Michigan DNR

STATE OF MICHIGAN
DEPARTMENT OF NATURAL RESOURCES

Number 2047
December 31, 1997

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FISHERIES DIVISION
RESEARCH REPORT

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Printed under authority of Michigan Department of Natural Resources
Total number of copies printed 200 — Total cost $430.98 — Cost per copy $2.15

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Abstract

The Betsie River in northern Michigan is classified as a marginal trout stream because in some reaches, instream summer temperatures exceed the tolerance limits for trout species. In 1989, Thompsonville Dam failed, which resulted in an additional 15 km of stream available to migratory steelhead *Oncorhynchus mykiss* adults and juveniles. However, water temperatures in the upper watershed may still limit the production and distribution of these fish. The objectives of this study were to: 1) describe the current thermal regime throughout the Betsie River watershed and characterize it in relation to juvenile steelhead life history requirements, 2) evaluate empirical water temperature models based on air temperature to predict instream temperatures throughout the watershed, and 3) develop a physical process temperature model to evaluate the thermal effects of removing a remaining low-head dam in the headwaters or, alternatively, the addition of cold water from the hypolimnion of the source lake. Under current channel conditions, summer temperatures in the upper Betsie River routinely exceed the optimal growth limits for steelhead and sometimes the upper incipient lethal level, with mean summer temperatures from 21-23°C and maximum temperatures up to 28°C. Although, instream water temperatures were strongly correlated with air temperatures ($r^2 = 0.81$ to 0.92), air temperature was a poor predictor of winter water temperatures. The physical process model predicted instream summer temperatures reasonably well and provided for simulation of management alternatives. Removal of Grass Lake Dam would likely result in mean daily summer water temperatures 2°C lower than under current conditions in both typical-flow and low-flow water years for the reach from Green Lake to Grass Lake. In the Grass Lake to Thompsonville reach, mean daily water temperatures were predicted to be less than 1°C

lower than under current conditions in a typical and low-flow year. The addition of hypolimnetic water would result in temperatures 4°C lower than under current conditions in the Grass Lake to Thompsonville reach. Although these management alternatives may provide better thermal habitat for juvenile steelhead during the summer in this 15 km reach of river, the trade-offs, including the loss of wetland habitat and fishery and recreational boating opportunities in the current impoundment, should be considered.

Introduction

Water temperature is an important and governing influence on fish ecology. Temperature influences species distributions, timing of life history events, and individual growth and survival (Hokanson et al. 1977, Adams and Breck 1990, Griffith 1993). In particular, when salmon and trout reside in the upper limits of their thermal tolerance, their growth rate can be very high, but growth rapidly declines when temperature exceeds the upper threshold (Griffith 1993, Elliott et al. 1995).

The Betsie River, a tributary to Lake Michigan, located in northwestern lower Michigan (Figure 1), drains approximately 67,126 ha. The main river channel is considered to be a marginal trout stream because summer temperatures in the upstream reaches of the river exceed the limits for growth and survival of most trout species. The two largest tributaries in the watershed, Dair Creek and Little Betsie River, are better suited for trout species. Although brown trout *Salmo trutta* are stocked in the Betsie River, their numbers are very low (Wicklund and Dean 1958, MDNR Fish Surveys, 1990). Rather, the fish species assemblage of the Betsie River is comprised of suckers, chubs, and minnows (Wicklund and Dean 1958, Bonham 1975). In spite of its marginal status, the river has historically supported a popular fishery for migratory adult steelhead *Oncorhynchus mykiss* (Wicklund and Dean 1958, Rakoczy 1987, 1988, 1990).

Prior to the early 1970's, the river was impounded by 3 dams: Homestead, Thompsonville, and Grass Lake. Homestead Dam, a former power generating structure, was removed in 1974 and was replaced by a 2 m high lamprey weir. The original dam had a crude fish ladder for passage of migratory salmonids. The lamprey weir is designed to allow for upstream passage of migratory salmonids but other species can only pass in a downstream direction.

Thompsonville Dam, also a former power generating structure, was approximately 3.1 m high with an impoundment around 5.7 ha (Bullen 1972). From anecdotal reports of local residents, a few migratory salmonids were known to pass over this dam, but it prevented the passage of most migratory fish. Thompsonville Dam was identified as one of the sources of heating in the Betsie River and its removal was recommended (Wicklund and Dean 1958, Bullen 1972). In 1989, Thompsonville Dam was breached during a flood in March which resulted in its collapse and which opened access to the upstream portion of the river to all migratory salmonids. This newly available reach contains high quality riffles and some of the steepest gradients in the watershed. In addition, juvenile and spawning steelhead gained access to the Little Betsie River, which enters the Betsie River upstream of the Thompsonville Dam. This is the largest tributary in the watershed. Thermal habitat limitations in the main channel still appear to limit the population of steelhead as evidenced by the low number of wild steelhead smolts produced from the watershed (Newcomb and Coon, 1997a) and the large differences in the densities and spatial distribution of age-0, age-1 and age-2 steelhead parr (Newcomb and Coon, 1997b).

The current thermal limitations in the Betsie River may, in part, be the result of the remaining low head dam, Grass Lake Dam. Grass Lake dam was constructed in 1951 to improve wetland habitat for waterfowl and northern pike *Esox lucious*. Grass Lake Dam is located approximately 6.7 km downstream of the river source at the outlet of Green Lake. The impoundment area floods approximately 463.6 ha of wetlands (Carbine 1945) which are currently dominated by cattail *Typha latifolia*.

Steelhead were introduced in 1876 and have become naturalized throughout the Great Lakes (Latta 1974, Biette et al. 1981). Steelhead have a complex life-history that includes a 2-3 year residency in the river before they emigrate to receiving ocean or lake. In the Great Lakes, steelhead spawn in the late winter and early spring (Biette et al. 1981) in water temperatures ranging from 10-15.5° C (Scott and Crossman 1973). Juvenile steelhead parr fed to satiation experience optimal growth at temperatures between 15 and 17.3° C, and their upper incipient lethal temperature is 25-26° C (Hokanson et al. 1977). In behavior studies, juvenile steelhead preferred temperatures in the range of 11-21° C (Coutant 1977, Kwain and McCauley 1978, Cherry et al. 1977). Growth ceases for parr in temperatures greater than 22° C and less than 8° C (Hokanson et al. 1977). Steelhead parr metamorphose into smolts and outmigrate in the spring in water temperatures from 10 to 13° C. At water temperatures greater than 13° C, smolts lose the capacity to smolt, revert back to parr and may remain in the watershed for another year (Zaugg and Wagner 1973).

Interest in improving the Betsie River steelhead fishery by management of the thermal regimes has focused on 2 options: 1) removal of Grass Lake Dam, and 2) changing the source of the initial water supply from the surface of Green Lake, to a hypolimnetic siphon that is diverted around the Grass Lake impoundment (Bullen 1972). Both of these options incur unique biological and financial costs. Removal of Grass Lake Dam would result in a large loss of wetlands, waterfowl habitat, a largemouth bass *Micropterus salmoides* and northern pike fishery, and recreational boating opportunities. In addition, the water level of Green Lake would likely decrease. The second option would require installation of a water control structure at the Green Lake outlet, where none currently exists, and would involve a large engineering effort to transport water around the Grass Lake flooding. A water diversion would also alter the thermal and flow regime of the river's source above Grass Lake Dam. An evaluation of the effects of these alternatives before implementation is needed in order to predict the potential benefits of such actions.

Methods used to evaluate thermal regimes include two basic approaches which differ in levels of complexity and predictability. The two types of models are statistical models and physical process models (Barthalow 1989). Statistical models incorporate empirical data and either simple or multiple regression analyses. Although straightforward, statistical models are limited in their abilities to predict changes in thermal regimes as a result of management actions. Physical process models incorporate additional parameters (e.g. stream gradient, discharge, humidity, and shading) and can be used to predict the influence of management actions on thermal regimes. The trade-off however, is that physical process models are usually much more difficult to develop and require more data than statistical models (Barthalow 1989).

The objectives of this study were to: 1) describe the current thermal regime throughout the Betsie River Watershed as it compares to the temperature requirements of juvenile steelhead, 2) develop a simple empirical statistical model that relates water temperature to meteorological influences such as air temperature, 3) develop a physical process model calibrated with empirical data, and 4) evaluate management alternatives for changing the thermal regime in the Betsie River.

Methods

We monitored water temperature at 7 locations in the Betsie River watershed (Figure 1, Table 1) on an hourly schedule by use of continuous logging temperature recorders (Stowaways™, Onset Instruments). All recorders to were tested with an ASTM thermometer to check for accuracy prior to and after deployment. Daily, weekly, and seasonal (winter: Dec-Feb, Spring: Mar-May, Summer: Jun-Aug, Fall: Sep-Nov) means were calculated for each station to use in describing the current thermal conditions (July 1993 - July 1996).

We developed empirical regression models of stream temperature using air temperature data from the Manistee, Frankfort, Cadillac, and Traverse City weather stations (National Climate Data Center 1993-1996). Mean daily water temperature at each site was the dependent variable in each regression model. We used SAS statistical software (SAS 1988) to obtain an r^2, significance level, y-intercept, and slope for each model.

The Betsie River has no permanent gages for recording river stage or discharge. We established five gaging stations in the watershed. We measured discharge at low, intermediate and high flows and used these to establish stage-discharge relationships (Figure 1) (Gordon et al. 1992). Because the Betsie River substratum is comprised predominantly of sand, there is a large potential for changes in channel morphology which could result in a change in the stage-discharge relationship. To ensure accurate flow ratings, discharge was measured at the gaging stations each year to monitor for a shift in the stage-discharge relationship, and establish a new rating curve if necessary (Gordon et al. 1982).

