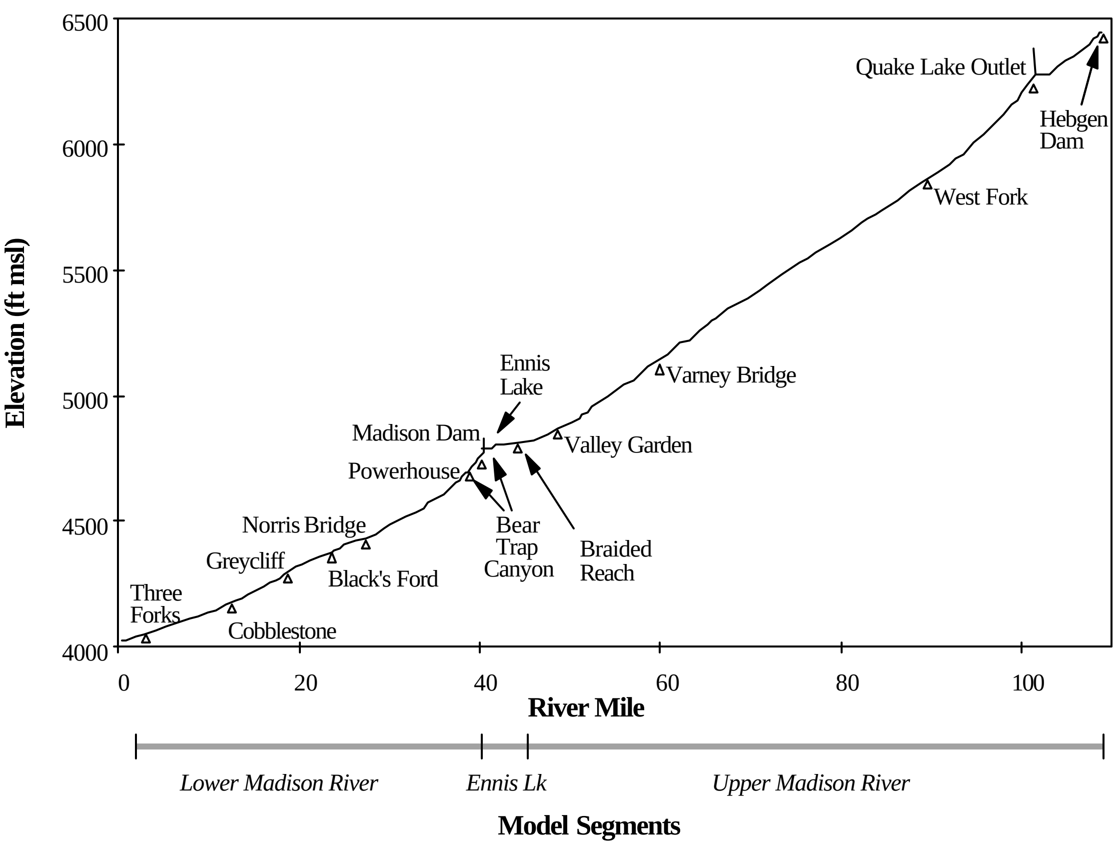
Hydropower operations have the potential to alter not only the flow pattern of a river system, but also the thermal regime, both of which are critical to healthy fish communities and other aquatic organisms. Relicensing of existing hydropower projects presents the opportunity to modify operations to minimize impacts of altered flow and temperature. Madison Dam is located in the middle of a 100-mile reach of a premier trout-fishing stream (Fig. 1). Several modifications to either project operation or design have been proposed for Madison Dam on the Madison River in southwestern Montana to reduce downstream temperatures. High water temperature in mid summer is a suspected cause of occasional fishkills that have been reported about once every 10-15 years in an area about 20 miles below Madison Dam. Suggested relicensing alternatives include removing the dam, raising the dam height, and bypassing the river around the lake. In this study, we used a combined hydrodynamic and water temperature



model to evaluate the effectiveness of the proposed alternatives for reducing temperatures in the lower Madison River downstream of Madison Dam.

Fig. 1. Madison River elevation from Hebgen Dam to Three Forks (river mile 109-0).

METHODS

A one-dimensional hydrodynamic and one-dimensional river temperature modeling approach was adopted to evaluate the relative heating and cooling of reaches along the Madison River above and below Madison Dam and within Ennis Lake. The model coverage began below Hebgen Dam and extended 109 miles downstream to the Three Forks confluence (the beginning of the Missouri River).

