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SIMULATING EFFECTS OF HYDRO-DAM ALTERATION ON THERMAL REGIME AND WILD STEELHEAD RECRUITMENT IN A STABLE-FLOW LAKE MICHIGAN TRIBUTARY

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ABSTRACT

Hydroelectric dams may affect anadromous fish survival and recruitment by limiting access to upstream habitats and adversely affecting quality of downstream habitats. In the Manistee River, a tributary to Lake Michigan, two hydroelectric dams potentially limit recruitment of anadromous rainbow trout (steelhead) by increasing tailrace water temperatures to levels that significantly reduce survival of young-of-year (YOY) fish. The objectives of this study were to determine whether proposed restoration scenarios (dam removals or a bottom withdrawal retrofit) would alter the Manistee River thermal regime and, consequently, improve wild steelhead survival and recruitment. Physical process models were used to predict Manistee River thermal regimes following each dam alteration scenario. Empirical relationships were derived from historical field surveys to quantify the effect of temperature on YOY production and potential recruitment of Manistee River steelhead. Both dam alteration scenarios lowered summer temperatures and increased steelhead recruitment by between 59% and 129%, but total recruitments were still low compared to other Great Lakes tributaries. Considering only temperature effects, bottom withdrawal provides the greatest promise for increasing natural steelhead recruitment by decreasing the likelihood of year-class failures in the warmest summers. Results of this study may allow managers to evaluate mitigation alternatives for Manistee River dams during future relicensing negotiations, and illustrate the utility of physical process temperature models in groundwater-fed rivers. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: temperature modeling; dam removal; hypolimnetic withdrawal; groundwater; river restoration; steelhead; Great Lakes; recruitment

INTRODUCTION

Anadromous rainbow trout, or steelhead (*Oncorhynchus mykiss*) were introduced to the Great Lakes in the late 1880s and now contribute to the valuable Great Lakes sport fishery. Although naturally reproducing steelhead runs are established in many Great Lakes tributaries (Biette *et al*., 1981), steelhead populations in most of the Great Lakes are currently sustained by stocking. In Lake Michigan, for example, approximately 70% of all steelhead caught are of hatchery descent (Rand *et al*., 1993). As in their native Pacific range, natural steelhead recruitment in many Great Lakes tributaries may be limited by dams that fragment spawning and nursery habitats, and alter flow and water quality patterns (Petts, 1984; Newcomb, 1998).

In the Manistee River, a Lake Michigan tributary in northwestern Lower Michigan, two hydroelectric dams appear to limit wild steelhead recruitment. First, neither dam has fish passage, preventing steelhead access to potential spawning and nursery habitats upstream. Second, both dams pass warm surface water from their reservoirs to produce electricity. Top withdrawal operation may raise tailrace temperatures sufficiently high in summer to significantly lower survival of young-of-year (YOY) steelhead. In the Manistee River, most steelhead spawn in

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March–April, and fry hatch at 2.8–3.0 cm from mid- to late May through to early June, reaching a size of 5–6 cm by July or August. Mean July and August water temperatures below Tippy Dam, the dam furthest downstream, frequently exceed the average monthly temperature limit of 20°C imposed in licences issued by the Federal Energy Regulatory Commission (Rozich, 1998), coinciding with the period of high mortality for steelhead fry (Woldt, 1998).

The potential for reducing summer water temperatures and enhancing wild steelhead recruitment is higher in the Manistee River than in any other Lake Michigan tributary. The Manistee River receives up to 90% of its annual flow from groundwater accrual (Hendrickson and Doonan, 1972; Berry, 1992), making it one of the most hydrologically and thermally stable rivers in the United States (Wiley *et al*., 1997). The importance of stable flow and temperature to the survival and recruitment of salmonids is well established (Latta, 1965; Hendrickson and Knutilla, 1974; Hall and Knight, 1981; Seelbach, 1993; Hinz and Wiley, 1997). Both Manistee River dams were constructed before adequate temperature records existed for the river. It is possible that without dams, the Manistee River could provide near-deal hydrologic and thermal habitat for rearing of steelhead. In contrast, potential of other fragmented Lake Michigan tributaries to produce steelhead is limited by their more southerly locations, less stable discharges, or relatively low abundances of suitable spawning habitat.

The overall objective of this study was to predict Manistee River summer temperatures and subsequent steelhead survival and recruitment under two different dam alteration scenarios. Specific objectives were to: (1) calibrate and use a heat transport model to predict river temperatures following hypothetical removal of both Manistee River dams; (2) calibrate and use a reservoir model to predict tailrace temperatures following a hypothetical mid-summer switch of Tippy Dam from top to bottom withdrawal; (3) develop statistical relationships between summer water temperature and YOY steelhead density from previous studies; and (4) use these models to predict change in steelhead smolt abundance below Tippy Dam under each temperature mitigation scenario. Although temperature models have been used to assess dam alterations under a variety of geographic, hydrologic, and climatic conditions (Wilson *et al*., 1985; Bevelhimer *et al*., 1997; Newcomb, 1998; Hanna *et al*., 1999), including the effect of aquifer pumping on river temperature in a spring-fed system (Saunders *et al*., 2001), this study represents the first use of process-based temperature models to predict thermal regimes in a predominantly groundwater-fed river.

STUDY SITE

The Manistee River flows approximately 370 km from its headwaters in the north-central portion of Michigan's Lower Peninsula to its mouth at Lake Michigan (Figure 1), draining 4 557 km^2 of highly permeable outwash and end moraines. Average annual discharge below Tippy Dam is 58.5 $m^3 s^{-1}$, and average flows during April and August are 84.8 $m^3 s^{-1}$ and 47.1 $m^3 s^{-1}$, respectively. Tippy Dam, built in 1924 approximately 60 km upstream from Lake Michigan, and Hodenpyl Dam, built in 1928 and 30 km further upstream of Tippy Dam, are situated on some of the highest gradient (up to 5 m km^{-1}) reaches in the river. Tippy Dam impounds a reservoir of approximately 37×10^6 m^3 with an average width of 400 m and maximum depth of 14 m. Hodenpyle Pond is larger (58×10^6 m^3), wider (650 m) and deeper (18 m maximum depth) than Tippy Pond. There is little development along most of the Manistee River and, as a result, its banks are well vegetated by species typical of eastern hardwood forests. The majority of natural recruitment of steelhead is currently limited to a 3 km reach immediately below Tippy Dam (Rozich, 1998). Further downstream, salmonid rearing habitat decreases in quality and abundance as the river widens (up to 65 m), deepens (>2 m), levels (<0.5 m km^{-1}), and becomes increasingly sandy.

Mean temperature of water entering Hodenpyl Pond ranges between 18°C and 20°C in July. Mean July temperature below Tippy Dam ranges between 1.5°C to 2.5°C higher depending on climatic conditions (Table I). Both dams reduce diel temperature fluctuation from more than ±1.0°C upstream to less than ±0.3°C downstream.

