ACUTE TEMPERATURE TOLERANCE OF JUVENILE CHINOOK SALMON FROM THE MOKELUMNE RIVER

Charles H. Hanson, Ph.D.
Hanson Environmental, Inc.

SUMMARY

A series of static acute tests were performed to determine the upper thermal tolerance limits for juvenile fall-run Chinook salmon from the Mokelumne River Fish Facility, California. Results of tests designed to determine the time-to-loss-of-equilibrium and time-to-death for fish exposed to constant elevated temperatures from 18 C (64 F) to 27 C (81 F) for fish acclimated at 12 C (54 F) are reported. Juvenile salmon tested at 18 C (64 F) experienced no loss of equilibrium or mortality over a period of 10,000 minutes. The time to 50% mortality (geometric mean resistance time) ranged from 7799 minutes at 21 C (70 F) to 21 minutes at 27 C (81 F). An increase in acclimation temperature from 12 C (54 F) to 18 C (64 F) resulted in an increase in the resistance time to 50% mortality from 52 to 140 minutes. Juvenile salmon exposed to a gradually increasing temperature experienced a rapid increase in mortality as temperatures exceeded 24 C (75 F). Results of these tests suggest that juvenile Mokelumne River fall-run Chinook salmon may have a lower thermal tolerance that that reported for juvenile spring-run Chinook salmon from northern Washington (Brett, 1952).

INTRODUCTION

The effects of elevated water temperature exposure on growth and survival of juvenile Chinook salmon within Central Valley tributaries including the Sacramento River system, the San Joaquin River system, and the Mokelumne River has been the subject of considerable discussion. Concern has been expressed over the effects of elevated water temperature exposure on Chinook salmon during their rearing period and during emigration either as a result of direct acute mortality or through indirect mechanisms such as increased susceptibility to predation or disease. Additional information is required, however, to better define the acute and chronic effects associated with various water temperature regimes. Information on the thermal tolerance of juvenile Chinook salmon provides, in part, a basis for establishing water management strategies which reflect instream temperature conditions associated with both juvenile rearing and emigration.

The only studies available to date on acute thermal tolerance of juvenile Chinook salmon within freshwater environments have been reported by Brett (1952). Brett's thermal tolerance studies, however, were conducted using spring-run Chinook salmon from the Pacific Northwest. A question exists as to whether or not juvenile spring-run Chinook salmon exhibit acute upper thermal tolerance characteristics similar to juvenile fall-run Chinook salmon which are the dominant salmon race produced in California's Central Valley tributaries. Furthermore, thermal tolerance for juvenile Chinook salmon may vary between stocks inhabiting northern areas where seasonal exposure to elevated water temperatures is substantially less than that which occurs within California's Central Valley tributaries which are located on the southern geographic borer of the Chinook salmon range. It can be hypothesized that Chinook salmon which have evolved within river systems such as the Mokelumne river where elevated water temperatures occur seasonally would have greater thermal tolerance than more northerly stocks.

To provide additional information on the acute thermal tolerance of juvenile fall-run Chinook salmon reared within the Mokelumne river system, the East Bay Municipal Utility District requested that a series of thermal tolerance tests be performed. The acute thermal tolerance tests have been designed and conducted to satisfy provisions contained within the 1990-91 Memorandum of Understanding (MOU) between the East Bay Municipal Utility District (EBMUD) and the California Department of Fish and Game (CDF&G) for an interim fisheries program for the Mokelumne River.

METHODS

A series of acute upper thermal tolerance tests were designed and conducted during April and May, 1991 using juvenile fall-run Chinook salmon from the Mokelumne River Fish Facility. The juvenile Chinook salmon used in these tests had an average fork length of 97 mm (S.D. = 13 mm) with a range in length from 58 to 134 mm. The juvenile Chinook salmon were of Feather River origin which were transported to the Mokelumne River Fish Facility as early fry where they were reared in raceways for approximately three months under Mokelumne River water quality conditions. The Mokelumne River Fish Facility water supply is directly from Camanche Reservoir and reflects water temperature and water quality characteristics of flows released into the lower Mokelumne River where salmon spawning, egg incubation, and juvenile rearing takes place.

The thermal tolerance tests were performed on-site at the Mokelumne River Fish Facility and exclusively utilized water supplies from Camanche Reservoir - Mokelumne River system. The test facility consisted of four independent water baths within which temperature could be regulated using submersible 100-watt heating elements. Water baths were aerated to promote mixing around the submersible heating units to help insure uniform regulation of water temperatures among the three aquaria contained within each water bath.