The hydrodynamic and temperature models used are particularly suited for screening analysis of structural and operational alternatives proposed for mitigation of high temperatures downstream of Madison Dam. Although a one-dimensional approach does not explicitly account for effects of thermal stratification in a lake environment, the models were deemed appropriate for use with Ennis Lake. Water temperature measurements taken in 1994 indicate that, under current conditions, Ennis Lake is weakly stratified, and, therefore, the assumption of well-mixed conditions is reasonable. However, for alternatives that utilize or induce significant vertical stratification in Ennis Lake (e.g., repositioning the outlet, significantly raising the dam, etc.) a one-dimensional model approach will be of limited value. A two-dimensional, vertical model or other hydrodynamic assessment that accounts for the effects of thermal stratification would have to be employed for in-depth analysis of these particular alternatives. Never-the-less a one-dimensional assessment provides sufficient information for a screening analysis, as well as determining the need for more detailed, two-dimensional assessment.

The **hydrodynamic model** (ADYN; Hauser 1991, FERC 1997) requires information on the river geometry and overall structure of the river system, flow characteristics of the mainstem and tributaries, and discharge information at the two dams. The **water temperature model** (RQUAL; Hauser 1991, FERC 1997) used in conjunction with ADYN, can compute water temperature, oxygen demand, and dissolved oxygen concentrations in rivers and reservoirs where the one-dimensional longitudinal flow assumption is appropriate. We used the combined models to study the effects of location, magnitude, and timing of interventions seeking to improve water temperature. The RQUAL model requires input information such as hydrodynamic updates of flow and velocity (supplied by the ADYN model), a variety of meteorological parameters, mass loadings for heat (i.e., water temperature) at the upstream boundary and lateral inflow sites, and miscellaneous site-specific data (e.g., latitude and longitude of the river, azimuth of the river at each node, bank width, riparian tree height, and various parameters related to streambed heat conduction and storage and solar radiation absorption). We calibrated the model on an hourly time step in order to capture the daily variation in river temperature. Once the model was calibrated, the coefficients and constants remained fixed for subsequent simulation runs.

Model Set Up - For modeling purposes, the Madison River was divided into three segments – Upper Madison River, Ennis Lake, and Lower Madison River (Fig. 1). Division of the river into these segments afforded flexibility for the sensitivity and alternatives analyses and allowed for the appropriate use of coefficients and constants for riverine versus lake conditions. An overview of pertinent input data used for the ADYN and RQUAL models during the calibration process is provided in Table 1. More detailed information on model parameters is presented in the environmental impact statement for the Missouri-Madison hydroelectric project (FERC No. 2188; FERC 1997).

Calibration - The bulk of the calibration data, including flow, meteorology, and water temperature data, was obtained from a pulse flow study conducted by Montana Power Company (MPC 1994) from July 12 to August 3, 1994. The hydrodynamic model was also calibrated to water travel times determined during a dye study in 1989. The temperature model was calibrated to match hourly temperature observations collected throughout the river for 1989-1994. A key aspect of the calibration was determination of the most appropriate air temperature data set.

Table 1. Input Data Source for Calibration of the Madison River Temperature Model

Data Type	Upper Madison River	Ennis Lake	Lower Madison River
Meteorology	Combination of Quake Lake, Valley Garden, and Bozeman airport data	Bozeman airport	Local (Sloan station)
Flow	Measured below Hebgen Dam	Computed from Upper Madison River model	Measured at Madison Dam and powerhouse
Water temperature	Measured	Measured	Measured
Lateral inflows	Estimated based on gage data or area-flow relationships	Estimated based on gage data or area-flow relationships	Estimated based on gage data or area-flow relationships

The calibration resulted in model predictions that closely tracked the natural diurnal variation in temperature. Water temperature predictions of the model (June 1 to September 15, 1991 and 1994) were compared to measured temperatures throughout the river. Representative comparisons of predicted versus observed temperatures at two sites for a 3-week period (12 July - 3 August 1994) are illustrated in Figure 2. At the Madison powerhouse (RM 39) just below Ennis Lake, computed temperatures precisely track the hourly measured data, and, in general, there is less than 0.5EC difference between measured and computed maximum/minimum temperatures. Further downstream at Greycliff (RM 19), near the end of the Lower Madison River segment, computed temperatures continue to track the measured data, while maximum/minimum temperatures agree within 1EC. Temperature predictions for the Upper Madison River segment compared to observed temperatures with similar accuracy. Figure 3 presents the temperature envelope for the 3-week period of analysis for the lower Madison River. Envelope values reflect the highest and lowest hourly temperatures computed at each location over the analysis period. The observed minimum, mean, and maximum temperatures correspond nicely with those predicted by the model.