METHODS

Physical process models were calibrated and used to simulate the potential for proposed dam alteration scenarios to mitigate high summer temperatures and increase steelhead recruitment in the Manistee River (Figure 2). The models incorporated physical stream attributes and heat flux processes that affect water temperature (evaporation, conduction, convection, radiation, and friction), making them suitable for temperature prediction following physical alteration of channel or dam. Thermal regimes were predicted and their effects on steelhead recruitment were

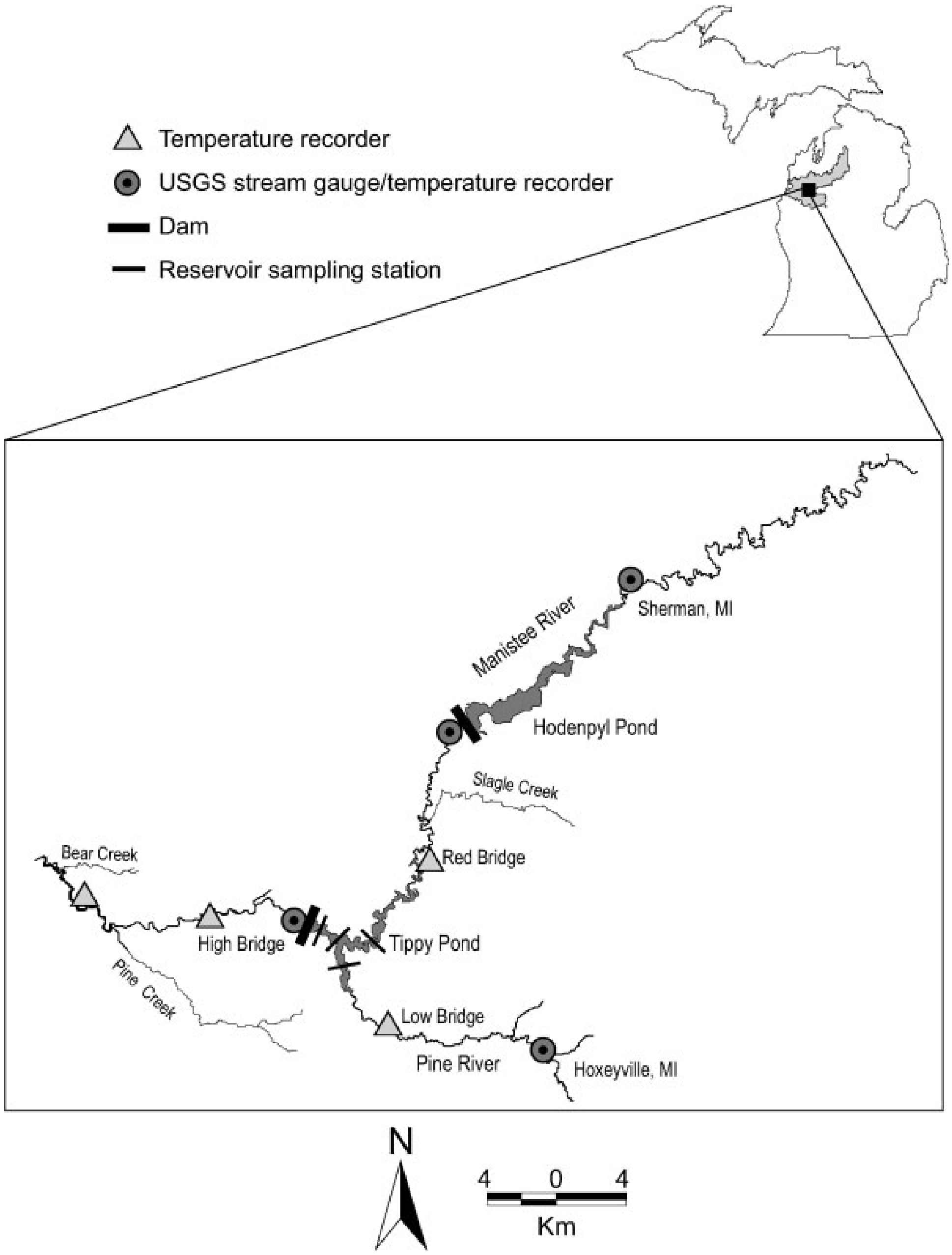

Figure 1. Location of dams, temperature recorders, and US Geological Survey stream gauge/temperature recorders in the Manistee and Pine rivers, Michigan

estimated following hypothetical dam removals and bottom withdrawal retrofits for the summers of 1999 and 2000, a relatively warm and cool summer, respectively. Thermal regimes following dam removals also were predicted for the summer of 1997, a year in which YOY steelhead densities were estimated (Woldt, 1998). Temperature regimes following bottom withdrawal retrofits were not predicted for 1997 because no temperature profiles were available to calibrate the model this year. For all scenarios, steelhead recruitment was predicted for the area below Tippy Dam; additional recruitment that may result from access to newly available upstream habitats under dam removal was not included. In this way, it was possible to compare the effect of each scenario on steelhead recruitment resulting only from changes in temperature.

Table I. Average monthly temperatures (°C) in Manistee River during May to September, 1997 to 2000. Average summer temperatures (May–September, inclusive) are reported with average daily temperature fluctuation (°C above and below mean temperature)

Year	Month	Hodenpyl Pond inflow	Hodenpyl Dam tailrace	Tippy Pond inflow	Tippy Dam tailrace	High Bridge
1997	May	10.0	10.5	—	10.5	10.8
	June	17.4	16.9	—	17.4	18.2
	July	18.4	20.5	—	20.5	20.9
	August	15.9	18.9	—	18.9	19.1
	September	13.5	16.2	—	16.3	16.4
	Summer	15.0 ± 0.9	16.6 ± 0.2	—	16.7 ± 0.3	17.1 ± 1.0
1998	May	15.8	15.6	—	15.7	—
	June	17.0	17.7	—	18.4	—
	July	19.2	21.0	—	21.7	—
	August	18.3	20.5	—	21.1	—
	September	15.3	18.6	—	18.9	—
	Summer	17.1 ± 1.1	18.7 ± 0.2	—	19.2 ± 0.3	—
1999	May	14.2	14.0	—	14.4	—
	June	18.6	18.8	—	19.1	—
	July	20.0	21.3	—	21.6	—
	August	17.7	20.5	—	20.7	—
	September	13.9	17.5	—	17.7	—
	Summer	16.9 ± 1.1	18.4 ± 0.2	—	18.7 ± 0.3	—
2000	May	14.3	13.6	14.2	14.1	14.8
	June	17.3	17.8	18.2	18.0	18.7
	July	17.9	20.1	20.0	20.3	20.9
	August	17.5	19.7	19.7	20.0	20.5
	September	14.3	18.0	18.0	17.9	18.8
	Summer	16.3 ± 1.1	17.8 ± 0.2	18.0 ± 1.2	18.1 ± 0.3	18.7 ± 1.1

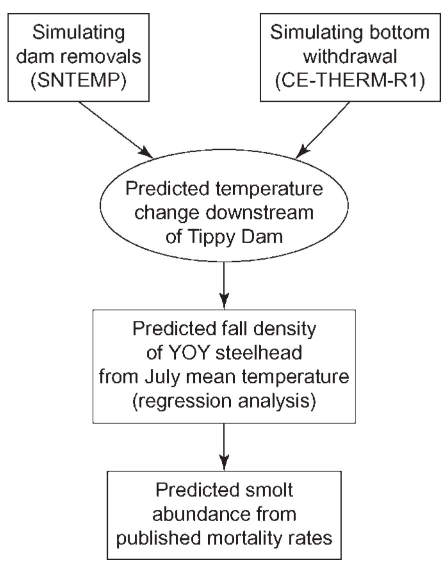

Figure 2. Flow diagram of models and analysis used to determine impacts of dam removals or bottom withdrawal on stream temperatures in Manistee River, MI

Predicting river temperatures following dam removals

SNTEMP, a model developed by the US Fish and Wildlife Service (Theurer *et al*., 1984), was used to predict Manistee River temperatures following removal of both Manistee River dams. SNTEMP considers dams to be discontinuities in the downstream transport of water and heat and 'resets' discharge and temperature below each dam encountered to those of measured outflow temperature. However, once reaches above and below dams have been calibrated, these discontinuities can be removed and temperatures in the free-flowing river can be predicted.

SNTEMP data requirements and data sources. SNTEMP requires a spatially defined network describing sources of discharge, changes in stream geometry or shade, locations of dams or diversions, and points of known water temperature. A network was used that extended from Sherman, MI, to the High Bridge road crossing below Tippy Dam, a distance of approximately 68 river kilometres (Figure 1). Also included was the 22 km reach of the Pine River downstream of Hoxeyville, MI, the only tributary contributing >10% of mainstem flows between Sherman and High Bridge.