To evaluate thermal habitat management alternatives, we modeled two stream segments of management interest with a stream reach physical process model developed by the U.S. Fish and Wildlife Service (Theurer et al. 1984, Barthalow 1989). Segment A extended 6.7 km from the Green Lake outlet to Grass Lake Dam and Segment B ranged 14.9 km from Grass Lake Dam to Thompsonville Dam (Table 1). The temperature model required 3 types of information including stream geometry (upstream and downstream elevations, stream width, Manning's N, and shading), meteorology (solar radiation, air temperature, relative humidity, cloud cover, daylength, and wind speed), and hydrology (stream discharge in and out of the reach and temperature of the water entering the reach). Wind speed and solar radiation were obtained from the Traverse City National Weather Service station and cloud cover was estimated from measured solar radiation. Relative humidity was calculated from measures of the dew point according to:

$$R_h = [(112 - 0.1*T_A + T_{dp}) / (112 + 0.9*T_A)]^8$$

where R_h = relative humidity, T_A = air temperature, T_{dp} = dew point temperature. Shading, according to Barthalow (1989), is the amount of the stream channel that is covered by shade in mid-day. Based on our measurements of the channel and stream bank vegetation, we estimated shading to be 0% for segment A and 5% for segment B.

We calibrated the 4 models (Segment A and Segment B for typical- and low-flow years) primarily by altering humidity (which is known to vary by as much as 20% away from the measurement site) (Barthalow 1989). Solar radiation was altered from the measured values in Traverse City within reasonable limits (Barthalow 1989) to also assist in calibration. Output from the model included minimum, mean, and maximum outflow temperatures, width, depth, and slope of the channel with varying flows, and heat flux components which indicate atmospheric and ambient conditions that contribute to heat gains and losses. After calibrating to the typical- and low-flow measured conditions, segment A input parameters were altered by increasing the gradient, decreasing channel width, and decreasing Manning's N values, to simulate morphological conditions that would exist with the removal of Grass Lake Dam. Outflow water temperatures predicted from this simulation were then used as starting temperatures at the upstream reach of segment B to evaluate the effects of dam removal on this downstream reach.

The second management alternative that was evaluated required changing the water temperature at the inflow of segment B to reflect a proposal to withdraw hypolimnetic water from Green Lake, divert it around the Grass Lake flooding and discharge it into the stream immediately below Grass Lake Dam (Bullen 1972). This scenario was simulated by using a water temperature of 7.2°C as the starting temperature for segment B and discharges that were measured in the typical and low-flow years.

Results

Current Thermal Regimes Throughout the Watershed

Water temperature varied spatially and temporally throughout the watershed. Green Lake and Woirel Bridge (sites 1 and 2) experienced the warmest water temperatures in summer and the tributaries (sites 6 and 7) had the coolest water temperatures in summer (Table 2). Mean winter water temperature was the warmest at sites 1,2, 6, and 7, and the coolest at main channel locations Thompsonville, M115, and Homestead (sites 3, 4, and 5).

Cumulative probability plots of temperature (exceedence curves) were developed with data from water years 1993-1995 to illustrate temporal patterns in which the water temperature was likely to exceed the preferred temperature range for juvenile steelhead (Figure 2, Table 3). In the upper watershed, (Green Lake and Woirel Bridge), the preferred temperature range and optimal growth temperatures were exceeded 20 and 30% of the time, respectively. At Thompsonville and Homestead, the preferred temperature range was exceeded between 1 and 7% of the time and optimal growth limits were exceeded 12-20% of the time. In the tributaries, Dair Creek and Little Betsie River, the preferred temperature limits were never exceeded and the optimal growth limits were exceeded only 3% of the time in Dair Creek and 7% in the Little Betsie River. Generally, all six sites were similar in their probabilities to be less than the lower preferred temperature (11°C) ranging from 52% at Woirel Bridge to 61% in Dair Creek.

Temperature and photoperiod interact to stimulate smoltification and emigration of juvenile steelhead. Photoperiod initiates the physiological changes, while temperature directs the rate and duration of smoltification (Wedemeyer 1980). Water temperature between 7 and 13°C is optimal for smoltification. Above this, smolts may revert back to parr and spend another year in the stream environment (Zaugg and Wagner 1973). In the Betsie River, the lower smolting temperature was reached in mid-April and the upper threshold was exceeded by mid-May (Figure 3). In the Little Betsie River, the lower smolting temperature threshold occurred in mid-April and suitable temperatures for smolting extend into mid-June (Figure 3).

Empirical Models of Water Temperature

Air temperature data from neighboring climatological stations were used to predict daily mean water temperature at Betsie River stations. We initially tested data from stations at Cadillac, Frankfort, Manistee, and Traverse City (NCDC 1993-1996). Data from all climatological stations produced significant relationships ($p < 0.001$) with an adjusted $r^2 > 0.80$. The Frankfort station accounted for the greatest variability in water temperature with r^2 values ranging from 0.826 to 0.908 at sites throughout the watershed (Table 4). Water temperature at tributaries and downstream sites were more strongly related to air temperature than at the upstream sites and the Green Lake outlet.

The predicted temperatures were plotted with observed temperatures to evaluate the empirical models (Figures 4 and 5). In all cases, the empirical models were poor predictors at very low air temperatures, from -10 to -5°C. The largest error from the observed values was observed at the Green Lake monitoring location and became progressively smaller in downstream locations, Thompsonville and Homestead. With a few exceptions, air temperature was a very good predictor of water temperature in the tributaries, Dair Creek and Little Betsie River at air temperatures above -7.0°C (Figure 5).

Stream Segment Water Temperature Model Results

Based on the limited 4 years of water temperature and hydrological observations, 1994 represented the typical flow and climatic conditions in the Betsie River watershed and 1995 represented a low-flow year. We used data for these two summers to develop a stream reach temperature model to evaluate management alternatives. The model for segment A (Green Lake to Grass Lake) was calibrated with the water temperature monitoring station 2.4 km downstream of Grass Lake Dam. We assumed that only minor differences in water temperature and discharge existed between the Grass Lake Dam outlet and Woirel Bridge, because discharge measurements did not differ between the sites.

The calibrated temperature model for segment A had an average error of 1.57°C and 1.52°C for 1994 and 1995 and most errors were less than 2°C different (Figure 6). Predicted temperatures for Segment B had mean differences of 0.58°C and 0.34°C for 1994 and 1995 (Figure 7). In all cases, the errors were randomly distributed and the models did not consistently over- or under-predict the measured values (Figure 8).

In the first simulation, we modeled the effects on water temperature as a result of removing of Grass Lake Dam by reducing the channel width and increasing the gradient, both of which would result with the removal of the structure. Mean daily water temperature declined in this scenario (Figure 9, Table 5). In segment A, during the typical-flow year, daily mean water temperature ranged from 0.88 to 6.51°C (mean = 3.72°C) less than under current conditions. In the low-flow year, daily mean water temperatures averaged 3.94°C less and ranged from 0.88 to 7.37°C less than under current conditions. For the Grass Lake to Thompsonville reach, water temperature averaged 1.22°C less in the typical year and 0.55°C less in the low-flow year with the dam removed (Figure 10).

A siphon draw from the hypolimnion of Green Lake to the outlet of Grass Lake has been suggested as a remedy to the thermal limitations in the upper Betsie River (Bullen 1972). Logistics in this plan included routing the water around the Grass Lake impoundment and directing it into the Betsie River channel below the Grass Lake Dam. We simulated this alternative with the reach model by using the climatic conditions and flows for the typical and low-flow years, and by using 7.2°C as the outlet temperature. This was the measured temperature during the summer months for the hypolimnion of Green Lake (Newcomb, unpublished data). This scenario resulted in mean daily water temperatures less than those simulated with the dam removal (Table 5, Figure 11). During the typical-flow year, the hypolimnetic release resulted in water temperatures ranging from 11 to 20°C at Thompsonville. During the low flow year, water temperatures ranged from 13 to 23°C, illustrating the strong effect that climatic conditions can have on water temperatures in this reach of the Betsie River. When compared with the dam removal alternative, the cold hypolimnion contribution provides water that is 2-4°C cooler than temperatures simulated without Grass Lake Dam in Segment B (Figure 11).

Discussion and Conclusions

Juvenile steelhead residing in marginal environments can face a number of consequences. In those environments that exceed the optimal growth limits defined by temperature, fish can experience a decline in growth rates or exhibit zero growth (Hokanson et al. 1977). Alternatively, fish will move out of an area that is too warm and into refuge areas which may already be occupied by resident fish (Bilby 1984), suggesting a temporal density dependent limitation and competition for space. Finally, when temperatures are near or at the lethal levels, mortality can occur either as a direct result of the heat, or from a secondary cause, such as infection or starvation (Coutant 1976).

On the other hand, juvenile steelhead residing in locations where the thermal regime remains below the optimal growth limits may experience slower growth and later age of smoltification. Although an additional year of residency in the stream may subject these fish to mortality in the stream environment, they are less likely to succumb to heat associated mortality.

Spring temperature regimes in the Betsie River give a very short opportunity for the process of smoltification and emigration to occur, particularly when the warming trend occurs rapidly. This short duration may cause fish to stay in the river as the water temperature increases above the required temperature for smoltification (Zaugg and Wagner 1973, Wedemeyer 1980) and may have serious implications for stocking fish. If smolts are stocked too late or too far upstream in the watershed, they will not have time to emigrate before reverting back to parr and residualizing within the river. This would put hatchery fish in direct competition for space with wild produced fish and this competition would be most extreme in marginal habitats during years of low flow.

Air temperature was a sensitive parameter in the physical process model and its use in predicting water temperatures can be applied in future management considerations. Several researchers have documented the dominating effect of air temperature on stream water temperature (Smith and Lavis 1975, Crisp and Howson 1982, Barthalow 1989, Stoneman and Jones 1996). The regression models provided in this manuscript can be used in future modeling applications in the Betsie River under the current instream conditions. If there were significant changes in channel morphology or if Grass Lake Dam were removed, new empirical models would need to be derived.

Under the current channel and flow conditions, the most thermally suitable area for juvenile steelhead in the summer is between Thompsonville and Homestead in the main channel of the Betsie River and in the tributaries. Locations above this reach may provide marginal thermal habitat in typical-flow years, but during low-flow years, conditions can exceed the lethal limits. Thermal conditions in the Little Betsie River are optimal for juvenile steelhead: summer temperatures only rarely warm above the optimal growth rates. Dair Creek temperatures are lower than optimal growth rates for much of the year, but this is not likely to limit the number of juvenile steelhead produced in this stream.