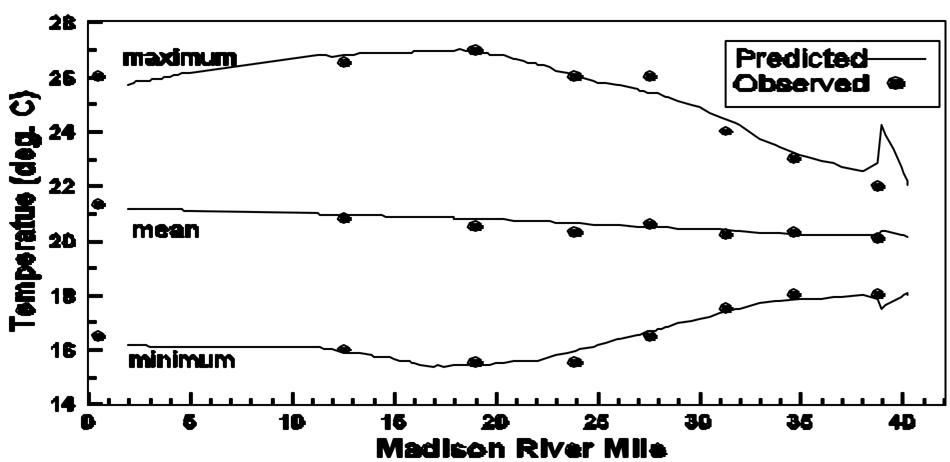


Figure 2. Model predictions versus observed temperatures at two sites on the Madison River, 12 July to 3 August 1994.

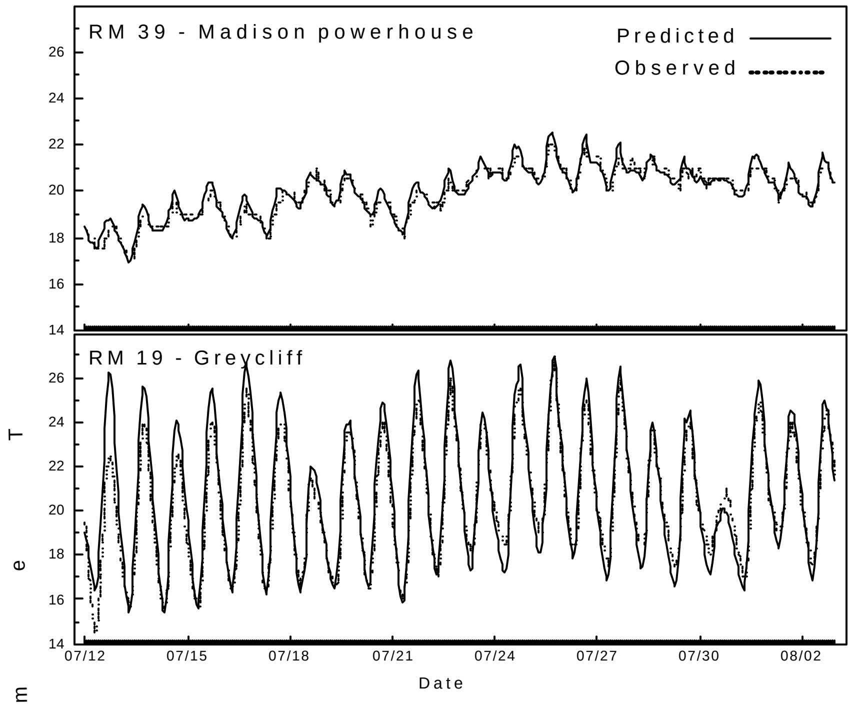


Figure 3. Lower Madison River water temperature envelope, 12 July to 3 August 1994: model predictions versus observed temperatures from RM 40 to RM 0.

Sensitivity Analysis - Using single variable analysis, a series of simulation runs were conducted to assess the sensitivity of the model to changes in flow (selected constant flows from 500-2500 cfs), release water temperature (±2EC), and air temperature (±2EC). For this analysis, we compared temperatures at two locations in the upper Madison River – RM 80 (29 miles below Hebgen Dam) and RM 48 (near the end of the upper Madison reach just above Ennis Lake); and several locations in the lower Madison (only RM 19 data are presented here). We calculated the deviation from base conditions for the mean water temperatures for each case considered for the three locations for 12 July - 3 August 1994. Base conditions included actual daily flows and water temperatures at Hebgen and Madison dams and air temperatures from meteorological data.