SNTEMP requires that data be provided on a time-step of sufficient duration to allow water to move through the network within the allotted time-step. It was determined that, without dams, the relatively high gradient and low flow resistance of the Manistee River would allow passage of water through the network in less than 24 hours. Therefore, a daily time-step was used because of the importance of daily temperature fluctuation to YOY steelhead survival.

SNTEMP requires data describing four components that collectively affect stream temperature: hydrology, stream geometry, stream shade, and meteorology (Appendix 1). Water temperature and discharge data were obtained from United States Geological Survey (USGS) stream gauges at network headwaters and dams. Groundwater inflow was estimated for six discrete model reaches (Table II) using a spatially explicit (ArcView 3.2, ESRI Inc.) model of groundwater velocity in Michigan's Lower Peninsula (Paul Seelbach, Michigan Department of Natural Resources, Ann Arbor, Michigan, unpublished data). Predicted groundwater velocities were summarized within 100 m buffers of each river segment, and values were standardized by segment length. Standardized predictions were regressed against known groundwater accrual rates (change in discharge between upstream and downstream locations during base-flow conditions and standardized by segment length) for each segment. The regression is described by the equation:

$$y = 1.67 \times 10^{-5} + 5.62 \times 10^{-8} x \tag{1}$$

where y = groundwater accrual rate ($m^3\,s^{-1}\,m^{-1}$) and x = total groundwater velocity m^{-1}. Length-standardized groundwater velocity summaries were calculated for specific reaches within the SNTEMP network model and Equation 1 was used to predict groundwater accrual for each reach (Table II). Average groundwater temperature

Table II. Estimated groundwater accrual rates for discreet reaches in the Manistee River, Pine River, and their tributaries

River	Reach	Mainstem accrual ($m^3\,s^{-1}$)	Tributary accrual ($m^3\,s^{-1}$)	Total accrual ($m^3\,s^{-1}$)
Manistee	USGS gauge at Sherman, MI, to Hodenpyl Dam	1.13	1.12	2.25
	Hodenpyl Dam to Red Bridge	1.07	1.41[a]	2.48[a]
	Red Bridge to Tippy Dam	1.13	0.52	1.65
	Tippy Dam to High Bridge	0.51	0.00	0.51
	High Bridge to Bear Creek	0.51	0.40[b]	0.91[b]
	Total Manistee accrual			7.80
Pine	USGS gauge at Hoxeyville, MI, to Manistee R. confluence	1.34	0.17	1.51
Total model accrual				9.31

[a] Includes the surveyed base-flow discharge of Slagle Creek (1.13 $m^3\,s^{-1}$).
[b] Includes the surveyed base-flow discharge of Pine Creek (0.40 $m^3\,s^{-1}$).

was estimated to be 10°C from periodic measurement of groundwater seeps in the watershed during the summers of 1999 and 2000. Base-flow temperature and discharge data for two high-volume groundwater tributaries, Slagle and Pine creeks, were entered as point sources to more accurately represent their spatial cooling potential rather than use the default assumption of uniform accrual of groundwater over a model reach.

USGS stream gauge elevations, topographic maps, and stream gradients (Rozich, 1998) were used to estimate elevations above sea level. Manning's number was estimated and width–discharge relationships were developed for each reach of homogenous stream geometry from physical habitat simulations (PHABSIM) conducted for recent relicensing of Tippy and Hodenpyl dams (Ichthyological Associates, 1991a,b).

Shade provided by topography and stream-side vegetation was estimated by measuring height of, and distance to banks and vegetation at four transects within each reach of homogenous stream-side vegetation with a laser range finder (Atlanta Laser Optics Inc.). Along each bank, vegetative density was estimated by multiplying vegetative continuity (quantity), averaged from independent observations of two observers, by shade quality, estimated with the light meter technique described by Bartholow (1989).

Stream-side air temperature and relative humidity were measured hourly during summer 2000 with a Hobo H8 Pro-Series data logger (Onset Computer Corp.) located between Hodenpyl and Tippy dams. Estimates of wind speed and percentage possible sunshine were obtained for 1999 and 2000 from Local Climatological Data (LCD) at Roscommon County Airport in Houghton Lake, MI, approximately 90 km from Tippy Dam. A model subroutine (SSSolar) was used to estimate ground-level solar radiation based on percentage possible sunshine at Houghton Lake. Air temperature and relative humidity data were estimated for 1999 from significant ($p < 0.001$) regressions developed between stream-side and Houghton Lake measurements in summer 2000.

SNTEMP calibration. Data from Hobo temperature recorders set at the Red Bridge, High Bridge, and Low Bridge road crossings were used to calibrate mean daily temperature predictions in stream reaches between Hodenpyl Dam and Tippy Pond, below Tippy Dam, and in the Pine River, respectively (Figure 1). A temperature recorder set upstream of Bear Creek was used to calibrate maximum daily temperature predictions below Tippy Dam (Figure 1). This recorder was necessary because water was calculated to take less than six hours, the minimum travel time assumed by SNTEMP when calculating maximum temperature, to travel downstream from Tippy Dam to High Bridge. Conversely, the recorder upstream of Bear Creek was calculated using Manning's equation (Allan, 1995) to be eight hours downstream from Tippy Dam.

Sensitivity analyses were performed for each model segment using SSTEMP, a simplified reach version of SNTEMP. Model predictions were most sensitive to groundwater discharge, groundwater temperature, and ground-level solar radiation, and therefore these variables were systematically adjusted to calibrate the model. These variables were used for calibration because we could not be certain our estimates actually represented conditions occurring at the river. The model was first calibrated for 2000, then re-run with hydrologic and meteorological data from 1999. Predicted and observed temperatures were compared and model parameters adjusted as necessary until model predictions of average daily temperature met goodness-of-fit criteria suggested by Bartholow (1989) for both years. Goodness-of-fit criteria were slightly relaxed for model predictions of maximum daily temperature due to the empirical rather than process-based estimates calculated by SNTEMP. No temperature recorder was set between Hodenpyl Dam and Tippy Pond in 1999 so verification of this reach was not possible. Calibration statistics for average and maximum daily temperatures are presented in Table III.

SNTEMP simulations. Removal of Manistee River dams was simulated by removing dams from the input files and re-running the model to simulate how heat would accumulate in the river if the river were allowed to flow downstream unhindered. Temperature simulations were run from May to September. Stream geometry and shade for impounded reaches after removing dams was assumed equal to values measured in river reaches upstream and downstream of Hodenpyl and Tippy dams.

Predicting river temperatures with bottom withdrawal

CE-THERM-R1, the stand-alone thermal component of the US Army Corps one-dimensional reservoir model CE-QUAL-R1 (Environmental Laboratory, 1995), was used to predict tailrace temperatures following hypothetical switch of Tippy Dam from top to bottom withdrawal. Hypothetical switch of Hodenpyl Dam to bottom draw was beyond the scope of this project and was not simulated. CE-THERM-R1 uses known heat fluxes to model the

Table III. Validation statistics for average and maximum daily water temperature predictions in SNTEMP model of Manistee River

River	Location	1999			2000		
		Mean error[a] (°C)	Dispersion error[b] (%)	Maximum error[c] (°C)	Mean error[a] (°C)	Dispersion error[b] (%)	Maximum error[c] (°C)
Predicted averages							
Manistee	Red Bridge[d]	—	—	—	0.27	0	−0.93
	High Bridge	0.39	2	−1.30	0.36	0	−0.98
Pine	Low Bridge	0.45	8	1.59	0.43	7	−1.34
Predicted maxima							
Manistee	Red Bridge[d]	—	—	—	0.45	4	1.18
	Bear Creek	0.52	12	1.72	0.60	16	−1.98
Pine	Low Bridge	0.65	20	2.26	0.55	16	1.69

[a] Mean of the absolute differences between predicted and observed temperatures in simulation period.
[b] Percentage of total days in simulation period (153 days) when predicted temperatures differed from observed temperatures by more than 1°C.
[c] Maximum difference between predicted and observed temperatures on any given day in simulation period.
[d] Temperature data from Red Bridge were unavailable for 1999 and, therefore, the model reach between Hodenpyl Dam and Tippy Pond could not be validated. For this reach, only original calibration statistics are shown.

physical movement and storage of heat in a reservoir over time. When calibrated, CE-THERM-R1 can be used to predict outflow temperatures following alteration of dam generation schedule or intake port configuration.

