3201

ELSEVIER

Environmental Science & Policy 3 (2000) S211–S216

Environmental Science & Policy

www.elsevier.com/locate/envsci

EXHIBIT R18

Assessing cumulative thermal stress in fish during chronic intermittent exposure to high temperatures

Mark Bevelhimer[a,*], Wayne Bennett[b]

[a]Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6036, USA
[b]Department of Biology, University of West Florida, 11000 University Parkway, Pensacola, FL 32514-5751, USA

Abstract

As environmental laws become increasingly protective and with likely future changes in global climate, thermal effects on aquatic resources are likely to receive increasing attention. Lethal temperatures for a variety of species have been determined for situations where temperatures rise rapidly resulting in lethal effects. However, less is known about the effects of chronic exposure to high (but not immediately lethal) temperatures and even less about stress accumulation during periods of fluctuating temperatures. In this paper we present a modeling framework for assessing cumulative thermal stress in fish. The model assumes that stress accumulation occurs above a threshold temperature at a rate dependent on the degree to which the threshold is exceeded. The model also includes stress recovery (or alleviation) when temperatures drop below the threshold temperature as in systems with large daily variation. In addition to non-specific physiological stress, the model also simulates thermal effects on growth. Published by Elsevier Science Ltd.

Keywords: Thermal stress; Temperature; Rainbow trout; Fluctuating temperature; Thermal effects; Environmental modeling; Stella

1. Introduction

The impact of power plants on the thermal regimes of aquatic ecosystems has been a concern for decades. As environmental laws become increasingly protective and with possible future changes in global climate, thermal effects on aquatic resources are likely to regain the attention received in the 1970s. Power plant thermal effects typically result from either the discharge of heated water used for cooling at fossil fuel and nuclear plants or changes in flow regimes and reservoir operations in the case of hydropower plants.

Operating licenses often include articles with criteria designed to protect aquatic resources, particularly fish, from thermal impacts. These criteria vary in both complexity and effectiveness, and rarely take into account temporal and cumulative aspects of thermal exposure on fish. Typical criteria include one or several of the following (listed in order of increasing complexity): (1) a single maximum temperature that may not be exceeded, (2) a time-averaged (daily or longer) mean temperature that may not be exceeded, or (3) criteria like type 1 or 2 above that vary monthly (or seasonally). Temporally variable criteria like type 3 are developed to account for acclimation to different seasonal temperatures and for variable susceptibility by different species and life stages.

These criteria are often established based on experimentally determined Critical Thermal Maxima (CTM) which measure an acute response (e.g., loss of equilibrium or death) to a rapid increase in temperature. A 2°C safety margin is usually included when using CTM results to establish thermal criteria (Coutant, 1977). In some cases, the effects of long-term exposure on mortality, reproduction, and early life stage development are also considered. These measures of thermal response are typically determined for different acclim-

* Corresponding author. Tel.: +1-865-576-0266; fax: +1-865-576-8543.
E-mail address: mb2@ornl.gov (M. Bevelhimer).

1462-9011/00/$ - see front matter Published by Elsevier Science Ltd.
PII: S1462-9011(00)00056-3

ation temperatures, but rarely include the additional effect of chronic exposure to sub-lethal temperatures that can be stressful but not lethal. It is common knowledge that the recent thermal history of a fish acclimates it to higher temperatures, thereby extending its tolerance limit (Parker and Krenkel, 1969; Jobling, 1994). However, beyond a certain point, acclimation benefits are exceeded, and prolonged exposure to non-lethal temperatures causes physiological stress which can reduce a fish's tolerance of high temperatures and ultimately affect population success.

Not only do most standard criteria fail to consider chronic effects, but they also do not account for stress recovery during periods of fluctuating temperature when temperatures periodically drop below stressful levels. Large daily fluctuations in water temperature as a result of either natural conditions or industrial operations can result in significantly different impacts than constant temperatures on which most regulatory criteria are based. In thermally fluctuating environments, it is likely that a single maximum temperature criterion would be exceeded repeatably for short durations rather than continuously for a long period. It is also possible that mean temperatures could remain below criteria based on average conditions that are presumed to be safe, but exposure to short-term temperature peaks could still be detrimental. The dynamics of stress recovery in fish is poorly understood, but may be an important factor in thermal effects in many situations.

