Predictive Model of Mortality of Young Fish in a Thermal Plume*

W. L. Templeton and R. J. Olson

Ecosystems and Applied Mathematics Departments
Pacific Northwest Laboratories
Battelle Memorial Institute
Richland, Washington U.S.A. 99352

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Introduction

The prediction of the effects of man's impact on his environment requires the use of innovative techniques to apply the results of classical laboratory and field studies for the management of contemporary problems. It is neither possible to anticipate all ways in which man will alter his environment, nor is it possible to perform detailed studies for all the current situations. However, the increasing demand for electrical power, with subsequent increases in the size of thermal power plants with concomitant thermal discharges into rivers, lakes, and estuaries, is one area where there is an urgent need to predict the effects of these discharges on the aquatic environment. Juvenile salmon migrate seaward at Hanford between April and August, often traveling in mid-river, essentially at the rate of water flow. Some of these fish can be presumed to encounter the thermal plumes at Hanford, either at the center line where maximum temperatures occur, or at its edges. Maximum thermal exposure

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(i.e., highest temperature for the greatest duration) would occur to fish if they entered the plume and were carried through the center line. In passing through the plume, the fish would be exposed to an abrupt temperature rise (that could be lethal under prolonged exposure) followed by a gradual, fluctuating return to sublethal temperatures a few degrees above those of the river upstream from the outfall.

A substantial amount of data has been accumulated on thermally induced mortality, equilibrium loss and behavior stress (Coutant 1969, 1970, a,b,c,d, Becker and Coutant 1970, Becker 1970, Becker et al 1971) in order to develop predictive models of effects of thermal plumes (Coutant et al 1970).

This paper discusses the development of these techniques and presents the results of some simulations of the effects on downstream migrating juvenile salmon in the Columbia River.

Acute Mortality Studies

Many of the test procedures developed by Brett (1952, 1956) and Fry (1956, 1967) were utilized by Coutant and Dean (1968) to determine median resistance times of juvenile chinook salmon (Oncorhynchus tshawytscha). Groups of ten fish were exposed to various elevated temperatures and times observed when each fish lost its ability to swim in a normal upright position (loss of equilibrium) and the subsequent death time. These fish weighed between 1 and 10 grams and were 30-100 mm in length; they represented stocks from various spawning times and various rearing temperatures. All fish were acclimated to 15 °C for three weeks prior to testing. Results of these tests are shown

in Table I for eight different test temperatures. For the simulation studies, the 250 individual death times were pooled to obtain a frequency distribution (Figure 1), and cumulative mortality curves were calculated for each temperature. The entire set of mortality curves is presented in Figure 2. Equilibrium loss curves for the same temperatures are presented in Figure 3. Attempts to fit a common mathematical function to either set of curves has not been successful, nor did we feel it was essential at this stage for the modeling effort.

Dean and Coutant (1968) and Dean (1969) used a probit bioassay procedure to establish a thermal exposure-mortality relationship for chinook salmon. The 50 percent mortality exposure compares favorably with our analysis although the probit procedure allows better definition at high and low temperatures. In either case, the large statistical errors associated with the mortality curves are probably acceptable considering the uncertainty in predicting the thermal exposure that a population of fish would encounter in a river.

Equilibrium Loss and Predation Studies

Ancillary studies have shown behavioral changes occur in fish when given sublethal thermal doses. When fish that loose equilibrium due to thermal exposure are returned to cooler water, they may recover temporarily, but ~80 percent die after 24 hours (Dean and Coutant 1968). Coutant (1970c, d) has shown that

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sublethal thermal doses may cause increased susceptibility to predation as shown by the selective predation of starved adult rainbow on thermally shocked juvenile chinooks under laboratory conditions. Sublethal doses probably induce a stress in migrating fish, but whether this results in increased predation in the river is still open for speculation.

Migration Patterns

The summer migration of juvenile chinook salmon peaks in August in the Columbia River which is also the time of highest river temperatures (18 °) and low flow rates (Park 1969, Becker 1970). Mains and Smith (1964) have reported chinook tend to migrate at night, close to the surface and close to the shores. Figure 4 based on their data, shows the percentage distribution of fish in the Columbia River. Seventy percent of the fish were found to move down the river in the night time at the lower flow conditions.

Simulation Studies

Modeling the exposure path and temperature exposures a fish may encounter has not been adequately developed in a turbulent river situation. Remote infrared imagery and field measurements in the Columbia River have allowed construction of typical temperature profiles. Figure 5 represents the temperature regime under conditions of low flow. The Δt of 12 °C in the first segment represents a mean temperature for the upper two feet. Field measurements (Becker and Coutant 1970, 1971) have indicated that in this area of the effluent "boil",

temperature increments are very variable. The condition shown under conditions of low flow and high ambient temperature represents a worst type condition and has been used in the simulation analysis. Juvenile fish entering the center line of the plume at the river velocity in the top two feet could be exposed to elevated temperatures of Δt 12 °C for 40 seconds, Δt 11.5 °C for 20 seconds, and Δt 11.0 °C, Δt 10.5 °C and Δt 10 °C for 15 seconds respectively.

