THE EFFECT OF ELEVATED HOLDING TEMPERATURES ON ADULT SPRING CHINOOK SALMON REPRODUCTIVE SUCCESS

by

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Abstract

The Effect of Elevated Holding Temperatures on Adult Spring Chinook Salmon Reproductive Success

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A three-pronged study was designed to investigate the possible link between timber harvest-related temperature elevations and spring chinook salmon (Oncorhynchus tshawytscha) reproductive success. The study had three objectives: a) to determine if temperatures experienced by adult spring chinook salmon prior to spawning influenced reproductive success, b) to determine if adult spring chinook salmon behaviorally regulate internal temperature through selection of cold-water refuges, and c) to characterize the thermal regimes historically tolerated by spring chinook salmon and to model the likely effects of forest practices on their success.

To determine if pre-spawning temperatures experienced by adult spring chinook salmon influenced reproductive success, 33 adult spring chinook salmon were collected from Roza Diversion Dam on the upper Yakima River and were transported to Priest Rapids State Salmon Hatchery. Fish were divided

into two temperature treatment groups: elevated temperature regime (19°C) and control temperature regime (14°C). At maturity, fish from both temperature treatment groups were spawned. All egg lots were maintained at constant temperature and monitored for rate of development; stage at egg mortality; egg weight, diameter, and volume; occurrence of developmental abnormality; rate of hatch; alevin length; and alevin and yolk sac weight. In addition, at the time of spawning, egg weight per kg female and egg quality (i.e., broken or opaque eggs) were recorded. Egg weight and quality did not differ between the two treatment groups. However, the elevated treatment group produced a greater number of pre-hatch mortalities and developmental abnormalities, as well as smaller eggs and alevins. Egg size did not appear to exert a significant effect on rate of development. However, there was a slight variation in time to completion of hatch.

Temperature-sensitive radio transmitters were used to study patterns of behavioral thermoregulation, habitat preference, and movement of 19 adult spring chinook salmon in the Yakima River. On average, fish maintained an internal temperature 2.5°C below ambient river temperature. This represented a 12 to 20 % decrease in basal metabolic demand or a savings of 17.3 to 29.9 cal $kg^{-1}hr^{-1}$. In addition to temperature selection, trends in habitat selection and movement pattern were observed. The Yakima Canyon, characterized by a relatively high proportion of riparian vegetation, a number of small side channels, and relatively deep water, was utilized as holding habitat. Fish were most commonly associated with islands, pools, and rock outcroppings along stream banks. Migration appeared to be modified to optimize temperature regimes and energy conservation. As the time of spawning approached, fish left thermal refuges and migrated to spawning grounds upstream and downstream of refuge areas.

In conjunction with the radio telemetry study, an investigation was conducted to determine the rate at which adult chinook salmon equilibrate to ambient temperature (9° and 19°C). A negative relationship was found between size and rate of equilibration. However, in all instances a greater amount of time was required to lose heat than to gain heat. Energy benefits derived from holding within cold-water refuge areas may be maintained over a period of time that is size dependent.

To synthesize experimental results, TEMPEST, a stream reach temperature model, and stream temperature records were used to characterize the thermal regimes historically tolerated by spring chinook salmon and to predict the likely effects of forest practices on their success. Input parameters (view factor, mean annual air temperature, groundwater temperature, and stream depth) were selected based on historical distribution of spring chinook salmon and on heat transfer processes.

View factor, mean annual air temperature, and stream depth had the greatest effect on maximum stream temperature while groundwater temperature significantly affected minimum stream temperature. Although all parameters affected stream temperature individually, the most significant alteration to stream temperature was from cumulative effects such as might be produced by general habitat degradation. Results indicated that small tributaries and stream reaches located less than 40 km from watershed divide (i.e., the headwaters or upriver extent of the watershed) that are dependent on riparian zone and upslope integrity to regulate water temperatures may have maintained historical temperatures below current levels. Spring chinook salmon holding within these reaches may be exposed to sub-lethal temperatures. However, stream reaches located greater than 40 km from watershed divide that are primarily dependent on air temperatures to regulate water temperatures may have always maintained relatively warm summer temperatures. Spring chinook salmon migrating through these lower reaches may have adopted migration patterns that allow them to enter these reaches when air temperatures, and hence water temperatures, are low. In addition, use of thermal refuges may further allow spring chinook salmon to conserve energy.

Although spring chinook salmon residing within cool-water refuges may be capable of mitigating sub-lethal temperature effects, thermal refuge areas need to be abundant and available to the fish. Subsurface seepage may play a large role in stream temperature modification and thermal refuge formation. However, previous studies indicated that subsurface water temperatures may become elevated due to land use alterations. The availability of suitable thermal refuges and appropriate holding habitat within mainstem rivers may determine long-term population survival.

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INTRODUCTION

Daily and seasonal fluctuations in temperature are natural characteristics of rivers, but logging practices can exaggerate these fluctuations by removing riparian vegetation, altering river depth (by sedimentation), increasing local air temperatures in clearcut areas, and altering groundwater quality and quantity (Brown and Krygier 1970; Swift and Baker 1973; Moring and Lantz 1975; Hartman 1982; Hewlett and Fortson 1982; Beschta et al. 1987; Holtby 1988; Meisner 1990; Adams and Sullivan 1990; Sullivan et al. 1990). Increased stream temperatures have been observed coincident with the beginning of intensive logging. These increases were apparent in all months of the year, but were particularly striking during summer (May-September) (Moring and Lantz 1975; Hartman 1982; Holtby 1988). Additionally, estimates of historical temperature data for Carnation Creek provided evidence that in most months temperatures were either outside the historical range or were unusually warm (Holtby 1988). Temperatures do not return to pre-logging levels until stream banks become revegetated (Holtby 1988). Thus, elevated stream temperatures may persist over many years.

Natural or anthropogenic fluctuations in water temperature can induce a wide array of behavioral and physiological responses in salmonids. Numerous authors have noted the influence of temperature on the life history traits of Pacific salmon (Brett 1952; Olson and Foster 1955; Combs

1965; Olson and Nakatani 1969; Moring and Lantz 1975; Bouck et al. 1975; Dong 1981; Heming 1982; Hartman 1982; Smith et al. 1983; Kamler and Kato 1983; Garling and Masterson 1985; Neitzel and Becker 1985; Beacham and Murray 1986a; Beacham and Murray 1986b; Brannon 1987; Tang et al. 1987; Holtby 1988; Cunjak 1988; Murray and McPhail 1988; Linley 1988). Mechanisms have evolved to synchronize the timing of salmonid life history events with their physical environment, and are believed to have been a major factor in development of specific stocks (Burger et al. 1985; Brannon 1987). Several authors have linked variation in temperature requirements to physiological and behavioral differences imposed by a variety of environmental temperature regimes (Brannon 1987; Tang et al. 1987; Murray and McPhail 1988). Temperature can affect the time of migration of adults and the time of spawning. Spawning time, in turn, influences the incubation temperature regime, which influences survival rates, development rates, and growth of embryos and alevins.

Previous research on temperature sensitivity of fishes emphasized lethal limits and temperature preference. Current concerns have centered on the effect of long-term exposure of salmonids to sub-lethal temperatures. Holtby (1988) reported that virtually all effects of an altered thermal regime on Carnation Creek coho salmon were associated with relatively small temperature increases. Effects of elevated water temperature could be even greater where water temperatures are naturally high. Alterations of tissue and blood chemistry may occur in association with prolonged exposure to elevated temperatures (Bouck et al. 1975; Strange 1980; Thomas et al. 1986). These alterations may lead to impaired functioning of the fish and thus decreased viability. Feeding, resistance to disease, successful reproduction, and sufficient activity for competition and predator avoidance are all necessary for the survival of the organism and population. Inability to maintain any of these activities at moderately extreme temperatures may be as decisive to continued survival as more extreme temperatures are to immediate survival.

Although there is growing concern regarding sub-lethal thermal effects on salmonids, little data exist on the effects of elevated temperatures on adults. Studies have investigated temperature sensitivity of salmonid eggs and alevins (Olson and Foster 1955; Combs 1965; Olson and Nakatani 1969; Ringler and Hall 1975; Dong 1981; Heming 1982; Kamler and Kato 1983; Garling and Masterson 1985; Neitzel and Becker 1985; Beacham and Murray 1986a; Beacham and Murray 1986b; Brannon 1987; Tang et al. 1987; Murray and McPhail 1988) but these experiments only examined effects from fertilization through emergence of the fry. Pre-spawning effects were not considered. However, decreased egg viability and survival were observed in adult sockeye salmon (O. nerka) and cutthroat trout (O. clarki) exposed to sub-lethal elevated temperatures (Bouck et al. 1975; Smith et al. 1983).

B. Ready (manager, Kalama State Salmon Hatchery, personal communication) has reported egg mortalities of 50% or more from adults held at temperatures from 14.4°C to 19.4°C.

Although laboratory studies have provided evidence of sublethal temperature effects, fish in the natural environment may be able to minimize these effects through temperature selection. Behavioral thermoregulation in fishes has been documented in a number of experiments conducted at coolant water discharge sites (e.g., Coutant 1969; Spigarelli et al. 1974; Gibbons and Sharitz 1981; Clair et al. 1984). Temperature preference data were derived from field distribution records and laboratory shuttle box and thermal gradient experiments (e.g., Kaya et al. 1977; Medvick et al. 1981). Development of temperature-sensitive radio and ultrasonic transmitters has made it possible to relate fish movements to specific water temperature levels in their natural habitat (Coutant 1969; Coutant and Carroll 1980). Complex interactions such as inter- and intra-specific competition, predator-prey relationships and physiochemical restrictions may cause the average temperatures occupied by fish at large to differ from the preferred temperatures determined in the laboratory (Coutant and Carroll 1980; Medvick et al. 1981; Fischer et al. 1987; Reeves et al. 1987).

Gibbons and Sharitz (1981) reported that fishes found in coolant water temperature regimes were not necessarily under continuous exposure to warmer waters. In addition, the consistently narrower fluctuation of body temperature observed in comparison with the fluctuation of environmental temperature, suggest that behavioral thermoregulation occurs (Coutant et al. 1969; Spigarelli et al. 1974; Beitinger 1976; McCauley and Huggins 1976; Wrenn 1976). Excursions into water temperatures above and below the zone usually occupied were short (Coutant and Carroll 1980). Because the thermal structure of rivers is dynamic and can become more so after anthropogenic alterations, the duration of stressful conditions and the availability of suitable refuges may determine population survival (Coutant and Carroll 1980). Thermal refuge areas may include groundwater seeps (lateral and pool bottom); tributaries; emerging streambed flow; deep water impoundments, and vegetative and topographic shading (Bilby 1984). Striped bass (Morone saxatilis) in a quarry utilized a submerged stream channel fed by a cool tributary as a refuge from high summer water temperatures (Coutant and Carroll 1980). In addition, rainbow (O. mykiss) and brown (Salmo trutta) trout on the Firehole River concentrated in a cold-water tributary during the warmest portion of the summer (Kaya et al. 1977).

The objectives of this study were to:

1) determine if pre-spawning temperatures that might be experienced by adult Yakima River spring chinook salmon influenced offspring survival and/or development

2) determine if adult Yakima River spring chinook salmon behaviorally regulate internal temperature through selection of cold-water refuges

3) determine the bioenergetic savings derived from utilization of thermal refuges

4) determine the rate at which adult chinook salmon equilibrate to ambient temperature

5) determine if migration patterns are modified to optimize temperature regimes and energy conservation

6) model the likely effects of forest practices on spring chinook salmon reproductive success

METHODS

The relationship between spring chinook salmon reproductive success and logging-related temperature elevations was evaluated from an adult holding study, a radio telemetry study, a temperature equilibration rate study, and review of stream temperature records and stream reach temperature modelling.

Study Site

The Yakima River, located in south-central Washington, originates near the crest of the Cascade Mountain Range above Keechelus Lake at an elevation of 2,104 m and flows 344.5 km southeastward to its confluence with the Columbia River (river kilometer 539.7) (Figure 1).

Adult Holding Study

To determine if pre-spawning temperatures experienced by adult spring chinook salmon influenced reproductive success by altering the number or size of eggs deposited by the female, their subsequent survival to emergence was assessed. Priest Rapids State Salmon Hatchery was selected as the study site because (1) it provided access to water of both elevated and non-elevated temperatures and (2) it permitted isolation of experimental fish and effluent from hatchery rearing and adult holding areas. Two water sources, well water (12° to

14°C) and river water (17° to 21°C), were mixed to provide similar water quality in each treatment group. Priest Rapids State Salmon Hatchery does not maintain a population of spring chinook salmon, hence, an alternative study population was identified. Yakima River adult spring chinook salmon were selected for use in the study because they were from a wild population (i.e., natural propagation), they were easily obtained at Roza Diversion Dam, and they were the same stock selected for the radio telemetry study.

On 26 June 1989, 33 adult spring chinook salmon were obtained from Roza Diversion Dam on the upper Yakima River (Figure 1). Fish were immediately injected with 0.5 cc per 4.5 kg erythromycin and 0.5 cc per 4.5 kg terramycin. A 4,560 L tank equipped with oxygen and aeration pumps was used to transport fish to Priest Rapids State Salmon Hatchery. Water in the tank was treated with 22.5 kg of salt (sodium chloride) and 11.3 kg of ice. During transportation the water temperature rose from 11.1°C to 18.3°C.

At the hatchery, fish were divided into two temperature treatment groups and placed within one of eight covered circular tanks. Shade cloth permitted diel and seasonal photoperiod and temperature cycles but protected the fish from direct sunlight. All circular tanks received well water (14°C) from 26 June 1989 to 7 July 1989. After 7 July 1989, each tank received a mixture of well and river water maintained at approximately 19°C (elevated temperature regime) and approximately 14°C (control temperature regime). Diurnal fluctuation within both the elevated and control tanks was approximately 1.5°C per day (Figure 2). Formalin treatments were provided (1:5,000) for one hour every day for the first five days and every other day until spawning occurred. Effluent from the eight circular tanks was treated with chlorine (2 ppm). An Omnidata datapod (Omnidata International, Inc., Logan, Utah) was used to record temperature. All mortalities were diagnosed for disease at Priest Rapids State Salmon Hatchery and were disposed of through upland burial.

As of 14 August 1989 it was evident that the majority of fish in the elevated treatment tanks would not survive to spawn (control treatment mortalities = 0; elevated treatment mortalities = 15). Mortalities from columnaris disease (_Flexibacter columnaris_) were increasing as the summer progressed. Therefore, all eight tanks were switched to well water (14°C) to reduce temperatures and columnaris-associated mortalities. On 21 August 1989 the 16 fish in the control group were divided into new elevated and control temperature treatment groups. The elevated group was housed in two tanks (tank I and tank III) and the control group was in one tank (tank VIII).

Upon reaching sexual maturity in September, fish from both temperature treatment groups were spawned. The size and quality of the eggs expelled per adult female (i.e., broken or opaque eggs) were recorded. Ovarian fluid samples were transported to the Washington Department of Fisheries Evergreen State Laboratory to determine Infectious Hematopoietic Necrosis (IHN) presence. Eggs (500 per female) and milt were transported to the University of Washington for fertilization and incubation. Eggs and milt were stored in separate plastic sampling bags and placed in coolers containing ice. Toweling was inserted between the sampling bags and the ice to prevent damage to gametes. Travel time to the university was approximately three hours.

At the university, the eggs were fertilized with milt from males of the same temperature treatment group and water-hardened in Wescodyne, a topical disinfectant. Fertilized eggs from individual females were subdivided into four groups of 125 eggs each and placed into separate egg cups. Egg cup position within the incubation unit was randomized. Incubation occurred in one of two troughs fed by chilled dechlorinated city water. Each trough contained a pump and float switch, which removed approximately 3.79 L of the incubation water once every seven minutes. Incubation effluent was disinfected with chlorine (2 ppm). Formalin treatments (1:4,000) were conducted for one hour once every three days until the eyed stage. Water temperature and dissolved oxygen were maintained at 9.5°C and 9 mg ml^{-1} oxygen, respectively, to ensure identical developmental conditions within the incubation unit. Egg mortalities were recorded and placed in Stockard's Solution (40 ml acetic acid, 50 ml formaldehyde, 60 ml glycerin, and 850 ml distilled water) to determine developmental stage at mortality (Fleming and Ng 1987). Records were maintained regarding the rate of egg development; stage at egg mortality; egg weight, diameter, and volume; occurrence of developmental abnormality; rate of hatching; alevin length; and alevin and yolk sac wet and dry weight. At 24 hours post-hatch, 10 alevins were randomly selected from each egg lot. Yolks were separated from the fish and wet weights were determined. Yolk sacs and fish were then placed in a drying oven for 48 hours at 60°C to determine dry weights. Weights were established using a Precisa 80 A balance. All samples were kept in a desiccator during the weighing process to minimize moisture absorption. Original plans were to terminate the experiment at yolk absorption. However, an unknown agent entered the incubation water immediately prior to hatch. Newly hatched alevins survived no more than 24 hours post-hatch. Although one female was diagnosed as IHN positive, histological analysis indicated that IHN was not the causative agent in the mass mortality of alevins. Chlorine was suspected as the causative agent.

Radio Tagging and Tracking

Temperature-sensitive radio transmitters were employed to study patterns of behavioral thermoregulation, habitat preference, and movement of adult spring chinook salmon in the Yakima River. The Yakima River was selected as the study site based on the following criteria: wild population of spring chinook salmon, ease of access to salmon for collection, low fishing pressure, upstream timber harvesting, elevated summer water temperatures, and availability of springs and tributaries of differing temperatures from the mainstem river.

On 17 and 18 June 1989, 19 adult spring chinook salmon were captured in a fish trap located at Roza Diversion Dam on the upper Yakima River (Figure 1). Individual fish were removed from the trap and immediately anesthetized with buffered tricaine methane sulfonate (MS-222). Length and weight were recorded and a temperature-sensitive radio transmitter was inserted into the stomach of each fish (method modified from Liscom et al. 1977) (Table 1). The transmitter antenna was sutured to the roof of the mouth with fishing line to prevent regurgitation of the transmitter or injury to the gills. High-frequency (151 MHz) radio telemetry equipment (Advanced Telemetry Systems, Inc., (ATS) Isanti, MN) was utilized. The encapsulated transmitters were cylindrical (50 mm long by 18 mm diameter and 26 g air weight) and had 300 mm external antennas. Transmitters were designed to operate for three to four months on lithium batteries. All transmitters were calibrated for temperature accuracy prior to use. After transmitter insertion, fish remained within a live box until equilibrium was regained. They were then transferred to a 6.1 m x 6.1 m net pen and held for approximately 24 hours to ensure complete recovery by the fish and functioning of the transmitter.