Each water bath was equipped with three 30 gallon (114 liter) all glass aquaria. A subterranean filtration system and aeration maintained dissolved oxygen concentrations in each aquaria throughout all tests. All aquaria were cleaned and allowed to cure using Mokelumne River water prior to use in these tests. The entire testing facility was located indoors to minimize the effects of atmospheric temperature fluctuations on water temperatures selected for use in these tests. All aquaria and each water bath were covered with styrofoam to provide additional insulation to help maintain water temperatures throughout each test duration. All tests were conducted under static conditions. Using this experimental system, water temperatures within each aquaria could be maintained within 0.1 C of the desired test temperature.

Water temperatures were routinely monitored using calibrated mercury thermometers. Water temperature and dissolved oxygen concentrations were also routinely monitored using a YSI Model 57 dissolved oxygen meter. Ammonia concentrations within each aquaria were monitored periodically throughout the duration of each thermal tolerance test using the Salicylate method.

Thermal tolerance tests were performed using 30 juvenile Chinook salmon in each of the three aquaria maintained at a specific test temperature, representing a total of 90 fish per treatment. Each test was accompanied by a corresponding control, maintained at ambient Mokelumne River temperatures. A total of 90 juvenile Chinook salmon were included in the controls. Both treatment and control fish were fed Oregon Moist Pellets daily in all tests which extended beyond 214 hours.

During each test, observations were recorded on swimming behavior, feeding activity, the time-to-loss-of-equilibrium, the time-to-death, and the corresponding length (fork length measured to the nearest mm) for each individual tested. The loss of equilibrium was defined as that point at which a juvenile Chinook salmon could no longer maintain a normal swimming attitude and was typically characterized by the fish becoming completely inverted (belly up). The time-to-death was defined by the cessation of opercular motion and no visible response to gentle probing. The tests were conducted for a duration of either 10,000 minutes (7 days) or 100% mortality.

The experimental design included two types of thermal exposure designed to determine upper thermal tolerance. The first set of tests involved the instantaneous exposure of juvenile Chinook salmon to a specified elevated water temperature which was then maintained at a constant level throughout the duration of the test. Acclimation temperature for all juvenile Chinook salmon used in these tests was 12 C (54 F). The test temperatures and corresponding temperature rise (delta-T) used in this series of experiments are summarized below:

Test Temperature		Delta T	
C	F	C	F
18	64	6	10
21	70	9	16
24	75	12	21
25	77	13	23
26	79	14	25
26*	79	8	15
27	81	15	27

*NOTE: One additional acute mortality test was conducted using salmon acclimated 7 days at 18 C (64F) for comparison with salmon acclimated at 12 C (54 F).

The second set of experiments consisted of exposing juvenile Chinook salmon to gradually increasing water temperatures. These tests were designed to more accurately reflect thermal conditions experienced by a juvenile Chinook salmon either as a result of seasonal warming or exposure to increasing water temperatures during downstream migration. The gradually increasing water temperature regime was initiated at a temperature of 13 C (55 F) and was then gradually raised at a rate of approximately 1 C (2 F) per day until 100% mortality occurred.

RESULTS

The time-to-loss-of-equilibrium for constant temperature static tests conducted at 24, 25, 26, and 27 C (75, 77, 79, 81 F) are presented in Figure 1. No loss of equilibrium was observed for juvenile Chinook salmon exposed to an elevated water temperature of 18 C (64 F) over an exposure period of 10,000 minutes. At a temperature of 24 C (75 F) 50% loss of equilibrium occurred after a period of 2432 minutes (geometric mean time) compared with a 50% loss of equilibrium after an 11 minute exposure to an elevated water temperature of 27 C (81 F). One hundred percent loss of equilibrium for fish exposed to 27 C (81 F) occurred after 56 minutes.

