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Thermal effects

Sylvia S. Talmage
Ecological Sciences Information Center,
Oak Ridge National Laboratory, Tenn.

Charles C. Coutant
Environmental Sciences Division,
Oak Ridge National Laboratory, Tenn.

REVIEWS AND MODELS

The United Nations Educational, Scientific and Cultural Organization (UNESCO) published a book [1] devoted to methods for predicting effects of power plant once-through cooling on aquatic systems. An international team reviewed effects and provided guides to environmental impact assessments. Different approaches for preoperational predictions and operational monitoring were distinguished, and beneficial uses for reject heat were identified.

Becker *et al.*[2] undertook a literature review and assessment program to examine the effects of once-through cooling systems on cooling impoundments. Ecological information related to possible plant operational effects was collected and evaluated for 14 sites. The primary physical, chemical, and biological effects as well as data deficiencies were discussed. No major ecosystem effects were identified.

A three-volume report by Tetra Tech, Inc.,[3] described a methodology, including computational procedures, analytic relationships, and models, that can be used to assess the integrated effects of several power plants on a single water body. Volume 1 provides typical cooling system operational parameters, characteristics of different water body types, prescreening procedures, and an overview of detailed assessment methods. Volume 2 describes the technical basis for computations performed by various models. Volume 3 describes the data requirements for use of the methodology.

Thermally induced biological effects of power plant entrainment and plume entrainment were modeled and evaluated. Schubel *et al.*[4] found that there was little increase in survival of striped bass larvae due to increasing ΔT (decreasing the cooling water flow rate) for Hudson River temperatures $\leq 16°C$. This was because of the marked synergism between thermal and physical stresses. Carter *et al.*[5] coupled a model of the excess temperature and velocity fields associated with the heated discharge from a large generating station sited on a tidal estuary with appropriate thermal resistance data to evaluate thermally induced mortality levels of striped bass larvae entrained in the thermal plume of the Indian Point Units 2 and 3 on the Hudson River. The model indicated that less than 10% of the larvae entrained in the plume would be killed. The thermal response model was applied to different water bodies using thermal resistance data for entrainable life stages of appropriate Representative Important Species.[6] In each situation it appeared that the most sensitive organisms were the ichthyplankton and juvenile fish. Recommendations for future research were made.

Ontario Hydro Corp. of Canada undertook a program to improve its present pre- and post-operating aquatic biological studies at existing generating sites on the Great Lakes.[7] The new studies include spatial biomass distribution and intake location, fish behavior at submerged intakes, fish viability in the forebay, fish by-pass modeling studies, effects of entrainment on plankton and fish, fish residency and spawning activity in thermal discharges, fish spawning studies, thermal discharge effects on the littoral zone, and thermal tolerances and preferences of fish. This program should allow for interstation comparisons.

Parkhurst and McLain[8] compared the environmental impacts of cooling reservoirs to cooling towers. Construction, operational, maintenance, efficiency, and water consumption impacts were compared, with the conclusion that adverse impacts for reservoir ecosystems appeared to be minor.

The feasibility of using once-through cooling was examined in the context of the physical aspects of water quality standards and guidelines for thermal discharges.[9] Thermal standards for different types of water bodies were identified, and characteristics of various discharge modes were examined. Although choice of a discharge system must be site specific, the submerged multiport diffusers were found to provide the greatest probability of meeting thermal standards in all receiving water bodies.

Krenkel[10] discussed problems in the establishment of water quality criteria. Knowledge about effects of pollutants such as temperature is not yet adequate to support definitive standards. Koops,[11] in discussing standards for cooling water, cited several studies showing that a decrease of the cooling water quantity with a resultant higher ΔT may lead to a decrease in total damage to entrained organisms.

A series of biological investigations, particularly in the rivers Severn and Trent (England), have shown that only minor effects in populations of individual species can be attributed to discharge of cooling water.[12] Downstream temperatures have occasinally reached more than 30°C in summer. The Central Electricity Generating Board is actively exploring potentially beneficial uses of the rejected heat.

Biesiadka *et al.*[13] summarized investigations on the benthos of the heated Konin Lakes (Poland). Their results show a decrease in number or elimination of some species and an increase in species and abundance of thermophilic groups.

Lehmkuhl[14] reviewed information on the effects of environmental disturbances on life histories of aquatic organisms. He noted that a wide variety of invertebrates have distinct temperature requirements, and minor alterations of temperature by thermal pollution can cause drastic effects on the animal community.

Thermal additions to aquatic systems may select for pathogenic species of organisms. Carter[15] and Duma[16] reviewed research on the incidence of primary amoebic meningoencephalitis. According to Carter, a considerable amount of research suggests that organic and thermal pollution of freshwater systems encourages the growth of bacteria, which, in turn, encourages the activity of the amoebae responsible for this disease.

Guthrie and Cherry[17] summarized results of their studies on bacterial interactions in thermally influenced waters. They found that thermal addition to water causes an increase in the total bacterial populations, but a decrease in bacterial diversity.

The effects of increased temperature on phytoplankton and zooplankton seasonal dynamics were examined by Swartzman and Adams[18] using a simulation model. Results indicated that those species with a lower phosphorus tolerance, a greater tolerance for nitrogen, and a lower optimal light intensity for growth would better survive the warmer temperatures. These characteristics are typical of blue-green algae that are usually found in warm waters.

The influences of temperature alterations on experimental predator-prey interactions were reviewed by Coutant *et al.*[19] Thermal shocks (both heat and cold) that increased prey vulnerability were quantified in several studies. A simulation model was described that followed predation among fry of largemouth and smallmouth bass as they grew and that predicted exclusion of smallmouth at higher temperatures. A partial differential equation model was developed to express the growth dynamics of young-of-the-year fish populations at different temperatures with size distributions taken into account.[20]

Progress in implementation of a Unified Transport Approach for developing mathematical models for the assessment of power plant impact on aquatic environments was reported.[21] The objective of the program is to develop fast-transient, one- and two-dimensional transport models and their associated general-usage computer codes that can be employed in estimating the thermal, radiological, chemical, and biological impact of power plant operation on rivers, estuaries, lakes, and coastal regions. Development and validation of these models are illustrated in applications at several sites where data were available.

In other modeling studies Ulanowicz [22] suggested that because community variables respond in a coherent manner to stress, macroscopic analyses of stressed ecosystems offer possible alternatives to compartmental models. He discussed the success of various attempts at linear and nonlinear modeling of stressor effects on ecosystems. Matis and Wehrly [23] reviewed a stochastic approach to compartmental modeling. The need for stochasticity in the model was motivated by two examples: vanadium depuration in marine organisms and thermal resistance of green sunfish. Fisher [24] proposed a model that provides a physicochemical basis for the parameters and formulation of a specific type of thermal dose-response curve. The model was applied to thermal response data for a variety of species of fish.

A study by McKenzie *et al.*[25] reviewed and evaluated fisheries management techniques for application to assessing impacts from power plants. Techniques in three categories were examined: catch removal, population dynamics, and nondestructive censuses.

A symposium edited by Thorp and Gibbons [26] addressed the subject of energy and environmental stress in aquatic systems. Half of the volume was devoted to studies of the response of organisms and communities to thermal effluents, including the effects of multiple and synergistic stresses. A symposium on the microbiology of power plant effluents reviewed the status of thermal microbiology in relation to power generation as well as operational and environmental implications and future research needs.[27, 28] Papers from these symposia are discussed in appropriate sections of this review.

Liden and Burton [29] reviewed literature on the acute effects of thermal increases upon several fish and invertebrate species indigenous to the Chesapeake Bay. These data, in addition to combined natural life history temperature data, were evaluated to ascertain what effects thermal discharge from the Calvert Cliffs nuclear plant would have upon populations of these species living in Chesapeake Bay.

A review of the 1978 thermal effects literature was coauthored by Talmage and Coutant.[30] Hannon [31] compiled a bibliography of electric utility documents on the subject of cooling system effects on aquatic systems.

SITE STUDIES

Cooling lakes and reservoirs. A cooling lake fishery (Lake Sangchris, Ill.) was systematically evaluated and modeled.[32] Fish growth, reproduction, food habits, movements, primary production, and other factors were compared with data from a nearby ambient flood control reservoir. Power plant operation on Lake Sangchris was not a limiting factor in the development of a viable fishery, although plant effects were observed.

Primary production, aquatic invertebrates, and fish were studied during 1975–77 to determine responses of organisms to a 15°C temperature gradient in Lake Columbia (Wis.).[33, 34] Seasonal and spatial changes in species composition of periphyton were shown. Modified life history and temperature-directed movement were identified as two important mechanisms by which invertebrates change distribution in a heterothermal environment. Species diversity, distribution, growth, and reproductive responses of fish in this newly impounded cooling lake are described.

The effects of power plant operation on the ecology of Belews Lake (N. C.) were systematically evaluated by studies on phytoplankton,[35] zooplankton,[36] benthos,[37] aquatic macrophytes, and fish.[38] Although general successional changes in the phytoplankton community appeared to be accelerated after plant operation, there was no evidence of detrimental effects on the plankton communities. Rotifer and cladoceran densities were greater than in other area lakes. Densities of several benthic populations either decreased or increased along the thermal gradient. The fishery yield was below that of similar lakes. Circulation of surface water by the power plant and ash basin discharge were implicated in some of the changes.

Primary productivity was significantly higher at the heated station in Lewis Creek Reservoir (Tex.) than at unheated stations.[39] Regression analysis indicated that the temperature optimum for the natural population was 25°C. The temperature tolerance range for the phytoplankton community subjected to higher temperatures was higher than for the community at ambient temperatures.

The freshwater littoral meiofauna along a temperature gradient in Par Pond (S. C.) was sampled over a 1-year period.[40] When compared with an ambient site, thermally affected sites demonstrated reduced faunal density. Although there was a reduction in number of species of rotifers, high "equitability" among the reduced species resulted in a high Shannon-Weaver diversity index.

The effects of thermal effluent on physicochemical and biological parameters of the Konin Lakes (Poland) were studied during several summers.[41] Changes attributed to heating and a decrease in retention time included a change in phytoplankton composition toward domination by diatoms; an increase in the biomass of filtering cladocerans; and a decrease in the abundance of rotifers, predatory copepods, and filtering calanoids.