Because of the poor understanding of thermal stress in fish in thermally dynamic environments and the uncertainty associated with the establishment of regulatory criteria, there is a high likelihood that many existing criteria are either under- or over-protective. From an environmental perspective, it is usually better to be over-protective; however, from a power production perspective it is obviously not desirable to spend unnecessarily for nonessential mitigation. A better understanding of the cumulative nature of thermal stress along with stress recovery dynamics is crucial in establishing regulatory criteria that are protective of the environment while at the same time not overly conservative.

It is common for many streams (both natural and impacted) to experience daily fluctuations of >4°C during the summer, and some may fluctuate as much as 10°C. Although the amount of daily fluctuation in ambient air temperature is probably the most important factor in dictating water temperature fluctuation, other factors such as the size of the water body, amount of flow, degree of mixing, and exposure to solar radiation are also important. Fig. 1 illustrates features of a typical thermal regime that affect cumulative thermal stress in fish. The temperature at which stress begins to occur is largely dependent on a fish's prior exposure history or acclimation. For example, typical seasonal acclimation allows fish to be more tolerant of high temperatures in summer than in winter. Even with acclimation there is a temperature beyond which stress occurs regardless of previous acclimation at sub-stressful temperatures. One aspect of stress accumulation of which little is known is stress recovery when exposure to high temperature is removed. The temperature at which recovery occurs, the rate of recovery, and the length of time for full recovery are largely unknown.

The purpose of this paper is to describe a model framework that we have developed to assess both the temporal aspects of thermal exposure and the dynamics of cumulative thermal stress and recovery in fish exposed to fluctuating temperature regimes.

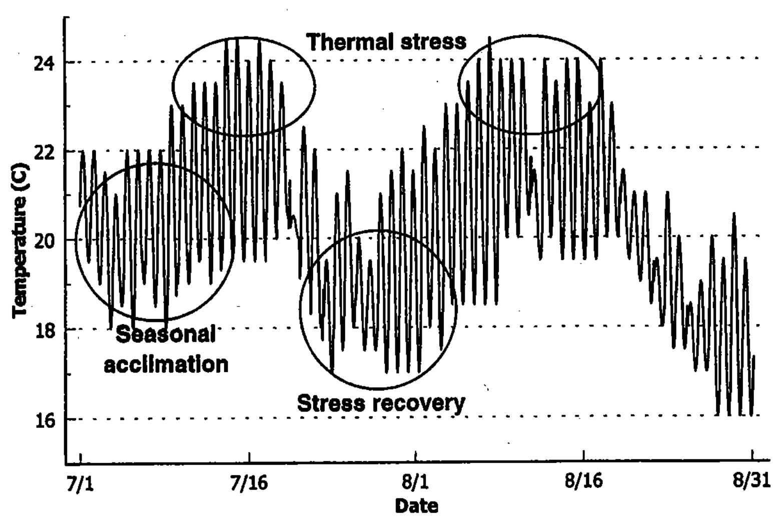

Fig. 1. Factors that affect thermal stress accumulation in fish in fluctuating environments.

2. Model description and results

The thermal effects model was designed in a systems dynamics framework using commercially available Stella® software. This system is user friendly and allows for easy manipulation of input parameters and state variables. The model described here was parameterized for rainbow trout (i.e., the bioenergetics parameters and temperature thresholds), but it is easily transferable to other species where basic physiological parameters are known. Below, we describe the thermal stress component of the model first and then describe the entire thermal effects model. Model simulations were performed with temperature regimes with different amounts of diel fluctuation.

2.1. Thermal stress component

The direct thermal stress component of the model is similar to damage-repair models developed for ecotoxicology investigations (Mancini, 1983; Breck, 1988; Meyer et al., 1995). Fig. 2 shows the relationship among those factors that affect stress accumulation and recovery including:

- the magnitude of high temperature exposure;
- the duration of high temperature exposure;
- stress recovery during periods of reduced temperature; and
- size- and species-specific effects on threshold temperatures.