Upon release from the net pen, individual fish were monitored for internal body temperature and movement within the river system for up to four months. Once a fish was located, an Omnidata datapod was used to obtain the water temperature in the vicinity of the fish. Water temperatures were recorded at various depths and locations to ensure accuracy. Temperature data provided a comparison between internal and ambient river temperature as evidence of behavioral thermoregulation. Additional stream temperature information was obtained from U.S. Bureau of Reclamation gage station records. The position of the fish and descriptive habitat information were also collected at this time.

Equilibration Rate Study

A study was also conducted to ascertain the rate at which adult chinook salmon equilibrate to ambient temperature. Five chinook salmon that had returned to the University of Washington's hatchery were anesthetized with MS-222 and a temperature-sensitive radio transmitter (ATS, 151.600 MHz) was inserted into the stomach of the fish. The fish ranged from 2.82 to 11.10 kg. The transmitter was used to determine the rate at which each fish equilibrated to an ambient bath temperature of 9°C and 19°C. The equilibration rate of the transmitter in water was also determined.

Stream Reach Temperature Modelling

A stream reach temperature model and stream records were used to characterize the thermal regimes historically tolerated by spring chinook salmon and to predict the likely effects of forest practices on their success. The temperature model selected was TEMPEST, a heat transfer model developed by Adams and Sullivan (1990), to evaluate stream sensitivity to various heating processes. A detailed description of TEMPEST can be found in Adams and Sullivan (1990) and Sullivan et al. (1990).

Input parameters were selected based on historical distribution of spring chinook salmon (Fulton 1968) and on heat transfer processes. Although selected geomorphic and environmental parameters do not represent all spring chinook salmon rivers during all seasons, modelling results do provide a basis for interpreting the processes driving temperature, determining temperature-sensitive rivers, and predicting historical stream temperature regimes. Input variables were selected to provide maximum temperature differentials. Fixed input parameters derived from field determinations included:

1) Mean solar insolation: 276.00 W/m^2
2) Clearness factor (i.e., 0 = complete cloud cover; 1.00 = no cloud cover): 1.00
3) Water emissivity (i.e., 0 = high turbidity; 1.00 = low turbidity): 0.95
4) Air velocity: 0.50 m/s
5) Relative humidity at 298°K: 0
6) Soil heat transfer coefficient: 6.75
7) Groundwater influx: 0.00072 kg/m^2

Varied input parameters included:

1) View factor (i.e., 0% = open canopy; 100% = closed canopy): 26%, *51%, 76%
2) Mean annual air temperature: 9.00°C, *11.00°C, 13.00°C
3) Ground water temperature: 9.00°C, *11.00°C, 13.00°C
4) Stream depth: 0.300m, *0.441m, 0.882m

* Default values derived from field determination

These four factors regulate heat input and output from the stream environment, and thereby determine stream temperature under any given level of solar loading (Adams and Sullivan 1990). Riparian cover was varied according to previous model findings (Sullivan et al. 1990). Shade values less than or equal to 25% provided the warmest temperatures, shade values of 26-75% provided moderate temperatures, and shade values equal to or greater than 76% provided the coolest temperatures. Input daily air temperatures were characteristic of south-west Washington summer air temperatures and were derived from field determination. Mean annual air temperature was varied plus or minus 2°C to represent alterations in temperature associated with timber removal or predicted elevations in regional mean annual air temperature owing to global warming (Moring and Lantz 1975; Hartman 1982; Holtby 1988; Hansen et al. 1988). In addition, groundwater temperature has been shown to vary by 3.0°C around the mean annual air temperature. Factors that may influence air temperature such as timber removal and global warming may also influence groundwater temperature, and therefore, groundwater temperature was also varied by 2°C. Groundwater input was not varied. Due to its extremely variable nature in the environment, there was little evidence to base input increases or decreases (Sullivan, personal communication). Stream depth, the primary geometric parameter, affects response time and magnitude of temperature fluctuation. Stream depth was manipulated to create various thermal inertia scenarios. All parameters were varied to provide insight into probable historical and future spring chinook salmon thermal regimes. Model calculations were conducted over a 40 day period, thereby, exposing the stream element to the same environmental conditions for 40, 24 hour periods to analyze the cumulative effect of sequential high temperatures.

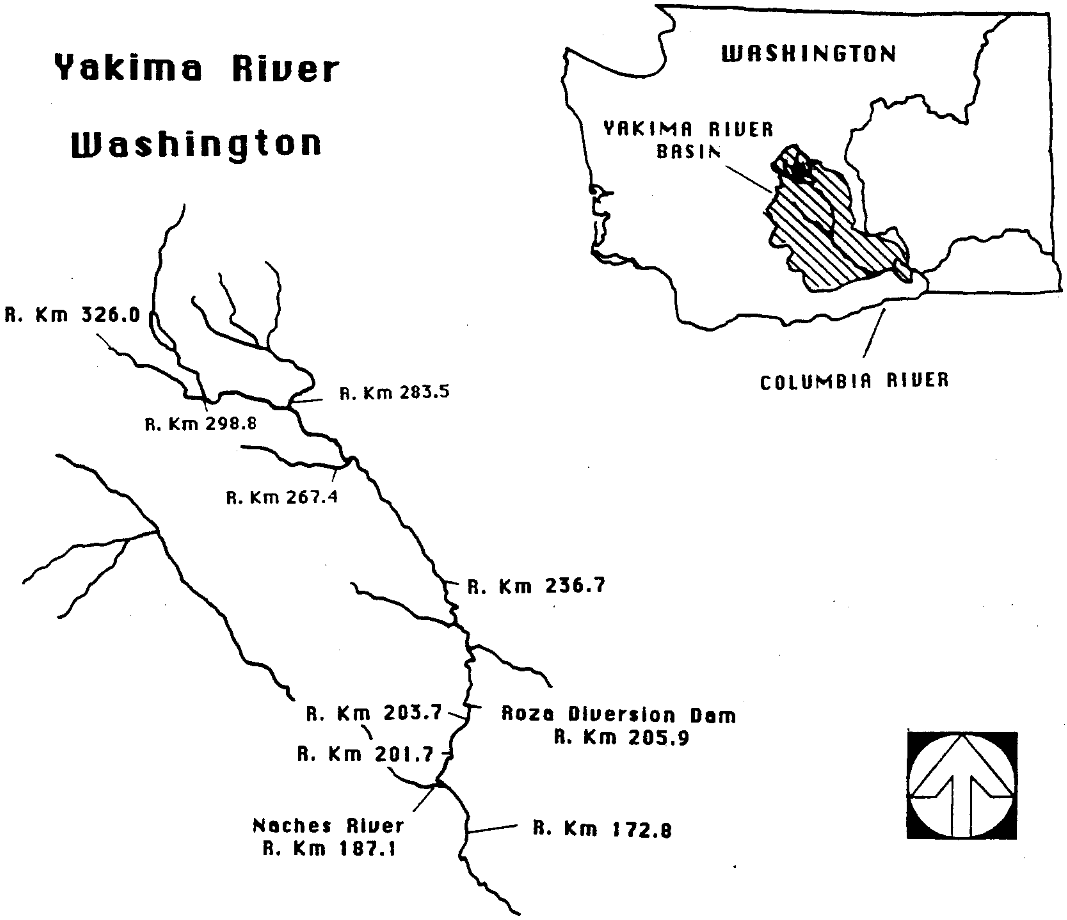

Figure 1: Vicinity Map of the Yakima River Basin Including River kilometers for Major Spawning and Holding Grounds.

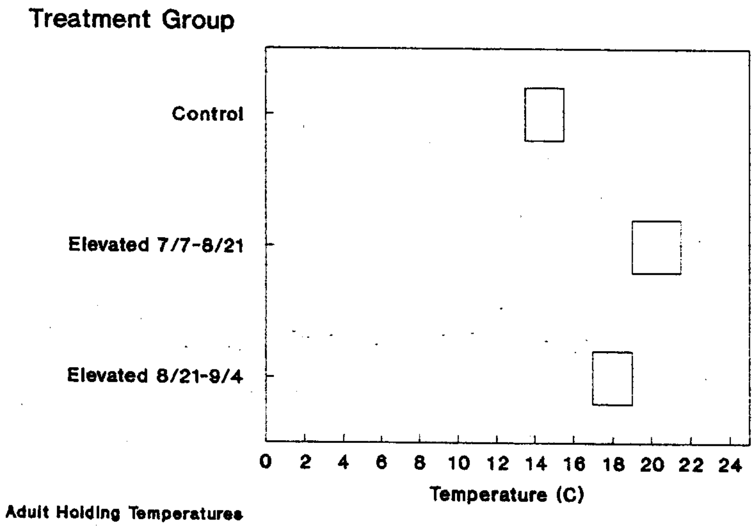

Figure 2: Adult Holding Study Control and Elevated Treatment Temperature Ranges Recorded Between 26 June and 3 October 1989.

Table 1: Summary of Weight, Length, and Sex for Radio Tagged Spring Chinook Salmon.

Fish #	Weight (kg)	Length (cm)	Sex
1	4.50	73.0	F
2	4.50	73.7	F
3	5.85	82.6	F
4	6.12	76.8	F
5	4.28	71.1	F
6	3.60	68.6	F
7	4.95	74.3	F
8	5.74	83.2	M
9	3.94	69.8	F
10	3.60	67.3	F
11	2.59	58.4	M
12	3.60	67.3	M
13	2.92	62.2	M
14	4.50	71.1	M
15	9.00	95.2	M
16	1.80	54.6	F
17	4.95	77.5	M
18	3.26	66.0	M
19	4.16	71.1	M

RESULTS AND DISCUSSION

Adult Holding Study

On 26 June 1989, 33 Yakima River adult spring chinook salmon were transported to Priest Rapids State Salmon Hatchery and were divided into two temperature treatment groups. Review of Columbia River temperatures compiled by the North Pacific Division, Corps of Engineers (1989), indicated that experimental fish were not exposed to sub-lethal temperatures prior to experimental manipulation of water temperatures. The upper temperature recorded during the spring chinook salmon migration was 13.9°C (Bonneville Dam, May 1989). As of 14 August 1989 it was evident that fish in the elevated treatment would not survive to spawning owing to columnaris-associated mortalities. Among the 17 elevated treatment fish, there were 8 male and 7 female mortalities occurring between 24 July 1989 and 17 September 1989. Two males survived to the conclusion of the study (3 October 1989). No elevated treatment females survived through completion of the study. *Flexibacter columnaris* are not only capable of surviving at increased temperatures, but are capable of increased virulence at these temperatures (Post 1987). Therefore, all eight tanks were switched to well water to reduce temperatures and columnaris-associated mortalities. Although *Flexibacter columnaris* was present on the gills of control fish, there were no mortalities among this group.

Fish exposed to increased temperatures undergo compensatory reactions to reduce the effect of elevated temperatures. Prolonged exposure to elevated temperatures and hence long-term compensatory reactions may weaken the fish's ability to resist infection or infestation (Wedemeyer and Goodyear 1984).

On 21 August 1989 the original control group, containing 16 fish, was divided into new elevated (tanks I and III) and control (tank VIII) temperature treatment groups. The control group contained two females and three males. Elevated group I (tank I) and group II (tank III) were comprised of three females and three males and two females and three males, respectively. Control temperatures ranged from 14°C to 15.5°C while elevated temperatures ranged from 17.5°C to 19°C. Diurnal fluctuation within both the elevated and control tanks was 1.5°C (Figure 2). Fish were again maintained on a mixture of well and river water until 4 September 1989 when access to river water was no longer available. Although fish did not receive the anticipated three month treatment period, crucial maturation processes were occurring during the experimental period. Peak exogenous and endogenous vitellogenesis occurs approximately one to two months prior to spawning with endogenous vitellogenesis occurring sometime after the initiation of external vitellogenesis (Gordon et al. 1987). Vitellogenin (lipophosphoprotein) is important in forming the energy reserve of the egg. If this step is altered by elevated temperatures, egg size, developmental rate, alevin weight, and/or yolk weight may be affected. Alteration of these life history parameters could lead to smaller progeny, and hence, altered fry migration timing and ultimately may decrease fry survival rates. Approximately one-half to one month prior to spawning, final oocyte maturation occurs (Gordon et al. 1987). At this time the correct genetic complement is achieved. In addition, coalescence of the yolk lipid droplets occurs. Disruption at this stage could lead to developmental abnormalities and degradation of yolk quality. Therefore, adult exposure to sub-lethal temperatures from 21 August 1989 to 4 September 1989 could produce substantial disruption of normal development.

Spawning began on 18 September 1989 and was completed on 3 October 1989. Seven egg-lots were incubated at the University of Washington (two egg-lots from control tank VIII, three egg-lots from elevated tank I, and two egg-lots from elevated tank III). All egg lots were monitored for rate of development; stage at egg mortality; egg weight, diameter, and volume; occurrence of developmental abnormality; rate of hatch; alevin length; and alevin and yolk sac weight. Owing to the large number of adult mortalities incurred during the holding period, statistical analysis could not be performed. However, trends in data were obtained and provide insights into the possible effects of sub-lethal temperatures on reproductive success. Differences between temperature treatment groups were observed in pre-hatch mortalities and developmental abnormalities. The control group had one mortality at developmental stage # 18, representing a 0.10 % mortality rate (Ballard 1973). Stage # 18 is characterized by a freely projecting trunk-tail equal in length to the part of the body attached to the yolk sac. The head is undercut as far back as the eyes and very little eye pigment is present. The tail is straight and contains 25-30 pairs of post-anal somites. However, Elevated Group I had a 0.80 % mortality rate (12 pre-hatch mortalities) including three eggs exhibiting developmental abnormalities, and Elevated Group II had a 0.90 % mortality rate (9 pre-hatch mortalities) including one egg exhibiting developmental abnormalities. Abnormalities in both groups included curvature of the spine and malformed body segments. Elevated Group I included one mortality at stage # 22; three mortalities between stage # 19 and # 20; two mortalities between stage # 18 and # 19; and six mortalities at stage # 17. Elevated Group II included three mortalities between stage # 19 and # 20; two mortalities between stage # 18 and # 19; and four mortalities at stage # 17. Stage # 17 is characterized by a trunk-tail projection shorter than the attached part of the trunk, but longer than the brain and pectoral-level spinal cord. Each pectoral mound shows a slight ridge in its surface. The heart is bent strongly to the left side. Up to 20 pairs of post-anal somites have formed. Development increases from stage # 17 to stage # 22 when hatching occurs. Abnormalities developed at approximately stage # 17.

At the time of spawning, egg weight per kg female and quality of eggs expelled (i.e., broken or opaque eggs) were recorded. Bouck et al. (1975) determined that female sockeye salmon exposed to elevated temperatures produced similar egg numbers, however, the eggs were smaller in the elevated temperature treatment group. Consistent with these findings, the number of eggs per female and quality of eggs did not differ substantially between the two treatment groups. The average number of eggs was 1,398.5 eggs kg^{-1} (control); 1,061.3 eggs kg^{-1} (Elevated Group 1); and 1,326.0 eggs kg^{-1} (Elevated Group 2). Larger salmon typically produce larger eggs (Hankin and Healey 1986), but females held at elevated temperatures produced smaller eggs when adjusted for weight and length. Average female weight and length were 2.76 kg and 65.62 cm (control); 3.92 kg and 72.60 cm (Elevated Group 1); and 3.08 kg and 68.75 cm (Elevated Group 2), while average egg weight and diameter were 0.185 g and 0.721 cm (control); 0.170 g and 0.704 cm (Elevated Group 1); and 0.165 g and 0.690 cm (Elevated Group 2). Average percent body weight composed of egg mass was 26.4 % (control); 18.5 % (Elevated Group 1); and 21.2 % (Elevated Group 2). This size discrepancy between treatment groups was also apparent in alevin lengths and alevin and yolk sac wet and dry weights. Alevin lengths were consistently greater in the control group (2.10 cm) than in either Elevated Group 1 (1.99 cm) or Elevated Group 2 (1.96 cm). Although Elevated Group 1 yolk weights were slightly greater than control group yolk weights, the alevin weights were consistently less than those of the control group. Elevated group 2 yolk and alevin weights were less than control group measurements (Table 2). This inconsistency in yolk sac weights may be due to the small sample size. However, alevin size was decreased in both Elevated Groups 1 and 2. Decreased yolk sac weights could further increase size discrepancies between control and elevated temperature groups at emergence. Smaller alevins could be subjected to increased predation rates, decreased overwintering survival, as well as reduced fry size and altered fry migration timing (Holtby et al. 1989).

There were no observable differences in fertilization rate between treatment groups. Although there have been reports of decreased egg fertility at temperatures ranging from 16.9°C to 19.0°C (Nooksack Spring Chinook Technical Group 1987), fertilization rates approached 95% for all egg lots.

Differences in egg size between treatment groups did not affect the rate of development to hatch. The number of days required by all egg lots to reach the 50 % eyed and the 50 % hatch stages was approximately 29.5 days and 57 days, respectively. However, the control treatment egg lots and elevated treatment egg lots # 10 and # 12 required 2.5 days to complete hatch. All other lots required two days to complete hatch.

Radio Telemetry Study

Temperature-sensitive radio transmitters were employed to determine if adult spring chinook salmon behaviorally regulate internal temperature through selection of cold-water refuges. Thermal refuge areas can include groundwater seeps (lateral and pool bottom), tributaries, emerging streambed flow, deep water impoundments, and vegetative and structural shading. Results of the study included trends in temperature selection, habitat selection, and movement pattern.

Temperature and Bioenergetics

A comparison of internal and ambient temperatures demonstrated that spring chinook salmon were capable of behavioral thermoregulation (Figure 3) (Appendix A). As exemplified by fish # 5, behavioral regulation of internal temperature occurred throughout the range of temperatures experienced (Figure 4). On 21 June 1989 the river reached a low temperature of 12.0°C. On that date, fish # 5 maintained an internal temperature of 10.6°C, 1.4°C below ambient. The river reached a high temperature of 19.5°C on 6 August 1989.

At that time, internal temperature was maintained at 17.8°C, 1.7°C below ambient. A 2.2°C (14.5°C vs. 12.3°C) divergence from ambient was recorded on 2 July 1989.