Folsom and Clifford [42] studied the population biology of the flatworm, *Dugesia tigrina*, in Lake Wabamun (Canada). The net effect of the thermal effluent was a numerical increase in the standing crop of *Dugesia* through increased prey populations, but a reduction in individual size.

Sigmon [43] presented data on species composition, density, and size of benthos in Lake Keowee (S. C.). Diversity and density were lower in the discharge canal because of reduced organic content of the canal sediments. Because of the hypolimnetic intake design, temperatures in the discharge canal were elevated only slightly above those observed in the epilimnion of the remainder of the lake.

Because the thermal plume at the Johnsonville Steam Plant (Kentucky Lake) reached the bottom only during the fall and winter, benthic insects were subjected to above-ambient temperatures only during the coldest part of the year.[44] In early spring, mayfly (*Hexagenia bilineata*) nymphs collected from the area influenced by the thermal plume were larger than those collected from the ambient station. Growth at the ambient station accelerated during late spring, however, and adult emergence occurred almost simultaneously at both stations. Emergence of *Hexagenia bilineata* occurred 2–3 weeks earlier in the discharge cove of the Kingston Steam Plant (Watts Bar Reservoir, Tenn.) than in the reference cove and intake canal.[45]

Life histories of yellow perch (*Perca flavescens*) in Keowee Reservoir and flat bullhead (*Ictalurus platycephalus*) in Lake Norman (N. C.) were studied.[46, 47] Prespawning water temperatures in Keowee and water temperatures in southern reservoirs in general were not conducive to yellow perch reproduction.

Annual variations in fecundity of white crappie (*Pomoxis annularis*) in Conowingo Pond (Pa.) were studied by Mathur *et al.*[48] Random variations in egg number were greater among years than between pre- and post-operational periods with respect to startup of the Peach Bottom Station Units 2 and 3.

Survival of Florida largemouth bass (*Micropterus salmoides*) introduced into Boomer Lake (Okla.) was less than for northern bass and was relatively independent of season or winter severity.[49] Although growth and food habits of the two populations were similar, Florida bass did not reproduce. Florida bass were more vulnerable than northern bass to experimental cold shocks.

Several species of fish inhabiting cooling ponds on the Savannah River Plant (S. C.) were studied for their response to thermal effluent. Largemouth bass had higher mean body temperatures than those from a nonheated area (36.2° and 31.4°C, respectively).[50] Mosquitofish (*Gambusia affinis*) were found to be a eurythermal species that adapted to the conditions of severe thermal stress.[51] Differences in amounts of asymmetry, hypothesized to be a measure of developmental homeostasis, were not demonstrated between populations of bluegill (*Lepomis macrochirus*), largemouth bass, and redbreast sunfish (*Lepomis auritus*) in heated and ambient temperature locations.[52]

Impingement data collected at two southeastern reservoirs, Watts Bar (Tenn.) and Lake Dardanelle (Ark.), related water temperature to impingement rates.[53, 54] Threadfin shad (*Drosoma petenense*) impingement at Watts Bar was highest following a 1-day temperature decline from 8° to 3°C. In the latter study the lower lethal temperature thresholds for threadfin and gizzard shad (*D. cepedianum*), were determined to be between 3.3° and 5.5°C and between 0° and 0.5°C, respectively.

Water samples collected from heated and ambient temperature stations of Par Pond (Savannah River Plant, S. C.) and processed for the presence of *Naegleria fowleri* were positive 43 and 2% of the time, respectively, suggesting that thermally altered waters in the southeastern U. S. may provide habitats conducive to the proliferation of this amoeba.[55] *Dactylaria gallopava,* a thermo-tolerant fungus that causes endemic encephalitis in poultry, was abundant in the microbial mats, in foam, and in soils at the edges of the cooling water effluents.[56] It was directly associated with effluents that had temperatures of 44°C and higher. Populations of *Escherichia coli* that were initially lactose positive changed to lactose negative in Par Pond when cooling water was being discharged.[57, 58] Densities were also higher, particularly in the hypolimnion, during reactor operation than when the reactor was not in operation.[59] The loss of the lactose characteristic prevents the recognition and identification of *E. coli* and may prevent the assessment of water quality based on coliform recognition.

Aermonas hydrophila is a pathogen for a wide range of freshwater fish, amphibians, and reptiles. Its cosmopolitan distribution is partly explained by its ability to live under a wide variety of environmental conditions in natural waters.[60] Densities of this bacterium showed distinct thermal optima (25°–35°C) and an upper thermal limit (45°C) when measured along thermal gradients created by geothermal and Savannah River Plant (SRP) nuclear reactor effluents.[61] Survival never exceeded 48 hours at temperatures of 45°C. Densities in the hypolimnetic waters were always greater than those from epilimnetic waters and were always greater when the SRP reactor was in full operation.[62] Studies in Par Pond indicated that *A. hydrophila* and red-sore disease are related to temperature-induced stress within the largemouth bass population.[63]

Aeromonas hydrophila was also found to be ubiquitous with alligators in their natural habitats.[64] However, mortality occurred only among alligators subjected to handling and when water temperatures were above 20°C. Peripheral blood components and serum protein electrophoretic patterns in normal and infected and/or thermally stressed alligators were described.[65]

Cattail (*Typha latifolia*) plants collected from both the hot and cold ends of Par Pond and maintained in the laboratory at 20° and 30°C showed no intersite differences in levels of malate dehydrogenase, amylase, protein content, growth, or survival.[66] Regardless of origin, all plants showed significantly higher amounts of total growth under the 30°C regime.

Streams and rivers. Guthrie *et al.*[67] and Cherry *et al.*[68] studied the effects of coal ash basin drainage and thermal loading on bacterial populations and aquatic insects in streams at the Savannah River Plant (S. C.). Both thermal loading and large concentrations of chemical elements from the coal ash basin reduced diversity and percentage of chromagens, although increasing total culturable bacteria. Temperature appeared to have a greater effect on community stability characteristics than did increased elemental concentration. Invertebrate density was lowest where coal ash effluent and temperature extremes (<10° and >38°C) were greatest. The most tolerant invertebrate to both stresses was the dragonfly *Libellula* sp.

Determinations of populations of total and fecal coliform organisms in the intake and discharge of the Quad Cities Station (Mississippi River, Ill.) indicated that condenser passage had little effect on the concentration of these organisms.[69] Populations exhibited considerable variability, but no consistent differences between intake and discharge were observed.

Paul *et al.*[70] described leaf processing and the effect of thermal effluent on leaf degradation in the New River (Va.). Decay coefficients (microbial decompositional activity) were significantly higher at a station downstream from the Glen Lyn plant than at an upstream station.

The life cycle of the freshwater prawn *Atyaephyra desmaresti* in the vicinity of a power station on the Moselle River (France) was compared with that of individuals at a similar, unheated site.[71] Life cycle stages were shorter and appeared earlier than at the control site.

The macroinvertebrate communities of the Great Miami River system (Ohio) were studied over a wide range of environmental conditions and stresses, including thermal discharges from power plants.[72] Similarity indices and subsequent polar ordination showed that river passage through the city of Dayton did not prohibit high biotic similarity between some sites below Dayton and undisturbed upstream locations. Pollution effects appeared to overwhelm the effect of normal environmental variables on faunal composition only during low-flow conditions.

Movement of ultrasonic-tagged largemouth bass and flathead and channel catfish passing the thermally influenced area of the Coosa River (Ala.) adjacent to the Gaston steam plant was studied during the warm season of the year.[73] Movement patterns suggested that the fishes avoided passing directly through the area of maximum temperature influence by traveling under or around it.

The effect of a thermal effluent on the attached algae of the Provo River (Utah) was studied from 1975 to 1977.[74] The algal flora in a section of the river 100–135 m long immediately below the discharge was significantly affected, with high diatom production but low diversity.

Changes in the vegetation of a South Carolina swamp 7.5 and 4.5 years following cessation of thermal pollution were compared.[75] Biomass changes were minor, but major floristic changes had occurred, with only 21% of the species found in both studies. Thermal discharge for a period of 14 years had previously destroyed the original woody flora.

Great Lakes. Primary productivity rates were measured at the Kewaunee nuclear power plant on Lake Michigan.[76] Lower rates of productivity occurred when there was a ΔT across the condenser. It was concluded that although individual phytoplankton may be killed by passage through the cooling system, populations suffer no permanent damage.

Growth of attached algae in the vicinity of the Nanticoke generating station (Lake Erie) was studied.[77] The temperature required to initiate *Cladophora* growth (11°C) was reached in February in the immediate discharge, April in the downstream discharge, and May in control areas. *Ulothrix* became dominant in the late fall when temperatures fell below 8°C.

Body temperatures of rainbow trout (*Salmo gairdneri*) caught at the Point Beach nuclear plant (Lake Michigan) were used to determine selected temperatures and to estimate acclimation temperatures under field conditions.[78] Body temperatures increased with increases in discharge temperature except at high temperatures. The modal body temperature of small trout was 19°C, while that of large trout was 15°C.

Estuarine and marine systems. Hein and Koppen[79] compared diatom assemblages in the intake and discharge canals of the Oyster Creek generating station (N. J.). The assemblages in the heated effluent had fewer species, lower diversity indices, and greater redundancy. Thermal discharges from this station did not affect mortality in natural populations of the clam *Mercenaria mercenaria* in Barnegat Bay.[80] Mortality rate curves, survivorship curves, and life tables of clams at thermally elevated and control sites were nearly identical.

Natural populations of marine phytoplankton from the intake and discharge of the Cape Cod and Montaup plants (Mass.) all demonstrated the same degree of recovery when grown in continuous cultures.[81] Neither populations exposed to elevated temperatures nor those subjected to chlorination and heat treatment showed any adverse permanent effects.

Respiratory rates of natural assemblages of plankton collected from the intake and discharge of the Indian River power plant (Del.) were measured to determine their effect on dissolved oxygen (DO) levels in the receiving estuary.[82] Planktonic community respiration rates were consistently less than required to induce DO levels detrimental to finfish and shellfish.

Phytoplanktonic nitrate reductase activity and primary productivity were severely reduced at the Millstone power station on Long Island Sound in summer.[83] The decrease occurred during the 6- to 9-hour transit through the cooling pond following entrainment at temperature increases of 11° and 14°C over ambient temperatures of 19.5°–20°C. In spring, at ambient temperatures of 4.3°–9.9°C, nitrate reductase activity was stimulated.

