Snake River Water Temperature Control Project

Phase II

Methods for managing and monitoring water temperatures in relation to salmon in the lower Snake River

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ABSTRACT

The second phase of a three-phase study of water temperature control and measurement in support of salmon recovery in the Snake River basin is described. The scientific literature and the available data provide a compelling case that temperature is an abiotic factor that is crucially important to the well being of salmon and steelhead in the federal Columbia River hydroelectric power system that is not being adequately addressed by existing monitoring programs. The Phase II project has three basic tasks that were executed in an iterative fashion; 1) water temperature and adult salmon data acquisition and compilation, 2) analysis of temperature and salmon data, and 3) design of temperature data acquisition in support of salmon recovery.

1) Water temperature and adult salmon data acquisition and compilation

Water temperature and adult salmon data acquisition and compilation was completed for all available electronically formatted data. Statistics descriptive of water temperatures, adult salmon migration, and the variability of each data set were computed. Adult immigrations were described from counts of adults passing dams. The longest time series of water temperatures, represented by the U.S. Army Corps of Engineers as hydroelectric turbine scroll case temperatures, provide an integrated value for the river as a whole, yet may be an imprecise and/or biased measure of the temperatures experienced by the immigrants, and are not actually scroll case measurements in some cases. The relationships

between scroll case temperatures and more spatially descriptive observations of temperature, such as transects, tri-level thermographs, gas saturation monitors, and others were explored.

Hypotheses concerning the effect of water temperature on fall chinook salmon immigration to the Snake River that are consistent with available data are offered to guide design and implementation of water temperature monitoring in Phase III of the project. With the exception of the transect data of 1991 and 1992, available water temperature data are not necessarily representative of the temperatures being experienced by immigrating salmon.

2) Analysis of temperature and salmon data

It may be feasible to use cool water releases from Dworshak Reservoir to create a migratory corridor or a series of thermal refugia within the reservoirs of the Lower Snake River system during the portions of the fall chinook immigration period when temperatures are highest. Regardless of whether or not temperature regimes in the migratory pathways are altered by human intervention, understanding and measuring the effect of temperature on survival is important to management of salmon and steelhead in the Columbia River watershed. Water temperatures at hydroelectric projects of the Columbia River and the Snake River have often exceeded the upper incipient lethal temperature level of 68F for salmon and steelhead during July, August, and September. Human intervention in the form of water releases from Dworshak Dam reduced the water temperatures in the reservoirs of the lower Snake River in 1991 – 1996 during the time period of juvenile and/or adult fall chinook salmon migration. It is possible that lowered temperatures during the 1991 to 1996 fall chinook immigrations increased the annual proportions of immigrants reaching Lower Granite Dam. Spatial detail available from present and historical water temperature measurements does not permit the full range of temperature conditions experienced by the immigrating salmon and steelhead to be measured and understood. The Lower Granite Dam (LWG) scroll case temperature differed significantly (α=0.05) from the mean, minimum, and maximum transect 5 and 6 temperatures for 1991 and 1992 with only a single exception. Information available from existing studies of migratory behavior of adult fall chinook salmon does not permit full understanding of the interactions between water temperature and fish behavior during critical periods of high water temperatures in August and early September. Adult fall chinook appear to spend less time in the hydroelectric system when they encounter the largest series of daily changes from warmer to cooler water temperatures at Ice Harbor Dam, the entry to the lower Snake River hydroelectric system. Since the lower Snake River dams were built, the annual timings of the fall chinook immigrations show a significant trend toward later arrival at Ice Harbor Dam, Lower Monumental Dam, and Little Goose Dam. The estimated annual proportion of fall chinook entering the Snake River at Ice Harbor Dam during August that reach Lower Granite Dam, 1986 - 1996, may be inversely proportional to scroll case water temperatures during August. The mean temperature experienced by fall chinook during the annual migratory period at Ice Harbor Dam has shown a significant downward trend over the time period 1986 - 1996, in part due to the effects of human intervention.

3) Design of temperature data acquisition in support of salmon recovery.

Our analyses resulted in the following recommendations:

- Implement a program of monitoring temperature measurements in the lower Snake River to support a numerical model of temperature regimes experienced in the Columbia River watershed by immigrating salmon and steelhead originating in the lower Snake River.
- Implement a program of placing temperature and depth sensing tags on adult fall chinook salmon captured at the Fish and Engineering Research Laboratory at Bonneville Dam that bear Snake River Passive Integrated Transponder tags.
- Apply the information gathered in the temperature monitoring and tagging program to the recovery program for Snake River salmon and steelhead through the evaluation of the temperature-survival hypotheses, leading to promulgation and adoption of a permanent program of temperature management.

We stress that our analyses are exploratory because the physical coincidence of the fish and the temperature measurements has not been established. Indeed, we do not expect scroll case temperatures that are usually taken in the interior of the dam to mirror the temperatures experienced by the fish in the river.

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INTRODUCTION

Temperature is a key physical factor that controls or influences all aspects of fish life, including salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) (Wootton 1990). During the course of their life cycle, anadromous Pacific salmon and steelhead of the Snake River basin occupy spawning and rearing habitats between the Bitterroot Mountains of Idaho and the North Pacific Ocean that are linked together by the habitats they pass through during their migration. Pacific salmon and steelhead evolved physiological and behavioral means of maintaining normal physiological function during the changes in water temperature they encounter in the thousands of miles they travel during transition from rearing to spawning grounds. Indeed, the ability to adapt to the natural variation in temperature and other key physical factors in spawning, rearing, and migratory habitats of North America has allowed Pacific salmon and steelhead to colonize a wide variety of freshwater and marine habitats from Monterey Bay, California to the Bering Sea (Groot and Margolis 1991, Groot, Margolis et al. 1995). Until recently, water temperature regimes in the series of linked habitats are assumed to have varied within a range to which salmon and steelhead are adapted.

Understanding the details of water temperature patterns is important because of the influence of temperature on the fundamental processes occurring in a lake or reservoir such as dissolved oxygen depletion and nutrient release (Thornton 1990). When reservoirs such as those of the Snake River, can thermally stratify for relatively brief periods, standard monitoring practice requires temperature measurements at time intervals and spatial scales appropriate to the expected times and scales of the temperature changes (Thornton 1990). The need for temperature monitoring with appropriate detail is doubly important in the Snake River, since it contains salmon species listed under the federal Endangered Species Act. In the long run, recovery of listed species in the Snake River is expected to be easier and much more cost effective if temperature problems can be identified and treated as they develop, rather than when they have reached a crisis level. Monitoring of a lethal factor, such as temperature is for fish, is the only objective approach for determining whether salmon recovery approaches are effective.

In a physiological sense, temperature is a lethal factor for all salmon and steelhead, even though a properly acclimated salmonid may survive exposure to the highest naturally occurring water temperatures in the migratory pathways (Fry 1971). Temperature is identified as a lethal factor, not because it is inevitably lethal, but because it is potentially lethal. Temperature is an important determinant of survival for fish because of the well-documented effects of temperature on critically important physiological processes (Wooton 1990). Temperature is a particularly important environmental factor for salmonids because these species are adapted to life in relatively cold waters (Brett 1971).

Alterations of key physical factors in freshwater rearing environments of salmon and steelhead in the contiguous United States and Canada have contributed to often severe declines in populations of anadromous salmonids (Busby, Johnson et al. 1993; Busby, Wainright et al. 1994; Busby, Wainright et al. 1996; Hard, Kope et al. 1996; Huntington, Nehlsen et al. 1996; Johnson, Flagg et al. 1991; Johnson, Waples et al. 1994; Matthews and Waples 1991; Mundy 1996; Nehlsen, Williams et al. 1991; Slaney, Hyatt et al. 1996; Waknitz, Matthews et al. 1995; Weitkamp, Wainright et al. 1995, Waples 1995). Some populations among each of the extant salmon and steelhead species in the Snake River basin have been listed under the federal Endangered Species Act. Among the factors recognized as contributing to the decline in the Snake River salmon and steelhead are alterations in the physical properties of the freshwater physical environment as a result of human development of the watershed (Matthews and Waples 1991; Waples, Johnson et al. 1991; Waples, Jones et al. 1991; Busby, Wainright et al. 1996).

Understanding the role of temperature in determining the survival of salmon and steelhead of the Snake River basin is essential to avoid their extirpation. Even when actions cannot be taken to change temperature conditions, understanding the effect of temperature on key life history parameters such as pre-spawning mortality is important to guide salmon recovery. In those cases where it is possible and desirable to change the temperatures during immigration, it is important to define the dimensions of temperature tolerance in terms of the local populations in the Snake River.

Our study contributes to understanding how to measure the effects of temperature on adult salmon and steelhead immigrating to the Snake River. The lower Snake River reservoirs (Figure 1) are an important link between the marine rearing environment of federally threatened and endangered Snake River salmon species and their freshwater spawning areas. Concern about high water temperatures in the lower Snake River reservoirs faced by the adult fall chinook (*O. tshawytscha*) salmon migration in 1990 prompted a trial effort to determine the feasibility of reducing temperatures in the lower Snake River reservoirs using cold water releases from Dworshak Reservoir. This led to more intensive efforts beginning in 1991 and continuing to date, including establishment of an extensive water temperature and velocity monitoring network in the reservoirs (Karr et al. 1992, Karr 1992, Karr 1993, Bennett et al. 1997). Results of the 1991 study demonstrated that water temperatures can be reduced through the lower Snake River reservoirs, and it established the need for the three work phases described below to be part of the salmon recovery program.

During **Phase I**, which is now completed (Karr et al. 1992, Bennett et al. 1997), the physical capability to reduce water temperatures in the lower Snake River reservoirs using cold water releases from Dworshak Reservoir supplemented with flow augmentation from Brownlee Reservoir was quantified. Water temperatures were reduced downstream from the point of release to below Ice Harbor Dam. Bennett et al. (1997) also present detailed graphs of the changes in the temperature profiles and velocity profiles brought about by the temperature control actions.

In the present study, **Phase II**, water temperature data drawn from transect and tri-level thermograph data of Phase I, and other measures of water temperature, were examined along with adult fish movement data. The first objective was to identify the magnitude and location of different temperature profiles of the lower Snake River created by upstream releases of cold water in 1991 and 1992. Temperature profiles were classified according to the salmonid temperature ranges and zones of Figure 2. Transect data (1991, 1992) and tri-level thermograph data (1991 - 1996) were used to prepare graphs and descriptions of cold water release actions and the resulting chronology of changes in downstream water temperatures. Transect and tri-level thermograph temperature data was also compared to dam scroll case temperature data to assess how well the scroll case temperatures represent the temperatures encountered by migrating salmonids.

The water temperature control experiments were conducted because of concern about the potential effect of water temperatures on the persistence of salmon and steelhead populations in the Snake River basin. During Phase II, testable hypotheses have been developed to explain the role of water temperatures during adult salmon and steelhead immigration and spawning. The temperature-survival hypotheses were synthesized from the literature on fish physiology and ecology. The degree to which existing data could be used to evaluate the temperature-survival hypotheses was examined.

Other existing water temperature and adult chinook salmon observations from the lower Snake River were gathered and examined to understand the feasibility of testing our hypotheses regarding the effect of water temperatures on adaptive behaviors, survival, and spawning success. Available data on adult salmon and steelhead were applied to test hypotheses on the association between adult salmon behavior and water temperatures. The behaviors, migratory timing at a locality, and average rate of migration between hydroelectric dams, are hypothesized to be related to adult survivals during immigration, and to spawning success. This general hypothesis is consistent with available observations and with the record of scientific literature. Formal, more specific hypothesis statements are given below. The longest time series of daily water temperature data from the hydroelectric system, the scroll case temperatures, were examined in relation to daily counts of adult fall chinook salmon at the lower Snake River Dams. We also investigated the feasibility of associating adult fish tracking data from Bjornn et al. (1992) and Mendel et al. (1992) with temperature records to examine the extent to which temperature affects adult fish movement. The results of analysis of all temperature data and the adult salmon observations provide the foundation for designing the Phase III work.

The next logical step in lower Snake River water temperature studies to support recovery of threatened and endangered salmon species, **Phase III**, is a field program to monitor water temperatures combined with telemetry on adult fall chinook. The objective is to put in place a data collection and analysis program that permits understanding of the association between fish behavior and water temperatures during the adult immigration, and that measures survival and spawning success in relation to exposure to water temperatures.

Comparing water temperature profiles with the migratory pathways chosen by the fish for their upstream migration through the lower Snake River reservoirs is expected to improve fish management capabilities in three ways. First, it can provide the basis for management decisions on future water temperature control actions. Second, it can permit estimation of water temperature standards for endangered species protection. Third it will provide additional capability to evaluate effectiveness of adult anadromous fish passage facilities at hydroelectric dams in the lower Snake River.

In presenting the following working hypotheses we suggest how measures of temperature and fish movements may be taken. Hypotheses are concepts of how physical factors in the environment interact with the biology of the animals to determine survival. Testable hypotheses can be evaluated by collection of data from the field, or in the laboratory. By formulating testable hypotheses, we hope researchers will challenge them with data, and retain them or replace them with improved working hypotheses. We believe that the purpose of monitoring and evaluation programs for salmon recovery should be to collect data to evaluate hypotheses concerning survival of the salmon.

The entry point to testable hypotheses on the relation between salmon behavior and survival and water temperatures experienced during immigration is the literature survey.

Literature Records

Definition of Temperature Zones and Ranges

The definition of ranges and zones according to the effects of temperature on fish, including salmon, are found in the scientific literature on fish physiology. The temperature-survival hypotheses for Columbia River salmon and steelhead are based on these published studies in fish physiology. The studies address a variety of levels of temperature related phenomena, from an individual's behavior to the density of mitochondria in its muscle cells. A compendium of works on salmon and steelhead has recently become available (Groot, Margolis et al. 1995).

The four temperature intervals (two ranges and two zones) of this study (Figure 2) were chosen from a larger classification of the influence of abiotic factors on the physiology of fish (Fry 1971). There are five levels of effects of physical factors on fish; lethal, controlling, limiting, masking, and directive (Fry 1971). A lethal factor may cause death, depending on its application. In a physiological sense, temperature is a lethal factor for salmon and steelhead in the Columbia River watershed, even though a properly acclimated salmonid might initially survive an arbitrarily brief exposure to the highest naturally occurring water temperatures in the migratory pathways. A controlling factor governs maximum and minimum rate of metabolic processes. Temperature is the overriding controlling factor because of its pervasive effect on metabolism. A limiting factor restricts the supply or removal of materials in the metabolic chain. It reduces the rate of metabolism below that permitted by controlling factors. A key limiting factor is oxygen, and the solubility of oxygen in water is inversely proportional to temperature. A frequently encountered masking factor is salinity, which modifies the effects of other factors. A directive factor elicits a response in the fish to a gradient in the factor, such as is the case for temperature or salinity. In studies of the physiology of fishes, temperature is of pervasive importance, as a primary lethal, controlling, limiting, and directive factor.

Definition of the Incipient Lethal Level, ILL

The five levels provide a conceptual framework within which to understand how the environment determines the capacity of the ectothermic organism to function. The five levels describe mechanisms by which the environment dictates the lifetime reproductive success of the organism through its influence on the energetic costs of metabolic processes. An outer boundary for each factor is termed the Incipient Lethal Level, ILL. The ILL defines the outer boundary on the level at which the organism can live indefinitely. The effective time, ET, is the time it takes for the factor to kill the fish outside the envelope defined by the ILL. Within the ILL, the fish is within its optimum range or its upper zone of tolerance for the factor (Figure 2) where the life span is not directly affected. Outside the ILL, above 68F or below 45F, the fish is in the zone of upper or lower resistance (Figure 2) in which events can be measured in terms of the amount of time to die, ET. The definitions of the classification are based on the mortality inflicted. Normal physiological processes such as growth, reproduction, feeding and digestion occur within the bounds defined by the ILL (Elliot 1981).

Since the concept of the ILL and the ET (Elliot 1981) are critically important to understanding the role of temperature in Snake River salmon recovery, a detailed explanation is in order. While acclimation may influence the ET, it does not change the ILL. A fish that is acclimated to higher (or lower) temperatures is likely to survive longer outside the ILL than a fish that is acclimated to temperatures in the center of the ILL. A fish acclimated to the lower bound of the ILL might die of shock if placed directly into water at a temperature above the upper bound of the ILL. A fish acclimated to a temperature near the upper bound of the ILL would be expected to survive longer if placed into temperatures higher than the upper bound of the ILL. Regardless of the temperature to which the fish is acclimated, at temperatures outside the ILL the fish is going to die eventually, if it does not return to temperatures inside the ILL. When a fish has returned from outside the ILL, it may die anyway if it has sustained damage from a disease associated with temperatures outside the ILL. The temperature history of the immigrants is therefore critically important to understanding the risks associated with immigration.

Definition of the Upper Incipient Lethal Temperature, UILT

The range of temperatures appropriate to support physiological processes in fish may vary by developmental stage (Wootton 1990). Our study is concerned with immigrating adult salmon and steelhead. We have chosen 68F (20C) to be the point where the zone of lower resistance starts (Figure 2) based on literature records discussed below from other species and locales (Coutant 1977). Subsequent research within the Snake River basin may further refine this initial concept. The upper ILL at the boundary between the zones of upper tolerance and lower resistance (68F) is called the upper incipient lethal temperature, the UILT. The lower resistance zone contains a lethal range starting at 70F (21.1C) (Figure 2) where the effect of temperature on immigrating salmon and steelhead becomes particularly negative, and at which the ET declines rapidly. At temperatures below 60F (15.6C) and above 45F (7.2C), the upper zone of tolerance contains an optimum range within which the effects of temperature on salmon and steelhead are thought to be benign. We take the lower incipient lethal temperature, the LILT, for salmon and steelhead to be 45F (7.2C), however as a practical matter we do not expect the LILT to be of concern for adult salmon in the Snake River basin.

Due to variation in the life cycle stage and methods of measurement used, there is a fairly wide range of values in the scientific literature for defining the best or optimum temperature bounds for salmonids, but there is general agreement on the bounds of the ILL. Variation in the ILL by age and physiological condition (stress, smoltification, sexual maturation) is to be expected (Wootton 1990). In a survey of the literature Coutant (1977) reported the lower and upper temperatures avoided by a number of Pacific salmon species by life cycle stage, as well as the temperature that was preferred, if reported, during each study. Coutant (1977) did not find a preferred temperature for every Pacific salmon species and life cycle stage. For juvenile sockeye the upper avoidance given by Coutant of 69.8F (21C) agrees closely with field observations for the upper avoidance temperature of 68.0F (20C) (Brett 1971). Juvenile sockeye in the laboratory preferred 51.1 to 55.0F (10.6 to 12.8C), and in the wild they preferred 58.1F (14.5C). Adult coho salmon were reported to prefer 52.5 to 61.9F (11.4 to 16.6C). Immature chinook salmon were reported to prefer 53.1F (11.7C) in the laboratory and 63.1F (17.3C) in the field (Coutant 1977). Until empirical values can be obtained for the salmon species and stocks of the Snake River, literature records will have to suffice.

Ranges of temperatures appropriate for spawning and incubation are similar to, but somewhat different from those of other life history stages. In incubation of chinook salmon eggs, Alderdice and Velson (in Healey 1991) reported the upper and lower bounds on temperatures for 50% pre-hatch mortality as 36.5-37.4 to 60.8F (2.5-3.0 to 16C). Note that gametes and early embryos are quite sensitive to changes in temperatures.

Due to the mechanism of action of temperature on physiological processes in the fish, the preferred temperatures most probably are those that do not increase the energetic costs of survival (see Wootton 1990). Preferred temperatures are therefore strongly dependent on the temperature to which the fish is accustomed, or acclimated. Further, the effects of temperature on fish outside the bounds of the ILL are dependent on acclimation. For example, acclimation temperatures had a significant effect on the lethal temperature at which 50% of juvenile coho salmon died (Thomas, Gharrett et al. 1986). Peak temperature within a time cycle producing death of 50% of animals was 82.4F (28C) for age-0 coho salmon and 78.8F (26C) for age-2 presmolts.

Fish survive indefinitely only within the range limits UILT and LILT (upper and lower incipient lethal temperature). Acclimation is possible over a range of temperatures within the ILL of the species, but it is also dependent on size, age, season, and genetic make up. Salmonids tend to be relatively stenothermal, as opposed to many of the cyprinids, such as goldfish, that are eurythermal. Effects of high temperature are complicated by the effect of temperature on solubility of oxygen. Solubility of oxygen is inversely proportional to temperature, therefore the cause of death at higher temperatures may be due to a variety of sources, including suffocation, failure of enzyme systems that mediate and enable metabolism, and disease. By definition of the ILL, outside the ILL the homeostatic capacity of the animal has been exceeded and it will eventually die in time ET if it cannot locate lower temperatures.

Physiological Basis of Temperature - Survival Hypotheses

Members of the salmon species are obligate ectotherms (poikilothermic), as is the case for nearly all species of fishes. Among the aquatic ectotherms, including the fall chinook salmon and steelhead originating in the Snake River, the interaction between the individual and the temperature of the surrounding waters holds the key to survival, not only for the individual, but for the population and the species as well. Temperature is a key determinant of survival due to its effect on essential physiological processes. The physiological processes of growth, reproduction, swimming, feeding and base metabolism, are all governed by temperature (Wootton 1990). Each change in temperature encountered by the fish costs energy, either in the form of behavioral thermoregulation, or in adjusting metabolic processes during acclimation to the new temperature (Elliot 1981). To conserve the energy costs associated with acclimating to, and living with, elevated temperatures, the individual uses behavioral thermoregulation (Brett 1971, Fry 1971) to minimize the energetic cost of the essential physiological processes.

Standard metabolism in fishes is proportional to temperature in all fish species so far tested, including salmon (Wootton 1990). The three components of total metabolic rate in fishes, R, are R_s, standard metabolic rate, R_a, swimming metabolic rate, and R_d, feeding metabolic rate. R is equal to the sum of its components, and all are individually affected by temperature. Allocation of energy among the three components is also affected by temperature. In brown trout at 59.0F (15C) the sum of the maximum energy expended on maintenance, R_d, and feeding, R_a, exceeds the maximum energy income by 54%, but at 41.9F (5.5C) expenditures exceed income by only 7% (Wooton 1990). Consequently, higher temperature can mean more energy allocation problems for the fish. Even though salmonids are capable of burst swimming speeds that are faster at higher temperatures up to about 15C (59F) (Paulik and DeLacy 1958 in Bjornn and Peery 1992, Brett 1971), in terms of their total energy budget they may not be able to afford to do so. As temperatures increase, at some point the requirements of standard metabolism become so high that any additional energy requirements, such as the requirement for burst swimming, can cause the fish to die.

Temperature is both a lethal and a controlling factor in the process of ventilation, or getting oxygen to the cells of the body (Jensen, Nikinmaa et al. 1993). Transport of oxygen from environment to tissue cells consists of the four steps of ventilation, diffusion from water to blood, blood gas transport, and diffusion from blood to cells. As in other ectotherms, all processes in fishes are affected by environmental temperature. The metabolic rate typically increases by a factor of 2-3 for every 18F (10C) rise. In parallel with this exponential rise in the metabolic demand for oxygen the solubility of oxygen in water decreases by 35% between 41 and 77F (5 and 25C). The ventilatory flow rate must increase with temperature to bring sufficient amounts of oxygen into contact with the gill. Heart rate and cardiac output also increase with temperature as a hedge against lowered oxygen concentrations in the water. The reaction between oxygen and hemoglobin, Hb, is exothermic whereby an increase in temperature reduces the affinity of Hb for oxygen (Jensen, Nikinmaa et al. 1993).

Temperature can act in combination with other abiotic factors, such as pH and aluminum compounds, to produce strong challenges to the ventilatory process in fishes. For example, the negative effects of temperature on respiration in fishes are exacerbated by changes in pH and the presence of aluminum (Jensen, Nikinmaa et al. 1993). The affinity of Hb for oxygen is also governed by pH. The level of pH becomes more and more critical as temperature increases, making acidification from air pollution more of a problem. Elevated aluminum concentrations obstruct gill functions along with acidification. Aluminum containing acid water is more lethal than acid water alone. Aluminum not only hampers uptake of oxygen but ion transport is also altered. Ion transport across gill lamellae is an important process in the physiology of waste elimination. Aluminum reduces diffusion of oxygen across gill lamellae by increasing mucous discharge. Increasing temperature and decreasing pH in the presence of aluminum compounds is therefore a potentially lethal combination (Jensen, Nikinmaa et al. 1993).

If a fish cannot avoid temperature change through behavioral thermoregulation, it invokes a wide range of physiological responses to acclimatize its metabolic processes to the new temperature regime (Wootton 1990). One of the physiological costs of acclimation is illustrated by the adaptation of fish muscle tissue to changes in temperature. In fish muscle tissue the metabolic responses to temperature vary with the time course of adaptation and the acclimation temperature (Johnston 1993). For example, density of mitochondria in muscle fiber changes according to acclimation temperature, being very much higher at 41F (5C) than at 77F (25C) in an anadromous species, the striped bass. The elevated density of mitochondria in cold adapted fish boosts the rate of ATP synthesis at low temperatures, reduces the average diffusion path lengths among mitochondria and myofibrils, and increases the area of exchange between mitochondria and cytoplasm (Johnston 1993). Acclimation to changes in temperature regime requires substantial physical alteration at the cellular level that imposes substantial energy costs on the organism.

Supporting Information from Columbia River

As demonstrated above, observations from the literature on salmonids and other fishes provide the factual basis for the temperature-survival hypotheses. The role of temperature in determining the rate of energy consumption in fishes, including the anadromous salmonids, through its effect on respiration and other basic physiological processes, is well established in the scientific literature. Specific literature records on the role of temperature in the ecology and health of salmonids in the Columbia River basin and nearby watersheds provide additional scientific context for our study.

In a recent comprehensive review of the literature prepared for the State of Oregon, McCullough identified the potentially dominant role of water temperature in determining the ecology and health of salmonid populations (McCullough 1993). Water temperature is known to have altered migratory behavior of adult salmon and steelhead in the Columbia and Snake rivers (Bjornn and Peery 1992). The extent to which temperature may have blocked salmon migrations prior to the time of the work of Bjornn and Peery (1992) is unknown. For salmon and steelhead entering the Snake River, water temperatures influence the rate of upstream migration and timing of passage (Bjornn, Ringe et al. 1992). Chinook salmon and steelhead slow migration and delay entering the Snake River at elevated temperatures (>68F) in early summer and fall (Bjornn, Ringe et al. 1992).

In one study of salmon and steelhead entering the Snake River, water temperatures in the river and the fish ladders at Ice Harbor Dam exceeded 68F (20C) during the latter part of July, August, and early September (Bjornn, Ringe et al. 1992). A hiatus in migration created by temperatures in the Snake River was noted. During this hiatus, few fish entered the Snake River until water temperatures declined in September. The observation of chinook stopping immigration at temperatures above 68F and resuming immigration below 68F is consistent with the hypothesis of behavioral thermoregulation.

Fall chinook immigrating to the Snake River have been radio-tagged and monitored during their migration (Mendel et al. 1992). In 1992, 96 fall chinook were captured, radio-tagged and released back into the fishway at Ice Harbor Dam. Due to concern about mortality that could result from handling adult fall chinook exposed to high water temperatures, the Snake River fall radio tagging program did not handle fish until temperatures declined below 70F (21.1C). Water temperatures usually decline below 70F at the beginning of September (Figure 3). As a consequence, detailed information on fall chinook movement during the critical time period of August is limited to daily counts from the fish ladders at the hydroelectric dams. Information on the rate of passage of radio tagged fall chinook in the lower Snake River in relation to water temperature has been summarized by the Snake River Laboratory of the Washington Department of Fish and Wildlife in Dayton, a sample of which is given in Table 1. Note that the radio-tagging data refer to time periods when water temperatures are generally declining (Compare Table 1 to Figure 3).

Water temperatures above the UILT may be encountered by Snake River basin fall chinook before they reach the Snake River. A monitoring program for water temperatures from March 1 to October 31, 1996 was intended to detect presence of temperature differences in fish ladders that might impact fish behavior (Dalen, Stansell et al. 1996). The criterion employed in examining temperature differences was a change of 0.5F (0.3C) or greater. Examination of hourly averages of temperature found no differences in temperature between contiguous locations (selection of locations may have influenced this outcome) at Bonneville and The Dalles. Temperature differences above the thresholds occurred in greater than 10% of hourly averages at John Day in both the north and south ladders. Most differences occur between 1300 h and 2200 h, and differences as high as 1.3F (0.7C) occur at 1800 h due to forebay surface water warming. Temperatures reached or exceeded 70.0F (21.1C) at Bonneville Dam 7 days (August 1 through August 7), at The Dalles Dam for 16 days (July 27 - through August 11), and at John Day Dam for 61 days (July 25 through September 23). High temperatures occur in late afternoons and in the late summer.

The influence of temperature on immigrating salmon is not limited to fall chinook and steelhead (Stuehrenberg, Swan et al. 1994). Although water temperatures in the main channels of the Columbia and Snake rivers are generally low when spring chinook salmon first enter freshwater, they are known to reside in thermal refugia in the tributaries during the summer until spawning in the late summer and early fall (McIntosh, Price et al. 1994).

Immigrating sockeye salmon also experience and respond to the effects of temperature. For example, it has been shown that Columbia River basin sockeye salmon have only a limited ability to change their immigratory timing behavior in response to changing thermal regimes brought about by development of the basin (Quinn and Adams 1996). The degree to which any salmon population may alter its immigratory behavior probably depends on where the behavior is measured. For example Quinn and Adams (1996) were working in the lower Columbia River at Bonneville Dams. Sockeye salmon at points higher in the drainage may show a greater ability to adapt timing to water temperature and flow conditions (Doug Hatch, Columbia River Inter-Tribal Fish Commission, personal communication). When timing of adult salmon migration through the Columbia River is tightly synchronized with a narrow time-window of physical conditions on the spawning grounds, salmon may be forced to migrate through water temperatures above the UILT in the lower river to stay on schedule for spawning. Closer to the spawning grounds, timing may be closely attuned to water temperatures and flow insofar as the maturation process permits.

For sockeye salmon, the cost of swimming at a particular speed increases with temperature. The role of temperature in the energetics of sockeye salmon immigration to the Columbia basin was established in an earlier study by Paulik and Delacy (1958) (in Bjornn, Ringe et al. 1992). The time to exhaustion decreased and swimming ability declined as the sockeye moved up the river from Bonneville Dam. Brett (1971), in a study of the relation of temperature to sockeye salmon bioenergetics, obtained similar results. Brett used the dependence of metabolic rate, measured as oxygen consumption, on temperature (Brett 1952; Brett 1971). Standard metabolism, R_s, increases exponentially in the sockeye salmon according to $R_s = e^{bT}$ where b is constant and T is temperature. The maximum metabolic rate, or active metabolic rate, increases sharply with temperature between 5 and 15C (41 and 59F) and then declines. The maximum swimming speed increases in proportion to temperature. An upper temperature threshold above which maximum swimming speed declined was found. It should be noted that acclimation is crucial to determining the effect of temperature on swimming rate. Fry and Hart (1948) (in

Johnston 1993) used a rotating drum to determine the effects of temperature on maximum swimming speeds in fish (Johnston 1993). It was found that acclimating fish to low temperatures increased their maximum swimming speed at low temperatures, but reduced their maximum swimming speed at high temperatures. It was concluded that the range of swimming speeds, and therefore upper temperature thresholds, differs at low and high temperatures (Johnston 1993). The finding that the upper temperature threshold at which maximum swimming speed declines depends to an extent on the temperature to which the fish has been acclimated agrees with the findings of Brett, and Paulik and DeLacy, discussed above.

Steelhead may be put at risk of extirpation in some localities by changes in temperature regimes (Busby, Johnson et al. 1993; Busby, Wainright et al. 1994; Busby, Wainright et al. 1996). In addition to changes in temperature regimes, other risk factors identified by the National Marine Fisheries Service in its status review of west coast steelhead were the current low levels of abundance, historical abundance and carrying capacity, trends in abundance, climate trends, and threats to genetic integrity from hatchery fish. In Oregon coastal streams, a risk of extirpation due to habitat blockages and shifts in temperature regimes was identified.

Temperature affects on related species and drainages

Anadromous species other than steelhead and salmon may also be at risk of extirpation due to factors related to temperature. In the review of the status of

Oregon's Umpqua River sea-run cutthroat trout, a wide variety of risk factors was considered, including alteration of temperature regimes, hatchery releases and supplementation, however the only conclusive evidence of risk was found to be time trends in abundance (Johnson, Waples et al. 1994).

Working Hypothesis

We believe the following hypotheses to be consistent with the available literature record. We have deferred citations to the literature record to the literature survey section in order to simplify the statements.

Hypothesis 1: Behavioral thermoregulation

Adult fall chinook salmon and steelhead exhibit measurable behavioral thermoregulation in response to water temperatures during immigration.

Our hypothesis is that the adults will alter their rate of immigration in order to find water temperatures that enable maintenance of homeostasis and minimization of energy expenditure during immigration. The timing of the immigration at fixed geographic reference points will vary in concert with variations in ambient water temperature. Such behavioral modifications are part of the physiological process of maintaining homeostasis. The hypothesis is consistent with the observation that adult fall chinook salmon exhibit normal physiological function at and below 60F (15.6C). As a basic homeostatic response, adult fall chinook will alter migratory behaviors to attain temperatures at and below 60F temperature. In the present context, homeostasis is the ability of a cold-blooded organism to maintain internal equilibrium in its physiological processes by altering its behavior to seek the appropriate temperature regime.

The hypothesis holds that when ambient temperatures are between 45F and 60F (7.2 and 15.6C), behavioral thermoregulation is not required for homeostasis. Above 60F, temperature may be a determinant of behavior during the salmon immigration, with its effect increasing until immigratory behaviors are halted altogether at some point above the upper incipient lethal temperature of 68F (20C). Changes in immigratory behavior above 60F are increasingly likely to be necessary to support homeostasis as water temperature approaches 68F. According to the hypothesis, above 68F changes in immigratory behaviors are highly likely to be necessary to support homeostasis.

The hypothesis is a logical extension of the concept that behavioral thermoregulation is an adaptive response exhibited by all fishes including adult chinook and steelhead during immigration. An adaptive behavioral response is an inherited behavior that allows its individuals to successfully exploit an environment. The heritable behavior improves the rate of survival of those individuals that exhibit it, therefore it becomes a common feature of the behavior through the process of natural selection. Such an adaptive behavior is known as behavioral thermoregulation (Wootton 1990).

Hypothesis 2: Temperature dependent spawning success

The total temperature units (i.e., degree days) accumulated by a fall chinook salmon during immigration has a direct and compelling effect on its spawning success.

It is the effect of temperature on the energy resources of the adult chinook (fall) spawner that makes this hypothesis and its evaluation relevant to recovery of endangered and threatened salmon. Each salmon has an energy budget within which it must complete its immigration and spawning. Energy available to support immigration and spawning is fixed because salmon do not feed after entering freshwater. As salmon immigrate through varying water temperature regimes, their rate of energy consumption will reflect not only the energy demands of swimming, but also the ambient temperature regime. At higher temperatures, the rate of energy consumption is higher. Since the amount of energy available to an individual adult salmon is finite and nonrenewable, in theory an individual salmon could use enough bodily energy during immigration to make it impossible for it to excavate a redd, or to successfully participate in spawning behaviors, even though it may reach the spawning grounds. In theory, behavioral thermoregulation is employed by the individual salmon to maximize its chances of retaining enough energy to spawn successfully.

Hypothesis 3: Temperature dependent survival

Cumulative exposure to water temperatures above 60F (15.6C) is inversely proportional to survival of steelhead and fall chinook from freshwater entry to spawning.

It is the cumulative effect of temperature on survival of the adult chinook salmon (fall) and steelhead that makes the hypothesis and its evaluation relevant to recovery of endangered and threatened salmon and steelhead. The mechanisms of mortality are alteration of physiological processes leading to death from disease, and from physical traumas to adult and eggs due to degradation in swimming performance. When adult salmon and steelhead become entrained in the upstream approaches to a hydroelectric facility, they are likely to experience substantial physical trauma as they pass downstream through turbines or through juvenile bypass facilities. As a cumulative effect, exposure to higher temperatures can be expressed outside the hydroelectric system in terms of increased pre-spawning mortality, reduced ability to construct redds, and inability to successfully produce offspring.

To evaluate the temperature-survival hypotheses directly, observations on ambient water temperature in relation to individual fish movements are needed. Behavioral modifications in response to temperature may be inferred from existing data by the degree of correlation between migratory behavior, as timing and average rate, and water temperatures. Information on the extent to which existing monitoring and research programs can enable hypothesis evaluation dictates the nature and scope of the new monitoring and research programs recommended in Phase III.

The preceding hypotheses provide a means of understanding and studying the role of temperature in the survival and spawning success of salmon and steelhead.

It is important to understand that temperatures above the upper tolerance level are neither immediately nor necessarily lethal. The salmon do not die immediately when they encounter temperatures outside the upper tolerance range. Outside the upper range of temperature tolerance, physiological processes that can lead to death are set in motion. Whether or not death or disability occurs depends on the duration of the exposure and other lethal factors such as disease. Temperature is termed a lethal factor in the scientific literature because of its ability to bring about death, not because it always causes death. It is important to bear in mind that experiencing a lethal factor does not necessarily result in death.

As a consequence of the pervasive and compelling effects of temperature on fishes documented in the scientific literature, it is important to understand how it acts on immigrating adult salmon. Understanding the temperature regimes experienced by salmon and steelhead immigrating to the Columbia River and its tributary, the Snake River (Figure 1), during the summer should be particularly important to their management. Adult fall chinook salmon and steelhead immigrate to the Columbia River watersheds during the time of year when water temperatures often exceed the upper limit of the optimum temperature range for salmon. Conservation of energy is essential for the individual to be able to complete its life cycle. Since the fall chinook salmon does not replenish its energy stores through feeding after departing the marine environment, it must survive the sixty to eighty days remaining in its life cycle on a finite energy reserve.

The immigrant steelhead has a similar need to conserve energy expenditures, however its post-marine life cycle schedule is longer, and therefore more flexible than that of the chinook. The steelhead is more flexible than the chinook because it can interrupt its immigration for longer periods of time without necessarily diminishing its spawning success. Chinook salmon are in a relatively tight race against time and declining energy reserves once the spawning migration is initiated. In both species, the amount of energy available for completion of spawning is finite, so the conservation of that energy is of paramount importance for completion of the life cycle. As a dominant abiotic environmental factor, temperature is therefore a crucial factor in the conservation of bodily energy reserves in salmon and steelhead.

As a frame of reference for studying the behaviors of fish and temperature, we have chosen four basic temperature ranges and adaptation zones (Figure 2) on the basis of literature records. The optimum temperature range (45-60F) and the lethal range (70F and above) are separated by zones of upper tolerance (60F – 68F) and resistance (68F – 70F). The boundary temperatures are called incipient lethal levels (ILL), with the upper (UILT) being 68F and the lower (LILT) being 45F. The ranges, zones, and incipient lethal levels of our study are based on classifications that were found useful in other studies of the physiology of fishes in relation to temperature (Fry 1971). In the section, Definition of Temperature Zones, below, a survey and synthesis of the literature provides a detailed description and discussion of the scientific basis for the ranges and zones chosen for this study.

Evaluating the temperature-survival hypotheses becomes very important in those situations where cold-water species such as salmon and steelhead may be subjected to an increase in the annual number of degree-days as a result of habitat alteration. The physical basis for the concern that impoundment can increase the annual time period of exposure of Columbia River basin salmonids to temperatures above the UILT is discussed below.

Effect of Reservoirs on Water Temperatures; Historic Characterization of the Columbia River Basin

A number of researchers over the past 40 years have examined the question of the effect of reservoirs on water temperatures. Although approached from different directions for different purposes, all of the research reached essentially the same conclusions, as the following discussions will show.

A compilation of water temperature data relating to the temperature profile of Lake Roosevelt and the effect on downstream temperatures was prepared at the request of the Atomic Energy Commission for use by the Bureau of Reclamation (Kramer 1962a). Daily water temperatures at Grand Coulee Dam in 1958 illustrate the pronounced temperature gradient or stratification from the spillway to the cooler water at depth (Figure 4).

During the month of August, water going over the spillway increased in temperature from about 68 to 72F. Water 255 feet deep (elevation 1035) also increased about 4F during August but remained consistently about 9F cooler than at the spillway, ranging from about 59 to 63F.

In 1961, the Atomic Energy Commission, Bonneville Power Administration, and Bureau of Reclamation drew on the above information to carry out a cooperative operation of Grand Coulee Reservoir to reduce the temperature of cooling water used downstream in the Hanford reach (Kramer 1962b).

As much of the system electrical generation load as possible was shifted to Grand Coulee to increase the rate of cool water release through the turbines and thus maximize the downstream cooling effect. The results (Figure 5) show that the cooling operation resulted in 8F cooler water in the Hanford reach during early August compared to the temperature with normal operation, the latter based on past experience.

Material presented at a symposium on water pollution research (US Department of Health Education and Welfare 1963) led to the conclusions that:

1. Large and deep impoundments generally decrease downstream water temperatures in the summer and increase them in the winter.
2. Shallow impoundments with large surface areas increase downstream water temperatures in the summer.
3. Water periodically withdrawn from the surface of a reservoir increases downstream water temperatures.
4. A reduction in normal streamflow below an impoundment causes marked temperature increases.

Grant County Public Utility District sponsored work to identify the temperature regime of the Columbia River from Priest Rapids, Washington to Arrow Lakes, British Columbia in recognition of the need to increase understanding of the effect that impoundment of the river above the Snake River confluence would have upon its temperature (Davidson 1964).

Grand Coulee Dam went from 12 generators in operation in 1949, to 15 in 1950, to the full quota for powerhouses 1 and 2 of 18 generators in 1951. Temperature data for those years show that the larger the number of generators in operation at the dam, the more rapid is the removal of the cool bottom waters of the reservoir and their replacement by the warmer waters entering the reservoir as well as those from its surface.

The full before-and-after Grand Coulee Dam effect (Figure 6) can be seen from the temperature regimes in the similar and representative years of 1936 and 1951, as measured downstream at Rock Island Dam. Peak temperatures before Grand Coulee in 1936 were about 6F warmer by late July than the peak after Grand Coulee in 1951 (Figure 6). Peak 1936 temperatures extended from late July through August and then rapidly decreased, while the 1951 peak shifted to later in the season and lasted longer, extending from mid-August through mid-October, a duration of about 8 weeks after Grand Coulee compared to five weeks before the project. From mid-September through December, the after-project temperatures steadily increased over the before-project temperatures from 3 to 10F.

The effect of reservoirs on stream temperatures can also be shown by comparing the temperatures for a given time period of two nearby streams, one with, and the other without, upstream storage control. The effect of impoundment on the cumulative temperature experienced by aquatic organisms as a result of impoundment can be seen in the comparison of the effect of Brownlee Reservoir, as measured below Hells Canyon Dam, with the free-flowing Salmon River at its mouth (Figure 7). Although maximum seasonal temperature is just as high in the free flowing river as it is in the impoundment, the temperatures in the impoundment are higher for longer periods of time. The area under the temperature curve for the impoundment is larger than the area under the curve for the river, indicating that there are more degree-days in the impoundment than in the river (Figure 7).

The Salmon River's response to weather fluctuations is much more rapid and pronounced than the Snake River (Figure 7). The Salmon warms faster, reaches its peak temperature sooner, and cools much faster than the reservoir-controlled Snake. The Salmon peaked at 71F one week into August; the Snake at about the same temperature 10 days later. The Salmon temperature dropped to 66F in about 9 days, on August 16; The Snake took until September 25, 39 days, to cool to 66F, at which time the Salmon had cooled to below 56F (Figure 7).

A Columbia River thermal effects study was initiated in 1968 in response to the problem of inconsistent Columbia River temperature standards adopted by Oregon and Washington for the river reach that they share (Environmental Protection Agency, 1971). The study concluded that

1. The major effect on temperature caused by reservoirs was the shifting of water temperature maximums to later in the year.

2. The construction of Brownlee Dam resulted in a reduction in downstream summer temperatures, an increase in fall temperatures, and a shift in the period of peak temperature from July to August. (Note that this was before the construction of Dworshak Dam.)

3. It had been demonstrated that the Grand Coulee release program could be used to lower Hanford water intake temperatures.

ACQUISITION OF DATA

The data sets acquired and placed in standard tabular spreadsheet format included water temperature and velocity collected from transects of lower Snake River reservoirs, counts of adult salmon at lower Snake River dams, hydroelectric turbine scroll case water temperatures, hydroelectric project water flows, tri-level thermograph recorded temperatures, fish ladder water temperatures, tributary temperatures, temperatures from total dissolved gas level monitoring facilities at lower Snake River Dams, and summary fall chinook radio tagging detections (Table 2). Water flow and spill at hydroelectric projects have been included in the data base as important physical covariates of both temperature and fish passage, however these were not the object of analysis during this phase of the project.

Data Sets

Transects

Water temperature and velocity data were taken at sixteen transect cross sections extending from the Clearwater River, above the confluence of the Clearwater and the Snake rivers (Stations 1 and 2), to below the confluence of the Columbia River and the Snake River (Station 16) in 1991 and 1992 (Table 3). The remaining 12 transects are at about ten-mile intervals through the lower Snake reach, three in each of the four reservoirs. Measurements of temperature and velocity were taken at twelve specific points in the transect during each day the transects were run in 1991 and 1992. Measurements at each transect were located at three sites; mid-channel and 1/4 of the width from each bank, and at four depths at each site; near the surface, 1/3 depth, 2/3 depth and near the bottom. Temperatures were recorded to the nearest 0.1 C and were converted into Fahrenheit. Depths were also recorded. During the data analysis portion of this project, errors were noted in some transect depths while some temperatures were converted to Fahrenheit incorrectly. These errors were corrected.

Tri-Level Thermographs

Permanent tri-level thermograph installations were made at the transects nearest each of the four lower Snake River dams; stations 5, 8, 11, and 14. The temperature sensors are programmed to record temperatures to the nearest 0.1C at one-hour intervals, and are capable of functioning for long periods without attention. They were attached to buoyed lines anchored about 200 feet from shore to be outside of the navigation channels, with the top sensor about 7-feet below the water surface to be clear of small-boat traffic and safe from vandalism. One of the other two sensors at each installation is about ½ depth and the other is near the bottom. An emitted signal directs the boat to the installation which is pulled up with a grappling hook in order to download the data into a laptop computer. The hourly data was converted to daily averages and the mean, standard deviation, minimum, and maximum daily temperatures calculated.

Fall Chinook Radio Tagging Recoveries

Fall chinook radio tagging recoveries compiled by the Snake River Laboratory of the Washington Department of Fish and Wildlife (Mendel et al. 1992) were summarized by date and dam (Table 1). Tagging recoveries prior to September are few, and somewhat limited for the purposes of studying the interactions of immigration and water temperatures, because tagging of fall chinook is delayed until water temperatures cool. The tagging is delayed under terms of the federal permit for handling the threatened fall chinook owing to the potential for stress related deaths in the high water temperatures typical of August. Consequently, observations on the average time required by an adult fall chinook to pass a Snake River hydroelectric project (Table 1) occur during time periods of naturally declining Snake River water temperatures.

We recommend trapping PIT tagged returning Snake River adult fall chinook at Bonneville Dam for application of depth and temperature sensitive radio tags in future studies. The PIT tag could be used to identify Snake River origin fall chinook salmon at the trapping facility at Bonneville Dam. Temperatures are generally lower at Bonneville Dam than at Snake River dams, and fall chinook salmon would be expected to be in the best possible physiological condition early in their migration up the Columbia River. Trapping, handling and holding facilities are well developed to insure the safety of the salmon at Bonneville Dam.

Fish Ladder Temperature Data

Temperature data from Snake River dam fish ladders was collected from 1991 through 1996 by University of Idaho personnel. Temperatures were recorded hourly at the upper and lower ends of the fish ladders as well as at the tailrace of the dam (Table 4). Temperatures were recorded to the nearest 0.1C and were then converted to degrees Fahrenheit. Numerous errors in the form of negative temperatures or sudden change of several degrees in an hour (with an offsetting change the following hour) were found in this data and corrected for the years 1991-1994. The hourly data was converted to daily averages and the mean, standard deviation, minimum, and maximum daily temperatures calculated.

Scroll case water temperatures

Daily scroll case water temperatures were provided by the U. S. Army Corps of Engineers North Pacific Division for its four lower Snake River Projects through the Columbia River Operational Hydromet Management System (CROHMS) data network. Data is collected daily to the nearest 1F. Temperature data since 1991 from Dworshak Dam is included in scroll case water temperature files. While using this data, a few errors in the form of one day changes of 10 degrees in water temperature (with an offsetting change the following day) were noted and corrected. When data was missing, values were linearly interpolated for use in statistical analyses.

Daily scroll case water temperatures were provided by the Idaho Power Company for its three Hells Canyon Complex projects through its Recreation Report. The report also provides daily average inflow to Brownlee Reservoir, and outflow average and range from Hells Canyon Dam. Daily scroll case temperatures generally decline during the course of the fall chinook immigration season at the lower Columbia and Snake River Projects (Figure 3, Table 5).

Fish Count Data from Mainstem Dams

Records of daily counts of salmon by species from the eight mainstem dams of the lower Columbia River and the Snake River are available for all years of record. Errors were found in some data from the 1960's, usually in the form of data entry errors, and corrected.

Flow and Spill Data

Records of daily flow and spill from the eight mainstem dams of the lower Columbia River and Snake River (1981-1996) are available for use in future analyses.

Total Dissolved Gas Monitoring Stations

Temperatures from the total dissolved gas monitoring program were acquired and tabulated for use in future analyses. These stations are typically located above the dams (although a few are located below dams), and data was acquired for the years 1993 through 1996 (Table 6). The data was collected hourly to the nearest 0.1C. From this data, the daily mean, standard deviation, minimum, and maximum temperatures were calculated.

Tributary Temperatures

Temperature sensors, similar to the tri-level thermographs previously described, are maintained by Idaho Power Company to record Snake River and tributary stream temperatures. These sensors also recorded at one-hour intervals, and were converted to daily average measurements.

ANALYSIS OF DATA

Data collected and summarized for this project were analyzed using two different methods. First was a series of graphical analyses depicting the temperature profile of the lower Snake River at a particular time or over the entire fall chinook migratory period. Second was a series of mathematical analyses using temperature data and estimates of fish passage at mainstem Snake River dams to describe the temperature profile faced by migrating fall chinook and to determine the circumstantial impacts of temperature on fish passage. This section groups the different graphical analyses but presents the mathematical analyses separately.

Graphical Analyses

Methods

Temperature Zones and Ranges in the Lower Snake River

One measure of the impact high water temperatures may have on salmonids migrating through the Snake River system is to determine the length of time that temperatures exceed both the optimum temperature and the UILT during the migratory period. To look at changes over the historical period, the mean daily water temperature at Ice Harbor Dam (as represented using scroll case temperatures) was plotted over three five-year periods. The first period (1963-1967) represents the time prior to the building of LMN, LGS, LWG, and Hells Canyon Dams. It should be noted that this does not represent ambient temperatures of the unimpounded Snake River for, by 1963, Brownlee and Oxbow dams had been completed along with other dams farther upstream. The second period (1992-1996) represents the time in which the temperature control program described in this report was conducted. And the third period (1986-1990) represents the most recent five-year interval prior to the temperature control program.

To estimate the extent to which any changes in temperatures have harmed fish passage, the percent of days between June 1 and September 30 that the IHR and LWG scroll case temperatures exceeded both optimum and UILT levels was plotted for the years 1963-1996. For comparison purposes, temperatures from the John Day Dam scroll case were also included as well as the mean flow at Ice Harbor Dam during this period.

Temperatures over Time

From 1991-1996, cold water was drawn from Dworshak Reservoir in an effort to either provide increased flow for juvenile downstream migration and/or to reduce water temperatures encountered by juveniles and by upstream migrating adults in the four lower Snake River reservoirs (Figure 1). The schedule of water releases from Dworshak Reservoir varied considerably over the years studied. To estimate the magnitude and extent of any temperature declines in the lower Snake River reservoirs, temperature data from tri-level thermographs in Snake River reservoirs was plotted along with the mean daily flow from Dworshak Dam. This was plotted over the period from late June through early October for the years 1991, 1992, and 1994-1996. In 1993, missing temperature data resulted in the analysis being terminated in early September. The mean daily mid-level thermograph temperature was used except in 1991 when scroll case temperatures were used prior to the installation of the thermographs. The resulting plots and supporting data were examined to quantify the decrease in water temperatures in the lower Snake River resulting from the releases from Dworshak Reservoir.