CE-THERM-R1 data requirements and data sources. CE-THERM-R1 requires data for variables that determine the thickness of individual layers of homogeneous water density. These include an initial set of vertical temperature profiles taken as close to spring turnover as possible, a relationship describing reservoir volume, the elevation and dimension of existing dam intake ports, and time-sequenced updates for inflow discharge, solid concentrations, and temperature, outflow release, and specific meteorological parameters. The day outflow temperatures reached 5°C was selected as the simulation start date, the temperature at which spring turnover is most likely to occur (Wetzel, 1983).

CE-THERM-R1 allows reservoir inflow from only two tributaries. However, Tippy Pond receives inflow from three sources: the Manistee mainstem, the Pine River, and groundwater seepage. To accommodate all inflows, Manistee River and Pine River discharges were combined, and weighted averages of daily temperature, and dissolved and suspended solid concentrations were calculated to allow their entry as one tributary.

Physical and chemical inputs were measured for the CE-THERM-R1 model from direct measurement of Tippy Pond. Vertical temperature and conductivity profiles were measured with a YSI-85 (Yellow Springs Instruments Inc.). Light penetration was measured with a Secchi disc, and water samples were collected with a Kemmerer water sampler at 1 m intervals at a site approximately 300 m upstream of Tippy Dam in 1999 and 2000 (Figure 1). Initial profiles were made on 4 May, just after stratification had begun, and monthly thereafter in summer 2000. In 1999, profiles were measured only on 27 July, when reservoir stratification was likely to be greatest. Total dissolved solids ($\mathrm{mg\,l^{-1}}$) were calculated from specific conductivity measurements (Environmental Laboratory, 1995), and water samples were analysed for total suspended solids ($\mathrm{mg\,l^{-1}}$) according to Standard Methods (American Public Health Association *et al*., 1992). Monthly profiles from three additional sites in summer 2000 (Figure 1) validated the lateral and longitudinal homogeneity of Tippy Pond and the appropriateness of CE-THERM-R1 for this application.

Time-sequenced input data were obtained from direct measurement or statistical approximation. Daily Manistee River and Pine River flows entering Tippy Pond were calculated from USGS stream gauges plus the accumulated groundwater between gauges and reservoir estimated with the groundwater accrual model (Equation 1) previously described. Daily inflow temperature from the Manistee River and Pine River were obtained from the same temperature recorders used for the SNTEMP model (Figure 1). Total dissolved solids (TDS) and total suspended solids (TSS) were measured monthly in each river, and from these data, daily TDS and TSS values were calculated for each tributary from significant ($p < 0.05$) linear relationships between TDS, TSS and mean weekly and daily discharge, respectively. Continuous groundwater accrual beneath Tippy Pond ($2.25 \pm 1.96\,\mathrm{m^3\,s^{-1}}$) was estimated as the average difference between daily outflow and inflow discharge not accounted for by reservoir storage or precipitation.

Temperature, TDS, and TSS of groundwater inflow were assumed to be constant over the simulation period. Individual intake port flow ($m^3 s^{-1}$) was calculated from the USGS stream gauge below Tippy Dam and daily turbine generation records. Daily meteorological data were obtained from the same sources used in the dam removal model.

Physical descriptions of Tippy Pond and the existing intake port configuration of Tippy Dam were provided by Consumers Energy Company, the owner of Tippy Dam. A bathymetric map of Tippy Pond was digitized into a GIS, and relationships ($r^2 = 0.99$) were developed to describe reservoir layer area and withdrawal zone width as they changed with depth (Appendix 2).

CE-THERM-R1 calibration. Calibration of 1999 and 2000 models required two steps: calibration of reservoir water budgets, and calibration of stratification cycles over the summer simulation periods. Water budgets were calibrated by accounting for large precipitation events and adjusting evaporation rates as necessary so that the difference between predicted and observed reservoir elevations was within 0.5 m each day. Sensitivity analysis revealed that Tippy Pond stratification was most sensitive to groundwater discharge and temperature, and to light attenuation and reservoir wind-sheltering coefficients. These parameters were adjusted, and predicted and observed monthly temperature profiles were compared to calibrate the models. Calibration statistics for both years are presented in Table IV.

CE-THERM-R1 simulation. Bottom withdrawal retrofit of Tippy Dam was simulated by changing water withdrawal elevations from upper to lower intake ports in the calibrated model. Specifically, water was withdrawn from upper intake ports from spring turnover to the end of June, then all water withdrawal was switched to lower intake ports until the end of September, and finally returned to upper intake ports through October, the end of the simulation period. Dimensions and elevations of existing and hypothetical Tippy Dam intake ports are presented in Table V. In this way, the volume of cold water from which to draw was maximized by allowing the reservoir to at least partially stratify while at the same time accumulating groundwater in the reservoir's bottom.

Table IV. Calibration statistics for CE-THERM-R1 reservoir model simulations of Tippy Pond temperatures during summer, 1999 and 2000. '*n*' represents number of discrete depths for which model predictions and field observations were compared

Year	Date	n	Mean error[a] (°C)	r^2	Mean percentage error[b]
2000	4 May	15	1.86	0.93	19.2
	8 June	15	1.52	0.93	11.7
	19 July	14	1.08	0.95	9.8
	1 September	14	1.03	0.99	8.2
	28 September	14	0.69	0.79	7.1
	All dates	72	1.24	0.96	11.1
1999	27 July	11	0.85	0.98	6.3

[a] Mean (over all depths) of the absolute difference between predicted and observed temperatures.
[b] Mean (over all depths) of the percentages that the absolute difference between predicted and observed temperatures was of observed temperature.

Table V. Existing and hypothetical intake port statistics (dimension, elevation, and configuration) for Tippy Dam, MI. First and second numbers for hypothetical bottom withdrawal scenario relate to top and bottom intake ports, respectively

Parameter	Existing	Hypothetical
Number of intake ports	3	6
Height (m)	6.4	6.4/4.0
Width (m)	9.1	9.1/7.0
Centreline elevation[a] (m)	10.1	10.1/3.0
Intake floor elevation[a] (m)	6.9	6.9/1.0
Minimum total discharge ($m^3 s^{-1}$)	9.9	9.9
Maximum discharge per port ($m^3 s^{-1}$)	53.0	53.0/28.0

[a] Distance from reservoir bottom located at 196.0 m above sea level.

Estimating YOY parr density and smolt recruitment of Manistee River steelhead

Step-wise regression analysis was used to develop predictive models relating July stream temperature metrics (daily mean, maximum, minimum, and average fluctuation) to fall density of YOY steelhead. For rivers without simultaneous temperature records, average July weekly maximum, minimum, and mean temperatures were estimated using regression models developed by Wehrly *et al*. (1998) that predict stream temperature from various landscape variables. Historical data on fall densities of YOY steelhead were collected from surveys in 16 Lower Michigan rivers (Taube, 1975; Gowing and Alexander, 1980; Carl, 1983; Seelbach, 1993; Newcomb, 1998; Woldt, 1998; Godby, 2000; Rutherford *et al*., 2000). In all surveys, YOY steelhead densities were estimated from multiple-pass depletion methods (Seber and LeCren, 1967) with DC stream shockers. Statistical analyses were conducted using SPSS 9.0 (SPSS Inc.) and analyses were considered significant at the $\alpha = 0.05$ confidence level.