Upper Madison Reach - At both RM 80 and RM 48, the largest changes in water temperature resulted from the ±2EC change in air temperature, resulting in a ±0.6EC change in water temperature at RM 80 and a ±0.7EC change at RM 48. Changes in release temperature from Hebgen Dam appears to impact water temperature at a moderate level at RM 80 (deviations of about 0.4EC), but to a lesser degree at RM 48 (about 0.2EC). Changes in flow had a marked effect on mean water temperature at RM 80, but only a minimal effect downstream at RM 48. These results suggest that based on single variable analysis, the local meteorology has the greatest impact on water temperatures at the lower end of the Upper Madison (i.e., at the upper end of Ennis Lake), while further up the river (i.e., RM 80) the effect of flow and release temperature are also important. At least a 2EC reduction in inflow temperatures would be required to reduce downstream river temperature even 0.2EC, suggesting that operational modifications at Hebgen Dam are not likely to measurably alter river temperature at the entrance to Ennis Lake.

<u>Lower Madison Reach</u> - The largest changes in water temperature in the lower Madison resulted from the ±2EC change in release temperatures from Madison powerhouse. The ±2EC in release temperature resulted in an approximate ±1.3EC change in the lower Madison. Changes in air temperature appear to impact water temperatures to a lesser degree. The ±2EC changes in air temperature altered water temperatures by ±0.3EC. Changes in flow appear to have a minimal effect on mean water temperatures. A high steady flow of 2100 cfs, reduced the mean water temperature by about 0.7EC. Conversely, low steady flows (1100 cfs) slightly increased mean and maximum water temperatures. These results suggest that based on single variable analysis, inflow water temperature from the Madison powerhouse has the greatest impact on lower Madison River water temperature.

Analysis of Alternatives - A series of mitigation and enhancement alternatives were investigated using the hourly ADYN hydrodynamics and RQUAL water temperature models. These alternatives include:

- Existing conditions
- Remove Madison Dam
- Raise Madison Dam by 40 feet
- Bypass the river around Ennis Lake

<u>Existing Conditions</u> - Existing conditions were simulated using the calibrated models for the three model segments for the Upper Madison River, Ennis Lake, and the Lower Madison River. Model runs are based on historic meteorology, historic operations, and available measured flow and water temperature information for 1 June to 15 September 1994, the period of highest water temperatures. To link the model segments, the flow and water temperature at the downstream boundary of the Upper Madison River (i.e., near Valley Garden) provided the input at the upstream boundary of the Ennis Lake model segment. Flow and water temperature at the downstream boundary of Ennis Lake then provide the input to the upstream boundary (i.e., Madison Dam and powerhouse) of the Lower Madison River model segment.

<u>Remove Madison Dam</u> - The removal of Madison Dam was simulated by coupling the Ennis Lake and Lower Madison River models into one continuous model. This alternative would involve draining Ennis Lake and restoring this section of the river to its natural pre-dam condition. Pre-dam geometry was based on 1903 topographic surveys of the 5-mile reach from below Valley Garden to the entrance to Bear Trap Canyon. Prior to the construction of Madison Dam and creation of Ennis Lake, this reach of the river consisted of flat, braided topography with shallow, wide sections. It was assumed there was no change in Hebgen operations, and flow and water temperatures at the upstream boundary of the coupled model

were provided by the Upper Madison River Existing Conditions simulations.

Raise Madison Dam - Constructing a new Madison Dam and raising the water level of Ennis Lake by 40 feet was evaluated with the goal of reducing rapid heating in the braided channel and upper reaches of Ennis Lake by inundating this portion of the river. Increasing the height of Madison Dam was accomplished in the model by altering the cross-section at the dam. Otherwise, the simulation runs for this alternative were based on the Existing Condition model. Given the limitation of one-dimensional modeling, potential thermal stratification of the lake as a result of increased depth was not taken into consideration. Stratification caused by increasing the lake's depth could have additional mitigating effects on river temperatures below Madison Dam, assuming multi-level intakes were used and low dissolved oxygen concentrations were not a problem.