Temperature-at-Depth

Using temperature data from the transects of Snake River reservoirs in 1991 and 1992, an analysis of temperature-at-depth was developed to show the geographic pattern in water temperatures at depth encountered by salmon immigrating to the Snake River basin (Karr, Tanovan et al. 1992). On each transect there are three stations where four different temperature measurements were made at equidistant depth intervals starting at the surface (Figure 8). All temperature data were assigned to one of four categories: 1) lethal (>70F, 21.1C), 2) resistance (68 -70F, 20 -21.1C), 3) upper tolerance (60 - 68F, 15.6 - 20C), and 4) optimum (45 - 60F, 7.2 -15.6C). Temperature categories were color coded and plotted by depth (along the y-axis). On each date sampled, the temperature categories for each transect were placed along the x-axis according to their distance above the mouth of the Snake River (Table 3). The resulting plot depicts the ambient temperatures available to salmon on that date, as they migrate upstream through the Snake River system.

Temperature Contours

Temperature data from the 1991 and 1992 transects (Karr et al. 1992) were also used to plot temperature isotherms using standard software implementing well-known curve fitting procedures (Keckler 1996). Temperature grids were created with the Kriging method, an exact interpolating method useful for small data sets. The anisotropic ratio was set at 20:1 giving more weight to observations on the X axis. This adjustment was made to account for the difference in scale between the X and Y axes (river width and depth).

Results

Temperature Zones and Ranges in the Lower Snake River

Regardless of the five-year time period examined, scroll case temperatures at IHR exceed optimum levels for well over three months (Figure 9). Also apparent in comparison of the 1963 -1967 and 1986-1990 time periods is evidence of the pattern of increasing duration of higher temperatures that was found to be associated with the impoundment of a free-flowing river (Figure 6). Scroll case temperatures exceed UILT five days later in 1986 -1990 compared to 1963 -1967, but stay above UILT nine days later. The peak temperature was 21 days later in 1986 -1990 compared to 1963-1967. Scroll case temperatures were much lower from late July to mid-September in 1992 -1996 than either 1986-1990 or 1963-1967. This was the period during which cool water was being released from Dworshak in 1992 -1996. Temperatures exceeded UILT for 63 consecutive days in 1963 –1967, for 67 consecutive days in 1962 -1996, but for only 43 consecutive days in 1992 -1996. It should be noted that the time pattern of maximum water temperatures in 1992 - 1996 was altered downward, since in these years cold water releases were being made from Dworshak Dam (see Figure 1).

Scroll case temperatures normally exceed optimum levels over 70% of the days studied at the dam localities of IHR, LWG, and JDA between June 1 and September 30 (Figure 10). It appears that scroll case temperatures are inversely related to flows at IHR. Scroll case temperatures are less likely to exceed UILT at John Day Dam than at IHR (Figure 11). Note that temperatures in the scroll case may at times differ substantially from those in the fish ladders and other localities. Again, there appears to be an inverse relation between flows at IHR and scroll case temperatures. The strength of this correlation was tested by correlating mean 7 day IHR scroll case temperatures with mean 7 day IHR flows for the years 1975-1996 (Figures 12 and 13). Higher flows led to stronger correlations than lower flows (Figure 13). The variation in the relations between flow and water temperature measures (Figures 12 and 13) clearly indicate that factors other than flow, such as air temperatures and upstream releases of cold water, are important determinants of water temperatures.

Temperatures over Time with Cold Water Releases

In 1991, Dworshak Reservoir releases were constrained by a commitment to limit the drawdown to five feet before Labor Day in response to local concerns about adverse impacts of deeper reservoir drafts on recreation and tourism.

Therefore modifications to Dworshak releases did not occur until August 16 when outflow temperatures were decreased to 45F (7.2C) and the outflow rate increased to the project hydraulic capacity of about 10 kcfs (Figure 14). Flows were held at 10 kcfs until the 5-foot drawdown constraint was reached on August 22. Flows were then dropped to 2 kcfs through Labor Day, after which flows were again raised to 10 kcfs for the remainder of September. Flows were then again returned to about 2 kcfs (Karr et al 1992). As measured by the transect observations, the temperatures within the reservoirs were reduced to the target adopted for the temperature control effort of 1991 (68F) on September 11 at LWG and September 21 at IHR (Figure 14).

In 1992, outflows from Dworshak reached 21 kcfs for two weeks in mid-July, and about 11 kcfs for eight days in mid-September. DWR release temperatures from 5/5 through 9/8 ranged from 45F to 57F and averaged 52F (11C). A 10F decrease from about 74F to 64F (23.3 to 17.8C) took place at transect station 5 in LWG reservoir in 11 days from July 4 to July 14, with the effect diminished to a decrease of about three degrees (71.5 to 68.5F [21.9 to 20.3C]) over eight days (July 20 to July 27) at IHR (Figure 15). These temperature reductions resulted from Dworshak cold water releases, whereas natural cooling caused sharp temperature declines at LWG starting about August 18, and reaching IHR about September 3. The additional mid-September

Dworshak release increased the rate of temperature decrease through the lower Snake reservoirs.

In 1993, Dworshak outflow increases were directed toward enhancing juvenile fall chinook emigration in July (up to 20 kcfs over an eight-day period) and keeping temperatures down over a 12-day period from August 1 to benefit the later run of adult fall chinook (up to 25 kcfs) (Figure 16). Release temperatures from 6/23 through 9/9 ranged between 45 and 52F (7-11C) and averaged 48F (9C). A relatively cool summer occurred in 1993, so both the daytime and nighttime temperature differential between the air and the water was much less than in other years examined. Primarily as a result of the lower air temperatures, the downstream changes in transect water temperatures in the 1993 tests, although apparent (Figure 16), were of a lesser magnitude than those observed in other years of the cool water releases.

In 1994, cold water releases from Dworshak, ranging from 20 to 25 kcfs, took place during the last three weeks in July during the juvenile fall chinook emigration. Release temperatures during that period ranged from 42 to 54F and averaged 48.6F (9.2C). Data from mid-level recording thermographs at transect stations 5, 8, 11, and 14 indicated that this water release regime resulted in pronounced decreases in water temperature through the entire 140 mile lower Snake reach (Figure 17). The results were a 9.5F (5.3C) drop in LWG reservoir over a 24-day period (7/7 to 7/30) diminishing with downstream distance to a 4.4F (2.4C) drop in IHR reservoir over a 26-day period (7/18 to 8/13).

These observed dates also provide a measure of water travel time through the lower Snake River under the flow rates present during that period.

In 1995, cold water releases from Dworshak were initiated on July 17 and continued until early September, which was six weeks of sustained flow at about 14 kcfs and an average release temperature of 50.5F (10.3C) (Figure 18). Results showed a maximum mid-depth thermograph temperature decline response at LWG of 5.5F (3.1C) over 32 days starting July 22, with a downstream maximum diminishing effect to 4.7F (2.6C) at IHR over 43 days starting July 29 (Figure 18). This lesser magnitude of temperature decrease than in 1994 is largely due to a combination of lower outflow rate (14 kcfs vs. 25 kcfs) and higher release temperature (50.5 °F vs. 48.6F [10.3 vs. 9.2C) in 1995.

In 1996, cold water releases from Dworshak were initiated on August 15 and continued to August 31 at about 21 kcfs, and then continued to September 10 at about 11 kcfs (Figure 19). Average release temperature during this period was 52.4F (11.3C) which was 1.9F (1.1C) higher than in 1995, and 3.8F (2.1C) higher than in 1994. The maximum mid-depth thermograph temperature decline at LWG was 7.8F (4.3C) over 18 days starting August 14, and gradually diminished to 5.5F (3.1C) at IHR over 14 days starting August 27.

Temperature-at-Depth and Temperature Contours

By combining the chronology of temperature events (Appendix A, Table A1, Figures A1 and A2) with the graphs of temperature at depth and temperature contour plots, the impact of cold water releases on the nature of the thermal regime through which immigrating adults must pass on dates of record is illustrated. The following results from 1991 illustrate the detail made possible by transect observations in 1991 - 1993. For example, by August 8, 1991, any adult salmon immigrating to the lower Snake River between Ice Harbor and Lower Granite Dams (Figure 1) would have experienced temperatures above the UILT (68F), with temperatures in most of the water column being in the lethal range (Figure 20). Resistance zone temperatures below the lethal (68 -70F) were to be found only at the deepest points in the reservoirs (Figure 21). Therefore, at all but a few of the deepest points in the lower Snake River on August 8, 1991, the immigrants would have experienced temperature levels in the lethal range. On August 23, however, the cooling effects of earlier releases of cold water from behind Dworshak Dam (Figure 1) were becoming apparent (Figure 22; Table A1). Temperatures at the depths of Lower Granite reservoir on August 23 have reached optimum levels with a steep gradient to lethal levels at the surface (Figure 23). Cooler waters have also infiltrated Little Goose reservoir while lethal levels persist elsewhere in the lower Snake River system. By August 27, with cold water releases from Dworshak Dam having been terminated August 21, temperatures at the upper end of Lower Granite reservoir are returning to resistance levels (Figure 24). The upper end and deeper portions of Little Goose reservoir are at upper tolerance temperature levels. Some resistance level temperatures have infiltrated Lower Monumental reservoir, but lethal temperatures persist through the rest of the system (Figure 25).

Discussion

The release of cold water from Dworshak Reservoir can affect temperatures of the Snake River from the mouth of the Clearwater River to its confluence with the Columbia River. The magnitude, timing, and duration of the effect is largely dependent on the magnitude of releases from Dworshak Reservoir, although total Snake River flow and air temperatures are necessarily significant factors that were not part of this study.

Cold water released from Dworshak Reservoir also affected the extent of stratification of the reservoirs behind Ice Harbor, Lower Monumental, Little Goose, and Lower Granite dams. Prior to releases, the Lower Snake River usually was homothermic with temperatures within or near the lethal range throughout the system. Following cold water releases, cooler waters infiltrated the system from Lower Granite Reservoir to Ice Harbor Reservoir. Reservoirs gradually became thermally stratified, with temperatures declining first near the bottom of the reservoirs. Eventually, cool water appeared at the surface, although temperatures were almost always cooler deeper in the reservoir than near the surface. When cool water releases stopped, water temperatures rose, first at Lower Granite Dam, eventually progressing downstream to Ice Harbor Dam. Temperatures rose first at the surface and last in the deep water. This suggests the possibility that it may be feasible to use cool water releases from Dworshak Reservoir to create a migratory corridor or a series of thermal refugia within the reservoirs of the Lower Snake River system during the portions of the fall chinook immigration period when temperatures are highest. Close monitoring of the deeper portions of the reservoirs in the system could allow sufficient water to be periodically released from Dworshak Reservoir to keep a base of cool water in the reservoirs. The fish may then be able to either migrate continuously through a corridor of cooler deep water, or immigrants may be able to find temporary refuge from the effects of the resistance zone temperatures in isolated pools of cooler deep water. The monitoring of water condition parameters other than temperature (such as dissolved oxygen levels) would be required to ensure that salmonids could use a plume of cold water in the deepest portion of the reservoirs.

Spatial detail in water temperature measurements comparable to that of the transects in 1991 – 1993 would provide the best monitoring of the conditions available to the salmon and steelhead immigrants. As demonstrated in the temperature-at-depth analyses and temperature contours of 1991 – 1993 (Figures 20 – 25), the substantial vertical temperature structure cannot be adequately described by spatial point estimates such as scroll case temperatures. Further comparisons of transect temperatures to scroll case and tri-level thermograph estimates are given below under Mathematical Analyses. Given the possibility that salmon and steelhead would temporarily use thermal refugia, rather than immigrate through adverse temperatures, documenting the existence of thermal refugia could be important to understanding timing of immigration and spawning success.

The possibility of vertical structure in reservoir temperatures, and the paucity of measures of vertical structure, means that the seasonal temperature dose in degree-days received by salmon and steelhead needs to be estimated *in situ* through the use of recording thermographs affixed to the immigrants. Recording thermographs smaller than the size of a half-dollar are commercially available. Externally affixing the thermal recorder tags to adult chinook salmon at Fisheries Engineering and Research Laboratory at Bonneville Dam that have been identified as of Snake River origin by PIT-tag information would produce data on the temperature regime experienced by the individual fish. Evaluation of the temperature-survival hypotheses is not possible given current data, however such evaluations would be relatively straightforward by the use of individual temperature doses.

Statistical analyses

Statistical analyses - correlation coefficients of temperature data

Methods

A number of different sources of temperature data provide records for different time periods for each of the four lower Snake River dam and reservoir complexes. These include scroll case temperatures, tri-level thermographs, gas monitoring stations, fish ladder temperatures, and transects (see Acquisition of Data). Each of these sites monitors temperatures at different locations in the migratory pathway through the lower Snake River system. The longest time series of temperatures in the lower Snake River reservoir system is from temperatures recorded daily at scroll cases at the hydroelectric dams. The other types of observations have been collected for varying lengths of time, raising the question as to how each data type relates to the scroll case temperatures and to other measures. Questions we were particularly interested in were, 1) How well do the scroll case temperatures reflect the information provided by observations from the other locations? and 2) Can the data set represented as scroll case temperatures serve some of the same purposes as more spatially detailed data collection procedures?

To investigate the extent to which the time series behavior of these data types may be similar, matrices of estimated product moment correlation coefficients, r, (Sokal and Rohlf 1969) were constructed for temperature measures around each dam using daily observations from the start of the fall chinook salmon migration through October 31 each year. The start of the fall chinook salmon migration is arbitrarily set at August 12 at Ice Harbor Dam, August 14 at Lower Monumental Dam, August 16 at Little Goose Dam, and August 18 at Lower Granite Dam. At most dams in most years, the U.S. Army Corps of Engineers ceases counting on October 31. By this date, fish passage has normally decreased to very low levels.

In addition to recording the sample size and equal variance Student's t value for each comparison, the significance probability (p value) for each of the following statistical tests was computed: 1) unequal variance t-test that the pairs compared were equal, 2) equal variance t-test that the pairs compared were equal, and 3) equal variance F test for homogeneity of variances. The matrices were constructed for each dam to compare daily temperatures recorded at scroll cases, tri-level thermographs (bottom, middle, and surface daily means), total dissolved gas monitoring stations (daily means), fish ladders (ladder bottom, top, and tailrace daily mean temperatures), and at transects (daily maximum, minimum, and mean temperatures) located in the head pond as well as immediately below the dam in question. In the years 1993 - 1996, there were temperature measures from seven other localities to compare to the scroll case temperatures. In the years 1991 and 1992 there were 23 other such measures.

As an illustration of the type of comparisons made, we compared temperatures recorded at various locations near and at Little Goose Dam from 1993-1996 (Table 8). Scroll case temperatures were compared to those recorded by tri-level thermograph number 8 at the bottom, the middle, and at the surface, the Little Goose tail race, the Little Goose adult fish ladder at the bottom and at top , and the Little Goose total dissolved gas monitoring station. Measures given for the comparison are the product moment correlation coefficient and its sample size, p values for unequal and equal variance t-test and equal variance F test, and the equal variance sample t values.

Comparison of scroll case temperatures to other measures of temperature taken at different localities near the Little Goose Dam on the Snake River, 1991 - 1992 included extra variables (Table 9). In 1991-1992, the other localities compared to the scroll case are the daily mean, minimum and maximum for transects numbers 5 through 9 (Tr 5 Mean, Tr 5 Min, Tr 5 Max), temperature tri-level thermograph number 8 at the bottom (TLT 8B), the mid-level (TLT 8M), and at the surface (TLT 8S), the Little Goose tail race (LGS TR), the Little Goose adult fish ladder at the bottom (LGS Bot), and at the top (LGS Top). Measures for the 1991-1992 comparison are the product moment correlation coefficient and its sample size, p values for unequal and equal variance t-test and equal variance F test, and the equal variance sample t-values.

Results

For the years 1993 through 1996, correlation coefficients for the scroll case at Little Goose Dam and other temperature measures ranged from very low (0.01, 1993, LGS Top, Table 8) to very high (0.99 LGS Top 1994, Table 8). Some correlations are not valid comparisons. For example, those with negative correlation coefficients are due to large data gaps resulting in correlation coefficients based on temperatures recorded on only a few days. The sample sizes and significance probabilities need to be consulted to interpret the correlation coefficients. Minimum transect temperatures most often did not correlate significantly positively with scroll case temperature measures, and with other measures such as those from total dissolved gas monitoring stations. Patterns of correlation among temperatures at different localities were similar to 1993 - 1996 when transect localities were incorporated into the comparisons of 1991 and 1992 (Table 9). Surface oriented measures of temperature and tailrace temperatures frequently have a significantly positive correlation with scroll case temperatures, whereas bottom temperature measures do not. Unfortunately for our analysis, as was the case in 1993 - 1996, the time series of other non-transect measures of temperature was not as complete as that of scroll case temperature, resulting in some invalid correlations.

Scroll case temperature measurements are often higher than other measures of temperature. For example the Little Goose daily scroll case temperature in 1991 is consistently one to seven degrees (F) higher than the mean daily temperature on the transects immediately upstream and downstream of Little Goose Dam (Figure 26). Similarly, the mean daily temperature recorded at the mid-level tri-level recording thermograph immediately below Little Goose Dam is generally one to four degrees (F) lower than that recorded at the Little Goose Dam scroll case for 1992, 1994, and 1995 (Figures 27, 28, and 29).

Discussion

The pattern of correlations observed among localities demonstrates that the daily temperatures collected in the vicinity of the dams and nearby reservoirs since 1991 are somewhat similar to scroll case temperatures. However, scroll case temperatures cannot capture the detail of the water temperature regime in the reservoirs. For example, scroll case temperatures tend to be biased high relative to the mid-level tri-level thermograph when water temperatures are warmest due to thermal stratification (Figures 27-29). The apparent similarity among temperature measures among the localities occurred because most measures of temperature 1991 - 1996 were taken in the upper portion of the water column and/or when there was little or no thermal stratification. Tri-level thermograph and transect temperatures are the only recording localities that measure temperatures near the bottom of the water column. Temperatures in deeper waters are often much cooler than those of surface waters, particularly after colder water from Dworshak Reservoir is added to the Snake River system.

Existing water temperature observations in the Snake River reservoirs inadequately characterize the system when cooler water is added from Dworshak Reservoir. Other than data from the tri-level thermographs, no temperature data is recorded in the lower portions of the water column. It is impossible to determine whether sufficient cold water exists at the reservoir bottoms to provide a migratory pathway which salmonids might use to travel from IHR to LWG while largely avoiding high water temperatures. More spatial resolution is necessary in temperature measurements to understand the range of temperatures available to immigrating salmon and steelhead.

Statistical analyses - comparison of scroll case and transect temperatures

Methods

To further explore how well scroll case temperatures reflect the information provided by the other locations, scroll case temperatures at IHR and LWG were compared to those recorded at transects immediately upstream and downstream of both dams for 1991 and 1992. Paired t-tests were used to test for differences between the daily scroll case temperature and the transect daily mean, minimum, and maximum temperatures. The t-statistics, p-values, and differences were tabled and the differences plotted over time.

Results

The LWG scroll case temperature differed significantly (α=0.05) from the mean, minimum, and maximum Transect 5 and 6 temperatures for 1991 and 1992 with only a single exception (Table 10). This exception was for maximum temperature at Transect 6 where the p-value was 0.06. The minimum Transect 5 temperature deviated from the scroll case temperature by as much as 13.6F while the maximum Transect 5 temperature deviated by as much as 11.7F. The minimum Transect 6 temperature deviated from the scroll case temperature by as much as 8.6F while the maximum Transect 5 temperature deviated by as much as 7.4F. Transect temperatures had the largest deviation from scroll case temperatures during summer Dworshak releases when LWG pool was most temperature stratified. These deviations decreased later in the season to the point where transect temperatures deviated little from scroll case temperatures in October (Figures 30 and 31)

The IHR scroll case temperature differed significantly (α=0.05) from the mean, minimum, and maximum Transect 14 and 15 temperatures in two of six tests in 1991 and five of six tests in 1992 (Table 11). The minimum Transect 14 temperature deviated from the scroll case temperature by as much as 7.6F while the maximum Transect 14 temperature deviated by as much as 10.4F. The minimum Transect 15 temperature deviated from the scroll case temperature by as much as 4.9F while the maximum Transect 15 temperature deviated by as much as 5.9F. Transect temperatures had the largest deviation from scroll case temperatures during summer Dworshak releases when IHR pool was most temperature stratified. These deviations decreased later in the season to the point where transect temperatures deviated little from scroll case temperatures in October (Figures 32 and 33).

Discussion

Temperatures recorded at dam scroll cases can differ significantly from temperatures recorded just a few miles away. This is particularly true in dam forebays where temperatures stratify. Differences tend to be less immediately downstream of dams (e.g. Transects 6 and 15) where mixing occurs as water flows through the turbines or over the spillways. Differences also tend to be less at IHR than at LWG. This likely results from Dworshak releases having less effect on the temperature of, and stratification, of IHR than LWG.

If temperature stratification could be maintained throughout the migratory period through the use of water releases from Dworshak, and other water quality issues don't prevent use of this cool water, it may be possible to maintain migratory pathways of relatively cool water for the use of anadromous fish.

Statistical analyses - time and fish averaged temperature descriptions

To describe ambient temperature conditions experienced by salmon in the hydroelectric system, two different sets of statistics were calculated. The first were time averaged temperature statistics, consisting of the mean and standard deviation of temperatures of during the period in which fall chinook are migrating (August 12, 14, 16, and 18 through October 31 at IHR, LMN, LGS, and LWG, respectively). Although these time-averaged temperatures are useful descriptors of physical conditions for general purposes, they may not necessarily be appropriate descriptors of ambient temperature conditions experienced by salmon in the hydroelectric system. The primary objective of this investigation is to provide statistics of temperature and fish movements that can be used to formulate, evaluate, and refine hypotheses explaining the roles of water temperature in determining fish behavior and survival.

Methods

In this study, the ambient temperatures for fish, and the migratory behavior of the adult salmon are described by fish weighted statistics. Fish weighted statistics for temperature and timing of migration are calculated by using the daily number of adult fish as weighting factors in Equations 2 and 3. Methods for the analysis of migratory time series as fish weighted time (Mundy 1982; Babcock and Mundy 1985; Matylewich and Mundy 1985) and standard statistical and time series methods (Freund 1962; Box and Jenkins 1976; Sokal and Rohlf 1981), were applied. A sample mean and sample standard deviation (see Equations 2 and 3) were calculated for each year (Sokal and Rohlf 1981).

In general, a weighted statistic is defined by its daily weighting factor, *f,* and its individual daily observations, *Y*

$$\bar{Y} = \frac{\sum fY_i}{n} \qquad (1)$$

where $n = \Sigma f$ and the sum operates over all dates . The sample variance of a weighted statistic is

$$Var(\bar{Y}) = \frac{(\sum_i fY_i^2 - \frac{\sum_i (fY_i)^2}{n})}{n-1} \qquad (2)$$

(Sokal and Rohlf 1969). Note that fish weighted statistics have the total number of fish as the sample size.

The mean fish weighted temperature, *Tfw*, is the product of the number of fish on day *i*, c_i , and the average temperature for day *i*, tp_i, summed over all dates of record, divided by the sum of the fish over all dates sampled in the migratory period (August 12, 14, 16, or August 18 through October 31 for IHR, LMN, LGS, and LWG respectively),

$$Tfw = \frac{\sum_i c_i * tp_i}{\sum_i c_i} \qquad (3)$$

An estimate of the variance is found by substituting c_i for f and tp_i for Y in Equation (2).

The mean fish weighted change in daily temperature, FWCDT, provides a statistic to describe the reaction of immigrating fish to changes in temperature and is calculated by substituting the daily change in temperature for f in equation 1. A FWCDT of zero means the behavior of the fish is indifferent with respect to changes in temperature, a positive value means the fish migrate when temperatures are increasing, while a negative value indicates fish migrate when temperatures are decreasing.

The difference between the annual fish weighted time (Equation 1) of the fall chinook migration at Ice Harbor and Lower Granite Dam in days was used to estimate the mean time of passage for fall chinook salmon through the Lower Snake River.

Results

Mean annual fall chinook weighted scroll case temperatures at Ice Harbor Dam demonstrate no apparent time trend over all years of record, 1963 - 1995 (Figure 34, $r^2 = 0.0254$). Mean fish weighted scroll case temperatures at Ice Harbor vary between 63F and 69F. However it should be noted that the time series behavior of the mean annual fish weighted temperatures forms a saw tooth pattern marked by a series of linear time trends of the same or opposite slope separated by short periods of one to three years. For example, the recent downward trend in time-averaged mean August scroll case temperature at Ice Harbor, 1986 to 1996 (Figure 35) is also reflected in mean annual fish weighted scroll case temperatures from 1990 to 1995. Note that the fish weighted means cover the entire migratory period at Ice Harbor, August 12 to October 31. Another negative linear trend in fish weighted scroll case temperature occurred from 1979 to 1985. Distinctly positive trends occurred from 1964 to 1967, and 1968 to 1971.

Moving up the river, the pattern in mean annual fish weighted temperatures is similar to Ice Harbor, with the degree of similarity declining with distance. At Lower Monumental, the saw tooth pattern in the annual time series is also apparent with mean annual fish weighted temperatures ranging from 62F to 69F (Figure 36). At Little Goose Dam the mean annual fish weighted scroll case temperatures range from just over 63F to 69F (Figure 37) with no apparent linear trend over all years of record (coefficient of determination 0.0838). A narrower window of variation in mean annual fish weighted temperatures, just under 61F to just under 67F, was observed at Lower Granite Dam (Figure 38).

Comparisons of annual fish weighted change in daily temperature, FWCDT, and the difference between the fish weighted time at Ice Harbor Dam and Lower Granite Dam (1975 - 1995), as days between Ice Harbor and Lower Granite, suggest that the fish move into declining temperatures at Ice Harbor Dam (Figure 39). Note that the difference between the fish weighted time at Ice

Harbor Dam and Lower Granite Dam is here defined as the seasonal average length of time the fall chinook are in the lower Snake River hydroelectric system. Adult fall chinook appear to spend less time in the Lower Snake River reservoirs when the immigration coincides with the largest negative daily changes in temperature at the entry to the lower Snake River system. Of the twenty-one years in the comparison, twelve have negative FWCDT, eight are positive and one is zero.

By contrast, the time averaged daily change in temperature, TADCT, is unrelated to average time fish spend between Ice Harbor and Lower Granite (Figure 40). Of the twenty-one TADCT, only five are negative, three are positive, and thirteen are zero. Over a sufficiently long time span, note that the expected value of the daily change in time-averaged temperature is zero.

At Lower Granite Dam there is no indication of a relation between the seasonal average length of time the fall chinook are in the lower Snake River hydroelectric system and the FWCDT (Figure 41). The amount of time adult fall chinook spend in the reservoir system does not appear related to the magnitude of negative daily changes in temperature at the exit point from the lower Snake River reservoir system. Of the twenty years (1977 - 1996) examined at Lower Granite for FWCDT, fourteen were negative, six positive and one zero.

Discussion

The best descriptors of ambient temperature conditions for salmon are temperature observations weighted by salmon abundance. These are fish weighted statistics, or simply weighted statistics. Note that the fish weighted mean temperature statistic (Equation 1) is identical to mean number of degree-days encountered by the average fish at the place where the temperature is being observed. Although the computational methods are described for temperature, they can also be applied to describe fish ambient conditions of flow, or any other physical factor.

Time averaged and fish averaged statistics over the same time interval, for example, the fall chinook immigration period, are not necessarily the same. The temperatures most important to salmon physiology and behavior at the population level are those that occur when most of the fish are present. Temperatures early or late in the migration, when few adult fish are actively immigrating, are not as important in determining the cumulative effects of temperature on the fish population as are temperatures in the middle of the migration when most fish are actively immigrating. On the other hand, temperatures above the UILT that halt the immigration altogether would have a profound influence on all measures of timing behavior, such as the fish weighted time statistic. Weighted statistics for temperature and other physical variables such as flow describe the values of the physical variables that are ambient (surrounding) with respect to the population, whereas time averaged values of the variables do not, unless the time distribution of abundance is uniform. For example, note the frequency of differences between the weighted temperatures and time averaged temperatures for fall chinook in the lower Snake River (Table

12). Although time averaged and weighted temperatures are often close to the same value, the fact that they are usually somewhat different, and occasionally strikingly different, supports the point.

An additional reason to use fish weighted statistics is that it provides a very large sample size relative to daily temperature values. In a weighted statistic (Equation 1) each fish is a sample of a temperature value, so the standard errors of the mean weighted temperatures are usually very small. Small standard errors mean very narrow confidence intervals, and high statistical power to detect any differences that may occur in weighted temperatures between dams and years. It should be noted that the standard errors of Equation 2 do not incorporate measurement errors associated with counting fish or temperature. Measurement errors are thought to be small, however this assumption should be challenged in future monitoring programs.

The results of the FWCDT analyses are consistent with our hypothesis that holds that the fish seek lower temperatures when temperatures are above 60F. The FWCDT values are predominantly negative, whereas the TADCT tend toward zero. The results allow us to not reject our hypothesis that the immigrating fall chinook salmon react positively to declining temperatures. Given the uncertainty about the relation between scroll case temperatures and the ambient temperature conditions of the fish, these results are encouraging, but we do not consider them to be definitive. Our analyses are exploratory because the physical coincidence of the fish and the temperature measurements has not been established. Indeed, we do not expect scroll case temperatures from the interior of the dam to mirror the temperatures experiences by the fish in the river. Salmon are also expected to select the lowest available temperatures in the river, so an average value may not adequately depict the temperatures they are experiencing. The temperature recording locations described in this study were not designed with fish behavior in mind. Future monitoring programs need to be designed in accord with fish behavior.

<u>Statistical analyses - migratory timing of adult salmon for comparison to temperature descriptions</u>

Methods

Weighted statistics of the timing of the adult fall migration permit statistical comparison of timing between dam localities and years. Using the same approach described for weighted temperatures (Equations 1 and 2). Annual mean timings with standard errors have been described for each dam locality (Table 13). Annual mean timings can be compared to weighted temperatures to help advise formulation of hypotheses on the effect of water temperatures on fish behavior.

Results

The mean date of passage for adult fall chinook the lower Snake River dams has varied from September 16 in 1996 at Ice Harbor Dam to October 1 in 1986 at Lower Granite Dam (Table 13). The annual mean date of passage at Lower Granite Dam is usually later than that of Ice Harbor Dam, which reflects the fact that the two projects are separated by about 98 river miles (Table 3). In 1985, 1993, and 1995 the mean dates of passage at Lower Granite were virtually the same as those at Ice Harbor (Table 13). This is not necessarily a logical impossibility, as discussed below.

Since the lower Snake River dams were built, the mean fish weighted time of passage of fall chinook salmon through the system has increased significantly at IHR ($p=0.006$, Figure 42), LMN ($p=0.005$, Figure 43), and LGS ($p=0.032$, Figure 44) but not at LWG ($p=0.512$, Figure 45). However, there has been no such increase in mean annual fish weighted temperature over time. There is also no significant relationship between mean annual timing and fish weighted mean temperatures at IHR ($R^2=0.0226$, Figure 46), LMN ($R^2=0.139$, Figure 47), LGS ($R^2=0.0006$, Figure 48), and LWG ($R^2=0.088$, Figure 49).

Discussion

Fish weighted statistics based on counts of adult salmon passing counting windows at the dams have some limitations for two reasons, the lack of measurement error and the comingling of different statistical populations. First, the sample variance of Equation 2 assumes there is no measurement error in the dam counts, but of course there is. For example, after ascending the fish ladder and being counted the fish may fall back through the dam by one of several routes. The “fall backs” may ascend to be counted again, or simply leave the system (Mendel et al. 1992). Such measurement errors are not reflected in the standard errors (Table 13) with the consequence that these are surely underestimates. Secondly, the dam counts at Ice Harbor Dam include some fall chinook from the mainstem Columbia River, as well as from Lyons Ferry Hatchery in the Snake River. Dam counts 98 miles up the Snake River at Lower Granite are less likely to have fall chinook from these two populations than are the Ice Harbor counts. Comingling of several populations in Ice Harbor dam counts may mask the true timing of the “Lower Granite” populations at Ice Harbor. Observations on individual arrival times of PIT-tagged adults would reduce the impact of these two limitations, however PIT tag detection for adults at dams is in the developmental stages.

It is not possible, at this time, to attribute the later migration of fall chinook salmon through the lower Snake River to any changes in temperature. However, given that fish whose migration is delayed may not have the energy reserves necessary for spawning, this trend should be of concern to fishery managers in the Columbia Basin. It should also be noted that the temperature measurements used in this study are not necessarily ambient with respect to the fish. The lack of a significant relation with such crude temperature measures is not a definitive test of the temperature-behavior hypotheses. Further examination of the relation between adult fall chinook timing and temperature in conjunction with improved monitoring of environmental variables is recommended.

Comparisons of annual fish weighted daily change in temperature and time weighted counterparts suggest that the fish may move into declining temperatures (Figure 39). Given the inexact nature of the temperature measures explained above, this is suggestive of a relation, but not definitive. Such a result is consistent with our hypothesis that the fish seek lower temperatures when temperatures are above 60F (15.6C). Standard errors of the annual mean timings are quite small due to large sample sizes in the absence of an estimate of measurement error.

Statistical Analyses – Fall Chinook conversion rates

Methods

The majority of fall chinook salmon entering the Snake River return to either Lyons Ferry Hatchery, the Tucannon and Palouse rivers, or to portions of the Snake River Basin upstream of Lower Granite Dam. Therefore, fishery managers can estimate what is referred to as a *conversion rate* for fall chinook salmon in the Snake River below Lower Granite Dam as:

$$C = \left(\sqrt{\frac{LWG}{LMN - LF - TP}} \right)^3$$

where LMN and LWG are the fall chinook salmon counts at LMN and LWG dams, respectively, LF is the number of fall chinook salmon returning to Lyons Ferry Hatchery, and TP is an estimated escapement to the Tucannon and Palouse rivers. The conversion rate is calculated from Lower Monumental Dam counts due to fallback and other factors affecting the precision of the Ice Harbor count discussed above. To obtain a per-project conversion rate, the square root of the two dam (LMN to LWG) estimate is calculated. The per-project conversion rate is then cubed to estimate an Ice Harbor-Lower Granite conversion rate (M. McClure, CRITFC, personal communication). The higher the conversion rate, *C*, the fewer fish are unaccounted for (and presumably the fewer mortalities) on the upstream migration.

Results

The conversion rate for 1986-1996 (B. Ringo, CRITFC, personal communication) is highly correlated with late summer water temperatures in the lower Snake River. For example, there is a significant linear relationship between fish weighted mean August IHR scroll case water temperatures and the fall chinook salmon conversion rate for the years 1986-1996 ($p=0.004$, Figure 50).

Two additional results are noteworthy with respect to interpretation of the relation between conversion rates and temperatures in the lower Snake River from 1986 to 1996. Conversion rates in August have been generally increasing over this time period with 1986 – 1990 clustered on the low side, and 1993 – 1995 clustered on the high side, and 1992 and 1996 being intermediate (Figures 50 and 51). At the same time, Ice Harbor scroll case temperatures in August have been declining due to Dworshak Reservoir releases (Figure 35). Nonetheless the lack of correlation between year and the residuals of the conversion rates with respect to the regression line (Figure 50), indicates that the relation apparent in Figure 50 is not solely an artifact of the increasing time trend in conversion rates. Further investigation is warranted.

Discussion

Cooler water temperatures apparently result in fewer missing fish, meaning fewer mortalities, during the migration in the Snake River below Lower Granite Dam. The relationship is suggestive, not definitive, because of lack of accounting for measurement error in the dam counts, and uncertainty regarding the applicability of scroll case temperatures to the ambient conditions of the immigrants, among other problems. Nonetheless, the inverse relation apparent between annual fall chinook conversion rate and the annual fish weighted mean water temperature is supportive of the temperature-survival hypothesis for fall chinook. According to hypothesis, as chinook expend energy at higher rates in warmer waters than in cooler waters, a lower proportion of the warm-water immigrants will have the energy reserves sufficient to permit them to ascend to the spawning grounds. Also according to this hypothesis, of those warm-water immigrants that do ascend to the spawning grounds, a smaller proportion will successfully spawn compared to cool-water immigrants.

FINDINGS AND RECOMMENDATIONS

Summary of findings

1. Regardless of whether or not temperature regimes in the migratory pathways are altered by human intervention, understanding and measuring the effect of temperature on survival is important to management of salmon and steelhead in the Columbia River watershed.

2. Water temperatures at hydroelectric projects of the Columbia River and the Snake River have often exceeded the upper incipient lethal temperature level of 68F for salmon and steelhead during July, August, and September.

3. Human intervention in the form of water releases from Dworshak Dam reduced the water temperatures in the reservoirs of the lower Snake River in 1991 – 1996 during the time period of juvenile and/or adult fall chinook salmon migration. It is possible that lowered temperatures during the 1991 to 1996 fall chinook immigrations increased the annual proportions of immigrants reaching Lower Granite Dam.

4. Spatial detail available from present and historical water temperature measurements does not permit the full range of temperature conditions experienced by the immigrating salmon and steelhead to be measured and understood.

5. Information available from existing studies of migratory behavior of adult fall chinook salmon does not permit full understanding of the interactions between water temperature and fish behavior during critical periods of high water temperatures in August and early September.

6. Adult fall chinook appear to spend less time in the hydroelectric system when they encounter the largest series of daily changes from warmer to cooler water temperatures at Ice Harbor Dam, the entry to the lower Snake River hydroelectric system.

7. Since the lower Snake River dams were built, the annual timings of the fall chinook immigrations show a significant trend toward later arrival at Ice Harbor Dam, Lower Monumental Dam, and Little Goose Dam.

8. The estimated annual proportion of fall chinook entering the Snake River at Ice Harbor Dam during August that reach Lower Granite Dam, 1986 - 1996, may be inversely proportional to scroll case water temperatures during August.

9. The mean temperature experienced by fall chinook during the annual migratory period at Ice Harbor Dam has shown a significant downward trend over the time period 1986 - 1996, in part due to the effects of human intervention.

Recommendations

1. Implement a program of monitoring temperature measurements in the lower Snake River to support a numerical model of temperature regimes experienced in the Columbia River watershed by immigrating salmon and steelhead originating in the lower Snake River.

2. Implement a program of placing temperature and depth sensing tags on adult fall chinook salmon captured at Bonneville II Dam that bear Snake River Passive Integrated Transponder tags.

3. Apply the information gathered in the temperature monitoring and tagging program to the recovery program for Snake River salmon and steelhead through the evaluation of the temperature-survival hypotheses, leading to promulgation and adoption of a permanent program of temperature management.

PHASE III IMPLEMENTATION: DEVELOPING BIOLOGICAL MANAGEMENT APPROACHES RESPONSIVE TO TEMPERATURE

Understanding the role of temperature in survival is key to success of salmon and steelhead recovery programs

Given the central role of temperature as a lethal factor for salmon and steelhead in the Columbia River watershed, it is prudent to explore the feasibility of management responses to temperature. Defining management responses is essential to success of salmonid recovery efforts. Even though a properly acclimated salmonid might initially survive an arbitrarily brief exposure to the highest naturally occurring water temperatures in the migratory pathways, the dose of temperature accumulated during immigration can kill or impair spawning function through its effect on depletion of energy reserves and associated physiological processes.

Acting in conjunction with normal fluctuations in climate and long term climatic trends, human alteration of thermal regimes in the migratory pathways could have added an important mortality factor that is not being incorporated into management decisions. The adult fish passage facilities at the hydroelectric facilities, and the heat storage capacity of their reservoirs, in addition to human uses of the water, all have contributed to alteration of thermal regimes in the migratory pathways of Columbia River anadromous salmonids. Water temperatures at hydroelectric projects of the Columbia River and the Snake River have often exceeded the incipient lethal temperature level of 68F for salmon and steelhead during July, August and September. Inability to provide appropriate management actions in response to the effects of mortality factors throughout the anadromous life cycle is a key reason that fisheries management programs fail to attain their objectives (Mundy 1996).

Regardless of whether temperature regimes in the migratory pathways have been, or can be, altered by human intervention, understanding and measuring the effect of temperature on survival is important to management of salmon and steelhead in the Columbia River watershed. It is especially important to provide protection to spawners in order to protect the long-term viability of the populations. If temperature is placing a substantial mortality load on the spawners that have successfully completed a four to five year life cycle, the effect on the persistence of the population can be profound. For salmon and steelhead originating in the Snake River basin, the loss of a single spawner can have a greater impact on the population than the loss of several hundred juvenile emigrants (smolts).

Management measures responsive to temperature induced mortalities are available at a variety of levels. At the physical level, it is known that temperature regimes in the lower Snake River can be altered by water releases from Dworshak Dam. Releases of water over a six-year period showed that water temperatures in the lower Snake River could be reduced during a critical time in the immigration of fall chinook and steelhead. Management responses other than cold water releases are also possible given information on the effect of temperature on survival of immigrants. For example, on the harvest management level, restrictions on future harvest by fisheries may be based not only on the apparent escapements, as measured at the dams, but also on the expectation of spawning success of the immigrants based on temperature.

On a hydroelectric facilities level, the priority placed on implementation of management actions such as improvements to adult fish ways, juvenile bypass facilities, and provision of flows during critical life history stages may also be advised by the relation between temperature and survival.

Available information and monitoring programs permit some encouraging, but incomplete, answers to questions posed by the temperature-survival hypotheses. Does exposure to temperature have an effect on survival of immigrants? Based on information in hand it is clear that temperatures exceed the upper incipient lethal temperature level at hydroelectric power projects of the Columbia and Snake rivers during the times when the threatened fall chinook salmon are immigrating in the summer.

Existing data also provide evidence that survival in immigrant fall chinook is related to water temperatures. The estimated annual proportion of fall chinook entering the Snake River at Ice Harbor Dam during August that reach Lower Granite Dam, 1986 - 1996, may be inversely proportional to scroll case temperatures during August. This observation is consistent with the hypothesis that survival is proportional to length of exposure to total temperature units. Temperature dose is the product of temperature and exposure time.

Questions remain about how well reported scroll case temperatures actually estimate the temperatures to which the salmon and steelhead are exposed.

What determines the length of exposure to temperatures in the hydroelectric system? Current data suggest that adult fall chinook may spend less time in the hydroelectric system when they encounter the largest series of daily decreases in temperature at Ice Harbor Dam. Since Ice Harbor Dam is the entry to the lower Snake River hydroelectric system, such behavior-temperature interactions could control the timing of the adult immigration. Decreasing temperatures appear to provide a cue to which the immigrants respond positively. On the other hand increasing temperatures would appear to have the opposite effect on immigration.

Do the populations show signs of the impacts of changing temperature regimes? Since the lower Snake River dams were built, the annual timings of the fall chinook immigrations show a significant trend toward later arrival at Ice Harbor Dam, Lower Monumental Dam, and Little Goose Dam. The trend toward later migration timing does not appear to be related to trends in temperatures that are now being measured. Evolutionary ecological theory predicts that anadromous fish populations seek to adapt to changes in temperature regimes by changes in behavior, such as migratory timing (Quinn and Adams 1996). Such a change is occurring in the fall chinook of the Snake River, but monitoring programs do not provide an explanation. If exposure to temperature is a determinant of fall chinook spawning success, and if unfavorable temperatures early in the migration now persist longer due to the heat storage capacity of the reservoirs, such a shift to later timing would be expected as an adaptive response.

The scientific literature and the available data provide a compelling case that temperature is an abiotic factor that is crucially important to the well being of salmon and steelhead in the federal Columbia River hydroelectric power system that is not being adequately addressed by existing monitoring programs. The Phase III proposal addresses what needs to be done to implement monitoring programs for water temperature in relation to immigrant salmon and steelhead.

In Phase III, we propose an integrated research program incorporating expertise from fish physiologists and population biologists, physical oceanographers, numerical modelers, and hydroelectric system specialists to implement a temperature monitoring program for the lower Snake River over a five-year period. The exact form of the monitoring system cannot now be projected, because it depends on information to be developed during the study. Phase III implementation requires the evaluation of the biological and physical hypotheses regarding the nature of temperature and heat transport in the river, and the interaction of thermal features with other physical factors such as flow, and fish behavior. The primary goal of Phase III is to implement a temperature monitoring program that provides essential information on the role of temperature in adult salmon and steelhead survival for the least cost.

Implement a temperature monitoring program designed for adult salmon and steelhead

The primary purpose of Phase III is to implement a program of monitoring temperature measurements in the lower Snake River to support a numerical model of temperature regimes experienced in the Columbia River watershed by immigrating salmon and steelhead originating in the lower Snake River. In the Columbia River estuary, for example, the availability of low cost physical data acquisition for tides, currents, water and air temperature, salinity, turbidity, and wind has made possible development of a detailed physical model of circulation and transport, known as CORIE (Baptista, Wilken et al. 1997). Such a system might be developed for the lower Snake River, consisting of the same three main components as CORIE: a real-time data acquisition system, a set of highly resolved numerical models of circulation and transport, and a data management system (Baptista, Wilken et al. 1997).

Development of CORIE has been assisted by prior work in the Great Lakes and in coastal ocean modeling of thermal structure and circulation (Schwab and Bedford 1994). Design of the monitoring system would occur over a period of several years during which the numerical models would help define the least-cost implementation.

Implement an adult fish tagging program to measure accumulated thermal dose

The facility for trapping and handling adult salmon and steelhead at Bonneville Dam is state-of-the-art. Fish are relatively early in the migration with maximum energy relative to that they will have at any other point in the hydroelectric system. Fall chinook are being implanted with passive integrated transponder (PIT) as juveniles prior to emigration from the Snake River. Detection of PIT tags in trapped adult fish will allow placing temperature and depth sensing tags on adult fall chinook salmon of Snake River origin. Information on temperature experienced by the fish throughout the federal hydroelectric system can be gathered in this way. Total degree days can be calculated as an average of individual experience, rather than as a fish weighted temperature (Equations 1-3, page 61). The problem attendant to tagging fish at Ice Harbor Dam during times of very high water temperatures could thus be avoided, and more information would be gathered.

This study could also provide an indication of how much radio tagging affects migration. When all fish passing Bonneville are subject to PIT tag detection, the proportion of all Snake River PIT tagged fish implanted with radio tags could then be calculated. The proportion of radio tagged fish arriving at Lower Granite Dam could be then be compared with the proportion of PIT tagged fish arriving. Travel times of radio tagged fish could also be compared to those of the PIT tagged population at large. Depending on the installation of adult PIT tag detectors at dams in the hydroelectric system, comparisons could be made at other points in the upstream migration as well

Evaluate the temperature – survival hypotheses to inform salmon recovery actions

A series of formal hypotheses can be specified for testing. The information gathered through the evaluation of the temperature-survival hypotheses in the temperature monitoring and tagging program would be applied to the recovery program for Snake River salmon and steelhead.

Formal Hypothesis Statements for Testing

Hypothesis 1: Behavioral thermoregulation.

Migratory behavior, as measured by rate of immigration, timing and dispersal of the migration at specific locations is related to temperature as measured in cumulative degree days within the environment of the immigrants.

Adult fall chinook salmon and steelhead exhibit measurable behavioral thermoregulation in response to water temperatures during immigration.

Formally stated, the model to be tested may be stated as

$$f(T) = y$$

where T is temperature and y is one of measures of migratory behavior described above.

$$y = a_0 + a_1 T_1 + \Lambda \ + a_n T_n + error$$

is the basic model where the subscripts *1, 2, ... , n* refer to locality, and the a_l are constants to be estimated from data. Interactions between localities may also be tested by adding interaction terms to the preceding model.

An alternative model for *f(T)* is

$$y = a_0 + a_1 \sum_{i=1}^{n} T_i + error$$

Hypothesis 2: Temperature dependent spawning success

The total temperature units (i.e., degree days) accumulated by a fall chinook salmon during immigration has a direct and compelling effect on its spawning success.

Spawning success, estimated redds as a proportion of spawners entering the hydroelectric system is a function of the hydroelectric system degree-days for the season. Degree-days is average daily temperature experienced by the average fish accumulated over the course of the season.

Hypothesis 3: Temperature dependent survival

Cumulative exposure to water temperatures, as degree days, is inversely proportional to survival of steelhead and fall chinook from freshwater entry to spawning. Degree days may be calculated using 60F as a reference point, where 60F is subtracted from the average daily temperature prior to multiplying by the number of fish in that reference frame and dividing by the number of fish to get the degree days (see Equations 1 - 3 page 60). Survival as measured by the ratio of immigrants reaching the spawning grounds to those entering the hydroelectric system is related to temperature as measured in cumulative degree-days within the environment of the immigrants. Survival may also be estimated as the ratio of the number of immigrants exiting the federal hydroelectric system to the number of those entering the hydroelectric system.

Form a design and implementation team for the Phase III Project

The exact form of the monitoring system cannot now be projected, because it depends on information to be developed during the Phase III study. A team of scientists from the disciplines of fish physiology and population biology, physical oceanography, numerical modeling, and hydroelectric system fish passage is needed to implement a temperature monitoring program for the lower Snake River over a five-year period. The design and implementation team would design and implement an initial monitoring program based on the information presented in this report. The team would annually adapt future work to the results obtained each year.

REFERENCES

Babcock, A. M. and P. R. Mundy (1985). A quantitative measure of migratory timing applied to the commercial brown shrimp fishery in North Carolina. North American Journal of Fisheries Management. 5: 181-196.

Baptista, A. M., M. Wilken, et al. (1997). Towards a Nowcast-Forecast System for the Columbia River Estuary. 5th International Conference on Estuarine and Coastal Modeling, Alexandria, Virginia.

Bennett et al. (1997). Thermal and velocity characteristics in the lower Snake River reservoirs, Washington, as a result of regulated upstream water releases. U.S. Army Corps of Engineers final completion report. Project 14-16-0009-1579. 178 pp.

Bjornn, T. C. and C. A. Peery (1992). A review of literature related to movements of adult salmon and steelhead past dams and through reservoirs in the lower Snake River. Walla Walla, WA, U.S. Army Corps of Engineers, Walla Walla District.

Bjornn, T. C., R. R. Ringe, et al. (1992). Migration of adult chinook salmon and steelhead past dams and through reservoirs in the lower Snake River and into tributaries - 1991. Walla Walla, Washington, U.S. Army Corps of Engineers Walla Walla District.

Box, G. E. P. and G. M. Jenkins (1976). Time Series Analysis: Forecasting and Control. San Francisco., Holden-Day.

Brett, J. R. (1952). Temperature tolerance in young Pacific salmon genus Oncorhynchus. Journal of the Fisheries Research Board of Canada 9: 265-323.

Brett, J. R. (1971). Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon. American Zoologist 11: 99-113.

Busby, P. J., O. W. Johnson, et al. (1993). Status Review for Oregon's Illinois River winter steelhead. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Busby, P. J., T. C. Wainright, et al. (1994). Status Review for Klamath Mountains Province Steelhead. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Busby, P. J., T. C. Wainright, et al. (1996). Status Review of West Coast steelhead from Washington, Idaho, Oregon, and California. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Coutant, C. C. (1977). Compilation of temperature preference data. Journal Fisheries Research Board of Canada 34: 739-745.

Dalen, J., R. Stansell, et al. (1996). Fishway Water Temperatures at Bonneville, The Dalles, and John Day Dams in 1995. Summary Report. Portland, Oregon, CENPP_CO_SRF, North Pacific Division, Portland District, U.S. Army Corps of Engineers.

Davidson, F. A. 1964. The temperature regime of the Columbia River from Priest Rapids, Washington to the Arrow Lakes in British Columbia. Ephrata, Washington, Public Utility District No. 2 of Grant County.

Elliot, J. M. (1981). Some aspects of thermal stress on freshwater teleosts. Stress and Fish. A. D. Pickering. London, Academic Press: 209-45.

Environmental Protection Agency (1971). Columbia River Thermal Effects Study, Volume 2 Temperature Prediction. 64 pp.

Freund, J. E. (1962). Mathematical Statistics. New Jersey, Prentice-Hall, Inc.

Fry, F. E. J. (1971). The effect of environmental factors on the physiology of fish. Fish Physiology. W. S. Hoar and D. J. Randall. London, Academic Press: 1 - 98.

Groot, C. and L. Margolis (1991). Pacific Salmon Life Histories. Vancouver, British Columbia, University of British Columbia Press.

Groot, C., L. Margolis, et al. (1995). Physiological Ecology of Pacific Salmon. Vancouver, British Columbia, University of British Columbia Press.

Hard, J. J., R. G. Kope, et al. (1996). Status Review of Pink Salmon from Washington, Oregon, and California. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Healey, M. C. (1991). Life history of chinook salmon. Pacific Salmon Life Histories. C. Groot and L. Margolis. Vancouver, British Columbia, University of British Columbia Press: 313-393.

Huntington, C., W. Nehlsen, et al. (1996). A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries 21(3): 6-14.

Jensen, F. B., M. Nikinmaa, et al. (1993). Environmental perturbations of oxygen transport in teleost fishes: causes, consequences, and compensations. Fish Ecophysiology. J. C. Rankin and F. B. Jensen. London, Chapman and Hall: 161-179.