Following relocation of a thermal discharge into Montsweag Bay (Maine), previously stressed populations of the intertidal alga *Ascophyllum nodosum* fully recovered.[84] Three years after the relocation, the population of *Spartina alterniflora* had only partially recovered.[85]

Reproduction of several benthic organisms in the warm water outfall of the Morro Bay (Calif.) power plant was studied by two investigators. The sea anemone *Anthopleura elegantissima* spawned earlier in the outfall than at control sites.[86] Although both *Mytilus edulis* and *M. californianus* were able to reproduce in the outfall, body component indexes showed that control populations were in better nutritional condition.[87] In summer, the outfall temperatures exceeded the extremely stressful level of 25°C.

The distributional responses of fish to operation of a newly constructed power plant were assessed for indigenous populations of the Anclote Anchorage and River (Fla.).[88] Increased abundance in winter and decreased abundance and diversity in summer in the vicinity of the plant were attributed to the thermal effluent.

Alden[89] used experimental field treatments to examine the thermal mortalities of copepods exposed to the heated effluents of the Crystal River (Fla.) generating station. Significant lethal effects were observed for all seven species examined, with mass mortalities occurring during the warmest months of the year. Estuarine species had steeper mortality curves and higher upper lethal thermal limits than the more neritic forms.

The results of a 3-year interdisciplinary study made in Card Sound (Fla.) were summarized by Thorhaug *et al.*[90] In contrast to effects observed at Turkey Point, little damage to the benthic community was observed at Card Sound. Reasons for the reduced effect of the thermal effluent are discussed. Thorhaug[91] also reported on the growth of the tropical marine seagrass *Thalassia testudinum* transplanted into an area of Turkey Point previously denuded by thermal effluents.

Environmental investigations performed at three locations of thermal effluents in Pearl Harbor, Hawaii, showed that cooling water systems produced only minor and localized impacts on the harbor system.[92] Harbor biota demonstrated a high resiliency to various perturbations.

As part of a study on the physiological ecology of two populations of *Mytilus edulis*, the effect of power plant heated discharge on one population was noted.[93] The "scope for growth" of the population adjacent to a power plant on the Plym Estuary (England) was negative for 4 or 5 months between January and May.

Attraction of eels and cod to the discharge of a power plant on Kiel Fjord (W. Ger.) was attributed to current and the resultant transport of planktonic food.[94] The benthic population in front of the plant was sharply reduced several days after plant shutdown.

Warming of water in the area of the Martigue-Poneau power plant (France) modified seasonal phytplankton succession.[95] *Skeletonema costatum* bloomed prematurely in late winter, and the bloom of *Chaetoceros decipiens* was more intense than in surrounding waters. Warm-water species of zooplankton were increased except in summer.[96]

Experimental ecosystems. Several experiments designed to simulate the effects of thermal additions on natural communities were reported. Three earthern channels constructed at the Greene County (Ala.) generating plant were used in a 2-year study to evaluate the effects of heated effluents on macroinvertebrates.[97] During most periods, oligochaetes and chironomid larvae were the dominant organisms sampled. The channel receiving heated effluent from the plant had the lowest species diversity with fewer mayflies than the channels receiving unheated and mixed unheated/heated water.

The effects of a 4°C temperature elevation were examined in two outdoor experimental stream communities with only steelhead trout (*Salmo gairdneri*) or both steelhead and coho salmo (*Oncorhynchus kisutch*) present (Utah).[98] Lower production, biomass, and survival of the treatment salmonids resulted from the higher maintenance requirements of treatment fish coupled with lower biomass of salmonid prey (chironomids, ephemeropterans, and ostracods), especially during late summer.

Production and yield of juvenile walleye (*Stizostedion vitreum*) in outdoor channels receiving cooling water from the Browns Ferry mortality occurred in the +6°C regimen channel when temperatures exceeded 34°C in August. Prior to August, total production ranged from 5.5 g/m^2 at ambient temperatures to 2.8 g/m^2 in the +6°C regimen.

The plankton community in a tank floated in the discharge of Harculo power station (Netherlands) was compared with that in a control tank.[100] Phytoplankton and populations of rotifers and copepods showed no damage after temperature shocks in these 2-week experiments. Cladocerans showed significant mortality after a shock of 13.5°, but recovered rapidly.

PRODUCERS

Effects on growth and production. Optimal growth conditions of temperature, light, and salinity were determined for the green alga *Mychonastes ruminatus*, isolated from Chesapeake Bay (Md.).[101] The alga grew at temperatures between 5° and 30°C with a maxi-

TABLE I. Effect of temperature on reproduction.

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Location	Reference Citation
Haliplanella luciae	Sea anemone	Fission at 25°, not at 15°	Laboratory	133
Centrostephanus rodgersii	Sea urchin	Onset of egg production at 20°; cessation at 24–26°	Australia	134
Tapes philippinarium	Manila clam	Spawned at 15°, 18°, 21°	Laboratory	135
Nassarius trivittatus	Snail	Egg capsules produced Oct. to Dec. (7°)	Outdoor laboratory	136
Canthocamptus staphylinus	Copepod	High temperature (12°) or long days inhibited egg production	Laboratory	137
Idotea balthica	Isopod	Fecundity reduced at 30° and above	Laboratory	138
Porcello dilatatus	Isopod	Reproductive diapause initiated by low temperatures and short days	France	139
Penaeus esculentus	Prawn	Reproductive growth cued by 2° rise above mean annual 26.3°; spawning cued by 2° drop in Apr. and May	Australia	140
Carassius auratus	Goldfish	Constant high temperatures, 20° and 30°, inhibited gonad growth	Laboratory	141
Catostomus tahoensis	Tahoe sucker	Spawned Apr.–Aug. at 11.7–22.7°	Pyramid Lake (Nev.)	142
Chondrostoma nasus	Nase carp	Spawned Apr.–May at 8°	Czechoslovakia	143
Cyprinodon nevadensis	Desert pupfish	Reproduction optimal at 28°	Laboratory	144
Dicentrarchus labrax	Sea bass	Spawned out of season under shortened seasonal temperature cycles	Laboratory	145
Engraulis mordax	Northern anchovy	Potential year-round breeding at 13–18°	San Pedro Bay (Calif.)	146
Esox lucius	Pike	Spawned in Mar. at 6–7°	USSR	147
Esox masquinongy	Muskellunge	Spawned in Apr. at 10° or higher	Middle Island Creek (W.Va.)	148
Gila bicolor	Tui chub	Spawned June–August at 15.5–22.2°	Pyramid Lake (Nev.)	149
Ictalurus platycephalus	Flat bullhead	Spawned June–July at 21–24°	Lake Norman (N.C.)	47
Lucioperca lucioperca	Pike-perch	Spawned in Apr. at 14–16°	USSR	147
Lutjanus campechanus	Red snapper	Spawned at 23–25°	Laboratory	150
Menidia menidia	Atlantic silversides	Spawned out of season at constant temperatures above 24°	Laboratory	151

TABLE I—(*Continued*)

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Location	Reference Citation
Micropterus salmoides	Largemouth bass	Spawned out of season when temperature raised from 16° to 23°	Laboratory	152
Perca flavescens	Yellow perch	Spawned at 10°	Keowee Reservoir (S.C.)	46
		Spawned at 10°	Laboratory	153
Perca fluviatilis	Perch	Spawned in Mar.–Apr. at 8–10°	USSR	147
Percopsis transmontana	Sand roller	Spawned in summer at 14–16°	Columbia River (Wash.)	154
Rutilus rutilus	Azov roach	Spawned in Mar.–Apr. at 7° up to 17–18°	Azov Sea (USSR)	155
Salmo gairdneri	Steelhead trout	Precocious sexual development related to age, water temperature, and photoperiod	Laboratory	156
Scophthalmus maximus	Turbot	Spawned out of season under shortened seasonal temperature cycles	Laboratory	145
Silurus glanis	Catfish	Spawned in May above 20–22°	USSR	147
Sparus aurata	Sea bream	Spawned out of season under shortened seasonal temperature cycles	Laboratory	145
Stizostedion vitreum	Walleye	Spawned at 8–12°	Clinch and Powell Rivers (Tenn.)	157

mal doubling rate of 1.67/day at 25°C. The influence of CO_2 supply, light intensity, and temperature on the concentration of extracellular organic substances in synchronous cultures of *Scenedesmus acutus* was measured.[102] Constant light and suboptimal temperature (35°C compared with 30°–33°C) reduced the accumulation of organic excreta in the medium.

Growth patterns of the green seaweed *Codium fragile* were determined in the field and laboratory.[103, 104] Maximal growth along the Rhode Island coast occurred during the summer and was significantly correlated with temperature. In the laboratory thalli grew best at 24°C, 24–30 g/l salinity, a minimal irradiance of 28 $\mu E/m^2/sec$ and 16-hour day length. In the Mediterranean Sea the reproductive season of *Caulerpa prolifera* occurred between the end of June and the beginning of October at seawater temperatures above 20°C.[105]

The optimum temperature for photosynthesis of natural populations of blue-green algae from Lake Mendota (Wis.) was between 20° and 30°C.[106] Temperature optimum for growth and photosynthesis of the three dominant species, *Aphanizomenon*, *Anabaena*, and *Microcystis*, was 25°C. Water temperature during the summer ranged from 12° to 24°C. In another study the lower temperature limit for *Microcystis* varied between 10.5° and 13.5°C, the thermal growth optimum between 28.8° and 30.5°C, and the upper temperature limit between 35.0° and 40.0°C.[107] The corresponding values for *Synechococcus* were 10.3°, 34.5°, and 44.3°C.

Three strains of the blue-green alga *Mastigocladus laminosus* were investigated for their nitrogen fixation ability.[108] One strain grew well at temperatures from 35° to 50°C with optimum growth at 45°C. Acetylene reduction activity was also greatest at this temperature.

Two studies measured the effects of temperatures on membrane structure of *Anacystis nidulans*. Cells grown at 25°C prior to chilling to 0°C appeared unchanged as judged by thin sectioning, whereas those grown at 39°C before chilling showed considerable morphological alteration.[109] The lipid composition was affected by growth temperature in *A. nidulans,* but not in *Anabaena variabilis*.[110] Ono and Murata[111] measured the temperature dependence of photosynthetic activities in thylakoid membranes of *A. nidulans*.