Bypass Braided Reach and Ennis Lake - Channeling around Ennis Lake (and the braided river reach just above the lake) would involve routing incoming river flows from the Valley Garden area to the Madison powerhouse. To make hydroelectric generation feasible under this alternative, the channel would be designed to release water into Ennis Lake in the vicinity of the powerhouse intake. To simulate this alternative, flow and water temperature at the downstream boundary of the Upper Madison River model near Valley Garden were directly used to drive the Lower Madison River model. We assumed that no additional warming of the water occurs en route between Valley Garden and the powerhouse. Therefore, this alternative as simulated represents river thermal conditions under the most favorable scenario of no heating caused by the braided channel or the lake.

RESULTS

Model simulations of the alternatives were evaluated for their effects on water temperatures, focusing on the Lower Madison River segment. The relative effects of the alternatives, as compared to 1994 Existing Conditions, are presented in Figure 4. This figure illustrates the temperature envelope (maximum and minimum) and mean water temperatures throughout the 40-mile study reach. The frequency of occurrence of specific temperatures at Greycliff for the various alternatives is shown in Figure 5. This information is important for evaluating the ecological impacts of the alternatives on aquatic habitat and the exposure of fish to given temperatures.

Raise Madison Dam - The second plot in Figure 4 illustrates that raising Ennis Lake by 40 feet increases the lake's thermal damping influence by making the temperature envelope slightly narrower than under existing conditions. However, it is likely that the overall temperature impact of raising the lake's elevation would be minimal. At the existing dam site, maximum temperature would be reduced by 0.8EC, mean temperature would be reduced by only 0.3EC, and minimum temperature would be increased by 0.5EC. Mean temperatures would be reduced by less than 0.3EC downstream of the Madison powerhouse and by only 0.1EC at Three Forks.

Bypass Braided Reach and Ennis Lake - Because it essentially eliminates the effects of heating in the braided reach upstream of Ennis Lake and within the lake, the channel alternative represents the upper bound in terms of reducing water temperatures in the lower Madison River. Water temperatures from above the braided reach (RM 45) would be translated directly downstream to releases from the powerhouse, and natural heating/cooling processes would commence at this point. As illustrated in the third plot in Figure 4, mean water temperatures would be lower than those under existing conditions, and temperature extremes would be shifted downward due to the absence of warming (approximately 2.3EC) in the braided reach and Ennis Lake. Mean river temperatures would be approximately 2.6, 1.7, and 1.1EC lower at the Madison powerhouse, Greycliff, and Three Forks, respectively. However, although mean temperatures would be reduced downstream of Madison Dam due to lower inflow temperatures, the rate of warming would be higher under the channel alternative as water temperature would rise more rapidly toward equilibrium with mean air temperature.

The effect of reduced water temperatures under the channel alternative is apparent in the temperature histogram (Figure 5). Water temperatures of 22EC or higher would be equaled or exceeded only 20 percent of the time under the bypass alternative, compared to 38 percent of the time under existing conditions. Higher temperatures such as 26EC would be equaled or exceeded less than 1 percent of the time under the bypass alternative.