The model (i.e., Eq. (1)) tabulates an index of thermal stress that has yet to be directly related to actual physiological stress or other health effects. The basic equation of this thermal stress submodel is:

$$\text{Thermal stress}(t) = \text{Thermal stress}(t - dt) + (\text{Accumulation} - \text{Recovery})\,dt, \qquad (1)$$

where t is the current time and dt is the size of the time step, an hour in the examples presented here. During any time step, accumulation or recovery occurs, but not both. Stress accumulates when ambient temperature exceeds a size- and species-specific temperature threshold:

$$\text{Accumulation} = \text{Ambient temperature} - \text{Threshold} \qquad (2)$$

Recovery occurs when temperature drops below the threshold at a rate that depends on the magnitude and duration below the threshold:

$$\text{Recovery} = (\text{Threshold} - \text{Ambient temperature})\,Z \qquad (3)$$

where Z is a factor that delays the rate of recovery such that it occurs more slowly than stress accumulation. For this demonstration, we assume that $Z = 0.25$; therefore, recovery occurs at a rate 25% of that at which it accumulates.

For the simulations presented here, the threshold temperature was set at 21°C, above which, the index of thermal stress increases. For example, 2 h at 23°C would increase the stress index by 4 [i.e., 2 × (23−21)]. Whereas, 2 h at 19°C would decrease the stress index by 1 [i.e., 2 × (21−19) × 0.25]. The thermal stress score does not go below 0, as that level represents a normal healthy stress-free fish.

To demonstrate how the model works we applied it to a two-month record of temperatures from the Madison River in Montana (Fig. 3). We used temperatures from two locations below a hydropower dam — site A, which is about 3.2 km downstream of the dam and reflects the thermal dampening effect of the impoundment, and site B, which is 14.5 km downstream of the dam. The two sites have different degrees of daily temperature fluctuation, 1–2°C at site A vs 4–5°C at site B. Even though the magnitude of daily fluctuation differs among the sites, the daily mean temperatures at the two sites are nearly the same – 19.9°C at site A vs 20.3°C at site B. See Bevelhimer et al. (1997) for a detailed description of thermal conditions in the Madison River.

Model results indicate that, on average, a fish at the downstream site (B) would have a stress index that is 2–3 times greater than a fish at the upstream site (A) even though the difference in mean temperature is only 0.4°C. Until the stress index is related to actual health effects, such as physiological performance, via laboratory experimentation, it is difficult to assign a biological meaning to these results.

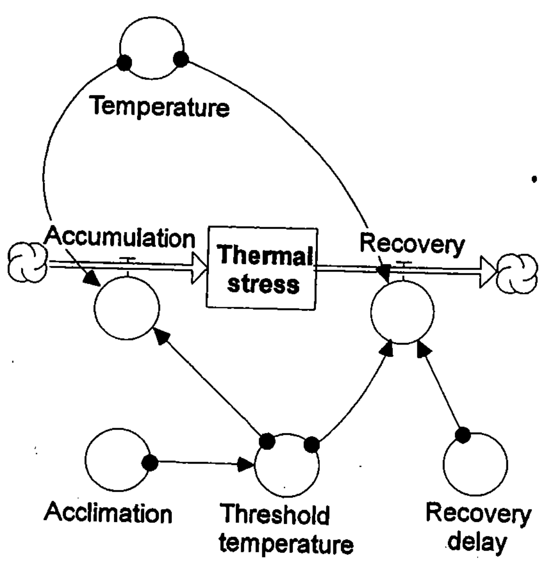

Fig. 2. Diagrammatic representation of direct thermal stress submodel.

2.2. Multiple effects model

The complete thermal effects model also includes the effects on growth as determined by a bioenergetics sub-model (Fig. 4). The bioenergetics model has become a common tool in fisheries science (Adams and Breck, 1990) and provides a means to assess growth as the difference between the caloric intake (i.e., food consumption) and energetic costs (i.e., respiration, activity, egestion, and excretion). Reduced growth and poorer physiological condition are long-term effects of chronic high temperature exposure that can result in greater susceptibility to other sources of mortality, such as disease and predation. Most of the relationships included in the bioenergetics model are sensitive to changes in temperature, which makes the model ideal for comparing differences in growth potential between the two temperature regimes.

The basic equation of the growth portion of the model is:

$$\text{Growth}(t) = \text{Growth}(t - \mathrm{d}t) + (\text{Food consumption} - \text{Food processing costs} - \text{Egestion} - \text{Excretion} - \text{Respiration})\,\mathrm{d}t \quad (4)$$

Parameters used in the bioenergetics portion of the model are the same as those in Van Winkle et al. (1997).

Just as there are differences in estimated thermal stress realized by fish at the two sites, the model also predicts differences in growth (Fig. 3). Fish at site A, which had less daily variation, had about 50% greater growth than fish at site B by the end of the two-month simulation.