Mickelson *et al.*[112] found that the diatoms *Skeletonema costatum* and *Chaetoceros septentrionalis* are closely related in their ability to utilize limiting ammonium at nutrient dilution rates of 0.01–0.03/h. *Thalassiosira gravida* could not compete with these two species for limiting ammonia nor under reduced temperature and light conditions. A brief temperature increase (base 18°–27°C) triggered changes in population densities of coexisting species, leading to an increase in the less abundant species.

Yoder[113, 114] compared the cell division rate of natural populations of *Skeletonema costatum* grown in dialysis culture (0°–22°C) with that predicted from a mathematical model. Regression analysis revealed that equations incorporating the effect of temperature (0°–10°C) and light intensity were sufficient to explain the observed cell division rate in many experiments, but the inclusion of silicate concentration improved the relationship.

The benthic diatom *Nitzschia ovalis* grew well at salinity levels of 8–53 g/l and temperatures of 12°–36°C.[115] Maximum growth rates

TABLE II. Effect of temperature on embryonic development.

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Reference Citation
Opistomum pallidum	Turbellarian	Duration of development followed Hoff/Arrhenius temperature rule	158
Hexarthra fennica	Rotifer	Egg development and life cycle shortened under fluctuating temperature regime	159
Neanthes japonica	Polychaete worm	Normal development between 10 and 30°, optimum at 20°	160
Cadlina luteomarginata	Sea slug	Hatched in 86, 35, and 25 d at 5°, 10°, and 15° respectively; mortality at 20°	161
Nassarius trivittus	Snail	Development proportional to temperatures; 55 d at 3.3–7.4°, 5–7 d at 21°	136
Diacyclops bicuspidus, Mesocyclops edax, Leptodiaptomus minutus, Aglaodiaptomus spatulocrenatus	Copepods	Development time decreased with increasing temperature, 4–27°; data fitted to Belehradek's equation	162
Eudiaptomus vulgaris	Copepod	Development/temperature relation expressed by given equation	163
Chydorus sphaericus	Cladoceran	Differences in duration of development under cyclic regimes explained by Kaufmann effect	164
Triops longicaudatus	Tadpole shrimp	Eggs developed and hatched at 14–29°	165
Chaoborus crystallinus	Phantom midge	20° thermoperiods with low temperatures at night and 14° thermoperiods caused retardation of development and induced dormancy	166
Ecdyonurus picteti	Mayfly	Development rate fitted to Belehradek function	167

TABLE II—(*Continued*)

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Reference Citation
Hexagenia rigida	Mayfly	Hatching occurred after 7 d at 32° and 77 d at 12°, no hatching at 8° or 36°	168
Tricorythodes minutus	Mayfly	Life cycle multivoltine at constant 18°, bivoltine at seasonal range of 0–29°	169
Acipenser güldenstadti	Sturgeon	Highest survival at 12–18°	170
Acipenser nudiventris	Sheap sturgeon	Highest survival at 11–15°	170
Acipenser stellatus	Sevryuga	Highest survival at 16–22°	170
Coregonus clupeaformis	Lake whitefish	Temperature-development time relations modeled; optimum survival at 4–6°	171
Huso huso	Beluga	Highest survival at 10–14°	170
Micromesistius poutassou	Blue whiting	Hatching occurred after 205 h at 6° and 70 h at 15°; relationship described by Belehradek's equation	172
Morone chrysops	White bass	Development ranged from 4.5 d at 14° to 1 d at 26°	173
Perca flavescens	Yellow perch	Incubation period inversely related to temperature; 228 temperature units over average daily 9.9° required	153
Perca fluviatilis	Perch	Highly significant inverse relationship between mortality and degree days above 14° in year of hatch	174
Prosopium williamsoni	Mountain whitefish	Optimum development temperature 6°	175
Salmo salar	Atlantic salmon	Optimum development temperature 10°	176

occurred at combinations of 28°, 30°, and 32°C and salinities of 28 and 32 g/l. Increases of temperature ranging from 10° to 15°C had no effect on growth of the diatom *Navicula ostrearia* cultured at 12°C.[116] Mortality occurred at 34°C.

Motile unicells of the yellow-brown alga *Olisthodiscus luteus* aggregated to form encapsulated masses of nonmotile cells in a benthic stage throughout a temperature range of 15°–30°C at salinities of 10–50 g/l.[117] Motile cells were released from benthic masses at 10°–30°C, but at 5°C cells were not motile, and at 0° cells lysed.

The cryptomonad algae *Cryptomonas ovata* and *Chroomonas* sp. were grown in cultures to determine optimum conditions of pH, light intensity, temperature, and photoperiod.[118] Both organisms showed the highest growth rate at 20°C.

Laboratory studies were conducted to determine the chemical composition of the dinoflagellate *Ceratium furca* and to evaluate the accuracy of growth rates determined from the maximum observed frequency of division.[119] The initiation of cell division was independent of temperature over the experimental range 15°–25°C.

Anderson and Morel[120] presented complementary laboratory and field data that demonstrated the seeding of a spring and a fall bloom of the toxic dinoflagellate *Gonyaulax tamarensis* by the temperature-induced germination of benthic hypnocysts. Germination of overwintering hypnocysts was initiated by a temperature increase; the fall bloom was seeded by hypnocyst germination and a temperature decrease from the summer level of 20°–22°C.

The seasonal growth and reproduction of the red alga *Dumontia incrassata* were described from two New Hampshire sites in relation to a variety of environmental factors.[121] The plant's maximum abundance and repro-

TABLE III. Effect of temperature on larval development.

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Reference Citation
Anonchus sp.	Nematode	No development at 5°; optimum between 15° and 20°	177
Crepidula fornicata	Snail	Shell growth rate increased over range 15–25°, growth rates intermediate with cyclic temperatures	178
Gammarus olivii	Amphipod	Growth curve equations at 5°, 10°, and 20° given	179
Daphnia longispina, *Ceriodaphnia quadrangula*, *Bosmina longirostris*	Cladocerans	Development time varied inversely with temperatures, 7–20°	180
Calanus pacificus, *Pseudocalanus* sp.	Copepods	Interactions among body size, food concentration, temperature, and growth rate	181
Enhydrosoma propinqum, *Microarthiridion littorale*, *Stenhelia bifidia*	Copepods	Water temperature/size frequency distributions given	182
Neomysis americana	Mysid shrimp	Development time of marsupial larvae ranged from 23–25 d at 10° to 12–14 d at 16°	183
Leptomysis lingvura, *Hemimysis speluncola*	Mysid shrimp	Growth rate inversely related to temperature, 10–22°	184
Pandulus jordani	Shrimp	Optimal growth and survival at 8–11°	185
Sergestes similis	Shrimp	Optimum temperature range 10–15°	186
Pacifastacus leniusculus	Crayfish	Growth in weight, length maximum at 22°, 20°	187
Cancer irroratus	Crab	Increased survival at 10° to 20° cyclic regime compared with constant 15°	188
Rhithropanopeus harrisii	Crab	Survival at 25–30° cyclic temperature, 5–30 g/l salinity; mortality at 30–35°, 5–30 g/l	189
Aedes dorsalis	Mosquito	Maximum survival and uniform growth at 25° compared with 20° and 30°	190
12 species of *chironomids*		Emergence related to light intensity and/or water temperature	191
45 species of stoneflies		Emergence related to water temperature, 8–15°	192
103 species of insects		Emergence related to water temperature	193

duction occurred during the winter-spring period of low temperatures (<10°C) and high nutrients. Photosynthesis of *Delesseria sanguinea* from the western Baltic showed an optimum for marine conditions at about 30 g/l salinity and 10°C.[122]

Carbon fixation in several species of freshwater red algae was investigated by Kremer.[123] Maximum rates of photosynthesis occurred at 25°C for *Lemanea annulata* and at 35°C for *Compsopogon hookeri.*

Maximum rates of NO_3^- uptake by the brown alga *Laminaria longicruris*, tested over the range 0°–15°C, were observed at 15°C, the approximate seawater temperature prevailing during the late summer months in St. Margaret's Bay (Canada).[124] Maximum net photosynthesis of the fucoid brown alga *Asco-*

phyllum nodosum, collected from the New Hampshire coast, was exhibited during summer at 18°–21°C.[125] Druehl[126] related the distribution of *Macrocystis integrifolia* in British Columbia (Canada) to seasonal seawater temperatures and salinities.

Community responses. Examination of 40 years of data from Lake Michigan water intakes at Chicago, Ill., revealed a change in the apparent temperature optima of phytoplankton.[127] An optimum temperature of 10°C for the plankton community was observed between 1936 and 1956, and for the past 20 years an optimum temperature range from 0° to 4°C was observed. Differences were attributed to the emergence of cold-water species such as *Stephanodiscus,* and decline in dominance of *Asterionella* and *Fragilaria.* More recently, however (1972–76) blue-green algae have also increased in abundance.

TABLE IV. Summary of recent distribution studies.