Johnson, O. W., T. A. Flagg, et al. (1991). Status review for lower Columbia River coho salmon. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Johnson, O. W., R. S. Waples, et al. (1994). Status Review for Oregon's Umpqua River Sea-Run Cutthroat Trout. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Johnston, I. A. (1993). Phenotypic plasticity of fish muscle to temperature change. Fish Ecophysiology. J. C. Rankin and F. B. Jensen. London, Chapman and Hall: 322-340.

Karr, M. H. (1992). Snake River water temperature control project. 1992 operations and results. Summary report. Portland, Oregon, Columbia River Inter-Tribal Fish Commission.

Karr, M. H. (1993). Snake River water temperature control project. 1993 Lower Snake River water flows and temperatures. A summary report. Portland, Oregon, Columbia River Inter-Tribal Fish Commission.

Karr, M. H., B. Tanovan, et al. (1992). Snake River Water Temperature Control Project Interim Report: Model Studies and 1991 Operations. Portland, Oregon, Columbia River Inter-Tribal Fish Commission, U.S. Army Corps of Engineers, University of Idaho.

Keckler, D. (1996). Surfer for Windows, Contouring and 3D Surface Mapping, Users Guide. Golden, Colorado, Golden Software, Inc.

Kramer, H. A. (1962a). A compilation of water temperatures near Grand Coulee Dam and in environs of Lake Roosevelt. Richland, Washington, Hanford Atomic Products Operation, General Electric Company.

Kramer, H. A. (1962b). Artificial cooling of the Columbia River by dam regulation, 1961. Richland, Washington, Hanford Atomic Products Operation, General Electric Company

Matthews, G. M. and R. S. Waples. (1991). Status review for Snake River spring and summer chinook salmon. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Matylewich, M. A. and P. R. Mundy (1985). Evaluation of the relevance of some environmental factors to the estimation of migratory timing and yield for the brown shrimp of Pamlico Sound, North Carolina. North American Journal of Fisheries Management 5: 197-209.

McCullough, D. (1993). Stream temperatures criteria for salmon. Literature review for the Oregon Department of Environmental Quality. Portland, Oregon, Columbia River Inter-Tribal Fish Commission.

McIntosh, B. A., D. M. Price , et al. (1994). Distribution Habitat utilization movement patterns, and the use of thermal refugia by spring chinook in the Grande Ronde, Imnaha, and John Day river basins. Portland, Oregon, Bonneville Power Administration Fish and Wildlife Division.

Mendel, G. et al (1992). Upstream passage and spawning of fall chinook salmon in the Snake River. *In* Blankenship, L. and G. Mendel. Upstream Passage, Spawning and stock identification of fall chinook salmon in the Snake River. Portland, OR, Bonneville Power Administration, Fish and

Wildlife Division.

Mundy, P. R. (1982). Computation of migratory timing statistics for adult chinook salmon in the Yukon River, Alaska, and their relevance to fisheries management. North American Journal of Fisheries Management 4: 359-370.

Mundy, P. R. (1996). The Role of Harvest Management in the Future of Pacific Salmon Populations: Shaping Human Behavior to Enable the Persistence of Salmon. Pacific Salmon and Their Ecosystems: Status and Future Options. R. J. Naiman and D. Stouder. New York, USA, Chapman Hall: 315-330.

Nehlsen, W., J. E. Williams, et al. (1991). Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4-21.

Quinn, T. P. and D. J. Adams (1996). Environmental changes affecting the migratory timing of American shad and sockeye salmon. Ecology 77(4): 1151-1162.

Schwab, D. J. and K. W. Bedford (1994). Initial Implementation of the Great Lakes Forecasting System: A Real-Time System for Predicitng Lake Circulation and Thermal Structure. Water Pollution Research Journal of Canada 29(2/3): 203-220.

Slaney, T. L., K. D. Hyatt, et al. (1996). Status of anadromous salmon and trout in British Columbia and Yukon. Fisheries 21(10): 20-35.

Sokal, R. R. and F. J. Rohlf (1969). Biometry. San Francisco, W.H. Freeman and Company.

Sokal, R. R. and F. J. Rohlf (1981). Biometry. San Francisco, W.H. Freeman and Company.

Stuehrenberg, L. C., G. A. Swan, et al. (1994). Migrational characteristics of adult spring, summer, and fall chinook salmon passing through the reservoirs and dams of the mid-Columbia River. Seattle, Washington, National Marine Fisheries Service Coastal Zone and Estuarine Studies Division.

Thomas, R. E., J. A. Gharrett, et al. (1986). Effects of fluctuating temperature on mortality, stress and energy reserves of juvenile coho salmon. Transactions of the American Fisheries Society 115: 52-59.

Thornton, K. W., Ed. (1990). Lake and Reservoir Restoration Guidance Manual. Clean Lakes Program. Washington D.C., U.S. Environmental Protection Agency.

U.S. Department of Health, Education, and Welfare (1963). Water temperature influences, effects, and control. Proceedings of the twelfth Pacific Northwest symposium on water pollution research. Corvallis, Oregon.

Waknitz, F. W., G. M. Matthews, et al. (1995). Status Review for Mid-Columbia

River summer chinook salmon. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Waples, R. S. (1995). Evolutionarily significant units and the conservation of biological diversity under the Endangered Species Act. *In* Nielson, J. L. Evolution and The Aquatic Ecosystem: Defining Unique Units in Population Conservation. Bethesda, Maryland, American Fisheries Society 17: 8-27.

Waples, R. S., O. W. Johnson, et al. (1991). Status review for Snake River sockeye salmon. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Waples, R. S., R. P. Jones Jr., et al. (1991). Status review for Snake River fall chinook salmon. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Weitkamp, L. A., T. C. Wainright, et al. (1995). Status Review of Coho Salmon from Washington, Oregon, and California. Seattle, National Marine Fisheries Service Northwest Fisheries Science Center.

Wootton, R. J. (1990). Ecology of teleost fishes. London, Chapman and Hall.

Table 1. Selected fall chinook radio tagging recoveries compiled by the Snake River Laboratory of the Washington Department of Fish and Wildlife (Mendel et al. 1992) for the years 1991, 1992, and 1994. Days to pass each dam were calculated by subtracting the last detection from the first detection at each dam and adding 1 day. Days of migration were calculated by subtracting the first detection at the next upriver dam from the last detection at each dam and adding 1 day.

	LMN					**LGS**					**LWG**			
chan/ code	First	Last	# Fish Pass	days to pass	days to migrate	First	Last	# Fish Pass	days to pass	days to migrate	First	Last	# Fish Pass	days to pass
1/34	09/28	10/01	1	4	9	10/09	10/27	1	19	2	10/28	10/28	1	1
1/44	10/30	11/05	1	7	2	11/06								
3/18	10/31	10/31	1	1	3	11/02	11/02	1	1	3	11/04	11/05	1	2
2/4	11/06	11/10	1	5	5	11/14								
1/36	11/11	11/12	1	2	2	11/13	11/14	1	2	6	11/19			
3/12	10/25	10/25[a]			6	10/30								
1/26						10/02	10/04	1	3	2	10/05	10/06	1	2
2/43						10/05	10/05	1	1	2	10/06			
2/29						11/10	11/10	1	1	2	11/11			
1/28						09/15	09/15[a]			3	09/17	09/19	1	3
3/17						09/17	09/17[a]			2	09/18	09/19	1	2
2/48						09/21	09/21[a]			2	09/22	09/28	1	7
3/14						09/24	09/24[a]			2	09/25	09/28	1	4
3/20						09/25	09/25[a]			3	09/27	09/29	1	3
1/49											10/22	10/23		2

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a The fish was only detected at the top of the fish ladder.

Table 2. List of available data. (Temperature and velocity data collected from transects of lower Snake River reservoirs; counts of adult salmon at lower Snake River Dams; hydroelectric turbine scroll case water temperatures; hydroelectric project water flows; tri-level thermographs; fish ladder water temperatures; summary fall chinook radio tagging.)

Type of Data	Location Collected	Source	Year	Duration	% Data Missing
Tri Level Thermograph at Transect 14	IHR pool, SR Mile 15.5, 180 feet from the right bank at depths of 7, 37, and 75 feet	Data collected by University of Idaho. Statistics by CRITFC	1991	9/14-10/25	0.0
			1992	5/5-9/27	0.0
			1993	4/1-8/25	25.6
			1994	5/1-9/14	0.0
			1995	6/5-10/31	0.0
			1996	5/25-11/25	9.0
Tri Level Thermograph at Transect 11	LMN pool, SR Mile 44.0, 180 feet from the right bank at depths of 7, 43, and 85 feet.	Data collected by University of Idaho. Statistics by CRITFC	1991	9/13-10/31	0.0
			1992	5/5-8/20	0.0
			1993	4/1-8/25	0.0
			1994	5/1-10/30	20.0
			1995	6/5-10/31	13.2
			1996	5/25-12/14	0.0
Tri Level Thermograph at Transect 8	LGS Pool, SR Mile 80.5, 164 feet from the right bank at depths of 7, 40, and 80 feet.	Data collected by University of Idaho. Statistics by CRITFC	1991	9/13-10/31	2.0
			1992	5/5-9/28	0.0
			1993	4/1-8/25	0.0
			1994	5/1-10/31	8.5
			1995	6/16-12/7	12.9
			1996	5/26-12/24	0.0
Tri-Level Thermograph at Transect 5	LWG Pool SR Mile 110.5, 230 feet from right bank at depths of 7, 35, and 70 feet	Data collected by University of Idaho. Statistics by CRITFC	1991	8/28-10/31	0.0
			1992	5/5-9/28	11.3
			1993	4/1-9/9	0.0
			1994	4/28-10/31	0.0
			1995	8/28-10/31	0.0
			1996	5/26-10/31	0.0

Table 2

Type of Data	Location Collected	Source	Year	Duration	% Data Missing
Transect temperatures and water velocities	14 locations in the Snake, Clearwater and Columbia rivers (Table 3)	University of Idaho, Validated by CRITFC	1991	25 days over the period 7/23-10/15	29.8
Transect temperatures and water velocities	14 locations in the Snake, Clearwater and Columbia rivers (Table 3)	University of Idaho, Validated by CRITFC	1992	25 days over the period 7/5-10/13	24.8
Fish Ladder Temperature	IHR-Top of Ladder, Bottom of Ladder, Tailrace	University of Idaho, Validated by CRITFC	1991	5/11 - 10/31	35.2
			1992	5/19 - 10/31	4.8
			1993	5/26 - 9/2	0.0
			1994	7/26 - 10/31	0.0
		Unvalidated	1995		
		Unvalidated	1996		
	LMN-Top of Ladder, Bottom of Ladder, Tailrace	University of Idaho, Validated by CRITFC	1991	8/30 - 10/31	41.8
			1992	5/19 - 10/31	14.5
			1993	5/26 - 9/2	8.7
			1994	5/26 - 9/2	45.5
		Unvalidated	1995		
		Unvalidated	1996		
	LGS-Top of Ladder, Bottom of Ladder, Tailrace	University of Idaho, Validated by CRITFC	1991	8/30 - 10/31	2.1
			1992	6/9 - 10/31	0.0
			1993	5/27 - 9/3	0.0
			1994	7/25 - 10/31	0.3
		Unvalidated	1995		
		Unvalidated	1996		
	LWG-Top of Ladder, Bottom of Ladder, Tailrace	University of Idaho, Validated by CRITFC	1991	5/25 - 10/31	31.1
			1992	6/9 - 10/31	0.0
			1993	5/28 - 9/3	0.0
			1994	7/25 - 10/31	5.7

Table 2

Type of Data	Location Collected	Source	Year	Duration	% Data Missing
Fish Ladder Temperature	LWG-Top of Ladder, Bottom of Ladder, Tailrace	Unvalidated	1995		
		Unvalidated	1996		
Scroll case Temperature[b]	IHR[c]	USACE-Some data validated or corrected by CRITFC	1962-1996	4/1-10/31 annually	Negligible
	LMN[d]		1972-1996	4/1-10/31 annually	Negligible
	LGS[e]		1972-1996	4/1-10/31 annually	Negligible
	LWG[f]		1975-1996	4/1-10/31 annually	Negligible
	DWR[g]		1991-1996	4/1-10/31 annually	Negligible
Ladder Fish Counts	IHR	FISHCOUNT database-validated by this project	1962-1996	Generally 4/1-10/31 annually	Negligible

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[b] Scrollcase temperatures are normally recorded throughout the year at all USACE projects. However, we only compiled data from April 1 through October 31 annually.

[c] Mercury thermometers are installed on two units; readings are taken from the operating unit.

[d] Mercury thermometers are installed on two units; readings are taken from the operating unit.

[e] Digital thermometer located in fishway sends readings to control room. Readings come from fishway as of 1996 season.

[f] Digital thermometer located at charged cooling water strainer (takes water temperature reading from lower river depths). Prior to 1996, “scroll case” temperatures came from both fishways and scroll case for as long as five years (Tanovan Bolyvong personal communication).

[g] Since about 1995 DWR “scroll case” temperatures are the temperature originating from the TDG station at the hatchery. Prior to this, data came from the cooling water intakes located in the project tailrace on the turbine side of the river. (Tanovan Bolyvong, USACE personal communication)

Table 2

Type of Data	Location Collected	Source	Year	Duration	% Data Missing
Ladder Fish Counts	LMN	FISHCOUNT database-validated by this project		Generally 4/1-10/31 annually	Negligible
	LGS			Generally 4/1-10/31 annually	Negligible
	LWG			Generally 4/1-10/31 annually	Negligible
Tributary Data		Idaho Power			
Gas Bubble Trauma Meters	IHR- Forebay Station in center of river 15.0' below average forebay levels	Total dissolved gas monitoring program	1993-1996	4/1-9/30	8.2
	LMN-Forebay station located in center of river near the north end of spillway 15.0' below average forebay levels		1993-1996	4/1-9/30	6.1
	LGS-Forebay station located in center of river near the north end of spillway 15.0' below average forebay levels		1993-1996	4/1-9/30	15.8

Table 2

Type of Data	Location Collected	Source	Year	Duration	% Data Missing
Gas Bubble Trauma Meters	LWG-Station located in center of river just north of spillway 15.0’ below average forebay levels	Total dissolved gas monitoring program	1993-1996	4/1-9/30	4.4

Table 3. Transect designation, station description, and location (river mile) of temperature transect and tri-level thermograph stations in the Snake, Clearwater, and Columbia rivers.

Transect	Station Description	River Mile Location
1A	North Fork Clearwater River	1.3
1B	Clearwater river above N. Fork	41.5
1C	Clearwater River below N. Fork	39.5
1	Snake River above Clearwater	140.5
2	Clearwater near mouth	0.8
3	Lower Granite Reservoir	129.5
4	Lower Granite Reservoir	119.5
5	Lower Granite Reservoir (transect and tri-level thermographs)	110.5
	Lower Granite Dam	107.6
6	Little Goose Reservoir	101.0
7	Little Goose Reservoir	91.5
8	Little Goose Reservoir (transect and tri-level thermographs)	80.5
	Little Goose Dam	70.0
9	Lower Monumental Reservoir	65.0
10	Lower Monumental Reservoir	57.5
11	Lower Monumental Reservoir (transect and tri-level thermographs)	44.0
	Lower Monumental Dam	41.7
12	Ice Harbor Reservoir	35.5
13	Ice Harbor Reservoir	25.0
14	Ice Harbor Reservoir (transect and tri-level thermographs)	15.5
	Ice Harbor Dam	9.6
15	Snake River Below Ice Harbor Dam	5.0
16	Columbia River below Snake R.	Columbia R.M. 323.5

Table 4. Mean monthly temperatures of fish ladders at four Snake River dams from 1991 through 1994. Temperatures were recorded at the upper and lower ends of the fish ladders and at the tailrace of each dam (T. Bjornn, University of Idaho, personal communication).

		1991			**1992**			**1993**			**1994**		
Project	Month	Tailrace	Lower	Upper	Tailrace	Lower	Upper	Tailrace	Lower	Upper	Tailrace	Lower	Upper
IHR	Aug	72.4	75.1		69.6	71.6	71.7	67.0	67.6	68.1	67.1	68.7	69.1
	Sep	68.6	72.1	68.2	67.4	69.7	67.7	66.3	67.7	67.7	68.0	68.7	68.4
	Oct	60.9	65.6	63.8	60.3	60.8	60.7				63.0	63.1	62.9
LMN	Aug	72.4		72.9	69.2	71.0	71.4	66.5	67.6	68.3	65.1	67.6	67.6
	Sep	69.5		69.1	70.2	67.0	67.6	67.0	67.4	68.0	68.2	68.9	69.0
	Oct	60.3		60.7		59.9	60.3					58.5	62.8
LGS	Aug		72.6	73.2	70.0	72.0	72.2	66.5	68.0	68.0	65.3	67.1	67.6
	Sep	66.8	68.1	68.4	66.0	66.5	66.3	68.1	69.0	68.9	69.0	69.5	69.8
	Oct	60.2	60.8	60.7	59.6	60.2	59.9				62.3	62.8	63.0
LWG	Aug	69.9	74.3	75.1	71.1	73.6	73.8	66.5	68.4	68.9	67.6	71.5	70.7
	Sep	66.0	66.6	67.3	62.7	65.9	65.5	66.2	69.0	69.8	68.4	69.4	68.2
	Oct	60.7	64.6	62.2	59.5	60.5	60.4				61.3	61.6	61.8

Table 5. Mean daily scroll case temperatures recorded during the fall chinook immigration followed by the range of years and number of years (N) on which it is based for Bonneville Dam (BON), The Dalles Dam (TDA), John Day Dam (JDA), McNary Dam (MCN), Ice Harbor Dam (IHR), Lower Monumental Dam (LMN), Little Goose Dam (LGS), and Lower Granite Dam (LWG).

Date	BON	TDA	JDA	MCN	IHR	LMN	LGS	LWG
1-Aug	70.2	68.8	67.8	68.2	70.1	69.2	70.7	70.3
2-Aug	70.2	69.5	68.1	68.4	70.3	69.3	70.4	70.4
3-Aug	70.2	69.3	68.0	68.5	70.3	69.3	70.6	70.6
4-Aug	70.3	69.6	68.6	68.6	70.6	69.3	70.6	70.2
5-Aug	70.3	69.5	68.6	68.6	70.6	69.6	70.7	70.8
6-Aug	70.7	70.2	68.6	68.7	70.6	69.7	70.8	70.7
7-Aug	70.7	70.1	68.4	68.9	70.6	69.8	70.7	70.9
8-Aug	70.9	69.8	68.5	68.8	70.8	70.0	70.7	71.2
9-Aug	70.6	69.9	68.5	69.0	70.9	70.2	71.4	71.3
10-Aug	70.6	70.2	69.0	69.2	71.0	70.2	71.3	71.2
11-Aug	70.8	70.0	69.0	69.3	71.0	70.5	71.4	71.4
12-Aug	70.7	70.1	69.0	69.3	71.1	70.6	71.5	71.1
13-Aug	70.9	70.3	68.8	69.3	71.3	70.6	71.3	71.8
14-Aug	71.0	70.6	68.9	69.5	71.1	71.0	71.4	71.5
15-Aug	71.0	70.4	68.9	69.3	71.2	70.7	71.4	71.1
16-Aug	70.9	70.6	69.2	69.3	71.3	70.7	71.4	71.4
17-Aug	70.9	70.5	68.4	69.2	71.4	70.8	71.4	71.5
18-Aug	70.9	70.6	69.1	69.1	71.3	70.8	71.4	71.6
19-Aug	70.9	70.3	68.6	69.2	71.3	70.7	71.4	71.3
20-Aug	70.8	70.2	68.9	69.2	71.1	70.7	71.4	71.5
21-Aug	70.7	70.5	69.1	69.2	71.1	70.7	71.6	71.5
22-Aug	70.6	70.3	69.1	69.3	71.1	70.7	71.5	71.4
23-Aug	70.7	70.3	69.1	69.1	71.1	70.8	71.3	70.9
24-Aug	70.4	70.0	68.5	69.2	71.1	70.7	71.1	70.9
25-Aug	70.1	70.2	68.9	69.1	71.0	70.8	71.1	70.7
26-Aug	70.2	70.0	68.4	69.1	70.9	70.8	71.0	70.3
27-Aug	70.3	69.9	68.6	69.0	70.9	70.8	71.0	70.5
28-Aug	70.7	70.0	68.4	68.9	70.8	70.7	70.9	69.9
29-Aug	70.2	69.8	68.4	69.1	70.7	70.8	70.9	69.7

Table 5 Date	BON	TDL	JDA	MCN	IHR	LMN	LGS	LWG
30-Aug	70.1	69.7	68.1	68.7	70.6	70.7	70.9	69.4
31-Aug	70.2	69.9	68.4	68.6	70.4	70.7	70.7	69.0
1-Sep	70.0	69.7	67.8	68.7	70.4	70.5	70.6	69.1
2-Sep	70.1	69.0	68.1	68.5	70.2	70.3	70.5	69.0
3-Sep	70.0	68.9	67.9	68.4	70.2	70.2	70.2	68.9
4-Sep	69.9	69.1	68.0	68.3	70.1	70.1	69.9	69.0
5-Sep	69.7	68.9	68.0	68.1	70.0	69.9	69.8	69.0
6-Sep	69.5	68.9	68.3	68.0	69.9	69.7	69.6	68.5
7-Sep	69.4	69.0	67.6	68.0	69.7	69.5	69.6	68.5
8-Sep	69.4	69.1	67.8	67.8	69.7	69.4	69.4	68.4
9-Sep	69.0	68.8	67.5	67.7	69.4	69.3	69.2	68.5
10-Sep	69.0	69.0	67.8	67.8	69.1	69.3	69.1	68.0
11-Sep	69.0	68.7	67.3	67.8	69.0	68.9	68.8	67.8
12-Sep	68.5	68.5	67.2	67.7	68.7	68.7	68.6	67.5
13-Sep	68.4	68.2	67.3	67.6	68.6	68.5	68.4	67.2
14-Sep	68.3	68.2	66.8	67.4	68.5	68.2	68.1	66.9
15-Sep	68.0	68.3	66.6	67.4	68.3	67.9	68.0	66.9
16-Sep	68.3	68.0	66.0	67.4	68.2	67.8	67.7	66.5
17-Sep	67.9	67.6	66.3	67.1	68.0	67.7	67.4	66.3
18-Sep	67.3	67.6	65.9	66.8	67.6	67.3	67.2	65.9
19-Sep	67.6	67.0	64.8	66.7	67.3	67.2	67.0	65.7
20-Sep	67.6	67.1	65.0	66.6	67.1	67.0	67.1	65.3
21-Sep	67.3	66.8	64.8	66.5	67.1	66.6	66.8	65.0
22-Sep	67.1	66.7	65.1	66.1	66.7	66.3	66.4	64.8
23-Sep	66.6	66.6	64.3	65.8	66.5	66.1	66.1	64.7
24-Sep	66.7	66.5	65.2	65.6	66.3	65.8	65.6	64.5
25-Sep	66.5	66.2	64.6	65.6	65.9	65.6	65.1	64.3
26-Sep	65.8	66.2	64.5	65.2	65.6	65.6	64.9	63.9
27-Sep	66.3	66.3	64.9	65.1	65.3	65.2	64.7	63.7
28-Sep	66.3	65.9	64.3	64.9	65.3	65.0	64.4	63.6
29-Sep	65.9	65.4	63.9	64.8	65.1	64.6	64.2	63.2
30-Sep	65.6	64.9	63.7	64.6	65.1	64.5	64.1	63.0
1-Oct	65.4	65.0	63.7	64.4	64.7	64.3	63.8	63.0
2-Oct	65.2	64.8	63.4	64.2	64.5	64.2	63.5	62.8

Table 5 Date	BON	TDL	JDA	MCN	IHR	LMN	LGS	LWG
3-Oct	65.0	64.2	63.3	63.9	64.3	63.9	63.0	62.4
4-Oct	64.6	64.4	62.6	63.8	64.0	63.7	63.0	62.4
5-Oct	64.2	63.9	62.8	63.4	63.9	63.3	62.9	61.8
6-Oct	64.1	63.8	62.2	63.2	63.7	63.0	62.7	61.5
7-Oct	63.7	63.6	62.4	63.0	63.4	62.9	62.6	61.2
8-Oct	63.5	63.4	61.8	62.8	63.2	62.5	62.4	61.1
9-Oct	63.4	63.2	61.6	62.6	63.0	62.2	62.2	60.8
10-Oct	63.1	62.7	61.6	62.5	62.7	62.0	61.7	60.5
11-Oct	62.8	62.6	61.1	62.2	62.4	61.7	61.7	60.3
12-Oct	62.5	62.2	60.2	61.9	62.1	61.4	61.4	60.2
13-Oct	62.6	62.1	60.8	61.6	61.9	61.2	61.1	60.0
14-Oct	62.0	61.6	61.0	61.3	61.4	60.9	60.9	60.0
15-Oct	61.8	61.4	60.2	60.9	61.3	60.6	60.5	59.8
16-Oct	61.5	61.4	60.2	60.6	60.9	60.5	60.3	59.8
17-Oct	61.2	61.0	60.4	60.4	60.6	60.1	59.9	59.2
18-Oct	61.2	60.7	59.6	60.3	60.3	59.8	59.8	59.0
19-Oct	60.5	60.3	59.3	60.1	59.9	59.5	59.5	58.5
20-Oct	60.4	60.5	59.0	59.6	59.4	59.3	59.2	58.3
21-Oct	60.3	60.2	58.7	59.3	59.2	58.9	58.9	58.1
22-Oct	60.1	59.9	58.2	59.1	58.9	58.8	58.5	57.5
23-Oct	59.9	59.1	58.1	58.8	58.6	58.5	58.3	57.3
24-Oct	59.5	59.1	57.6	58.6	58.4	58.2	58.1	57.1
25-Oct	59.5	58.9	57.5	58.2	58.2	58.0	57.8	56.8
26-Oct	59.1	58.5	58.2	58.1	57.8	57.8	57.5	56.5
27-Oct	58.7	58.4	57.1	57.9	57.6	57.5	57.2	56.0
28-Oct	58.6	58.2	57.0	57.4	57.3	57.2	57.3	55.8
29-Oct	58.4	57.6	56.8	57.2	56.9	56.8	57.0	55.6
30-Oct	57.6	57.3	56.9	57.0	56.8	56.5	56.4	55.4
31-Oct	57.4	57.1	56.0	56.8	56.5	56.3	56.2	55.1
Range	1981-1995	1981-1995	1981-1995	1960-1996	1963-1996	1971-1996	1970-1996	1975-1996
N	15	15	15	37	34	26	27	22

Table 6. Daily mean temperatures from the total dissolved gas monitoring program in the Snake River. Gas bubble trauma monitoring stations are located above the dams (1993 – 1996).

	ICE HARBOR				LOWER MONUMENTAL				LITTLE GOOSE				LOWER GRANITE			
DATE	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
1-Aug	66.5	71.9	72.4	71.1	67.3	69.0	72.6	70.5	66.4	67.6		71.4	67.3	69.0	72.6	70.5
2-Aug	67.6	73.0	72.1	70.9	69.4	69.5	72.8	70.3	69.7	66.5		70.4	69.4	69.5	72.8	70.3
3-Aug	67.9	72.8	72.5	70.8	69.7	68.4	72.4	70.2	72.1	65.8		70.4	69.7	68.4	72.4	70.2
4-Aug	68.3	73.0	72.5	70.3	68.0	68.2	71.5	69.8	69.3	65.6		70.3	68.0	68.2	71.5	69.8
5-Aug	68.6	72.2	72.4	69.7	69.1	66.4	71.4	69.2	68.6	62.9		69.8	69.1	66.4	71.4	69.2
6-Aug	69.4	70.6	72.7	69.3	69.3	66.9	71.9	68.9	69.6	63.4		69.3	69.3	66.9	71.9	68.9
7-Aug	68.9	72.5	72.6		68.8	69.8	71.2	69.6	68.6	65.9		69.8	68.8	69.8	71.2	69.6
8-Aug	68.8	70.0	72.0		68.7	67.6	71.1	70.4	69.3	64.8	69.8	71.5	68.7	67.6	71.1	70.4
9-Aug	69.0	70.8	71.3		69.0	67.7	71.0	71.0	69.3	65.7	71.5	72.1	69.0	67.7	71.0	71.0
10-Aug	69.0	71.8	71.3		69.0	69.0	71.4	71.7	69.3	66.7	70.8	73.2	69.0	69.0	71.4	71.7
11-Aug	69.1	72.5	71.2		68.9	69.4	70.6	70.5	67.8	67.7	69.1	71.0	68.9	69.4	70.6	70.5
12-Aug	69.7	73.4	71.1		69.7	69.4	70.6	71.1	68.7	68.0	68.9	70.2	69.7	69.4	70.6	71.1
13-Aug	69.3	74.3	70.8	71.8	70.0	69.9	72.0	71.5	68.2	68.2	70.1	72.0	70.0	69.9	72.0	71.5
14-Aug	69.4	74.0	70.6	72.4	70.7	70.1	72.5	70.9	67.9	68.0	70.1	71.8	70.7	70.1	72.5	70.9
15-Aug	69.6	71.8	70.3	70.6	70.7	68.1	72.5	70.1	68.3	66.1	69.1	68.3	70.7	68.1	72.5	70.1
16-Aug	69.6	73.6	70.6	67.7	70.3	68.3	75.1	70.7	68.7	67.1	69.0	68.4	70.3	68.3	75.1	70.7
17-Aug	69.3	74.0	70.1	68.0	69.7	68.9	75.2	70.6	68.0	67.9	68.6	68.1	69.7	68.9	75.2	70.6
18-Aug	69.4	73.3	69.9	67.2	70.7	70.5	73.4	70.0	69.6	69.5	68.4	67.9	70.7	70.5	73.4	70.0

Table 6

	ICE HARBOR				LOWER MONUMENTAL				LITTLE GOOSE				LOWER GRANITE			
DATE	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
19-Aug	69.3	72.3	69.6	67.0	71.2	69.6	72.1	69.9	70.2	70.4	68.8	67.5	71.2	69.6	72.1	69.9
20-Aug	69.1	71.9	69.5	66.8	69.1	68.7	72.7	69.5	68.8	69.5	68.4	67.2	69.1	68.7	72.7	69.5
21-Aug	69.4	71.6	70.1	66.7	68.9	68.9	73.5	69.7	68.4	69.7	68.1	67.9	68.9	68.9	73.5	69.7
22-Aug	69.6	73.3	70.2	66.9	70.5	68.9	70.9	70.5	69.3	69.2	68.7	68.4	70.5	68.9	70.9	70.5
23-Aug	69.3	73.8	69.9	66.6	70.4	69.4	69.8	70.7	69.9	69.9	68.4	68.4	70.4	69.4	69.8	70.7
24-Aug	69.0	73.0	70.1	66.6	69.8	70.0	69.0	71.0	69.5	70.4	66.9	68.3	69.8	70.0	69.0	71.0
25-Aug	68.8	72.5	69.9	66.8	68.4	69.8	69.3	70.9	69.4	71.1	68.4	70.1	68.4	69.8	69.3	70.9
26-Aug	68.6	73.3	69.7	66.9	65.6	69.8	68.8	70.7	69.4	71.6	67.3	70.7	65.6	69.8	68.8	70.7
27-Aug	68.5	72.2	69.7	66.8	66.1	71.0	69.5	68.9	69.6	72.3	68.3	69.0	66.1	71.0	69.5	68.9
28-Aug	68.6	74.5	69.4	66.5	68.6	71.0	69.5	68.8	69.1	72.9	67.7	68.0	68.6	71.0	69.5	68.8
29-Aug	68.6	73.7	68.8	66.6	69.0	70.3	69.3	69.8	70.1	71.3	66.6	68.7	69.0	70.3	69.3	69.8
30-Aug	68.9	72.4	68.6	66.1	69.6	70.8	70.0	68.4	70.9	71.8	67.6	67.1	69.6	70.8	70.0	68.4
31-Aug	69.0	73.8	69.1	65.3	68.8	71.9	71.1	67.4	70.5	72.4	68.6	63.8	68.8	71.9	71.1	67.4
1-Sep	69.2	75.5	69.6	65.1	68.4	72.1	71.2	66.7	70.6	72.8	69.1	63.8	68.4	72.1	71.2	66.7
2-Sep	69.0	75.1	68.5	65.5	68.8	70.7	71.3	66.3	70.1	72.1	70.1	64.3	68.8	70.7	71.3	66.3
3-Sep	70.5	74.3	69.1	64.5	70.2	70.3	72.3	65.8	71.5	71.5	72.1	63.7	70.2	70.3	72.3	65.8
4-Sep	69.4	73.9	68.4	63.4	69.4	69.9	69.6	65.3	71.1	71.3	69.3	61.9	69.4	69.9	69.6	65.3
5-Sep	71.0	72.9	69.0	62.8	70.4	71.0	69.1	65.0	71.4	71.8	67.2	61.0	70.4	71.0	69.1	65.0

Table 6	**ICE HARBOR**				**LOWER MONUMENTAL**				**LITTLE GOOSE**				**LOWER GRANITE**			
DATE	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
6-Sep	70.5	72.6	69.3	62.8	71.9	71.1	69.5	65.1	72.1	72.0	68.4	61.3	71.9	71.1	69.5	65.1
7-Sep	71.0	73.9	69.1		71.3	71.1	68.1	65.2	71.8	71.6	68.1	62.0	71.3	71.1	68.1	65.2
8-Sep	71.0	73.0	69.4		70.2	70.8	67.4	65.0	71.5		68.9	61.8	70.2	70.8	67.4	65.0
9-Sep	71.1	74.7	69.9	63.2	70.7	70.3	67.9	64.9	71.4		69.6	61.9	70.7	70.3	67.9	64.9
10-Sep	70.8	72.3	69.0	63.7	70.9	70.1	68.7	65.6	71.9		69.1	62.5	70.9	70.1	68.7	65.6
11-Sep	70.2	74.5	69.0	63.3	69.7	70.4	68.7	66.5	69.3		69.3	62.9	69.7	70.4	68.7	66.5
12-Sep	70.1	72.4	70.2	62.9	69.3	70.3	70.1	65.3	69.0		69.9	63.2	69.3	70.3	70.1	65.3
13-Sep	70.5	71.4	71.0	61.8	69.3	70.5	71.6	64.2	69.5		70.3	62.1	69.3	70.5	71.6	64.2
14-Sep	69.8	74.7	71.1	61.8	68.8	70.1	71.8	64.4	69.2		71.1	62.2	68.8	70.1	71.8	64.4
15-Sep	69.6	73.5	70.7	61.7	68.6	70.0	71.9	64.3			71.7	62.3	68.6	70.0	71.9	64.3
16-Sep	69.5	74.0	69.8	61.4	68.6	70.3	71.8	64.2	68.8		70.8	61.9	68.6	70.3	71.8	64.2
17-Sep	69.4	72.8	69.3	61.4	68.3	71.0	71.5	64.3			70.3		68.3	71.0	71.5	64.3
18-Sep	68.8	71.3	69.4	61.1	67.7	70.9	71.7	64.3	68.5		69.3		67.7	70.9	71.7	64.3
19-Sep	68.2	72.6	69.4	60.7	67.1	71.1	72.7	64.0			69.7		67.1	71.1	72.7	64.0
20-Sep	67.8	73.1	69.9	60.3	66.7	70.7	71.6	63.5			69.9		66.7	70.7	71.6	63.5
21-Sep	67.6	72.7	69.8		67.0	71.4	69.9	63.1			69.5		67.0	71.4	69.9	63.1
22-Sep	67.4	74.1	68.9	59.3	66.7	71.2	68.7	63.0	66.9		69.0		66.7	71.2	68.7	63.0
23-Sep	67.3	75.2	68.4	59.2	66.2	70.9	70.0	62.7	66.9		68.9		66.2	70.9	70.0	62.7
24-Sep	66.8	74.4	68.2		65.9	70.8	70.0	62.4	66.7		68.8		65.9	70.8	70.0	62.4
25-Sep	66.9	75.3	67.8		66.0	70.5	70.0	62.7	66.5		67.9		66.0	70.5	70.0	62.7

Table 6	ICE HARBOR				LOWER MONUMENTAL				LITTLE GOOSE				LOWER GRANITE			
DATE	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996	1993	1994	1995	1996
26-Sep	66.2	73.7	67.6		65.9	70.4	70.3	62.5			67.4		65.9	70.4	70.3	62.5
27-Sep	66.4	71.1			66.3	70.4		62.3	66.3				66.3	70.4		62.3
28-Sep	66.0				65.9	70.6		62.3	66.1				65.9	70.6		62.3
29-Sep								62.4								62.4
30-Sep								62.9								62.9

Table 7. **Hydroelectric dams of the Columbia Columbia/Snake rivers with miles from the mouth of the river, year placed in operation, and length of reservoir in miles (Mundy et al. 1994).**

Reservoir			
Columbia River	**Location**	**Year**	**Length**
Bonneville	145.5	1938	46
The Dalles	191.5	1957	24
John Day	215.6	1968	76
McNary	292.0	1953	61
Priest Rapids	397.1	1959	18
Wanapum	415.8	1963	38
Rock Island	453.4	1933	21
Rocky Reach	473.7	1961	42
Wells	515.1	1967	29
Chief Joseph	545.1	1955	52
Grand Coulee	596.6	1941	151
Snake River			
Ice Harbor	9.7	1961	32
Lower Monumental	41.7	1969	29
Little Goose	70.0	1970	37
Lower Granite	107.6	1975	39
Hells Canyon	247.0	1967	22
Oxbow	273.0	1961	12
Brownlee	285.0	1958	57

Table 8. Correlation coefficients between temperature measurements from tri-level thermograph (TLT 8 bottom, middle, and surface), fish ladder (top, bottom, and tailrace), and total dissolved gas (TDG) monitoring locations at Little Goose Dam (LGS), on 77 dates, August 16 – October 31, 1993 - 1996.

1993

		Tri-Level Thermograph Station 8			Fish Ladder			Gas Monitoring Stations	
	Scroll case	Bottom	Middle	Surface	Tail race	Bottom	Top	TDG1	TDG2
Scroll case	1.000								
TLT 8B	0.699	1.000							
TLT 8M	0.507	0.933	1.000						
TLT 8S	0.637	0.785	0.777	1.000					
LGS TR	0.660	0.657	0.551	0.309	1.000				
LGS Bot	0.175	-0.191	-0.221	-0.367	0.516	1.000			
LGS Top	0.014	-0.348	-0.417	-0.532	0.308	0.914	1.000		
TDG	0.339	0.187	0.042	-0.158	0.734	0.839	0.727	1.000	
Mean	66.94	67.68	68.32	66.77	67.31	68.37	68.23	69.42	
St.dev.	3.16	0.94	0.69	0.68	0.86	0.80	1.11	1.64	
N	77	10	10	10	19	19	19	38	

1994

		Tri-Level Thermograph Station 8			Fish Ladder			Gas Monitoring Stations	
	Scroll case	Bottom	Middle	Surface	Tail race	Bottom	Top	TDG1	TDG2
Scroll case	1.000								
TLT 8B	0.959	1.000							
TLT 8M	0.948	0.992	1.000						

TLT 8S	0.518	0.535	0.937	1.000				
LGS TR	0.989	0.976	0.964	0.501	1.000			
LGS Bot	0.986	0.975	0.971	0.684	0.995	1.000		
LGS Top	0.987	0.974	0.969	0.673	0.996	1.000	1.000	
TDG	0.929	0.561	0.778	0.838	0.912	0.930	0.943	1.000
Mean	67.51	66.21	66.62	70.12	66.01	66.62	66.89	71.01
St.dev.	3.834	4.39	4.59	0.73	3.84	3.89	3.93	1.50
N	73	77	77	30	77	77	77	22

Table 8. Continued.

1995

	Tri-Level Thermograph Station 8				Fish Ladder			Gas Monitoring Stations	
	Scroll case	Bottom	Middle	Surface	Tail race	Bottom	Top	TDG1	TDG2
Scroll case	1.000								
TLT 8B	0.273	1.000							
TLT 8M	0.971	0.940	1.000						
TLT 8S	0.975	0.750	0.995	1.000					
LGS TR									
LGS Bot									
LGS Top									
TDG	0.404	0.841	0.872	0.762				1.000	
Mean	63.32	65.45	62.68	63.13				67.09	
St.dev.	4.15	0.99	4.13	4.39				0.93	
N	77	46	77	77	0	0	0	41	

1996

	Tri-Level Thermograph Station 8				Fish Ladder			Gas Monitoring Stations	
	Scroll case	Bottom	Middle	Surface	Tail race	Bottom	Top	TDG1	TDG2
Scroll case	1.000								
TLT 8B	0.838	1.000							
TLT 8M	0.853	0.997	1.000						
TLT 8S	0.960	0.902	0.919	1.000					

LGS TR									
LGS Bot									
LGS Top									
TDG 1	-0.235	-0.822	-0.819	-0.572				1.000	
TDG 2	0.214	0.635	0.578	0.239				-0.798	1.000
Mean	62.77	61.64	62.11	63.17				71.01	64.95
St. dev.	4.13	3.22	3.31	4.16				1.50	2.83
N	77	77	77	77	0	0	0	22	31

Table 9. Correlation coefficients between temperature measurements from tri-level thermograph (TLT 8 bottom, middle, and surface), fish ladder (top, bottom, and tailrace), and temperature transects at monitoring locations at Little Goose Dam (LGS) from August 16 – October 31, 1991 – 1992.

1991	Scroll Case	Tri-level Thermograph Station 8			Fish Ladder			Transect 5			Transect 6			Transect 7			Transect 8			Transect 9		
		Bottom	Middle	Surface	Tail race	Bottom	Top	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
TLT 8B	0.965	1.000																				
TLT 8M	0.965	0.999	1.000																			
TLT 8S	0.978	0.992	0.994	1.000																		
LGS TR	0.984	0.976	0.977	0.990	1.000																	
LGS Bot																						
LGS Top	0.978	0.973	0.974	0.984	0.996		1.000															
Tr5 Mean	0.922	0.926	0.933	0.958	0.914		0.919	1.000														
Tr5 Min	0.557	0.803	0.807	0.793	0.593		0.619	0.742	1.000													
Tr5 Max	0.975	0.939	0.944	0.957	0.987		0.964	0.952	0.572	1.000												
Tr6 Mean	0.855	0.850	0.862	0.925	0.861		0.889	0.961	0.807	0.892	1.000											
Tr6 Min	0.829	0.688	0.708	0.799	0.841		0.863	0.945	0.805	0.879	0.992	1.000										
Tr6 Max	0.877	0.884	0.888	0.932	0.860		0.898	0.974	0.804	0.901	0.990	0.971	1.000									
Tr7 Mean	0.912	0.895	0.906	0.944	0.898		0.917	0.955	0.659	0.961	0.931	0.924	0.936	1.000								
Tr7 Min	0.872	0.865	0.875	0.862	0.878		0.859	0.925	0.707	0.918	0.942	0.938	0.930	0.978	1.000							
Tr7 Max	0.925	0.772	0.785	0.849	0.917		0.938	0.956	0.677	0.954	0.933	0.920	0.947	0.986	0.955	1.000						
Tr8 Mean	0.965	0.952	0.960	0.985	0.973		0.965	0.938	0.550	0.986	0.894	0.880	0.906	0.966	0.922	0.963	1.000					
Tr8 Min	0.937	0.891	0.898	0.935	0.943		0.964	0.890	0.536	0.954	0.873	0.862	0.880	0.957	0.928	0.955	0.974	1.000				
Tr8 Max	0.935	0.769	0.789	0.854	0.970		0.917	0.903	0.576	0.943	0.881	0.871	0.893	0.926	0.879	0.948	0.969	0.939	1.000			
Tr9 Mean	0.973	0.928	0.928	0.901	0.975		0.951	0.912	0.557	0.954	0.846	0.820	0.883	0.919	0.865	0.931	0.966	0.941	0.940	1.000		
Tr9 Min	0.914	0.605	0.608	0.606	0.894		0.886	0.880	0.546	0.908	0.828	0.815	0.864	0.908	0.850	0.921	0.938	0.931	0.914	0.975	1.000	
Tr9 Max	0.990	0.979	0.982	0.968	0.974		0.961	0.911	0.544	0.963	0.847	0.820	0.876	0.903	0.857	0.928	0.965	0.937	0.946	0.982	0.938	1.000
Mean	**66.3**	**61.3**	**61.4**	**61.7**	**63.9**		**65.0**	**64.6**	**62.0**	**66.7**	**64.3**	**63.8**	**64.8**	**65.3**	**64.0**	**66.7**	**66.0**	**64.6**	**68.1**	**66.3**	**65.6**	**67.0**
Stdev	**5.886**	**3.023**	**3.136**	**3.544**	**5.276**		**5.105**	**3.484**	**2.202**	**4.881**	**3.064**	**2.938**	**3.283**	**4.073**	**3.290**	**4.517**	**3.782**	**3.087**	**4.347**	**3.605**	**3.641**	**3.833**
N	**77**	**48**	**48**	**48**	**47**		**63**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**	**20**

Table 9. Continued.

1992	Scroll Case	Tri-level Thermograph Station 8			Fish Ladder			Transect 5			Transect 6			Transect 7			Transect 8			Transect 9		
		Bottom	Middle	Surface	Tail race	Bottom	Top	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
TLT 8B	0.962	1.000																				
TLT 8M	0.958	0.989	1.000																			
TLT 8S	0.937	0.959	0.985	1.000																		
LGS TR	0.992	0.973	0.958	0.932	1.000																	
LGS Bot	0.984	0.955	0.959	0.969	0.988	1.000																
LGS Top	0.982	0.953	0.958	0.967	0.986	0.999	1.000															
Tr5 Mean	0.902	0.965	0.958	0.938	0.911	0.924	0.922	1.000														
Tr5 Min	0.704	0.754	0.688	0.578	0.725	0.643	0.639	0.822	1.000													
Tr5 Max	0.961	0.966	0.988	0.996	0.963	0.982	0.982	0.953	0.670	1.000												
Tr6 Mean	0.899	0.951	0.941	0.925	0.910	0.928	0.924	0.994	0.806	0.947	1.000											
Tr6 Min	0.903	0.958	0.948	0.929	0.914	0.927	0.924	0.990	0.800	0.953	0.997	1.000										
Tr6 Max	0.896	0.955	0.944	0.928	0.907	0.926	0.923	0.991	0.804	0.941	0.998	0.990	1.000									
Tr7 Mean	0.936	0.974	0.983	0.980	0.939	0.960	0.959	0.977	0.719	0.983	0.975	0.975	0.976	1.000								
Tr7 Min	0.938	0.979	0.975	0.957	0.940	0.952	0.951	0.978	0.743	0.975	0.979	0.979	0.980	0.996	1.000							
Tr7 Max	0.924	0.940	0.965	0.990	0.927	0.969	0.968	0.955	0.641	0.985	0.953	0.952	0.955	0.992	0.981	1.000						
Tr8 Mean	0.975	0.985	0.996	0.987	0.980	0.986	0.985	0.946	0.697	0.990	0.944	0.946	0.943	0.981	0.975	0.977	1.000					
Tr8 Min	0.976	0.991	0.972	0.921	0.981	0.961	0.960	0.952	0.774	0.969	0.951	0.955	0.949	0.968	0.975	0.945	0.984	1.000				
Tr8 Max	0.942	0.923	0.954	0.987	0.947	0.985	0.985	0.917	0.601	0.979	0.920	0.919	0.923	0.969	0.955	0.985	0.985	0.944	1.000			
Tr9 Mean	0.978	0.967	0.965	0.947	0.977	0.983	0.980	0.891	0.676	0.962	0.895	0.897	0.898	0.934	0.931	0.932	0.985	0.971	0.967	1.000		
Tr9 Min	0.986	0.978	0.972	0.942	0.987	0.978	0.973	0.903	0.710	0.962	0.905	0.908	0.907	0.937	0.935	0.929	0.986	0.978	0.960	0.997	1.000	
Tr9 Max	0.941	0.909	0.919	0.935	0.937	0.982	0.985	0.874	0.601	0.956	0.885	0.885	0.891	0.929	0.925	0.941	0.973	0.943	0.980	0.984	0.972	1.000
Mean	**65.2**	**67.7**	**68.4**	**68.7**	**64.5**	**65.2**	**65.0**	**66.0**	**62.9**	**67.8**	**65.6**	**65.2**	**65.9**	**66.6**	**65.8**	**67.3**	**67.1**	**66.1**	**68.3**	**67.2**	**66.8**	**67.9**
Stdev	**5.230**	**4.059**	**3.899**	**4.235**	**4.966**	**5.154**	**5.208**	**5.273**	**4.621**	**5.399**	**5.127**	**5.156**	**5.250**	**5.335**	**4.874**	**5.662**	**4.694**	**4.232**	**5.340**	**4.303**	**4.242**	**4.703**
N	**76**	**44**	**44**	**44**	**77**	**77**	**77**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**	**13**

End Table 11.

Table 10. Differences (degrees F) between temperatures recorded at the Lower Granite Dam scroll case and the daily mean, minimum, and maximum transect temperatures recorded immediately upstream (#14) and downstream (#15) of LWG. Differences are expressed as scroll case temperatures minus transect temperatures, therefore a positive number means the scroll case temperature is greater than that at the transects. Also noted are the t-statistics and p-values for a paired-t test between temperatures recorded at the scroll case and mean, minimum, and maximum transect temperatures. Data presented is for the time period from start of data collection (July 23 in 1991 and July 1 in 1992) through September 30.

1991

	Transect 5 (n=19)			Transect 6 (n=19)		
Difference	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Mean	2.1	5.6	-0.5	2.5	3.0	1.8
Min	-0.8	1.3	-2.8	-1.4	-1.4	-1.4
Max	6.4	13.6	1.5	7.8	8.4	7.4
Std Dev	1.7	3.2	1.4	1.9	2.4	2.2
T-Stat	4.55	6.05	-1.94	3.93	4.62	2.97
P-value	0.00	0.00	0.06	0.00	0.00	0.01

1992

	Transect 5 (n=28)			Transect 6 (n=27)		
Difference	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Mean	-2.4	1.8	-5.6	-1.6	-1.2	-2.0
Min	-6.9	-2.4	-11.7	-4.8	-4.5	-7.4
Max	4.0	10.5	1.0	4.2	4.4	4.2
Std Dev	-2.2	2.9	3.5	-1.5	2.3	2.5
T-Stat	-4.80	3.21	-8.50	-3.58	-2.62	-4.21
P-value	0.00	0.00	0.00	0.00	0.01	0.00

Table 11. Differences (degrees F) between temperatures recorded at the Ice Harbor Dam scroll case and the daily mean, minimum, and maximum transect temperatures recorded immediately upstream (#14) and downstream (#15) of IHR. Differences are expressed as scroll case temperatures minus transect temperatures, therefore a positive number means the scroll case temperature is greater than that at the transects. Also noted are the t-statistics and p-values for a paired-t test between temperatures recorded at the scroll case and mean, minimum, and maximum transect temperatures. Data presented is for the time period from start of data collection (July 23 in 1991 and July 2 in 1992) through September 30.

1991

	Transect 14 (n=19)			Transect 15 (n=19)		
Difference	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Mean	0.3	1.8	-2.8	0.1	0.4	-0.4
Min	-1.7	-0.4	-9.0	-2.4	-1.8	-3.6
Max	4.6	7.6	2.4	3.1	3.5	2.7
Std Dev	1.5	1.7	3.2	1.3	1.3	1.6
T-Stat	0.76	4.40	-3.80	0.30	1.35	-1.20
P-value	0.45	0.00	0.00	0.77	0.19	0.24

1992

	Transect 14 (n=24)			Transect 15 (n=24)		
Difference	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Mean	-1.8	-0.1	-4.7	-2.1	-1.8	-2.7
Min	-4.4	-2.1	-10.4	-5.1	-4.9	-5.9
Max	0.62	2.6	0.4	0.4	0.7	0.4
Std Dev	1.5	1.1	3.0	1.5	1.4	1.7
T-Stat	-6.69	-1.08	-8.38	-7.70	-6.96	-8.43
P-value	0.00	0.29	0.00	0.00	0.00	0.00

Table 12. Mean annual August – October scroll case temperatures from four Snake River dams. Time averaged and fall chinook weighted temperatures are listed for Ice Harbor Dam, Lower Monumental Dam, Little Goose Dam, and Lower Granite Dam.