3. Discussion

The effects of fluctuating temperature regimes on temperature tolerance, thermal stress accumulation and recovery, and growth are still largely a mystery. Developing a model that assesses these effects will require a basic understanding of the relationships between fluctuating temperature and tolerance, stress, and growth. These relationships have been investigated in a variety of laboratory experiments although few definitive conclusions have been drawn. For example, studies by Otto (1974), Heath et al. (1993), and Bennett and Beitinger (1997) all found that fluctuating temperature regimes increased a fish's tolerance of high temperatures, while a recent study by Currie (1995) found no such enhancement.

The effects caused by fluctuating conditions can also be quite complex and not always easily explained. Greater growth under conditions of greater daily temperature fluctuation as predicted by the model (see Fig. 3) has also been observed in laboratory studies

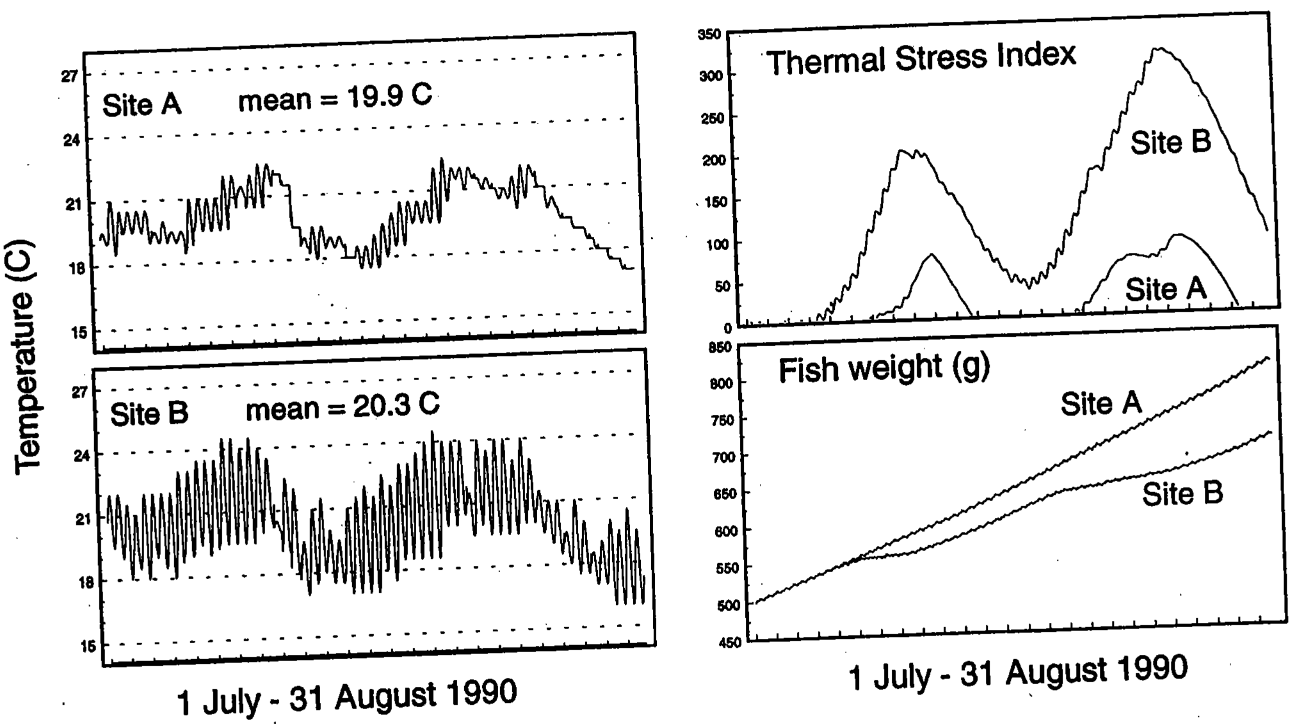

Fig. 3. Model predictions of thermal stress (top right panel) and growth (bottom right panel) for fish exposed to two thermal regimes (left panels) of similar mean temperature but different daily variability.

(Cox and Coutant, 1981; Konstantinov and Zdanovich, 1987). However, the difference in growth under these conditions is not necessarily just a function of the amount of variability, but might also be a function of how near the mean temperature is to stressful levels. Hokanson et al. (1977) found that temperature fluctuations within the preferred temperature range resulted in greater growth than constant temperatures with the same mean, but when the mean of the fluctuating regime exceeded the optimal temperature range, constant conditions resulted in greater growth than did the fluctuating regime.