Scientific Name	Common Name	Temperature (°C) and Location	Reference Citation
Daphnia pulicaria	Water flea	<22°, Wintergreen Lake, Mich.	199
Alosa pseudoharengus	Alewife	Young at 17–19°, adults at 11–14°, Lake Michigan	200
Alosa sapidissima	American shad	13–15°, Atlantic Coast	201
Atherinops affinis	Topsmelt	19–26°, Redondo Beach, Calif.	202
Citharichthys stigmaeus	Speckled sanddab	<15°, Redondo Beach, Calif.	203
Cottus cognatus	Slimy sculpin	<6° at night, Lake Michigan	200
Dorosoma cepedianum	Gizzard shad	>12° at 0–5 m, Ottoville Quarry, Ohio	204
Esox lucius	Northern pike	14–19°, Lakes, Ontario, Canada	205
Gambusia affinis	Western topminnow	31°, Mammoth Warm Spring, Ariz.	206
Gila bicolor	Tui chub	Up to 22° in summer, Pyramid Lake, Nev.	207
Leiostomus xanthurus	Spot	Inverse temperature/abundance relationship, Apalachicola Bay, Fla.	208
Myoxocephalus quadricornus	Fourhorn sculpin	<5°, Lake Michigan	200
Notropis hudsonius	Spottail shiner	17–20°, Lake Michigan	200
Notropis lutrensis	Red shiner	5–27.2° seasonally, South Canadian River and Pond Creek, Ok.	209, 210
Osmerus mordax	Rainbow smelt	7–8° (day), 11–16° (night), Lake Michigan	200
Perca flavescens	Yellow perch	Juveniles at >15° (day), >17° (night), adults at 7–8°, 11–17°, Lake Michigan	200
		14–19°, Lakes, Ontario, Canada	205
Percopsis omiscomaycus	Trout perch	15–16° (day), 7–16° (night), Lake Michigan	200
Salmo gairdneri	Rainbow trout	<20° at >4 m, Ottoville Quarry, Ohio	204
		Young at 19°, adults at 15°, Lake Michigan	78
Salmo henshawi	Lahontan cutthroat trout	7–15°, Pyramid Lake, Nev.	207
Stizostedion vitreum	Walleye	10.6–11.2° epilimnion of West Blue Lake Can.	211
		Avoided >24°, Norris Reservoir, Tenn.	157

Temperature played an important role in regulating standing crop of phytoplankton in the Mississippi River through its effect on photosynthesis.[128] The temperature optimum for photosynthetic capacity shifted from 16°C in spring to 28°C in summer. The primary production and general ecology of a periphyton community of a New England lowland stream were studied by Sumner and Fisher.[129] A mathematical expression relating periphyton photosynthesis per unit chlorophyll *a* to temperature, light, and periphyton density was established with submersible light-dark chambers in situ. Low temperature was one of several factors responsible for restricting primary productivity in a hypersaline Antarctic lake.[130]

Higher plants. Effects of variable temperatures on the growth and vegetative reproduction of an aquatic plant were examined by exposing populations of *Spirodela oligorrhiza* to cyclic, acyclic, and constant temperature regimes.[131] Growth rates under the cyclic and acyclic regimes (10°–25°C) were not significantly different from those at a constant temperature equal to the mean of the range (17.5°C). Population growth was directly related to temperature in both constant and variable thermal regimes. The photosynthetic rate of the submerged hydrophyte *Utricularia purpurea* was measured in the laboratory.[132] Photosynthetic rate increased with temperature from 5° to 24°C.

CONSUMERS

Reproduction. The processes of gonad development and spawning are highly temperature dependent, yet species specific. Newly published information is summarized in Table I.

Development. Embryonic and larval development occur within a limited tempera-

TABLE V. Thermal tolerance studies.

Scientific Name	Common Name	Type of Temperature Tolerance	Reference Citation
Ochromonas sociabilis	Flagellate	High	213
Dugesia japonica	Planarian	High, low	214
Pomatoceros triqueter	Polychaete	High, low	215
Tubifex tubifex	Oligochaete	High, thermal shock	216
Erpobdella octoculata	Leech	High, thermal shock	216
Crassostrea gigas	Oyster	High (F)	217
Ostrea edulis	Oyster	High (F)	217
Mytilus edulis	Mussel	High	218
Trichomya hirsuta	Bivalve	High	218
Mya arenaria	Clam	High	219
Littorina littorea	Snail	Low	220
Nassarius obsoletus	Snail	Low	220
Murex pomum	Snail	High, low	221
Physa fontinalis	Snail	High, thermal shock	216
Strongylocentrotus purpuratus, *S. franciscanus*	Sea urchins	High	222
Pisaster ochraceus, *P. giganteus*	Starfish	High	222
Gammarus fossarum	Amphipod	High, thermal shock	216
Asellus aquaticus	Isopod	High, thermal shock	216
Lirceus brachyurus	Isopod	High	223
Eurytemora affinis	Copepod	High, thermal shock	224, 225
Euphausia pacifica	Crustacean	High	226
Macrobrachium amazonicum	Shrimp	Low, coldshock	227
Macrobrachium ohione	Shrimp	High	228
Macrobrachium rosenbergii	Shrimp	Low	229
Palaemonetes spp.	Shrimp	High	228
Penaeus spp.	Shrimp	High	228
Callinectes sapidus	Crab	High	228
Cancer magister	Crab	High	230
Panopeus herbstii	Crab	High	228
Chironomus thummi	Midge	High, thermal shock	216
Geotria australis	Lamprey	High	231
Alosa pseudoharengus (eggs, larvae)	Alewife	High, thermal shock	232, 233
Alosa sapidissima (eggs, larvae)	American shad	High, thermal shock	233

TABLE V—(*Continued*)

Scientific Name	Common Name	Type of Temperature Tolerance	Reference Citation
Brevoortia tyrannus	Atlantic menhaden	Thermal shock	234
Carassius auratus	Goldfish	High, low	235
Cynoscion regalis (eggs, larvae)	Weakfish	High, thermal shock	236, 237
Cyprinion macrostomus	Fish	High	238
Cyprinodon elegans	Pupfish	High	239
Dorosoma cepedianum	Gizzard shad	Low (F)	54
Dorosoma petenense	Threadfin shad	Low (F)	53, 54
Esox lucius	Northern pike	High	205
Esox masquinongy	Muskellunge	High	240
Gambusia nobilis	Pecos gambusia	High	239
Heteropneustes fossilis	Indian catfish	High, low	241
Ictalurus melas	Black bullhead	High	242
Leiostomus xanthurus	Spot	Thermal shock	243
Lepomis gibbosus	Pumpkinseed	High	244
Microgadus tomcod	Atlantic tomcod	High, thermal shock	232
Micropterus dolomieui	Smallmouth bass	Low	245
Morone chrysops (eggs)	White bass	High	173
Morone saxatilis	Striped bass	High	246
(eggs)		High, thermal shock	232
(eggs, larvae)		High, thermal shock	233
Oncorhynchus kisutch	Coho salmon	High	244
Paralichthys dentatus (eggs, larvae)	Summer flounder	High, thermal shock	237
Perca fluviatilis	Perch	High	247
Pomatoschistus microps	Sand goby	High	248
Prinotus evolans (eggs, larvae)	Striped searobin	High, thermal shock	237
Salmo clarki	Cutthroat trout	High	249
Salmo gairdneri	Rainbow trout	High	250
Stizostedion lucioperca	Pikeperch	High	247
Tautoga onitis (eggs, larvae)	Tautog	High, thermal shock	197, 237
45 species of estuarine fish		High	228
56 species of marine fish		Low (F)	251

(F) indicates field study.

ture range, and the rate of development is controlled by temperature. Table II summarizes new information on embryonic development prior to hatching. Table III includes larval and early juvenile development.

Morphology. Hydra (*Hydra oligactis*) size was inversely proportional to rearing temperature, ranging from greater than 100 μg at 10°C to 30 μg at 25°C.[194] The mean tentacle number of buds of *Hydra viridis* varied with several factors, among them temperature.[195] Buds produced at higher temperatures had lower tentacle numbers.

Blastula formation of the starfish *Asterina pectinifera* was normal between 13° and 23°C.[196] At high temperatures (25°–26°C) most embryos became abnormal.

The effect of elevated temperature on early embryonic development of tautog *Tautoga onitis* was studied by Olla and Samet.[197] When incubation temperature was gradually raised from 20° to 24.2° to 26.3°C, anatomical deformities, including stunted embryos and/or abnormal body curvatures, as well as increased mortality occurred. Anomalies were also observed in American shad (*Alosa sapidissima*) following incubation of eggs at higher than optimum temperatures.[198]

Distribution. Recent distribution studies are summarized in Table IV. Environmental requirements associated with 363 North American species of freshwater Plecoptera (stoneflies) were tabulated by Surdick and Gaufin.[212] Eleven ecological parameters including temperature were considered. The report is designed to be applicable to water quality investigations and to provide a baseline from which further ecological and systematic research is encouraged.

Temperature tolerance. Studies concerning the tolerance of aquatic organisms to temperature extremes are referenced in Table V.

All studies are laboratory studies except those designated (F) for field studies.

Oxygen metabolism. Respiration is temperature dependent and serves as an indicator of thermal stress. Species investigated for thermal effects on respiration are listed in Table VI.

Growth. Growth of aquatic organisms occurs within a limited temperature range. Growth rates are usually controlled by temperature. New studies on effects of temperature on growth are summarized in Table VII.

Feeding. Feeding rate of the ctenophore *Mnemiopsis leidyi* on mixed natural zooplankton was independent of food concentration but was a function of both temperature and size of the ctenophore.[306] The feeding rate (1/mg dry wt/day) ranged from 0.01 for larger ctenophores at lower temperatures (10°–15°C) to about 0.1 for smaller ctenophores at higher temperatures.

In the laboratory, food consumption and assimilation of the pond snail *Lymnaea stagnalis* was positively related to temperature from 5° to 25°C.[307] It was suggested that feeding in the field starts in spring at a water temperature of 8°–11°C.

Filtering rate (ml/animal/day) of *Daphnia ambigua* followed a complex pattern with temperature.[261] The rate increased with temperature from 6.5° to 11.3°C, dropped at 13.3°C, and increased at higher temperatures.

Different weight classes of the dragonfly nymph *Mesogomphus lineatus* were allowed to devour larvae of *Culex fatigans* over the temperature range 10°–40°C to study the interaction of body weight and temperature on satiation time, maximum food intake, and return of appetite.[308] Number of larvae eaten per hour by a 50 mg nymph increased linearly from one at 10°C to eight at 35°C. Maximum food intake, but not satiation time, was dependent on temperature.

The capture of *Daphnia pulex* by the damselfly *Ischnura elegans* increased in a sigmoid manner with temperature, while the handling time declined logarithmically from 5° to 16°C after which it remained constant.[309] Onset and termination of growth in the field correlated with the temperature at which the attack response begins to increase markedly. Rate of consumption of chironomid larvae by dobson flies (*Corydalus cornutus*) increased with temperature from 10° to 30°C.[271] Nymphs did not feed at 5°C.

Fingerling largemouth bass (*Micropterus salmoides*) were trained to accept carp eggs readily as food at 27°C.[310] Success at 22° and 25°C was not as great. Food consumption, food conversion, and growth of grass carp (*Ctenopharyngodon idella*) were similar in tanks maintained at 18.3°, 23.9°, and 29.4°C.[311] The least growth and food consumption occurred in fish held at 12.8°C.