The average number of observations per fish during the four month tracking period was 12.2. Combining radio telemetry data for the 19 fish, the average recorded difference between internal and ambient river temperature was 2.5°C. At no time was internal temperature equal to or greater than ambient (i.e., fish consistently maintained an internal temperature below that of the ambient river temperature). On 25 June 1989, fish # 11 maintained an internal temperature 7.2° C (9.3° C vs. 16.5° C) below ambient, the greatest divergence from ambient temperature that was recorded.

Metabolic savings derived from inhabiting cool-water refuges can be approximated utilizing the Q_{10} law and bioenergetic data collected on sockeye salmon (Fry 1957; Brett 1965a; Brett 1965b; Brett 1967; Fry 1971; Brett and Glass 1973). The Q_{10} law states that the metabolic response of all organisms follows a general law of doubling with each 10°C increase. Although metabolic rate increases through the full tolerance range of the organism, the rate of increase diminishes at its upper level (Brett 1970). At temperatures between 10°C and 20°C a doubling of the metabolic rate is a conservative estimate for salmon. Therefore, a salmon in a refuge that is 2.5°C below ambient river temperature could operate at a basal metabolic rate 25 % lower than its counterpart holding at ambient river temperature.

Bioenergetic data extrapolated from temperature-weight response surfaces for active and standard metabolic rates (oxygen consumption in mg O_2 kg^{-1} $^{hr-1}$) of sockeye salmon were used to estimate hourly and daily energy expenditure (Brett and Glass 1973). Rate of oxygen consumption was converted to rate of energy expenditure using an oxycalorific equivalent dependent on food consumption. A value of 13.6 J $O_2{}^{mg-1}$ was found to be suitable for fish which have a metabolism based on protein and lipid rather than carbohydrate (Wootton 1990). Thus, utilizing bioenergetic data obtained from sockeye salmon (0.002 to 2.0 kg) and extrapolated to spring chinook salmon (1.8 to 6.1 kg), a 2.5°C decrease in internal temperature was found to produce a 12 to 20 % decrease in basal metabolic rate (i.e., rate of energy expenditure by a resting fish) or a savings of 17.3 to 29.9 cal kg^{-1} hr^{-1}. At the maximum or active metabolic rate (i.e., maximum sustainable aerobic rate), a 3.2 to 6.2 % decrease in metabolic rate or a savings of 71.5 to 130 cal kg^{-1} hr^{-1} was calculated to occur. However, the actual energy savings experienced by spring chinook salmon may be less than that calculated utilizing bioenergetic data derived from sockeye salmon. The active metabolic rate of sockeye salmon exceeds that determined for other salmonids by 30 to 40 % (Brett and Glass 1973).

Bardach and Bjorklund (1957) determined that freshwater fishes including rainbow trout (O. mykiss) were capable of detecting temperature changes as slight as 0.05°C. An ability to locate even small temperature variations may produce meaningful reductions in basal metabolic rate. In addition, a thermal refuge may provide an area of decreased velocity, enabling fish to further conserve energy (Hawkins and Smith 1986). Although energy benefits may be derived from inhabiting thermal refuge areas, costs may also be incurred. Refuge areas supplied by groundwater or subsurface seeps may have low dissolved oxygen concentrations (Bilby 1984). Duration of stay within such a refuge would be dependent on cost/benefit ratios that may vary with size.

A range of possible basal and active metabolic savings is produced at each temperature due to an increased metabolic efficiency with weight. At 15°C a 6.1 kg and a 1.8 kg adult salmon expend 139.8 cal kg^{-1} hr^{-1} and 159.3 cal $kg^{-1}hr^{-1}$, respectively (Brett and Glass 1973). Although metabolic rate (O_2 hr^{-1}) increases with size, the relative metabolic efficiency also increases (O_2 $kg^{-1}hr^{-1}$). The maximum or active metabolic rate is limited by the availability and uptake of oxygen. Therefore, metabolic savings decrease at upper activity levels.

Equilibration Rate Study

The equilibration rate study demonstrated that chinook salmon resist internal temperature fluctuation. Moreover, a greater amount of time was required to lose heat than to gain heat, hence ascending temperature curves were steeper than descending temperature curves (Appendix C). A 3.0 kg chinook salmon required approximately 36 minutes to equilibrate to 8.6° C from 17.0° C and only 28 minutes to equilibrate to 17.9° C from 8.6° C (Figure 5). The time to equilibrate increased with the size of the fish. For example, a 2.82 kg fish required approximately 33 minutes to equilibrate to the 19°C bath whereas the 2.82 and 11.10 kg fish required 37 minutes and 62 minutes, respectively to equilibrate to the 9°C bath. Due to inadequate oxygen levels within the test apparatus, the 11.10 kg fish was not allowed to fully equilibrate to the elevated temperature, and the ascending temperature curve is incomplete. Size-related differences in equilibration rates are presumably determined mainly by surface to volume ratios.

Resistance to internal temperature fluctuation may allow adult chinook salmon to maintain energy benefits derived from cool-water refuge areas for an extended period, the length of which is size dependent. Larger fish are able to maintain lowered internal temperatures longer than smaller fish. This would provide an extended time period to locate a new holding location prior to equilibration with ambient river temperature. For example, the 2.82 kg fish required 7 minutes to increase internal temperature from 12°C to 15°C whereas the

11.10 kg fish required 16 minutes. Conceivably, larger fish may spend more time locating a holding site that would provide the greatest energy benefit whereas smaller fish, attempting to minimize unnecessary energy expenditures, may occupy the first available holding site. In addition, there is an increase in relative metabolic efficiency (O_2 $kg^{-1}hr^{-1}$) with size. However, smaller fish exhibit a lower overall metabolic rate (O_2 hr^{-1}). It is possible that the decreased oxygen requirements of small fish could enable them to remain in a thermal refuge supplied with oxygen-poor groundwater for a longer period of time than larger fish. This might allow smaller fish to inhabit a broader range of thermal refuge areas.

Spigarelli et al. (1974) observed that the heat exchange half-time of alewives exposed to elevated temperatures was shorter than that of alewives exposed to reduced temperatures. They concluded that fish may be capable of limited physiological thermal regulation. Current studies suggest that changes in blood flow patterns away from the gills and periphery allow the organism to conserve heat (R. Huey, University of Washington, personal communication). However, conservation of heat does not appear to be an adaptive response. In all instances, Yakima River spring chinook salmon maintained internal temperatures below ambient river temperature. Dead fish display similar rates of heating and cooling (R. Huey, University of Washington, personal communication), and therefore, limited physiological thermal regulation may be a function of thermodynamic or physiological processes.

Habitat Selection and Migration

Spring chinook salmon utilized the Yakima Canyon (river kilometer 188.5 to 225.1) as holding habitat from the time of release to the approximate time of spawning. There is evidence that the Yakima Canyon has historically provided abundant adult holding habitat. According to Yakima River maps compiled from 1936 survey data, the canyon provided many large resting pools (more than 24 pools/km greater than 20 m^2 and 0.9 m deep) not abundant elsewhere on the lower or middle river (J. Sedell, USDA Forest Service, Pacific Northwest Forest and Range Experimental Station; personal communication). As the majority of spring chinook salmon home to natal streams (Quinn and Fresh 1984), Yakima River spring chinook salmon may have evolved homing patterns that allow them to exploit holding habitat located within the canyon. In addition to large pools, the canyon contains large quantities of riparian vegetation both on the shoreline and on islands, a number of small side channels, and deeper water than most areas outside the canyon. The majority of fish holding were associated with islands (67% of total observations), and pools and rock outcroppings (33% of total observations) along the stream bank. Stream flow associated with islands may be diverted downward through loose mounds of gravel that accumulate at island tips (Burger et al. 1985). Because diverted stream flow is not exposed to solar radiation it may become cooler than surface flow. Therefore, re-emergence of subsurface flow as seepage could produce thermal refuge areas. In addition, refuge areas may be linked to groundwater seeps and subsurface flow associated with rock outcroppings and fissures, as well as vegetative and topographic shading. Both riparian vegetation and canyon walls provided shading absent from many locations elsewhere in the Yakima River Basin. Although a few tributaries located within the canyon were available for holding (Appendix B), fish did not frequent them but rather were associated with pools and banks receiving cool-water inputs. However, streams that are too shallow for salmon to hold may provide thermal refuges through subsurface seepage.

As the time of spawning approached, fish moved into areas identified as perennial spawning sites by stream surveys (Fast 1988). Prior to this study it had been believed that all fish migrating above Roza Diversion Dam (river kilometer 205.9) spawned from river kilometer 236.7 to 326.0 (Figure 1). However, tagged fish moved both upstream and downstream of Roza Diversion Dam (Table 3). At the conclusion of the study (28 September 1989), it was estimated that 10 of the 19 fish spawned in Area I from river kilometer 236.7 to

326.0; four fish spawned in Area II from river kilometer 201.7 to 203.7; and five fish spawned in Area III from river kilometer 172.9 to 187.2 (Figure 1).

It was difficult to determine whether three fish (fish # 5, # 8, and # 13), located in the reservoir above Roza Diversion Dam at the conclusion of the study, spawned in Area I or Area II. All three fish initially moved upstream approximately 6.4 to 8.1 kilometers. In July they moved downstream approximately 1.6 to 3.2 kilometers and held in the reservoir. As time of spawning approached it is possible that these fish moved to spawning grounds below Roza Diversion Dam. However, fish # 5 was not located after 11 September 1989 and fish # 8 and # 13 were not located after 28 September 1989.

Additionally, there were three fish that presumably were lost to poaching (fish # 2, # 7, and # 15). Fish # 2 was monitored from release at Roza Diversion Dam and moved upstream. On 4 July 1989 a number of fishermen were observed in the vicinity of the fish and on 8 July 1989 transmitter readings indicating transmitter exposure to air temperatures were recorded. On 26 July 1989 fish # 15 was also located in an area of high fishing pressure. During the 6 August 1989 tracking session transmitter readings again indicated transmitter exposure to air temperatures. It was assumed that the transmitters were no longer within the stomachs of fish # 2 and # 15. Fish # 7 was located on spawning grounds below

Roza Diversion Dam on 26 July 1989. On 28 September 1989 a very strong signal from fish # 7 was received from the city of Yakima. It is not clear whether the tag was discovered after the fish had spawned and was retrieved or the fish was removed from the river before spawning.

In addition to observations of both upstream and downstream movement from Roza Diversion Dam, radio telemetry data indicated that fish entered and moved into the Naches River system prior to returning to Yakima River holding areas and Yakima River spawning grounds. Fish # 6 was observed at river kilometer 201.6 near the town of Selah on 8 July 1989; within the Naches River (approximately 6.4 km above the confluence with the Yakima River) on 26 July 1989; and at river kilometer 187.1 near the town of Yakima on 28 September 1989 (Figure 6).

As with all telemetry studies, there were concerns regarding possible behavioral alterations from handling stress and transmitter insertion. Some studies report tagged fish either not leaving the release site or immediately moving downstream out of the system or to a second holding location (Granstrand and Gibson 1981; Wampler 1984; Milligan et al. 1984; Hiss et al. 1990). However, there were two reasons to believe that radio tagging did not disturb the behavior of the fish. First, all fish migrated to known spawning areas. Second, all fish that were eventually located below Roza Diversion Dam initially displayed alternating upstream movement and holding within the canyon until spawning dates approached (Table 3). At that time, they rapidly moved downstream and were later located in the vicinity of known spawning grounds (Appendix A). For example, fish # 16 was located at river kilometer 215.7 on 20 June 1989; river kilometer 227.0 on 28 June 1989; river kilometer 235.1 on 11 July 1989; and river kilometer 172.8 in Yakima on 28 September 1989 (Figure 7).

Migration appeared to be modified to optimize temperature regimes and energy conservation. Sockeye salmon, summer steelhead (O. mykiss), and Atlantic salmon (Salmo salar), have also been observed to delay upstream migration prior to spawning (Ricker and Robertson 1935; Spence 1981; Lough 1983; Hawkins and Smith 1986). The sockeye salmon, summer steelhead, and Atlantic salmon made rapid upstream progress early in their migration and then held within tributaries and pools located both above and below spawning grounds until spawning dates approached. This delay in upstream travel and selection of low velocity and sheltered habitat could reduce energy store expenditures until time of spawning (Hawkins and Smith 1986). Thus, delays in spawning migration may be due to habitat selection rather than to difficulties or errors in location and selection of spawning streams. Early returning salmon species spend many months in freshwater prior to spawning. As salmon do not feed during upstream migration, energy conservation may be critical to spawning success

(Gilhousen 1980). Gilhousen (1980) determined that between 5 and 26 % of fat and 40 and 70 % of protein remained in post-spawning Fraser River sockeye salmon, with males retaining more than females. As a large portion of the energy reserves may be consumed by the conclusion of spawning, excess energy expenditure prior to spawning may reduce spawning success, especially in females. Delays in spawning migration that allow fish to exploit refuge areas of decreased temperature and velocity may decrease energy expenditure, and hence, increase energy devoted to behavioral and physiological processes involved in successful reproduction.

Stream Reach Temperature Modelling

To synthesize experimental results, a temperature model and stream records were combined to characterize the thermal regimes historically tolerated by spring chinook salmon and to predict the likely effects of forest practices on their success. Modelling results provided a basis for interpreting the processes driving temperature, determining temperature-sensitive rivers, and predicting historical stream temperature regimes. Adams and Sullivan (1990) described three conclusions drawn from model results. First, the daily mean stream temperature is always very near the daily mean air temperature when the stream is in equilibrium with the environment. Adams and Sullivan (1990) demonstrated that environmental parameters have little influence on the daily mean stream temperature after an initial heating period. In other words, a maximum equilibrium stream temperature will always be reached where heat loss balances heat gain and no further change in water temperature occurs with increased energy input (Sullivan et al. 1990). However, fluctuations in stream temperature about the mean are strongly influenced by solar insolation, riparian vegetation, and diurnal fluctuations in air temperature. Second, stream depth, the primary geometric parameter affecting thermal inertia, affects both the response time and magnitude of stream temperature fluctuations. Third, groundwater influx is an important factor in the average temperature of small streams (Adams and Sullivan 1990). Based on these conclusions, Sullivan et al. (1990) determined that water temperatures tend to be below air temperature at distances less than 40 km from watershed divide (i.e., the headwaters or upriver extent of the watershed). At distances greater than 40 km, water temperatures tend to be slightly greater than air temperatures, with little change in either parameter. Furthermore, the maximum equilibrium temperature for the river system occurs at approximately 40 km from the watershed divide. They concluded that water temperature was primarily related to air temperature in reaches below the point where a river reaches maximum system equilibrium. Upstream of this location, environmental factors were thought to have a significant effect on stream temperature (e.g., riparian canopy, groundwater input, and groundwater temperature, air temperature, and stream depth).

Model results reflected findings by Sullivan et al. (1990). View factor, mean annual air temperature, groundwater temperature, and stream depth individually and in combination influenced stream reach temperature (Table 4). View factor, mean annual air temperature, and stream depth had the most significant impact on stream temperatures. Although there was little difference between the 24% and the 51% view factor maximum temperatures, at 76% shade, maximum temperature decreased by 3.00°C. However, minimum temperatures decreased as shade decreased from 51% to 24%. Because air/water temperature differentials drive stream temperature, a decrease in air temperature may produce a concomitant decrease in water temperature. Canopy closure can buffer air temperatures near the air/stream interface, and hence, the temperature differential between the two may be less than that found under an open canopy. During the evening and nighttime when air temperatures are coolest, increased energy loss may drive stream temperatures below canopied minimum temperatures. However, TEMPEST may be less accurate for minimum temperatures and may have underpredicted them (Sullivan, personal communication).

Air temperature also influenced stream temperature. A 2.0°C increase in mean annual air temperature produced a 2.02°C increase in maximum stream temperature. As stream temperature moves toward equilibrium with air temperature, mean annual air temperature is extremely important in predicting stream temperature. TEMPEST was also quite sensitive to stream depth. Depth determines the thermal inertia of a stream. As depth was decreased by 1.41m, maximum stream temperature increased by 0.01°C. This minimal change in stream temperature may indicate a common maximum equilibrium temperature. However, as stream depth decreased, the minimum stream temperature decreased by 5.93°C. Decreased stream depth decreased the response time to air temperature extremes and increased the magnitude of temperature fluctuation. As stream depth increased, maximum and minimum stream temperatures decreased by 3.06°C and 3.04°C, respectively. Increased stream depth served to buffer water temperature from maximum and minimum air temperatures.

The parameter with the least overall effect on stream temperature was groundwater temperature. However, stream temperature change did occur in response to groundwater temperature. An increase in groundwater temperature of 2.00°C produced a 1.71°C increase in stream temperature (groundwater inflow = 0.00072 kg m^{-2}). However when the model was adjusted to produce a 4.00°C increase in groundwater temperature, stream temperature actually decreased 1.22°C. Unlikely groundwater predictions may reflect inadequate input data. It is unlikely that groundwater temperature would greatly affect water temperature in large rivers. Large volumes of river water would tend to mask the effect of small volumes of groundwater. As cooler water mixes with large quantities of warmer stream flow the actual area of influence produced by the groundwater may be quite limited. However, this does not decrease the importance of groundwater in establishing thermal refuges or maintaining temperatures in small streams. In addition, groundwater temperature did significantly decrease minimum stream temperatures. A 2.00°C decrease in groundwater temperature produced a decrease in minimum stream temperature of 4.82°C. Although this magnitude of temperature decrease is unlikely, it is not unrealistic to assume that groundwater may lower minimum stream temperatures. As there is no solar input at night groundwater may significantly lower minimum and mean stream temperatures, and hence, may mitigate thermal stress induced by elevated temperatures (Thomas et al. 1986).

Although all parameters affected stream temperature individually, the most significant alteration to stream temperature was from cumulative effects such as might be produced by general habitat degradation. Past studies have indicated that timber harvesting may lead to decreased riparian canopy and stream depth, as well as increased groundwater and local air temperatures (Brown and Krygier 1970; Swift and Baker 1973; Moring and Lantz 1975; Hartman 1982; Hewlett and Fortson 1982; Nooksack Spring Chinook

Technical Group 1987; Meisner 1990). Alteration of these parameter values to reflect possible post-timber harvesting conditions, produced an increase in maximum stream temperature of 6.52°C. Minimum temperatures increased between 0.58° and 4.73°C and mean temperature increased between 3.37 and 4.43°C (View factor = 26%, groundwater temperature = 11.00°C, stream depth = 0.300m). When mean air temperature was also increased (plus 2°C), maximum stream temperature increased by 7.6°C; minimum temperature increased between 1.66 and 5.28°C, and mean temperature increased by 4.98°C.