If Grass Lake Dam were removed, the largest improvement in temperature would be observed in the reach from Green Lake to Grass Lake, with little improvement to the thermal regime in the Grass Lake to Thompsonville reach during either a typical-flow or low-flow year (Figures 9 and 10). The hypolimnetic flow diversion and release would provide no benefit for trout habitat in the Green Lake to Grass Lake reach and would decrease the mean summer temperature in the Grass Lake to Thompsonville reach (Figure 11). When compared with downstream locations such as M-115, Homestead and Little Betsie River, mean monthly water temperature under the dam removal scenario is still greater than the mean monthly temperature at sites with greater densities of juvenile steelhead (Table 5, Newcomb and Coon 1997b). Because the river begins as a surface outflow from a lake, the upper river water temperatures are dominated by the lake surface temperatures which tend to be inert as a result of the ability of the large body of water to retain heat. This tendency towards inertia, combined with the large outflow of water that begins the river (approximately 0.9 - 3.3 cms during the summer) and daily climatic conditions is what directs the thermal regime in the upper watershed until enough groundwater accumulates in the channel to begin cooling.

The stream reach model, while providing an indication of conditions under altered channel and thermal regimes, cannot incorporate the effects of tributaries or changes in flows without considerable more effort in the modeling application. The stream network model (Theurer et al. 1984) would be a logical next step consideration for further refinement of this analysis. Results from the network model could indicate stream temperatures at designated locations throughout the year. In addition, the influence of shading could be further analyzed over the length of the Betsie River.

Areas where groundwater is seeping into the stream channel may provide important micro-thermal habitat areas that give refuge to fish during periods of high water temperature. Bilby (1984) identified 4 types of micro-thermal habitat areas as lateral seeps, pool bottom seeps, cold tributary mouths and flow through the streambed. In areas of the Betsie River watershed, where the river flows near glacial moraines, lateral seeps are evident and prolific, although their influence has not been quantified other than as an increase in discharge. These types of features are limited in the reach between Grass Lake and Green Lake, and may be too few to provide refuge to a large number of juvenile steelhead. One potential habitat management alternative is to identify these features in this reach and provide instream structures to prohibit mixing of the warm and cold water as much as possible (Bilby 1984). Objects, such as woody debris, that would divert the warm water or create a small pool effect may increase these potential refuge areas. Additional research would need to be conducted to assess the existence of these cooler micro-thermal areas and the feasibility of their development.

Other research found thermally stratified pools to be an important microhabitat for adult steelhead in the summer months (Nielson et al. 1994). However, the reach between Grass Lake and Thompsonville has a wide channel, likely a remnant effect from logging in the 1800’s, with a steep gradient. Pools are scarce nor are they deep enough to stratify.

Acknowledgments

We thank M. Wilson, D. Weisenreder, J. Ladonski, J. Holmes, J. Kozfkay, T. Weaver, and S. Laprad for their invaluable assistance in sampling. Several volunteers braved ice and snow to monitor staff gages including D. Mills, Dr. C. Nelson, L. Tipper, D. Gillespie, and C. Barnes. Temperature monitoring equipment was generously donated by the Challenge Chapter of Trout Unlimited. Additional funding and support provided by several chapters of the Michigan Salmon and Steelhead Fishermen's Association, Michigan River Guide's Association, Michigan Department of Natural Resources Fisheries Division, Michigan State University and the Michigan Agricultural Experiment Station, and funds from the Federal Aid in Fish Restoration Act, Michigan F-35-R, study no. 645.

Table 1. Sites and reaches used for monitoring flow and temperature in the Betsie River watershed.

Site	Distance upstream of river mouth (Km)	Modeling Reach
Green Lake	74.7	Segment A
Grass Lake	68.0	
Woirel Bridge	64.4	Segment B
Little Betsie River	53.8	
Thompsonville	53.1	
M115	46.9	
Dair Creek	24.0	
Homestead	17.7	

Table 2. Mean water temperature by season at sites in the Betsie River watershed.

	Fall			Winter			Spring			Summer			
Site #	93	94	95	93	94	95	94	95	96	93	94	95	96
1	11.8	14.9	11.9	1.6	1.8	1.1	5.4	6.1	6.3	23.2	21.4	23.4	21.0
2	9.7	12.9	10.7	1.2	0.9	0.4	7.9	9.0	9.0	22.5	21.6	23.4	21.2
3	9.3	11.7	9.3	0.7	1.0	0.2	8.3	7.8	6.7	20.5	19.2	20.9	19.1
4	9.1	11.3	9.3	0.9	1.7	0.8	8.1	7.8	7.5	19.0	18.1	19.8	18.1
5	8.7	11.0	8.7	0.9	1.7	0.4	8.0	8.1	7.0	18.3	17.6	19.1	17.6
6	7.5	9.3	7.6	1.4	2.0	0.8	6.9	7.2	5.9	14.7	14.0	16.1	14.1
7	8.1	10.0	8.2	1.0	1.8	0.7	7.3	7.4	6.6	15.9	15.9	17.4	15.7

Sites: 1 = Green Lake
2 = Woirel Bridge
3 = Thompsonville
4 = M115
5 = Homestead
6 = Dair Creek
7 = Little Betsie River.

Table 3. Probability of exceeding, meeting, or remaining below preferred and optimal growth temperatures for juvenile steelhead at sites throughout the Betsie River watershed.

	SITE					
	Green Lake	Woirel Bridge	T-ville	Homestead	Little Betsie River	Dair Creek
Percent of time:						
likely within optimum growth range	3.6	4.2	6.8	10.6	13.1	7.3
likely within preferred temperature range	23.7	26.7	35.0	39.7	39.5	35.1
exceeding preferred range	18.6	17.9	10.6	1.1	0	0
under preferred range	55.3	52.3	55.3	56.3	57.2	60.8

Table 4. Results of regression modeling water temperature as a function of air temperature measured at Frankfort, Michigan. All results are significant, $P < 0.001$.

Site	R^2	Coefficient (Slope)	Y-intercept
Green Lake	0.8261	0.7563	4.9637
Woirel Bridge	0.8658	0.7807	4.9306
Thompsonville	0.8966	0.7165	4.2612
M115	0.9059	0.6561	4.5494
Homestead	0.9096	0.6342	4.4173
Little Betsie River	0.9031	0.5714	4.1635
Dair Creek	0.9076	0.5106	4.0146

Table 5. Mean daily water temperature in June, July, and August for the river at the downstream section of Segments A and B, in the Betsie River under current conditions and under simulated conditions of removing Grass Lake Dam and releases of hypolimnetic water from Green Lake at Grass Lake Dam. Data from sites at M-115, Homestead, and the Little Betsie River are also included for comparison.

Management Alternative	Typical-Flow Year (1994) °C			Low-Flow Year (1995) °C		
	June	July	August	June	July	August
Current State						
Segment A	21.2	22.7	21.0	24.0	24.2	25.2
Segment B	19.0	20.3	18.7	21.0	20.7	21.5
M-115	17.9	19.0	17.4	19.6	19.5	20.2
Homestead	17.4	18.4	16.7	18.8	18.8	19.4
Little Betsie River	15.9	16.7	15.0	17.1	17.4	17.9
Dam Removal						
Segment A	18.4	19.9	19.3	21.8	21.5	21.9
Segment B	18.3	19.6	18.1	20.9	20.1	21.2
Hypolimnetic Discharge						
Segment B	15.2	15.6	13.7	18.9	18.3	19.0

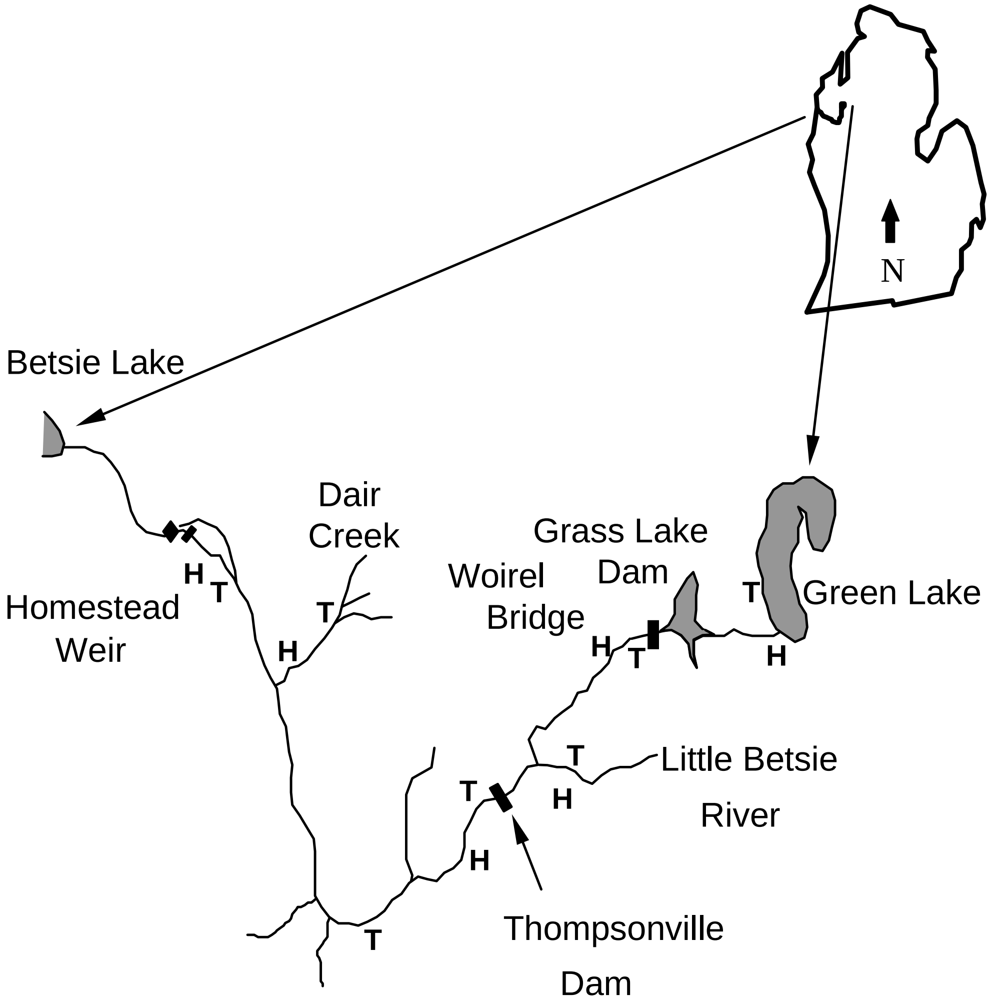


Figure 1. Location of the Betsie River watershed and temperature monitoring locations (T) and flow monitoring locations (H).