The rate of food intake by *Sarotherodon mossambica*, an introduced African cichlid fish, increased with temperature, reaching a maximum at 35°C.[312] Absolute growth peaked at 30°C regardless of salinity. The gross conversion efficiency was highest at 20°C in seawater and at 25°C in fresh and brackish waters.

The digestion rate of flounder (*Platichthys flesus*) fed with polychaete worms was faster at 15°C than at 10°C.[313] An exponential model was fitted to the results. Digestion of threadfin shad by sauger (*Stizostedion canadense*) was significantly reduced at 5° and 10°C compared with that at 15°C.[53] The digestive efficiency of temperature acclimated mummichogs (*Fundulus heteroclitus*) was determined using amphipods as prey.[314] From 13° to 19°C efficiencies were temperature independent and were the maximum possible.

The effect of temperature on gastric evacuation of several fish species was studied. The gastric emptying time in turbot (*Scophthalmus maximus*) was found to decrease with temperature (8°–15°C).[315] Times to complete gastric evacuation in plaice (*Pleuronectes platessa*) decreased from 67.3 hours at 5°C to 20.2 hours at 21°C.[316] Complete gastric evacuation in trout (*Salmo gairdneri*) acclimated at 7°, 13°, and 19°C required 49, 41 and 33 hours, respectively.[317] Gastric evacuation in tilapia (*Sarotherodon mossambicus*) was not influenced by temperature and required 14 hours. Gastric evacuation rates in perch (*Perca fluviatilis*) over the temperature range 4.0°–21.7°C were empirically described by an exponential function.[318]

Elliott and Persson[319] reviewed and criticized studies on rates of gastric evacuation and food consumption of fish. Quantitative studies show that the evacuation rate is related to water temperature by an exponential or power-law function. Two new methods of calculating gastric evacuation rates are proposed. Both assume that the rate is exponential.

Temperature and other stresses. Temperature can control the rates and extent of ac-

TABLE VI. Effects of temperature on oxygen metabolism.

Scientific Name	Common Name	Reference Citation
Anonchus sp.	Nematode	177
Tubifex tubifex	Oligochaete	252
Nereis succinea, N. virens	Oligochaetes	253
Donax serra, D. sordidus	Bivalves	254
Corbicula fluminea	Clam	255
Mya arenaria	Clam	219
Noetia ponderosa	Clam	253
Polymesoda caroliniana	Clam	256
Spisula solidissima	Clam	253
Modiolus demissus	Mussel	256
Bullia digitalis	Snail	257
Busycon canaliculatum	Snail	253
Cassidula aurisfelis	Snail	258
Cerithidea obtusa	Snail	258
Goniobasis cahawbensis, G. cochliaris	Snails	259
Lymnaea stagnalis	Snail	260
Murex pomum	Snail	221
Nerita articulata	Snail	258
Xiphosura limulus	Horseshoe crab	253
Daphnia ambigua	Cladoceran	261
Daphnia pulex	Cladoceran	262
Lirceus brachyurus	Isopod	223
Acartia clausi	Copepod	263
Anomalocera patersoni	Copepod	263
Calanus spp.	Copepod	263
Centropages typicus	Copepod	263
Clausocalanus arcuicornis	Copepod	263
Mesocyclops brasilianus	Copepod	264
Pleuromamma gracilis	Copepod	263
Tachidius discipes	Copepod	265
Cambarus acuminatus	Crayfish	266
Callinectes sapidus	Crab	253
Cancer irroratus	Crab	188
Cancer maenas	Crab	267, 268
Cancer magister	Crab	230, 269
Emerita talpoida	Crab	270
Hemigrapsus nudus	Crab	253
Libinia emarginata	Crab	253, 270
Pachygrapsus crassipes	Crab	268
Panopeus herbsti	Crab	253
Corydalus cornutus	Dobson fly	271
Limnephilus rhombicus	Caddisfly	272
Mellita quinquiesperforata	Sand dollar	273
Gasterosteus aculeatus	Threespine stickleback	274
Heteropneustes fossilis	Indian catfish	275
Ictalurus melas	Black bullhead	242
Leiostomus xanthurus	Spot	276
Lepomis cyanellus	Green sunfish	277
Lepomis macrochirus	Bluegill	278
Lutjanus campechanus	Red snapper	279
Melanostigma pammelas	Eelpout	280
Micropterus salmoides	Largemouth bass	277, 281
Morone americana	White perch	276
Pimephales promelas	Fathead minnow	282
Salmo salar (eggs)	Atlantic salmon	283
Tilapia nilotica	Tilapia	284, 285
Trinectes maculatus	Hogchoker	276

tion of other stresses on aquatic organisms. Table VIII summarizes new data on temperature-stress interaction. In addition, Capuzzo [322] reviewed the effect of temperature on the toxicity of free chlorine and chloramine to several species of marine animals. For all species tested, except the copepod *Acartia tonsa,* temperature had a synergistic effect on the toxicity of both halogen forms. It is suggested that the effect of temperature in enhancing the toxic effects of chlorinated cooling waters to marine animals is the result of an interaction of uptake rates and regulation of physiological rates. The greatest enhancement in sensitivity can be expected at the upper limit of a species' thermal tolerance.

Vernberg [354] reviewed the effects of multiple environmental factors and their interactions on aquatic organisms. Although these studies are difficult to pursue because of the complexity of the natural environment, some advances have been made with the help of statistical and computer techniques.

Temperature selection and thermoregulation. When presented with a choice of ambient temperatures, as in a thermal gradient, motile organisms tend to congregate in a narrow range of temperatures. Such behavior is called temperature selection or behavioral thermoregulation.

Numerous authors have suggested that temperature is a major factor influencing the distribution and success of a species in nature and that laboratory-selected temperatures are relevant in explaining the field distribution of a species. Beitinger and Magnuson,[304] among others, have suggested that maximum growth rates occur at a species' final temperature preferendum. Recent laboratory studies on temperature preference are summarized in Table IX.

A symposium on thermoregulation in ectotherms was organized by Reynolds.[372] Among the topics presented were significance of skewness in ectotherm thermoregulation,[373] behavioral thermoregulation and the final preferendum paradigm,[374] ontogenetic and nonthermal effects on thermal preferenda of fish,[375] mechanisms of fish distribution in heterothermal environments,[376] physiological and ecological correlates of preferred temperature in fish,[377] temperature as an ecological resource,[378] and the role of behavior in temperature acclimation and tolerance in ectotherms.[379]

Activity. Sinking rates of fasting *Hydra oligactis* reared at 10°, 15°, and 25°C were determined in a water column at 10°, 21°, and 26°C.[194] The sinking rate was directly correlated with water temperature and inversely correlated with fasting time and rearing temperature. The results are discussed with respect to seasonal distribution in lakes. Harbison and Campenot [380] studied the effect of lowered temperatures on the swimming rate of salps. Type of response was related to oceanic and vertical and horizontal distribution patterns.

Philipson [381] investigated the undulatory behavior of larvae of *Hydropsyche* sp. in relation to water temperature and dissolved oxygen concentration. A rise in temperature from 10° to 25°C resulted in decreased quiescent time and an increase in undulation rate. Undulation rate is probably related to oxygen uptake and thus energy expenditure.

Temperature had little effect on the movement and relocation of larvae of black flies in artificial streams.[382] At lower temperatures, 2°–18°C, the number of larvae relocating remained fairly constant; as temperature increased further relocation rates dropped sharply.

Burrowing activity of the bivalve *Macoma balthica* was tested in the laboratory.[383] Burrowing was more rapid at 16° than at 4°C. Locomotor activity of the snail *Melanoides tuberculata* was crepuscular in nature and was relatively independent of temperature.[384] The free-running period of the rhythm was slightly shorter at 20° compared with 18°C.

Activity of perch (*Perca fluviatilis*), studied in the laboratory, increased with water temperature from 2° to 13°C and with day length.[385] Temperatures used reflected seasonal ambient temperatures. Observations on salmon (*Salmo salar*) and sea trout (*Salmo trutta*) smolt migration in a chalkstream over a period of 4 years indicated a relationship between number of fish migrating during the day and maximum afternoon water temperatures.[386, 387] Both solar radiation and water temperature were correlated with intensity and timing of movement.

Migration of twaite shad (*Alosa fallax*) in the Severn estuary (England) reached a peak soon after the temperature dropped below 19°C; migration ceased below 9°C.[388] The migratory route of American shad (*Alosa sapidissima*) in the Atlantic Ocean was studied using 14 years of catch data.[201] All shad catches and peak entry of shad into home estuaries occurred at bottom temperatures of 3°–15°C, with most frequent catches at 7°–13°C.

TABLE VII. Effects of temperature on growth.

Scientific Name	Common Name	Condition Observed and Temperature (°C)	Reference Citation
Corals		High density growth bands at 29–30°; low density bands at 26–27°	286
10 species of flatworms		Survival and growth in laboratory related to field distribution temperatures	287
Perinereis nuntia	Polychaete	Optimum growth at 20°	288
Mytilis californianus	Mussel	Assimilation and scope for growth greater at 15° than at 9°	289
Tapes philippinarum	Manila clam	Growth (soft tissue) inversely proportional to temperature, 12–21°	135
Tapes japonica	Clam	Condition similar at 12°, 15°, 18°, and 21°	290
Crassostrea gigas	Oyster	Increase in weight with increase in temperature, 12–21°; condition similar at 12°, 15°, 18°, and 21°; 15° optimum for growth	290, 291, 292
Ostrea edulis	Oyster	Increase in weight proportional to temperature, 12–21°; condition similar at 12°, 15°, 18°, and 21°	290, 291
Dreissena polymorpha	Mussel	Growth optimum at 10–15°; highest rate at 8°, diminished with increasing temperature	293, 294
Neritina violacea	Snail	Greatest shell increase at 27.5°	295
Physa acuta	Snail	Growth more rapid at 26° than at 22°	296
Physa integra	Snail	Growth rate similar at 21° and 26°	297
Physa stagnalis	Snail	Growth rate greater at 26° than at 21°	297
Daphnia magna	Cladoceran	Growth at 6–22°; optimum efficiency at 9°	298
Acartia clausii	Copepod	Increase in growth with temperature, 10–20°, in laboratory; constant rate in field	299
Cyclops spp.	Copepods	Growth rate increased with temperature, 10°, 15°, 20°	300
Panulirus homarus	Rock lobster	Little effect of temperature on growth (24–28°), decreased growth at 30°	301
Anguilla anguilla	Eel	Optimum growth at 20–22°	302
Abudefduf abdominalis (juveniles)	Maomao	Highest growth rate at 29.4° and 32.4° when tested at 23.4–32.4°	303
Esox lucius (yearlings)	Northern pike	Best growth at 19° for weight and 21° for length; growth low at 4° and 27.5°	205
Lepomis macrochirus (juveniles)	Bluegill	Optimum growth rate at 30–31°	304
Micropterus dolomieui (fry)	Smallmouth bass	Model describes growth rates and size distributions; growth rate greater at 25.6° than at 20.1° and 31.1°	20
Perca fluviatilis	Perch	Growth optimum at 26°	247
Salmo trutta	Brown trout	Maximum growth rates computed from field temperatures using growth model	305
Stizostedion lucioperca	Pikeperch	Growth optimum at 28–30°	247
Stizostedion vitreum (juveniles)	Walleye	Maximum survival temperature with continued growth: 32–33°	99

TABLE VIII. Interaction of temperature and other stresses.