These results indicate that timber harvesting and other land use alterations that may decrease riparian canopy and stream depth, and/or increase groundwater and mean annual air temperatures may significantly alter stream temperature regimes, and therefore, may expose adult spring chinook salmon to sub-lethal temperatures during freshwater migration. The adult holding study indicated that egg viability and alevin survival may be reduced if adults are exposed to stream temperatures between 17.5 and 19°C. Although radio telemetry results indicated that adult spring chinook salmon were capable of locating thermal refuges, timber harvesting may alter the number and extent of available cool-water sources. At the point where a river reaches the system's maximum equilibrium temperature (approximately 40 km from watershed divide), environmental parameters (riparian canopy, groundwater temperature) exert less influence over stream temperature. However, stream depth would be very important in determining stream response time to air temperature and magnitude of stream temperature fluctuation, as well as in providing deep holding pools. Although a system reaches a maximum equilibrium temperature, decreased depth would decrease response time to maximum temperatures and would increase temperature fluctuation. At points closer to the watershed divide, cumumlative impacts on environmental integrity would have the greatest effect on stream temperature. Hence, timber harvesting and other land use practices may alter the thermal regime of large rivers, as well as small tributaries and cool-water input regions utilized as thermal refuges.

During the past 100 years, land use practices have altered riparian zone and upslope integrity, as well as stream stability (Sedell and Luchessa 1982). These alterations can lead to short and long-term changes to the riparian canopy, mean air temperature, groundwater temperature, and stream depth (Brown and Krygier 1970; Swift and Baker 1973; Moring and Lantz 1975; Hartman 1982; Hewlett and Fortson 1982; Sedell and Luchessa 1982; Swank and Vose 1988; Meisner 1990; Sullivan et al. 1990). Therefore, it is very probable that stream reaches located less than 40 km from divide maintained historical temperatures below current levels. As riparian canopies were removed and sediment entered streams, water temperatures may have increased, exposing adult spring chinook salmon to sub-lethal temperatures. However, stream reaches located greater than 40 km from divide and those at their maximum equilibrium temperature may have always experienced relatively warm temperatures. Therefore, spring chinook salmon and other species such as summer steelhead migrating through these reaches may have adopted homing patterns that allow them to enter these reaches when air temperatures, and hence water temperatures, are low, thereby optimizing thermal regimes. In addition, utilization of thermal refuges produced by groundwater seepage and cool tributaries may allow fish to further conserve energy. Although these lower stream reaches may have historically maintained high summer temperatures, anthropogenic alterations to the environment may have altered spring thermal regimes and thermal refuge availability. Timber harvesting may alter groundwater influx, groundwater temperature, local air temperatures, and stream depth thereby reducing thermal refuge habitat and possibly reducing the viability of spring chinook salmon populations.

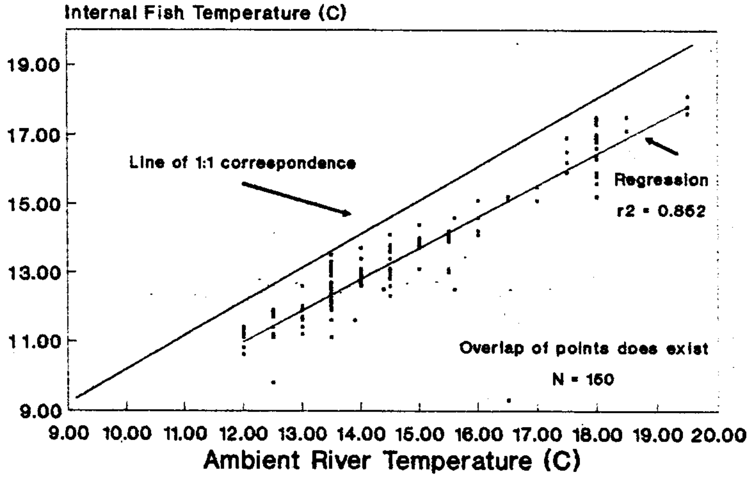

Figure 3: Internal Temperatures of 19 Adult Spring Chinook Salmon Observed Over the Summer in Relation to Ambient River Temperatures.

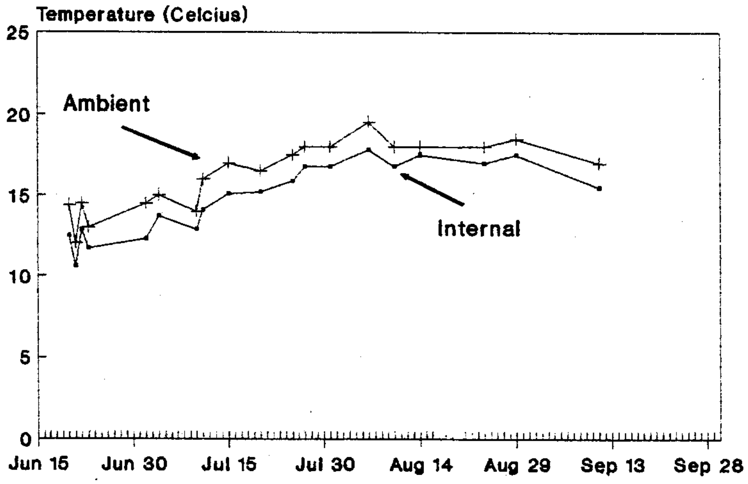

Figure 4: Internal Temperatures of Fish # 5 Observed Over the Summer in Relation to Ambient River Temperatures.

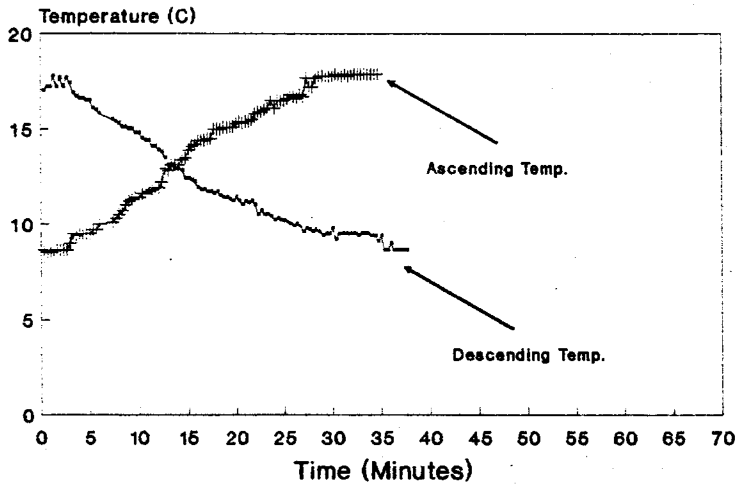

Figure 5: Rate of Temperature Equilibration of a 3.00 kg Chinook Salmon.

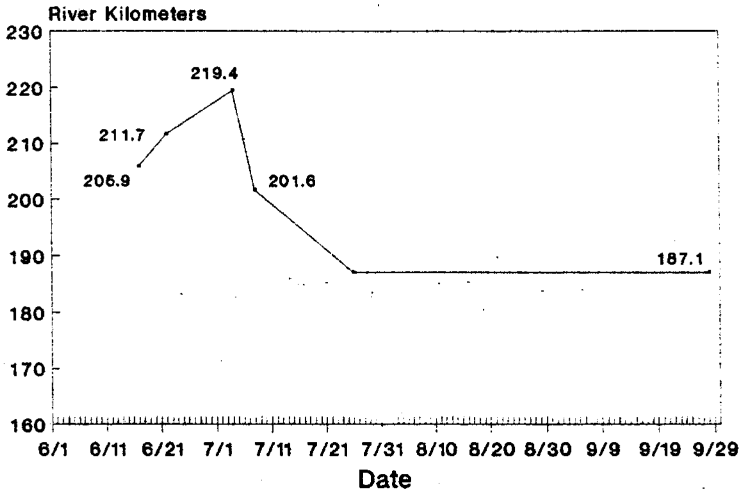

Figure 6: Movement Pattern of a Spring Chinook Salmon (Fish # 6) within the Yakima River System Between 19 June and 28 September 1989.

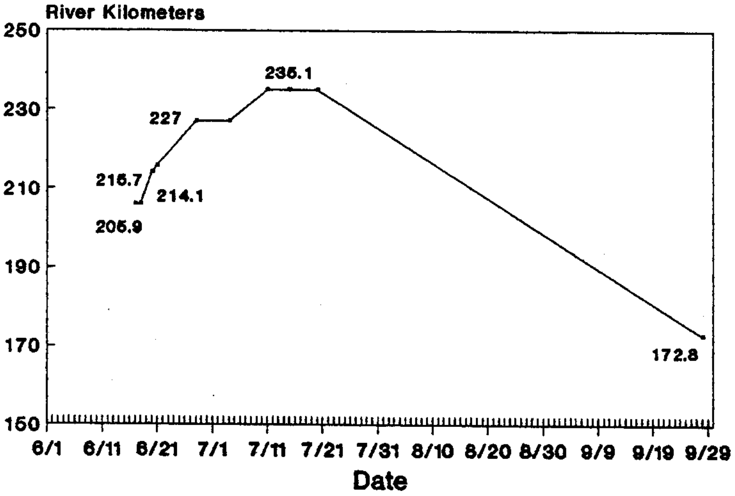

Figure 7: Movement Pattern of a Spring Chinook Salmon (Fish # 16) in the Yakima River System Between 19 June and 28 September 1989.

Table 2: Adult Holding Study Egg, Alevin, and Yolk Sac Measurements.

Measurements	Control (Tank VIII)	Elevated 1 (Tank I)	Elevated 2 (Tank III)
No. of fish	N = 5	N = 6	N = 5
No. of Females	2	3	2
No. of eggs	1,000	1,500	1,000
Female weight	2.76 kg	3.92 kg	3.08 kg
Female length	65.62 cm	72.60 cm	68.75 cm
Eggs/female	3,848	4,263	4,158
Eggs/kg female	1,398.5	1,061.3	1,326.0
Egg mass/kg female	26.4 %	18.5 %	21.2 %
Egg weight	0.185 g	0.170 g	0.165 g
Egg diameter	0.721 cm	0.704 cm	0.690 cm
Egg volume	0.188 ml	0.183 ml	0.170 ml
Yolk wet weight	0.1423 g	0.1479 g	0.1383 g
Yolk dry weight	0.0666 g	0.0703 g	0.0648 g
Alevin wet weight	0.0456 g	0.0431 g	0.0387 g
Alevin dry weight	0.00654 g	0.00586 g	0.00522 g
Alevin length	2.10 cm	1.99 cm	1.96 cm

Mean female weight and length

Egg sample size = 30 eggs

Yolk/Alevin sample size = 10

Table 3: Summary of Spring Chinook Salmon Movement in the Yakima River System Between 19 June and 28 September 1989.

Fish #	No. of Observ.	Total Km Travelled	Net Upriver Travel (km)*	Days Prior to Downstream Move.
1	7	27	-11.5	12
2	20	17.9	17.9	0
3	6	119.5	119.5	0
4	5	46.4	-6.6	7
5	20	25.1	9.8	7
6	5	45.9	-13.5	18
7	8	4.2	0	7
8	22	17	8.2	12
9	7	81.8	-24.3	12
10	6	42	42	0
11	11	75.8	75.8	0
12	9	31.2	-13.5	18
13	21	20.3	9.8	12
14	5	81.8	-24.3	12
15	11	13.5	9.8	5
16	9	91.4	-29.2	34
17	8	91.5	91.5	0
18	4	65.4	-31.6	25
19	13	90.5	90.5	0

* Negative numbers indicate final locations below the release point

Table 4: Stream Reach Temperature Predictions Derived from TEMPEST.

VARIABLE	MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
A. View Factor*			
24%	19.81°C	13.62°C	16.66°C
51%	19.74°C	16.67°C	17.92°C
76%	16.81°C	10.64°C	13.67°C
B. Mean Annual Air Temp.			
13.00°C	18.82°C	12.63°C	15.67°C
11.00°C	19.74°C	16.67°C	17.92°C
9.00°C	17.72°C	11.54°C	14.58°C
C. Groundwater Temp.			
13.00°C	18.52°C	12.33°C	15.37°C
11.00°C	19.74°C	16.67°C	17.92°C
9.00°C	18.03°C	11.85°C	14.88°C
D. Depth			
0.300m	19.75°C	10.74°C	15.09°C
0.441m	19.74°C	16.67°C	17.92°C
0.882m	16.69°C	13.62°C	15.15°C

* View Factor: 100 % = complete shade; 0 % = no shade

Table 4: Stream Reach Temperature Predictions Derived from TEMPEST (continued).

E. Depth (0.300m), View Factor (24%), Groundwater Temp. (13.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
21.53°C	12.52°C	16.86°C

F. Depth (0.441m), View Factor (51%), Groundwater Temp. (11.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
19.74°C	16.67°C	17.92°C

G. Depth (0.882m), View Factor (76%), Groundwater Temp. (9.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
15.01°C	11.94°C	13.49°C

H. Depth (0.300m), View Factor (24%), Groundwater Temp.(13.00°C), Mean Air Temp.(13.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
22.06°C	13.05°C	17.39°C

I. Depth (0.441m), View Factor (51%), Groundwater Temp.(11.00°C), Mean Air Temp.(11.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
19.74°C	16.67°C	17.92°C

J. Depth (0.882m), View Factor (76%), Groundwater Temp. (9.00°C), Mean Air Temp. (9.00°C):

MAX. TEMP.	MIN. TEMP.	MEAN TEMP.
14.46°C	11.39°C	12.94°C

SUMMARY AND CONCLUSIONS

The relationship between spring chinook salmon reproductive success and logging-related temperature elevations was addressed in a series of studies evaluating physiological and behavioral responses to elevated stream temperatures. The adult holding study provided information on the effects of pre-spawning sub-lethal temperatures on subsequent embryo and alevin survival. The elevated temperature treatment group had greater numbers of pre-hatch mortalities and developmental abnormalities. In addition, females held at elevated temperatures produced smaller eggs and alevins. While the small sample size precluded statistical analysis of results, the data suggest that mature spring chinook salmon exposed to sub-lethal elevated temperatures may produce eggs of decreased viability even though eggs are incubated under optimum conditions. Mortalities within the redd may significantly decrease spring chinook salmon populations. In addition, decreased alevin weight and length at emergence may decrease fry survival through effects on swimming performance, vulnerability to predators, and subsequent growth (Holtby 1988; Murray and McPhail 1988; Holtby et al. 1989). Furthermore, energy stores which are rapidly depleted between late summer and early winter could decrease the overwintering survival of unusually small fry (Cunjak and Power 1987; Cunjak 1988).

Early life history parameters have been identified as possible mechanisms by which fry emergence timing is regulated (Brannon 1987; Linley 1988; Murray and McPhail 1988). Alteration of these events through sub-lethal temperature effects may lead to altered fry migration timing and/or smaller progeny. If mechanisms controlling temporal patterns in salmonid behavior exist to achieve synchronized emergence with environmental events, alterations to this temporal sequence through alteration of egg and alevin size could have an adverse effect on spring chinook salmon populations.

Radio telemetry results demonstrated that Yakima River spring chinook salmon behaviorally thermoregulated. Fish appeared to hold within the Yakima Canyon where energy benefits derived from cold-water refuge areas may be maximized. In spring chinook salmon, as with other poikilotherms, river temperature increases lead to basal metabolic rate increases. Therefore, less energy may be allocated to gamete production and other behavioral and physiological events associated with reproduction. The salmon temporarily halted their spawning migration to reside in cold-water, low velocity refuge areas, allowing them to conserve energy for gamete production, mate selection, redd construction, spawning, and redd guarding by females. In addition, the equilibration rate study demonstrated that adult chinook salmon display resistance to internal temperature fluctuation, and hence, may maintain energy benefits derived from cool-water refuge areas for an extended period, the length of which is size dependent.

Results derived from both experimental manipulation and field studies indicate a) egg and alevin survival may decrease due to adult exposure to sub-lethal elevated temperatures and b) adult Yakima River spring chinook salmon are capable of behavioral thermoregulation. However data generated from the TEMPEST model indicate that these results require cautious interpretation. Although spring chinook salmon holding in freshwater may be capable of mitigating sub-lethal temperature effects through use of cold-water refuge areas, these areas need to be abundant and available to the fish. It has been suggested that subsurface flow may play a large role in stream temperature modification and thermal refuge formation (Swift and Baker 1973; Hewlett and Fortson 1982; Meisner 1990; Sullivan et al. 1990). Previous studies indicate that subsurface water temperatures may become elevated due to land use alterations, such as timber harvesting, that require removal of vegetation (Hewlett and Fortson 1982; Meisner 1990; Sullivan et al. 1990). Subsurface flow and water contained in shallow storage areas may become elevated due to increased soil temperatures following vegetation removal (Swank and Vose 1988). In addition to subsurface seepage, small tributaries serve as thermal refuges (Kaya et al. 1977). As tributaries tend to be small and may be ephemeral, they are difficult to protect from land use alterations. However, they serve important functions as both thermal refuges and moderators of downstream temperature. Because the thermal regime of a river can vary substantially over time and because these differences in temperature can be increased by anthropogenic alterations, the duration of stressful conditions and the availability of suitable refuges may determine a population's survival (Coutant and Carroll 1980).

Although a river system may provide cold-water refuge areas, elevated temperatures may be experienced by fish on the spawning grounds or in intermittent areas with few refuge sites. If pre-spawning holding temperatures are critical to offspring survival, it is important to document temperature regimes experienced by adults during freshwater migration. Fish exposed to sub-lethal elevated temperatures maintain elevated basal and active metabolic rates, and hence, may have decreased energy reserves available for successful reproduction. Elevated temperatures may have a more profound effect on female survival due to the disproportionate expenditure of energy between males and females prior to spawning (Gilhousen 1980). In addition, prolonged exposure to elevated temperatures may weaken the fish's ability to resist infection or infestation. Thermal protection of spawning and incubation reaches alone may not be adequate to protect spring chinook salmon populations. Land use management plans should identify and protect mainstem adult holding sites as well.