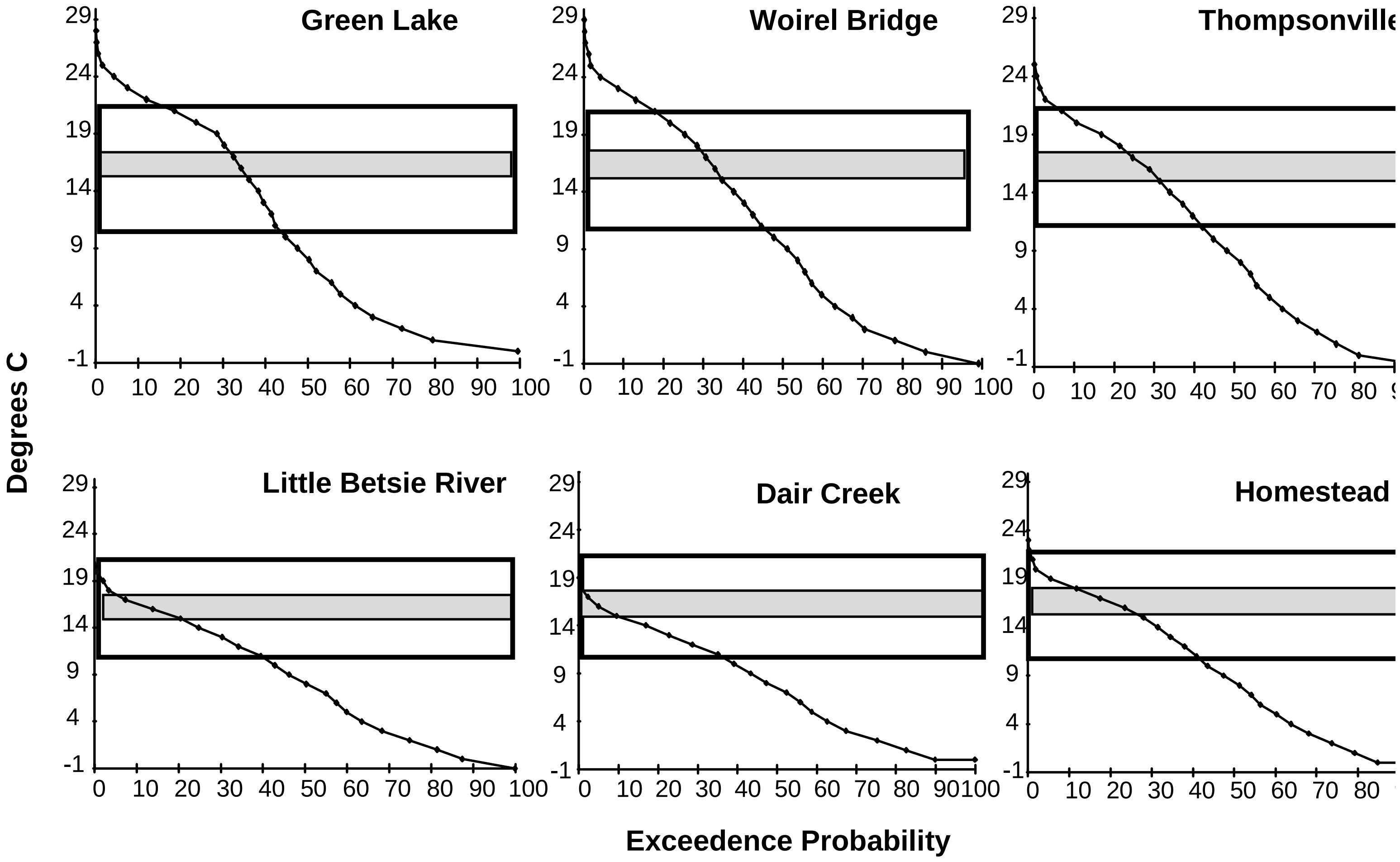


Figure 2. Temperature exceedence curves for sites in the Betsie River watershed, water years 1993-19
The large rectangle indicates temperatures preferred by juvenile steelhead and the inner rectangle indica
the temperature range of optimum growth of juvenile steelhead (Hokanson et al. 1977, Wismer and Chri
1987).

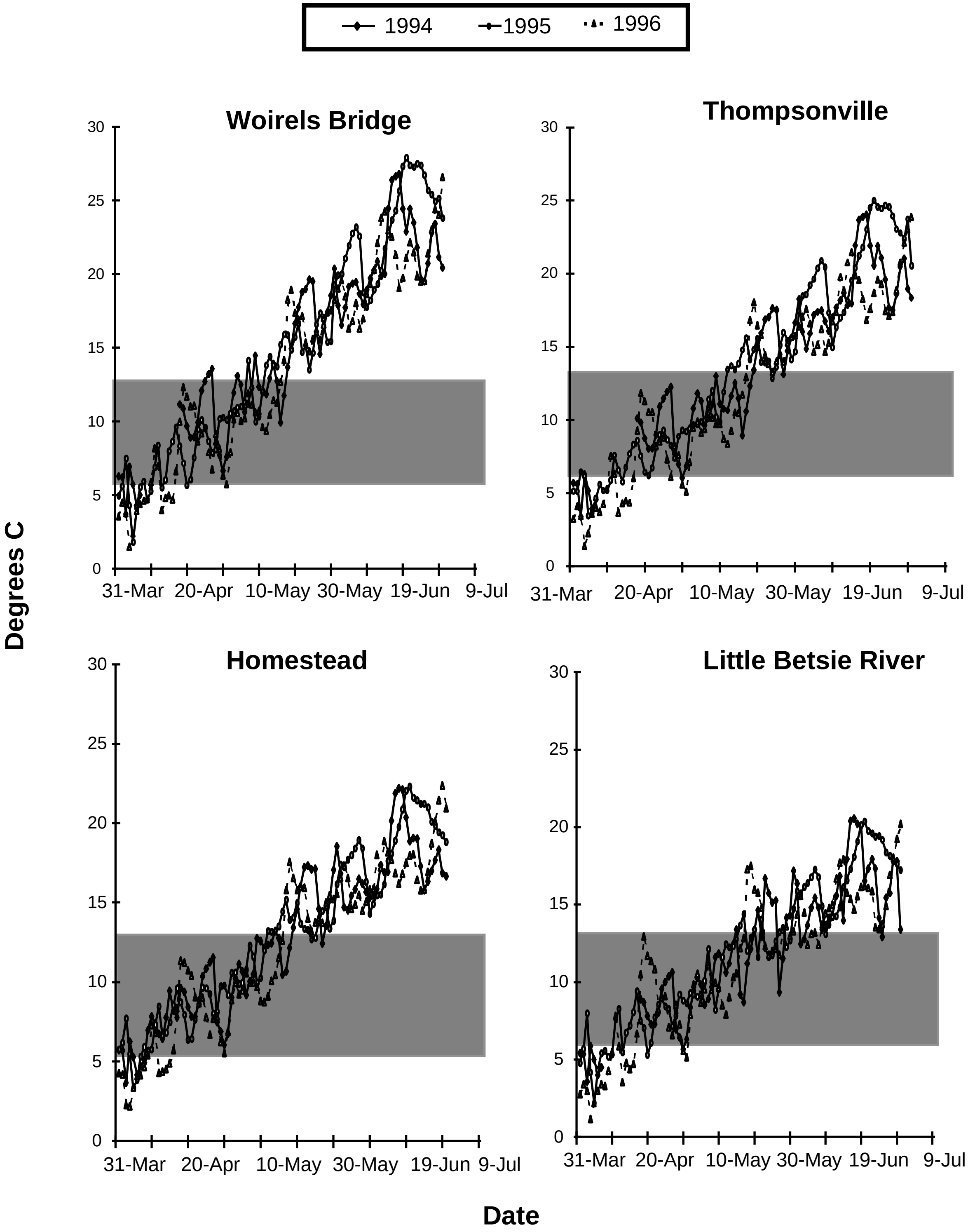


Figure 3. Spring water temperatures during steelhead smolt emigration in the Betsie River watershed, 1994-1996. Shaded rectangles denote smoltification temperatures, above which smolts will revert to parr.