	ICE HARBOR		L. MONUMENTAL		L. GOOSE		L. GRANITE	
Year	Time Averaged	Fish Weighted	Time Averaged	Fish Weighted	Time Averaged	Fish Weighted	Time Averaged	Fish Weighted
1963	68.2	68.6						
1964	63.4	63.9						
1965	64.4	63.2						
1966	66.4	67.6						
1967	68.1	66.8						
1968	63.2	64.7						
1969	64.4	65.2						
1970	65.3	66.2			63.0	63.4		
1971	66.0	67.1	65.4	66.1	64.4	65.2		
1972	65.3	64.8	65.0	65.8	64.7	64.9		
1973	64.6	65.8	64.5	65.6	64.0	65.0		
1974	65.2	66.5	65.2	65.5	65.1	64.7		
1975	68.4	68.8	64.9	65.8	64.7	66.4	63.7	64.9
1976	66.3	67.4	66.0	66.8	65.9	66.3	65.4	64.4
1977	65.9	66.5	65.0	65.6	64.5	65.0	64.3	63.1
1978	65.0	65.9	64.6	64.8	64.1	63.6	63.8	63.8
1979	68.8	69.7	68.5	69.0	68.4	68.9	65.9	67.0
1980	66.9	67.2	65.4	65.7	66.2	66.6	64.4	64.1
1981	66.9	68.6	66.5	67.3	66.6	66.2	65.0	64.1
1982	65.9	67.7	65.4	66.5			64.2	64.0
1983	66.2	67.0	66.4	66.3			64.4	62.6
1984	65.8	66.9	65.1	65.8			63.3	62.8
1985	64.6	64.0	63.6	62.1			62.0	62.1
1986	66.6	65.3	65.8	63.4			64.4	60.8
1987	67.4	68.1	66.5	66.3			65.3	64.0
1988	67.2	67.3	66.0	65.8			66.6	65.9
1989	66.2	66.7	65.5	65.8			63.3	62.9
1990	68.0	68.8	67.1	66.9			66.2	65.0
1991	67.4	67.1	66.9	66.7	66.3	65.4	64.6	62.3
1992	65.5	65.9	65.2	65.5	65.1	64.9	63.5	62.9
1993	65.2	65.8	65.5	66.4	66.9	68.4	63.7	64.6
1994	65.9	66.6	66.2	66.9	67.6	67.9	65.7	65.0
1995	64.4	64.7	64.3	64.5	63.3	63.8	61.7	62.9

Table 13. Migratory timing of fall chinook salmon in the lower snake River, 1963 – 1995. Mean annual fish weighted timing, standard errors (s.e.), and number of fish for each year of record at Ice Harbor Dam, Lower Monumental Dam, Little Goose Dam, and Lower Granite Dam.

	ICE HARBOR			L. MONUMENTAL			L. GOOSE			L. GRANITE		
Year	Mean	s.e.	N	mean	s.e.	N	mean	s.e.	n	mean	s.e.	N
1963	9/21	0.13	12838									
1964	9/17	0.14	10924									
1965	9/20	0.13	12005									
1966	9/18	0.12	15018									
1967	9/28	0.10	19022									
1968	9/19	0.10	23855									
1969	9/20	0.12	16796									
1970	9/18	0.14	10163				9/19	0.18	6041			
1971	9/19	0.12	11004	9/20	0.10	10203	9/20	0.13	6084			
1972	9/23	0.16	9436	9/19	0.22	5192	9/21	0.37	2316			
1973	9/19	0.14	8353	9/19	0.17	5437	9/20	0.22	3169			
1974	9/22	0.26	2814	9/25	0.26	3020	9/27	0.39	1283			
1975	9/18	0.28	2558	9/18	0.23	3053	9/19	0.35	1605	9/22	0.35	2174
1976	9/18	0.35	1474	9/22	0.27	2085	9/24	0.49	1068	9/29	0.50	1218
1977	9/20	0.31	1756	9/23	0.31	1947	9/23	0.36	1256	9/29	0.38	1797
1978	9/17	0.41	1593	9/20	0.57	1013	9/25	0.50	1271	9/23	0.51	1442
1979	9/17	0.34	2056	9/20	0.40	1284	9/22	0.45	1190	9/21	0.38	1394
1980	9/22	0.37	1719	9/21	0.65	913	9/22	0.67	698	9/26	0.65	753
1981	9/20	0.29	2102	9/23	0.33	1624	9/27	0.38	1385	9/27	0.32	1714
1982	9/20	0.22	3519	9/22	0.29	2378				9/25	0.32	2134
1983	9/21	0.27	2735	9/22	0.38	1524				9/27	0.38	1433
1984	9/19	0.27	2445	9/21	0.43	1226				9/24	0.42	1322
1985	9/25	0.15	8907	9/28	0.19	5827				9/24	0.34	2127
1986	9/27	0.16	5798	9/29	0.16	4873				10/1	0.24	2410
1987	9/24	0.14	8375	9/28	0.21	4556				9/29	0.43	1212
1988	9/22	0.22	5882	9/22	0.32	3031				9/28	0.61	848
1989	9/20	0.21	5990	9/21	0.32	2918				9/25	0.61	923
1990	9/23	0.22	5317	9/27	0.35	2380				9/30	0.72	535
1991	9/24	0.18	6026	9/24	0.24	3245	9/26	0.39	1122	9/30	0.42	992
1992	9/23	0.20	5530	9/22	0.29	2493	9/22	0.38	1324	9/24	0.52	894
1993	9/21	0.28	3137	9/20	0.31	2296	9/20	0.37	1425	9/20	0.45	1168
1994	9/26	0.27	3133	9/27	0.30	2548	9/29	0.45	1219	9/29	0.48	1000
1995	9/25	0.20	5202	9/28	0.22	4616	9/27	0.31	2297	9/26	0.39	1348
1996	9/16	0.23	4618	9/19	0.24	3766	9/20	0.31	2338	9/22	0.36	1687

Figure 1. Map of the Lower Snake River Basin showing the major hydroelectric dams, and the location of water temperature monitoring transects. Symbols used in this report for dams are DWR, Dworshak Dam; LWG, Lower Granite Dam; LGS, Little Goose Dam; LMN, Lower Monumental Dam; IHR, Ice Harbor Dam.

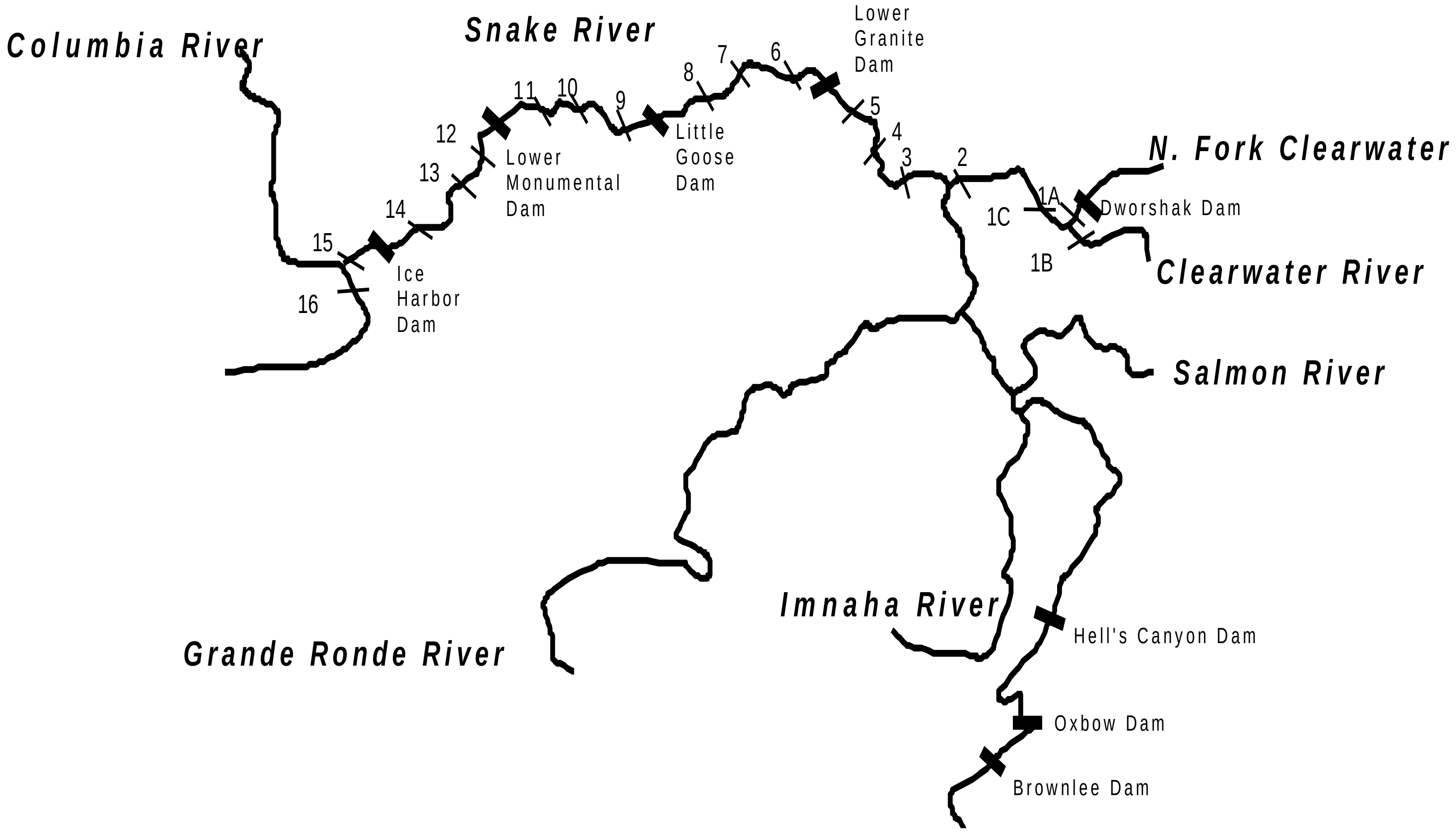
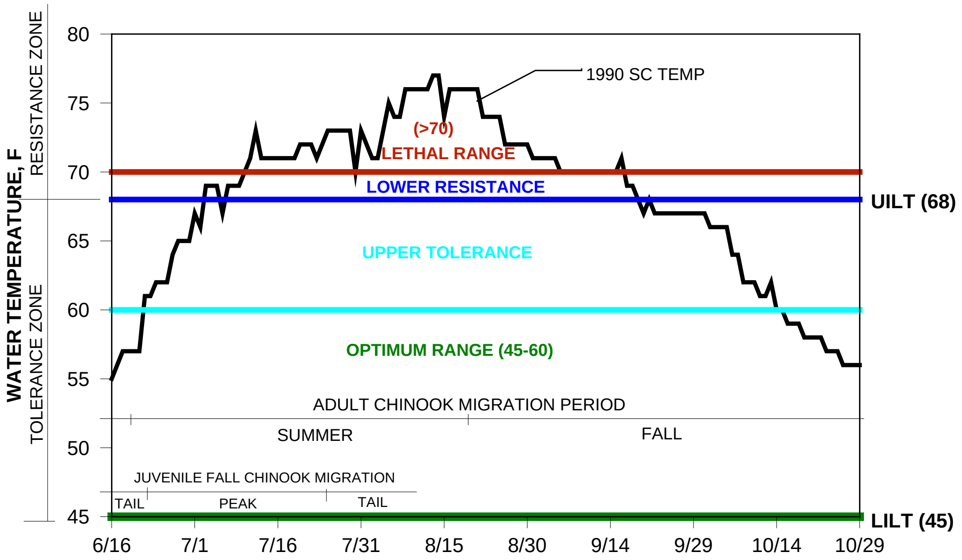


Figure 2. Chinook salmon migration periods and Lower Granite Dam 1990 daily scroll case temperatures. Isotherms mark the two primary temperature classifications, resistance (>68 F) and upper tolerance (45-68 F). The lethal range of the zone of resistance starts at 70 F, and the optimum range of the zone of upper tolerance is 45-60 F. *After Brett 1952*



TEMPERATURE ZONES AND RANGES ARE ADAPTED FROM BRETT, 1952

UILT =Upper Incipient Lethal Temperature
LILT = Lower Incipient Lethal Temperature

Figure 3. Mean daily scroll case temperatures at Ice Harbor Dam during the fall chinook immigration, 1962-1995.

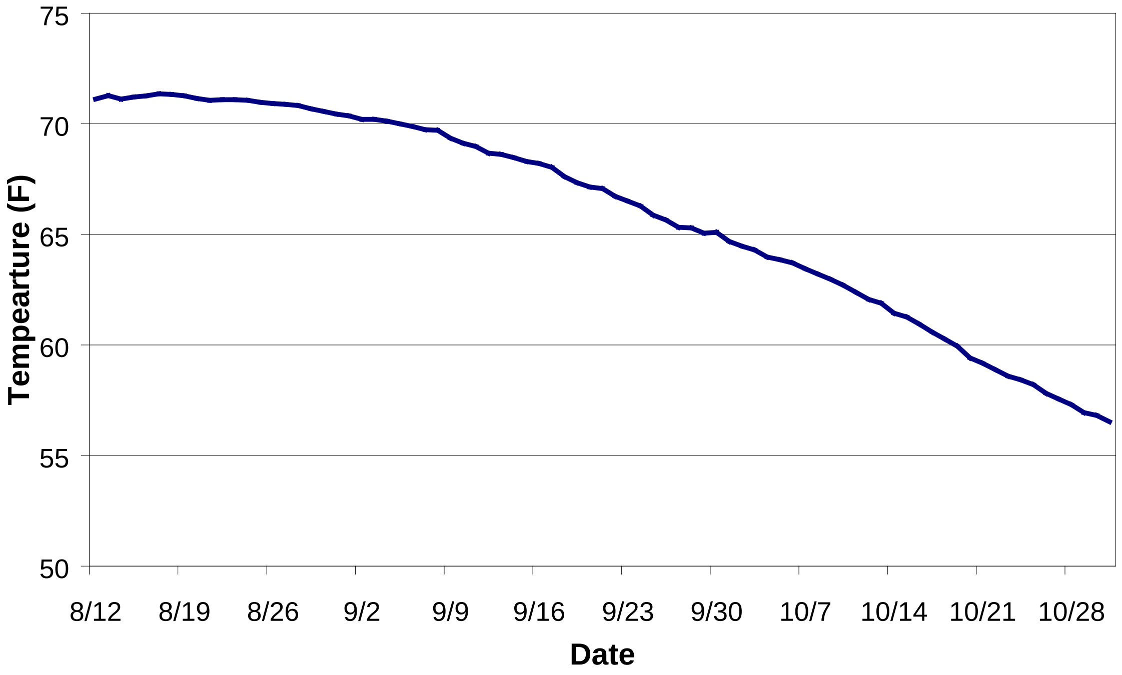
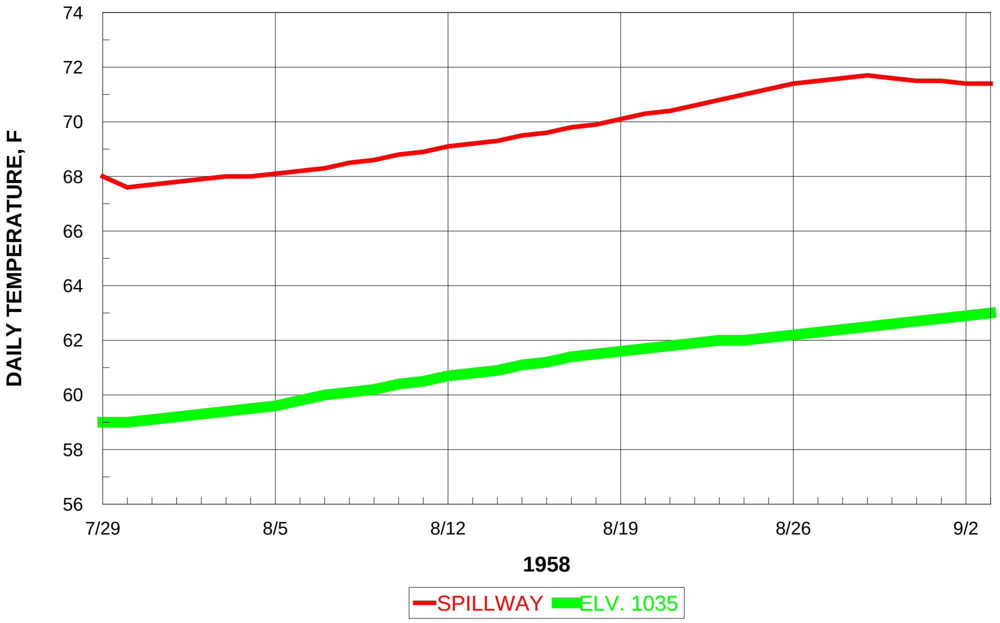
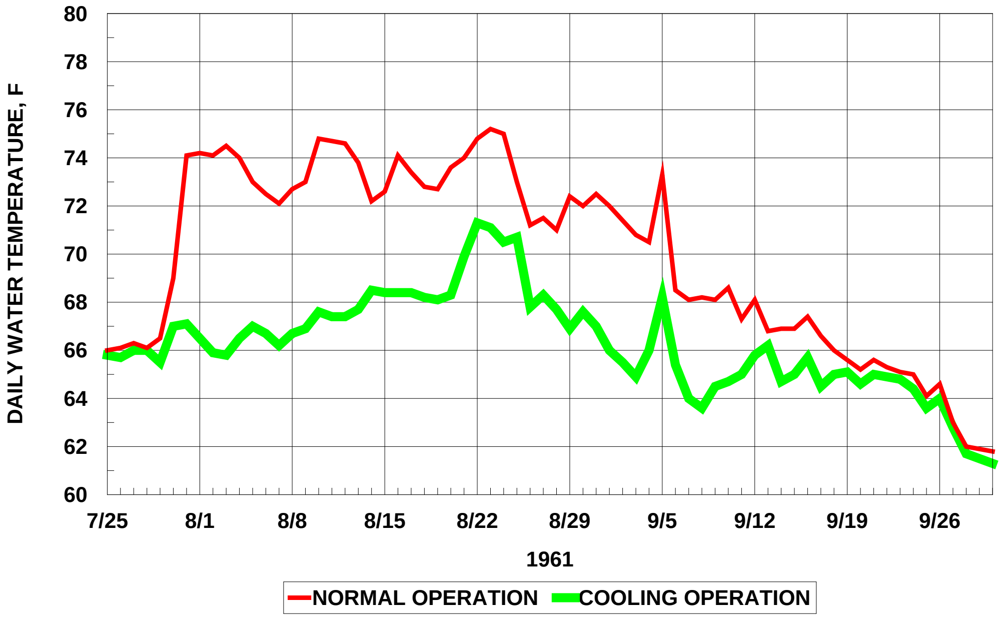


Figure 4. 1958 daily water temperatures at Grand Coulee Dam spillway versus elevation 1035 (255 feet below full pool elevation).



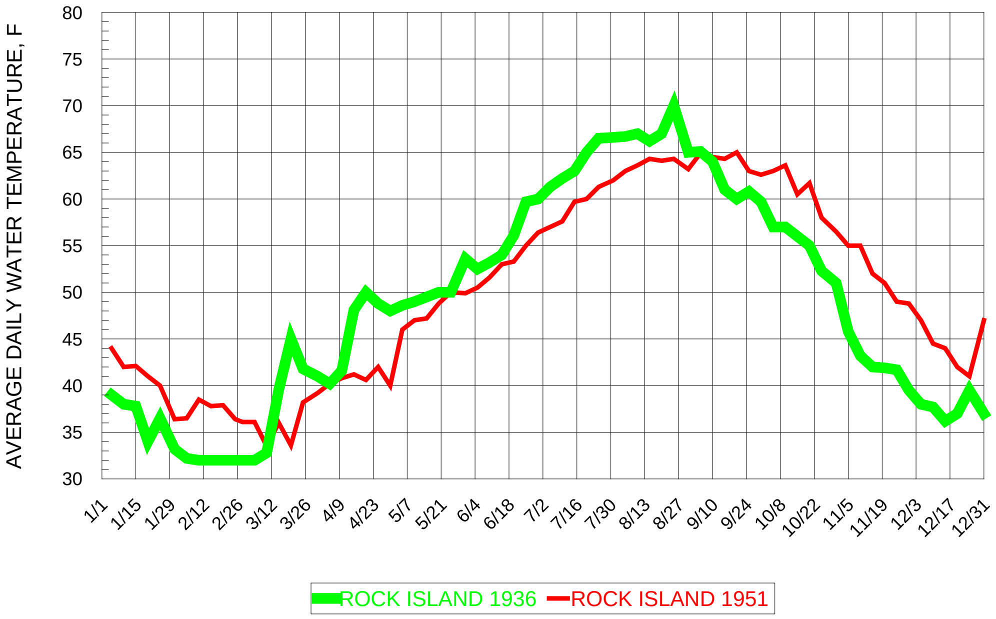
DATA FROM KRAMER, 1962

Figure 5. Artificial cooling of the Hanford reach by regulating Grand Coulee Dam.



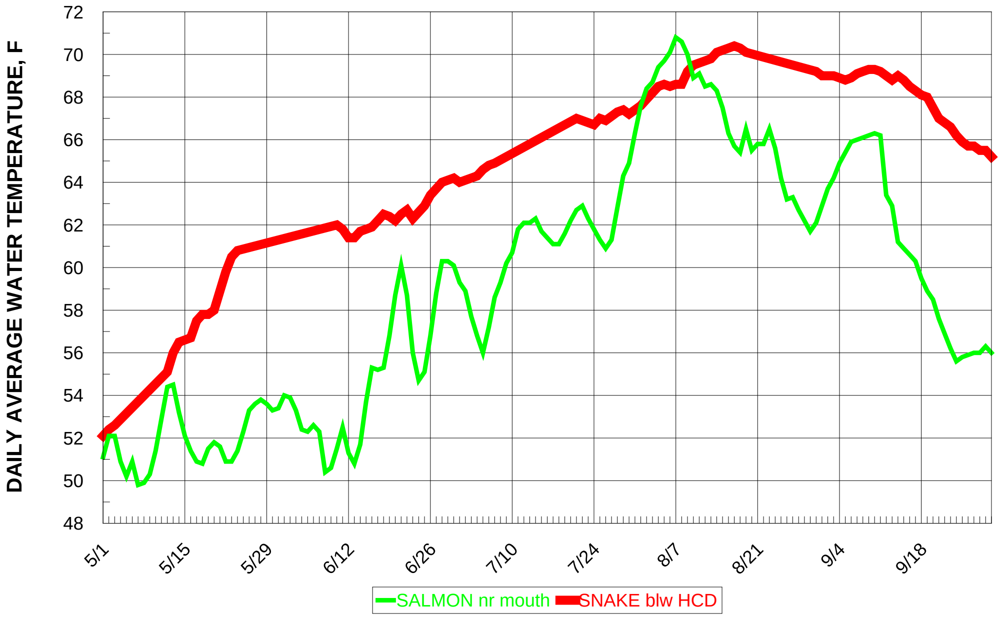
ADAPTED FROM KRAMER, 1962

Figure 6. Historical water temperatures in the mid-Columbia as measured at Rock Island Dam before Grand Coulee (1936) compared with temperatures after Grand Coulee (1951).



SOURCE :DATA FROM DAVIDSON, 1964

Figure 7. 1993 May through September daily water temperatures of the Salmon River near its mouth compared to the Snake River below Hells Canyon Dam. Data from the Phase I report of the Snake River Water Temperature Control Project (Karr 1993).



IDAHO POWER COMPANY DATA

Figure 8. Cross sectional profile of the Snake River, on Transect 5 which is located at Snake River mile 110.5, in Lower Granite Reservoir. The spacing of the stations on the transect and the depths of temperature recordings (X) at each station are typical of those at the other transects.

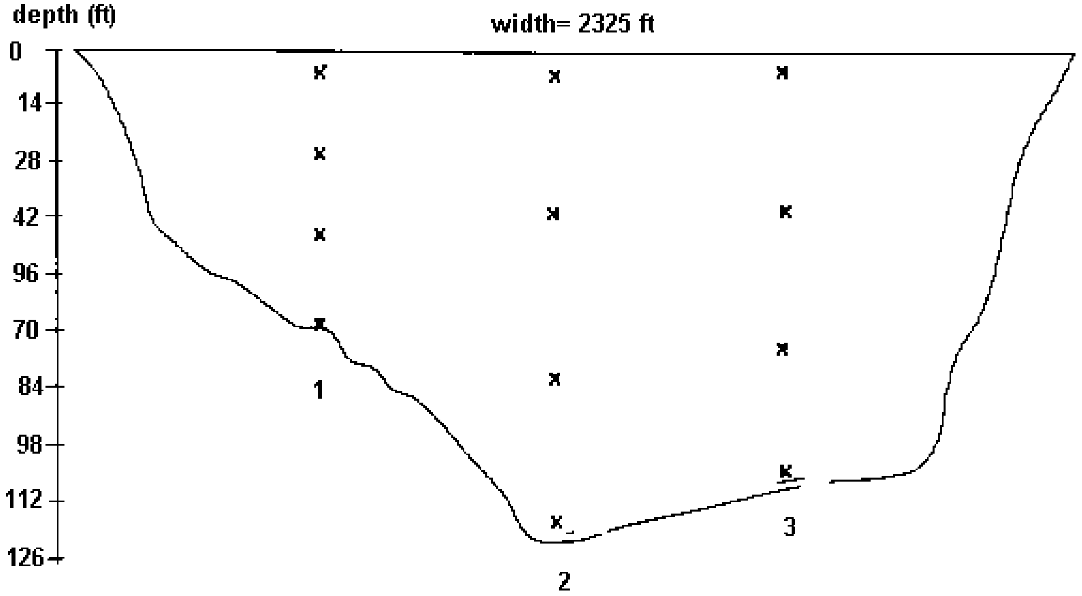


Figure 9. Mean daily scroll case temperatures at Ice Harbor Dam for the periods 1963-1967, 1986-1990, and 1992-1996. The upper limit of the optimum temperature range and the upper incipient lethal temperature for chinook salmon are shown for comparison purposes.

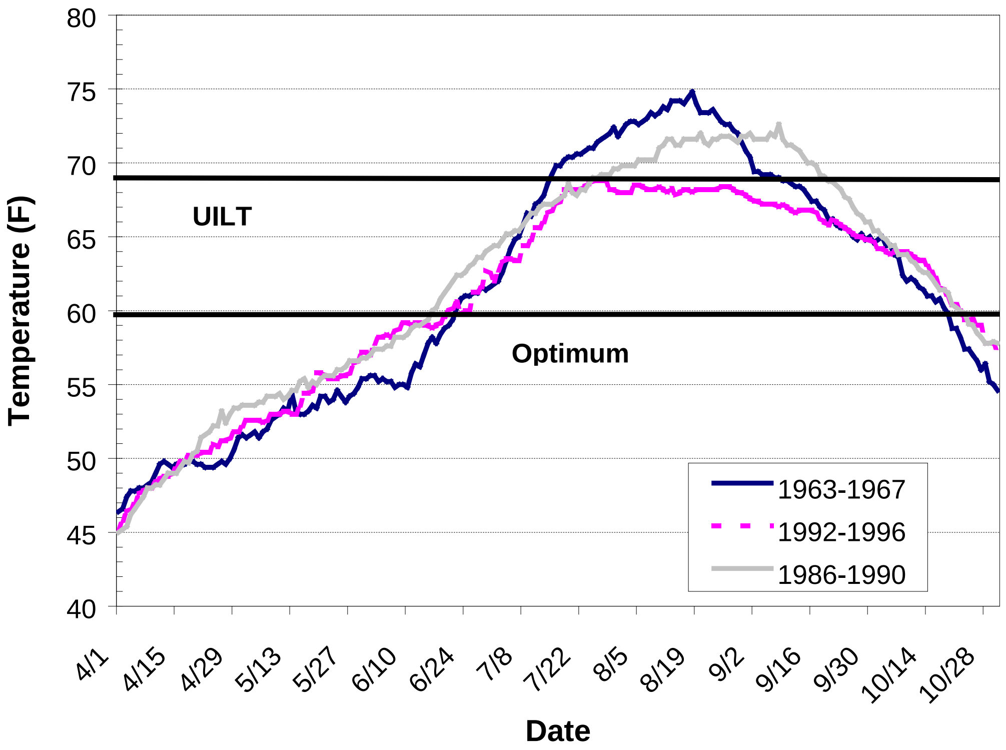


Figure 10. Percentage of days between June 1 and September 30 that scroll case temperatures exceed optimum levels (60F) at Ice Harbor (IHR), Lower Granite (LWG), and John Day (JDA) dams 1963-1996. The mean daily flow at Ice Harbor Dam (kcfs) over this period is included for comparison purposes.

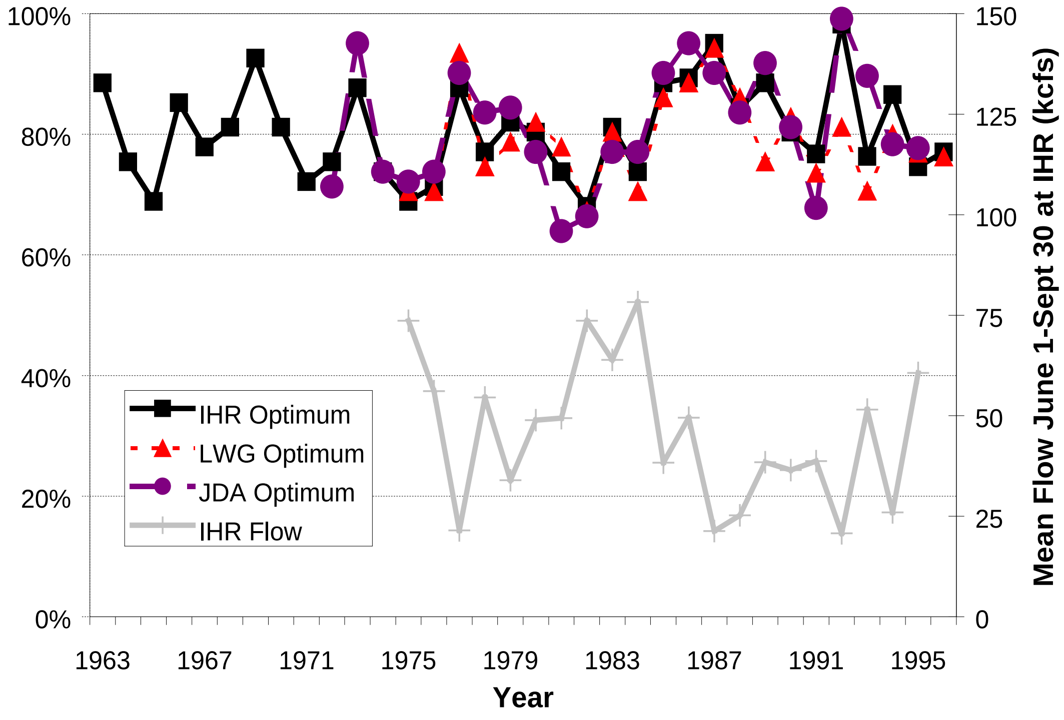


Figure 11. Percentage of days between June 1 and September 30 that scroll case temperatures exceed UILT (68F) at Ice Harbor (IHR) and John Day (JDA) dams 1963-1996. The mean daily flow at Ice Harbor (kcfs) over this period is included for comparison purposes.

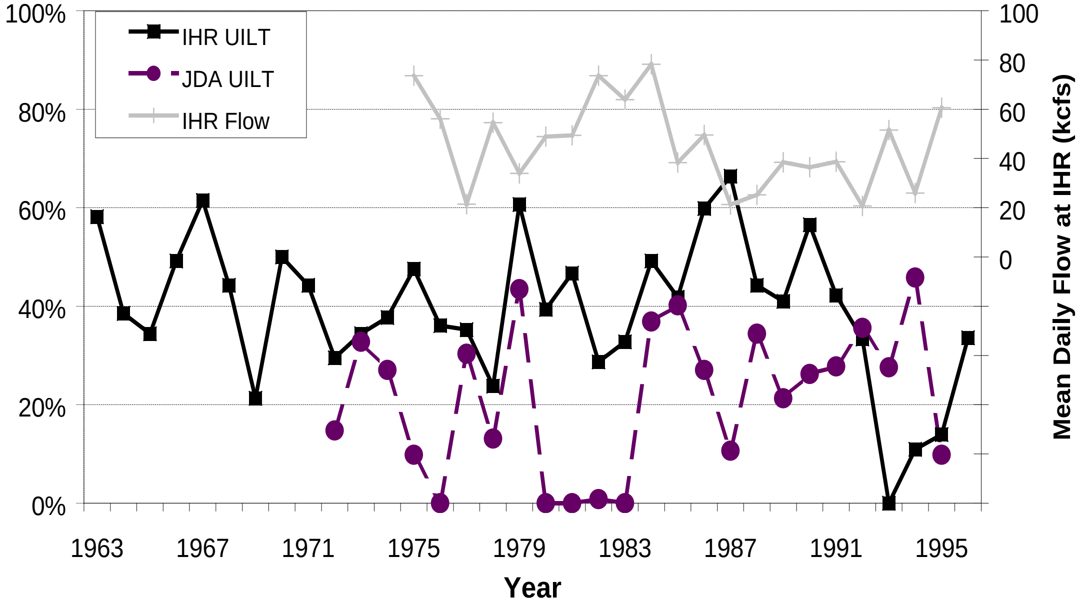


Figure 12. Correlation between the mean seven day flow and seven day scroll case temperatures (June 1-September 26) at Ice Harbor Dam 1975-1996.

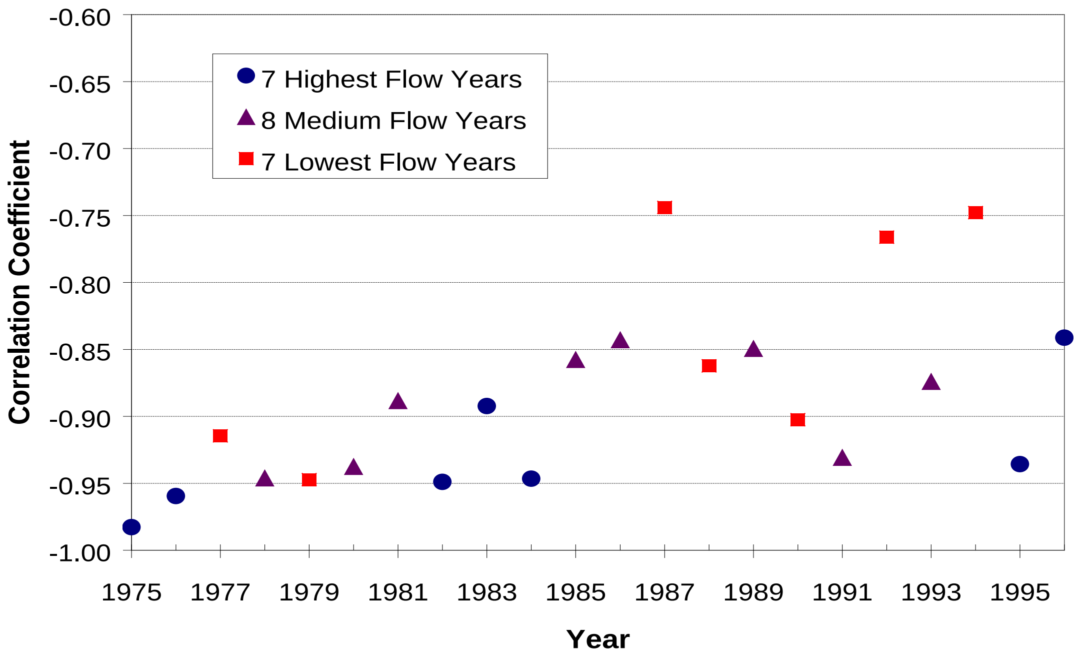


Figure 13. Relationship between the correlation between the mean seven day flow and seven day scroll case temperatures (June 1-September 26) at Ice Harbor Dam 1975-1996 and the mean seven day flow (June 1-September 26) at Ice Harbor Dam.

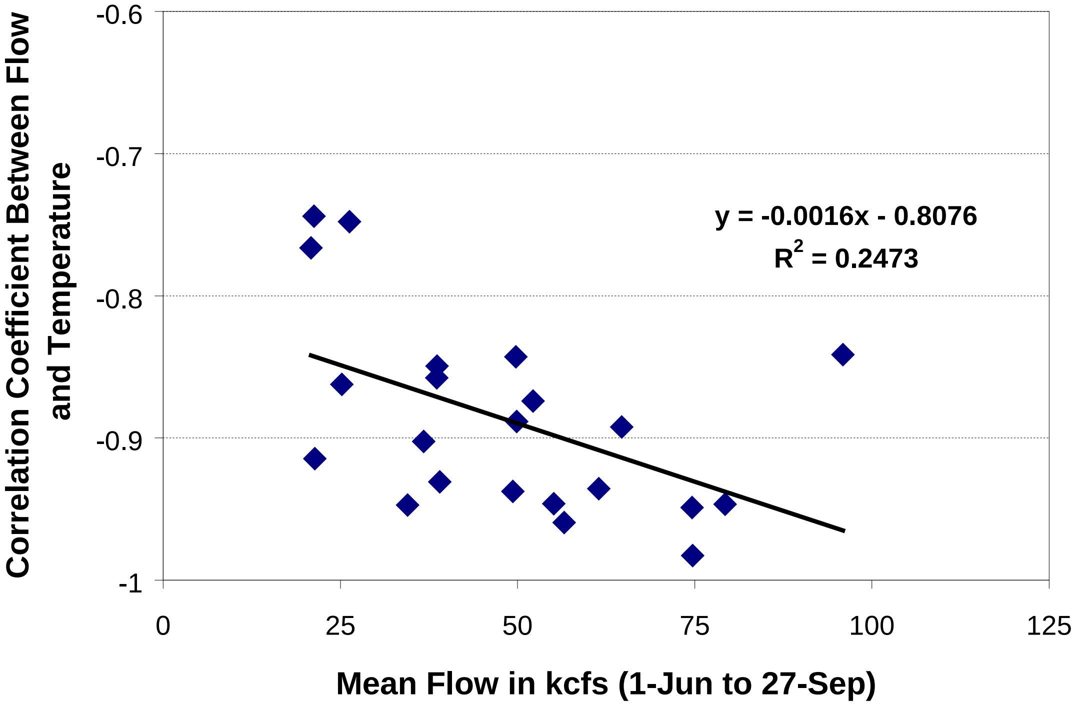
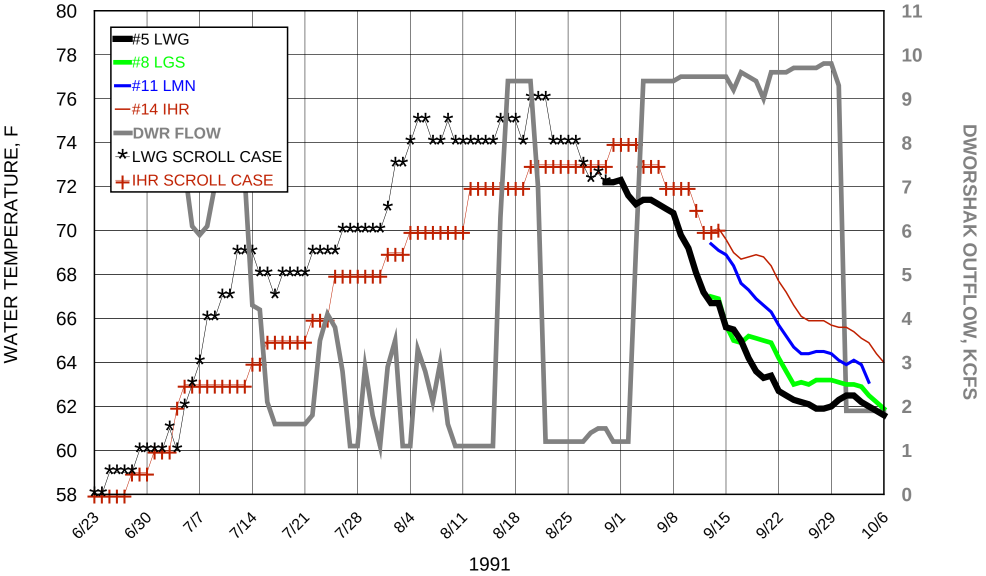
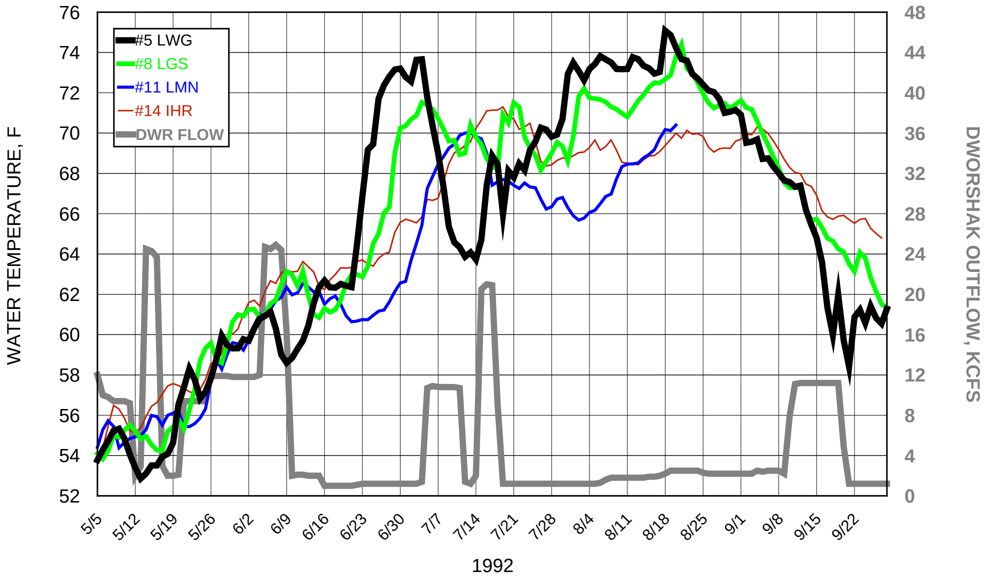


Figure 14. 1991 daily mean water temperatures in the lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14 for September, and from temperatures reported as scroll case measurements at Lower Granite (LWG) and Ice Harbor (IHR) dams prior to September, compared with Dworshak Dam cold water release rates.



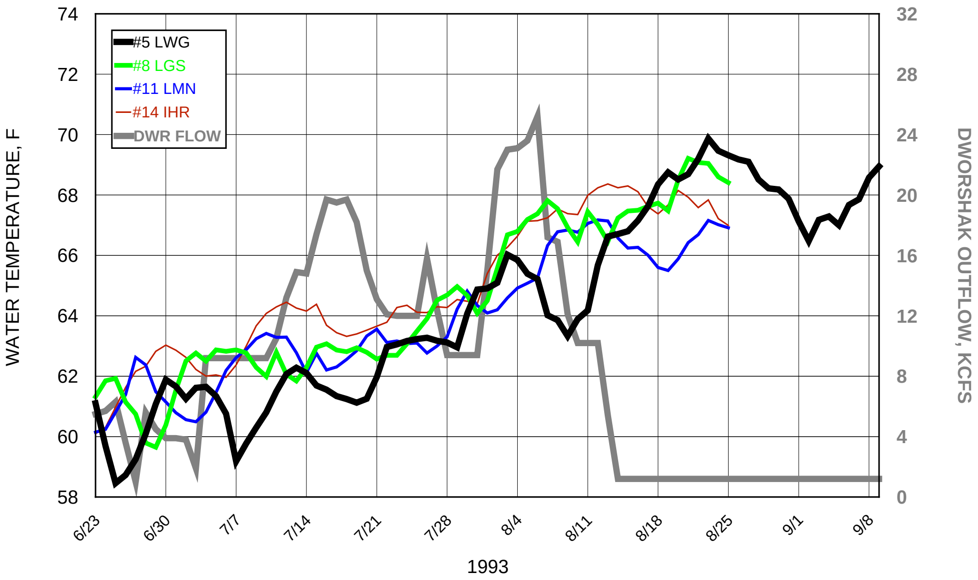
STATIONS LOCATED AS FOLLOWS: #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS DAM; #11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM. DWR RELEASE TEMPERATURES FROM 6/23 THRU 10/6 RANGED BETWEEN 45 AND 54 AND AVERAGED 50 F.

Figure 15. 1992 daily mean water temperatures in the lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14, compared with Dworshak Dam cold water release rates.



STATIONS LOCATED AS FOLLOWS: #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS, DAM;
#11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM
DWR RELEASE TEMPERATURES FROM 5/5 THRU 9/28 RANGED BETWEEN 45 AND 57 AND AVERAGED 52 F.

Figure 16. 1993 daily mean water temperatures in the lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14, compared with Dworshak Dam cold water release rates.



STATIONS LOCATED AS FOLLOWS: #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS, DAM;
#11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM
DWR RELEASE TEMPERATURES FROM 6/23 THRU 9/9 RANGED BETWEEN 45 AND 52 AND AVERAGED 48 F.

Figure 17. 1994 water temperatures in lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14 compared with Dworshak cold water release rates.

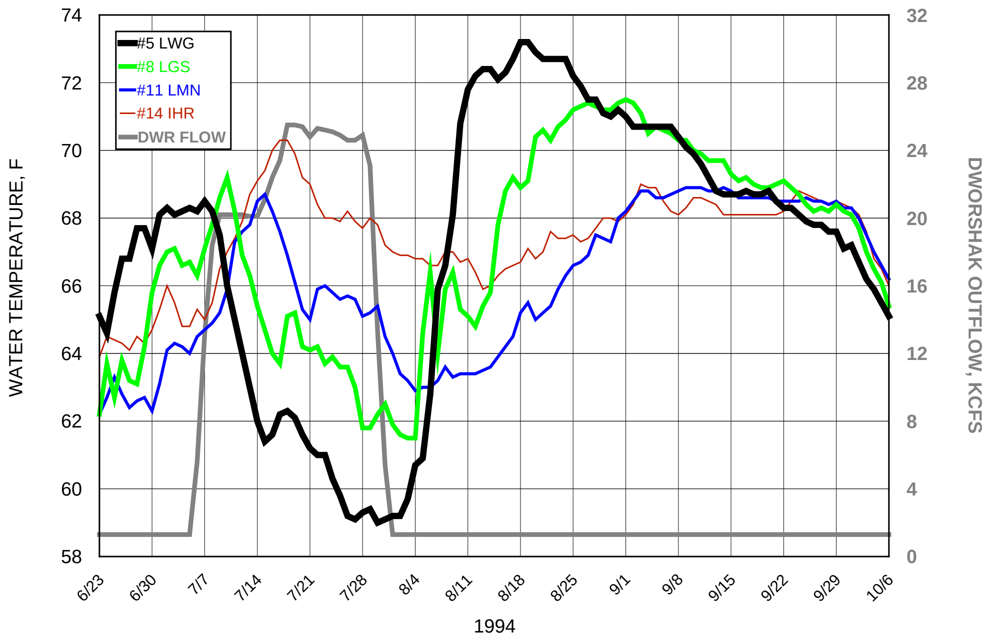
1994 DWORSHAK FLOW AND TEMPERATURE RELEASES

- Dworshak outflow increased from 1.3 kcfs on 7/5 to 20.2 kcfs on 7/9, held at that flow through 7/14, then increased to 25+ kcfs on 7/18, held at that level through 7/28, then decreased to 1.3 kcfs by 8/1. Total period of augmented flow was about **28 days**.

- Dworshak water release temperatures from 7/5 through 8/1 ranged from 42 to 54 °F and averaged **48.6 °F.**

1994 DOWNSTREAM TEMPERATURE REDUCTIONS

	START		END		PER IOD	
	Date	**°F**	**Date**	**°F**	**No. Days**	**∆°F**
LWG	7/7	68.5	7/30	59.0	24	**9.5**
LGS	7/10	69.2	8/4	61.5	26	**7.7**
LMN	7/15	68.6	8/4	62.9	21	**5.7**
IHR	7/18	70.3	8/13	65.9	26	**4.4**



DATA FROM MID-DEPTH (ABOUT 40 FT.) RECORDING THERMOGRAPHS AT TRANSECT STATIONS LOCATED AS FOLLOWS: #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS DAM; #11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM.

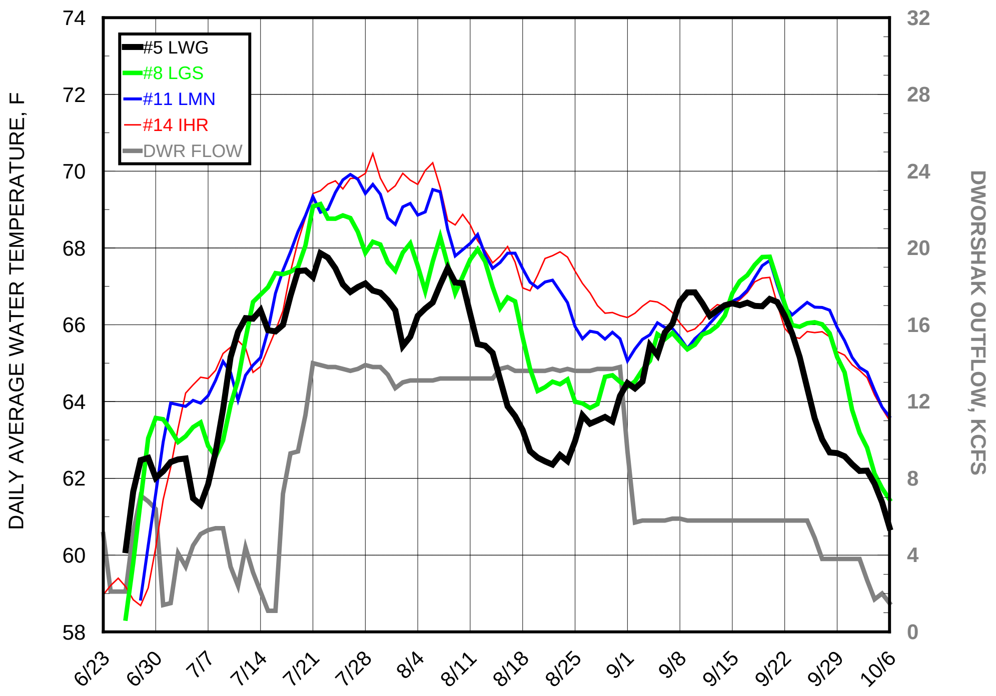
Figure 18. 1995 water temperatures in lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14 compared with Dworshak cold water release rates.

1995 DWORSHAK FLOW AND TEMPERATURE RELEASES

- Dworshak outflow increased from 1.1 kcfs on 7/16 to 14.0 kcfs on 7/21, held near that flow through 8/31, then decreased to 5.8 kcfs by 9/2, and held at that level through the third week of September. Total period of augmented flow was about **49 days**.

- Dworshak water release temperatures from 7/16 through 9/2 ranged from 46 to 56 °F and averaged **50.5 °F.**

1995 DOWNSTREAM TEMPERATURE REDUCTIONS						
	START		END		PER IOD	
	Date	°F	Date	°F	No. Days	Δ°F
LWG	7/22	67.9	8/22	62.4	32	**5.5**
LGS	7/22	69.1	8/27	63.8	37	**5.3**
LMN	7/26	69.9	9/1	65.1	38	**4.8**
IHR	7/29	70.5	9/9	65.8	43	**4.7**



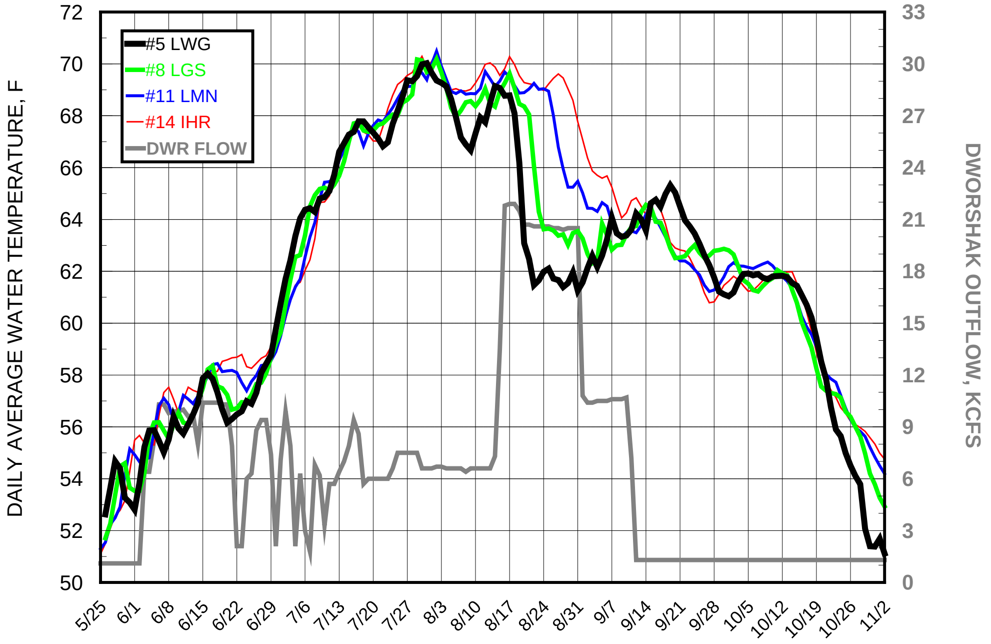
DATA FROM MID-DEPTH (ABOUT 40 FT.) RECORDING THERMOGRAPHS AT TRANSECT STATIONS LOCATED AS FOLLOWS: #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS DAM; #11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM.