Figure 2 shows the relationship between percent mortality for juvenile Chinook salmon and the time-to-death when exposed to constant water temperatures between 21 and 27 C (70 and 81 F). Juvenile Chinook salmon exposed to a constant water temperature of 18 C (64 F) experienced no mortality during the 10,000 minute duration of this test. The time to 50% mortality (geometric mean resistance time) ranged from 7799 minutes for juvenile Chinook salmon exposed to an elevated water temperature of 21 C (70 F) to 21 minutes for fish exposed to 27 C (81 F). A substantial increase in the time to 50% mortality occurred between tests conducted at 25 C (77 F; 142 minutes) and 24 C (75 F; 4325 minutes). Based on results from previous investigations (Brett, 1952) it was anticipated that the relationship between percent mortality and time-to-death would be reflected by relatively parallel lines representing each of the specific temperature conditions tested. Results for thermal tolerance studies conducted at a temperature of 24 C (75 F) demonstrated a substantially different slope than for those tests conducted at other elevated water temperatures (Figure 2). Results of the 24 C (75 F) test suggest that the juvenile Chinook salmon tested as part of this experiment were substantially more tolerant to elevated water temperatures than was exhibited by other tests. Examination of water temperature records, water quality, and the size of fish utilized in the 24 C (75 F) test failed to provide any evidence of factors contributing to the observed difference in thermal tolerance.

The time-to-death and corresponding length measurements for individual Chinook salmon can be used to evaluate potential trends reflecting size-specific thermal tolerance. Figure 3 shows the relationship between fish size and the time-to-death for tests conducted at 25 and 26 C (77 and 79 F). Although characterized by a high degree of variability in the time-to-death for individual Chinook salmon the overall trend, as reflected by a least square linear regression, suggests that smaller fish may have greater tolerance to elevated water temperature than do larger juvenile Chinook salmon. Although the slopes of these linear regressions were statistically significant ($P < 0.05$) the R^2 values were low ($R^2 = 0.8$ for 25 C exposure; $R^2 = 0.12$ for 26 C exposure), reflecting the high degree of variability inherent in this relationship.

Prior thermal history for juvenile Chinook salmon has been found to be a significant factor influencing thermal tolerance. Juvenile fish acclimated to higher temperatures have been found to have greater thermal tolerance than fish acclimated at lower temperatures. To provide additional information on the role of acclimation temperature as a factor influencing thermal tolerance of juvenile Chinook salmon from the Mokelumne River, a series of comparative tests were performed to evaluate the time-to-loss-of-equilibrium and time-to-mortality for juvenile Chinook salmon exposed to a constant elevated water temperature of 26 C (79 F) following acclimation at water temperatures of 12 C (54 F) and 18 C (64 F). Prior thermal tolerance tests conducted as part of this investigation showed that juvenile Chinook salmon experience no loss of equilibrium or mortality during a 10,000 minute exposure to water temperatures of 18 C (64 F).

The effect of acclimation temperature was tested using a group of 90 juvenile Chinook salmon held at a water temperature of 18 C (64 F) for a period of 7 days prior to being exposed to the elevated test temperature. Juvenile Chinook salmon within both the 12 and 18 C (54 and 64 F) test groups actively fed throughout the acclimation period and exhibited no other behavioral signs of stress.

The influence of acclimation temperature on thermal tolerance of juvenile Chinook salmon is clearly shown in Figure 4 for both the time-to-loss-of-equilibrium and time-to-mortality. Acclimation at 18 C (64 F) substantially increased the tolerance of juvenile Chinook salmon exposed to an elevated water temperature of 26 C (79 F). The resistance time to 50% loss of equilibrium increased from 46 minutes to 132 minutes for fish acclimated at 12 C (54 F) and 18 C (64 F) respectively. The increase in acclimation temperature from 12 C (54 F) to 18 C (64 F) also contributed to an increase in the resistance time to 50% mortality from 52 minutes to 140 minutes (Figure 4).

Juvenile Chinook salmon rearing in the Mokelumne River and emigrating through the Bay-Delta system will not typically experience a rapid and prolonged exposure to elevated water temperatures such as the conditions tested in the acute mortality studies. Temperature exposure for juvenile Chinook salmon under actual field conditions is likely to represent a gradual increase in water temperature and acclimation which may influence thermal tolerance as illustrated in Figure 4. A series of tests conducted as part of this investigation offered the opportunity to examine mortality for juvenile Chinook salmon exposed to a gradually increasing temperature regime. Water temperatures during this test (Figure 5) increased from 13 C (55 F) to 26 C (79 F) over a period of approximately 290 hours (17,400 minutes; 12 days). Dissolved oxygen concentrations throughout this extended test were maintained at an average level of 7.9 mg/l (S.D.

= 0.5 mg/l) with no detectable ammonia concentration. No control mortality occurred for juvenile Chinook salmon held 12 days.