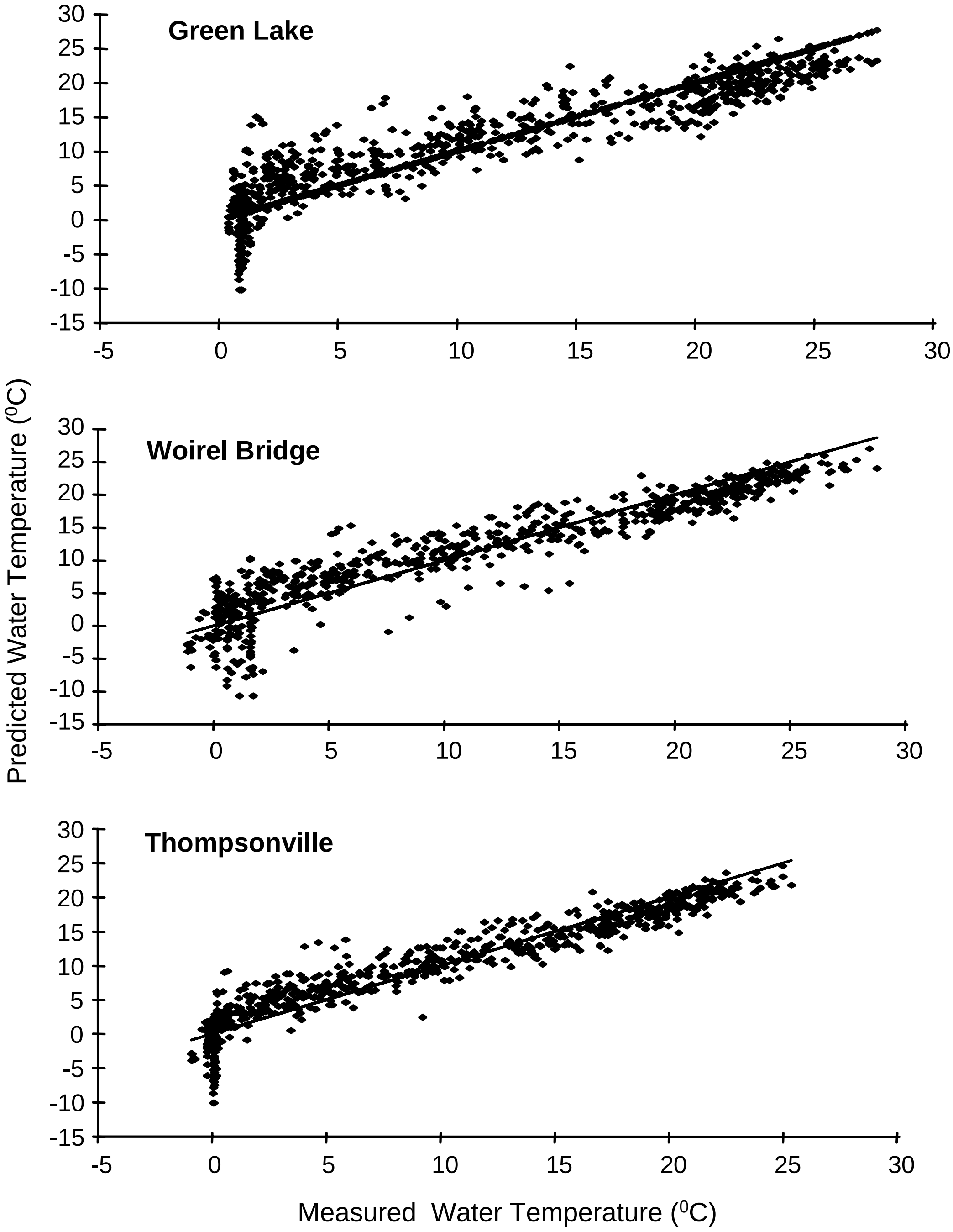


Figure 4. Predicted water temperature (symbols) as a function of air temperature and measured water temperature (line) at sites in the Betsie River, 1993-1996.

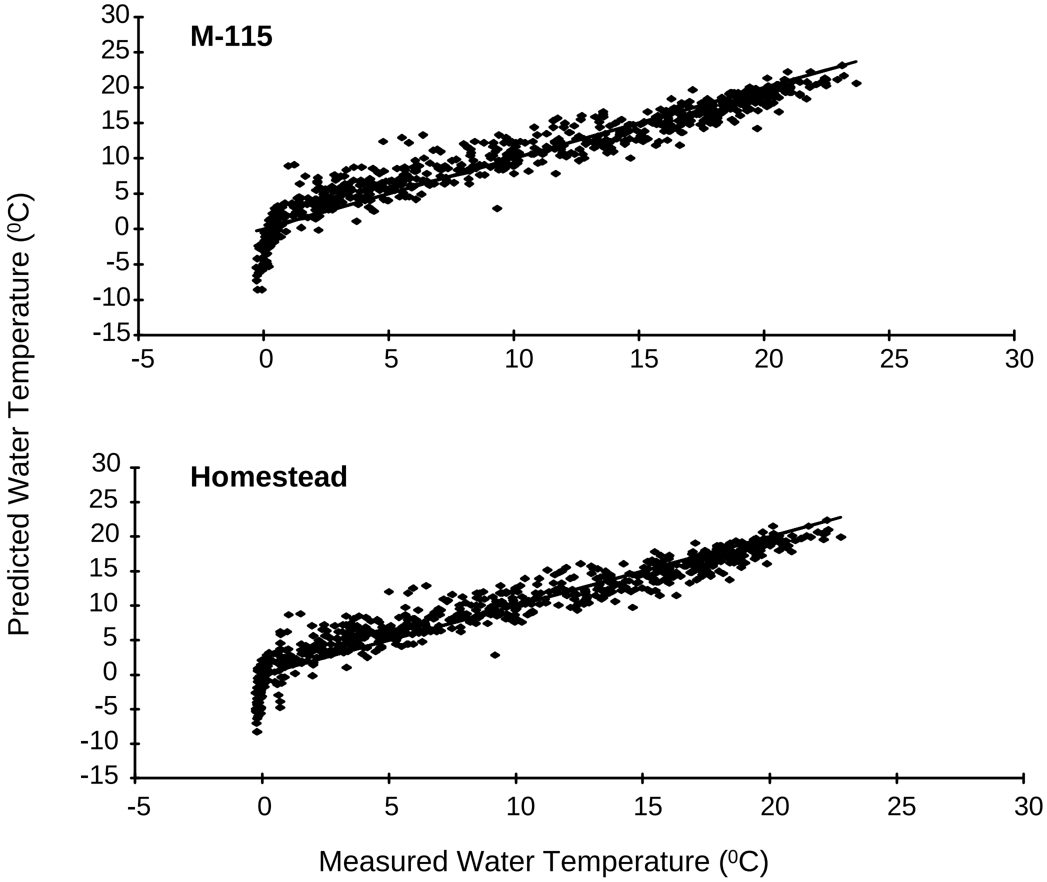


Figure 4 (continued). Predicted water temperature (symbols) as a function of air temperature and measured water temperature (line) at sites in the Betsie River, 1993-1996.

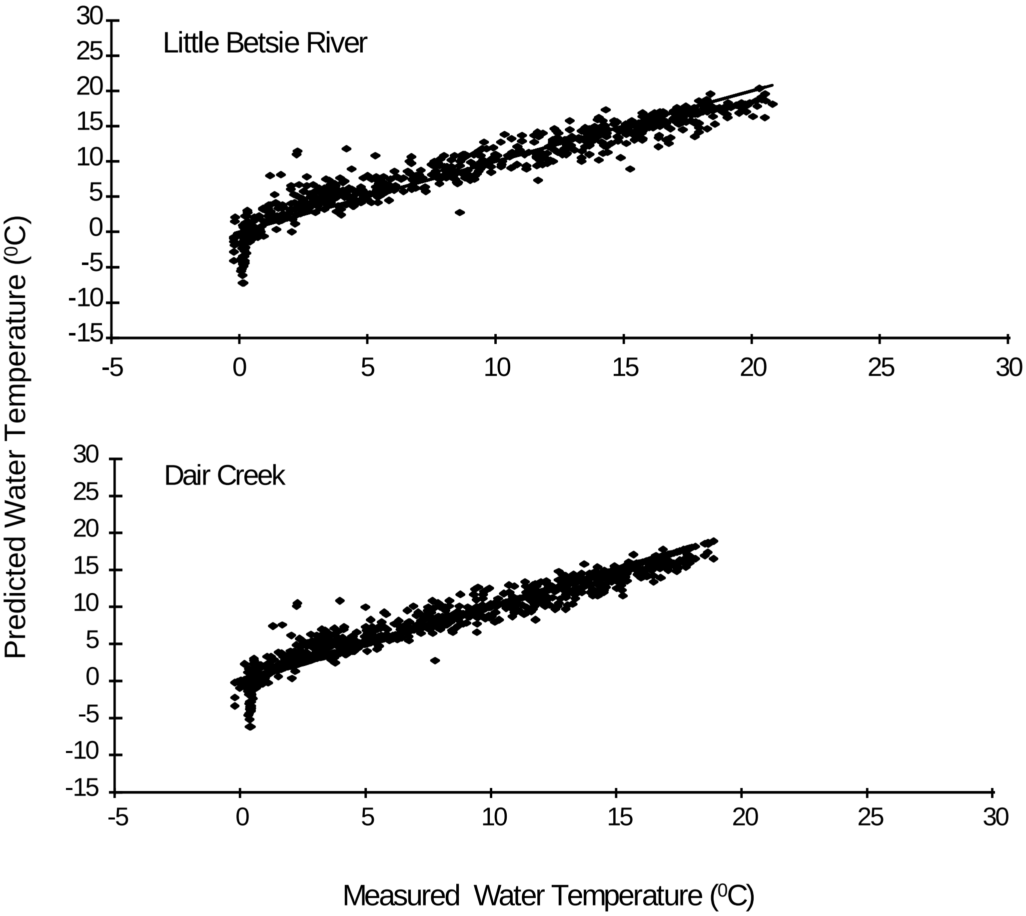


Figure 5. Predicted water temperature (symbols) as a function of air temperature and measured water temperature (line) at tributary sites in the Betsie River watershed, 1993-1996.