One of the reasons for developing this model is to provide a tool that can be used to reduce the impact of power plant operations on fish populations. In order to be both protective and cost efficient, mitigative measures need to be more responsive to short-term changes in plant operations and environmental conditions. For such a system to be effective, real-time monitoring must provide adequate warning for mitigative measures to be invoked prior to environmental impact. We believe this model, once fully developed and tested, will be able to forewarn of impending thermal effects before they occur and also serve as a basis for implementing effective regulatory criteria.

The model as currently configured still requires groundtruthing to assign biological meaning to the thermal stress index. Ideally, the data required for groundtruthing will come from laboratory experiments designed to better understand cumulative thermal stress and the relationships between the magnitude and duration of high temperature exposure and fish health effects. In the absence of such directed experimental data, there exists a large body of literature (e.g., NAS-NAE, 1973) that describes the effects of exposure to high temperature on fish mortality that can be used to calibrate the model.

We believe the model framework presented here can

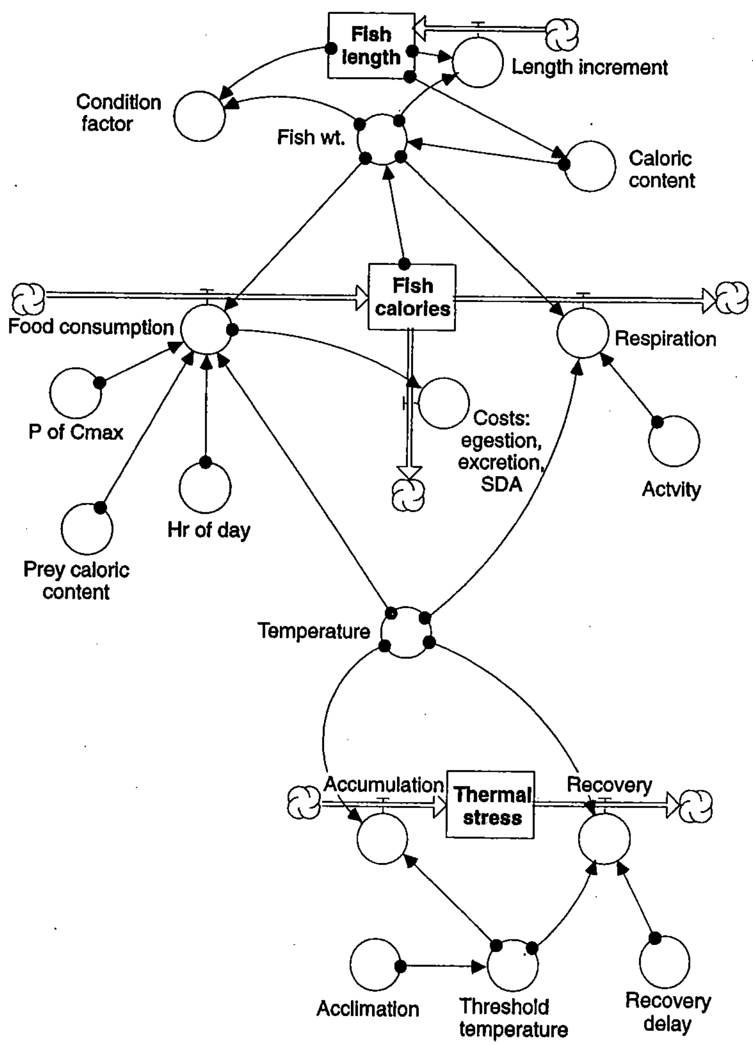

Fig. 4. Diagrammatic representation of complete thermal stress model.

be used to provide a better assessment of temperature effects at thermal outfalls and dam tailwaters resulting in (1) better temperature criteria development and (2) more accurate and timely monitoring. This tool will allow users to more precisely determine potential environmental effects and thus design and implement corrective measures that directly address specific problems.

Acknowledgements

This work was supported in part by the Electric Power Research Institute under contract DOE ERD-87-00672 with the US Department of Energy. Oak Ridge National Laboratory is managed by Lockheed Martin Energy Research Corporation for the US Department of Energy under contract number DE-AC05-96OR22464. We thank W. Van Winkle, S. M. Adams, and J.E. Breck for providing constructive comments on an early draft of the manuscript. This is Publication No. 4922 of the Environmental Sciences Division, Oak Ridge National Laboratory.