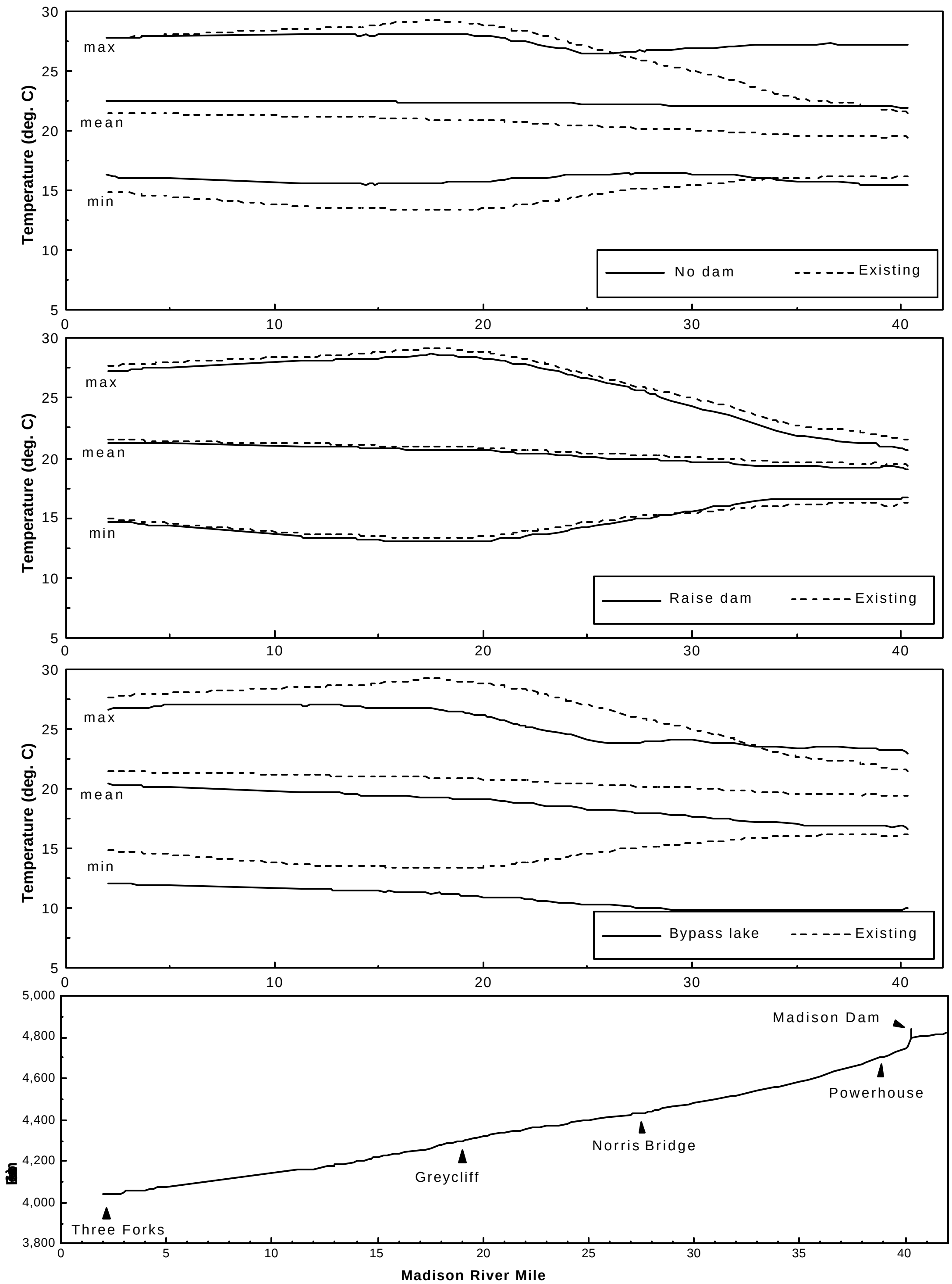


Figure 4. Simulated Lower Madison River water temperature envelopes for three alternatives and existing conditions.

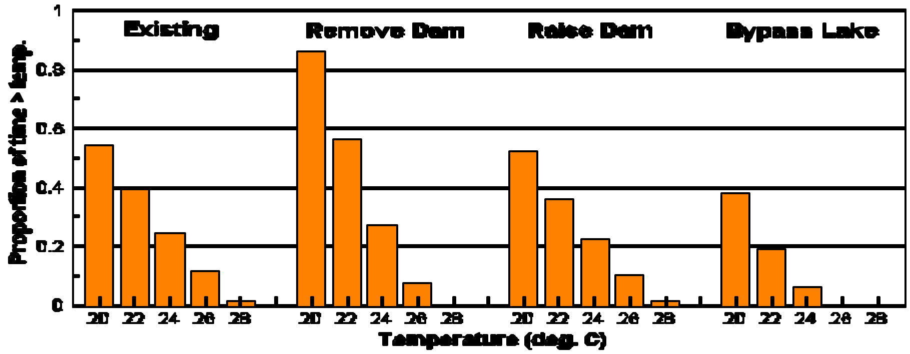


Figure 5. Water temperature occurrence frequencies at Greycliff (RM 19), 1 July to 15 August, 1994.

SUMMARY

Our temperature model simulations suggest that the braided reach of the Madison River upstream of Ennis Lake and the shallow reaches at the southern end of the lake contribute significantly to the heating of the river. Removing Madison Dam would intensify warming in this section of the river by exposing naturally wide, shallow reaches that are currently inundated by Ennis Lake. Constructing a new Madison Dam and increasing the depth of Ennis lake by 40 feet would have only marginally positive effects on water temperatures downstream. Of the construction alternatives evaluated, channeling around Ennis Lake would have the most positive effect in terms of reducing water temperatures. However, even under this alternative, mean and maximum water temperatures at Greycliff would be reduced by only 1.7EC and 2.6EC, respectively. Considering the limited thermal benefits predicted by the alternative simulations, the potential economic costs and environmental impacts of the construction and operation associated with these alternatives become important considerations. In all likelihood, these costs will be high, and none of these alternatives is a very attractive solution to the thermal problems in the Madison River.

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KEYWORDS:

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