Figure 19. 1996 water temperatures in lower Snake River reservoirs from mid-depth recording thermographs at transect stations #s 5, 8, 11, and 14 compared with Dworshak cold water release rates.

1996 DWORSHAK FLOW AND TEMPERATURE RELEASES

- Dworshak outflow increased from 6.6 to 21.8 kcfs on 8/13, held at about 21.0 kcfs through 8/31, then increased to 10.8 kcfs on 9/1, held at that level through 9/10, and decreased to 1.3 kcfs for the remainder of September. Total period of augmented flow was about **28 days**.
- Dworshak water release temperatures from 8/15 through 9/10 ranged from 49 to 56 °F and averaged **52.4 °F.**

1996 DOWNSTREAM TEMPERATURE REDUCTIONS						
	START		**END**		**PER IOD**	
	Date	**°F**	**Date**	**°F**	**No. Days**	**Δ°F**
LWG	8/14	69.1	8/31	61.3	18	**7.8**
LGS	8/17	69.6	9/3	62.3	18	**7.3**
LMN	8/21	69.0	9/9	63.3	20	**5.7**
IHR	8/27	69.6	9/9	64.1	14	**5.5**



DATA FROM MID-DEPTH (ABOUT 40 FT.) RECORDING THERMOGRAPHS AT TRANSECT STATIONS LOCATED AS FOLLOWS; #5, 2.9 MILES ABOVE LWG DAM; #8, 10.5 MILES ABOVE LGS DAM; #11, 2.3 MILES ABOVE LMN DAM; AND #14, 5.9 MILES ABOVE IHR DAM.

Figure 20. Temperature categories, by depth and distance, from the mouth of the Snake River on August 8, 1991. Colors refer to the temperature category where red is lethal (>70 F, 21.1C), magenta is resistance (68-70 F, 20-21.1C), blue is tolerance (60-68 F, 15.6-20C), and green is optimum (<= 60 F, 15.6C). The location of Ice Harbor (IHR), Lower Monumental (LMN), Little Goose (LGS), and Lower Granite (LWG) dams is indicated by vertical lines.

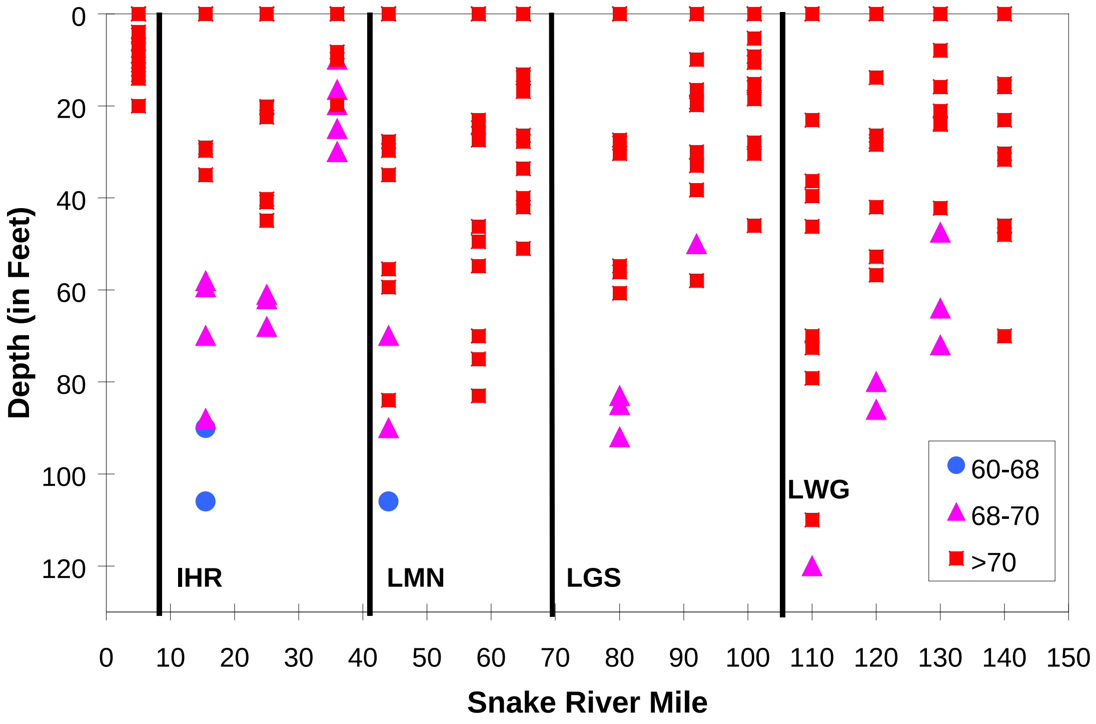


Figure 21. Temperature contours (F) from 15 stations on the Snake River plotted for August 8, 1991.

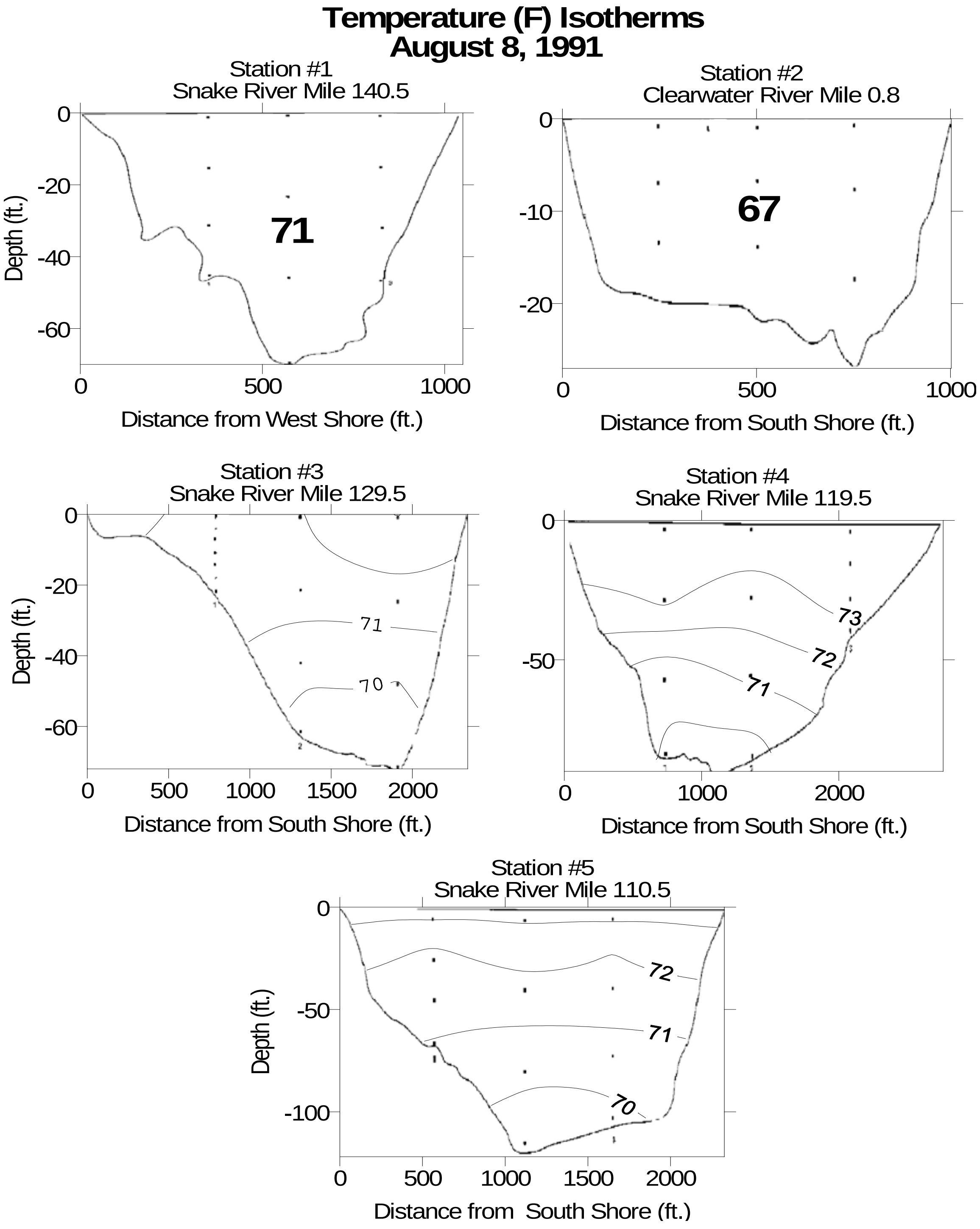


Figure 21 continued

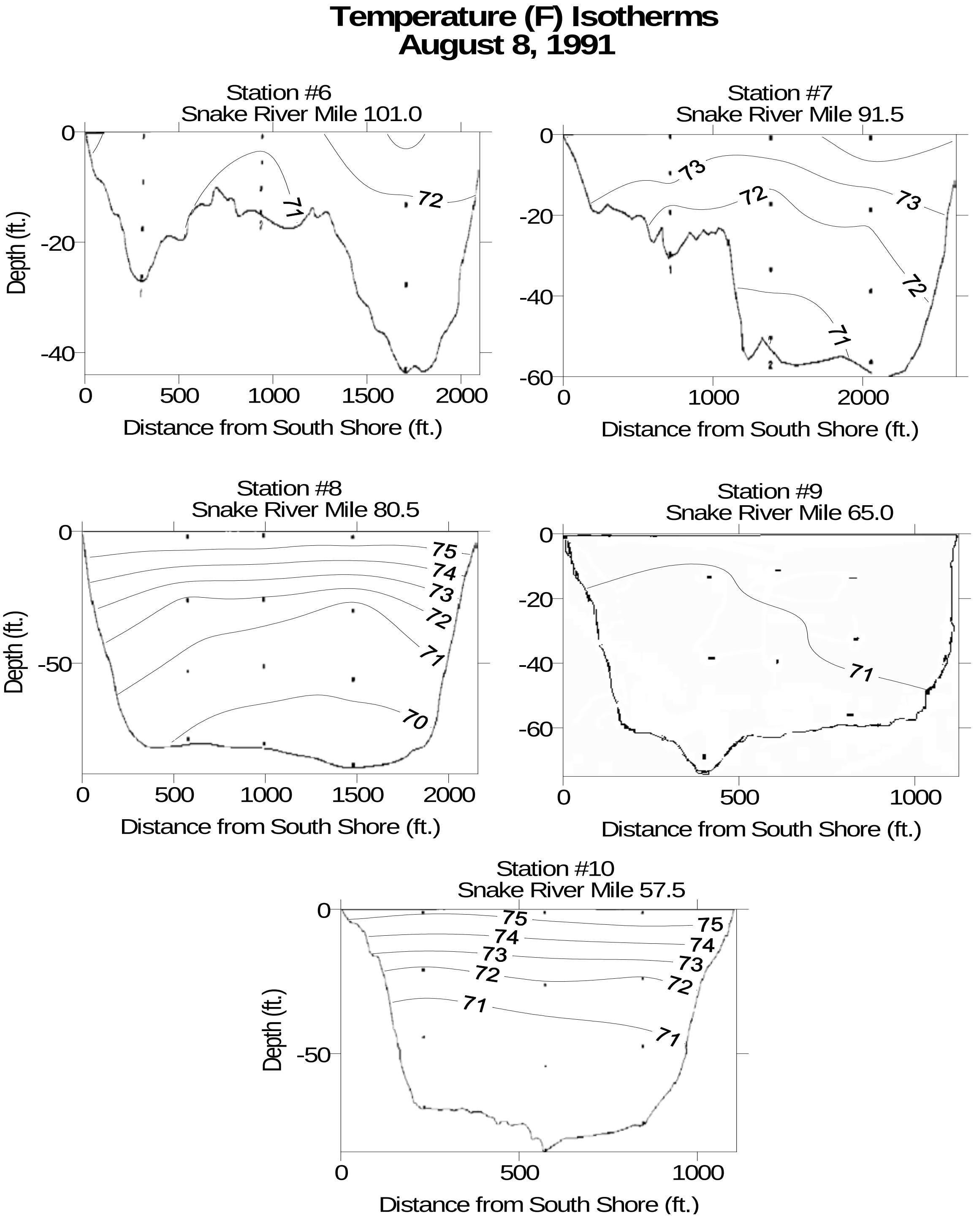
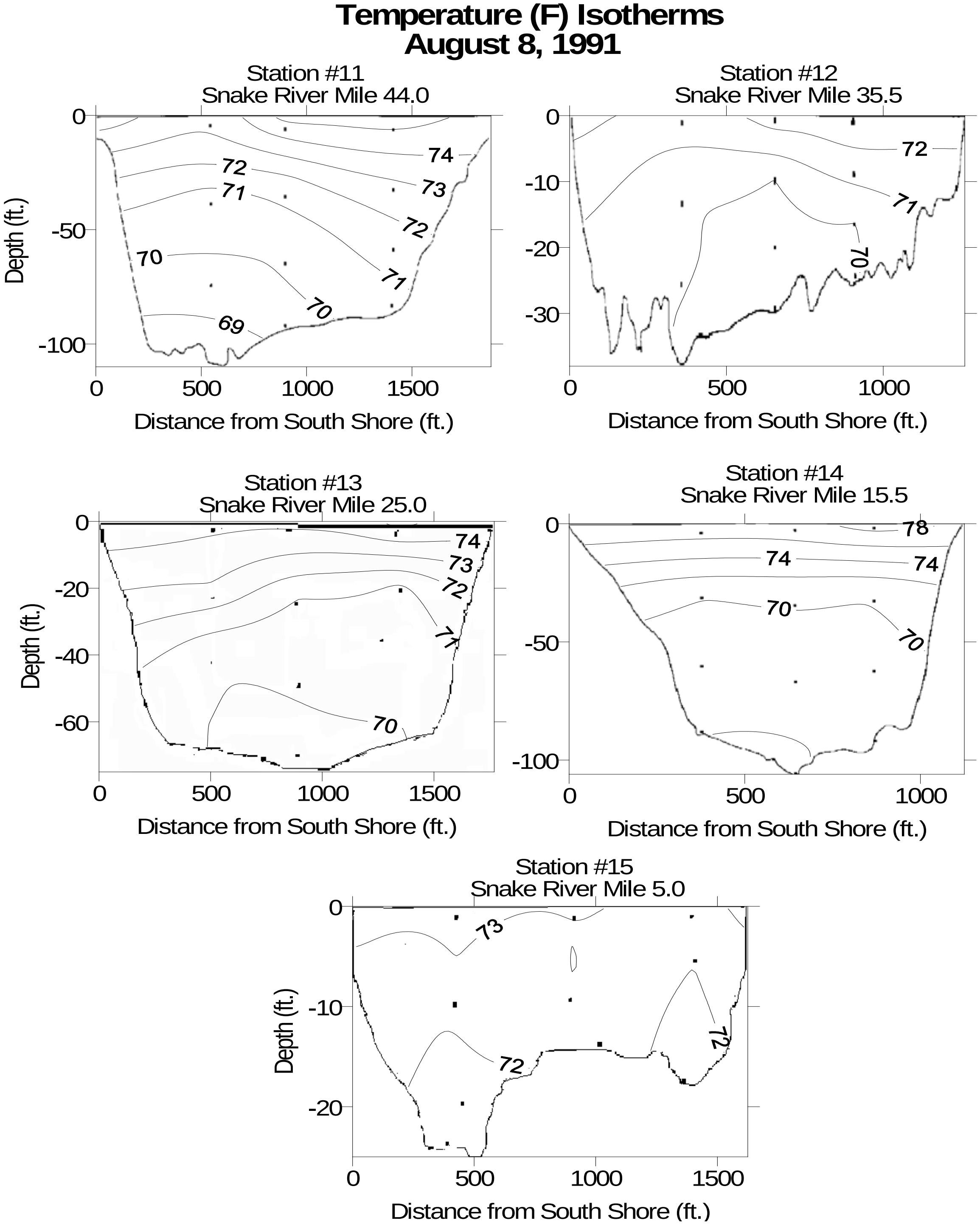


Figure 21 continued



Temperature (F) Isotherms
August 8, 1991

Figure 22. Temperature categories, by depth and distance, from the mouth of the Snake River on August 23, 1991. Colors refer to the temperature category where red is lethal (>70 F, 21.1C), magenta is resistance (68-70 F, 20-21.1C), blue is tolerance (60-68 F, 15.6-20C), and green is optimum (<= 60 F, 15.6C). The location of Ice Harbor (IHR), Lower Monumental (LMN), Little Goose (LGS), and Lower Granite (LWG) dams is indicated by vertical lines.

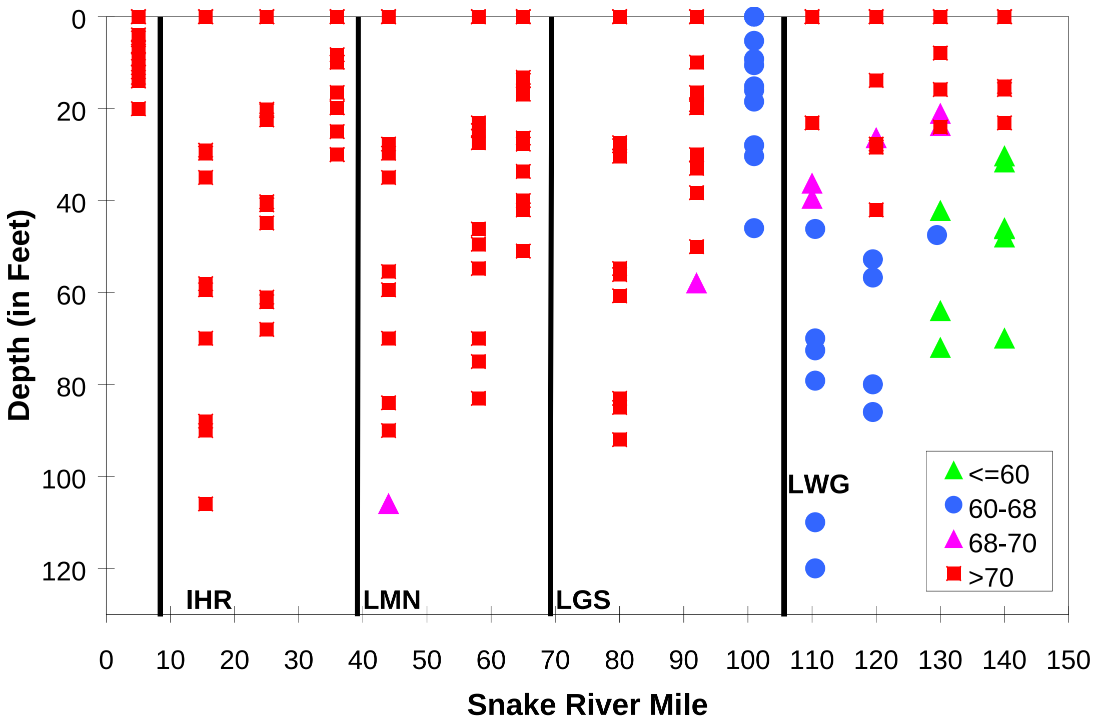


Figure 23. Temperature contours (F) from 15 stations on the Snake River plotted for August 23, 1991.

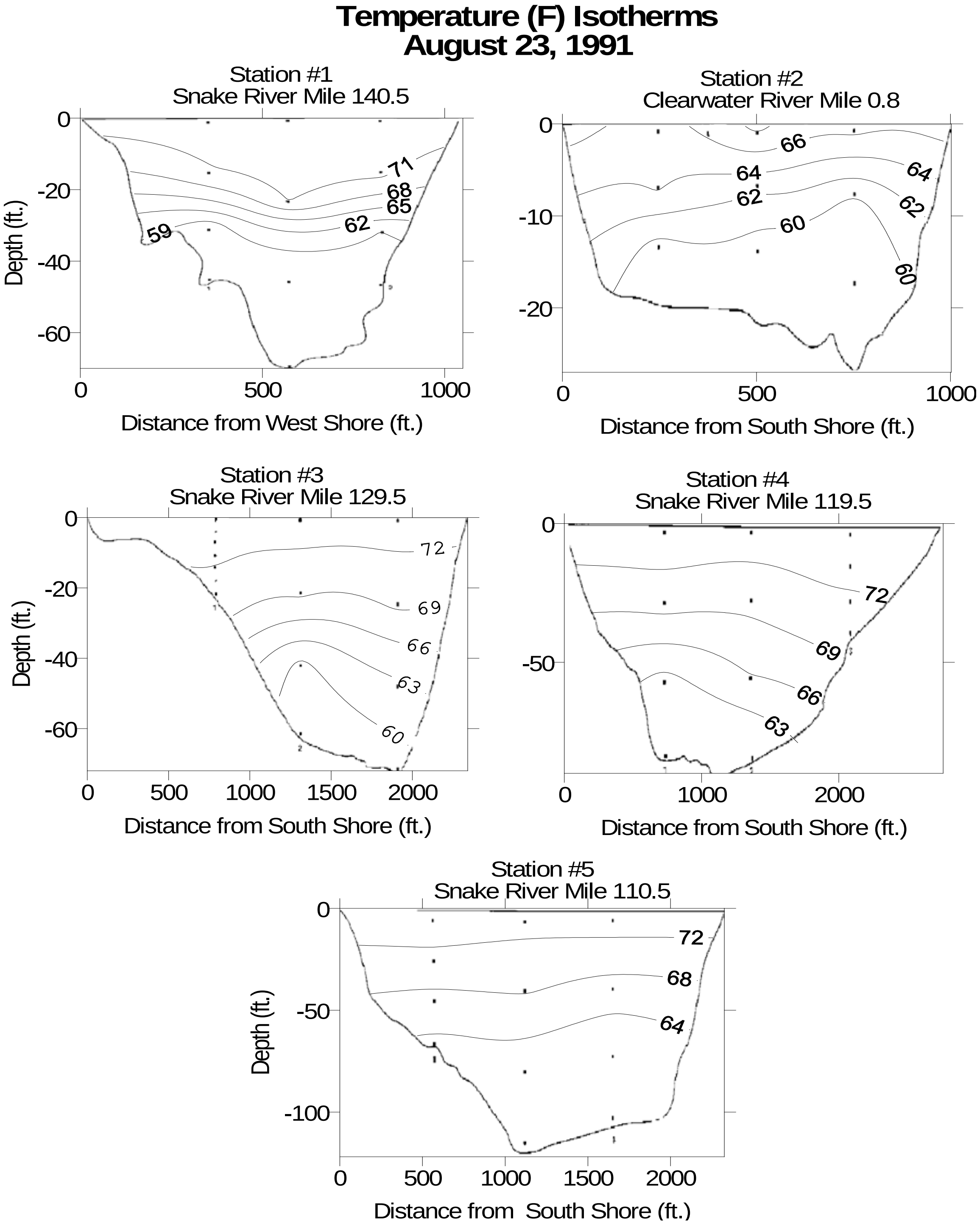


Figure 23 continued

Temperature (F) Isotherms
August 23, 1991

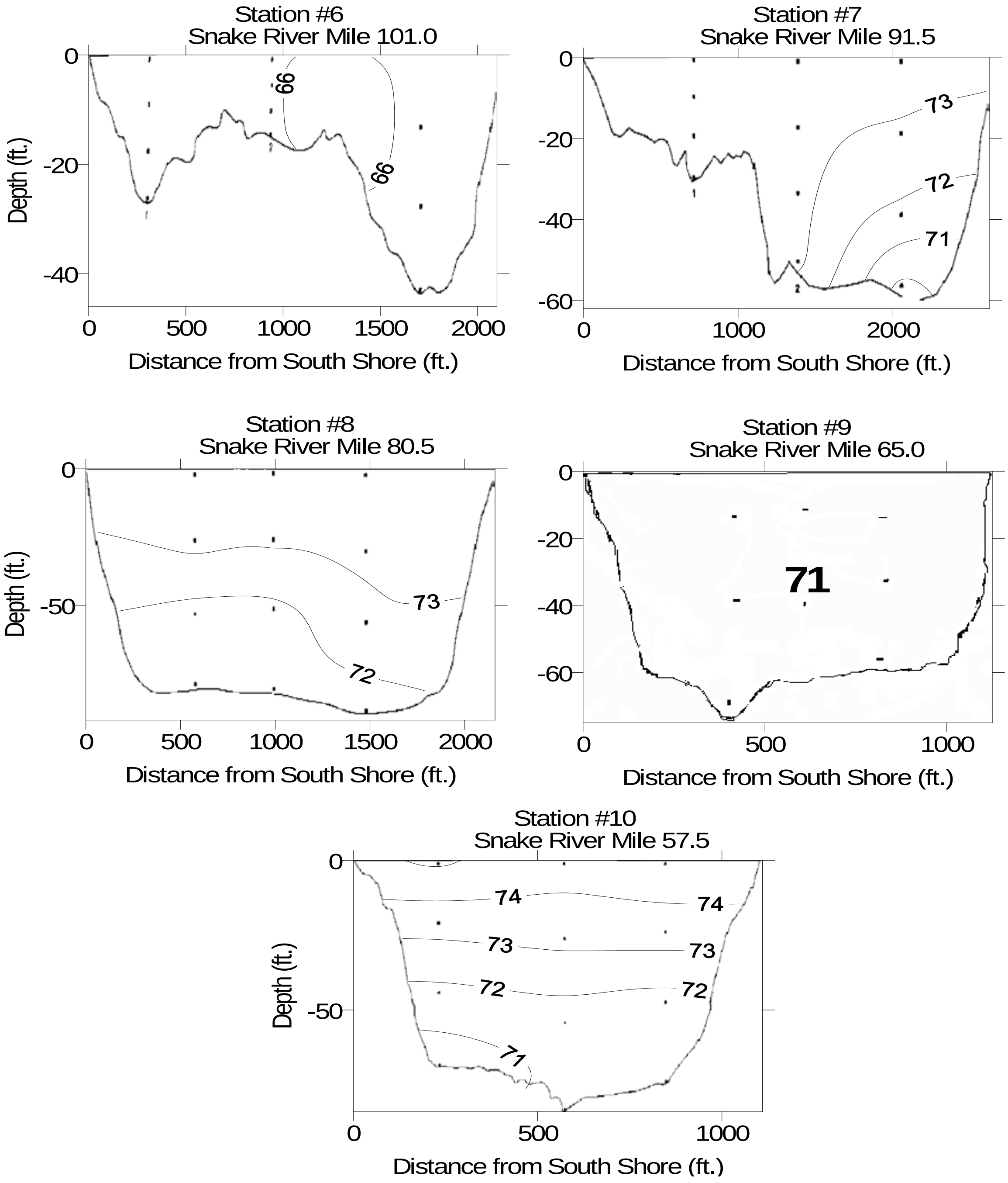


Figure 23 continued

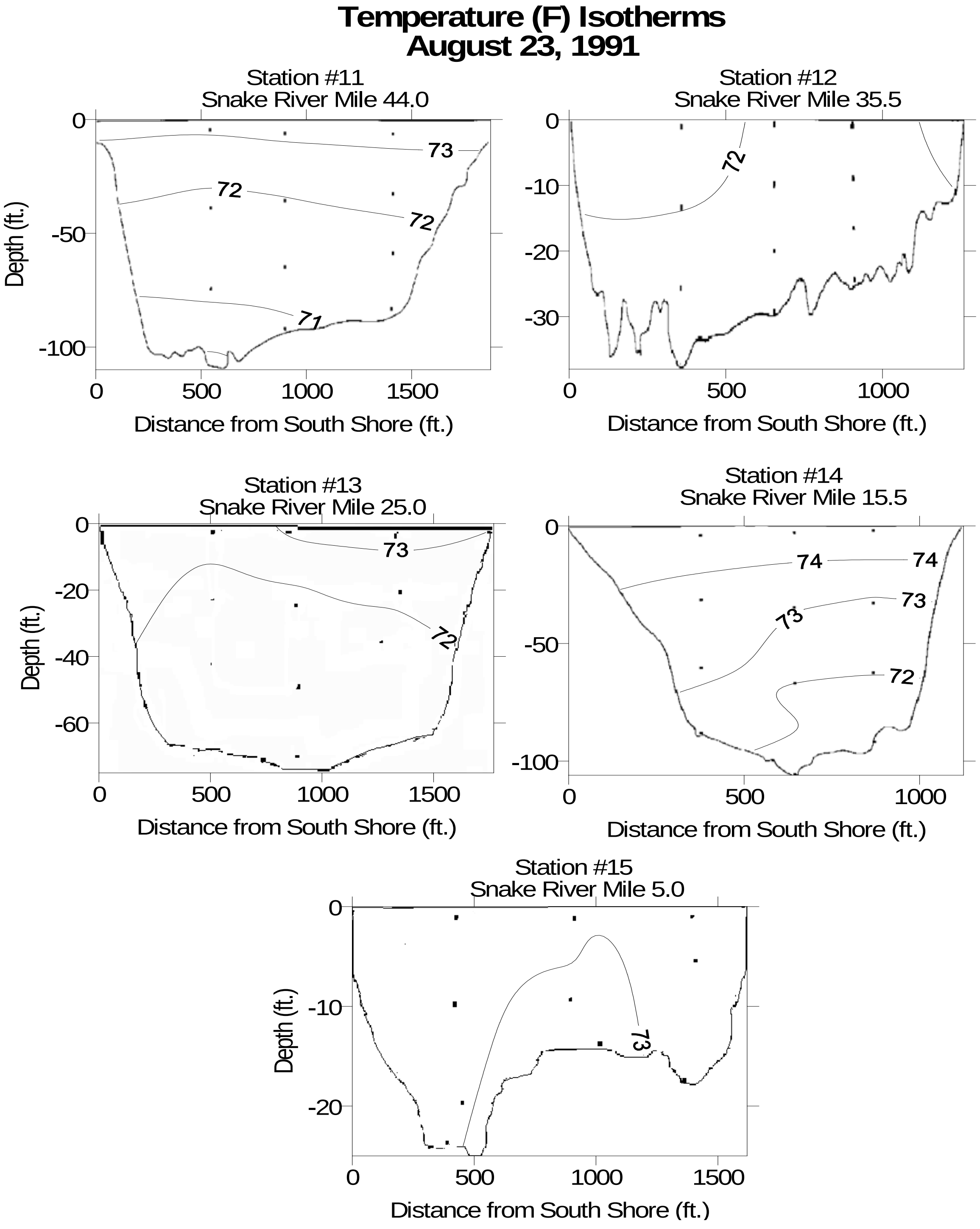


Figure 24. Temperature categories, by depth and distance, from the mouth of the Snake River on August 27, 1991. Colors refer to the temperature category where red is lethal (>70 F, 21.1C), magenta is resistance (68-70 F, 20-21.1C), blue is tolerance (60-68 F, 15.6-20C), and green is optimum (<= 60 F, 15.6C). The location of Ice Harbor (IHR), Lower Monumental (LMN), Little Goose (LGS), and Lower Granite (LWG) dams is indicated by vertical lines.

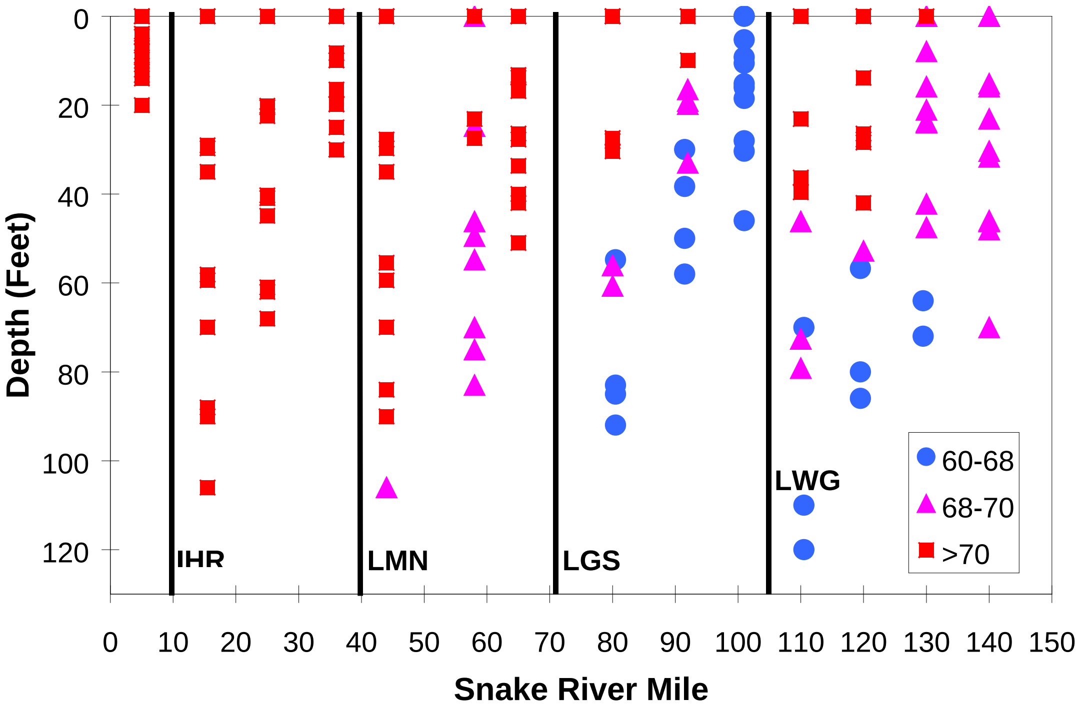
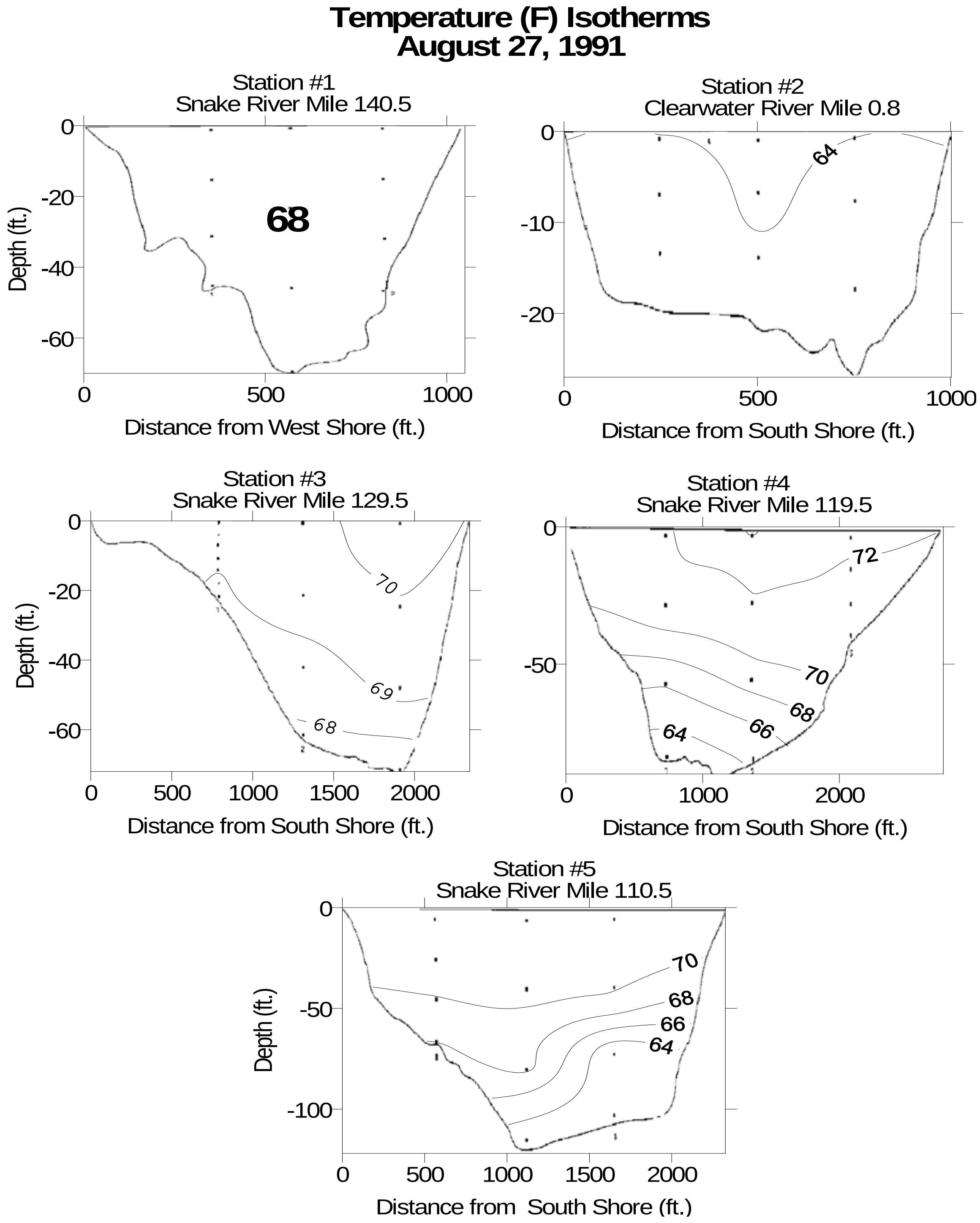


Figure 25. Temperature contours (F) from 15 stations on the Snake River plotted for August 27, 1991.



Temperature (F) Isotherms
August 27, 1991

Station #1
Snake River Mile 140.5

Station #2
Clearwater River Mile 0.8

Station #3
Snake River Mile 129.5

Station #4
Snake River Mile 119.5

Station #5
Snake River Mile 110.5

Figure 25 continued

Temperature (F) Isotherms
August 27, 1991

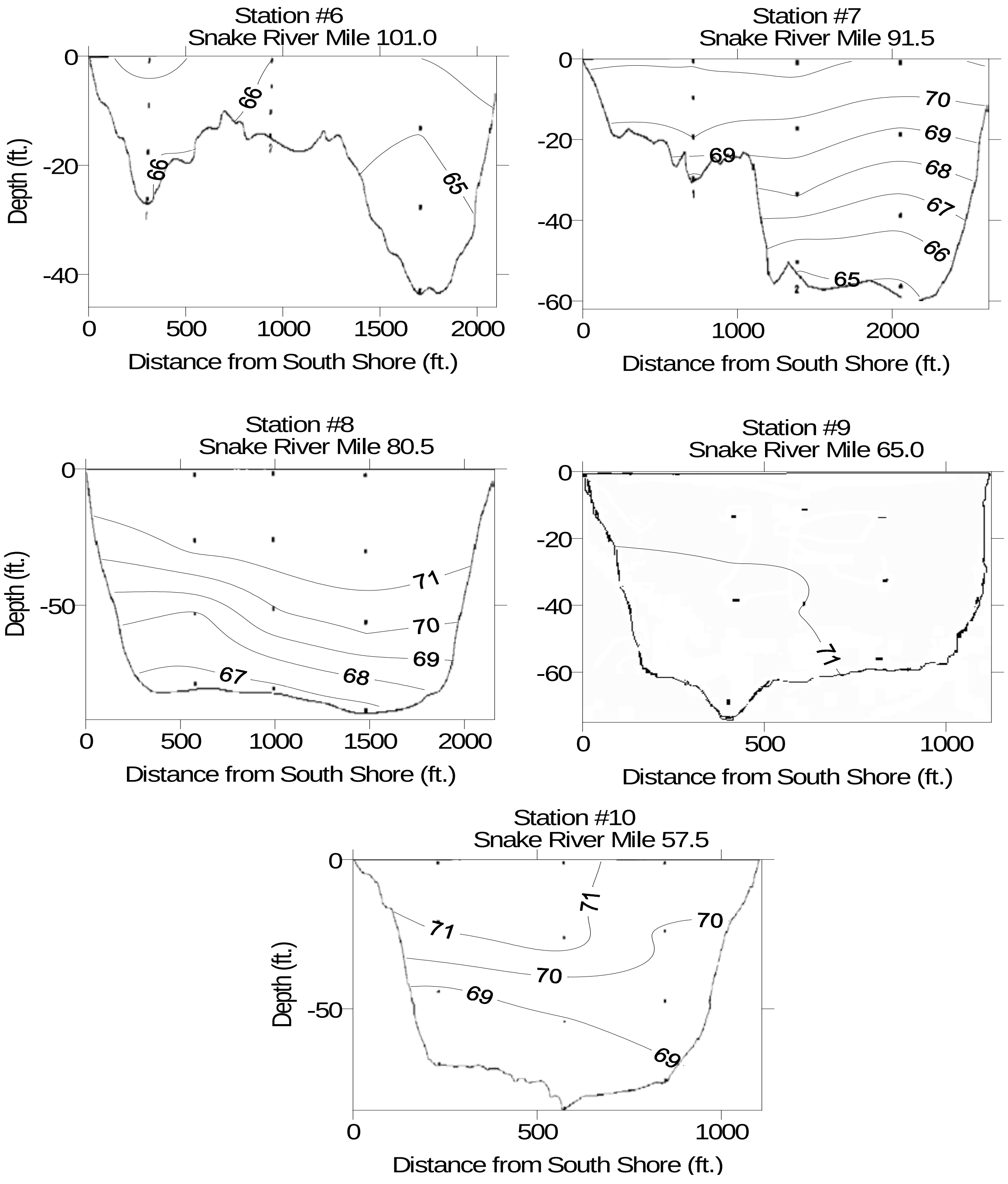


Figure 25 continued

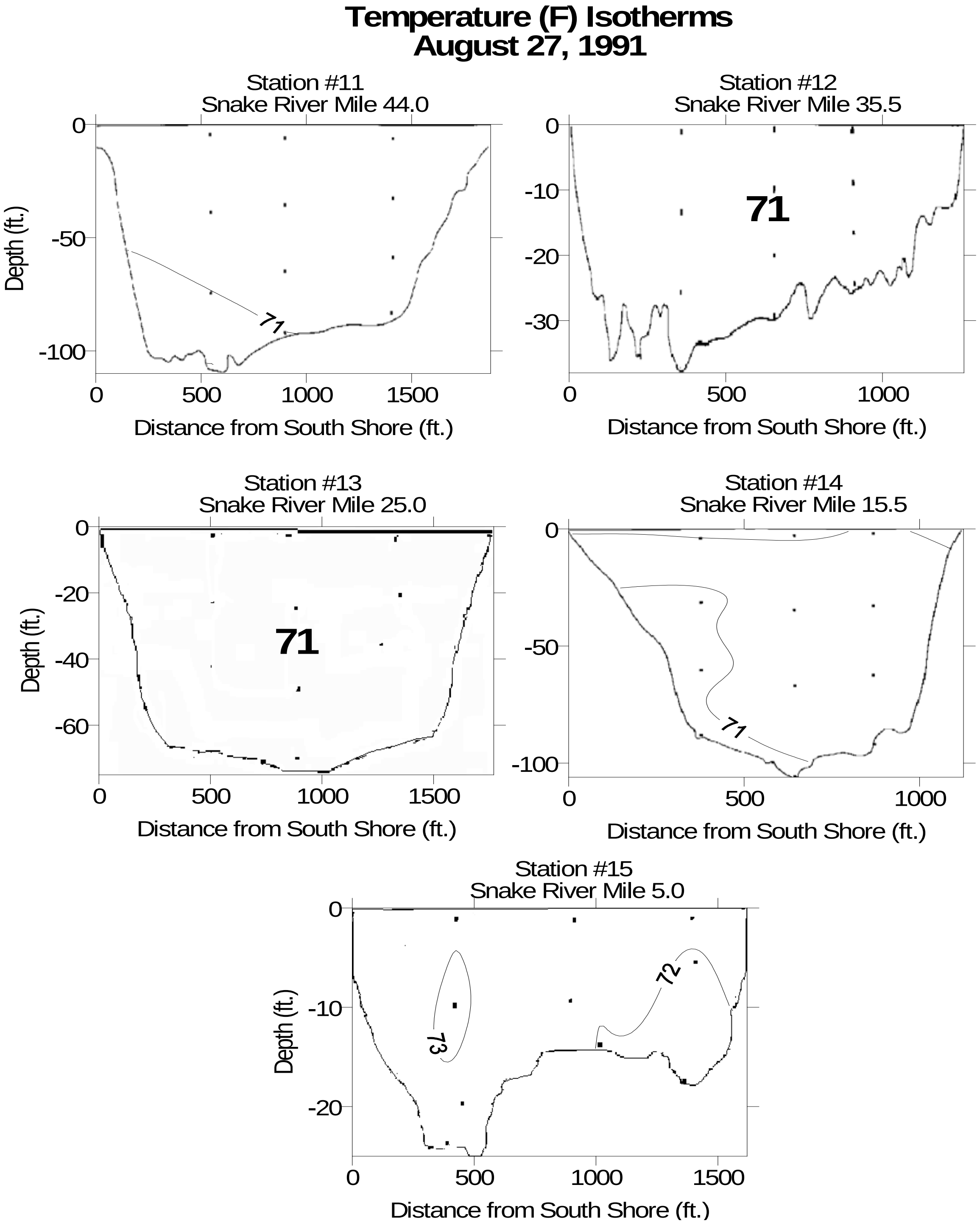


Figure 26. Daily mean scroll case temperatures at Little Goose Dam (LGS) in 1991, and daily mean transect temperatures at the first transect up river (transect 8) and down river (transect 9) from Little Goose Dam.

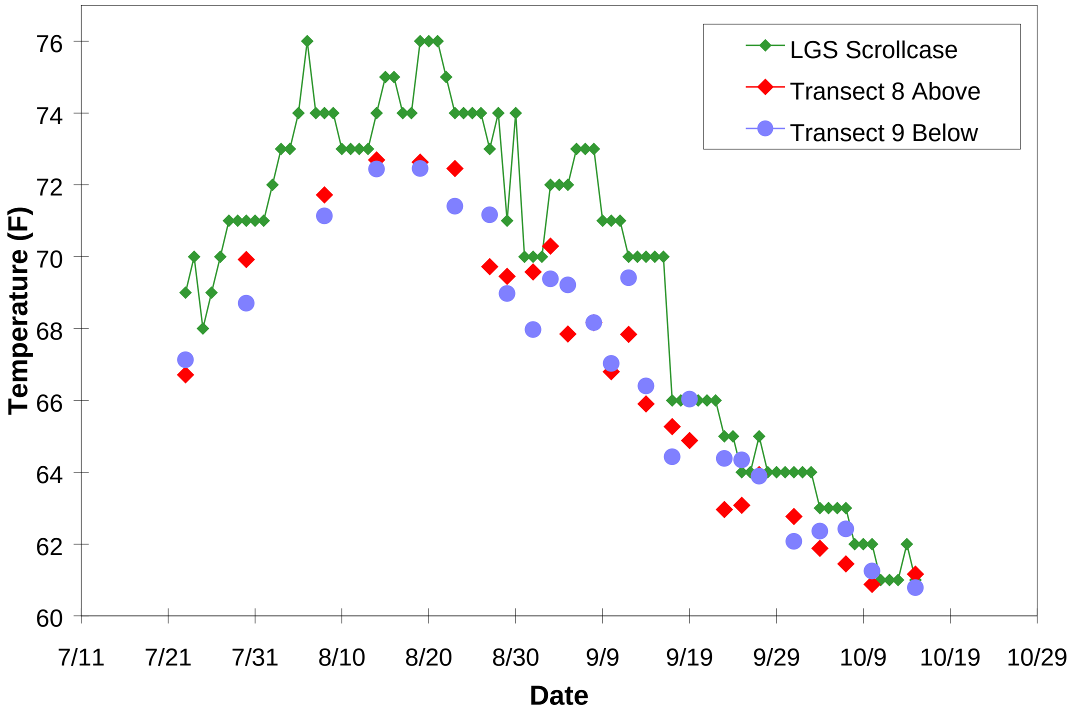


Figure 27. Daily mean scroll case temperatures at Little Goose Dam in 1992, and daily mean mid-level tri-level thermograph temperatures below the dam.

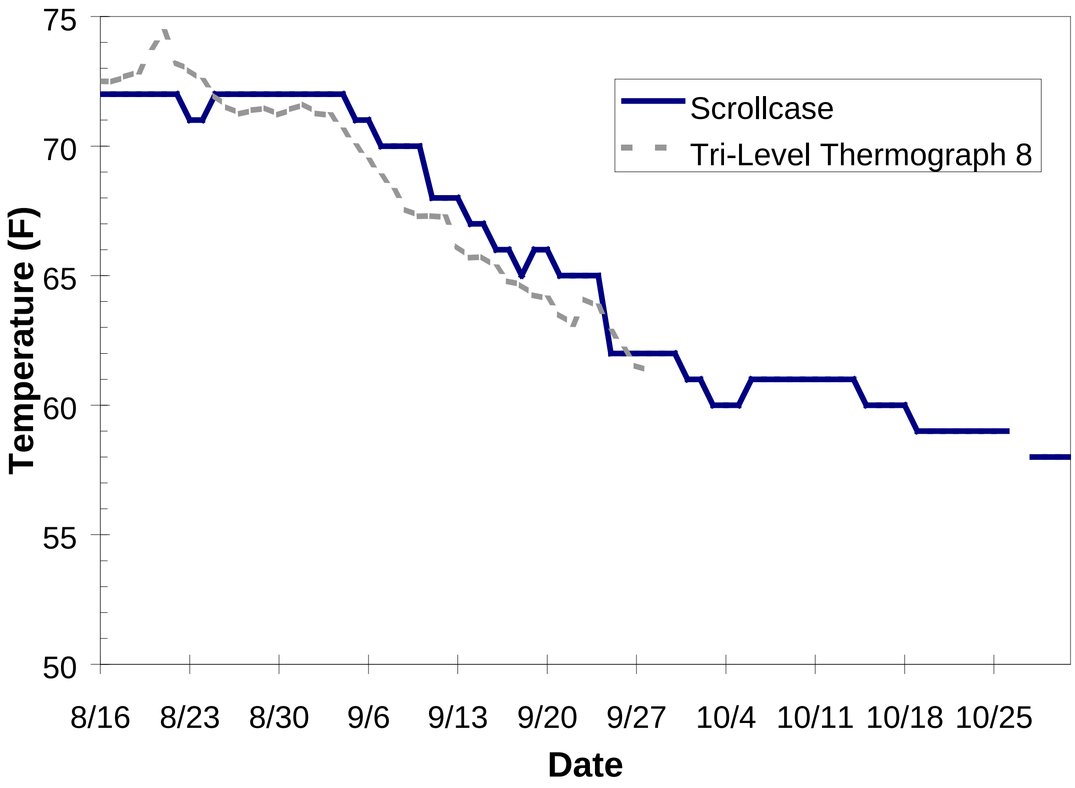


Figure 28. Daily mean scroll case temperatures at Little Goose Dam in 1994, and daily mean mid-level tri-level thermograph temperatures below the dam.

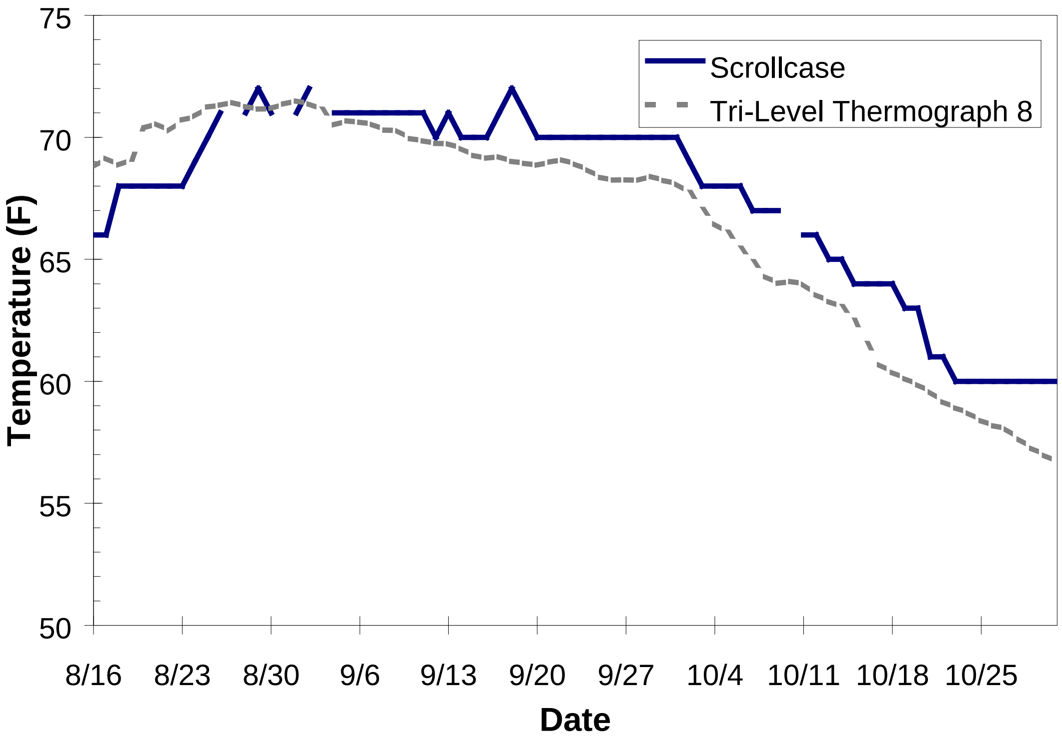


Figure 29. Daily mean scroll case temperatures at Little Goose Dam in 1995, and daily mean mid-level tri-level thermograph temperatures below the dam.