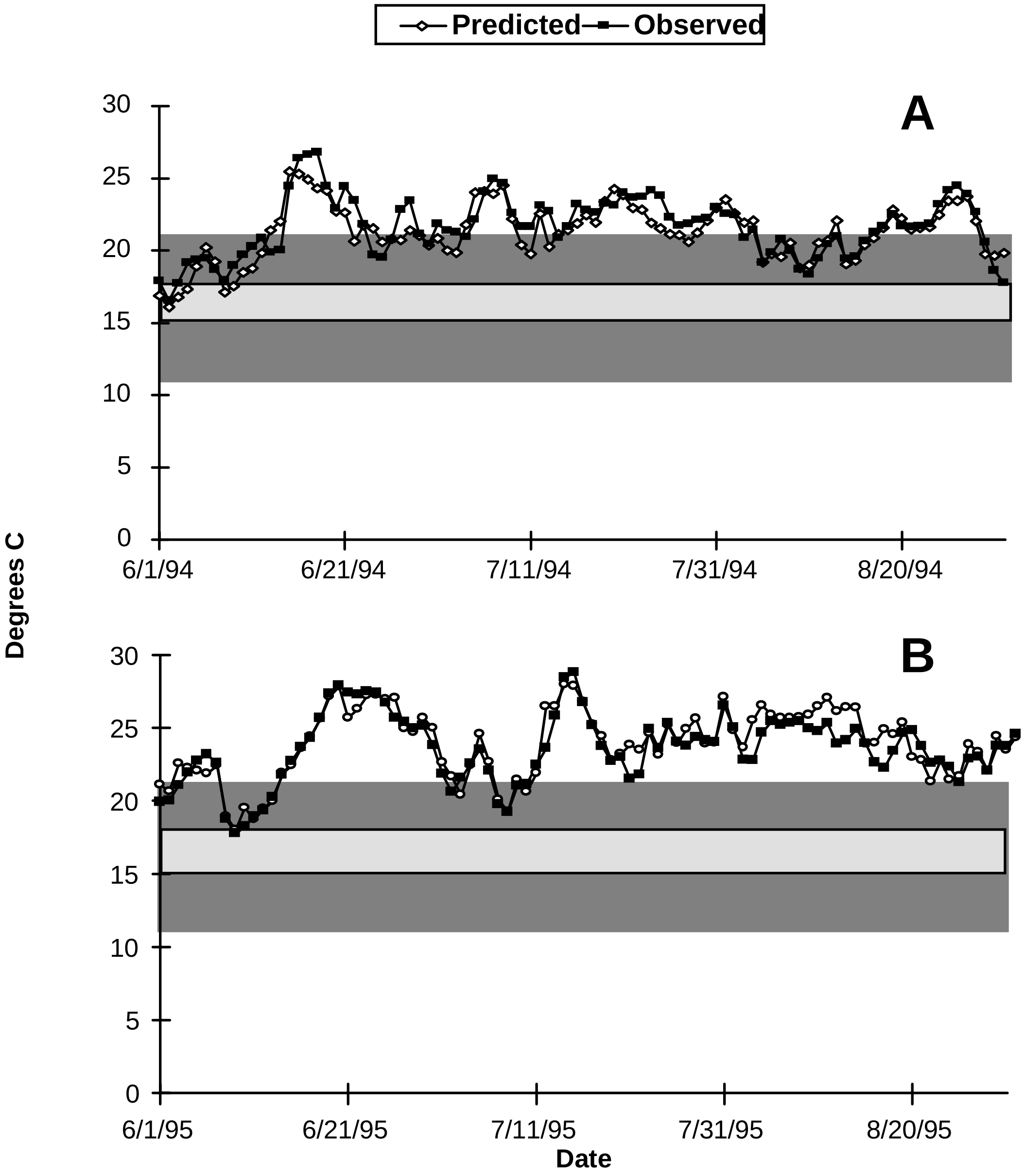


Figure 6. Measured and predicted summer temperatures from the stream reach temperature model for segment A, Green Lake to Grass Lake, in the Betsie River during a typical-flow (a) and low flow water year (b). The large shaded area indicates water temperatures preferred by juvenile steelhead and the inner rectangle identifies optimum growth temperatures for juvenile steelhead (Hokanson et al 1977, Wismer and Christie 1987).

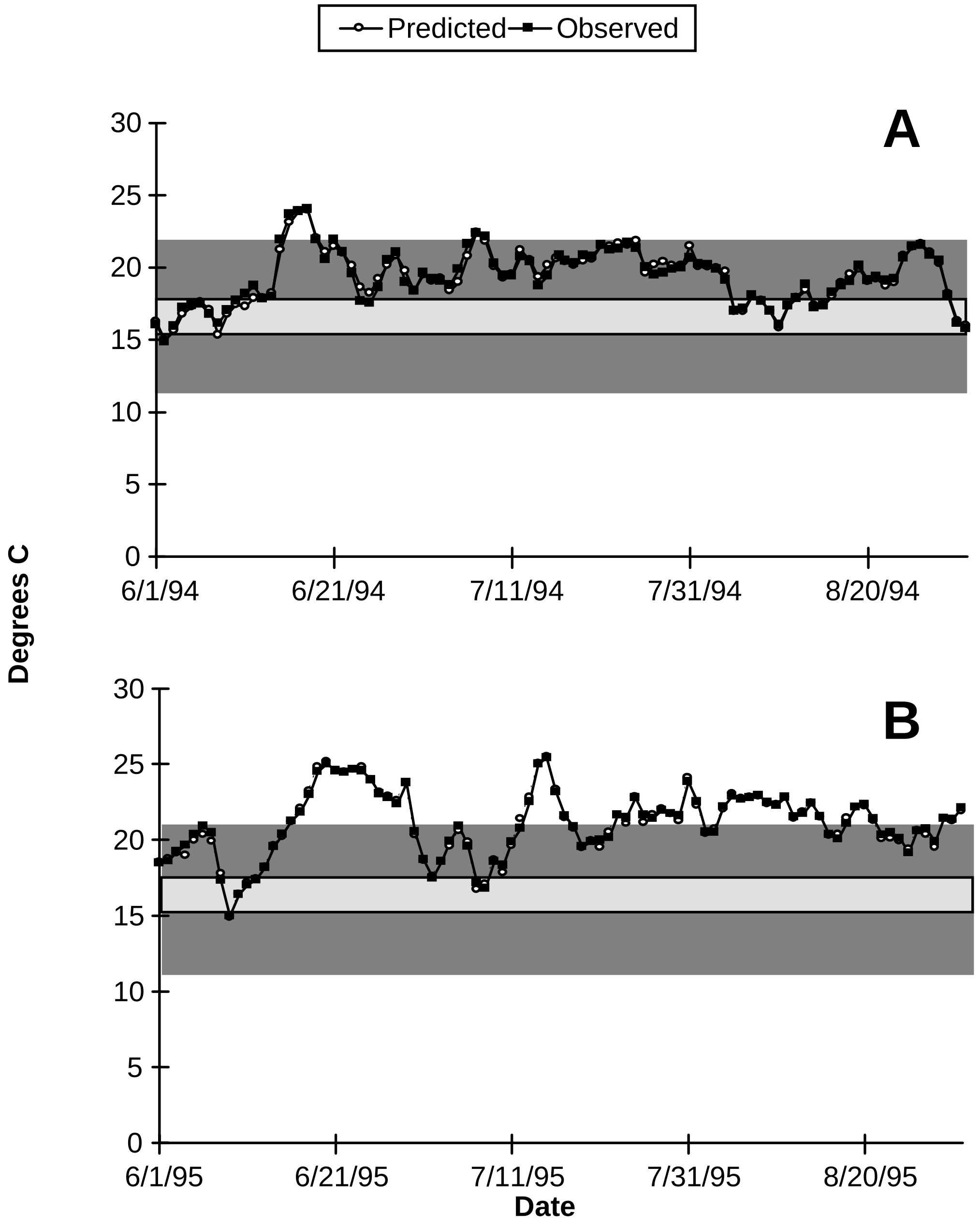
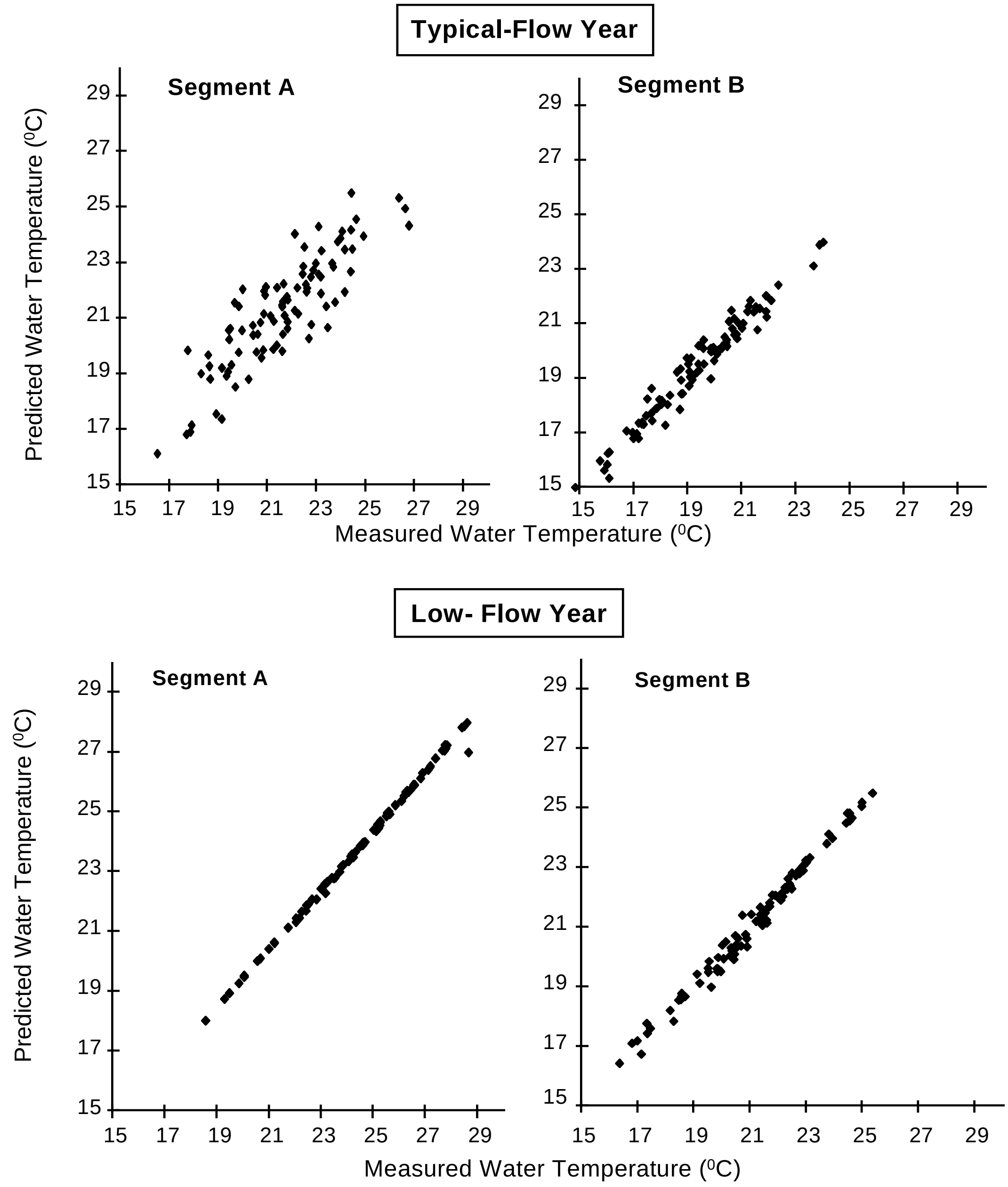


Figure 7. Measured and predicted summer temperatures from the stream reach temperature model for segment B, Grass Lake to Thompsonville, in the Betsie River during a typical-flow (a) and low-flow water year (b). The large shaded area denotes temperatures preferred by juvenile steelhead and the smaller inner rectangle indicates the optimum growth temperatures for juvenile steelhead (Hokanson et al 1977, Wismer and Christie 1987).