The following areas have been identified for further investigation prior to formulation of management plans and regulations regarding thermal sensitivity of spring chinook salmon:

a) Does timber harvest alter the availability of cool water sources (e.g., a reduction of thermal refuges through temperature elevation of subsurface water supplies or small tributaries) and additionally are certain sources more sensitive to timber harvesting practices?

b) Are cool water sources limited? How much variation is there in number and type of thermal refuge areas across river systems?

c) How are cool water sources identified within a river system for management purposes?

d) How are habitat requirements of pre-spawning salmon incorporated into management plans?

LIST OF REFERENCES

ADAMS, T., and K. SULLIVAN. 1990. The physics of forest stream heating: a simple model. Weyerhaeuser Technical Report.

ARMY CORPS OF ENGINEERS. 1989. Annual fish passage report: Columbia and Snake Rivers for salmon, steelhead and shad. North Pacific Division Corps of Engineers, U. S. Army Engineer District Portland and Walla Walla.

BALLARD, W. W. 1973. Normal embryonic stages for salmonid fishes, based on Salmo gairdneri Richardson and Salvelinus fontinalis (Mitchill). J. Exp. Zool. 184: 7-26.

BARDACH, J. E., and R. G. BJORKLUND. 1957. The temperature sensitivity of some American freshwater fishes. Amer. Natur. 91: 233-251.

BEACHAM, T. D., and C. B. MURRAY. 1986a. Effect of female size, egg size, and water temperature on developmental biology of chum salmon (Oncorhynchus keta) from the Nitinat River, British Columbia. Can. J. Fish. Aquat. Sci. 42: 1755-1765.

BEACHAM, T. D., and C. B. MURRAY. 1986b. Comparative developmental biology of pink salmon Oncorhynchus gorbuscha, in Southern British Columbia. J. Fish Biol. 28: 233-246.

BEITINGER, T. L. 1976. Behavioral thermoregulation by bluegill exposed to various rates of temperature change. pp. 176-179. In: G. W. Esch and R. W. McFarlane (ed.) Thermal Ecology II, U. S. National Technical Information Service, Springfield.

BESCHTA, R. L., R. E. BILBY, G. W. BROWN, L. B. HOLTBY, and T. D. HOFSTRA. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. pp. 191-232. In: E. O. Salo and T. W. Cundy (ed.) Streamside Management: Forestry and Fishery Interactions, Institute of Forest Resources, University of Washington.

BILBY, R.E. 1984. Characteristics and frequency of cool-water areas in a Western Washington stream. J. Freshwater Ecol. 2: 593-602.

BOUCK, G. R., G. A. CHAPMAN, P. W. SCHNEIDER, and D. G. STEVENS. 1975. Effects of holding temperatures on reproductive development in adult sockeye salmon (Oncorhynchus nerka). pp. 24-40. In: J. R. Donaldson (ed.) 26th Annual Northwest Fish Culture Conference, Otter Creek, Oregon.

BRANNON, E. L. 1987. Mechanisms stabilizing salmonid fry emergence timing. Can. Spec. Publ. Fish. Aquat. Sci. 96: 120-124.

BRETT, J. R. 1952. Temperature tolerance in young Pacific salmon, Genus Oncorhynchus. J. Fish. Res. Bd. Can. 9: 265-323.

BRETT, J. R. 1965a. The relation of size to rate of oxygen consumption and sustained swimming speed of sockeye salmon (Oncorhynchus nerka). J. Fish. Res. Bd. Can. 22: 1491-1501.

BRETT, J. R. 1965b. The swimming energetics of salmon. Sci. Amer. 213 (2): 80-85.

BRETT, J. R. 1967. Swimming performance of sockeye salmon (Oncorhynchus nerka) in relation to fatigue time and temperature. J. Fish. Res. Bd. Can. 24: 1731-1741.

BRETT, J. R. 1970. Fishes - metabolism and activity. p. 538. In: O. Kinne (ed.) A Comprehensive, Integrated Treatise on Life in Oceans and Coastal Waters, Vol. 1, Part I, Wiley-Interscience.

BRETT, J. R., and N. R. GLASS. 1973. Metabolic rates and critical swimming speeds of sockeye salmon (Oncorhynchus nerka) in relation to size and temperature. J. Fish. Res. Bd. Can. 30: 379-387.

BROWN, G. W., and J. T. KRYGIER. 1970. Effects of clearcutting on stream temperature. Water Resour. Res. 6: 1133-1139.

BURGER, C. V., R. L. WILMOT, and D. B. WANGAARD. 1985. Comparison of spawning areas and times for two runs of chinook salmon (Oncorhynchus tshawytscha) in the Kenai River, Alaska. Can. J. Fish. Aquat. Sci. 42: 693-700.

CLAIR, J. B., J. R. SPOTILA, E. A. STANDORA, and J. W. GIBBONS. 1984. Behavioral thermoregulation of largemouth bass, Micropterus salmoides, and bluegill, Lepomis macrochirus, in a nuclear cooling reservoir. Env. Biol. Fishes 11: 41-52.

COMBS, B. D. 1965. Effect of temperature on the development of salmon eggs. Prog. Fish-Cult. 27: 134-137.

COUTANT, C. C. 1969. Behavior of a sonic-tagged chinook salmon and steelhead trout migrating past Hanford thermal discharges. pp. 21-26. In: Biological Effects of Thermal Discharges: Annual Progress Report for 1968. AEC Research and Development Report, Battelle Memorial Institute Pacific Northwest Laboratories, Richland, Washington, BNWL-1050.

COUTANT, C. C., C. D. BECKER, E. F. PRENTICE. 1969. Passage of downstream migrants. pp. 9-12. In: Biological Effects of Thermal Discharges: Annual Progress Report for 1968. AEC Research and Development Report, Battelle Memorial Institute Pacific Northwest Laboratories, Richland, Washington, BNWL-1050.

COUTANT, C. C., and D. S. CARROLL. 1980. Temperatures occupied by ten ultrasonic-tagged striped bass in freshwater lakes. Trans. Am. Fish. Soc. 109: 195-202.

CUNJAK, R. A. 1988. Physiological consequences of overwintering in streams: the cost of acclimatization? Can. J. Fish. Aquat. Sci. 45: 443-452.

CUNJAK, R. A., and G. POWER. 1987. The feeding and energetics of stream-resident trout in winter. J. Fish Biol. 31: 493-511.

DONG, J. N. 1981. Thermal tolerance and rate of development of coho salmon embryos. Master's thesis. University of Washington.

FAST, D. E. 1988. Spring and summer chinook spawning ground surveys Yakima and Wenatchee Rivers. Yakima Indian Nation. Fisheries Resource Management.

FISCHER, R. U., E. A. STANDORA, and J. R. SPOTILA. 1987. Predator-induced changes in thermoregulation of bluegill, Lepomis macrochirus, from a thermally altered reservoir. Can. J. Fish. Aquat. Sci. 44: 1629-1634.

FLEMING, I. A., and S. NG. 1987. Evaluation of techniques for fixing, preserving, and measuring salmon eggs. Can. J. Fish. Aquat. Sci. 44: 1957-1962.

FRY, F. E. J. 1957. The aquatic respiration of fish. pp. 1-63. In: M. E. Brown (ed.) The Physiology of Fishes, Vol. 1, Metabolism, Academic Press, Inc., New York.

FRY, F. E. J. 1971. The effects of environmental factors on the physiology of fish. pp. 1-98. In: W. S. Hoar and D. J. Randall (eds.). Fish Physiology, Vol. 6, Academic Press, Inc., New York.

FULTON, L. A. 1968. Spawning areas and abundance of chinook salmon (Oncorhynchus tshawytscha) in the Columbia River basin-past and present. U.S. Fish and Wildlife Service, Special Scientific Report, Fisheries No. 571.

GARLING, D. L., and M. MASTERSON. 1985. Survival of Lake Michigan chinook salmon eggs and fry incubated at three temperatures. Prog. Fish-Cult. 47: 63-66.

GIBBONS, J. W., and R. R. SHARITZ. 1981. Thermal ecology: environmental teachings of a nuclear reactor site. BioScience 31: 293-298.

GILHOUSEN, P. 1980. Energy sources and expenditures in Fraser River sockeye salmon during their spawning migration. International Pacific Salmon Fisheries Commission Bulletin 22: 34-39.

GORDON, M. R., K. C. KLOTINS, V. M. CAMPBELL, M. M. COOPER. 1987. Farmed salmon broodstock management. B. C. Research, Ministry of the Environment, Industrial Research Assistance Program, National Research Council of Canada, Victoria, B. C.

GRANSTRAND, R. L., and J. D. GIBSON. 1981. Third year Skagit River spring chinook radio-tracking study 1981. Skagit System Cooperative. LaConner, Washington.

HANKIN, D. G., and M. C. HEALEY. 1986. Dependence of exploitation rates for maximum yield and stock collapse on age and sex structure of chinook salmon (Oncorhynchus tshawytscha) stocks. Can. J. Fish. Aquat. Sci. 43: 1746-1759.

HANSEN, J., I. FUNG, A. LACIS, D. RIND, S. LEBEDEFF, R. RUEDY, G. RUSSELL, and P. STONE. 1988. Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. J. Geophys. Res. 93: 9341-9364.

HARTMAN, G. (Ed.). 1982. Proceedings of the Carnation Creek Workshop, a 10 Year Review. Malaspina College, Nanaimo, British Columbia.

HAWKINS, A. D., and G. W. SMITH. 1986. Radio-tracking observations on Atlantic Salmon ascending the Aberdeenshire Dee. Department of Agriculture and Fisheries for Scotland, Scottish Fisheries Research Report Number 36.

HEMING, T. A. 1982. Effects of temperature on utilization of yolk by chinook salmon (Oncorhynchus tshawytscha) eggs and alevins. Can. J. Fish. Aquat. Sci. 39: 184-190.

HEWLETT, J. D., and J. C. FORTSON. 1982. Stream temperature under an inadequate buffer strip in southeast Piedmont. Water Resour. Bull. 18: 983-988.

HISS, J. M., P. E. BIGELOW, and S. R. HAGER. 1990. Pre-spawning adult distribution of Queets River spring-summer chinook and feasibility of radio telemetry to study adult in-river migration. Fisheries Assistance Office, U.S. Fish and Wildlife Service, Olympia, Washington.

HOLTBY, L. B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (Oncorhynchus kisutch). Can. J. Fish. Aquat. Sci. 45: 502-515.

HOLTBY, L. B., T. E. MCMAHON, and J. C. SCRIVENER. 1989. Stream temperatures and inter-annual variability in the emigration timing of coho salmon (Oncorhynchus kisutch) smolts and fry and chum salmon (O. keta) fry from Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. 46: 1396-1405.

KAMLER, E., and T. KATO. 1983. Efficiency of yolk utilization by Salmo gairdneri in relation to incubation temperature and egg size. Pol. Arch. Hydrobiol. 30: 271-306.

KAYA, C. M., L. R. KAEDING, and D.E. BURKHALTER. 1977. Use of a cold-water refuge by rainbow and brown trout in a geothermally heated stream. Prog. Fish-Cult. 39: 37-39.

LINLEY, T. J. 1988. Maternal influences upon embryonic development in chinook salmon (Oncorhynchus tshawytscha). Master's thesis. University of Washington.

LISCOM, K. L., G. E. MONAN, and L. C. STUEHRENBERG. 1977. Radio-tracking studies of spring chinook salmon in relation to evaluating potential solutions to the fallback problem and increasing the effectiveness of the powerhouse collection system at Bonneville Dam, 1976. p. 37. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Servive, Northwest and Alaska Fisheries Center, Seattle, WA.

LOUGH, M. J. 1983. Radio telemetry studies of summer steelhead trout in the Cranberry, Kispiox, Kitwanga and Zymoetz Rivers and Toboggan Creek, 1980. British Columbia Fish and Wildlife Branch, Smithers, British Columbia, Skeena Fisheries Report # 80-04.

MCCAULEY, R. and N. HUGGINS. 1976. Behavioral thermoregulation by rainbow trout in a temperature gradient. pp. 171-175. In: G. W. Esch and R. W. McFarlane (ed.) Thermal Ecology II, U. S. National Technical Information Service, Springfield.

MEDVICK, P. A., J. J. MAGNUSON, and S. SHARR. 1981. Behavioral thermoregulation and social interactions of bluegills, Lepomis macrochirus. Copeia 1981: 9-13.

MEISNER, J. D. 1990. Effect of climatic warming on the southern margins of the native range of brook trout, Salvelinus fontinalis. Can. J. Fish. Aquat. Sci. 47: 1065-1070.

MILLIGAN, P. A., W. O. RUBLEE, D. D. CORNETT, and R. A. C. JOHNSTON. 1984. The distribution and abundance of chinook salmon (Oncorhynchus tshawytscha) in the upper Yukon River Basin as determined by a radio-tagging and spaghetti tagging program: 1982-1983. Can. Tech. Rep. of Fish. and Aquat. Sci. No. 1352

MORING, J. R., and LANTZ, R. L. 1975. Alsea watershed study: part I, biological studies. Fish. Res. Rep. No. 9, Oregon Department of Fish and Wildlife.

MURRAY, C. B., and J. D. MCPHAIL. 1988. Effect of temperature on the development of five species of Pacific salmon (Oncorhynchus) embryos and alevins. Can. J. Zool. 66: 266-273.

NEITZEL, D. A., and C. D. BECKER. 1985. Tolerance of eggs, embryos, and alevins of chinook salmon to temperature changes and reduced humidity in dewatered redds. Trans. Am. Fish. Soc. 114: 267-273.

NOOKSACK SPRING CHINOOK TECHNICAL GROUP. 1987. K. Doughty (ed.) Nooksack River spring chinook technical report. p. 39.

OLSON, P. A., and R. F. FOSTER. 1955. Temperature tolerance of eggs and young of Columbia River chinook salmon. Trans. Am. Fish. Soc. 85: 203-207.

OLSON, P. A., and R. E. NAKATANI. 1969. Effects of chronic variable water temperatures on survival and growth of young chinook salmon. pp. 17-20. In: Biological Effects of Thermal Discharges: Annual Progress Report for 1968. AEC Research and Development Report, Battelle Memorial Institute Pacific Northwest Laboratories, Richland, Washington, BNWL-1050.

POST, G. 1987. Textbook of Fish Health. T.F.H. Publications, Inc., N. J. pp. 51-54.

QUINN, T. P., and K. FRESH. 1984. Homing and straying in chinook salmon (Oncorhynchus tshawytscha) from Cowlitz River Hatchery, Washington. Can. J. Fish. Aquat. Sci. 41: 1078-1082.

REEVES, G. H., F. H. EVEREST, and J. D. HALL. 1987. Interactions between the redside shiner (Richardsonius balteatus) and the steelhead trout (Salmo gairdneri) in Western Oregon: the influence of water temperature. Can. J. Fish. Aquat. Sci. 44: 1603-1613.

RICKER, W. E., and A. ROBERTSON. 1935. Observations on the behavior of adult sockeye salmon during the spawning migration. Can. Field-Nat. 49: 132-134.

RINGLER, N. H., and J. D. HALL. 1975. Effects of logging on water temperature and dissolved oxygen in spawning beds. Trans. Am. Fish. Soc. 104: 111-121.

SEDELL, J. R., and K. J. LUCHESSA. 1982. Using the historical record as an aid to salmonid habitat enhancement. Symposium on Acquisition and Utilization of Aquatic Habitat Inventory Information, Portland, Oregon, Oregon State University, Corvallis.

SMITH, C. E., W. P. DWYER, and R. G. PIPER. 1983. Effect of water temperature on egg quality of cutthroat trout. Prog. Fish-Cult. 43: 176-178.

SPENCE, C. R. 1981. Radio telemetry and mark recovery assessment of adult summer run steelhead in the Chilcotin River system, 1979-1980. Ministry of Environment, Fish and Wildlife Branch, Williams Lake, British Columbia.

SPIGARELLI, S. A., G. P. ROMBERG, W. PREPEJCHAL, and M. M. THOMMES. 1974. Body-temperature characteristics of fish at a thermal discharge on Lake Michigan. pp. 119-132. In: J. W. Gibbons and R. R. Sharitz (ed.) Thermal Ecology, U.S. Atomic Energy Commission, Oakridge.

STRANGE, R. J. 1980. Acclimation temperature influences cortisol and glucose concentrations in stressed channel catfish. Trans. Am. Fish. Soc. 109: 298-303.

SULLIVAN, K., J. TOOLEY, K. DOUGHTY, J. CALDWELL, and P. KNUDSEN. 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Final Report. Timber/Fish/Wildlife Temperature Work Group. In press.

SWANK, W. T., and J. M. VOSE. 1988. Effects of cutting practices on microenvironment in relation to hardwood regeneration. pp. 71-88. Workshop Proceedings: Guidelines for Regenerating Appalachian Hardwood Stands, May 24-26, 1988, WV. Southeastern Forest Experiment Station, USDA Forest Service.

SWIFT, L. W., and S. E. BAKER. 1973. Lower water temperatures within a streamside buffer strip. Southeastern Forest Experiment Station, Asheville, N. C. U. S. Department of Agriculture Forest Service Research Note SE-193.

TANG, J., M. D. BRYANT, and E. L. BRANNON. 1987. Effect of temperature extremes on the mortality and development rates of coho salmon embryos and alevins. Prog. Fish-Cult. 49: 167-174.

THOMAS, R. E., J. A. GHARRET, M. G. CARLS, S. D. RICE, A. MOLES, and S. KORN. 1986. Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon. Trans. Am. Fish. Soc. 115: 52-59.

WAMPLER, P. L. 1984. Radio telemetry assessment of adult summer run steelhead behavior following release in the upper Elwha River. Fisheries Assistance Office, U. S. Fish and Wildlife Service, Olympia, Washington.

WEDEMEYER, G. A., and C. P. GOODYEAR. 1984. Diseases caused by environmental stressors. pp. 424-434. In: O. Kinne (ed.) Diseases of Marine Animals, Hamburg, Federal Republic of Germany.

WOOTTON, R. J. 1990. Ecology of Teleost Fishes. Chapman and Hall, New York.

WRENN, W. B. 1976. Temperature preference and movement of fish in relation to a long, heated discharge channel. pp. 191-194. In: G. W. Esch and R. W. McFarlane (ed.) Thermal Ecology II, U. S. National Technical Information Service, Springfield.