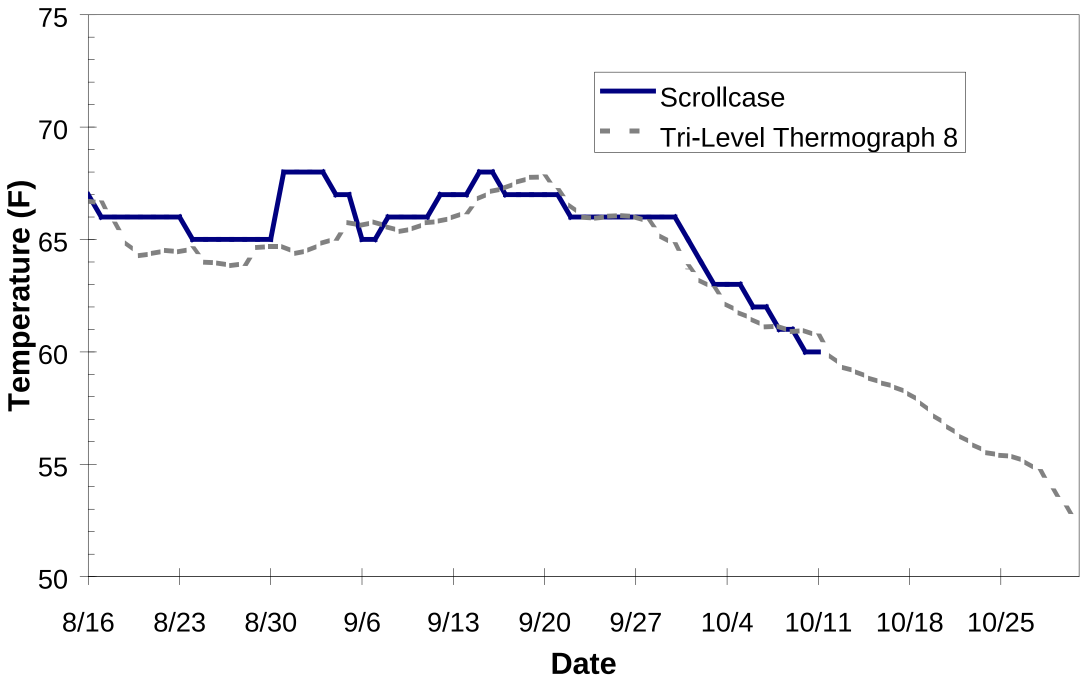


Figure 30. Difference between the 1991 daily scroll case temperature at Lower Granite Dam and the daily minimum and maximum temperatures at Transect 5, located immediately above Lower Granite Dam. (Mean Transect 5 temperatures and all mean, minimum, and maximum daily Transect 6 temperatures are located within the bounds of the maximum and minimum Transect 5 temperatures.)

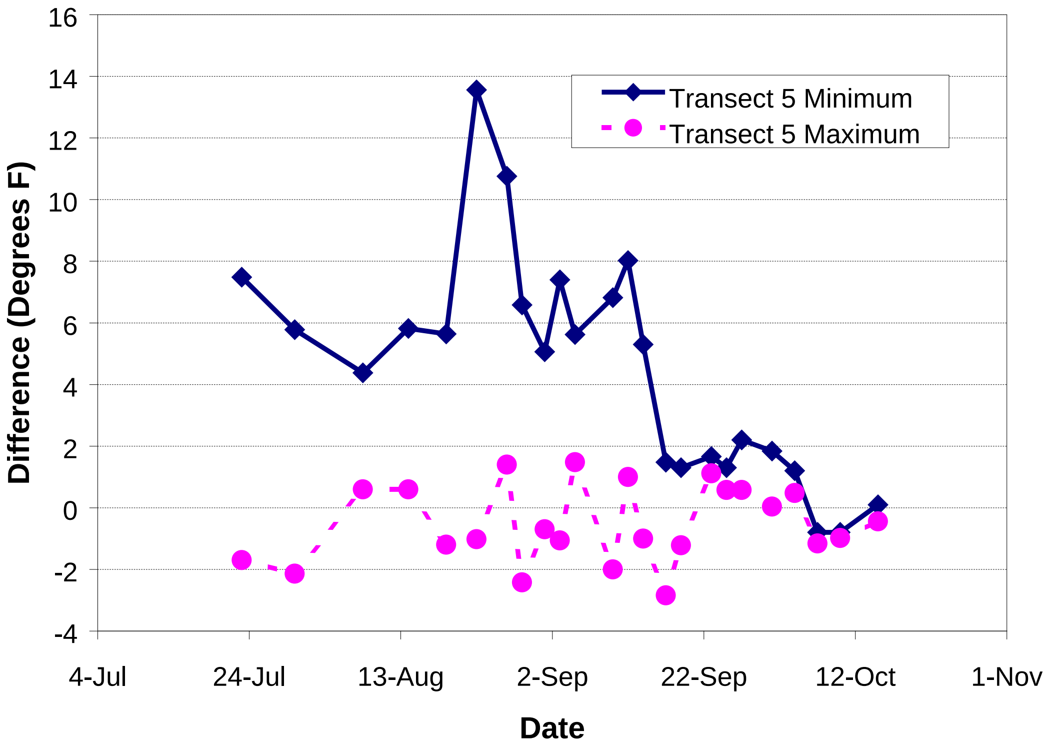


Figure 31. Difference between the 1992 daily scroll case temperature at Lower Granite Dam and the daily minimum and maximum temperatures at Transect 5, located immediately above Lower Granite Dam. (Mean Transect 5 temperatures and all mean, minimum, and maximum daily Transect 6 temperatures are located within the bounds of the maximum and minimum Transect 5 temperatures.)

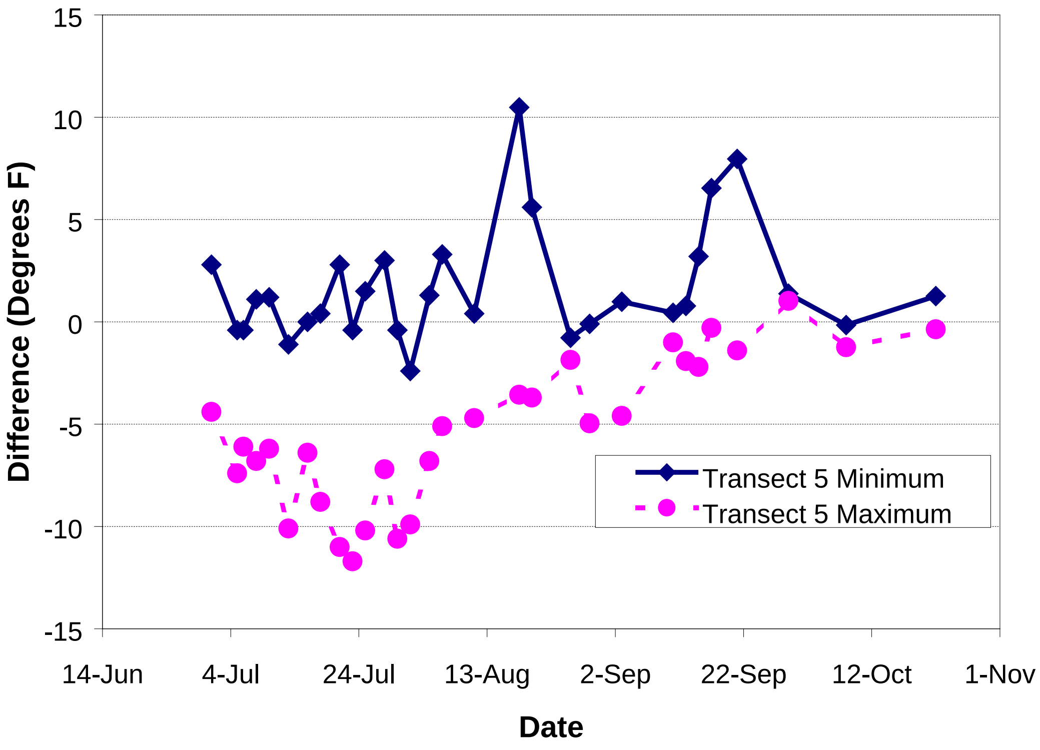


Figure 32. Difference between the 1991 daily scroll case temperature at Ice Harbor Dam and the daily minimum and maximum temperatures at Transect 14, located immediately above Ice Harbor Dam. (Mean Transect 14 temperatures and all mean, minimum, and maximum daily Transect 15 temperatures are located within the bounds of the maximum and minimum Transect 14 temperatures.)

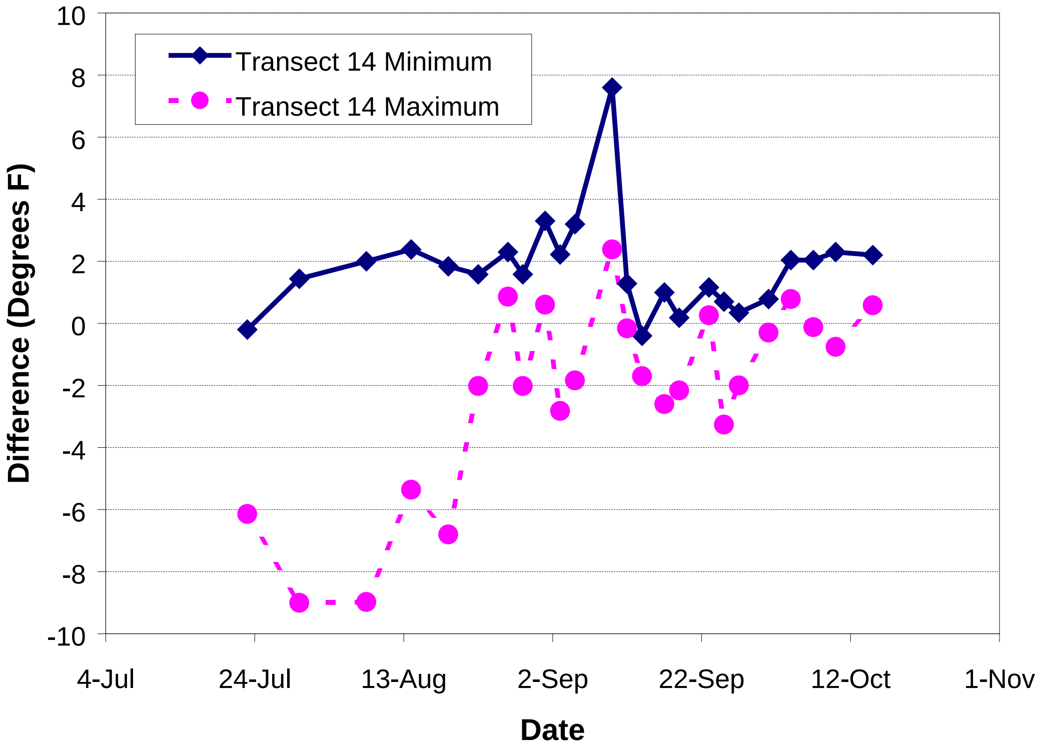


Figure 33. Difference between the 1992 daily scroll case temperature at Ice Harbor Dam and the daily minimum and maximum temperatures at Transect 14, located immediately above Ice Harbor Dam. (Mean Transect 14 temperatures and all mean, minimum, and maximum daily Transect 15 temperatures are located within the bounds of the maximum and minimum Transect 14 temperatures.)

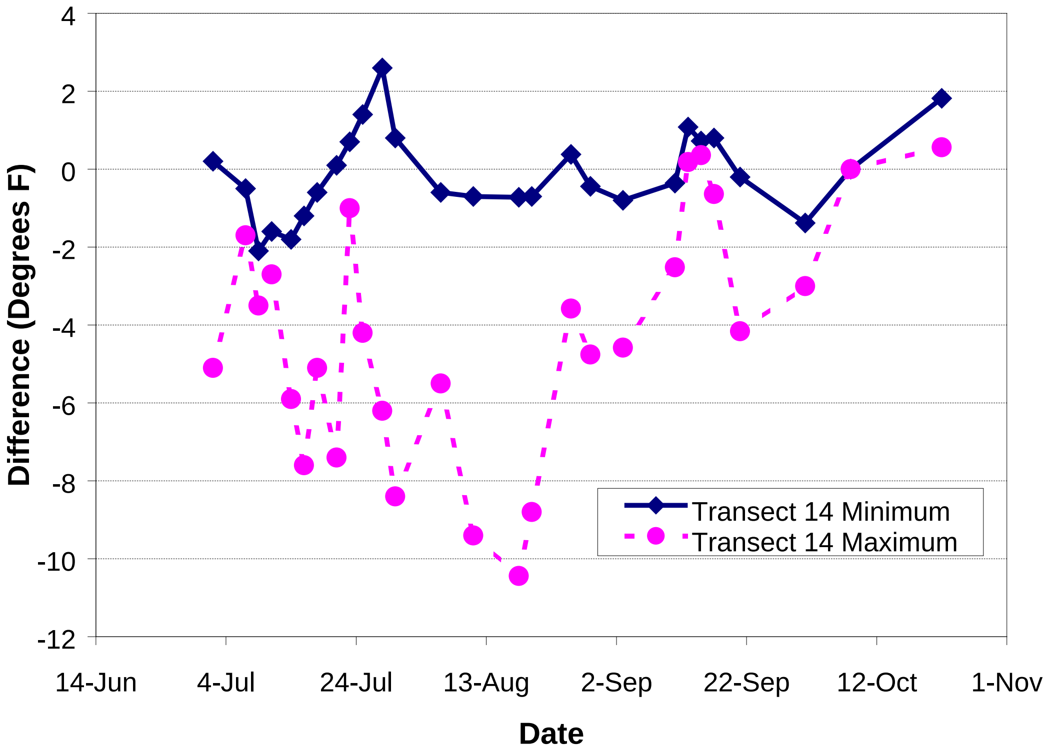


Figure 34. Mean fall chinook weighted scroll case temperatures at Ice Harbor Dam, 1960 to 1995.

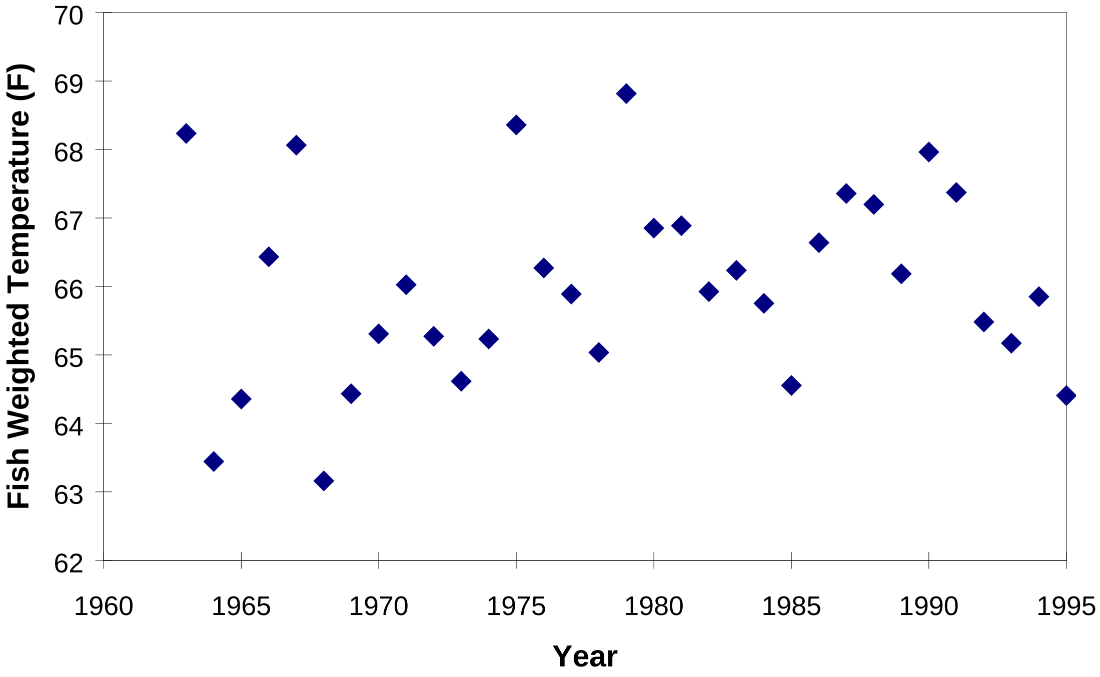


Figure 35. Linear relationship between mean scroll case temperatures during August and year, Ice Harbor Dam 1986 – 1996.

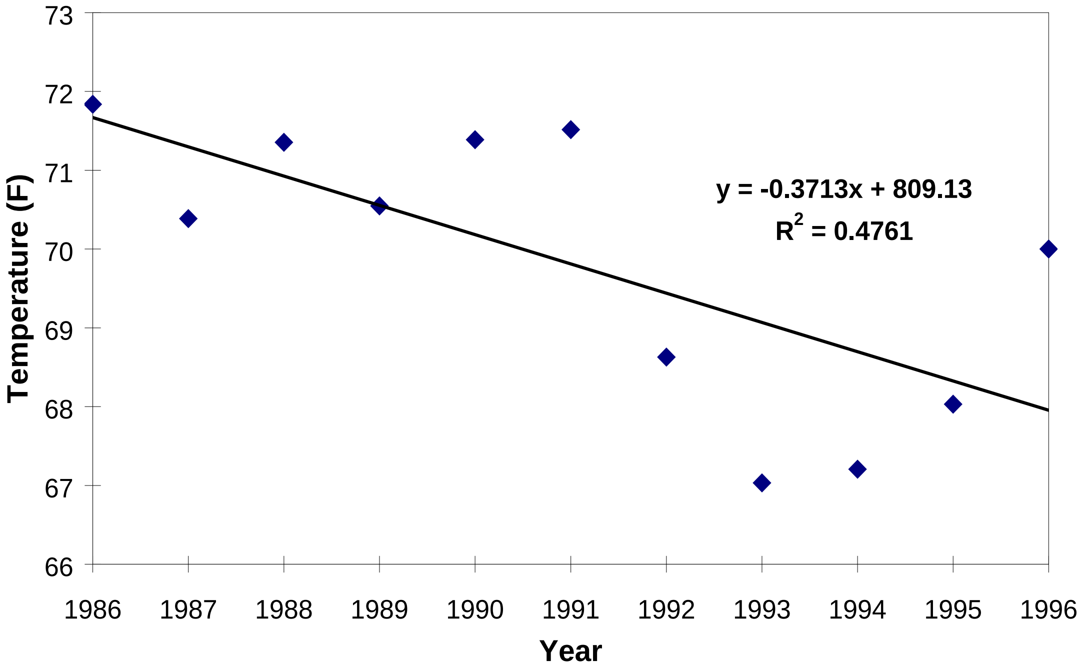


Figure 36. Mean fall chinook weighted scroll case temperatures at Lower Monumental Dam, 1971 to 1995.

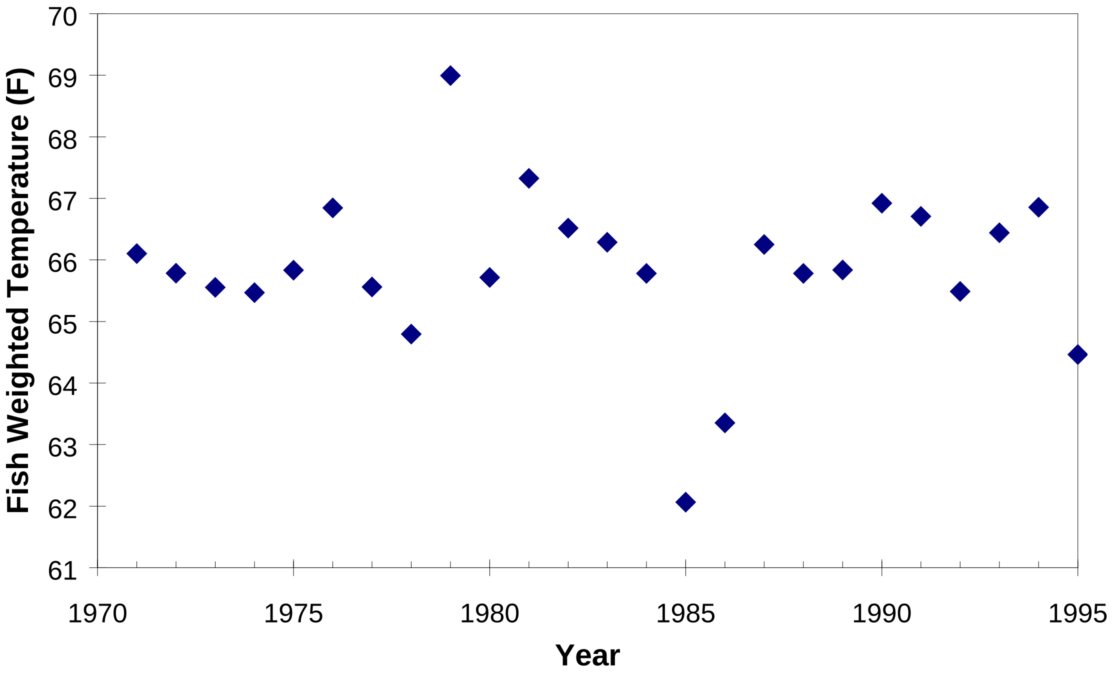


Figure 37. Mean fall chinook weighted scroll case temperatures at Little Goose Dam, 1970 to 1995.

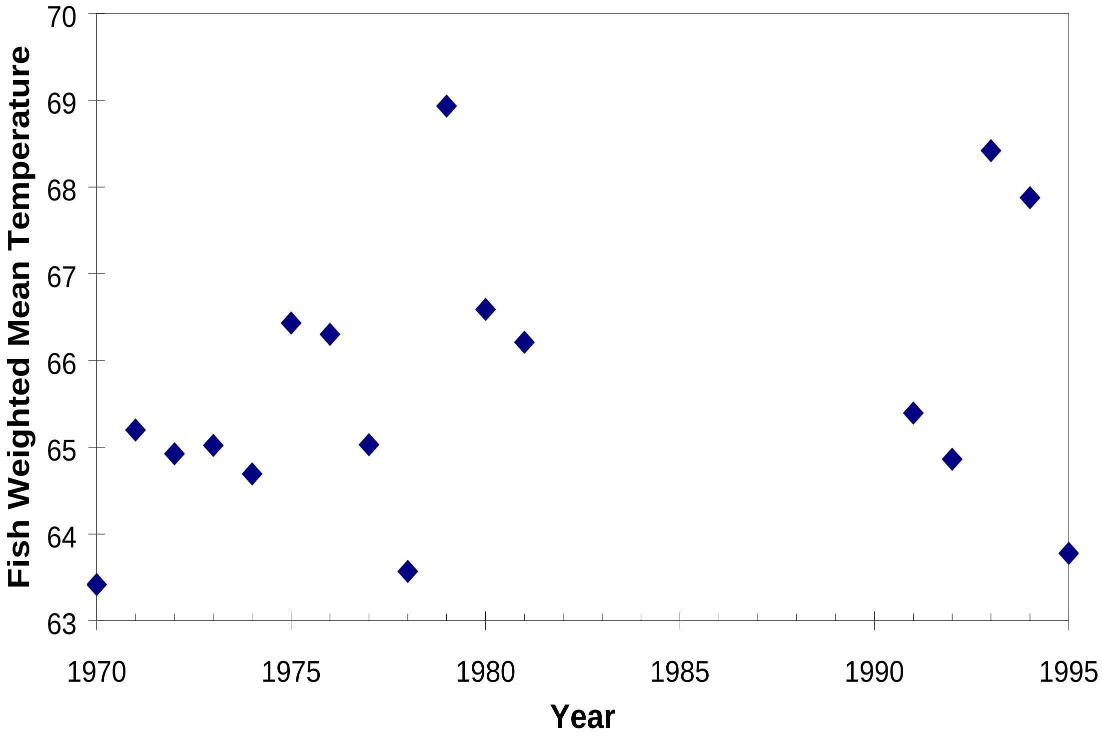


Figure 38. Mean fall chinook weighted scroll case temperatures at Lower Granite Dam, 1971 to 1995.

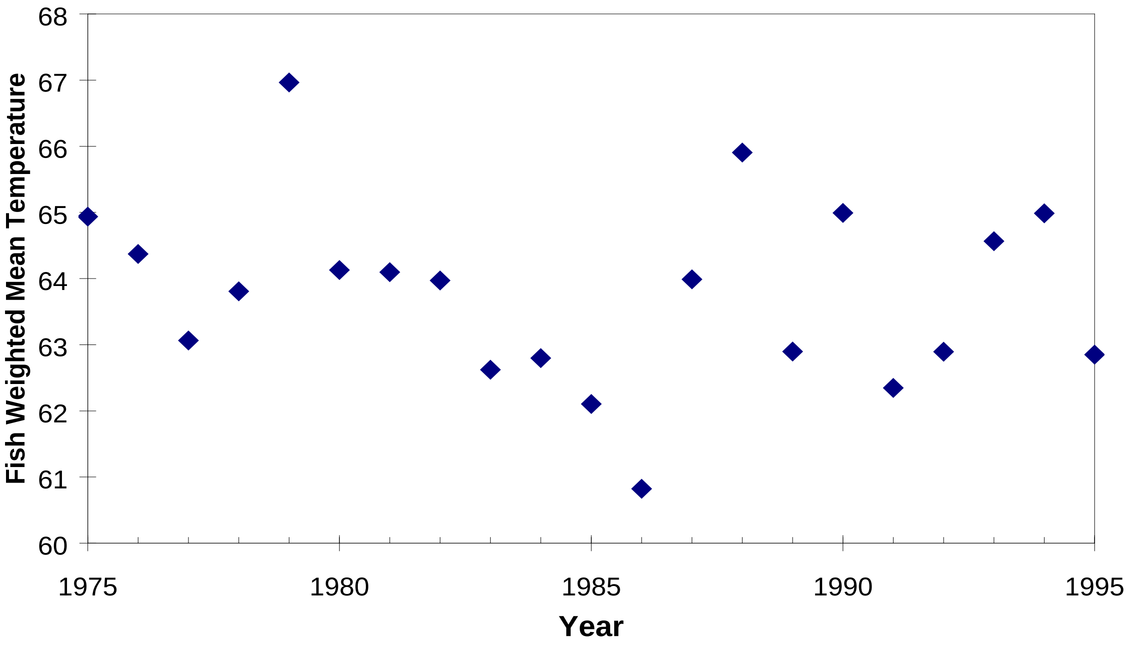


Figure 39. Linear relationship between mean fall chinook weighted daily change in temperature at Ice Harbor Dam (IHR) and days spent between Ice Harbor Dam and Lower Granite Dam (LWG).

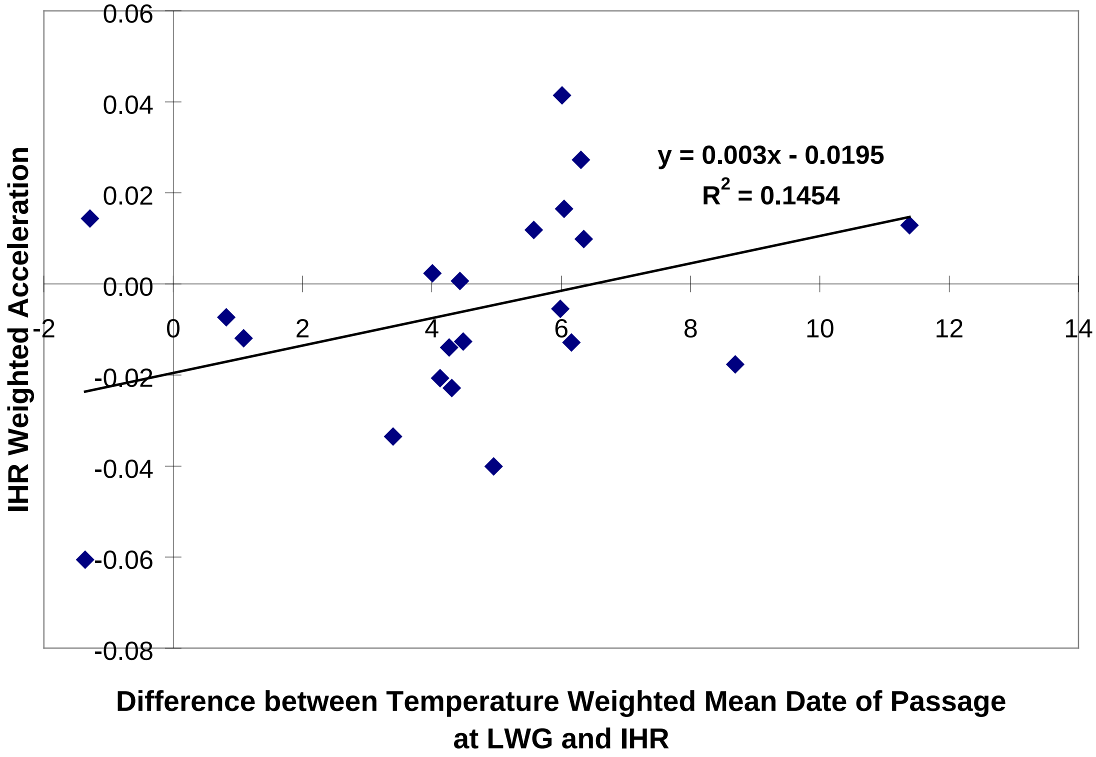


Figure 40. Comparison between mean daily change in temperature at Ice Harbor Dam (IHR) and days spent between Ice Harbor Dam and Lower Granite Dam (LWG).

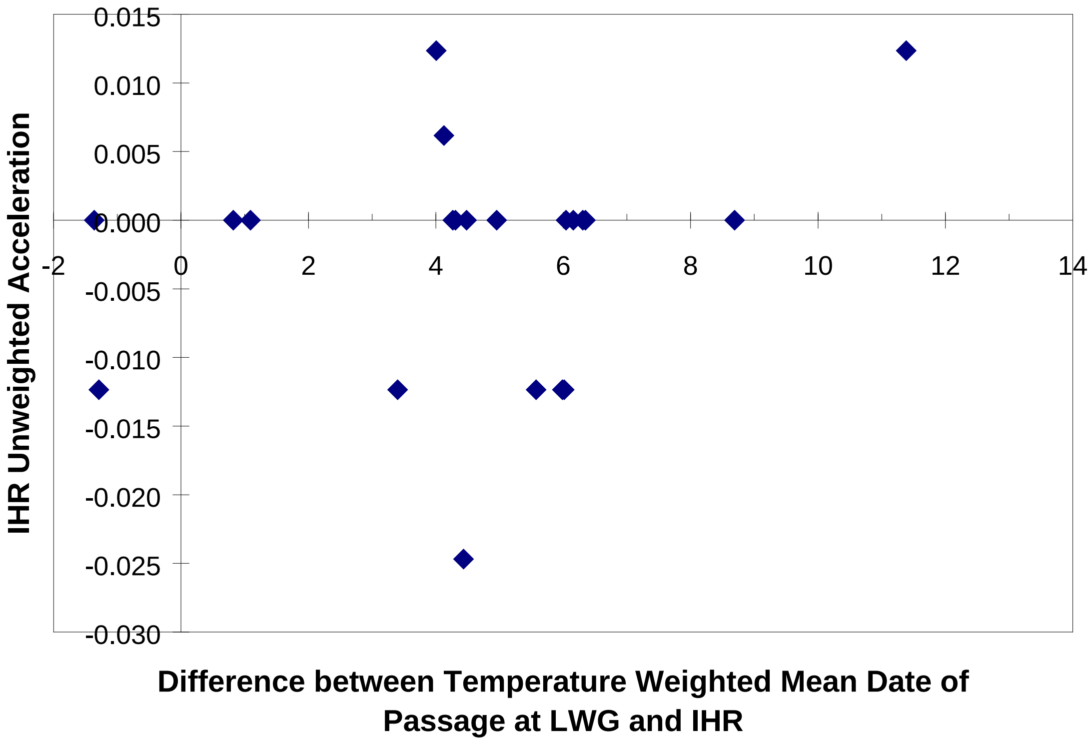


Figure 41. Comparison between mean fall chinook weighted daily change in temperature at Lower Granite Dam (LWG) and days spent between Ice Harbor Dam (IHR) and Lower Granite Dam.

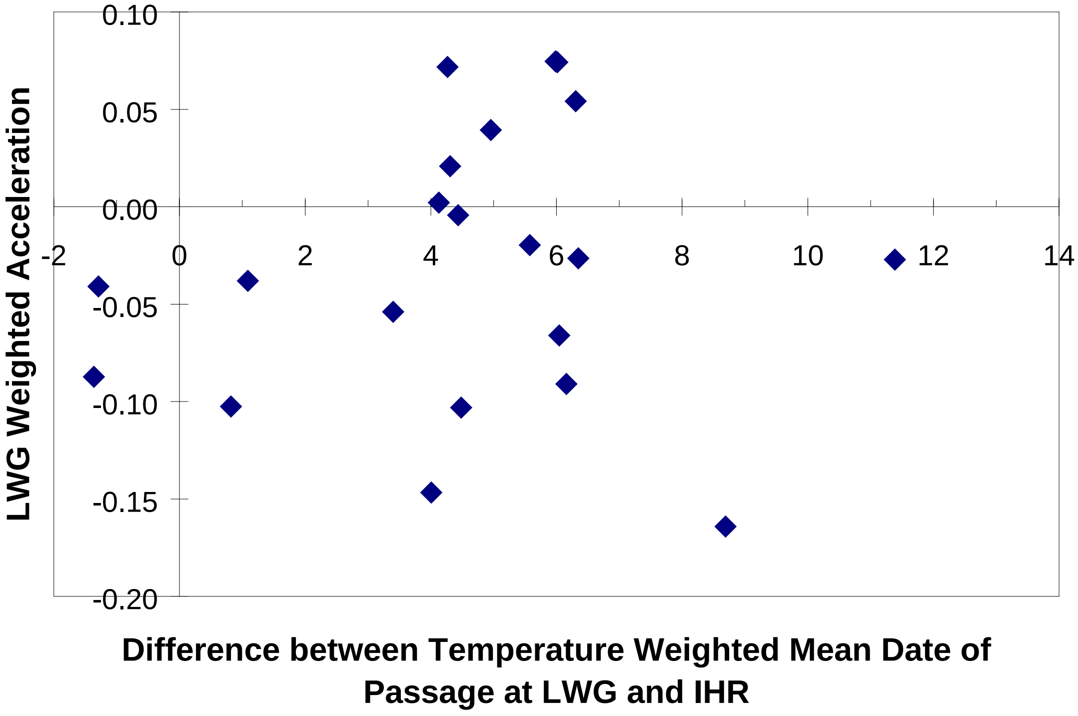


Figure 42. Linear relationship between mean fall chinook weighted passage date and year, Ice Harbor Dam 1963-1995.

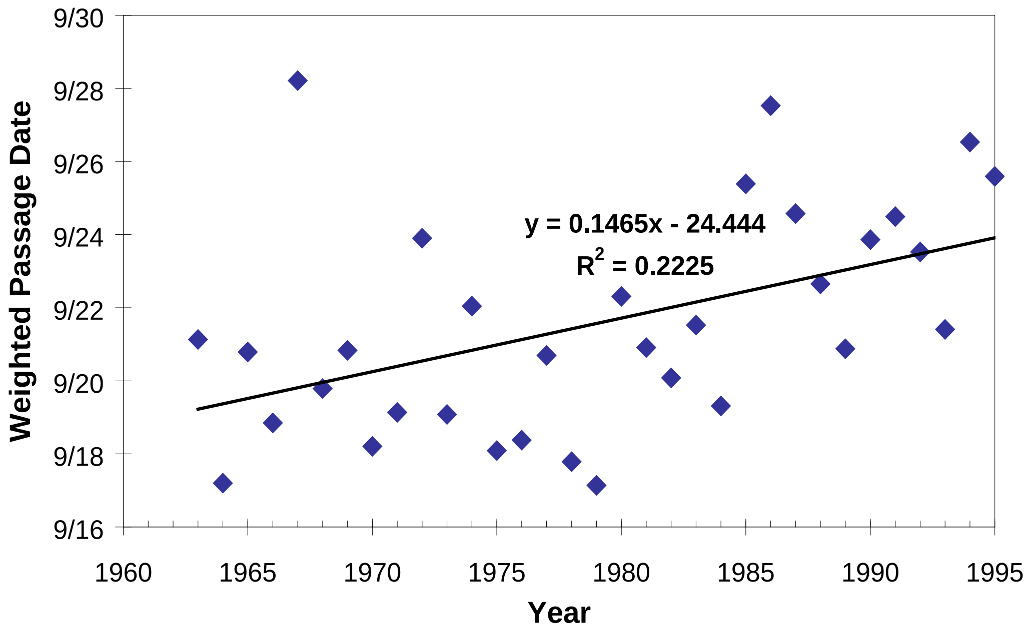


Figure 43. Linear relationship between mean fall chinook weighted passage date and year, Lower Monumental Dam 1971-1995.

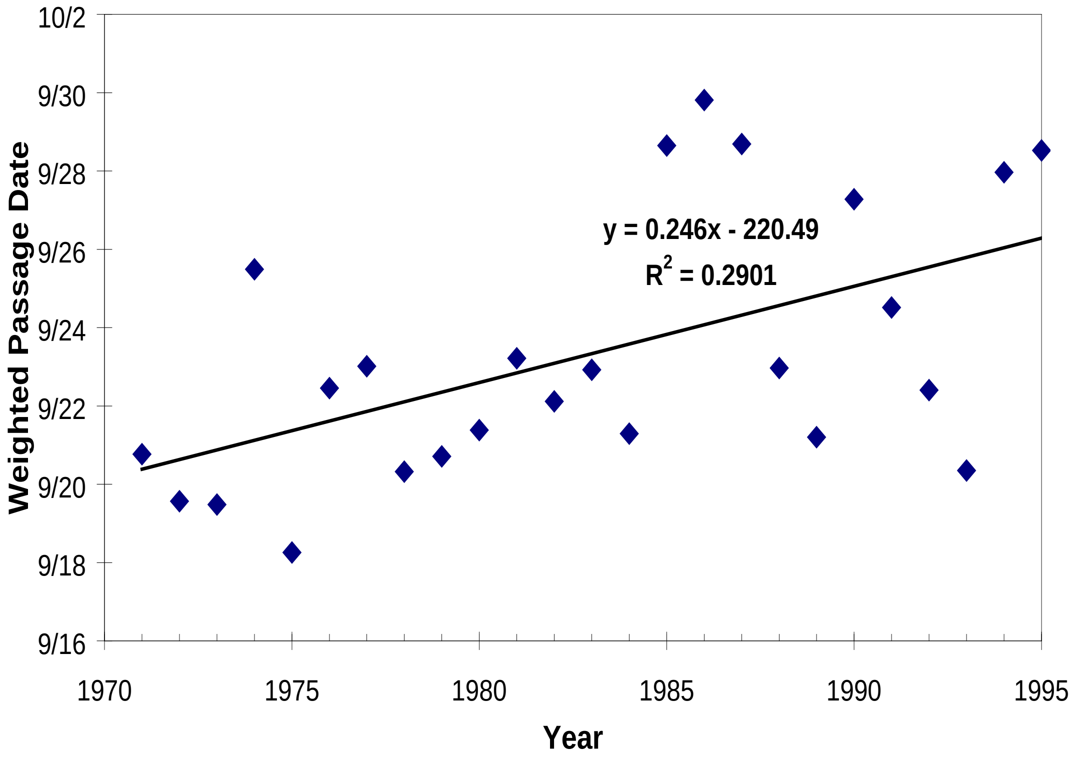


Figure 44. Linear relationship between mean fall chinook weighted passage date and year, Little Goose Dam 1970-1982 and 1991-1995.

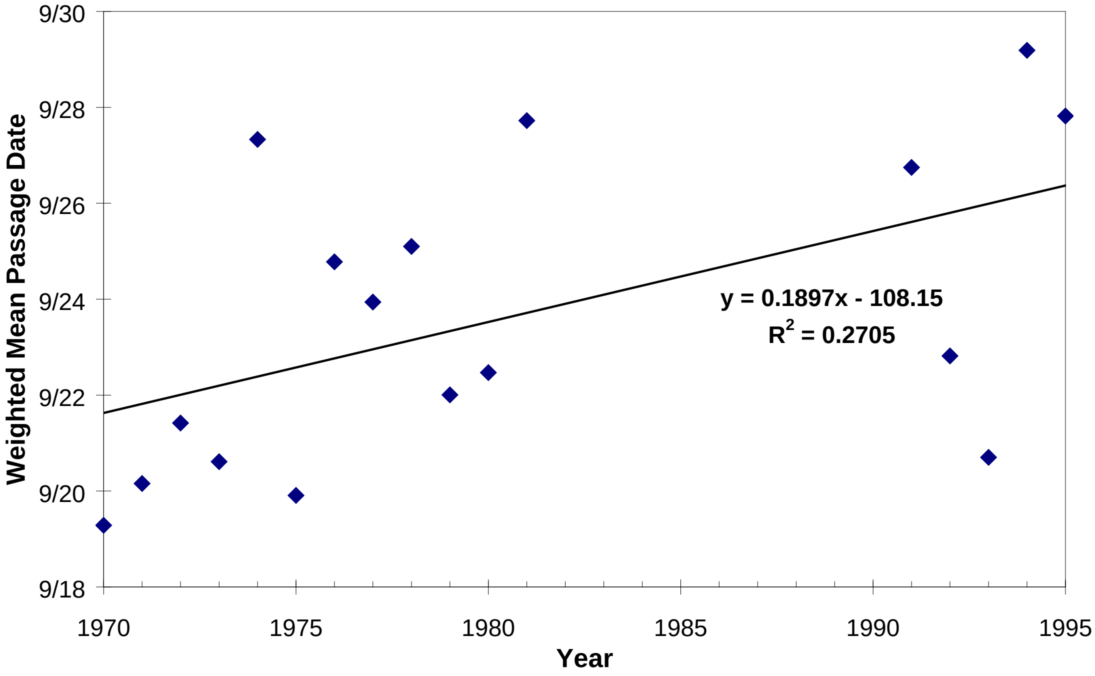


Figure 45. Comparison between mean fall chinook weighted passage date and year at Lower Granite Dam, 1975-1995.

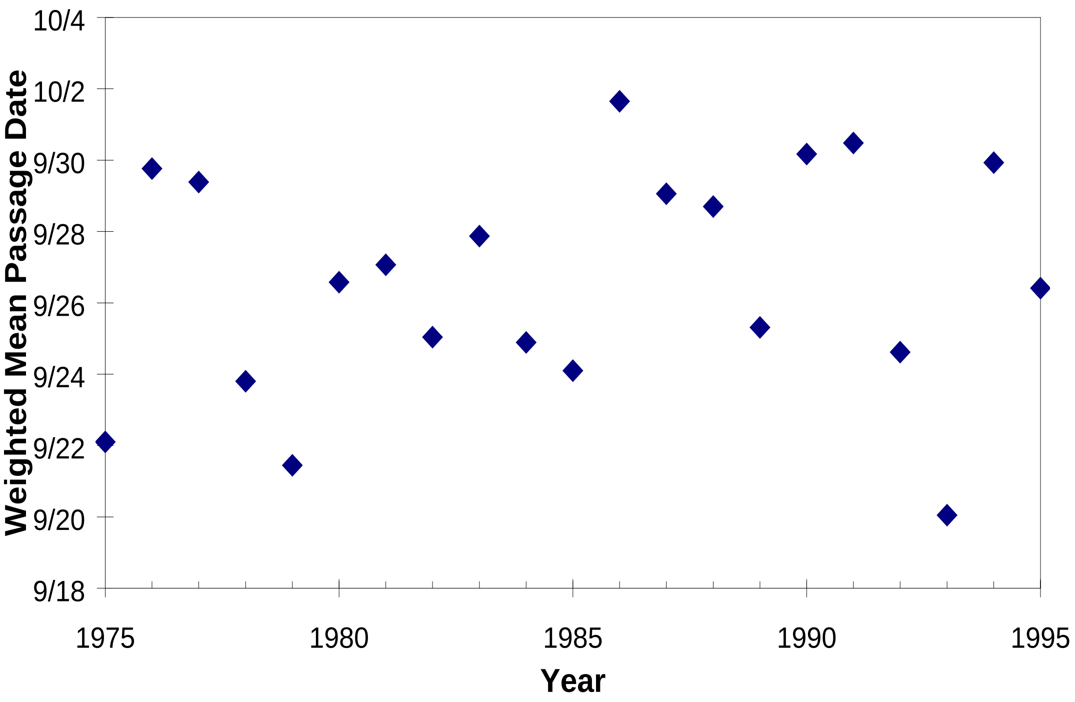


Figure 46. Comparison between mean fall chinook weighted passage date and mean fall chinook weighted scroll case temperature at Ice Harbor Dam, 1963-1995.

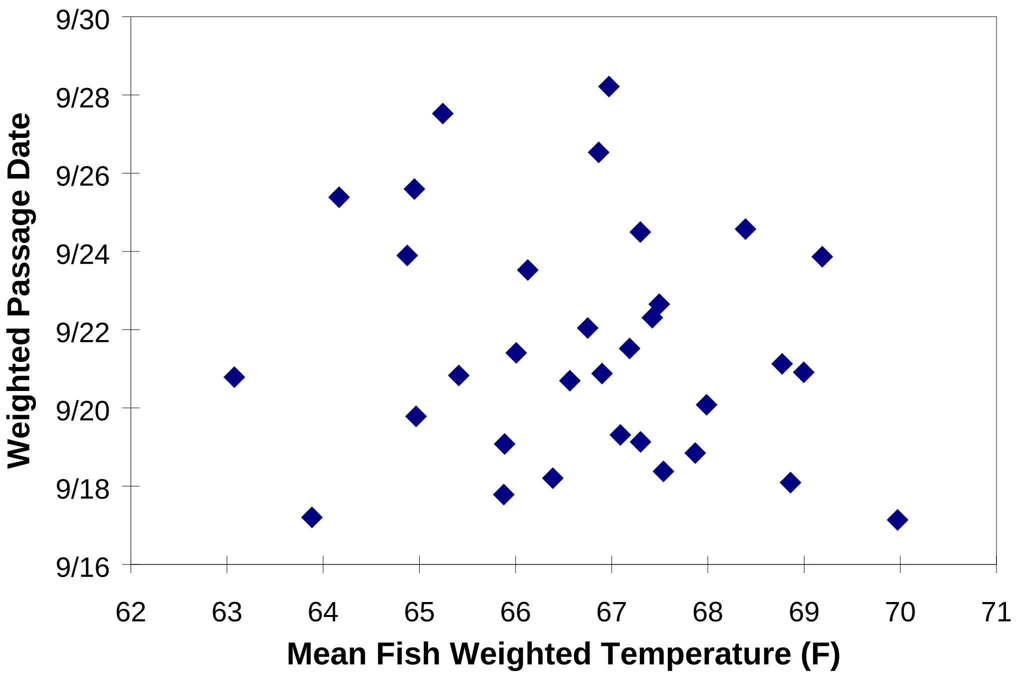


Figure 47. Comparison between mean fall chinook weighted passage date and mean fall chinook weighted scroll case temperature at Lower Monumental Dam, 1971-1995.

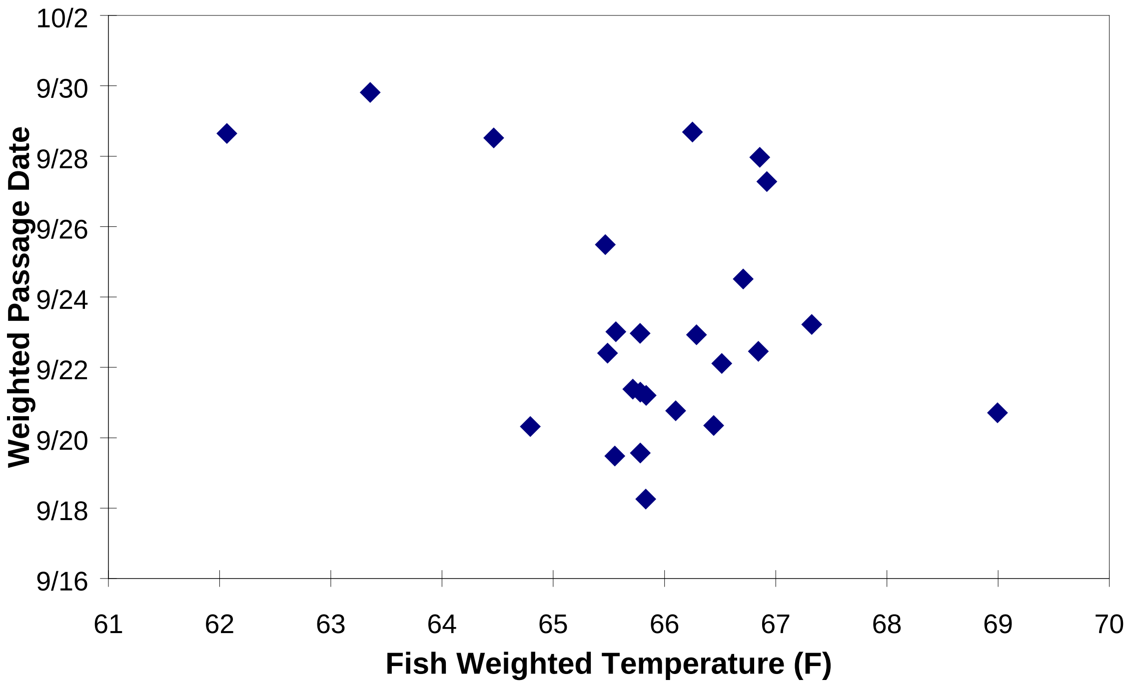


Figure 48. Comparison between mean fall chinook weighted passage date and mean fall chinook weighted scroll case temperature at Little Goose Dam, 1970-1982 and 1991-1995.

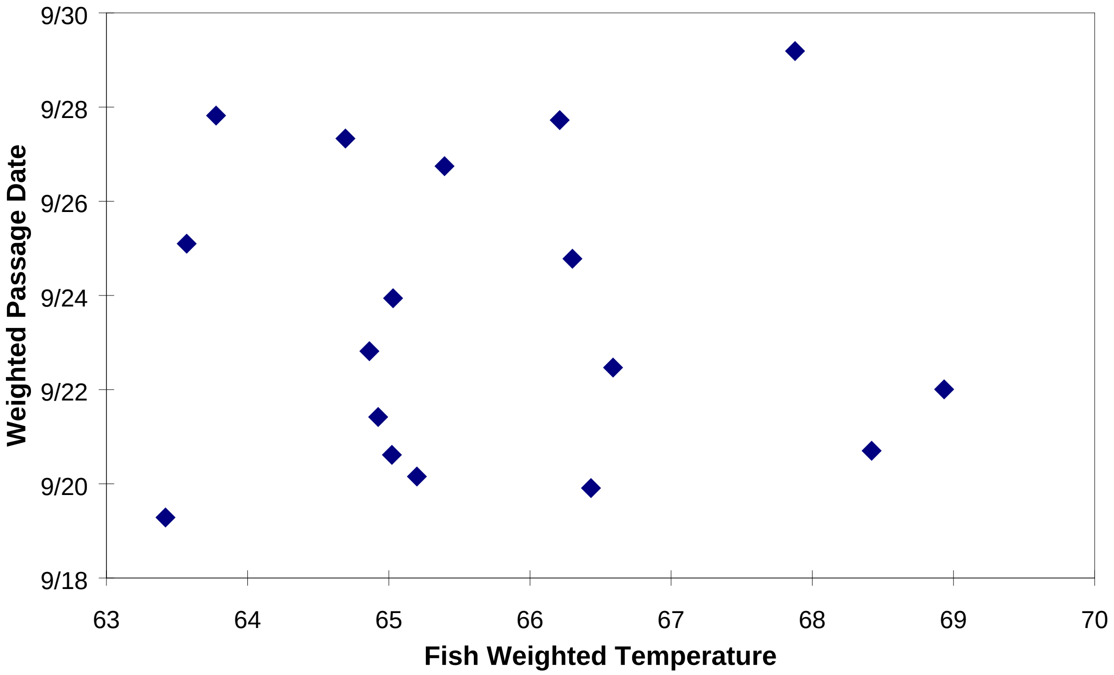


Figure 49. Comparison between mean fall chinook weighted passage date and the mean fall chinook weighted scroll case temperature at Lower Granite Dam, 1975-1995.