To estimate the contribution of naturally reproduced steelhead from the Manistee River to Lake Michigan, fall YOY cohort densities were adjusted to account for mortality during the 2+ years steelhead parr typically spend in the natal streams in Michigan (Seelbach, 1993). Therefore, density of steelhead smolts was predicted by multiplying fall YOY cohort densities by average daily mortality rates for the overwinter period (% dying d^{-1}, $A = 0.94\,d^{-1}$), the spring-to-fall yearling period ($A = 0.77\,d^{-1}$), and the yearling overwinter period ($A = 0.34\,d^{-1}$) before two-year old smolts leave the river. The period-specific daily mortality rates were averaged from values reported in the literature (Taube, 1975; Seelbach, 1987; Newcomb, 1998; Woldt, 1998; Godby, 2000). Total numbers of emigrating steelhead smolts were calculated by multiplying smolt density by the estimated steelhead nursery area below Tippy Dam (47.2 ha). The relative effectiveness of dam alteration scenarios to increase natural steelhead recruitment was compared using abundance estimates for each year for which temperature predictions were possible.

RESULTS

Predicted river temperatures following dam removals

Simulated removal of Tippy and Hodenpyl dams lowered predicted temperatures below Tippy Dam in all years (Figure 3). During the summer of 1999, one of the hottest on record, average summer (1 May to 30 September), water temperatures decreased approximately 1.0°C (from 18.7°C to 17.7°C), while during the relatively cool summer of 1997 (third coolest in last 30 years), average summer temperatures decreased 0.7°C (from 16.7°C to 16.0°C). Average summer water temperatures decreased 0.9°C, from 18.0°C to 17.1°C, in 2000. Similarly, average temperatures during July were lower in all years following hypothetical dam removals by 0.9 to 1.5°C.

Dam removals caused Manistee River temperatures to be more responsive to ambient climatic conditions. Temperatures with dams in place generally followed a smooth trajectory over the summer, gradually increasing in May and June, peaking in July and gradually decreasing in August and September. With dams hypothetically removed, temperatures were predicted to be much more variable from one day to the next (Figure 3). Removing the dams also increased average diel temperature fluctuation in the Manistee River immediately below the dam site from less than ± 0.5°C to almost ± 2°C in summer (Figure 3).

Removing Manistee River dams also returned a natural seasonal temperature oscillation to the river. The free-flowing river warmed up sooner in spring and cooled faster in fall than when impounded (Figure 3). In May, water temperatures were, on average 0.4°C, 1.0°C and 1.3°C warmer in 1997, 1999, and 2000, respectively, with dams removed. Conversely, in September, average water temperatures were between 1.7°C and 3.0°C cooler in the free-flowing river than in the impounded river.

Predicted average temperature and diel temperature fluctuation changed little at High Bridge, the downstream boundary of current steelhead nursery habitat in the Manistee River, from those predicted at Tippy Dam. The relatively short distance (*c*. 9 km) and high river volume were sufficient to moderate downstream warming between these two locations.

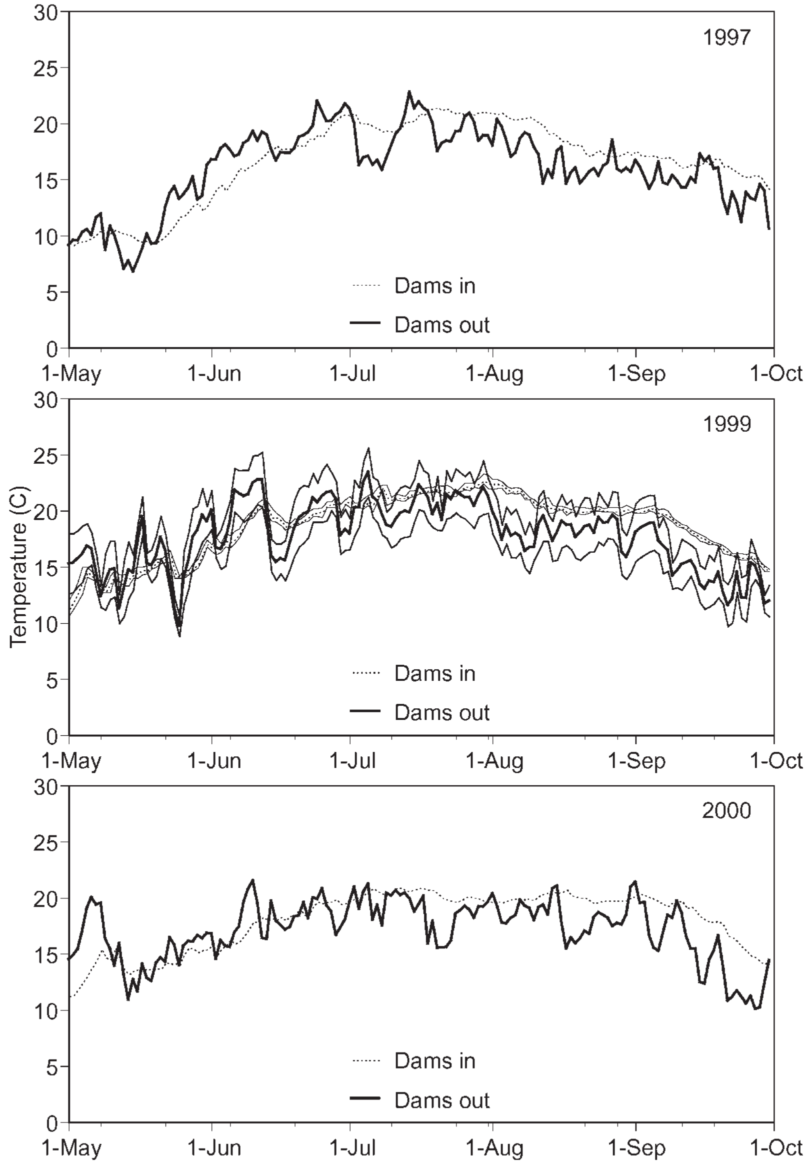

Figure 3. Comparison of Manistee River summer temperatures with dams in place (dotted line) and dams removed (solid line) during 1997, 1999, and 2000. Minimum and maximum temperatures are shown for both dam scenarios in 1999

Predicted river temperatures with bottom withdrawal

Hypothetical mid-summer switch of Tippy Dam from top to bottom withdrawal lowered predicted downstream water temperatures throughout the bottom withdrawal period (July to September). After initial drops of over 2.0°C, water temperatures downstream of Tippy Dam averaged approximately 19.0°C for the remainder of the bottom withdrawal period in both 1999 and 2000 (Figure 4). This switch to bottom withdrawal decreased tailrace temperatures an average of 1.2°C in 1999 and 0.9°C in 2000 compared to tailrace temperatures under top withdrawal over the same period. Average tailrace temperatures in July were 1.4°C and 1.2°C lower with the switch in 1999 and 2000, respectively, while average tailrace temperatures in August were reduced approximately 1.0°C in both years.