Appendix A: Behavioral Thermoregulation and Fish Movement

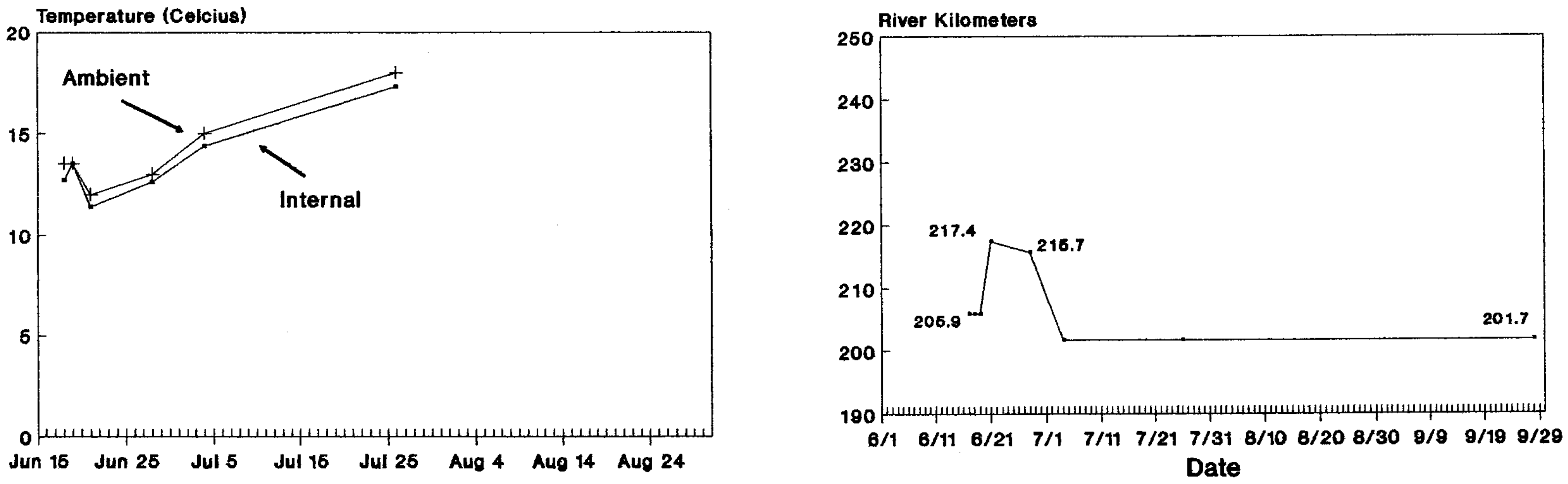

Figure 8: Fish # 1

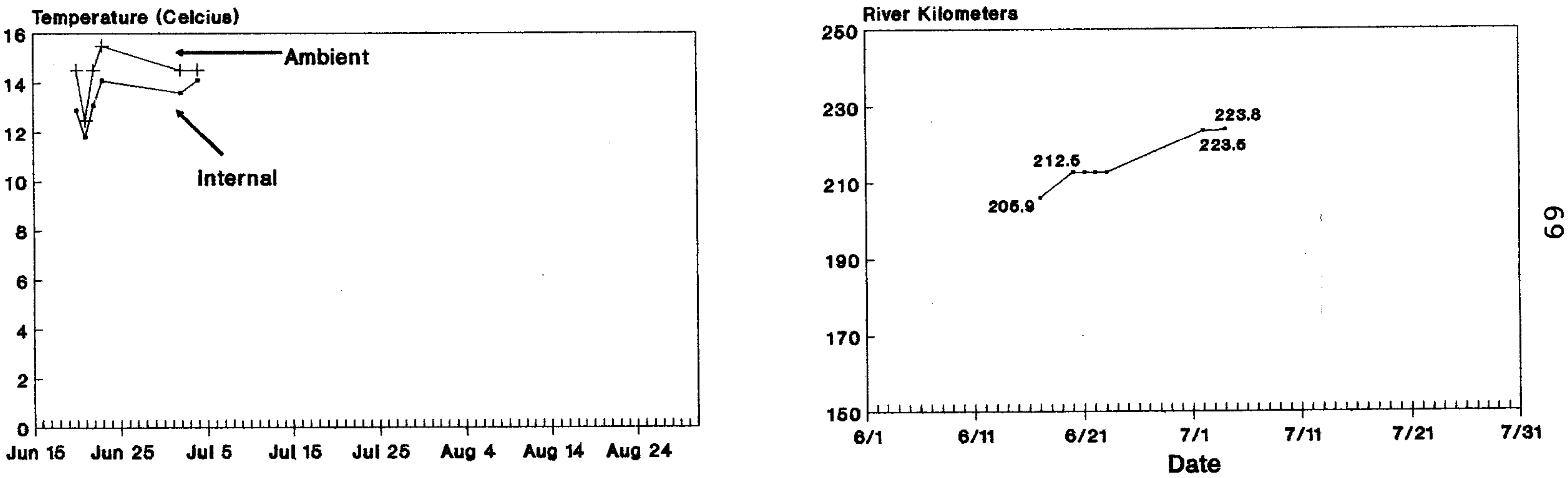

Figure 9: Fish # 2

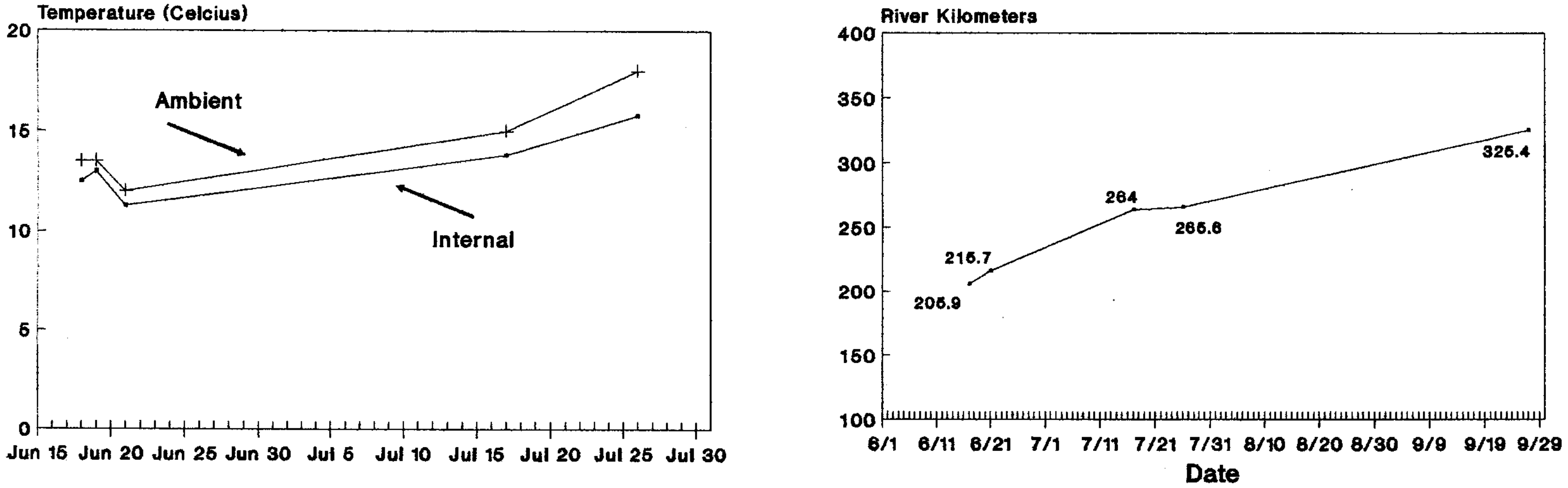

Figure 10: Fish # 3

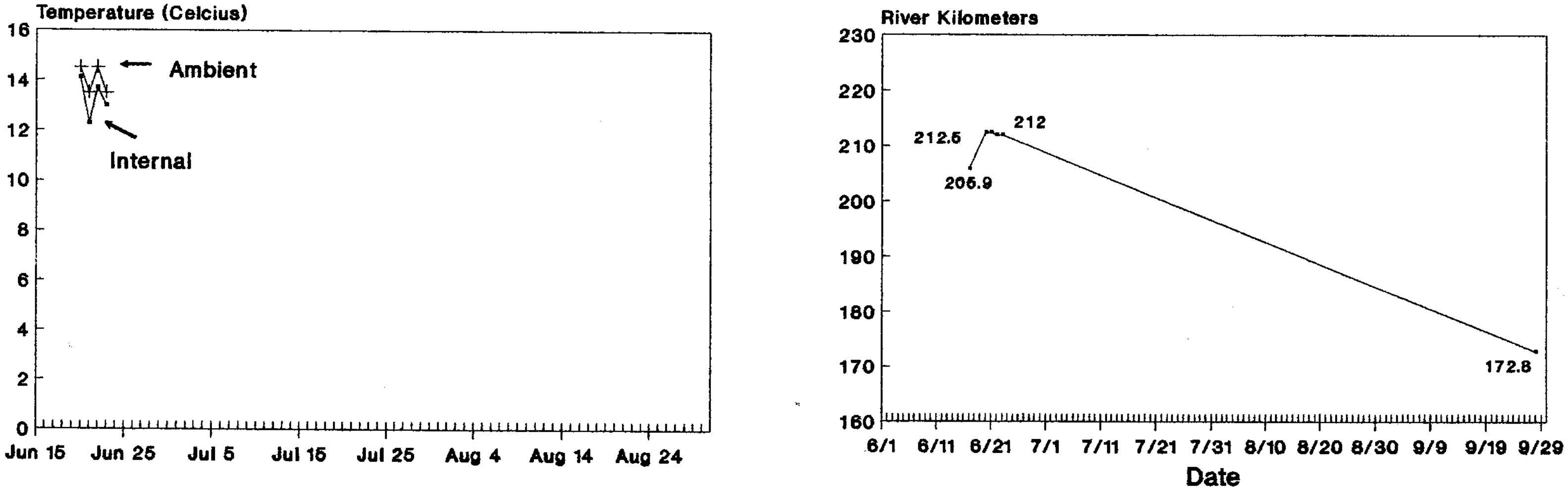

Figure 11: Fish # 4

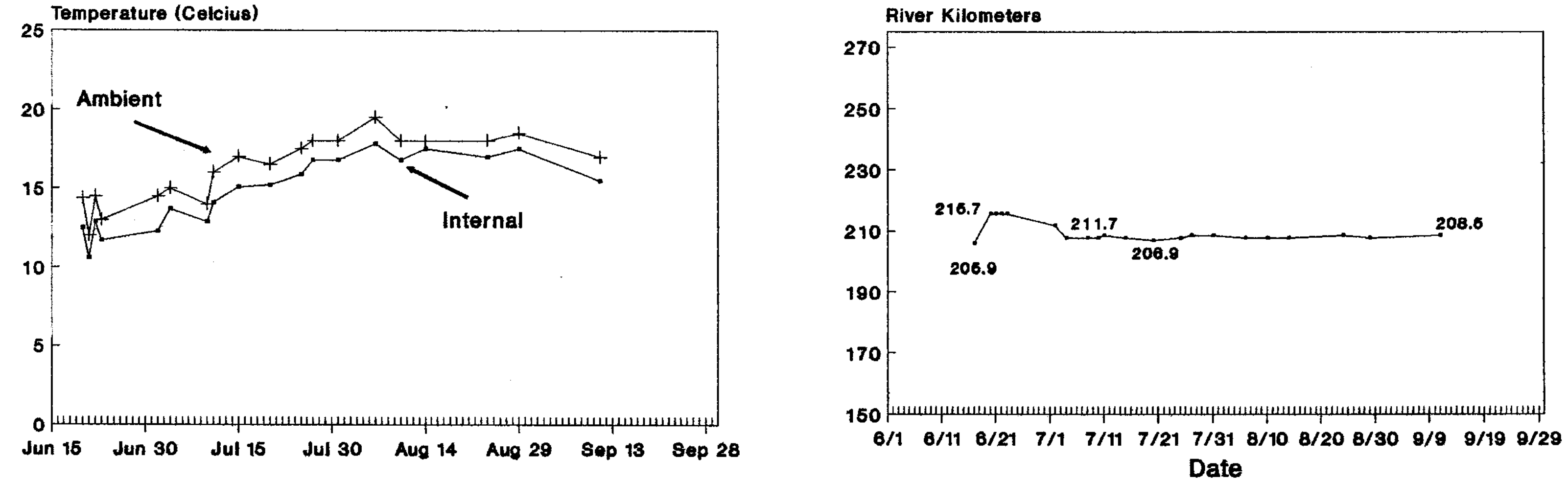

Figure 12: Fish # 5

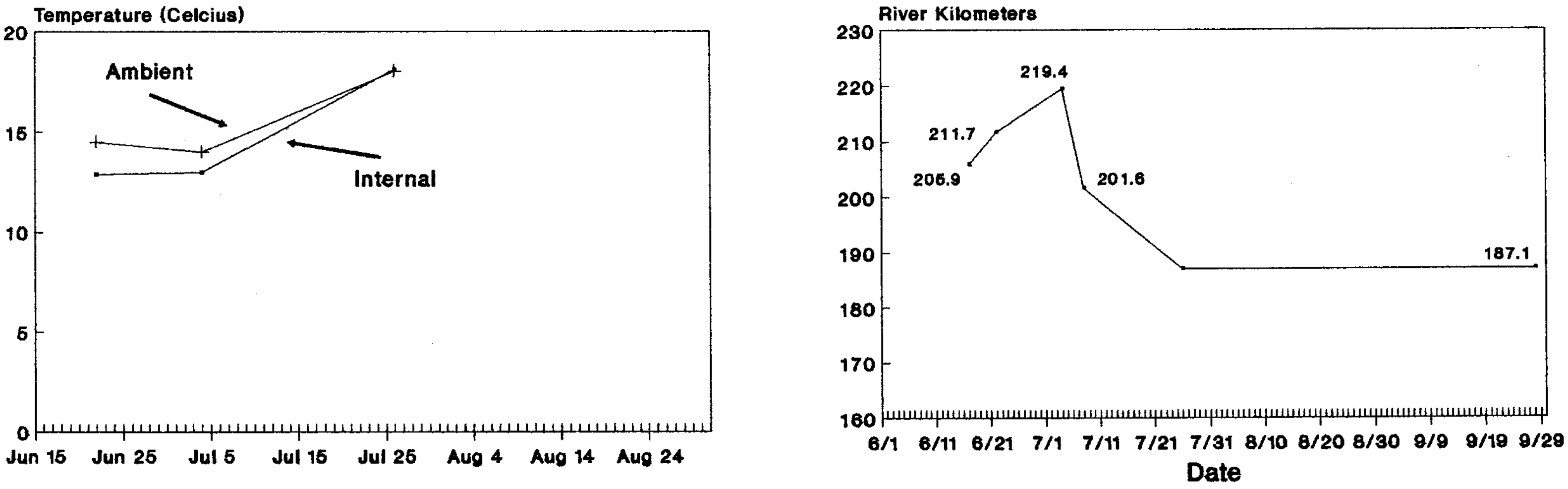

Figure 13: Fish # 6

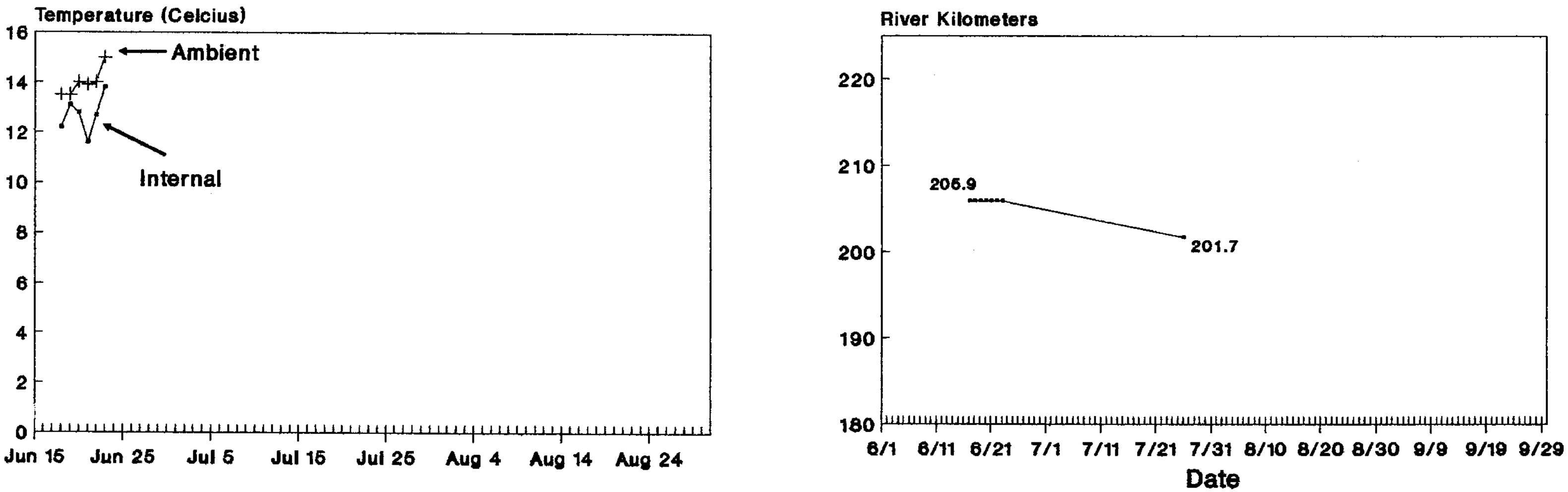

Figure 14: Fish # 7

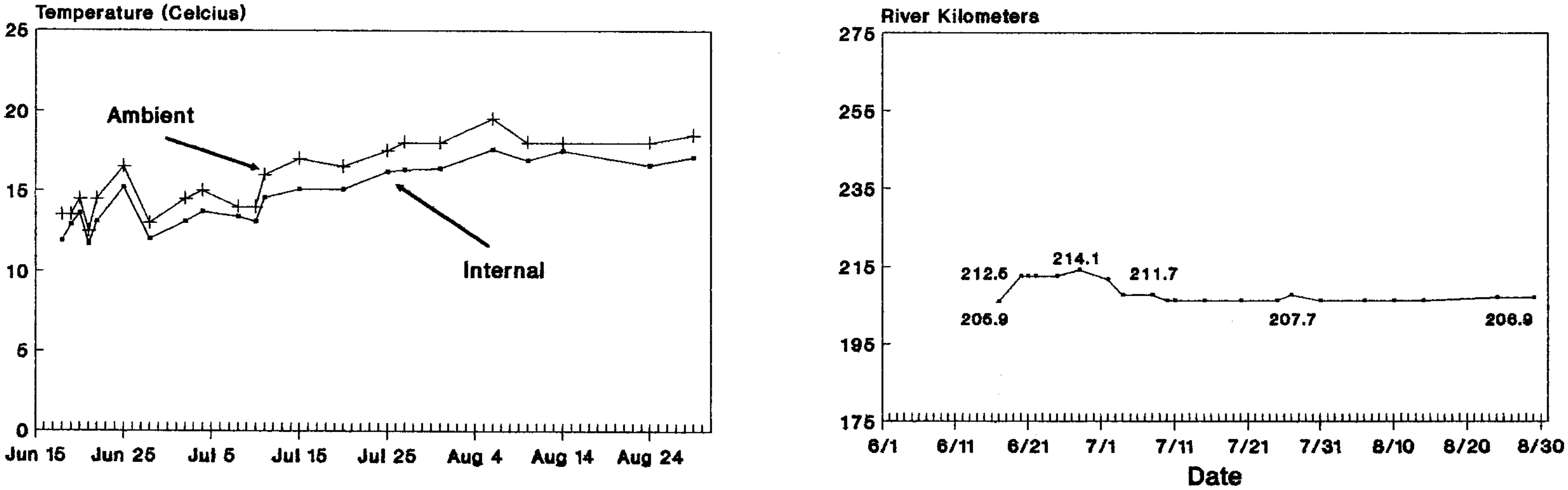

Figure 15: Fish # 8

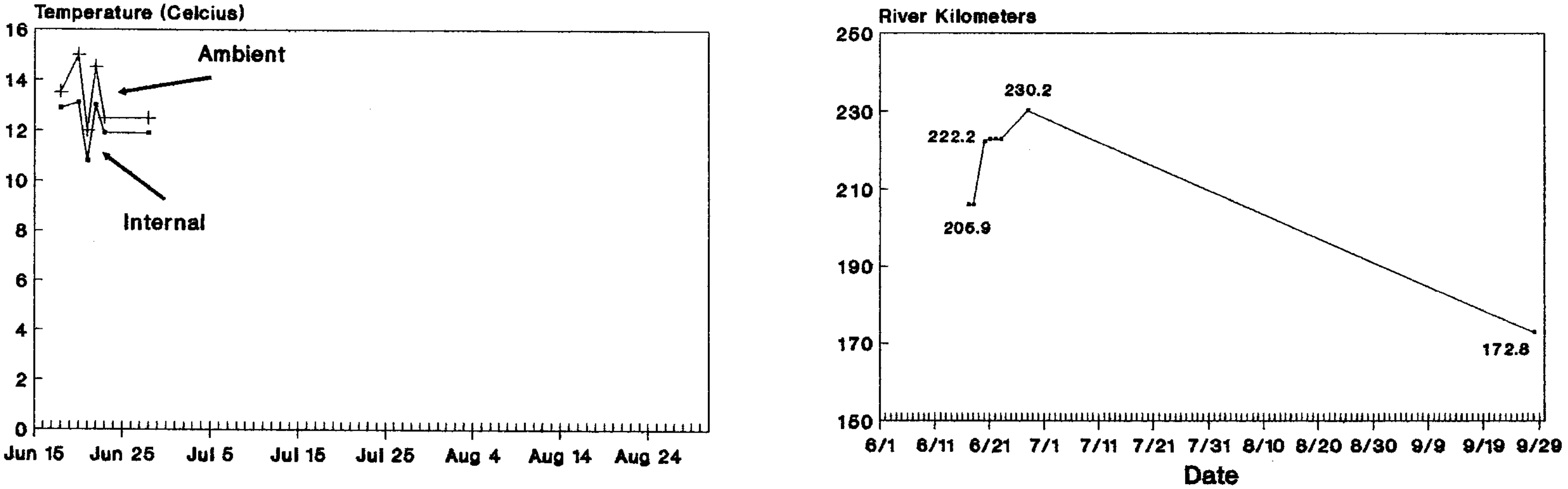

Figure 16: Fish # 9

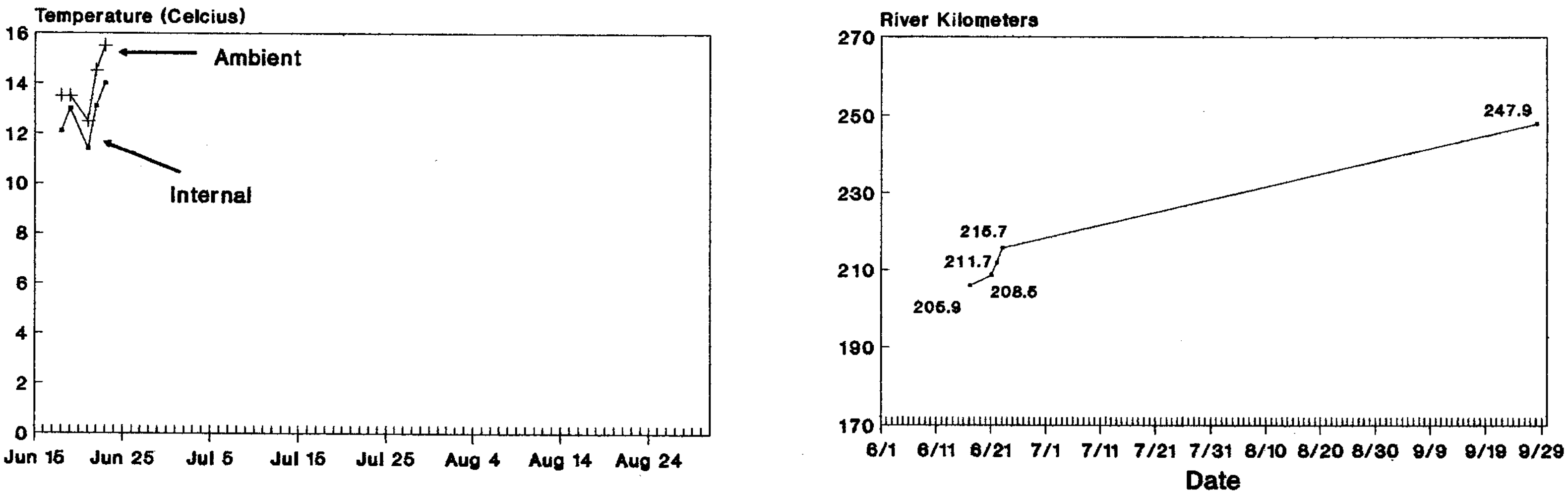

Figure 17: Fish # 10

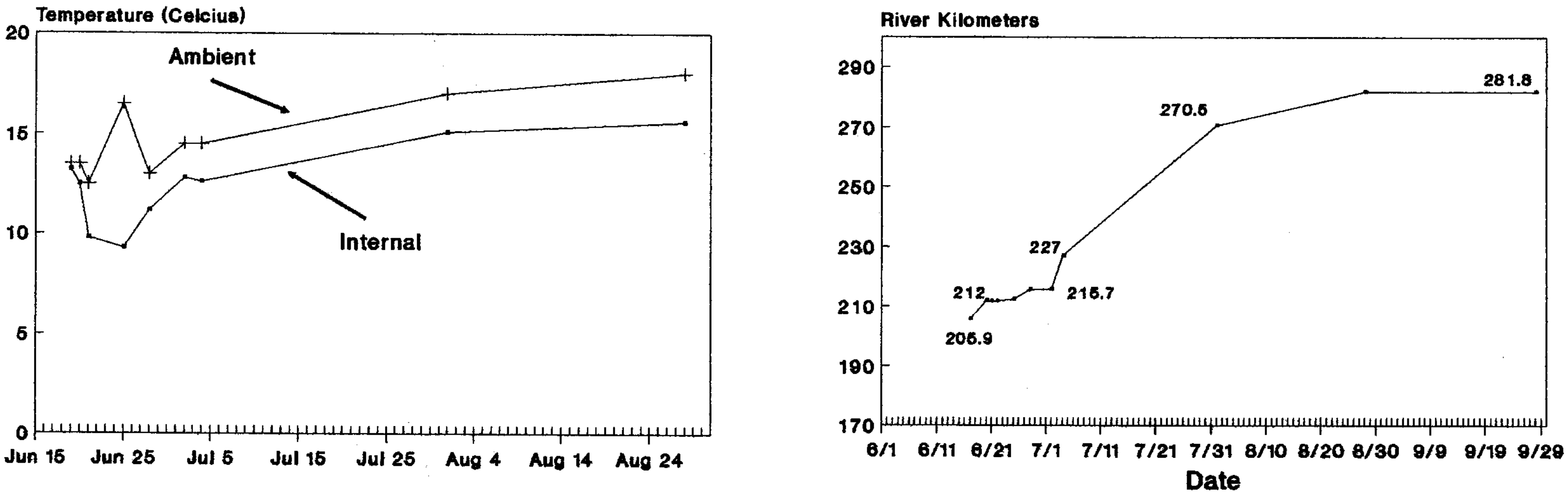

Figure 18: Fish # 11