Typical-Flow Year

Low- Flow Year

Figure 8. Predicted and measured mean daily temperature for segment s A and B in the Betsie River for a typical-flow and low-flow water year.

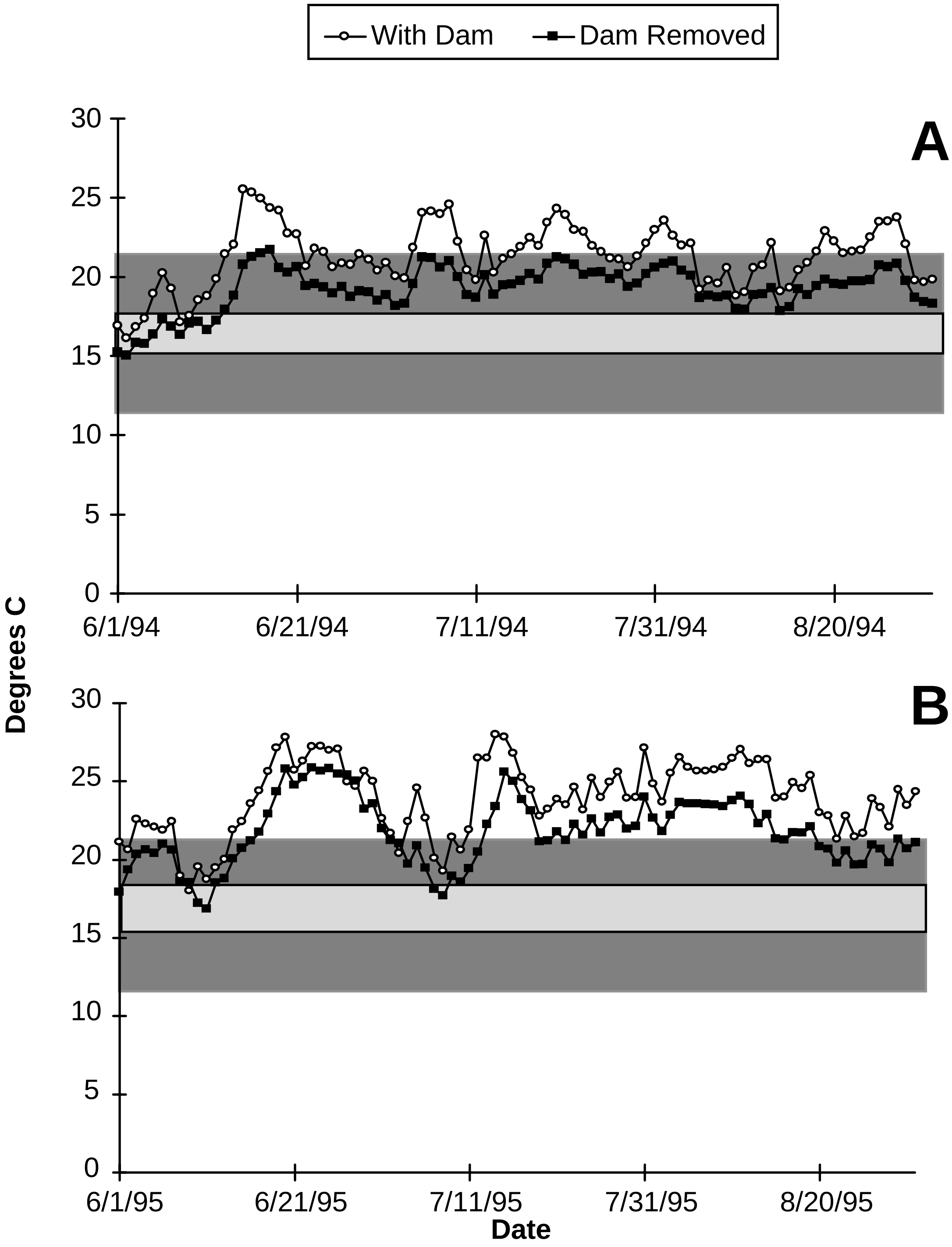


Figure 9. Comparison of temperatures under current conditions with Grass Lake Dam and simulated conditions of dam removal in a typical- (A) and low-flow (B) water year for Segment A. Shaded area indicates temperatures preferred by juvenile steelhead and smaller rectangle depicts optimal growth temperatures (Hokanson et al. 1977, Wismer and Christie 1987).

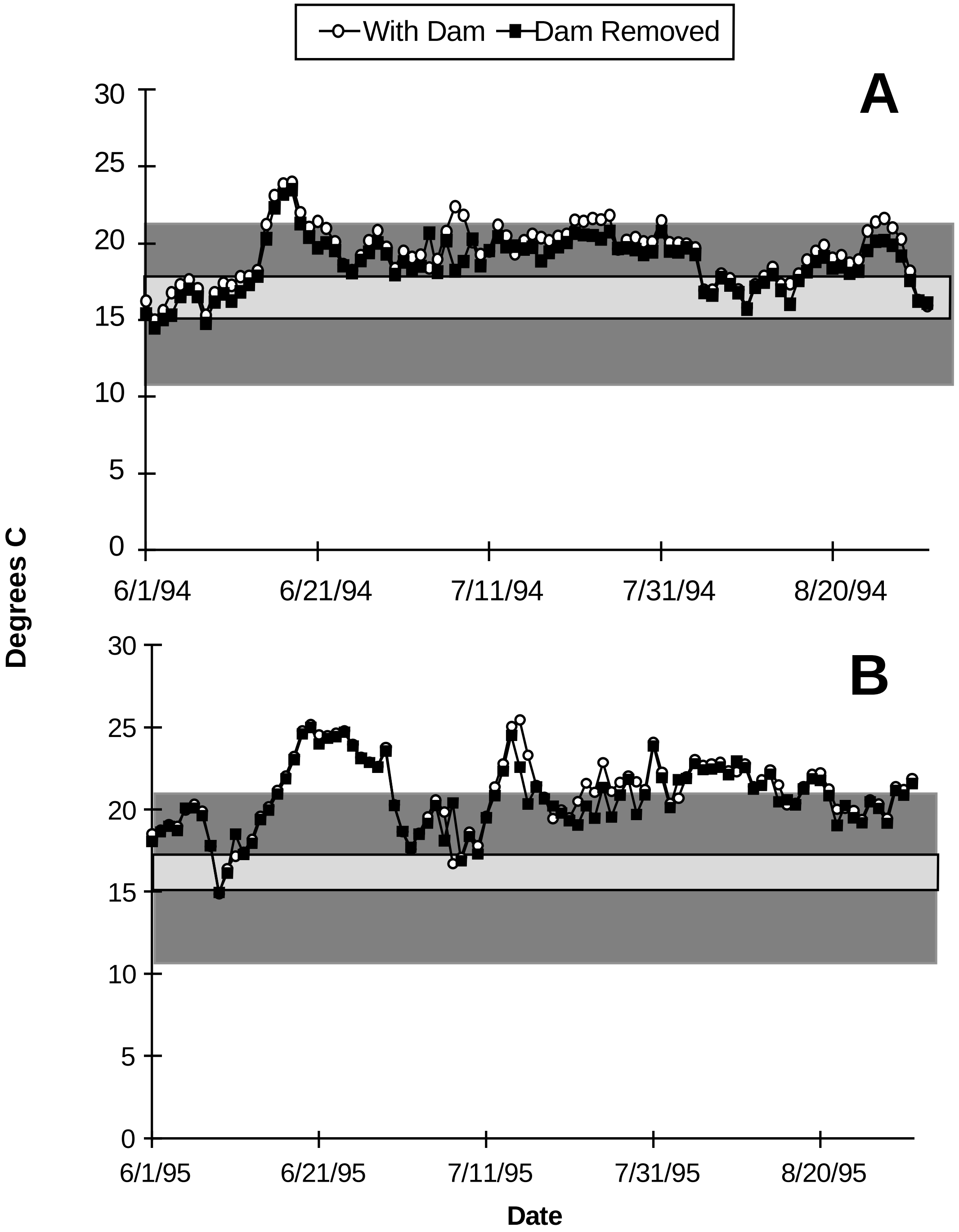


Figure 10. Comparison of water temperatures from Grass Lake Dam to Thompsonville under current conditions with Grass Lake Dam present and simulated conditions with the dam removed for a typical- (A) and low-flow (B) year. Large shaded area indicates preferred temperatures for juvenile steelhead and small inner rectangle depicts optimum growth limits (Hokanson et al. 1977, Wismer and Christie 1987).