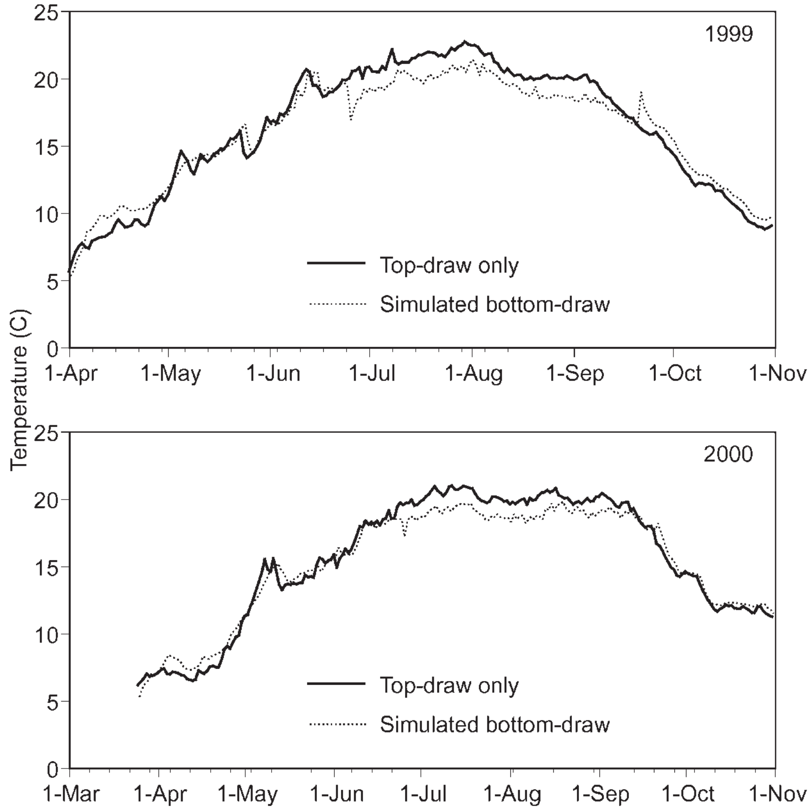

Figure 4. Comparison of tailrace temperatures below Tippy Dam with (dotted line) and without (solid line) hypothetical bottom withdrawal retrofit of Tippy Dam, 1999 and 2000

Estimated recruitment of Manistee River steelhead smolts

July mean temperature best predicted ($r^2 = 0.77$) the relationship between fall YOY steelhead density and temperature. The relationship was significant ($p < 0.005$) and was described by the formula:

$$\ln(y) = 17.659 - 0.577\,x \tag{2}$$

where y = fall density of YOY steelhead (number ha^{-1}) and x = mean of July temperatures (°C) above 17°C.

In 1999 and 2000, removing both dams or switching to bottom withdrawal increased the fall density of YOY steelhead parr and potential smolt abundance in the river (Table VI, Figure 5). However, the relative effectiveness of temperature mitigation strategies varied among years depending on ambient summer temperatures. In the relatively cool summers of 1997 and 2000, removing dams increased fall YOY parr densities and potential smolt abundances by 129% and 119%, respectively. Bottom withdrawal increased fall YOY parr density and smolt abundance only 84% in the summer of 2000. In contrast, bottom withdrawal increased fall parr density and smolt abundance by 108% in the relatively warm summer of 1999, while removing the dams increased fall parr density and smolt abundance by only 59%.

DISCUSSION

Hypothetical alteration of Manistee River thermal regime

Modelling suggested that mid-summer temperatures in the Manistee River would decrease by removing both dams and restoring a free-flowing river. However, decreases would be modest because the dams are located far

Table VI. Comparison of estimated fall young-of-year steelhead densities for the Manistee River below Tippy Dam under existing dam operations and both dam alteration scenarios for the years 1997, 1999, and 2000

Scenario	Year	Fall density (No. ha^{-1})
Existing dam operations	1997	322
	1999	192
	2000	378
Both dams removed	1997	738
	1999	305
	2000	828
Tippy Dam bottom withdrawal	1997	—
	1999	399
	2000	697

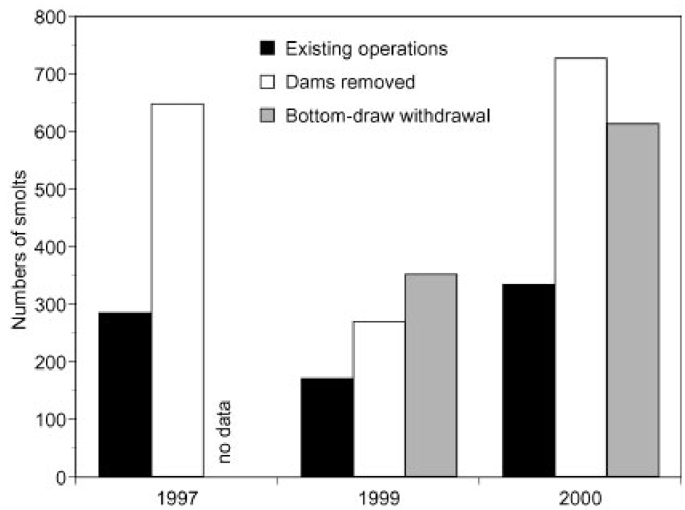

Figure 5. Predicted steelhead smolt recruitment from the Manistee River under existing operations and two hypothetical dam alteration scenarios, 1997, 1999 and 2000

enough downstream that river temperatures have generally warmed to within 2°C of temperatures below Tippy Dam before ever being impounded. The Manistee River receives a large volume of groundwater input over most of its length. However, when the river reaches its first impoundment, it has increased in volume and has been sufficiently warmed by ambient conditions that its thermal mass overwhelms the significant input of cold groundwater under and between the impoundments (Table II). This large groundwater inflow is sufficient only to moderate further warming as the river moves downstream.

Predicted dam removal effects on water temperature in other midwestern streams are variable and dependent upon the unique hydrology, geometry, and geographic location of the impounded river. Lessard (2000) found temperatures below low head dams (<6 m) to be, on average, 3°C higher than upstream temperatures in nine Michigan trout streams. The impact of these dams on stream temperatures was greater than in the Manistee River because in comparison to the Manistee River, these dams were built far enough upstream so that groundwater provides a relatively larger proportion to total stream discharge. In the Betsie River, a Lake Michigan tributary immediately north of the Manistee River, Newcomb (1998) predicted that removing a dam from the upper reaches would have a similarly small effect as dam removal on the Manistee River. The limited effect of dam removal in the Betsie River was instead due to the continued warm surface water discharge from a headwater lake. In contrast, Bevelhimer *et al*. (1997) predicted that removing a top withdrawal dam would actually increase summer temperatures in the Madison River, MT, due to exposure of the naturally wide river channel currently inundated by the reservoir.

Bottom withdrawal is an effective alternative to dam removal to mitigate high summer temperatures in the Manistee River. The combination of groundwater accrual and hypolimnion persistence during bottom withdrawal is sufficient to provide a continuous supply of colder water for downstream release. Tippy Dam, like most dams maximizing vertical head, was built on a high-gradient rapid (Rozich, 1998). Therefore, the former river channel now inundated by Tippy Pond cuts deep into the surrounding moraines, allowing for significant groundwater accrual from the reservoir bottom. These high moraines, coupled with a relatively narrow reservoir width (<500 m wide over most of its length), also provide Tippy Pond with shelter from prevailing summer winds, at least partially contributing to the stability of reservoir stratification even during bottom withdrawal. The ability of bottom withdrawal to lower Manistee River summer temperature below 19°C after switching from top withdrawal is limited by the reservoir's relatively small volume (*c*. $37 \times 10^6\,m^3$), and shallow depth (maximum depth of 14 m). By comparison, bottom withdrawal from Lake Powell (*c*. $30 \times 10^9\,m^3$) through Glen Canyon Dam (over 200 m high) lowers Colorado River temperatures by approximately 10°C in summer (Clarkson and Childs, 2000).