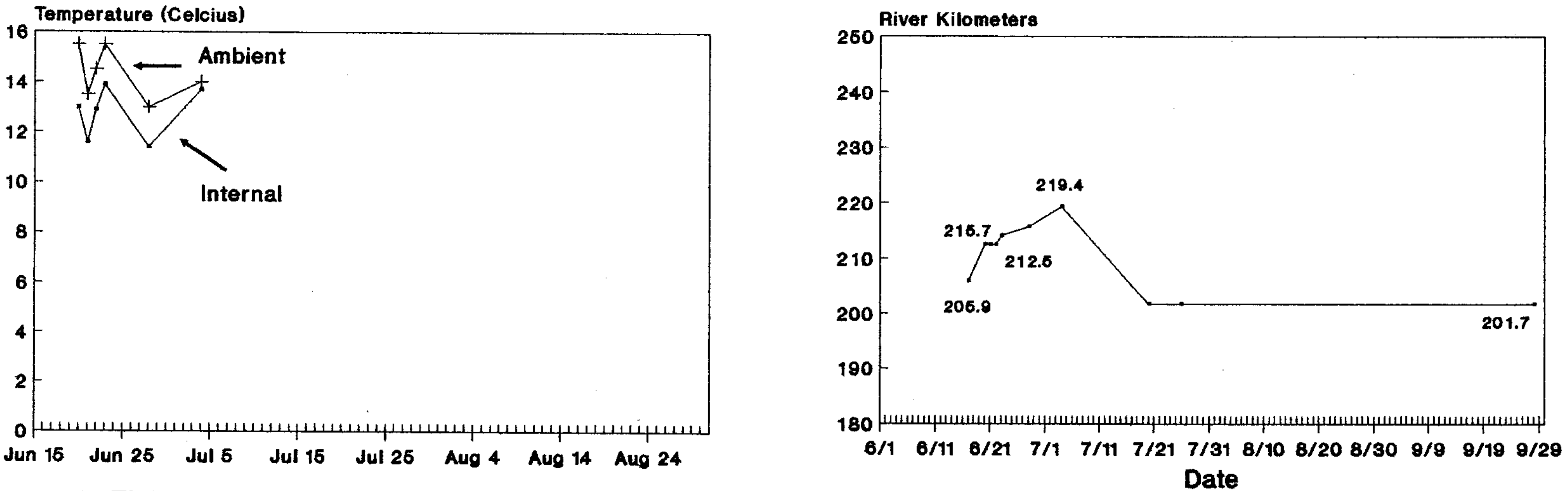

Figure 19: Fish # 12

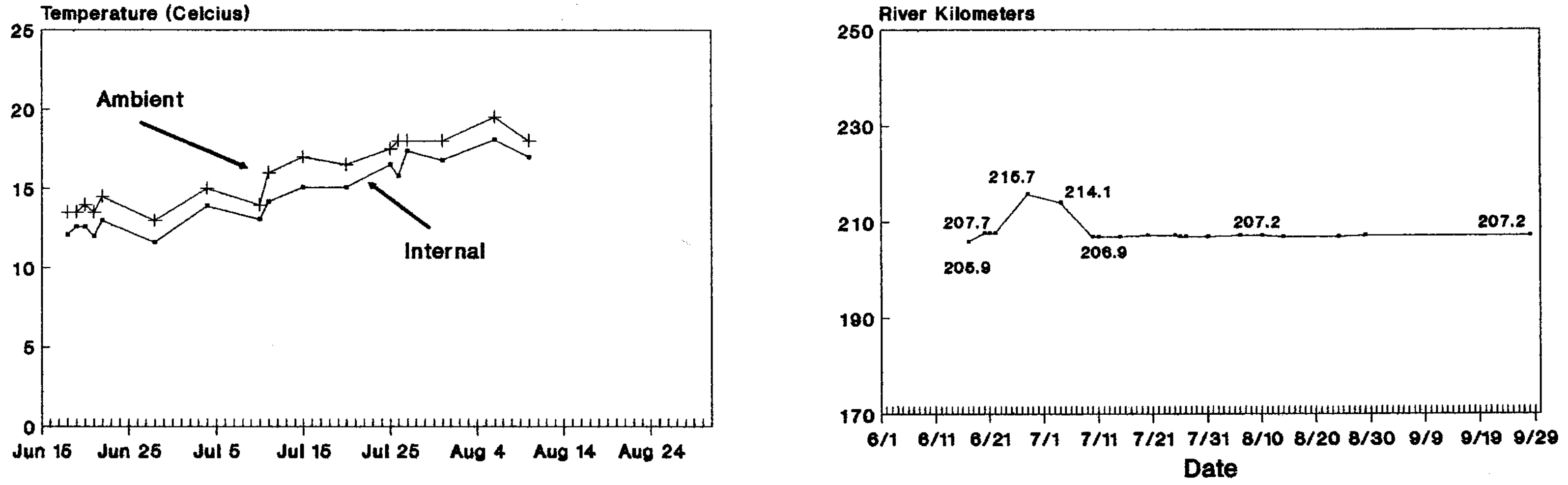

Figure 20: Fish # 13

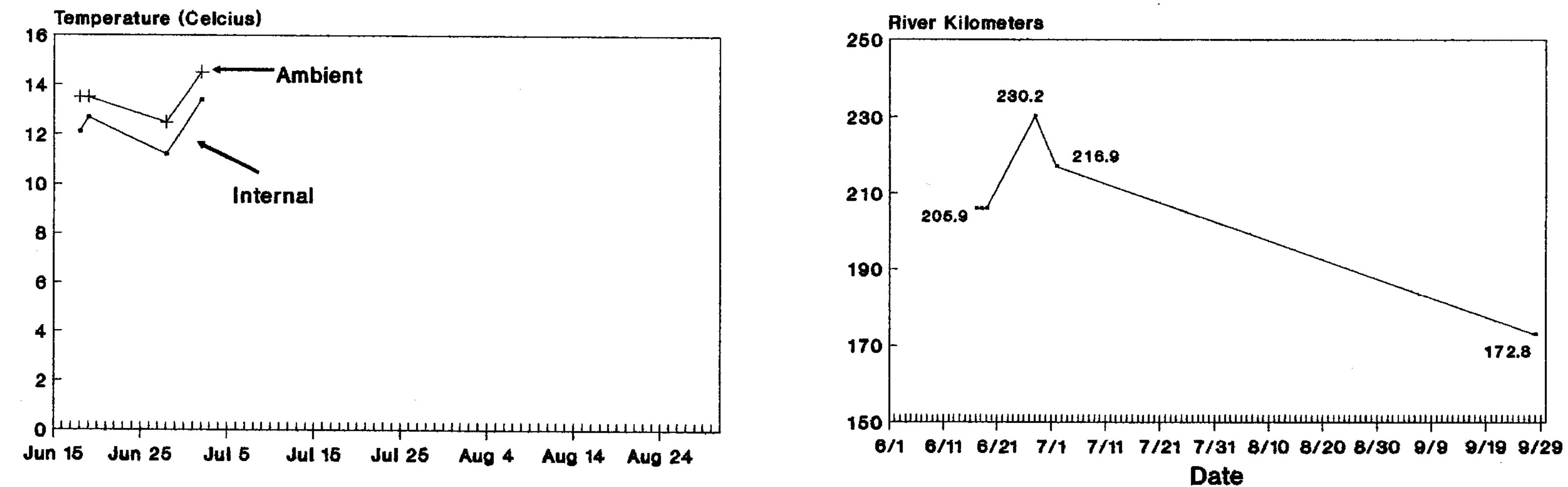

Figure 21: Fish # 14

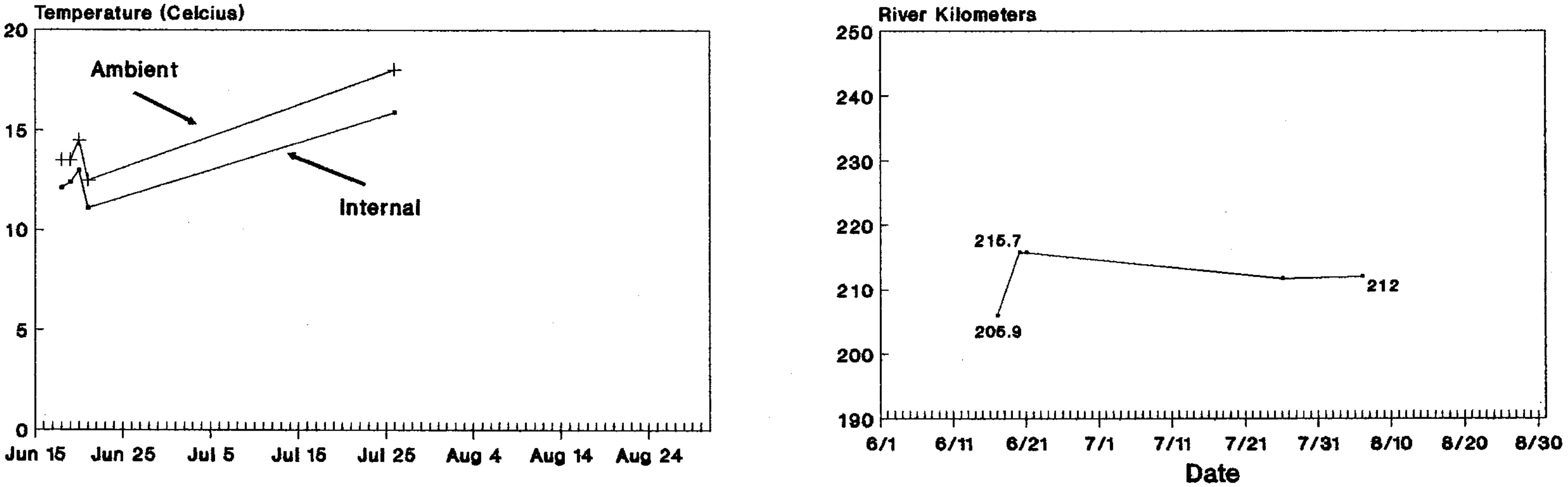

Figure 22: Fish # 15

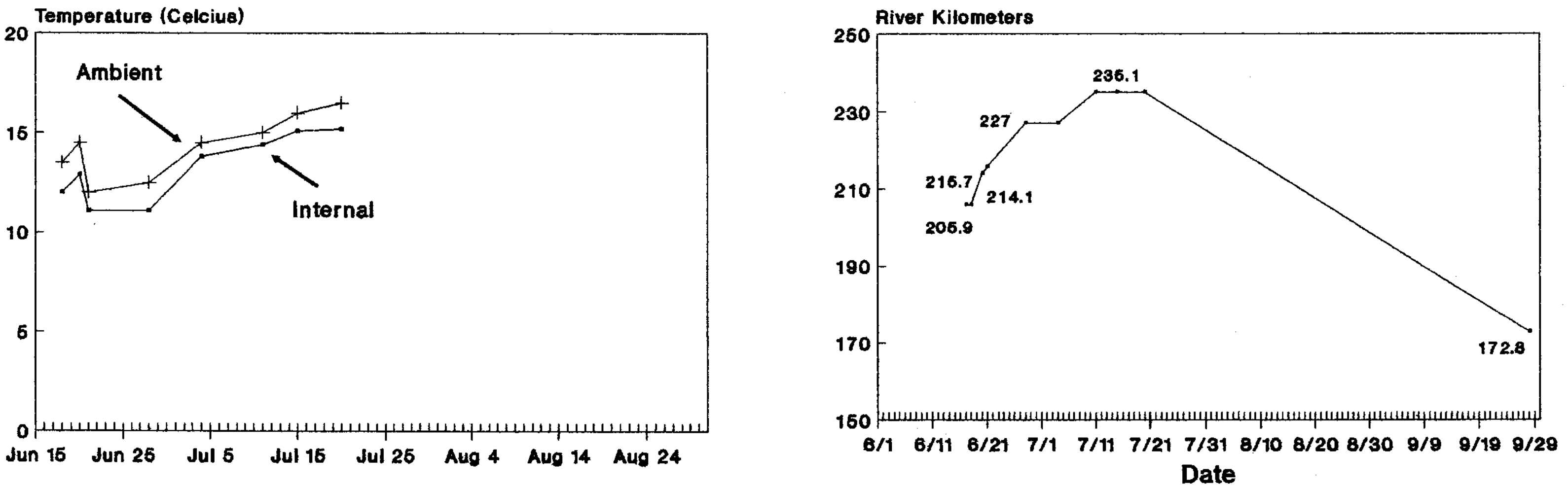

Figure 23: Fish # 16

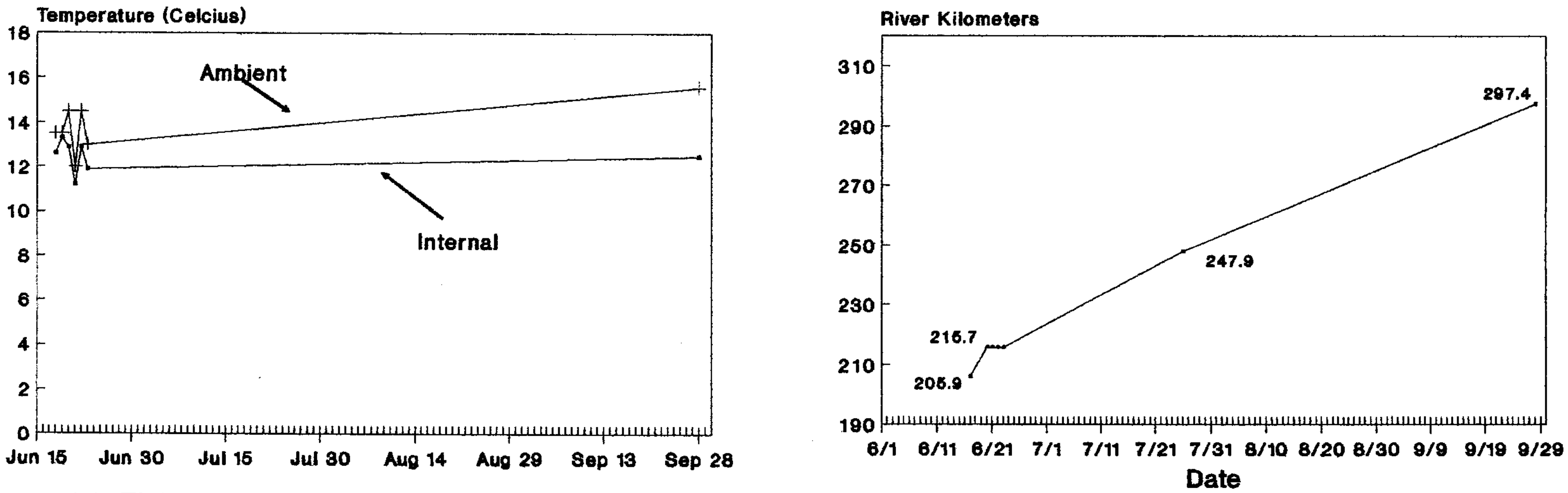

Figure 24: Fish # 17

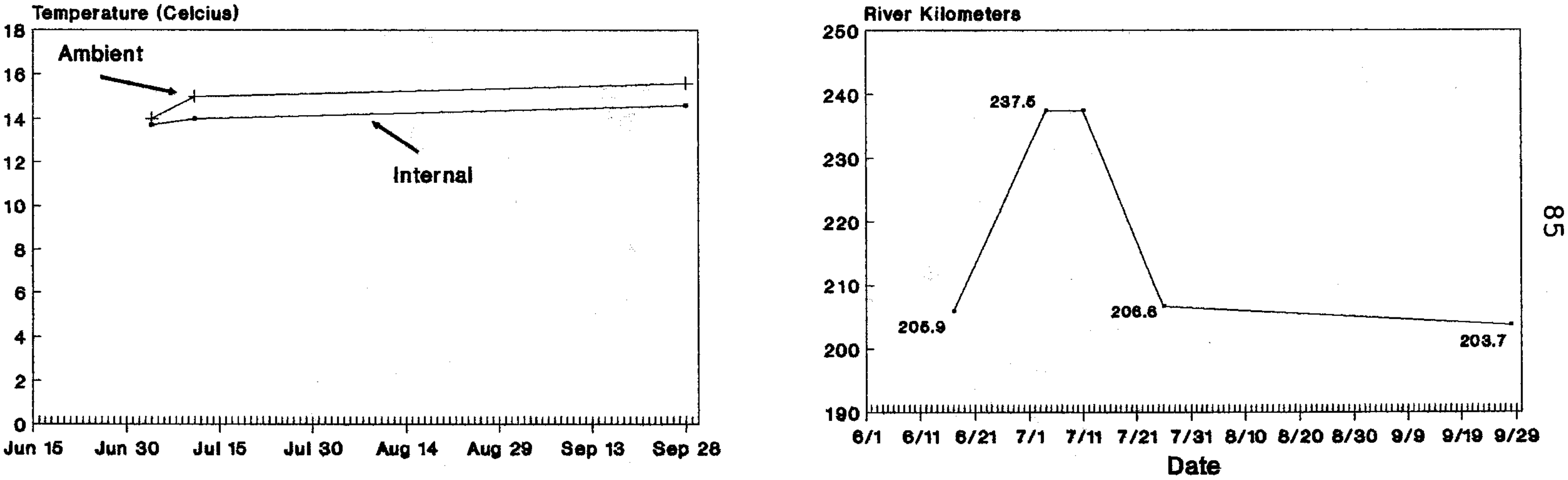

Figure 25: Fish # 18

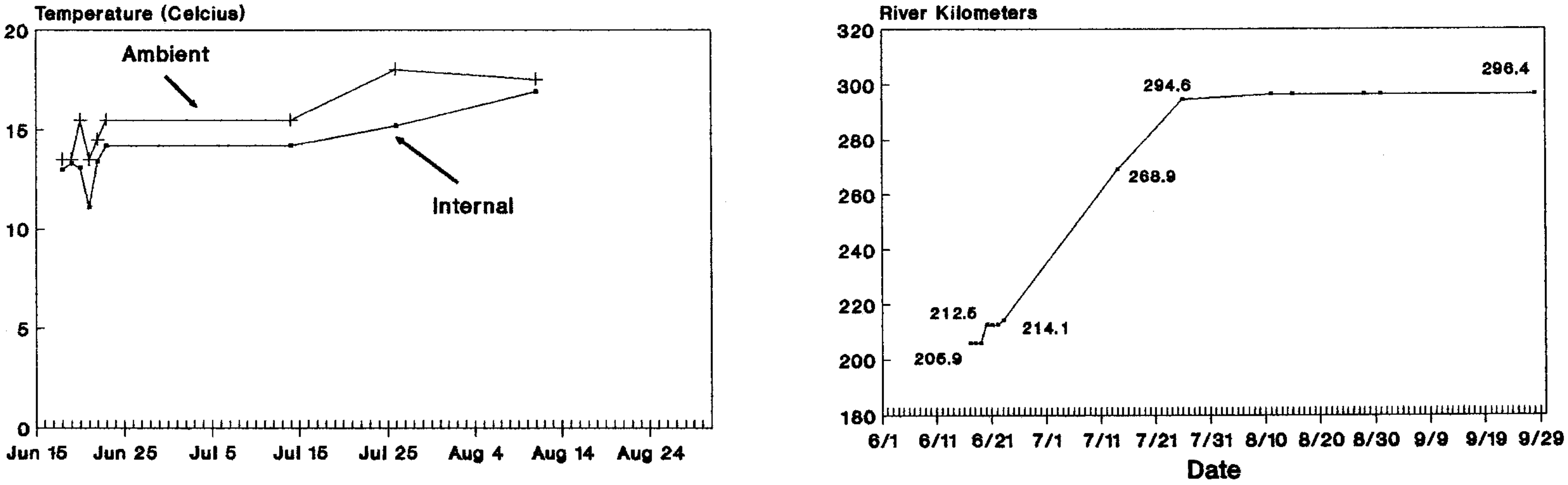

Figure 26: Fish # 19

Appendix B: Selected Landmarks and Tributaries of the Yakima River

River Kilometer	Name
172.9	Wide Hollow Creek
187.2	Naches River
203.3	Yakima-Kittitas Co. Line
205.9	Roza Diversion Dam
209.3	Burbank Creek
210.9	Roza Creek