The laboratory-derived curves were used to estimate the percentage mortality, equilibrium loss, and delayed mortality for each temperature exposure. At the 40-second exposure to Δt 12 ° or 30 °C, we would expect a mortality of 12 percent (Figure 2), with an additional 43 percent having lost equilibrium. Delayed mortality will add a further 38 percent mortality to the initial 12 percent acute mortality if the exposure was terminated in 40 seconds. Thus, we predict that 50 percent mortality could occur under this extreme exposure.

For the purposes of this simulation, we assumed that thermal exposures received were additive. Since the curves show that a 40-second exposure at 30 °C is equivalent to 80 seconds at 29.5 °C in terms of mortality, we assumed the exposures were equivalent. When the exposure changed, we transposed the fish to the equivalent exposure point on the next temperature curve. By continuing this procedure, we predicted that the fish encountering this exposure pattern could incur 43 percent mortality (Figure 2). The procedure was also carried out for equilibrium loss which predicted a further 38 percent mortality (Figure 3).

Discussion

Under the conditions of low river flow and high ambient river temperature, there is clearly the potential for significant loss of fish when they pass through the center line of the plume. However, we could show no loss when fish pass beyond 20 yards from the center line, nor could we show any effects when the river flow was increased to 80,000 cfs and above, or if the ambient temperatures were below 16 °C. At the higher flows, increased mixing and dilution and rate of passage combine to reduce the exposure. Field experience, when young salmonids were deliberately drifted downstream through the plumes, supports this analysis (Becker and Coutant 1970, Becker et al 1971).

The application of this type of analysis to predict the potential effect upon fish populations depends upon two major considerations; the frequency of occurrence of low flow conditions and high ambient temperatures during the period of migration and the distribution of the downstream migrants relative to the thermal plumes. On the Columbia River, the rate of flow is dependent upon the power demand and operation of the upstream hydroelectric dams. The low flow conditions that produced an effect with this simulation occur very rarely; the average discharge in the period July to September being in the range of 80 to 200 cfs.

Studies on the distribution of fish across the river in the area of the Hanford discharges have not been made. The data used for these simulations were obtained in 1955 and indicate that less than one percent of the downstream migrants

could pass through the center line area of the plumes (Mains and Smith 1964). However, the studies were made when only two major upriver dams were completed and may not be representative of conditions in a fully-regulated river in 1969.

This study, coupled with the other extensive data collected at Hanford over the last two decades (Templeton and Coutant 1971), indicates that the biological cost of Hanford reactor discharges to local anadromous fish populations is minimal.

We hope that the basic principles that we have developed for studying and predicting the direct effects in mixing zones can be applied on a broader basis, since we believe that the best practical method of investigation of these problems is the direct approach of working onsite with local fish species and local water.

The type of approach that we have outlined in this paper could be used to advantage in the initial planning stages of industrial and municipal discharge structures to predict the potential loss of fishery resources as a result of a proposed engineering design.

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Table 1.

JUVENILE CHINOOK THERMAL RESISTANCE

<u>TEST TEMPERATURE</u>	<u>NUMBER OF TESTS</u>	<u>AVERAGE GEOMETRIC MEAN ± STANDARD DEVIATION</u>
26.0	24*	151.2 ± 32.6 MINUTES
27.0	25	62.8 ± 18.1 MINUTES
27.5	25	42.5 ± 11.3 MINUTES
28.0	25	22.2 ± 8.6 MINUTES
28.5	25	10.8 ± 3.3 MINUTES
29.0	25	215 ± 88 SECONDS
29.5	25	118 ± 20 SECONDS
30.0	25	82 ± 23 SECONDS

* TEN FISH PER TEST USED TO CALCULATE GEOMETRIC MEANS

Fig I.

FREQUENCY DISTRIBUTIONS OF JUVENILE CHINOOK TIMES TO DEATH

Figure

JUVENILE CHINOOK MORTALITY AS RELATED TO THERMAL EXPOSURE

Figure

JUVENILE CHINOOK EQUILIBRIUM LOSS AS RELATED TO THERMAL EXPOSURE

Fig 4.

DISTRIBUTION OF MIGRATING JUVENILE CHINOOK IN COLUMBIA RIVER

(AFTER MAINS AND SMITH, 1964)

Figure 5

TEMPERATURE PROFILE OF PLUME UNDER LOW RIVER FLOW CONDITIONS (41,000cfs)