The ability of the two dam alteration scenarios to lower Manistee River summer temperatures varied depending upon ambient summer conditions. This variation is attributed to differences in thermal mass under each scenario. The large volumes of water in Tippy and Hodenpyl impoundments have a relatively high thermal mass and are relatively insensitive to day-to-day changes in ambient temperature. This large thermal mass suppresses diel temperature fluctuation, dampens weekly temperature variability, and delays spring warm-up and fall cool-down (Smith and Lavis, 1975; Crisp, 1987; Webb and Walling, 1993). In contrast, with dams removed, the free-flowing river has less thermal mass, is more responsive to sources of heat flux, and consequently, more closely follows ambient temperatures. Thus, temperatures in the free-flowing river will be more affected by year-to-year differences in ambient temperature than will be temperatures in the top or bottom layers of Tippy Pond. For this reason, removing dams lowered Manistee River temperatures more in the relatively cool summer of 2000 than bottom withdrawal. In the relatively warm summer of 1999, water temperatures in the free-flowing river were only slightly lower than they were with top withdrawal. In contrast, releasing cold hypolimnetic water during the summer of 1999, when ambient temperatures were hottest, lowered Manistee River temperatures considerably more.

Effect of temperature mitigation on steelhead smolt recruitment

Both dam alteration scenarios increased predicted natural steelhead smolt abundance in the Manistee River, but neither increased abundance to a level as high as that estimated in other Great Lakes tributaries with more optimal steelhead habitat (Table VII). Under the best dam alteration scenario, using the most optimistic method of estimation for the coolest summers modelled, fall density of YOY steelhead in the Manistee River would range between 700 and 850 fish ha^{-1}, nearly three times lower than fall densities in the adjacent Little Manistee River, a stable-flow, relatively unimpacted tributary.

Natural steelhead recruitment in the Manistee River would increase only modestly because neither dam alteration scenario lowered summer temperatures sufficiently to significantly increase survival of YOY fish. Our temperature modelling suggests that July temperatures in the Manistee River would range between 19°C and 21°C under either dam alteration scenario. Therefore, even during the coolest summers, July temperatures below Tippy Dam would remain at or above the upper threshold of the preferred temperature range (17–19°C: Cherry *et al.*, 1977; Hokanson *et al.*, 1977) for YOY steelhead survival.

Bottom withdrawal provides the greatest opportunity to increase the currently modest numbers of wild steelhead smolts in the Manistee River if dam removal is not feasible. With bottom withdrawal, the persistence of a hypolimnion throughout the summer would enable July–August water temperatures to be lowered to 19–20°C while diel temperature fluctuations would remain almost negligible. Hokanson *et al*. (1977) determined that above a mean daily temperature of 17°C, yield of YOY rainbow trout was higher under constant temperatures than fluctuating temperatures while the reverse was true below 17°C. While these gains in yield were largely the result of faster growth under constant temperatures, mortality rates were also lower for YOY rainbow trout exposed to constant temperatures above 17°C (Hokanson *et al*., 1977). Even in cooler summers, removing dams would not lower Manistee River temperatures below 17°C to provide steelhead with the added benefit of the restored natural diel fluctuation. Bottom withdrawal, therefore, provides the greatest potential to avoid year-class failures in the warmest years, a potentially critical improvement for local stock sustainability (Sinokrot *et al*., 1995; Van Winkle

Table VII. Comparison of fall densities of wild young-of-year steelhead parr in various Great Lakes tributaries

River	Fall density (No. ha^{-1})	Summer temp. (°C)	Source
Betsie River, MI[a]	124	18.2[b]	Newcomb (1998)
Muskegon River, MI[a]	209	21.1[c]	Godby *et al.* (in press)
Manistee River, MI[a]	338	20.6[c]	Woldt (1998)
Little Betsie River, MI	764	16.2[b]	Newcomb (1998)
Dair Creek, MI	1123	14.7[b]	Newcomb (1998)
Bear Creek, MI	1411	18.4[c]	Woldt (1998)
Platte River, MI[a]	1500	18.7[c]	Taube (1975)
Baldwin River, MI	1910	16.2[c]	Carl (1983)
Little Manistee River, MI	2300	16.8[c]	Seelbach (1993)
Bothwell Creek, Ont.	2545	12–23[d]	Alexander and MacCrimmon (1974)
Bigelow Creek, MI	2672	18.3[c]	Carl (1983); Godby *et al.* (in press)
Pine Creek, MI	3415	14.1[c]	Carl (1983); Woldt (1998)
Black River, MI	6900	<18.0[d]	Stauffer (1972)

[a] Impounded river.
[b] Summer mean.
[c] July mean.
[d] Summer range.

et al., 1997) and regional trout habitat preservation (Meisner *et al*., 1987; Keleher and Rahel, 1996; Eaton and Scheller, 1996) in light of projected scenarios of global warming.

Other sources of mortality besides temperature may significantly affect wild steelhead recruitment in the Manistee River. Food limitations (e.g. Cada *et al*., 1987; Filbert and Hawkins, 1995), intra-specific competition (e.g. Dunham and Vinyard, 1996; Keeley, 2001) and inter-specific competition (e.g. Fausch and White, 1981; Cunjak and Green, 1983; Baltz and Moyle, 1984) for feeding stations, and susceptibility to predation (e.g. Ricker, 1941; Roos, 1960), parasitism and disease are all mechanisms potentially affecting survival of YOY steelhead. Temperature affects all of these mechanisms, providing a number of indirect pathways by which it can affect survival of YOY steelhead. The effect of these indirect mechanisms may be especially high in the Manistee River because temperatures below Tippy Dam are at the maximum preferred temperatures for YOY steelhead. Therefore, lowering Manistee River summer temperatures with either dam alteration may increase YOY survival (and resulting smolt recruitment) to levels higher than previously predicted because lowering summer temperatures is likely to increase survival of YOY steelhead more than the direct physiological effect of temperature alone.

CONCLUSION

Simulation of proposed dam alteration scenarios revealed that small but physiologically important reductions in temperature could increase wild steelhead recruitment in the Manistee River. However, increases in recruitment would be modest under either scenario because summer temperatures below Tippy Dam would remain high enough to continue limiting survival of YOY steelhead. Bottom withdrawal retrofit provides the greatest potential for long-term enhancement of wild steelhead below Tippy Dam by consistently lowering downstream temperatures during the hottest months of the hottest years, when year-class failures are most likely to occur. However, before a sound temperature mitigation strategy can be chosen, estimation of steelhead recruitment from upstream habitats exposed when removing dams, and comprehensive accounting of other biological and economic costs and benefits associated with each dam alteration scenario should be calculated.

Because of the ecological importance of stream temperature, preventing or mitigating anthropogenic thermal degradation is a common concern for resource managers (Coutant, 1999). Today, dams are only one of many human activities that contribute to modification of stream temperature in watersheds nationwide. However, now that the federal procedure for relicensing dams requires ‘equal consideration’ of fish and wildlife as it does power production, the dam relicensing process has become a powerful tool for river restoration. As a result, alteration or removal of dams whose environmental costs outweigh their economic benefits is more likely to occur.