References

Adams, S.M., Breck, J.E., 1990. Bioenergetics. In: Schreck, C.B., Moyle, P.B. (Eds.), Methods for Fish Biology. American Fisheries Society, Bethesda, Maryland, pp. 389–416.

Bennett, W.A., Beitinger, T.L., 1997. Temperature tolerance of the sheepshead minnow, *Cyprinodon variegatus*. Copeia 1997, 77–87.

Bevelhimer, M.S., Alavian, V., Miller, B., Hauser, G., 1997. Modeling Thermal Effects of Operational and Structural Modifications at a Hydropower Facility on a Premier Trout Stream in Southwestern Montana. WATERPOWER '97: Proceedings of the International Conference on Hydropower 1997 (vol. 1), 40–49.

Breck, J.E., 1988. Relationships among models for acute toxic effects: applications to fluctuating concentrations. Environmental Toxicology and Chemistry 7, 775–778.

Coutant, C.C., 1977. Physiological considerations of future thermal additions for aquatic life. In: Marois, M. (Ed.), Proceedings of the World Conference Toward a Plan of Actions for Mankind, Volume 3 — Biological Balance and Thermal Modifications. Pergamon Press, New York, pp. 251–266.

Cox, D.K., Coutant, C.C., 1981. Growth dynamics of juvenile striped bass as a function of temperature and ration. Transactions of the American Fisheries Society 110, 226–238.

Currie, R.J., 1995. Upper and Lower Temperature Tolerances of Three Freshwater Game-fish Species Exposed to Cycling Temperatures. Masters Thesis, University of North Texas, Denton, Texas 96 pp.

Heath, A.G., Turner, B.J., Davis, W.P., 1993. Temperature preferences and tolerances of three fish species inhabiting hyperthermal ponds on mangrove islands. Hydrobiologia 259, 47–53.

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

Jobling, M., 1994. Fish Bioenergetics. Chapman and Hall, London 309 pp.

Konstantinov, A.S., Zdanovich, V.V., 1987. Peculiarities of fish growth in relation to temperature fluctuation. Journal of Ichthyologia 26, 65–74.

Meyer, J.S., Gulley, D.D., Goodrich, M.S., Szmania, D.C., Brooks, A.S., 1995. Modeling toxicity due to intermittent exposure of rainbow trout and common shiners to monochloramine. Environmental Toxicology and Chemistry 14, 165–175.

Mancini, J.L., 1983. A method for calculating effects on aquatic organisms of time varying concentrations. Water Resources 17, 1355–1362.

NAS-NAE (National Academy of Sciences National Academy of Engineering), 1973. Water quality criteria 1972: A report of the Committee on Water Quality Criteria, Environmental Studies Board. EPA-R-73-033, US Government Printing Office, Washington, DC 446 pp.

Otto, R.G., 1974. The effects of acclimation to cyclic thermal regimes on heat tolerance of the western mosquitofish. Transactions of the American Fisheries Society 103, 331–335.

Parker, F.L., Krenkel, P.A., 1969. Thermal Pollution: Status of the Art. Vanderbilt University, Nashville, TN.

Van Winkle, W., Rose, K.A., Shuter, B.J., Jager, H.I., Holcomb, B.D., 1997. Effects of climatic temperature change on growth, survival, and reproduction of rainbow trout: predictions from a simulation model. Canadian Journal of Fisheries and Aquatic Sciences 54, 2526–2542.

Mark S. Bevelhimer, PhD, is a Research Staff Scientist in the Environmental Sciences Division of Oak Ridge National Laboratory, Tennessee. He is also an adjunct professor at the University of Tennessee — Knoxville. For the past 18 years he has investigated the response of fish to temporally and spatially variable environments. His interests in fisheries and aquatic systems include thermal ecology, bioenergetics, simulation modeling, hydropower impacts, instream flow, and contaminant effects.

Wayne A. Bennett, PhD, is an Assistant Professor of Vertebrate Physiology at the University of West Florida in Pensacola. His primary area of research is physiological ecology of marine and estuarine vertebrates. His interests in thermal physiology of fishes include: resistance/tolerance interactions, acclimation kinetics, mechanisms of thermal intolerance, and thermal ecology.