As temperatures gradually increased (Figure 5), the first mortality occurred at a water temperature of 21 C (70 F). Mortality remained relatively low through an exposure period of approximately 250 hours after which time mortality very rapidly increased to levels between 80 and 100%. The rapid increase in mortality observed as water temperatures increased above 24 C (75 F) is consistent with results of the acute mortality study (Figure 2) in which 100% mortality occurred for juvenile Chinook salmon exposed to an elevated water temperature of 25 C (77 F) within a period of 280 minutes (4.7 hours).

DISCUSSION

Results of this investigation have shown the sensitivity of juvenile Chinook salmon to water temperatures approaching the upper lethal threshold. Juvenile Chinook salmon in these studies reduced or stopped feeding activity at water temperatures exceeding 21 C (70 F). Evidence of stress, including flared opercular movement, a more vertical orientation, and erratic swimming motion preceded the loss of equilibrium (Figure 1), particularly in those tests conducted at a water temperature of 24 C (75 F). Exposure of juvenile Chinook salmon to elevated water temperature conditions contributing to increased stress, erratic swimming behavior, or a loss of equilibrium has been found to contribute directly to increased susceptibility of juvenile Chinook salmon to predation (Coutant, 1973). Therefore, exposure of salmon to elevated water temperature conditions which do not result in acute mortality may contribute indirectly to an increase in juvenile salmon mortality.

The increase in thermal tolerance of juvenile Chinook salmon acclimated to higher water temperatures (Figure 4) is consistent with results of thermal tolerance studies conducted with salmon fry (Brett 1952) and for other fish species. As elevated water temperatures approach lethal limits, however, the effects of gradual temperature increase (acclimation) becomes a progressively less significant factor influencing thermal tolerance (Figure 5).

Thermal tolerance for juvenile spring-run Chinook salmon (mean fork length 44 mm) from Washington State (Brett 1952) and fall-run juvenile Chinook salmon (mean length 97 mm) from the Mokelumne River, California (this study) can be compared although differences in methods exist between the two studies. It was hypothesized that juvenile Chinook salmon from California, which have evolved under warmer seasonal water temperatures than those occurring within Washington, would exhibit a greater tolerance to elevated water temperatures. Results of a comparison of the estimated geometric mean resistance time for juvenile Chinook salmon tested by Brett (1952) acclimated to water temperatures of 10 and 15 C (50 and 59 F) can be compared with geometric mean resistance times for juvenile Chinook salmon from the Mokelumne River (acclimation temperature 12 C; 54 F). Geometric mean resistance times from these two studies are summarized below for exposure to comparable elevated water temperatures:

Acclimation Temperature (C)	Resistance Time (min) at Various Test Temperatures			
	27 C	26 C	25 C	Source
15	100	300	2500	Brett
12	21	45	142	This Study
10	--	95	335	Brett

Comparison of results from these two investigations suggests that the thermal tolerance of Mokelumne River fall-run Chinook salmon is lower than thermal tolerance reported for spring-run Chinook salmon from Washington tested by Brett (1952). Factors contributing to this apparent difference may include a greater thermal tolerance by spring-gun Chinook salmon juveniles than fall-run juveniles, a size-specific difference in thermal tolerance in which smaller juvenile salmon, such as those used in tests conducted by Brett, exhibit greater thermal tolerances than larger salmon which may be undergoing other physiological changes associated with the smolting process (see Figure 3), or potential differences between the methods and protocol used in conducting the two thermal tolerance investigations.

Results of these acute thermal mortality studies, conducted on juvenile fall-run Chinook salmon from the Mokelumne River, provide additional information on temperatures resulting in both acute mortality and loss-of-equilibrium which has not been previously available for Central Valley Chinook salmon stocks. The results of this study will be useful in defining appropriate temperature regimes for long-term chronic growth and physiological investigations on the effects of elevated water temperature on juvenile Chinook salmon rearing for extended periods in various central valley tributaries. Furthermore, results of this investigation provide information on elevated water temperature regimes which result in physiological stress and ultimately a loss-of-equilibrium for juvenile Chinook salmon which has been shown (Coutant 1973) to increase their susceptibility to predation. As a result of the indirect effects of elevated water temperature on the survival of juvenile Chinook salmon, (e.g., increased susceptibility to predation, reduced growth or condition, increased susceptibility to disease, etc.), results of acute thermal tolerance studies should not be used by themselves for establishing instream water temperature objectives for the protection of juvenile Chinook salmon.

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