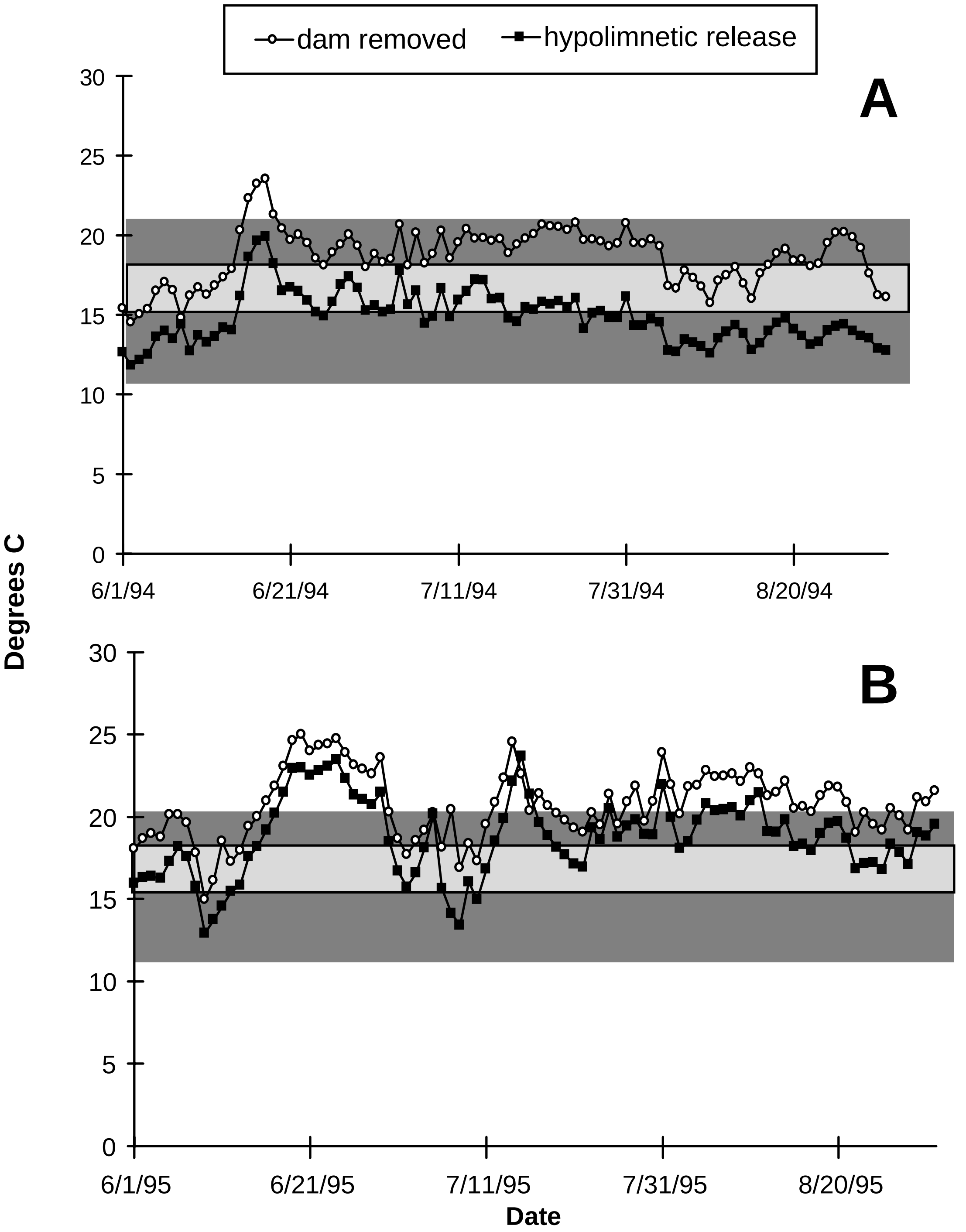


Figure 11. Comparison of water temperatures simulated for the dam removal and the addition of cold hypolimnion water in the Grass Lake to Thompsonville reach of the Betsie River in a typical- (A) and low-flow (B) water year. Shaded area represents water temperatures preferred by juvenile steelhead and smaller rectangle depicts optimum growth ranges (Hokanson et al. 1977, Wismer and Christie 1987).

Literature Cited

Adams, S. M. and J. E. Breck. 1990. Bioenergetics. Pages 389-415 *in* C. B. Schreck and P. B. Moyle, editors. Methods for fish biology. American Fisheries Society, Bethesda, Maryland.

Barthalow, J. M. 1989. Stream temperature investigations: field and analytic methods. Instream Flow Information Paper No. 13. U.S. Fish and Wildlife Service Biological Report 89(17). 139p.

Biette, R. M. and D. P. Dodge, R. L. Hassinger, and T. M. Stauffer. 1981. Life history and timing of migrations and spawning behavior of rainbow trout (Salmo gairdneri) populations of the Great Lakes. Canadian Journal Fisheries and Aquatic Sciences 38:1759-1771.

Bilby, R. E. 1984. Characteristics and frequency of cool-water areas in a western Washington stream. Journal of Freshwater Ecology 2:593-602.

Bonham, M. 1975. As assessment of the Betsie River trout population since chemical rehabilitation in 1965. Michigan Department of Natural Resources, Fisheries Division, Lansing, Michigan.

Bullen, B. 1972. Green Lake (Grand Traverse Co.) - Grass Lake (Benzie Co.) habitat improvement project. Michigan Department of Natural Resources, Fisheries Division, Roscommon, Michigan.

Carbine, W. F. 1945. An investigation of Grass Lake, Benzie County, to determine whether fish would benefit from any elevation of the water level. Institute for Fisheries Research, Ann Arbor, Michigan.

Cherry, D. S., K. L. Dickson, J. Cairns Jr., and J. R. Stauffer. 1977. Preferred, avoided and lethal temperatures of fish during rising temperature conditions. Journal of the Fisheries Research Board of Canada 34: 239-246.

Coutant, C. 1976. Thermal effects on fish ecology. Pages 1057-1063 *in* J. R. Pfafflin and E. N. Ziegler, editors, Encyclopedia of environmental science and engineering. Gordon and Breach Science Publishers. New York.

Coutant, C. 1977. Compilation of temperature preference data. Journal of the Fisheries Research Board of Canada 34:739-745.

Crisp, D. T. and G. Howson. 1982. Effect of air temperature upon mean water temperature in streams in the North Pennines and English Lake District. Freshwater Biology 12:359-367.

Elliott, J. M., M. A. Hurley, and R. J. Fryer. 1995. A new, improved growth model for brown trout, *Salmo trutta*. Functional Ecology 9:290-298.

Gordon, N. D., T. A. McMahon, and B. L. Finlayson. Stream Hydrology: An introduction for ecologists. John Wiley and Sons, New York. 526p.

Griffith, J. S. 1993. Coldwater streams. Pages 405-426 *in* C. C. Kohler and W. A. Hubert, editors. Inland fisheries management in North America. American Fisheries Society, Bethesda, Maryland.

Hokanson, K. E. F., C. F. Kleiner, and T. W. Thorslund. 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth rate and mortality rates and yield of juvenile rainbow trout, *Salmo gairdneri*. Journal of the Fisheries Research Board of Canada 34: 639-648.

Houston, A. H. 1982. Thermal effects upon fishes. Report NRCC No. 18566. National Research Council of Canada. Associate Committee on Scientific Criteria for Environmental Quality. 200p.

Latta, W. C. 1974. A history of the introduction of fishes into Michigan. Pages 83-96 in Michigan Fisheries Centennial Report, 1873-1973. Michigan Department of Natural Resources. Fisheries Division. Lansing.

National Climatic Data Center. Periodic. Local climatological data. Asheville, NC.

Newcomb, T. J. and T. G. Coon. 1997a. Evaluation of alternate methods for estimating number of outmigrating steelhead smolts. Michigan Department of Natural Resources, Fisheries Division, Fisheries Research Report.

Newcomb, T. J. and T. G. Coon. 1997b. Density, distribution and survival of steelhead parr in a thermally diverse watershed. Michigan Department of Natural Resources, Fisheries Division, Fisheries Research Report.

Nielsen, J. L., T. E. Lisle, and V. Ozaki. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Transactions of the American Fisheries Society 123:613-626.

Rakoczy, G. P. and R. D. Rogers. 1987. Sportfishing catch and effort from the Michigan waters of Lakes Michigan, Huron, and Erie, and their important tributary streams, April 1, 1986-March 31, 1987 (Appendices). Michigan Department of Natural Resources, Fisheries Division, Fisheries Technical Report No. 87-6b.

Rakoczy, G. P. and R. D. Rogers. 1988. Sportfishing catch and effort from the Michigan waters of Lakes Michigan, Huron, and Erie, and their important tributary streams, April 1, 1987-March 31, 1988 (Appendices). Michigan Department of Natural Resources, Fisheries Division, Fisheries Technical Report No. 88-9b.

Rakoczy, G. P. and R. D. Rogers. 1990. Sportfishing catch and effort from the Michigan waters of Lakes Michigan, Huron, and Erie, and their important tributary streams, April 1, 1988-March 31, 1989 (Appendices). Michigan Department of Natural Resources, Fisheries Division, Fisheries Technical Report No. 90-2b.

Smith, K. and M. E. Lavis. 1975. Environmental influences on the temperature of a small upland stream. Oikos 26:228-236.

SAS Institute Inc. 1988. SAS/STAT® User's Guide, Version 6, Fourth Edition, Volume 2, Cary, North Carolina. 846 pp.

Scott and Crossman. 1973. Freshwater fishes of Canada. Fisheries Research Board of Canada. Bulletin 184. 966p.

Stoneman, C. L. and M. L. Jones. 1996. A simple method to classify stream thermal stability with single observations of daily maximum water and air temperatures. North American Journal of Fisheries Management 16:728-737.

Theurer, F. D., K. A. Voos, and W. J. Miller. 1984. Instream water temperature model. Instream Flow Information Paper 16. U.S. Fish and Wildlife Service FWS/OBS-84/15. 250p.

Wedemeyer, G. A., R. L. Saunders, and W. C. Clarke. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Marine Fisheries Review 42:1-14.

Wicklund, R. G. and B. C. Dean. 1958. Betsie River Watershed: Survey and plans report. Michigan Department of Conservation, Fish Division, Lake and Stream Improvement Section. Lansing, Michigan.

Zaugg, W. S. and H. H. Wagner. 1973. Gill ATPase activity related to parr-smolt transformation and migration in steelhead trout (Salmo gairdneri): influence of photoperiod and temperature. Comparative Biochemistry and Physiology 45B:955-965.