Scientific Name	Common Name	Stress	Observed Effect (°C)	Reference Citation
Paramecium tetraurelia	Protozoan	Cu	Copper tolerance decreased with increasing temperature (12–34°)	320
Laomedea loveni	Hydra	Cd	More toxic at high temperature-low salinity combinations	321
Brachionus plicatilis	Rotifer	Cl (free, chloramine)	Synergistic effect of temperature (20°, 25°, 27.5°) on toxicity	322
Mytilus edulis	Mussel	Salinity, Cd	Little effect of temperature on Cd toxicity (0–50 ppb)	323
Mytilus galloprovincialis	Mussel	As (arsenate)	Increased temperature (25° compared with 12°) enhanced uptake and loss	324
Crassostrea virginica	American oyster	Cl (free, chloramine)	Synergistic effect of temperature (20°, 25°) on toxicity	322
		Cl (chlorine-produced oxidants)	Toxicity varied with season, temperature, and physiological condition	325
(embryos, larvae)		Cu, salinity	High Cu level (20 pbb) altered salinity and temperature tolerance of embryos; larvae more tolerant	326
Bulinus truncatus	Snail	Molluscicides	More toxic at 30° than at 20°	327
Macrocyclops albidus	Copepod	Insecticides	Thermal tolerance lowered	328
Acartia tonsa	Copepod	Cl (free, chloramine)	No effect of temperature (10° to 28°) on toxicity	322
Gammarus sp.	Amphipod	Hg	Uptake increased with temperature increase and other variables	329
Daphnia pulex	Cladoceran	Cl, flow, ΔT	Combined stresses reduced the levels of adenosine triphosphate; mortality from mechanical stress	330
		2,4-D; 2,4,5-T (herbicide)	Respiration increased with temperature and 3 ppm 2,4,5-T	262
Cambarus latimanus	Crayfish	Cd	Temperature tolerance not significantly related to Cd concentration in tissues	331
Eualus spp.	Shrimp	Oil	Toluene more toxic at 12° than at 40°	332
Pandalus goniurus	Shrimp	Oil	Naphthalene more toxic at 12° than at 40°	332

TABLE VIII—(*Continued*)

Scientific Name	Common Name	Stress	Observed Effect (°C)	Reference Citation
Palaemonetes pugio	Grass shrimp	Salinity, Zn	Development rates retarded at both high and low salinity-temperature conditions and in increasing zinc concentrations (0.25 to 1 mg/l)	333
		Cl	Results analyzed by regression model techniques	334, 335
Callinectes sapidus	Blue crab	Cl	Interactions established by regression model techniques	335
Clibanarius vittatus	Hermit crab	Salinity	Temperature (15° and 25°) did not affect osmoregulation	336
Pagurus longicarpus, *P. pollicaris*	Hermit crabs	Salinity	Temperature (15° and 25°) did not affect osmoregulation	336
Rhithropanopeus harrisii	Mud crab	Salinity, hydrocarbons	Low salinity reduced tolerance to phenanthrene; temperature effect marginal	337
Aplodinotus grunniens	Freshwater drum	Cl (mono-chloramine)	48-h LC_{50} values decreased from 2.45 to 1.75 mg/l TRC with temperature (10° and 20°)	338
Brevoortia tyrannus	Menhaden	Gas supersaturation	No effect of temperature (15–30°) on mortality	339
Carassius auratus	Goldfish	Cu, Cr, Zn, cyanide	24-h LC_{50} values decreased with temperature (5°, 15°, 30°)	340
Catostomus commersoni	White sucker	Cl (mono-chloramine	48-h LC_{50} values decreased from 1.09 mg/l TRC at 10° to 0.36 at 27°	338
Cyprinus carpio	Carp	Cl (mono-chloramine)	48-h LC_{50} values decreased from 2.37 mg/l TRC at 10° to 1.50 at 30°	338
		Pressure, flow Cl	Complicated survival pattern	341
Fundulus heteroclitus	Killifish	Salinity, oil	Oil more toxic at high and low temperature conditions (20°, 25°, 30°)	342
Gambusia affinis	Mosquitofish	Hg ($HgCl_2$, CH_3HgCl)	Synergistic effect of temperature (10°, 18°, 26°) on bioaccumulation and mortality	343
		Ionizing radiation	Lethal temperature significantly reduced at 1 500 rads and above	344
		Insecticides	Thermal tolerance significantly lowered at 5 and 10 μg/l	345
Ictalurus punctatus	Channel catfish	Cl (mono-chloramine)	48-h LC_{50} values decreased from 0.78 mg/l TRC at 10° to 0.67 at 30°	338
		Cu, Cr, cyanide	Little effect of temperature (5°, 15°, 30°) on toxicity; some effect with Cu	340

TABLE VIII—*(Continued)*

Scientific Name	Common Name	Stress	Observed Effect (°C)	Reference Citation
Lepomis macrochirus	Bluegill	Cl (mono-chloramine)	48-h LC_{50} values decreased from 3.00 mg/l TRC at 10° to 1.23 at 30°	338
		Cu, Cr, Zn cyanide	No temperature effect on toxicity of Cr, cyanide; higher sensitivity at lower temperatures for Cu and at higher temperature for Zn (5°, 15°, 30°)	340
		HCN	Juvenile fish more sensitive at lower temperatures (4–30°)	346
		Hg (CH_3HgCl)	Bioaccumulation increased exponentially with temperature (9°, 21°, 33°)	347
		Glyphosates (herbicides)	Toxicity increased with increasing temperature (17°, 22°, 27°)	348
Morone chrysops	White bass	Cl (mono-chloramine)	48-h LC_{50} values decreased from 2.87 mg/l TRC at 10° to 1.15 at 30°	338
Morone saxatilis	Striped bass	Pressure, flow, Cl	Complicated survival pattern	341
		Cl (total residual)	Percent mortality increased as TRC concentration and ΔT increased	349
Notemigonius crysoleucus	Golden shiner	Cu, Cr, Zn, cyanide	No temperature effect on toxicity of Cu, Zn; slight decrease in 24-h LC_{50} with increase in temperature (5°, 15°, 30°) for Cr, cyanide	340
Notropis atherinoides	Emerald shiner	Cl (total residual)	96-h LC_{50} values decreased with temperature increase (10°, 25°)	350
		Cl (mono-chloramine)	48-h LC_{50} values decreased from 0.63 mg/l TRC at 10° to 0.35 at 30°	338
Notropis cornutus	Common shiner	Cl (mono-chloramine)	48-h LC_{50} values decreased from 0.78 mg/l TRC at 10° to 0.45 at 30°	338
		Cl (total residual, combined residual, hypochlorous acid, chloramine)	Avoidance response varied with chlorine fraction and temperature; threshold avoidance to TRC at 0.10 to 0.20 mg/l	351
Notropis spilopterus	Spotfin shiner	Cl (mono-chloramine)	48-h LC_{50} decreased from 0.65 mg/l TRC at 10° to 0.41 at 30°	338
Oncorhynchus gorbuscha	Pink salmon	Oil	96-h TL_m for toluene and water soluble fraction lower at 4° than at 12°	332

TABLE VIII—(*Continued*)

Scientific Name	Common Name	Stress	Observed Effect (°C)	Reference Citation
Oncorhynchus kisutch	Coho salmon	Gas supersaturation	No effect of temperature (8–20°) on gas bubble disease mortality	352
Oncorhynchus nerka	Sockeye salmon	Gas supersaturation	No effect of temperature (8–20°) on gas bubble disease mortality	352
Oncorhynchus tshawytscha	Chinook salmon	Gas supersaturation	Mortality increased with increasing temperature (8–20°)	352
Perca flavescens	Yellow perch	HCN	Juvenile fish more sensitive at lower temperatures (4–30°)	346
Pimephales promelas	Fathead minnow	Low dissolved oxygen	DO at which surface film used for O_2 increased with temperature (6° to 30°)	353
		HCN	Juvenile fish more sensitive at lower temperatures (4–30°)	346
Salmo gairdneri	Rainbow trout	Cu, Cr, Zn, cyanide	24-h LC_{50} values for Cr, Zn, cyanide unaffected by temperature, Cu more toxic at 30° than at 5°	340
		HCN	Juvenile fish more sensitive at lower temperatures (4–30°)	346
		Glyphosates (herbicides)	Toxicity increased with increasing temperature (7°, 12°, 17°)	348
		Gas supersaturation	Mortality increased with increasing temperature (8–20°)	352
Salvelinus fontinális	Brook trout	HCN	Juvenile fish more sensitive at lower temperatures (4–30°)	346
Stizostedion canadense	Sauger	Cl (monochloramine)	48-h LC_{50} values decreased from 1.14 mg/l TRC at 10° to 0.71 at 30°	338

Activity levels of adult and juvenile alewives (*Alosa pseudoharengus*), recorded in the laboratory, were diurnal with little influence of temperature (1.8°–25°C).[389] Temperature influenced activity only at a lower stress level of 3°C. Spontaneous swimming activity of northern pike (*Esox lucius*) fed ad libitum in the laboratory was maximal at 19°–20°C, close to the optimum for growth.[205]

Home range and seasonal movements of muskellunge in two Canadian lakes were determined by radiotelemetry.[390] All fish established and used home ranges when water temperatures were less than 5°C. Males, but not all females, again established home ranges when water temperatures exceeded 15°C. Distances traveled outside home ranges were maximum for both sexes at temperatures of 10°–15°C.