217.4	Squaw Creek
219.3	McPherson Canyon Creek
225.1	Umtanum Creek
236.7	Wilson Creek
248.7	Manastash Creek
266.3	Thorp Hwy. Bridge
267.4	Taneum Creek
283.5	Teanaway River
294.8	Crystal Creek
296.7	Tillman Creek
298.8	Cle Elum River
325.4	U.S. Hwy. 10, Easton
326.0	Lake Easton Dam

Appendix C: Equilibration Rate

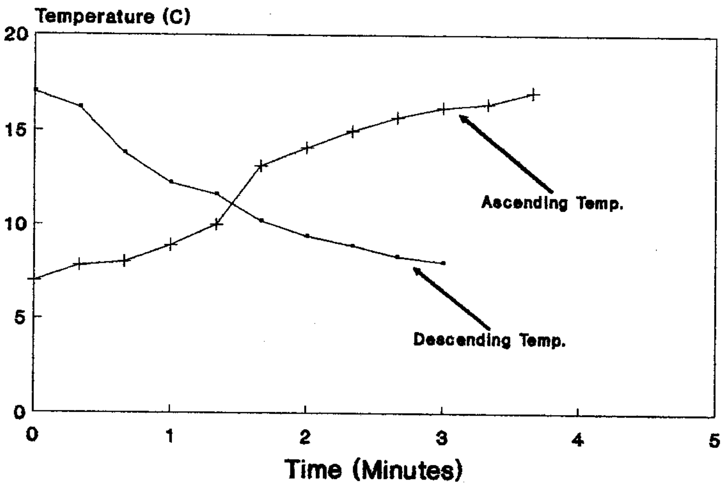

Figure 27: Transmitter

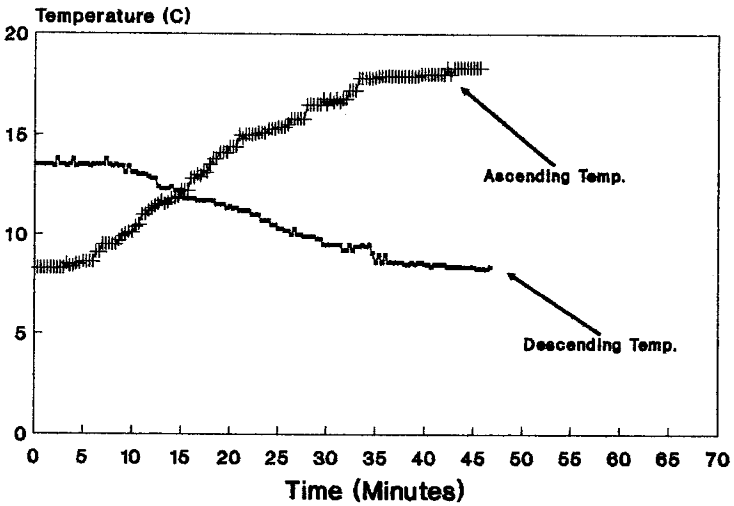

Figure 28: Fish I (2.82 kg)

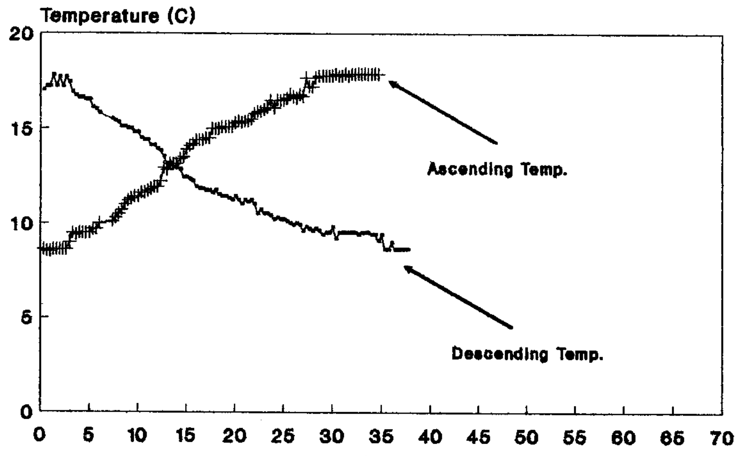

Figure 29: Fish II (3.00 kg)

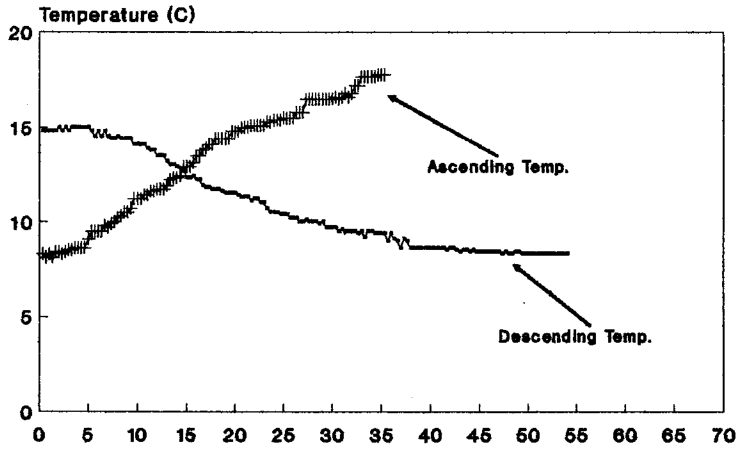

Figure 30: Fish III (3.98 kg)

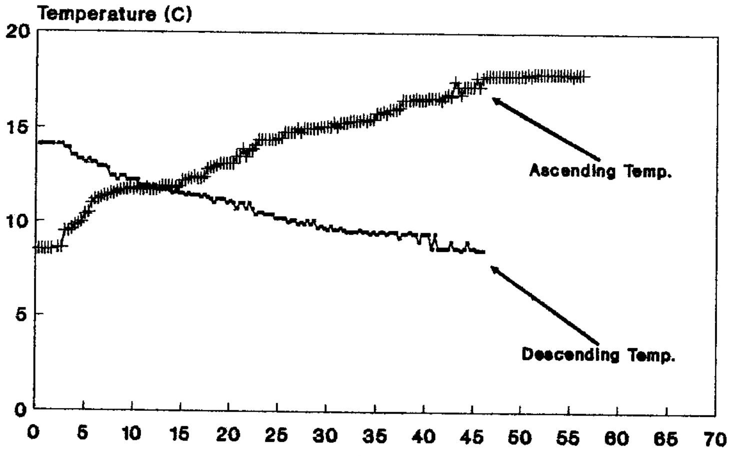

Figure 31: Fish IV (7.74 kg)

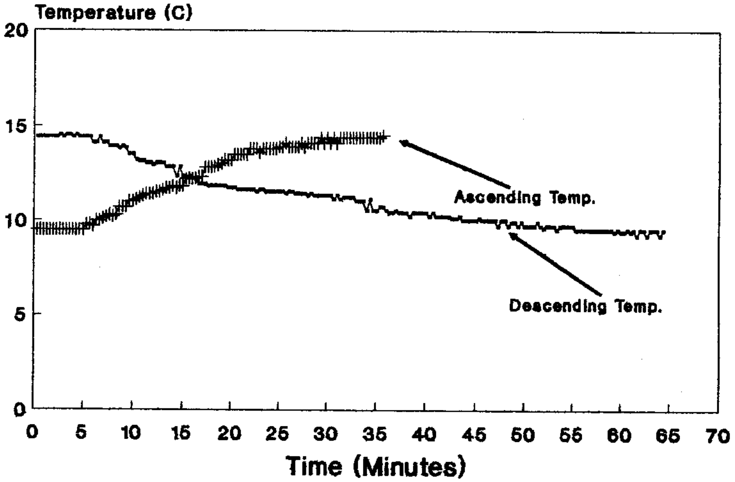

Figure 32: Fish V (11.10 kg)