Appendix 1. Variable values for calibrated SNTEMP model of the Manistee River, Michigan

Variable	Manistee River reaches								Pine River reaches	
	Sherman gauge to Hodenpyl Dam	Hodenpyl Dam to Red Br.	Red Br. to Tippy Pond	Tippy Pond to Pine R. confluence	Pine R. confluence to Tippy Dam	Tippy Dam to Saw Dust Hole	Saw Dust Hole to High Br.	High Br. to Bear Cr.[a]	Hoxeyville gauge to Low Br.	Low Br. to Manistee R. confluence
Distance upstream From Bear Cr. (km)	81.0 to 55.0	55.0 to 37.9	37.9 to 27.9	27.9 to 25.5	25.5 to 22.5	22.5 to 17.9	17.9 to 13.3	13.3 to 0.0	47.0 to 42.2	42.2 to 25.5
Stream geometry										
Upstream latitude (radians)	0.775540	0.774190	0.773012	0.772412	0.772369	0.772407	0.772756	0.772614	0.771249	0.771468
Upstream elevation (m)	249.0	225.0	209.7	197.9	195.0	191.4	187.4	186.5	259.1	245.6
Manning's n	0.035	0.031	0.036	0.036	0.035	0.036	0.032	0.031	0.055	0.045
Width coefficient	24.541	26.995	27.799	27.799	27.799	27.799	13.149	13.149	15.480	16.470
Width exponent	0.1445	0.1301	0.191	0.191	0.191	0.191	0.39	0.39	0.0	0.0
Shade										
Azimuth (radians)	0.698132	0.261799	0.261799	−1.4137	−1.4137	−0.99484	1.30897	−1.309	−1.1519	−1.0122
Stream width (m)	41.0	41.0	41.0	57.5	57.5	57.5	58.0	59.0	15.5	16.5
East topographic altitude (radians)	0.0495	0.0495	0.0495	0.112423	0.112423	0.112423	0.042916	0.036035	0.214123	0.193894
West topographic altitude (radians)	0.0676	0.0676	0.0676	0.091854	0.091854	0.091854	0.081400	0.068708	0.217000	0.203017
East crown diameter (m)	7.1	7.1	7.1	7.5	7.5	7.5	7.5	7.3	4.7	5.4
West crown diameter (m)	6.9	6.9	6.9	6.6	6.6	6.6	7.6	7.4	6.2	5.1
East vegetation height. (m)	20.5	20.5	20.5	25.6	25.6	25.6	18.1	16.5	37.0	30.2
West vegetation. height (m)	17.8	17.8	17.8	18.7	18.7	18.7	19.4	18.6	48.0	23.0
East vegetation offset (m)	18.5	18.5	18.5	43.8	43.8	43.8	11.3	11.0	3.1	9.1
West vegetation offset (m)	16.7	16.7	16.7	11.8	11.8	11.8	14.5	11.7	3.1	5.9
East vegetation density	0.844	0.844	0.844	0.408	0.408	0.408	0.316	0.346	0.810	0.784
West vegetation density	0.841	0.841	0.841	0.355	0.355	0.355	0.334	0.417	0.819	0.690

Continues

Appendix 1. Continued

Variable	Manistee River reaches: Shzerman gauge to Hodenpyl Dam	Hodenpyl Dam to above Red Br.	Slagle Greek[b]	Above Red Br. to Pine R. confluence	Pine R. to confluence to Tippy Dam	Tippy Dam to High Br.	Pine Creek[b]	High Br. to Bear Cr.	Pine River reaches: Hoxeyville gauge to Low Br.	Low Br. to Manistee R. confluence
Distance upstream From Bear Cr (km)	81.0 to 55.0	55.0 to 40.3	44.3	40.3 to 25.5	25.5 to 22.5	22.5 to 13.3	6.0	13.3 to 0.0	47.0 to 31.0	31.0 to 25.5
Hydrology										
Lateral inflow ($m^3 s^{-1}$)	2.25	1.35	1.13	1.34	0.31	0.51	0.40	0.51	1.21	0.30
Lateral inflow temperature (°C)	11.35[c]	11.43[c]	14.5	11.1[c]	10.5	10.5	13.3	10.5	10.5	10.5

Meteorology

Station latitude (radians): 0.773175; Station elevation (m): 213.0 Mean annual air temperature (°C): 10.5°C

Time period

Air temperature calibration constant: 0.0; Air temperature calibration coefficient: 0.0

Wind speed calibration constant: 0.0 Wind speed calibration coefficient: 0.0

	May	June	July	August	September
Dust coefficient	0.06	0.06	0.06	0.06	0.06
Ground reflectivity	0.190	0.215	0.240	0.265	0.290

Job control

Global air temperature calibration constant: 0.0	Global air temperature calibration coefficient: 1.0	Bowen ratio: 0.0
Global wind speed calibration constant: 0.0	Global wind speed calibration coefficient: 1.0	
Global humidity calibration constant: 0.0	Global humidity calibration coefficient: 1.0	
Global sunshine calibration constant: 0.0	Global sunshine calibration coefficient: 1.0	
Global solar calibration constant: 0.0	Global solar calibration coefficient: 1.1	
Evaporation factor (A): 40.0	Evaporation factor (B): 15.0	Evaporation factor (C): 0.0

	1st	2nd	3rd	4th
Maximum daily air temperature regression coefficients:	20.44	−0.0247	−5.42	3.27

[a] Latitude and elevation at Bear Creek are 0.773035 radians and 182.5 m, respectively.
[b] Slagle and Pine creeks entered as point source discharges.
[c] Calculated as weighted average of groundwater (10.5°C) and tributary temperatures within reach.

Appendix 2. Variable values for calibrated CE-THERM-R1 model of Tippy Pond, Manistee River, Michigan

Record	Variable	Variable description	Value
JOB	IFIRST	Julian date for which initial update data are specified	32
	ILAST	Julian date of last inclusive simulation day	304
	NHOI	Simulation interval (h)	24
	IPRT	Output interval (h)	720
	ISTART	Julian date of first simulation day	85
MODE	MODE	Peaking or run-of-river flow	NORMAL
	STRUCT	Water flows through ports, weir, or both	PORT
	CHOICE	Specified or model selected port flows	SPECIFY
PHYS1	NTRIBS	Number of tributaries	2
	NUME	Number of initial layers	13
	XLAT	Latitude (radians)	44.25
	XLONG	Longitude (radians)	85.91
	TURB	Dust attenuation coefficient (dimensionless)	0.08
	AA	Evaporative heat flux coefficient (m/mb s)	0.6×10^{-9}
	BB	Convective heat flux coefficient (1/mb)	1.2×10^{-9}
	ELEMSL	Reservoir bottom elevation (m)	196.02
PHYS2	RLEN	Reservoir length (m)	11808
	SDZMIN	Minimum layer thickness (m)	0.5
	SDZMAX	Maximum layer thickness (m)	2.0
OUTLET	NOUTS	Number of outlets	3/6[a]
PHYS3	ELOUT(I)	Centreline elevation of *i*th port (m)	10.07/3.0[b]
	PVDIM(I)	Vertical dimension of *i*th port (m)	6.35/4.0[b]
	PHDIM(I)	Horizontal dimension of *i*th port (m)	9.14/7.0[b]
CURVE	CURVE	Equation to predict layer area with depth	POLY
AREAC	ACOEF(1)	First area/depth coefficient	−4475.8
	ACOEF(2)	Second area/depth coefficient	218722.0
	ACOEF(3)	Third area/depth coefficient	5169.8
WIDTHC	WCOEF(1)	First withdrawal zone width/depth coefficient	140.03
	WCOEF(2)	Second withdrawal zone width/depth coefficient	0.38
MIXING	SHELCF	Sheltering coefficient (dimensionless)	0.1
	PEFRAC	Penetrative convection fraction (dimensionless)	0.2
	CDIFW	Wind eddy diffusion coefficient (dimensionless)	0.0
	CDIFF	Advection eddy diffusion coefficient (dimensionless)	0.0
	CDENS	Critical density (kg/m^3)	0.1
LIGHT	EXCO	Extinction coefficient (1/m)	0.548
	SURFRAC	Fraction of solar radiation absorbed in surface layer	0.440
	EXTINS	Shading coefficient of suspended solids (1/m mg/l)	0.1
SETTL	TSETTL	Suspended solid settling velocity (m/day)	8.64
Groundwater inflow beneath reservoir (m^3 s^{-1})			2.25
Groundwater temperature (°C)			9.5
Groundwater total dissolved solids (mg/l)			288.9
Groundwater total suspended solids (mg/l)			0.1

[a] Number of outlet ports for calibration/number of outlet ports in simulation.
[b] Dimension of upper outlet port/dimension of lower outlet port.

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