Temperature-swimming performance relations of several Great Lakes fish were reviewed by Griffiths.[391] Rainbow smelt were extremely stenothermal fish which are particularly susceptible to abrupt temperature declines. Littoral species (goldfish, centrarchids) maintained high performance over a wide tem-

TABLE IX. Temperature preference studies.

Species	Age or Size	Acclimation Temperature (°C)	Preference Temperature (°C)	Reference Citation
Limulus polyphemus (Horshoe crab)			15–40°, 29.4°	355
Orconectes obscurus (Crayfish)		6–33°	30°	356
Homarus americanus (American lobster)	400–500 g		15–21° first 6 days 10–29° second 6 days	357
Panulirus argus (Spiny lobster)	Juveniles		25–35°, 30°	358
Palaemonetes vulgaris (Grass shrimp)			27°	359
Typhlocaris galilea (Prawn)		23–26.5°	26–27°	360
Abudefduf abdominalis (Damselfish)	Adults Juveniles	22.3–26.3° 22.3–26.3°	25.9° 30.2°	361
Acanthurus triostegus (Surgeonfish)	Adults Juveniles	22.3–26.3° 22.3–26.3°	29.2° 29.3°	361
Atherinops affinis (Topsmelt)	3–198 days 14.5 mm 60 mm	10–21° 21.5° 15°	19–23°, 26° 27° 26°	202, 362
Carassius auratus (Goldfish)	80–100 mm	15°, 25°	19.2°, 26°	363
Chaetodon multicinctus (Butterflyfish)	Adults Juveniles	22.3–26.3° 22.3–26.3°	24.0° 27.0°	361
Cheilotrema saturnum (Black croaker)	42 mm	17.0°	28°	362
Citharichthys stigmaeus (Speckled sanddab)	Adults 90 mm	10–19.7° 18.9°	8–13°, 9° 10°	203, 362
Cymatogaster aggregata (Shiner surfperch)	109 mm	18.2°	21°	362
Cyprinodon elegans (Pupfish)	Adults		20–30°	239
Damalichthys vacca (Pile surfperch)	69 mm	18.1°	11°	362
Embiotoca jacksoni (Black surfperch)	118 mm	16.7°	18°	362
Enneacanthus gloriosus (Bluespotted sunfish)	10–60 mm	22°	28.5°	364
Esox masquinongy (Muskellunge)	20–25 cm		21.9° (dawn) 27.3° (afternoon)	365
Gambusia affinis (Western topminnow)	Adults		31°	206
Gambusia nobilis (Pecos gambusia)	Adults		20–30°	239
Gasterosteus aculeatus (Three-spined stickleback)		20°	10°	366

TABLE IX—(*Continued*)

Species	Age or Size	Acclimation Temperature (°C)	Preference Temperature (°C)	Reference Citation
Heteropneustes fossilis (Indian catfish)		28°, 16°	30°, 28.6°	241
Hypsoblennius gilberti (Rockpool blenny)	4.4 mm	19.4°	26°	362
Lepomis cyanellus (Green sunfish)	80–100 mm	25°	28.2°	363
Leuresthes tenuis (California grunion)	8.1 mm	16.5°	27°	362
Morone americana (White perch)	51–65 mm	6–33°	28.9–30.6°	367
Notropis lutrensis (Red shiner)		Seasonal ambient	12.8–25.1°	209
Oxyjulis californica (Senorita)	120 mm	17.2°	16°	362
Oxylebius pictus (Painted greenling)	3.4 mm	16.0°	29°	362
Paralabrax clathratus (Kelp bass)	196 mm	21.0°	15°	362
Paralabrax maculatofasciatus (Spotted sand bass)	179 mm	20.6°	25°	362
Paralichthys californicus (California halibut)	94 mm	20.5°	22°	362
Perca flavescens (Yellow perch)	60 g	20°	20.2°	368
Pleuronichthys coenosus (C–O sole)	134 mm	10.0°	7°	362
Salmo gairdneri (Rainbow trout)	Fry, fingerlings	10.6–12.7°	13–15°	369
Salmo salar (Atlantic salmon)	Early alevins Advanced alevins	4–12° 4–12°	<6° 12–16°	370
	Fry	10.6–12.7°	13–15°	369
Salmo trutta (Brown trout)	Adults	0–5°	12.2°	371
Salmo x Salvelinus (hybrids)	Fry, fingerlings	10.6–12.7°	13–15°	369
Salvelinus fontinalis (Brook trout)	Fry Fingerlings	10.6–12.7° 12.1°	9–11.5° 17.5°	369
Salvelinus namaycush (Lake trout)	Fry, fingerlings	10.6–12.7°	9–11.5°	369
Salvelinus hybrids	Fry	10.6–12.7°	9–11.5°	369
Sarotherdon mossambica (Mozambique mouthbrooder)	40 mm	15–35°	31–32°	312
Scorpaena guttata (Sculpin)	64 mm	17.6°	17°	362
Sebastes serranoides (Olive rockfish)	82 mm	17.0°	17°	362

perature range when allowed time for acclimation. Salmonids displayed the greatest capacity to maintain performance in thermally unstable regimes.

Reynods and Casterlin [392] monitored locomotor activity of goldfish (*Carassius auratus*) and bluegill (*Lepomis macrochirus*) in the laboratory. Both fish exhibited a significant "activity well" or decrease in spontaneous locomotor activity in the region of their final preferendum (28°C for goldfish, 31°C for bluegills). These results are discussed in relation to a thermokinetic interpretation of thermoregulatory behavior and to the correspondence between thermal preferenda and thermal optima.

DECOMPOSERS

Three strains of psychrotrophic and one mesophilic bacteria were tested for their reactions to sudden temperature increases at low temperatures.[393] Following 5°C temperature increases over the base range 5°–25°C, the three psychrotrophic strains, *Cytophaga johnsonae, Cytophaga* sp. and *Pseudomonas fluorescens*, adapted to the new temperature, showed a lower growth rate, and showed a higher growth rate respectively at the new temperatures. The mesophilic *Enterobacter cloacae* adjusted immediately to the new growth rate of temperature-adapted cultures. When different sources of carbon and phosphorus were added to cultures of *C. johnsonae* at 5° and 20°C, a complex temperature-dependent substrate-accelerated elimination of this species took place.[394]

The effects of cooling systems on river bacteria were simulated in the laboratory by heating samples of Rhine River water to 30°–60°C, then incubating at lower temperatures.[395] Enzyme activity of psychrophilic and mesophilic bacteria was inhibited above 30°C and above 40° C, respectively. Carpenter and Adams [396] investigated the effects of selected environmental factors on the decay of shoots of *Myriophyllum spicatum* in Lake Wingra, Wis. Decay coefficients increased with increasing temperature to 28°C and then declined. Both water temperature and initial tissues nitrogen content were useful factors for predicting *M. spicatum* decay rates.

DISEASES AND PARASITES

To better quantitate the effects of temperature on disease processes, several major infectious diseases of Pacific salmonids were studied in the laboratory.[397] Diseases studied included those caused by the bacteria *Flexibacter columnaris, Aeromonas salmonicida,* and *A. hydrophilia* and the Bacterial Kidney Disease bacterium; the protozoan *Ceratomyxa shasta;* and the Oregon sockeye salmon virus (IHN). Although mortality rates depended on fish species and pathogen, in general, progress of all the diseases was a logarithmic function of temperature (3.9°–23.3°C).

A new bacterial disease affecting primarily pond-reared fingerling channel catfish (*Ictalurus punctatus*) was described.[398] Optimum growth temperature of the causative organism, a previously unidentified species of *Edwardsiella*, was between 25° and 30°C.

Atlantic menhaden and Atlantic croaker (*Micropogon undulatus*) captured in the lower Cape Fear River (N. C.) were examined for incidence of the parasite *Lernaeenicus radiatus* in relation to water temperature and salinity variations.[399] Highest incidence increases on each species occurred in April (16°–23°C). Parasite abundance increased inversely to water temperature and salinity with highest incidences occurring in fish from lower saline and colder waters.

BENEFICIAL USES

A state-of-the-art assessment of research, demonstration, and commercial projects that involve the use of power plant condenser cooling water for agricultural and aquacultural purposes was conducted by the Tennessee Valley Authority.[400] Although a large number of research and feasibility studies have been conducted, few commercial enterprises are presently utilizing thermal effluent.

Malouf and Breeze [292] assessed the feasibility of culturing the Pacific oyster *Crassostrea gigas* in heated effluents. Based on maintenance requirements and energy assimilation, 15°C was determined to be the optimum temperature for growth of juvenile oysters.

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Entrainment and impingement at cooling water intakes

Mary S. Uziel
Ecological Sciences Information Center,
Oak Ridge National Laboratory,
Oak Ridge, Tenn.

REVIEWS AND MODELING STUDIES

General reviews. Literature on the effects of power plant entrainment on phytoplankton and zooplankton was reviewed to determine whether ecosystem effects of entrainment could be definitely documented.[1] While these studies did not provide a definitive assessment at the ecosystem level, they did provide a large, consistent data base indicating that the effects of entrainment were generally small and unlikely to cause ecosystem-wide impacts.

A variety of quantitative techniques for assessing population and ecosystem effects of impingement and entrainment on major fish and invertebrate species were presented along with guidance for the interpretation of calculated or measured effects.[2] Simpler, less costly approaches were followed by increasingly complex methods so that the investigator could select those appropriate for the situation.

Available information on natural mortality of fish eggs and larvae was compiled by Dahlberg.[3] Problems such as interpretation and use of survival data, major factors influencing mortality rates, relationship of survival rates to reproductive strategies, and possibility of critical periods were discussed. Development of survival data lags far behind modeling in impact assessment, and, as a result, important decisions are being made from incomplete data.

The environmental impacts, both adverse and beneficial, of cooling reservoirs were compared to cooling towers as an alternative closed cycle cooling system.[4] A review of pertinent literature on cooling reservoir ecosystems revealed that entrainment, thermal,