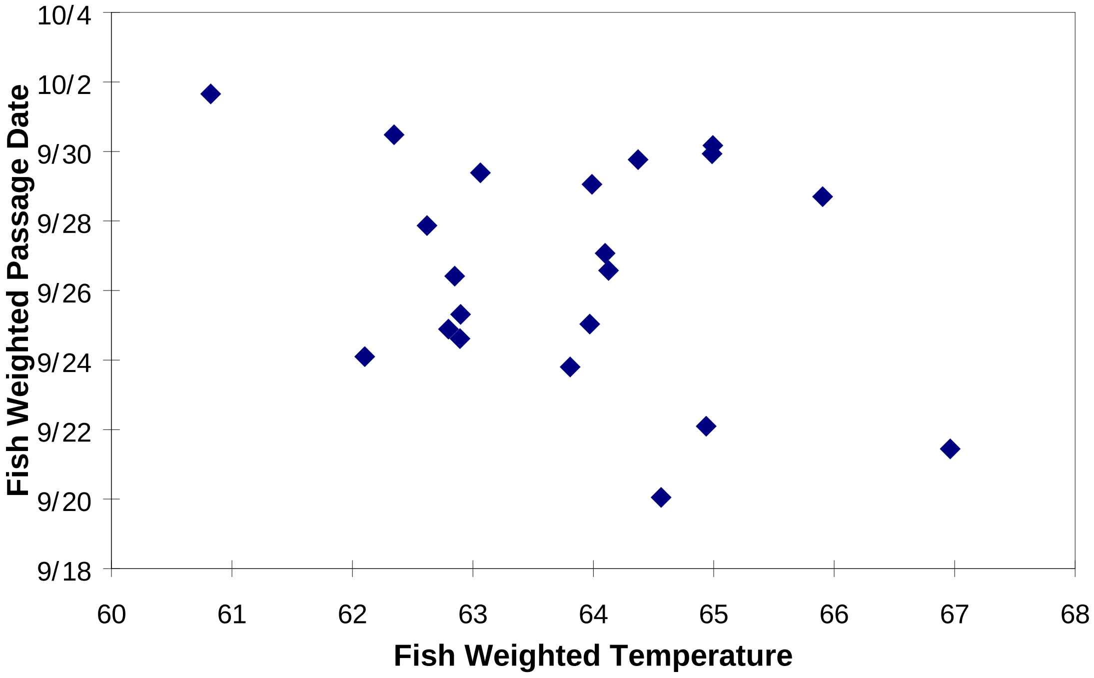


Figure 50. Linear relationship between estimated annual proportion of fall chinook entering the Snake River at Ice Harbor Dam that reach Lower Granite Dam (IHR-LWG conversion rate) and the fall chinook weighted mean scroll case temperature during the month of August, Ice Harbor Dam 1986-1996.

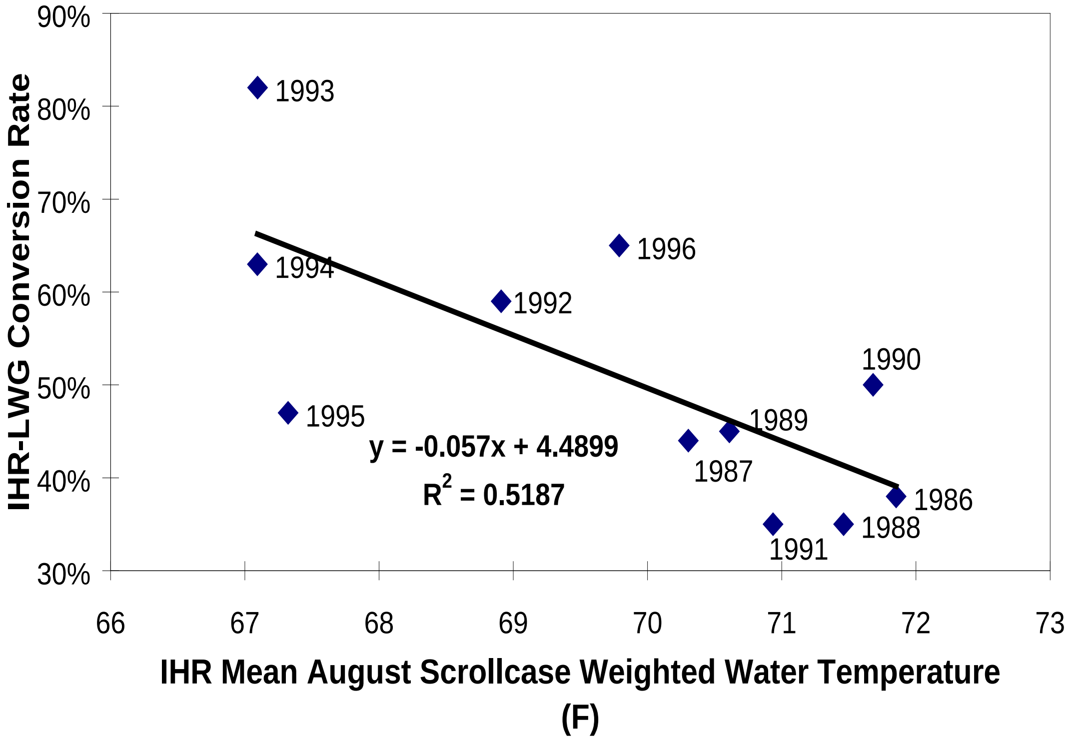
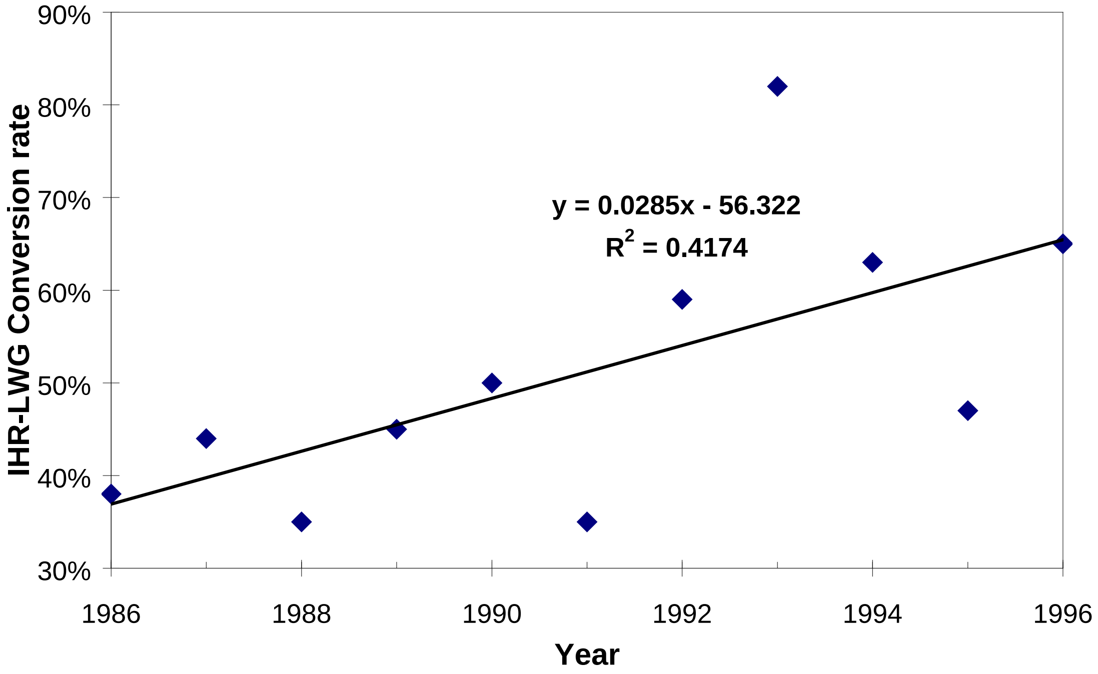


Figure 51. Linear relationship between estimated annual proportion of fall chinook entering the Snake River at Ice Harbor Dam that reach Lower Granite Dam (IHR-LWG conversion rate) and year, 1986 – 1996.



APPENDIX A: TEMPERATURE-AT-DEPTH OF THE LOWER SNAKE RIVER IN 1991 AND 1992

Using temperature data from the transects of Snake River reservoirs in 1991 and 1992, an analysis of temperature-at-depth was developed to show the geographic pattern in water temperatures at depth encountered by salmon immigrating to the Snake River basin (Karr, Tanovan et al. 1992). On each transect there are three stations where four different temperature measurements were made at equidistant depth intervals starting at the surface (Figure 8). All temperature data were assigned to one of four categories: 1) lethal (>70F, 21.1C), 2) resistance (68 -70F, 20 -21.1C), 3) upper tolerance (60 - 68F, 15.6 - 20C), and 4) optimum (45 - 60F, 7.2 -15.6C). Temperature categories were color coded and plotted by depth (along the y-axis). On each date sampled, the temperature categories for each transect were placed along the x-axis according to their distance above the mouth of the Snake River (Table 3). The resulting plot depicts the ambient temperatures available to salmon on that date, as they migrate upstream through the Snake River system. The plots are displayed in Figure A1 while a description of these figures is given in Table A1.

Table A1. Chronological description of temperature regime in the lower Snake River during the migration of fall chinook salmon in 1991 and 1992. Symbols for dams in order of reference are DWR, Dworshak Dam; LWG, Lower Granite Dam; IHR, Ice Harbor Dam; LMN, Lower Monumental Dam; LGS, Little Goose Dam.

1991

July 23. Significant flows from DWR were terminated by July 16. Warm water is entering LWG pool and collecting at the surface and mid-depths of the reservoir. Cool water persists throughout most of IHR, LMN, and LGS reservoirs with warmer water pooling at the surface.

July 30. Temperatures have surpassed lower resistance levels throughout LWG reservoir while upper resistance levels persist through most of LGS pool. Temperatures in LMN and IHR pools are predominately at the upper tolerance or lower resistance levels.

August 8. Temperatures are in the lethal range (LR) throughout most of the system with lower resistance zone temperatures at some of the lower depths of the reservoirs.

August 14. Slightly cooler waters are entering LWG reservoir with temperatures at the upper end still within the resistance level. Lethal rangetemperatures persist throughout the rest of the lower Snake River.

August 17. LR water is once gain entering the upper end of LWG reservoir. The cooler water of August 14 has pooled at the deeper reaches of LWG reservoir with some being spilled over into LGS reservoir. LR waters persist throughout the rest of the system.

August 23. Significant flows from Dworshak were initiated on August 16. Temperatures at the depths of LWG pool have reached optimum zone with a steep gradient to resistance zone and LR levels at the surface. Cooler waters have also infiltrated LGS reservoir while LR waters persist elsewhere in the lower Snake River system.

August 27. DWR reservoir releases reduced to minimum on August 21. Temperatures at the upper end of LWG reservoir are at resistance levels. The upper end and deeper portions of LGS reservoir contain tolerance zone (TZ) waters. Some resistance zone (RZ) waters are in LMN reservoir but LR waters persist through the rest of the system.

August 29. Cooler water is entering the system. Temperatures at the upper ends and deeper sections of LWG and LGS reservoirs have reached the TZ, with RZ and LR temperatures persisting along the surface of LWG and LGS reservoirs and elsewhere in the system.

Table A1

September 1. Temperatures at the upper end of LWG pool are increasing to the RZ. LWG, LGS, and LMN reservoirs all show some temperature stratification with cooler water found at the upper reaches and depths of each reservoir, with LR waters at the surface. Temperatures in IHR reservoir remain at and above LR.

September 3. Cold water releases are increased at DWR reservoir on September 3. Temperatures in LWG, LGS, and LMN reservoir are starting to become more uniform with RZ waters predominating. Temperatures are within LR at most surface sites while some TZ waters have collected in the depths of LWG pool. Temperatures are LR throughout IHR pool.

September 5. Cool water releases continue from DWR reservoir. Temperatures have cooled to TZ levels in the deeper portions of LWG, LGS, and LMN pools while LR waters persist at IHR pool.

September 8. Cooler water has infiltrated the entire lower Snake River system. zone waters predominate in LWG and LGS pools and are also found in the depths of LMN and IHR pools.

September 10. Cooling continues in LWG and LGS pools. However, some warming has occurred in LMN and IHR pools with water temperatures reaching the RZ.

September 14. Cooling continues in LWG, LGS, and LMN reservoirs. Some warmer water persists in IHR reservoir and at the lower reaches of LMN reservoirs.

September 17. Water temperatures are at within the TZ nearly everywhere but across transect 6 in IHR reservoir.

September 19. Water temperatures are generally within the TZ throughout the system.

September 23-October 15. Cooling continues.

1992

July 1. LGS and LWG reservoir temperatures are within RZ with some in LR. The only exception is at the upper end of LWG reservoir. Temperatures downstream in LMN and IHR reservoirs are generally within TZ with some patches warmer, particularly near the surface and at IHR dam. Salmon would not be inhibited by temperature in IHR and LMN reservoirs but could be impeded by attempted avoidance of RZ in LGS and uniform LR water in LWG.

July 7. Increased releases of cold water began at DWR on July 5. Water temperatures are showing cooling at the upper end of LWG reservoir. LR waters are moving downstream into LMN reservoir and temperatures in nearly all of IHR are within the RZ. Fish passing through IHR and LWG would necessarily encounter RZ levels, while LMN and LGS present uniform LR levels.

Table A1

July 9. Cold water releases continue at DWR. Water temperatures in LWG reservoir have declined to TZ everywhere except near the surface just upstream of LWG Dam. Temperatures at the upper end of LGS reservoir have cooled to RZ. Warm water continues to move downstream, with nearly all of LMN reservoir containing LR waters and IHR reservoir warming to RZ and LR levels throughout.

July 11. Cold water releases continue at DWR. Water temperatures have declined to TZ throughout LWG reservoir and in the upper LGS reservoir. LR waters have moved downstream into LMN and IHR reservoirs.

July 13. Cold water releases have terminated at DWR. Surface temperatures in LWG reservoir increase as TZ waters reach the upper end of LMN reservoir. LR waters remain in the rest of LMN and IHR reservoirs.

July 16. Cold water releases are resumed at DWR from July 15-17. Water temperatures remain at TZ levels in LWG and LGS reservoirs, at TZ levels in LMN and at LR levels in IHR reservoir.

July 18. DWR water releases have terminated until September. Surface temperatures in LWG and LMN reservoirs begin to increase. TZ waters infiltrate LWG, LGS, and LMN reservoirs while lethal water temperatures persist in IHR reservoir.

July 21. Surface temperatures increase throughout LWG, LGS, and LMN reservoirs. RZ waters has moved down to IHR reservoir. The system has stratified, except immediately downstream of LWG and LGS dam where mixing has occurred in the powerhouses.

July 23. Warming has put most water temperatures in LWG to lethal levels. Cooler water persists in the upper LMN. Mixing results in cooler water temperatures downstream of LWG, LGS, and LMN dams but warming occurs downstream.

July 25. The reservoirs appear to be stratifying with warmer water near the surface and cooler water below.

July 28. Warming continues from LWG downstream and from the surface down.

July 30. LWG reservoir reaches LR.

August 1. LWG and LGS reservoir temperatures are at LR. Temperatures also increase at LMN and IHR reservoirs.

August 4. LR waters persist in LWG and LGS reservoirs. Warming continues at LMN and IHR reservoirs.

August 6. LWR waters persist in LWG and LGS reservoirs. Warming continues at LMN and IHR reservoirs.

August 10. LR waters dominate LWG and LGS reservoirs and predominate in LMN and IHR reservoirs.

August 17. LR waters are found virtually everywhere in the system.

August 19. LR waters are found virtually everywhere in the system.

August 25. Cooling begins in upper LWG reservoir. Temperatures remain at LR elsewhere.

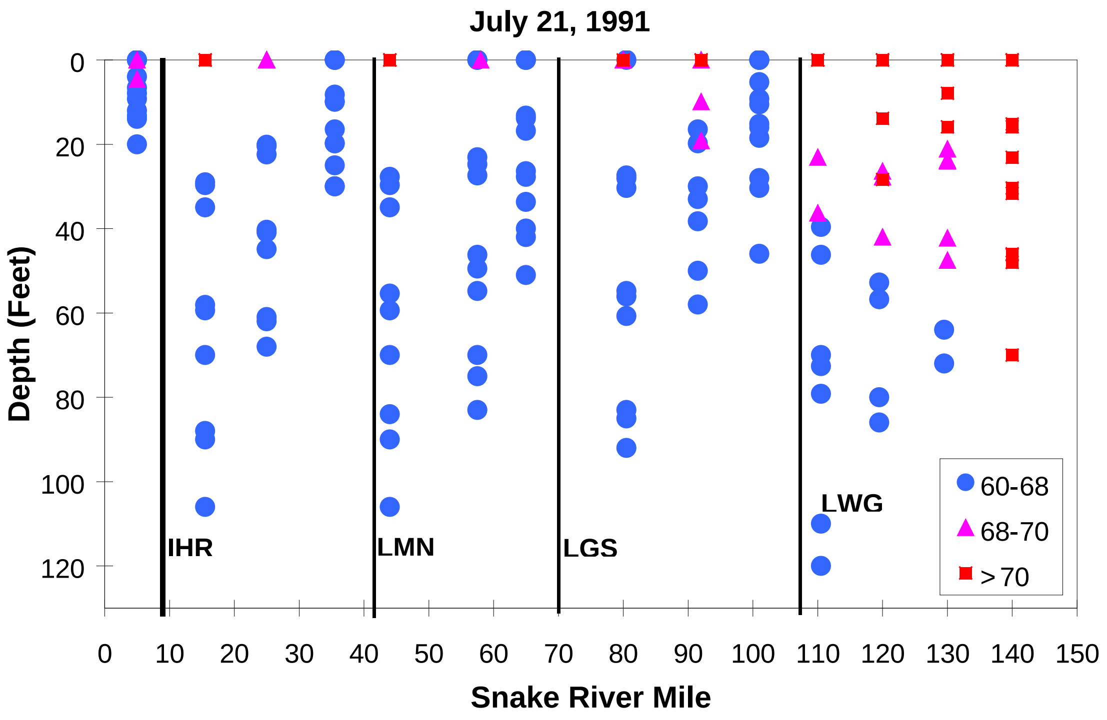
Table A1

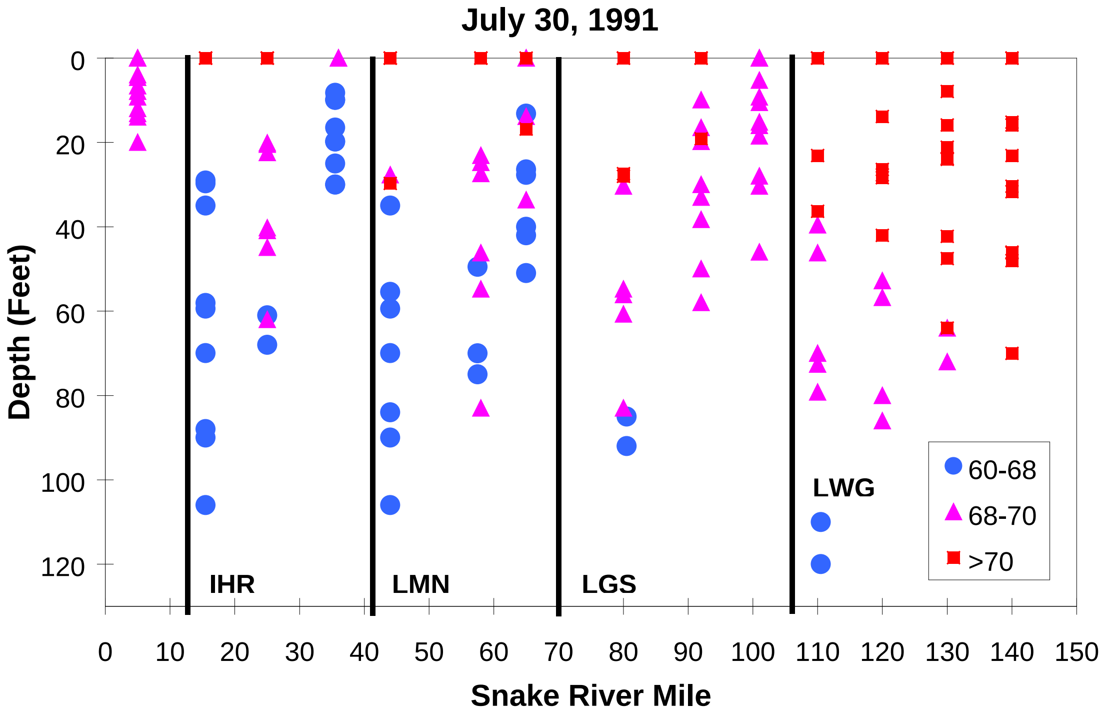
August 29. Cooling appears to have halted in upper LWG reservoir. Cooler water is infiltrating bottom sections of LWG reservoir.

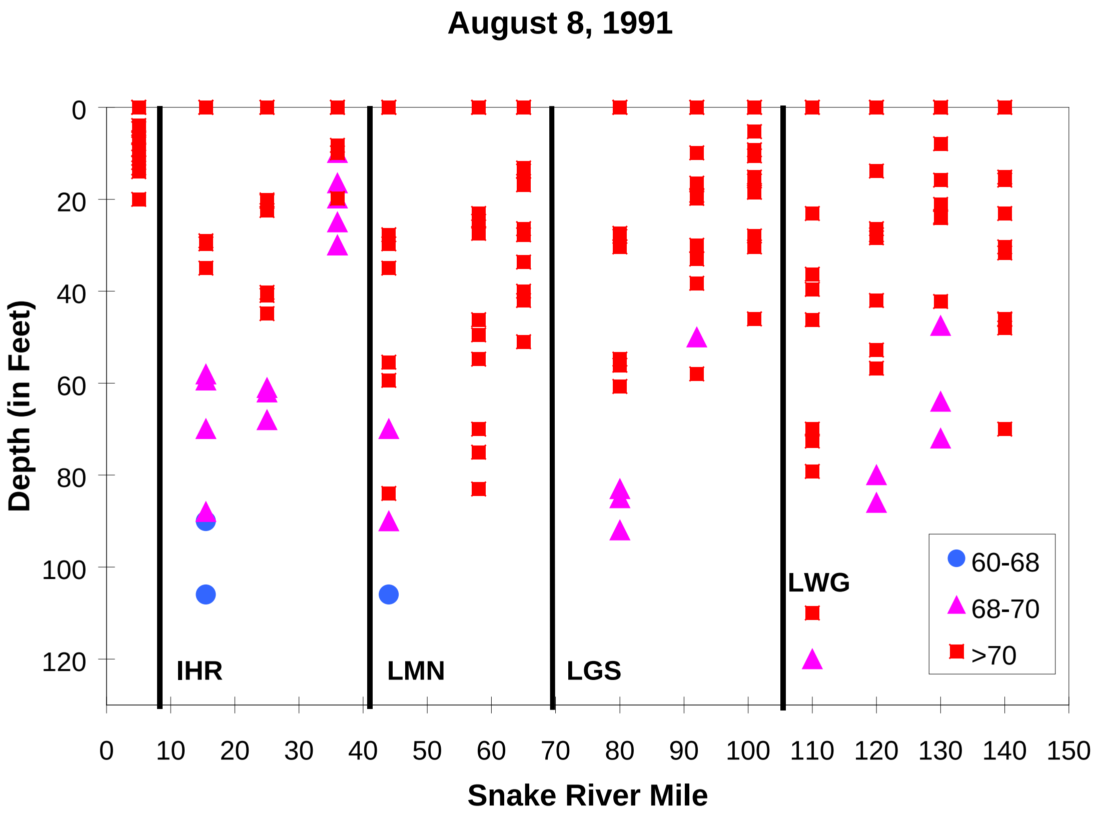
September 2. TZ waters have infiltrated the bottom of LWG reservoir and entered LMN reservoir.

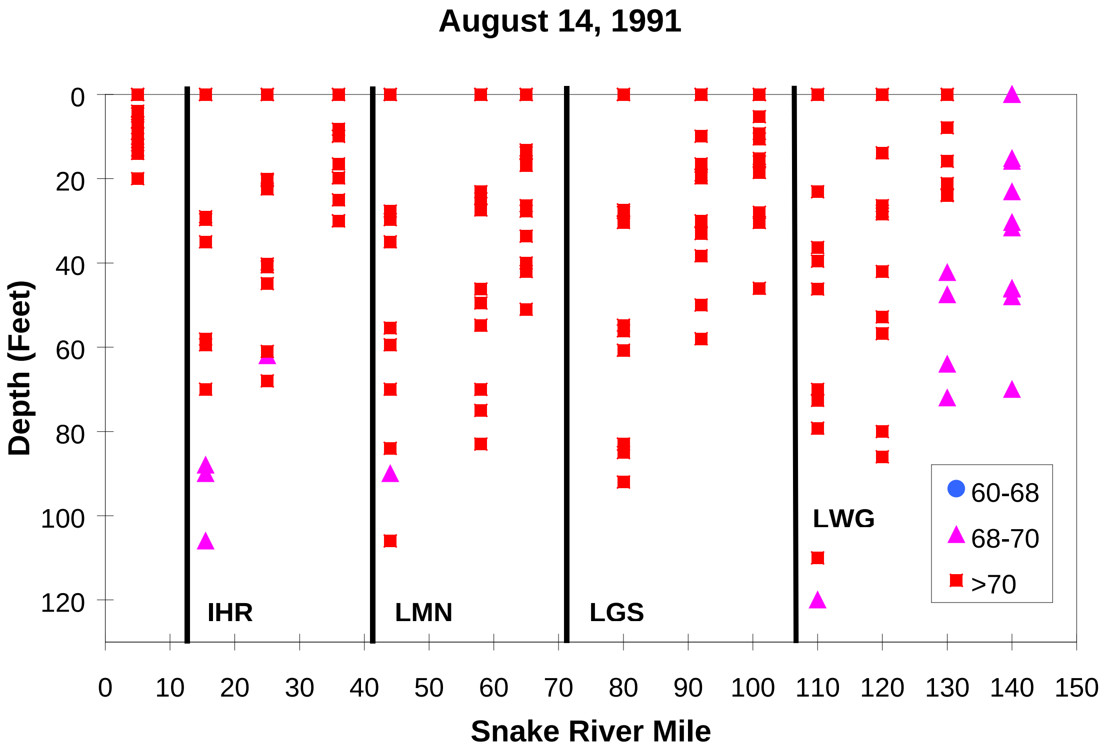
September 10. TZ waters are found throughout LWG and LMN reservoirs and temperatures in LGS and IHR reservoirs have declined to RZ.

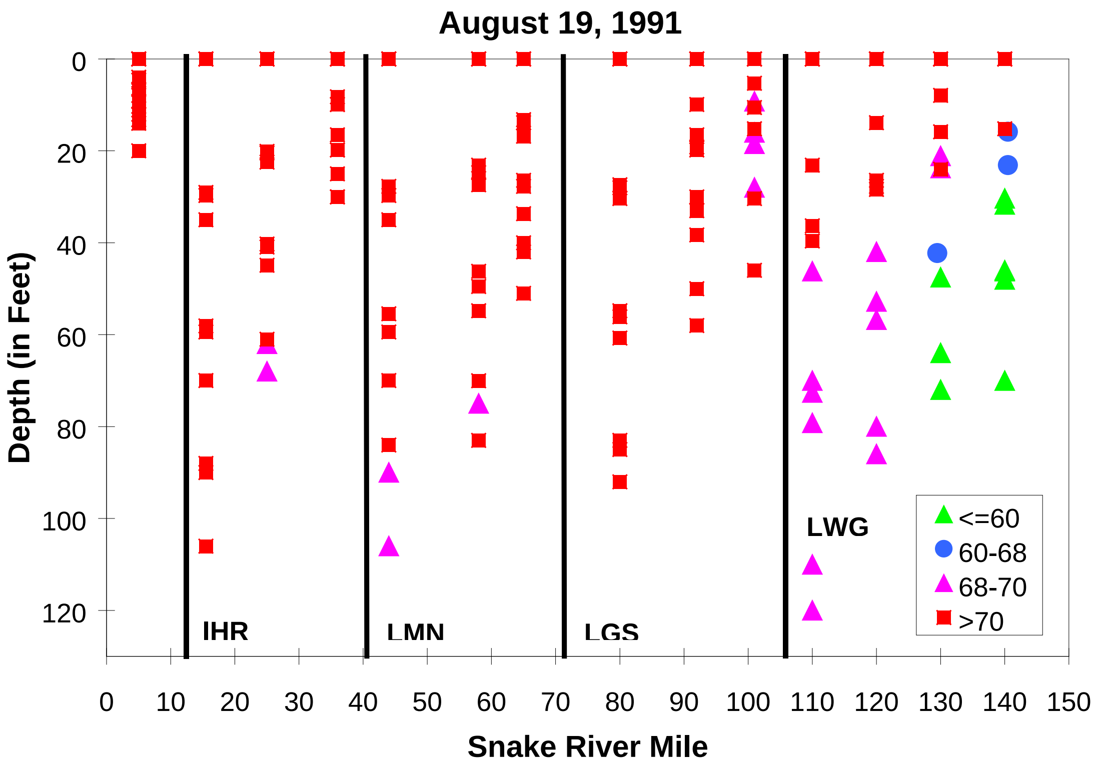
Figure A1. Temperature categories, by depth and distance, from the mouth of the Snake River on August 8, 1991. Colors refer to the temperature category where red is lethal (>70 F, 21.1C), magenta is resistance (68-70 F, 20-21.1C), blue is tolerance (60-68 F, 15.6-20C), and green is optimum (<= 60 F, 15.6C).

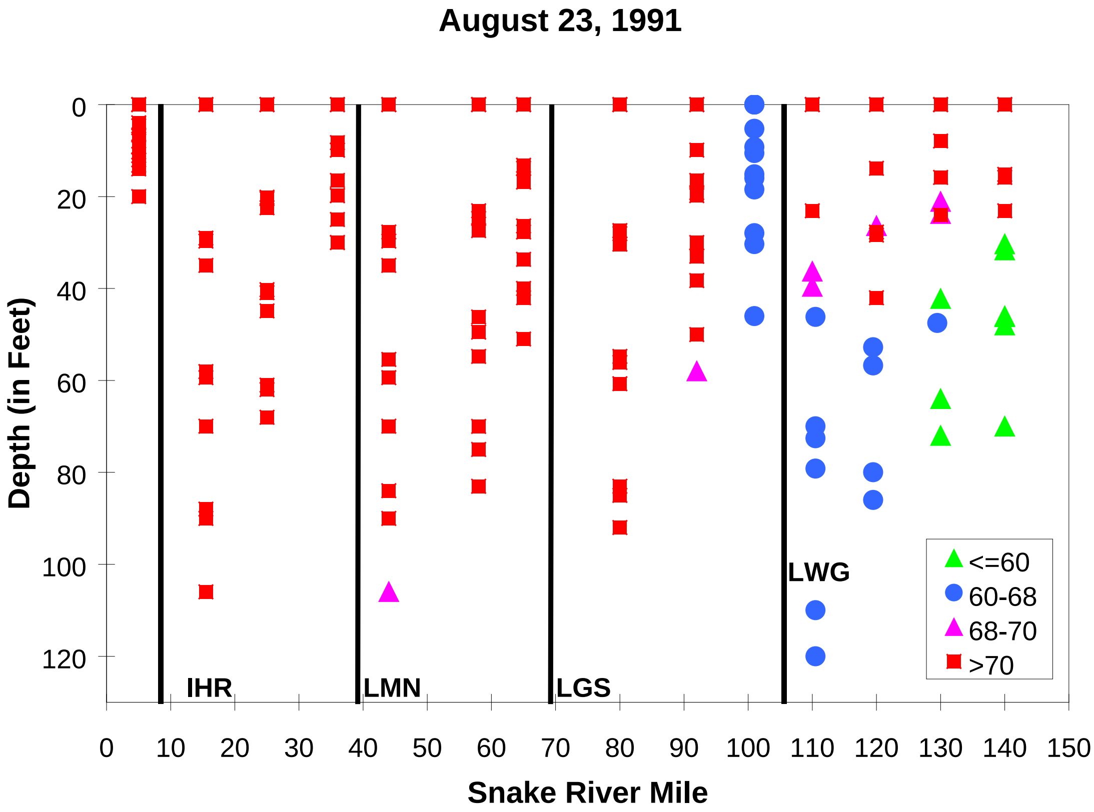




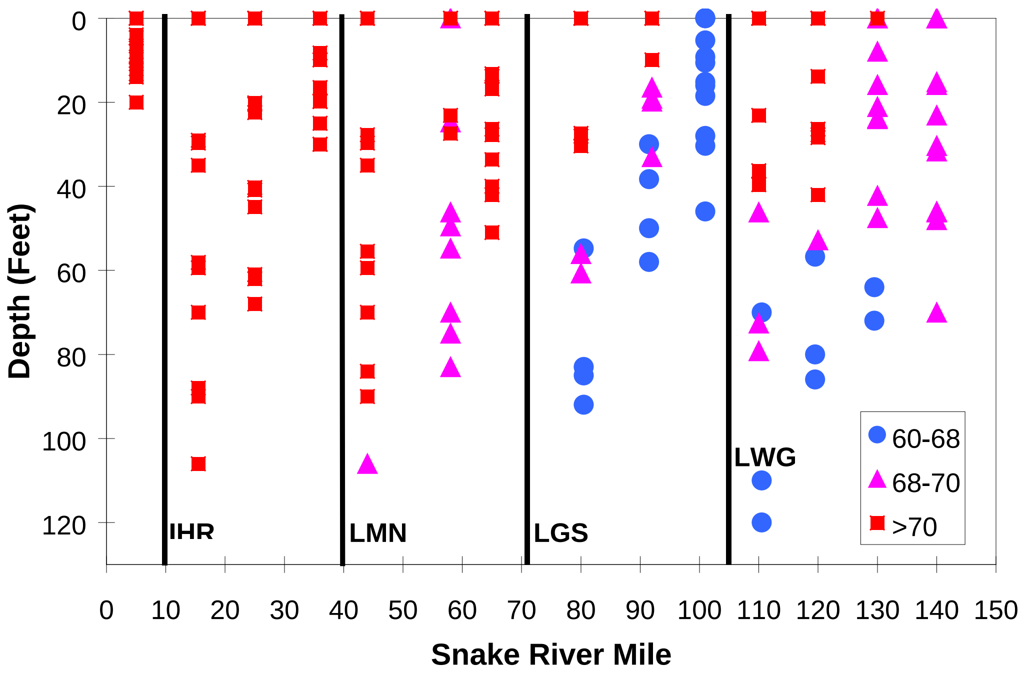

August 8, 1991
Depth (in Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
60-68
68-70
>70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


August 14, 1991
Depth (Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
60-68
68-70
>70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile

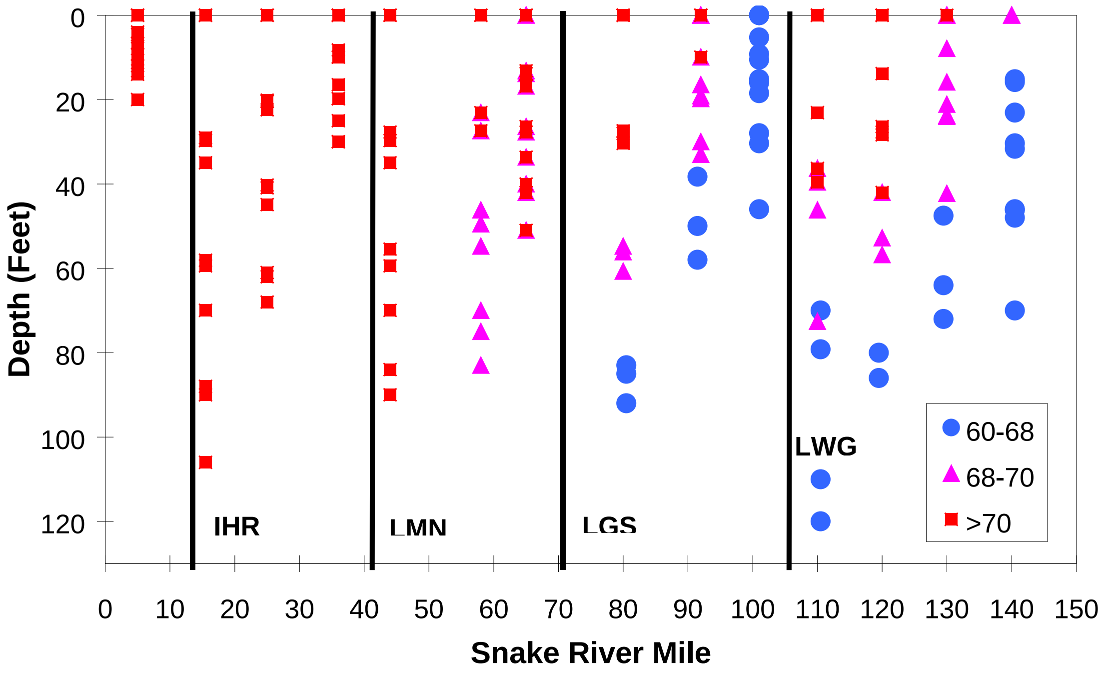

August 19, 1991
Depth (in Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile
▲ <=60
● 60-68
▲ 68-70
■ >70

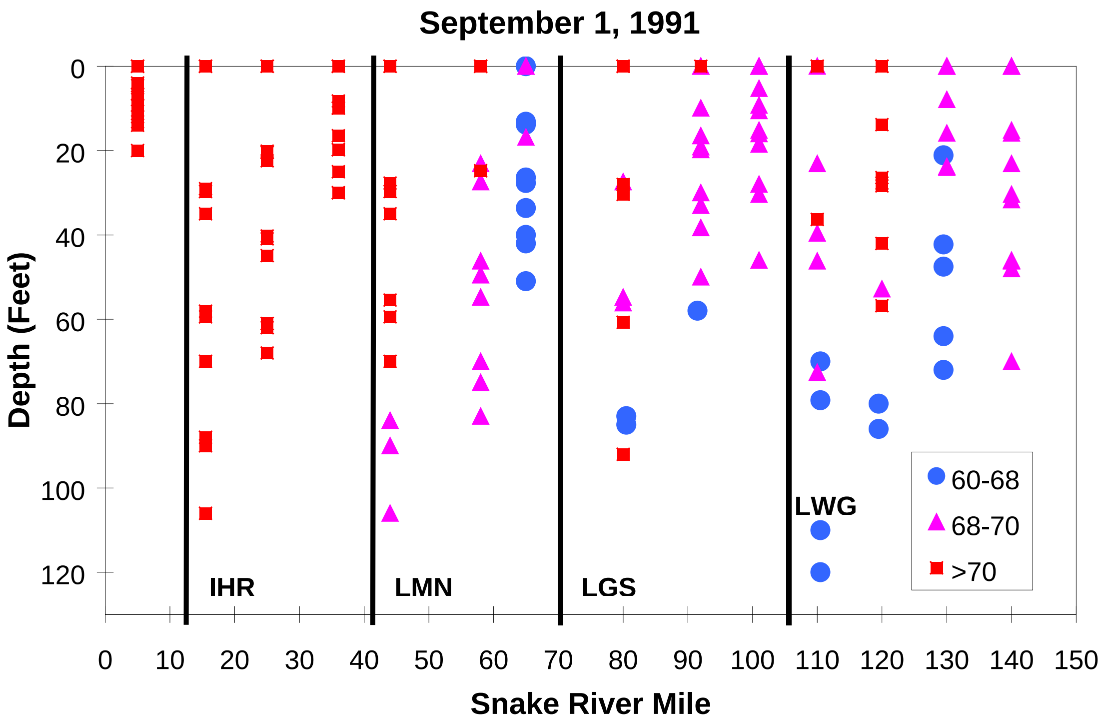

August 23, 1991
Depth (in Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile
▲ <=60
● 60-68
▲ 68-70
■ >70

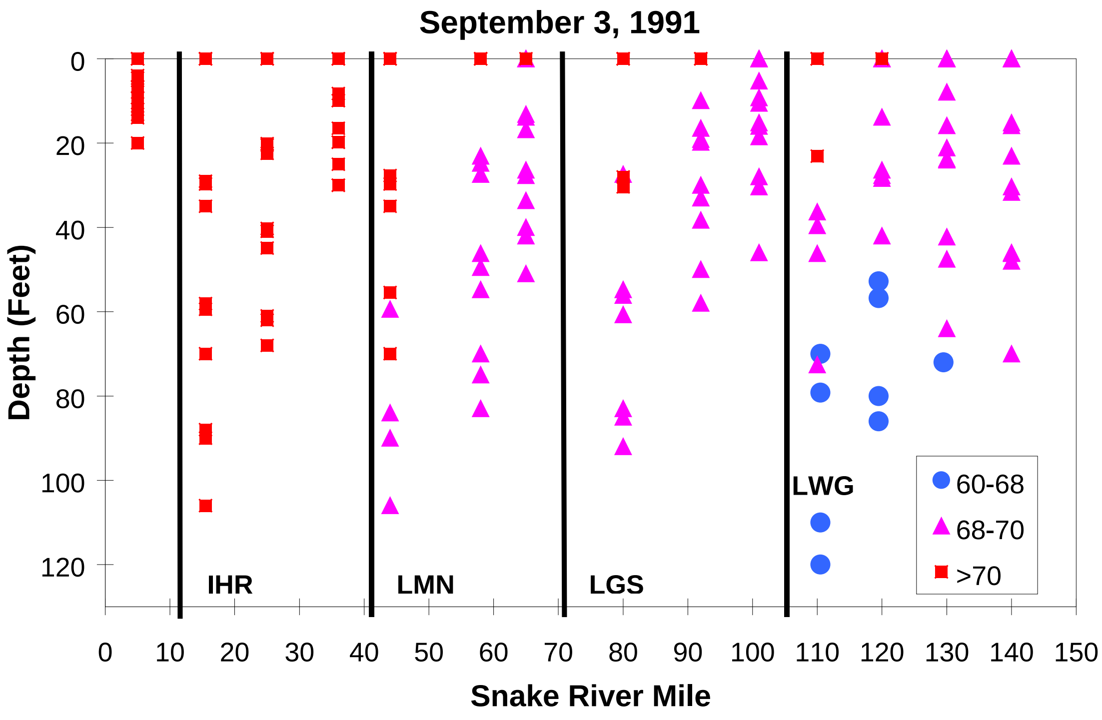
August 27, 1991

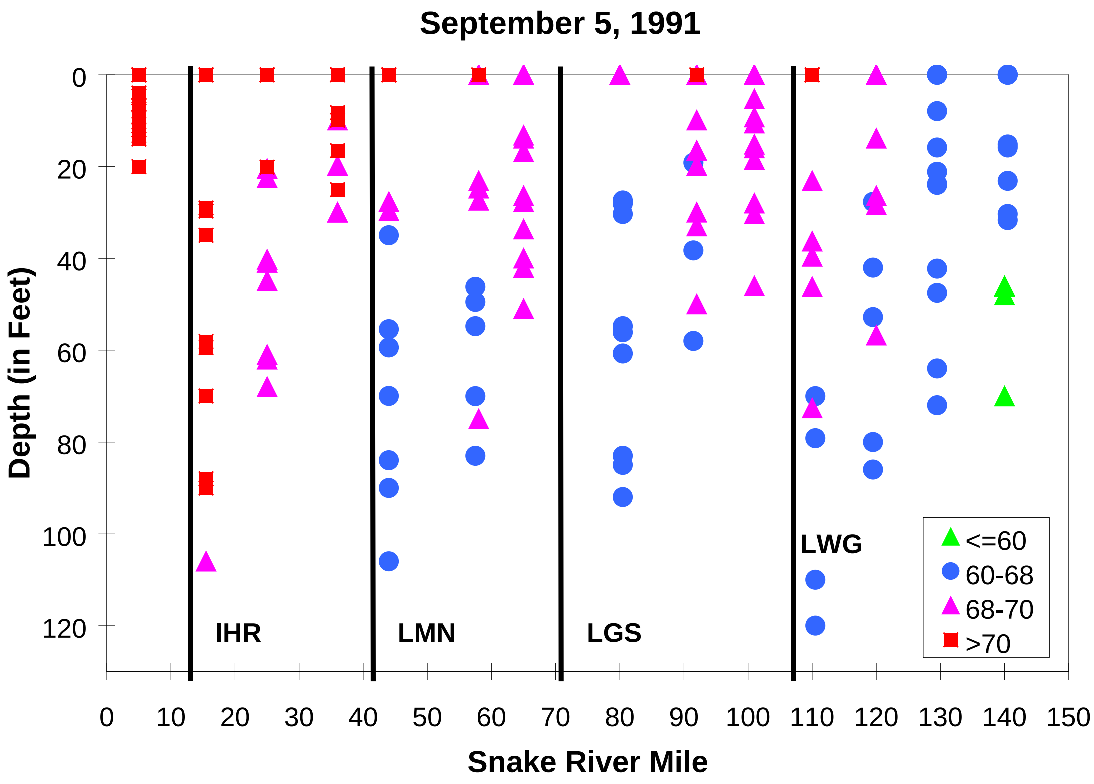


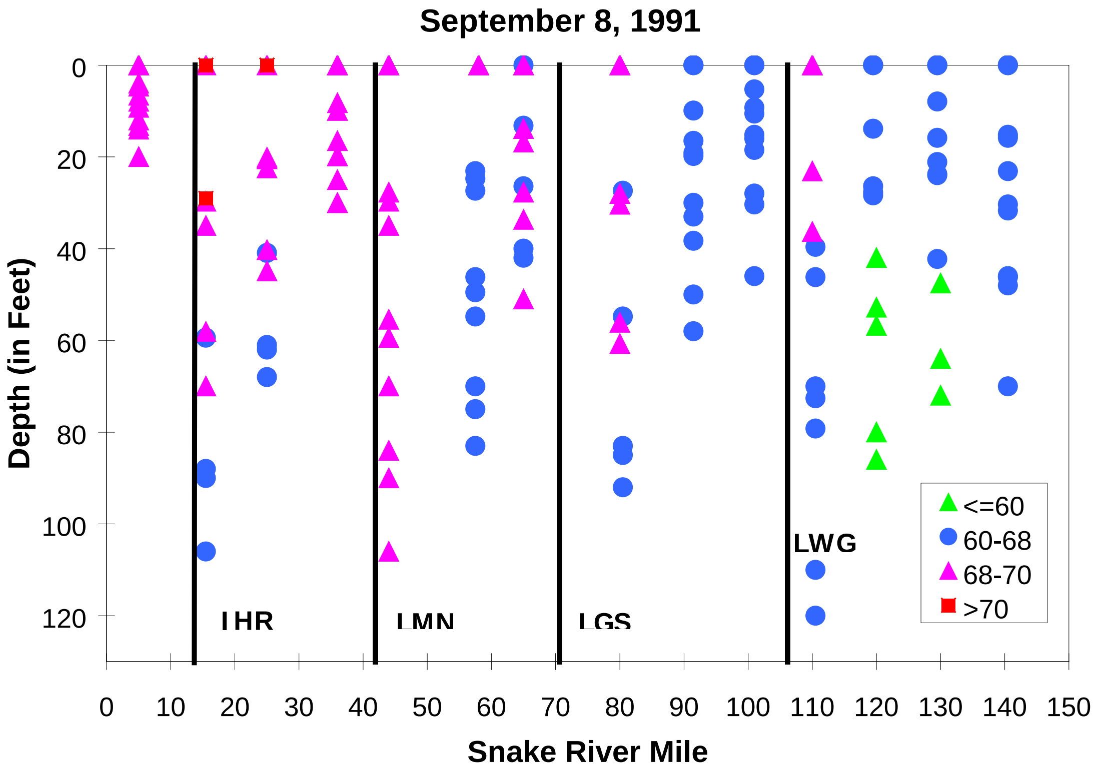
August 29, 1991




September 1, 1991
Depth (Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
● 60-68
▲ 68-70
■ >70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


September 3, 1991
Depth (Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
● 60-68
▲ 68-70
■ >70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


September 5, 1991
Depth (in Feet)
0
20
40
60
80
100
120
IHR
LMN
LGS
LWG
▲ <=60
● 60-68
▲ 68-70
■ >70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


September 8, 1991
Depth (in Feet)
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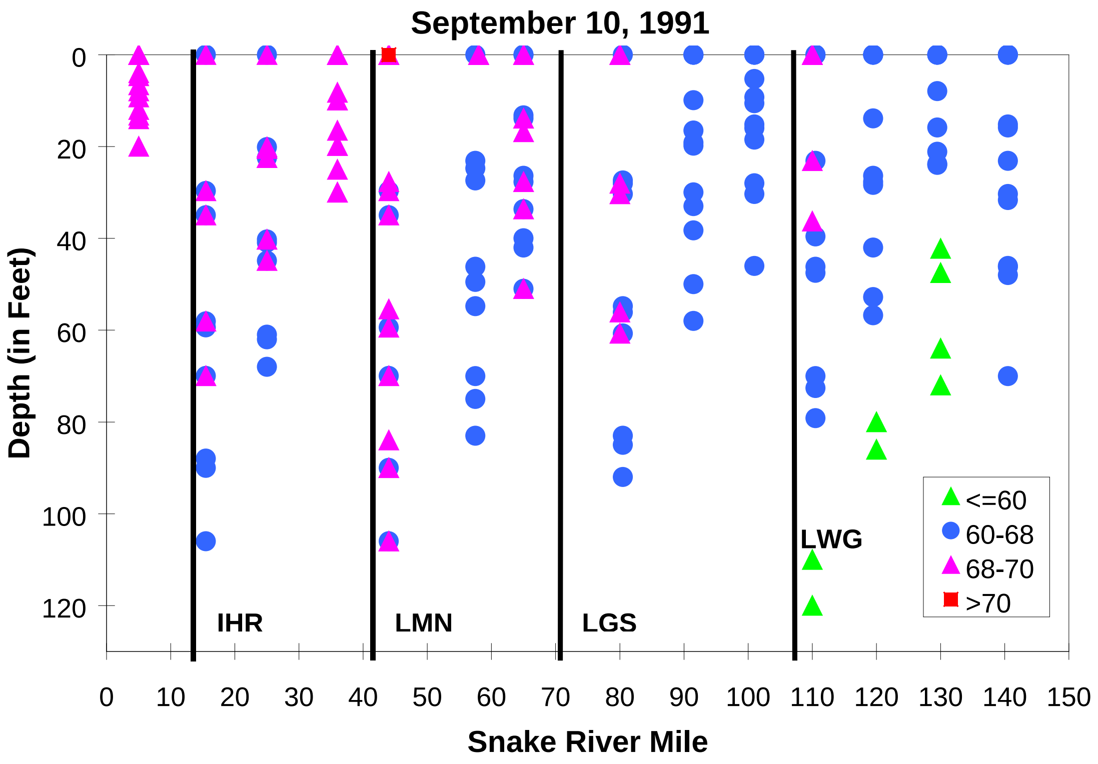
40
60
80
100
120
IHR
LMN
LGS
LWG
▲ <=60
● 60-68
▲ 68-70
■ >70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


September 10, 1991
Depth (in Feet)
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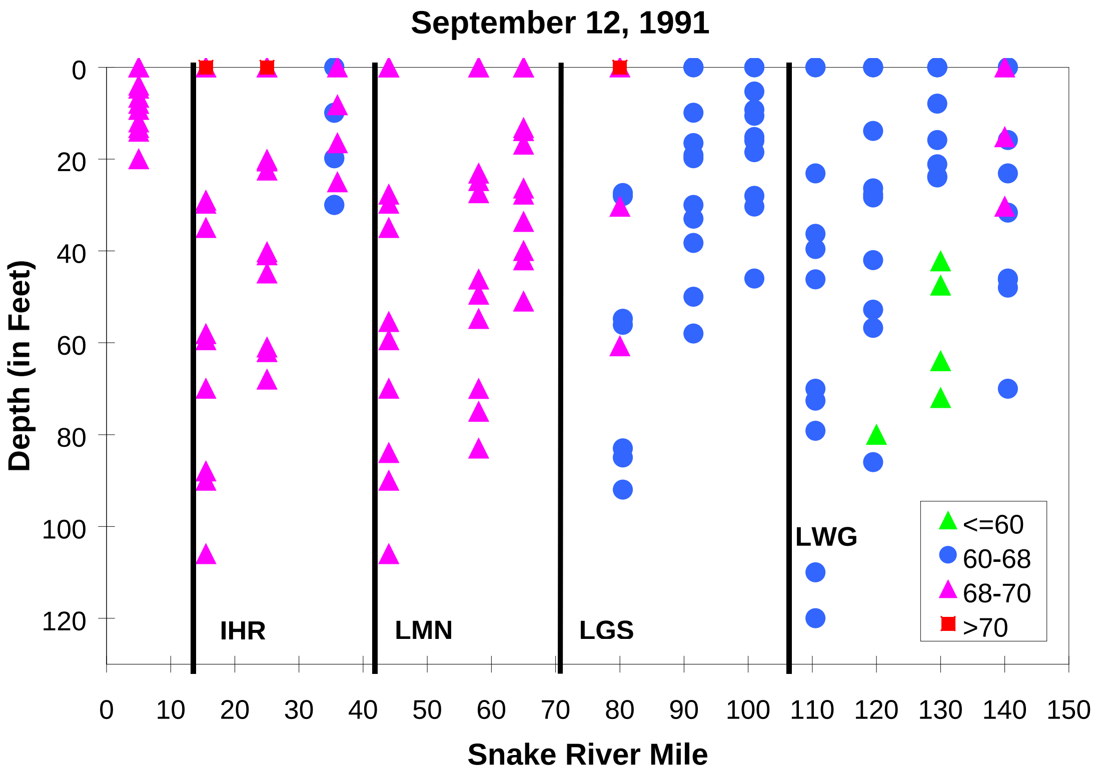
20
40
60
80
100
120
IHR
LMN
LGS
LWG
<=60
60-68
68-70
>70
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile


September 12, 1991
Depth (in Feet)
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100
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IHR
LMN
LGS
LWG
<=60
60-68
68-70
>70
0
10
20
30
40
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60
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80
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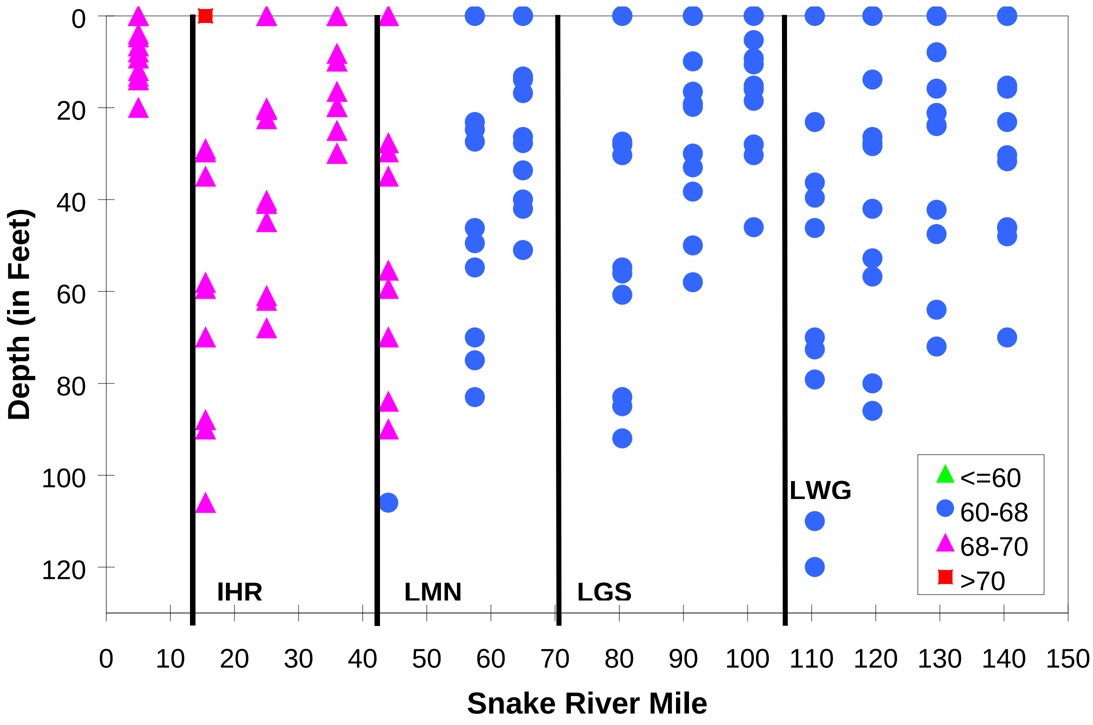
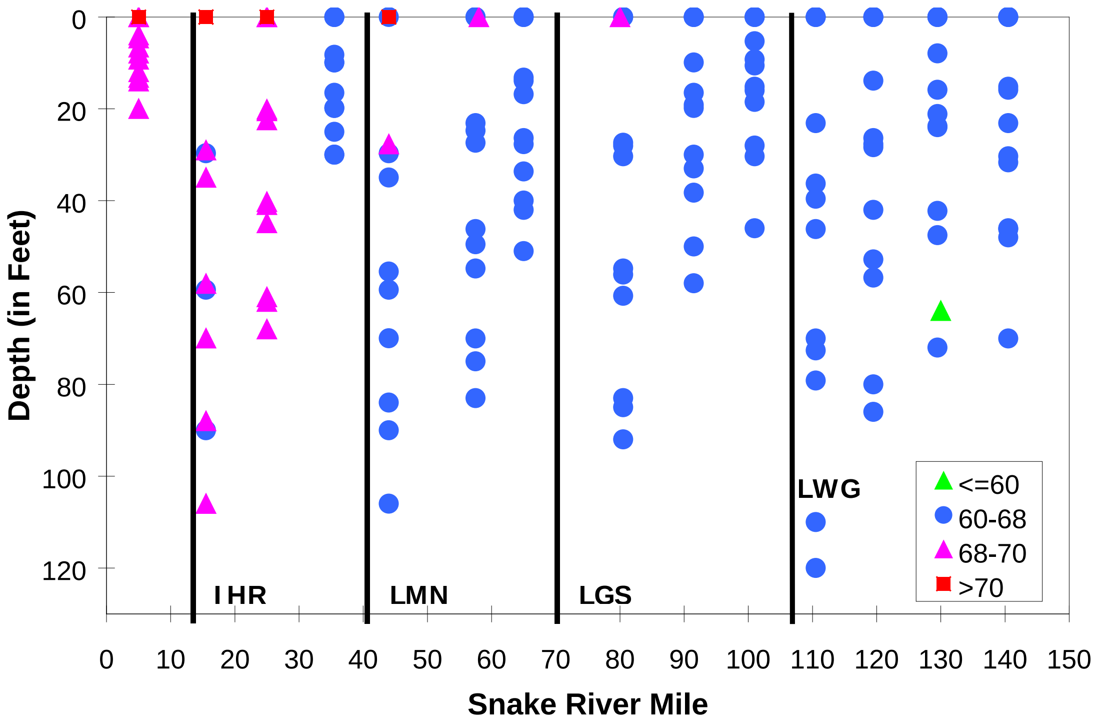
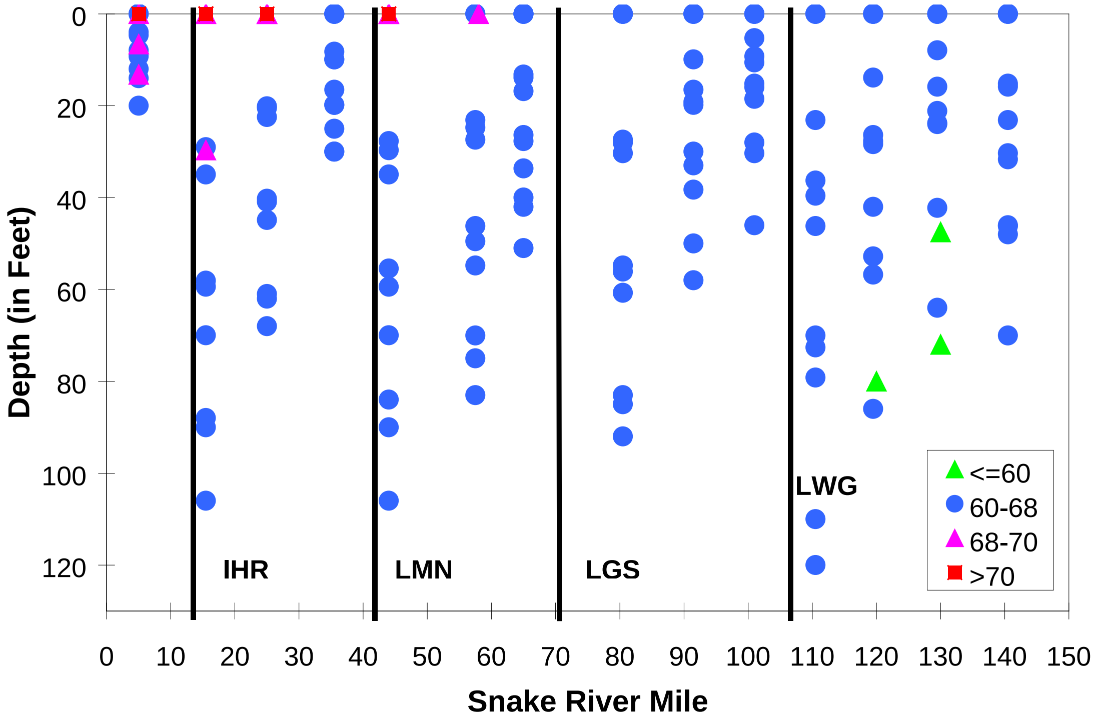
100
110
120
130
140
150
Snake River Mile

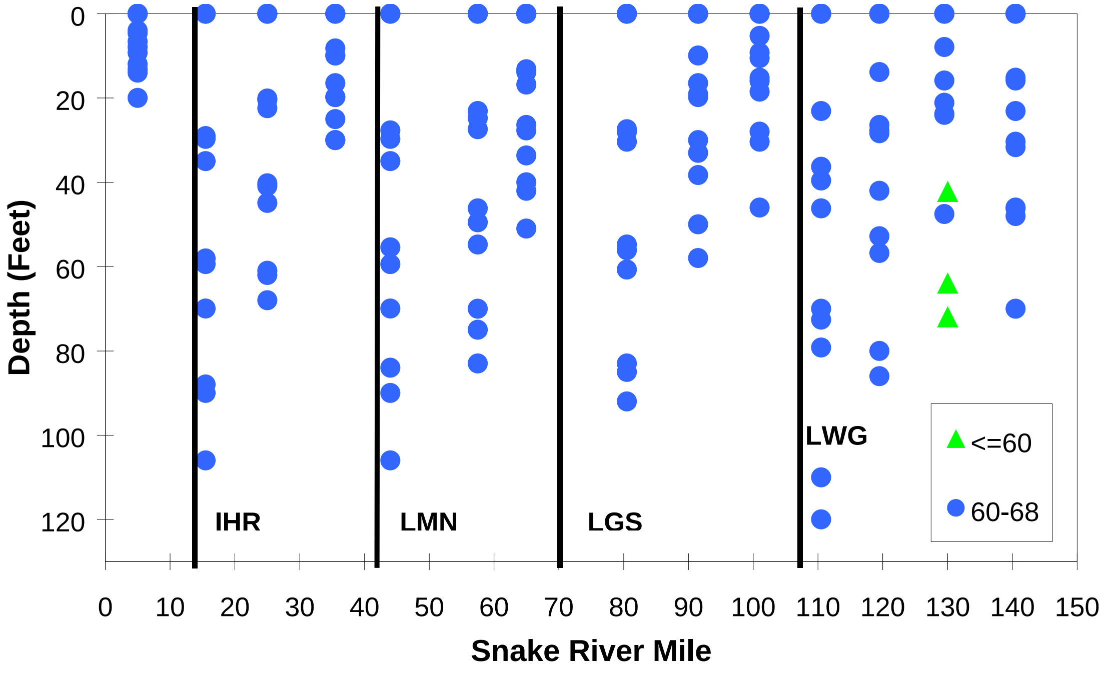


September 14, 1991

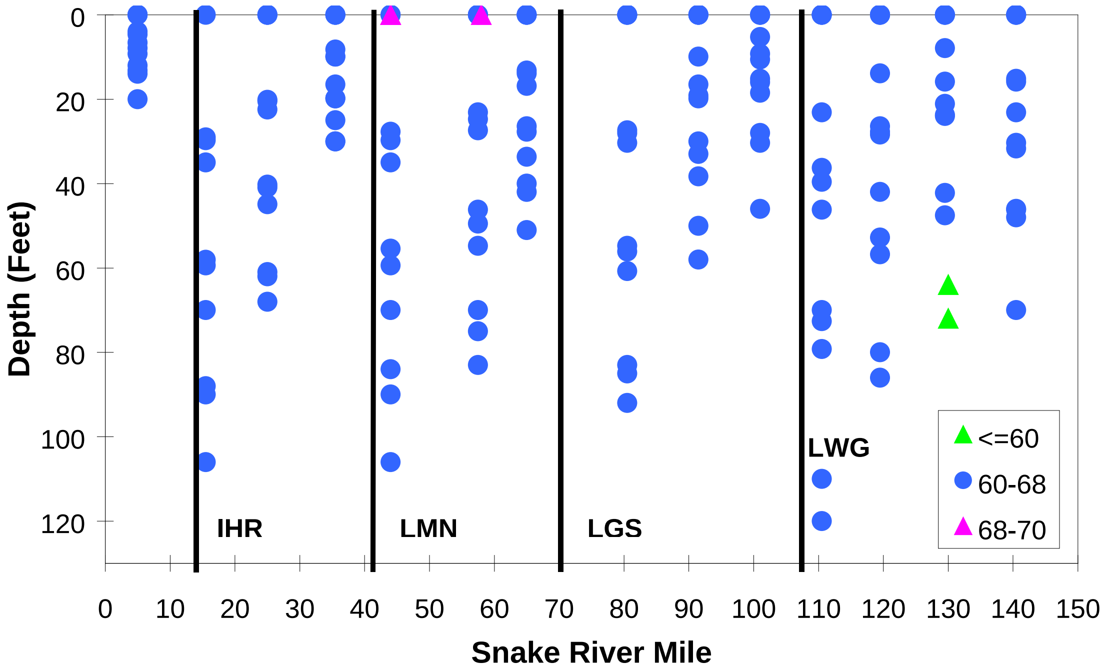


September 17, 1991

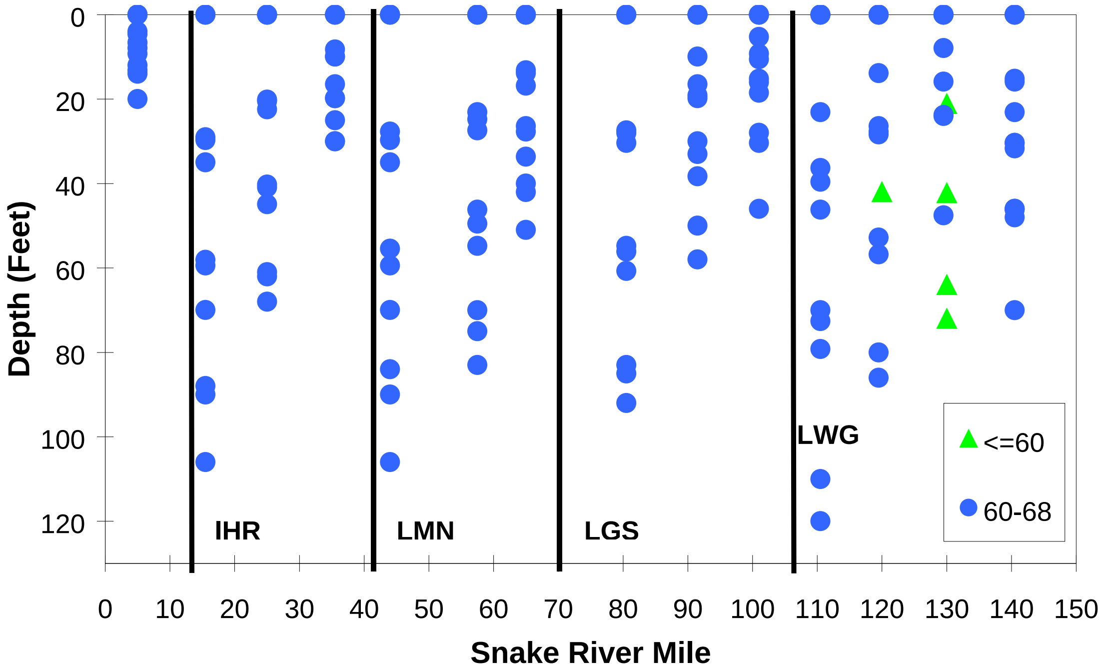

September 19, 1991


September 23, 1991

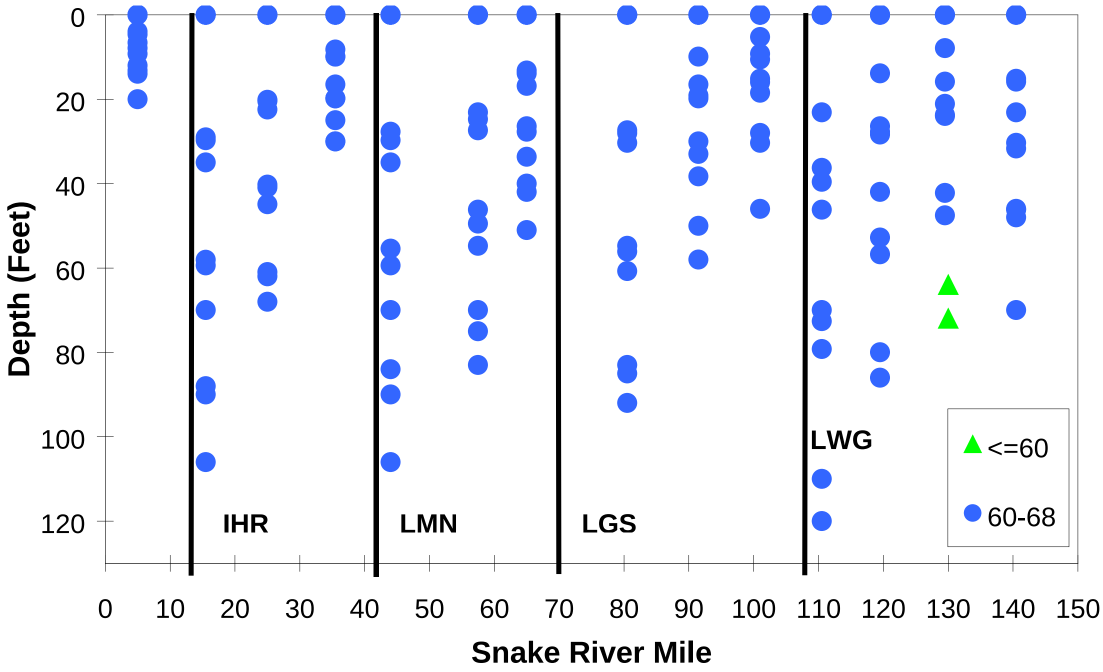
September 25, 1991



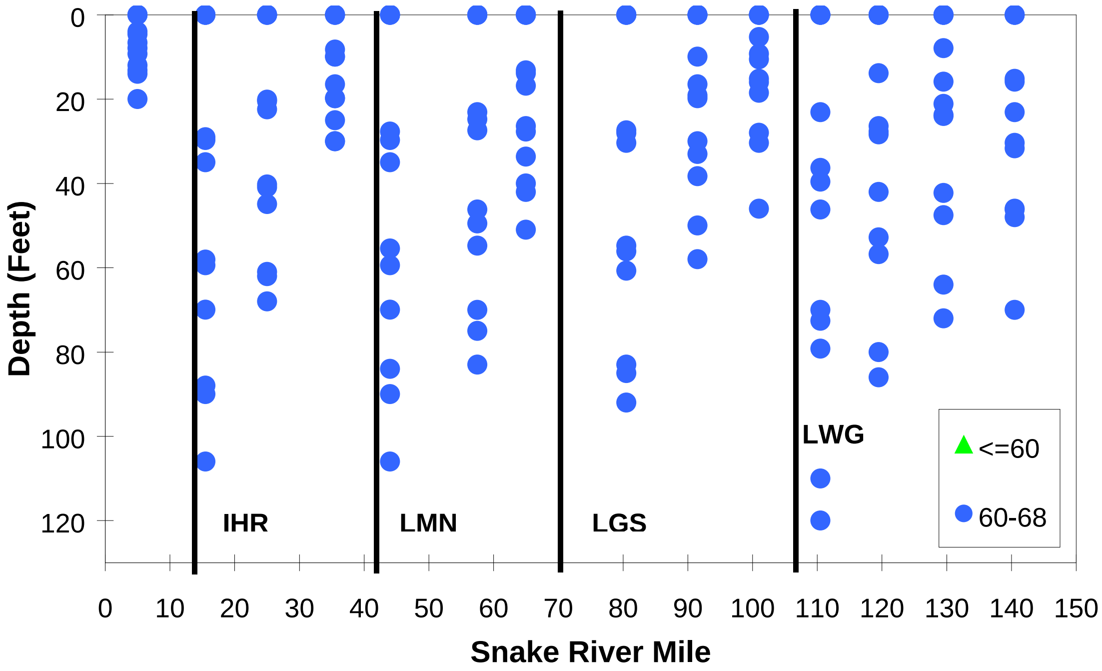
September 27, 1991



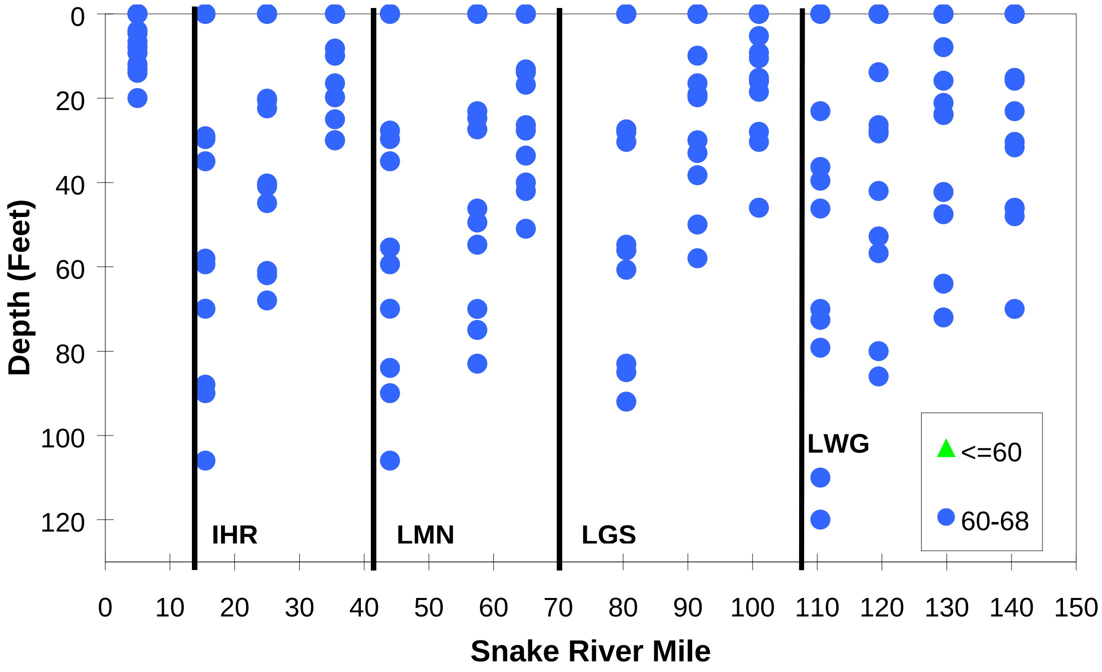
October 1, 1991



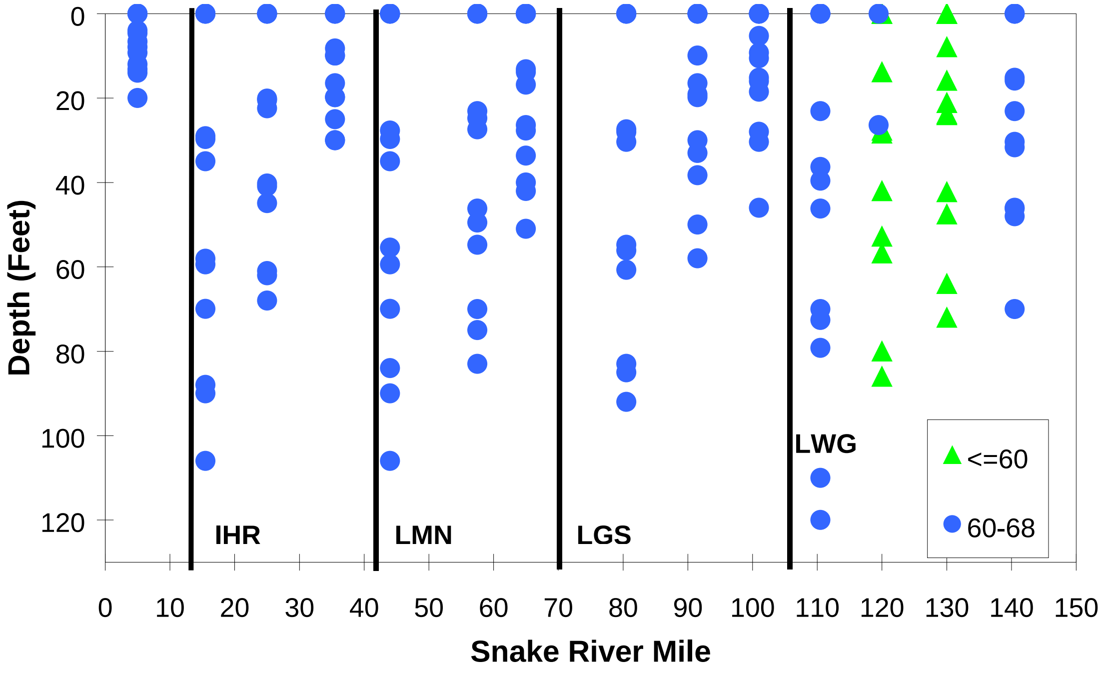
October 4, 1991

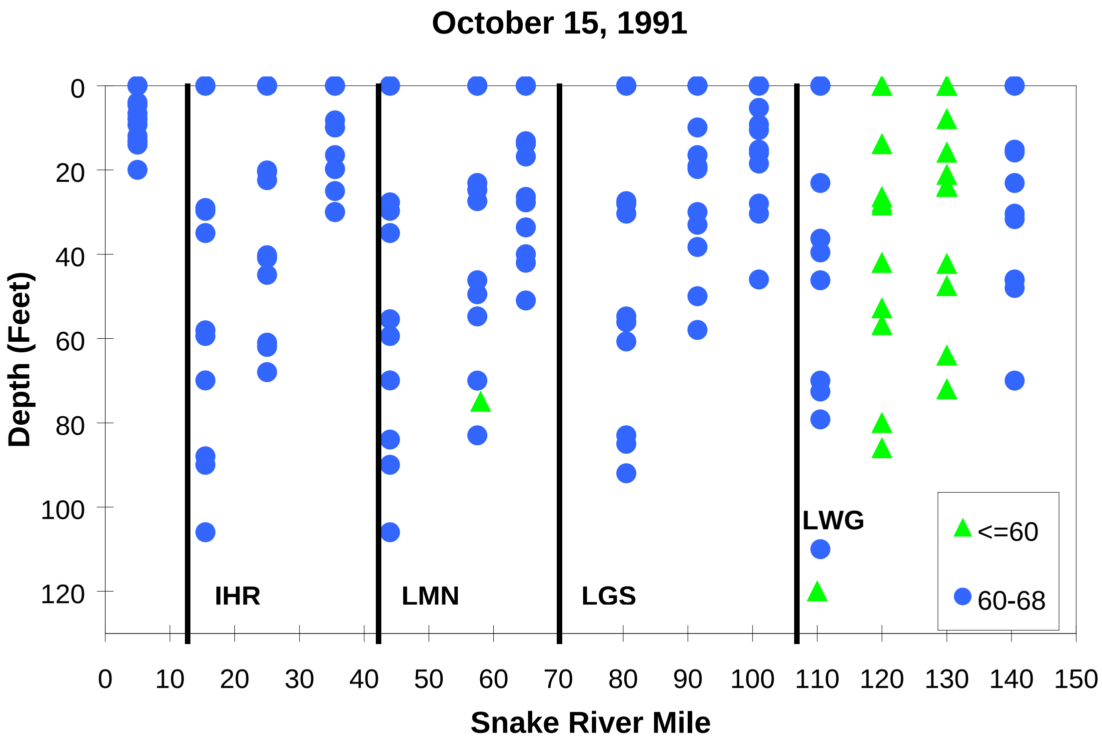


October 7, 1991



October 10, 1991




October 15, 1991
Depth (Feet)
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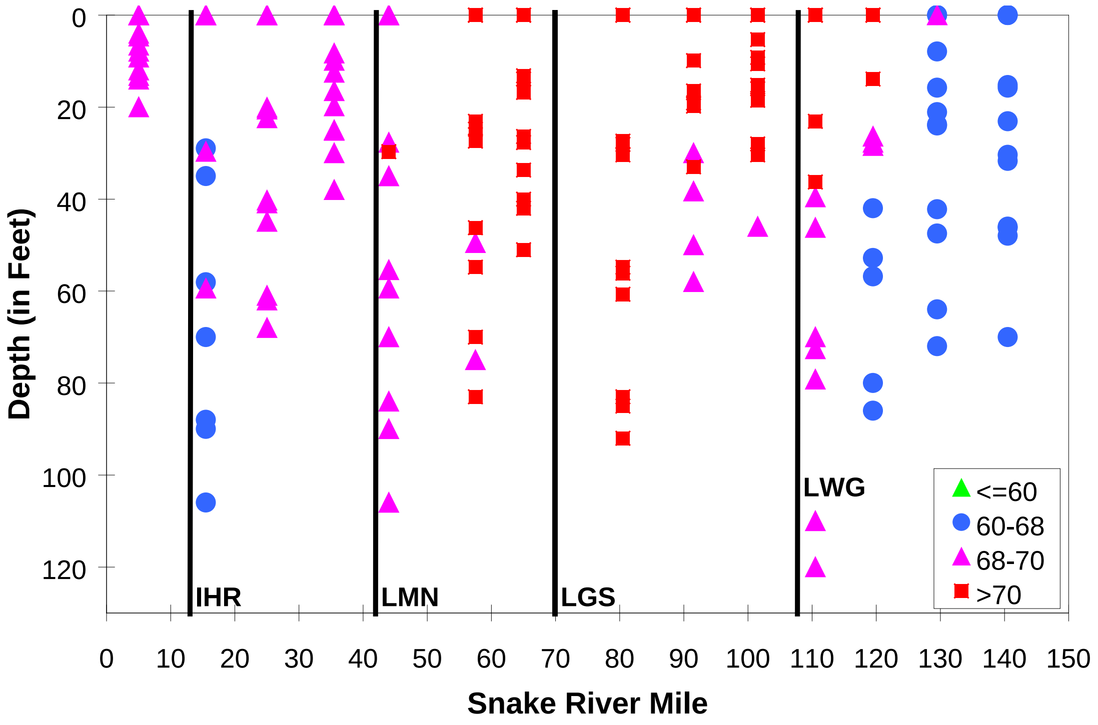
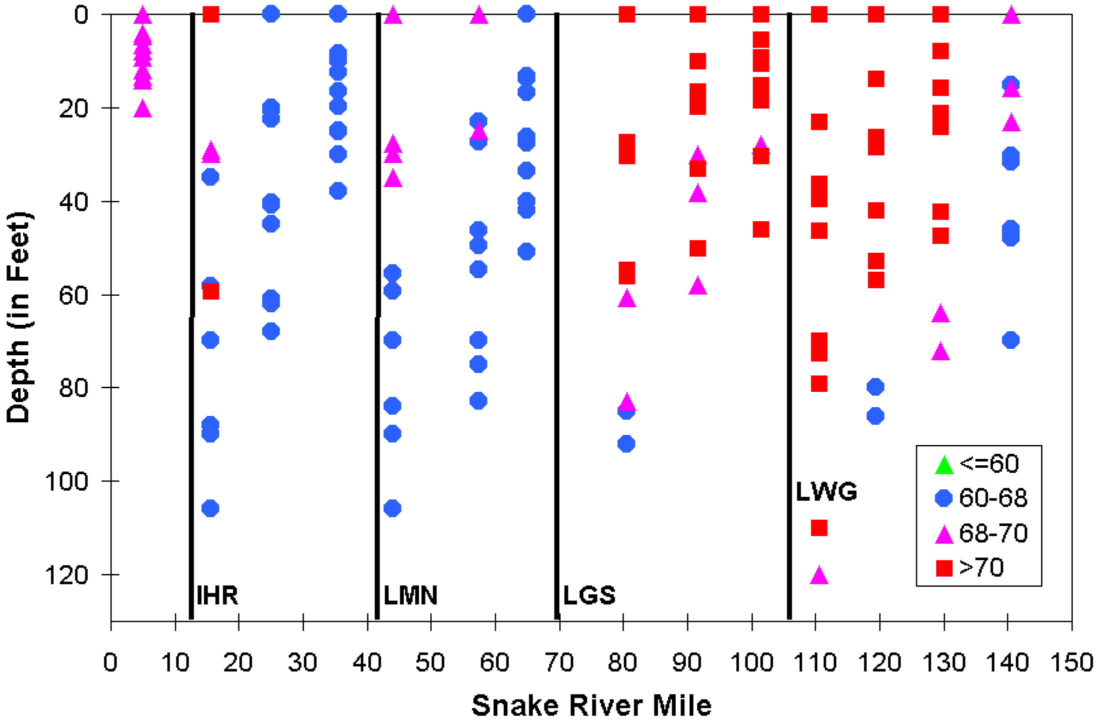
60
80
100
120
IHR
LMN
LGS
LWG
▲ <=60
● 60-68
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
Snake River Mile

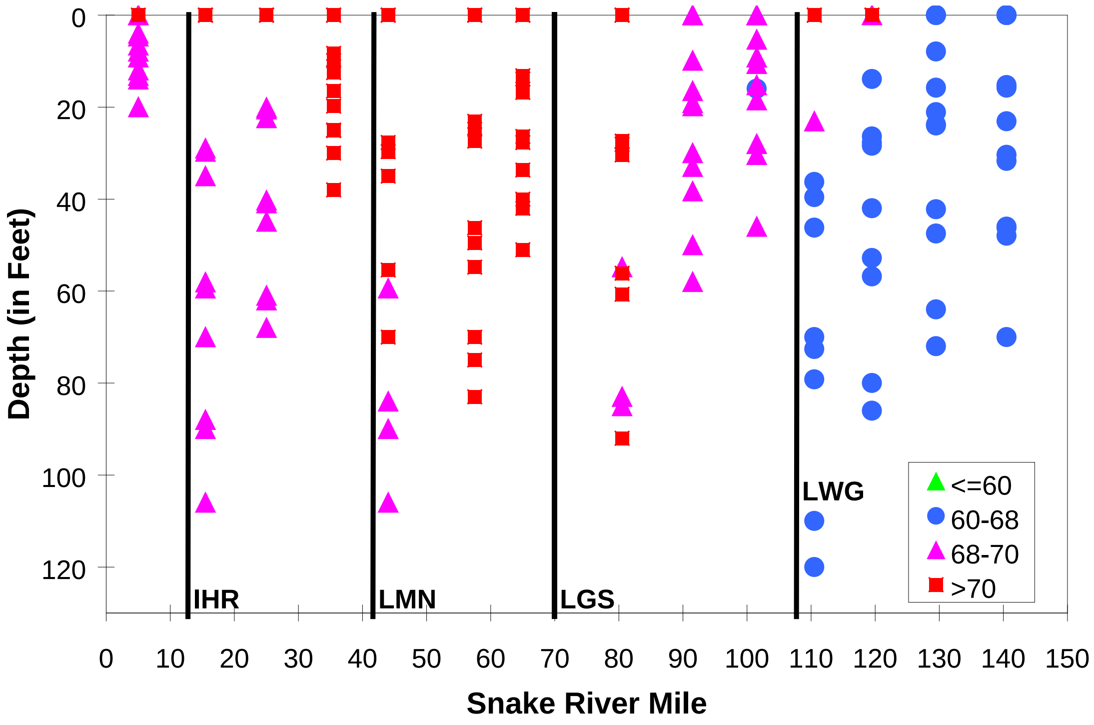
July 1, 1992



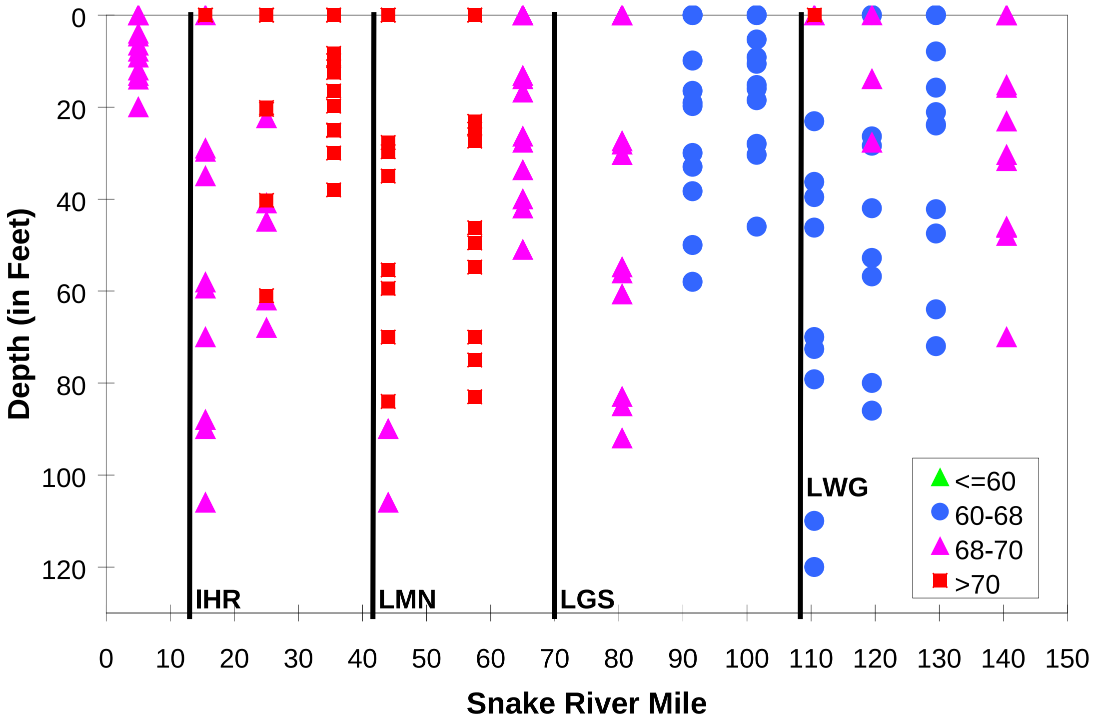
July 7, 1992



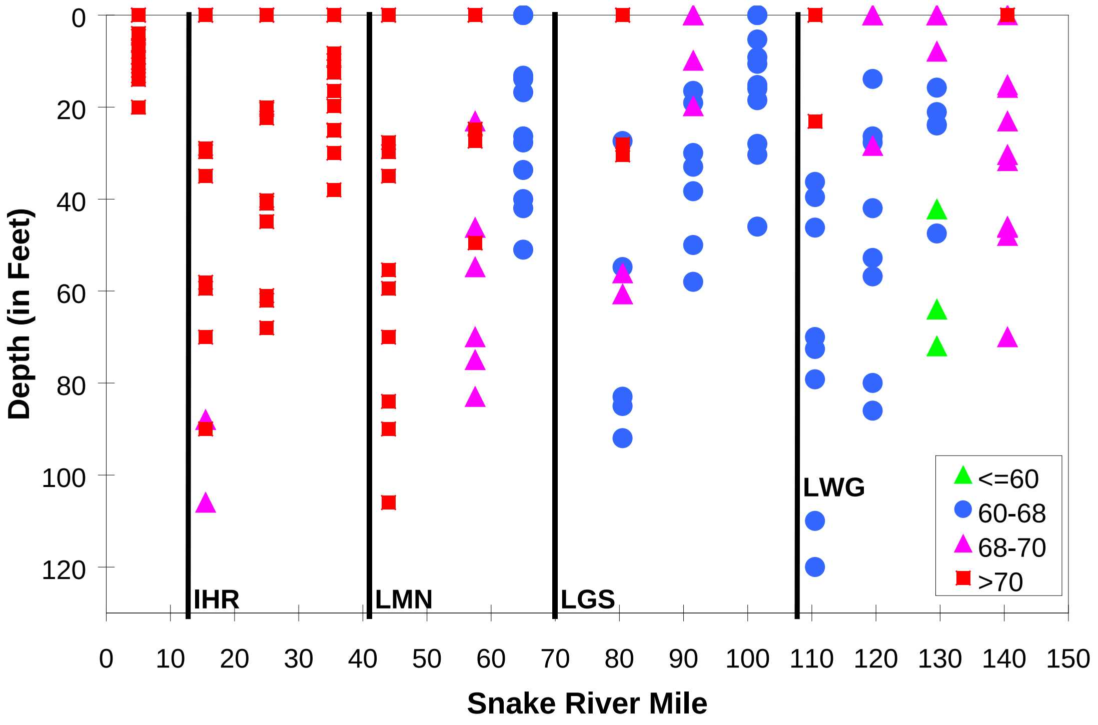
July 9, 1992



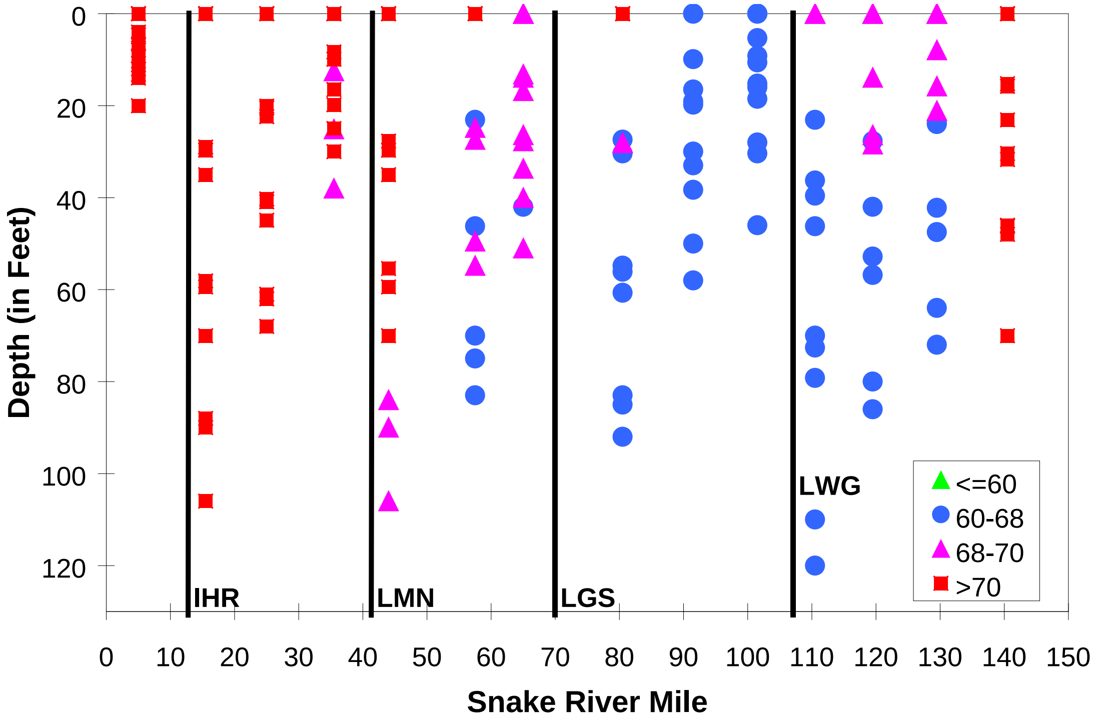
July 11, 1992



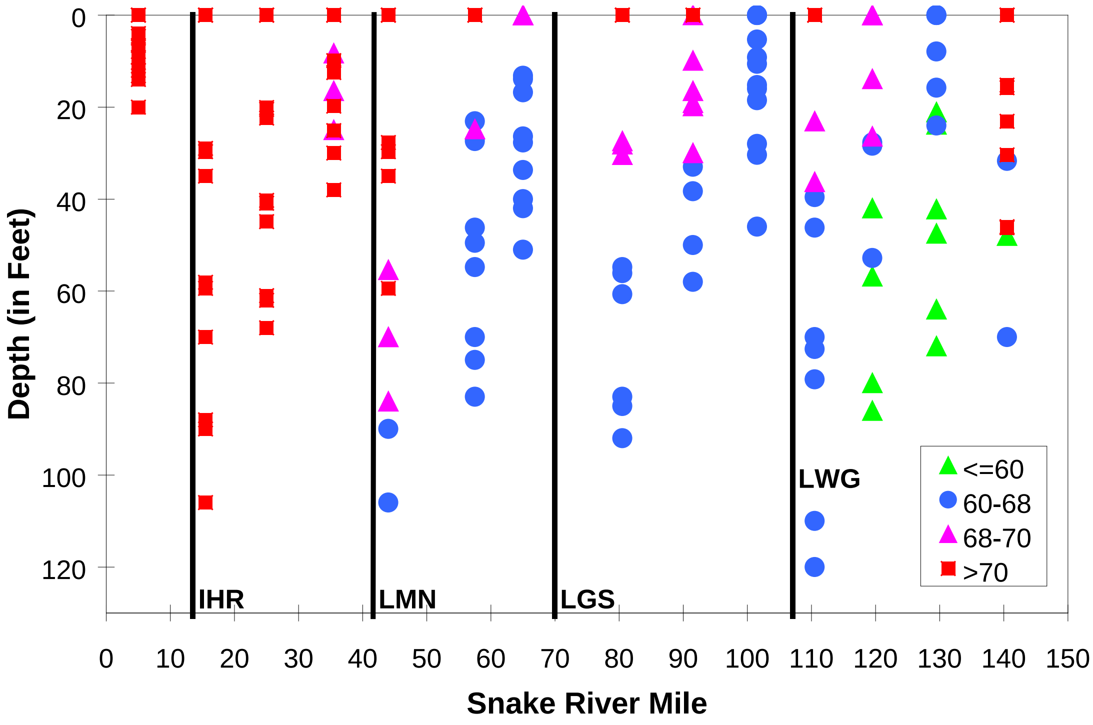
July 13, 1992



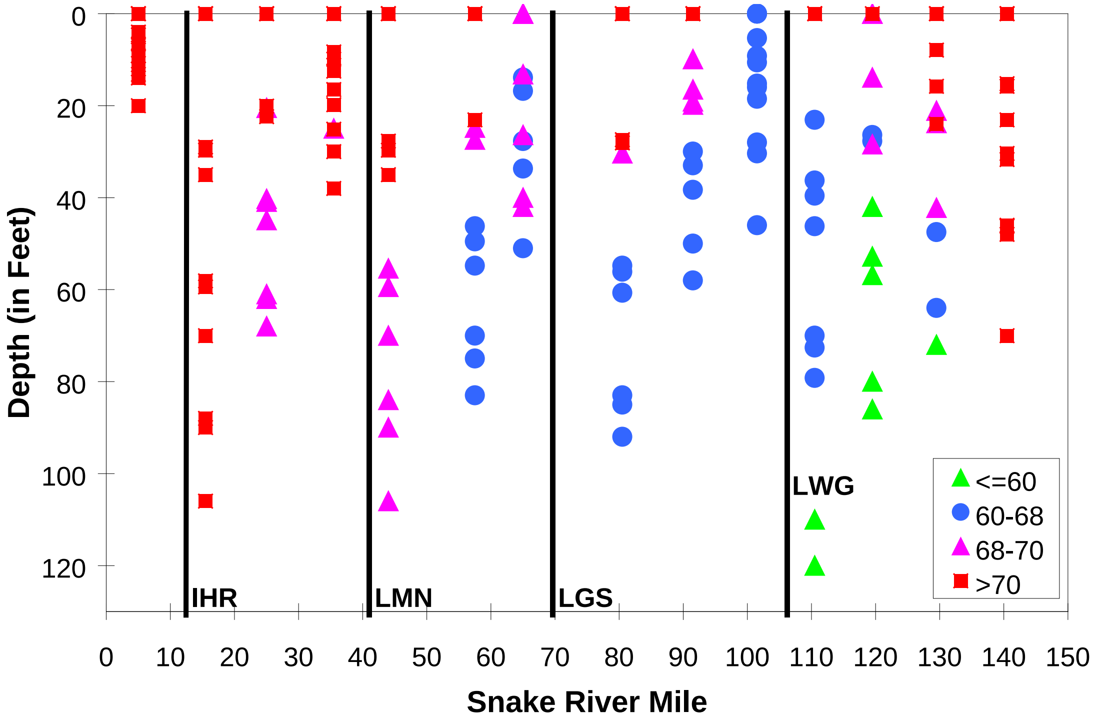
July 16, 1992

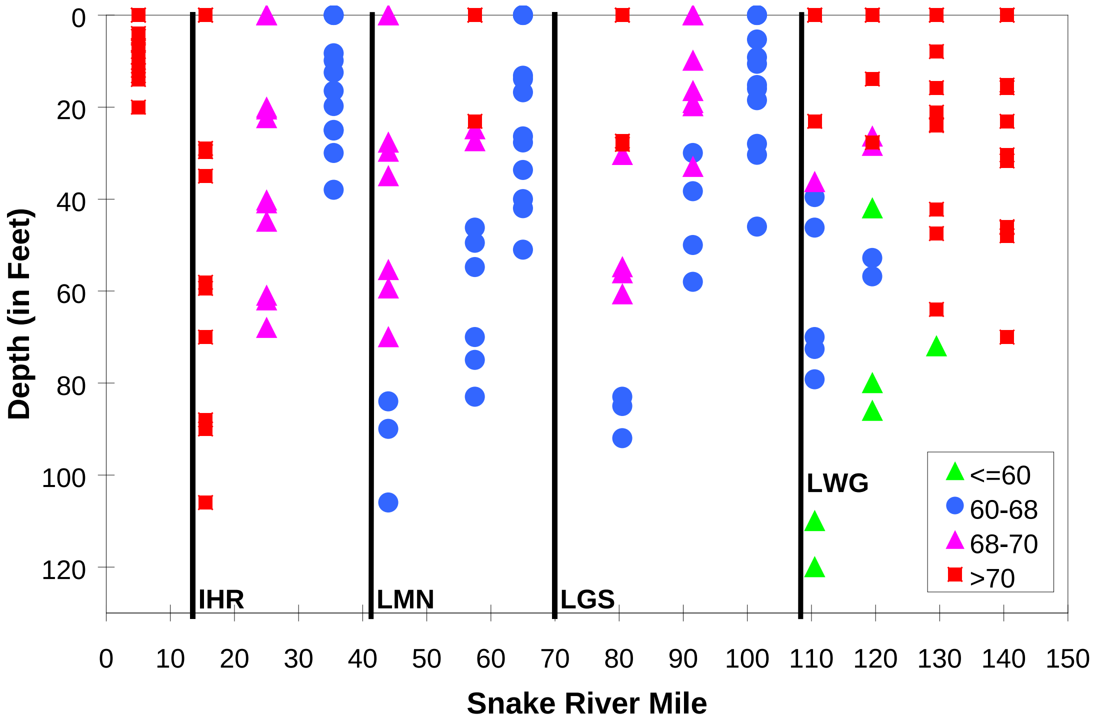


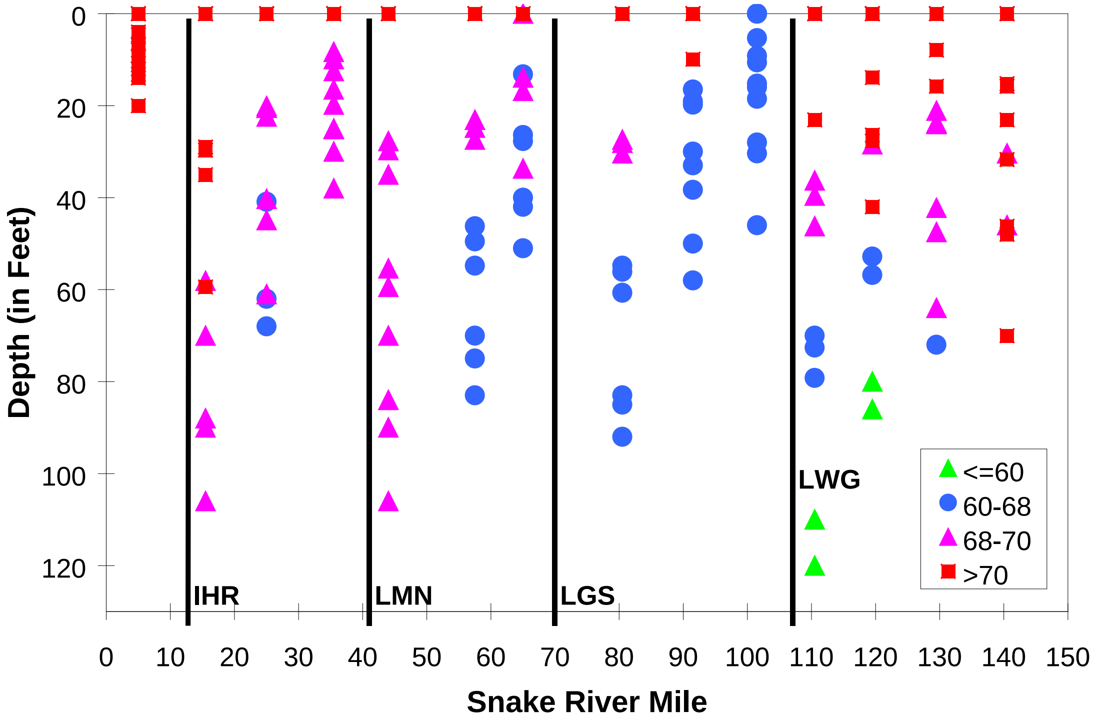
July 18, 1992



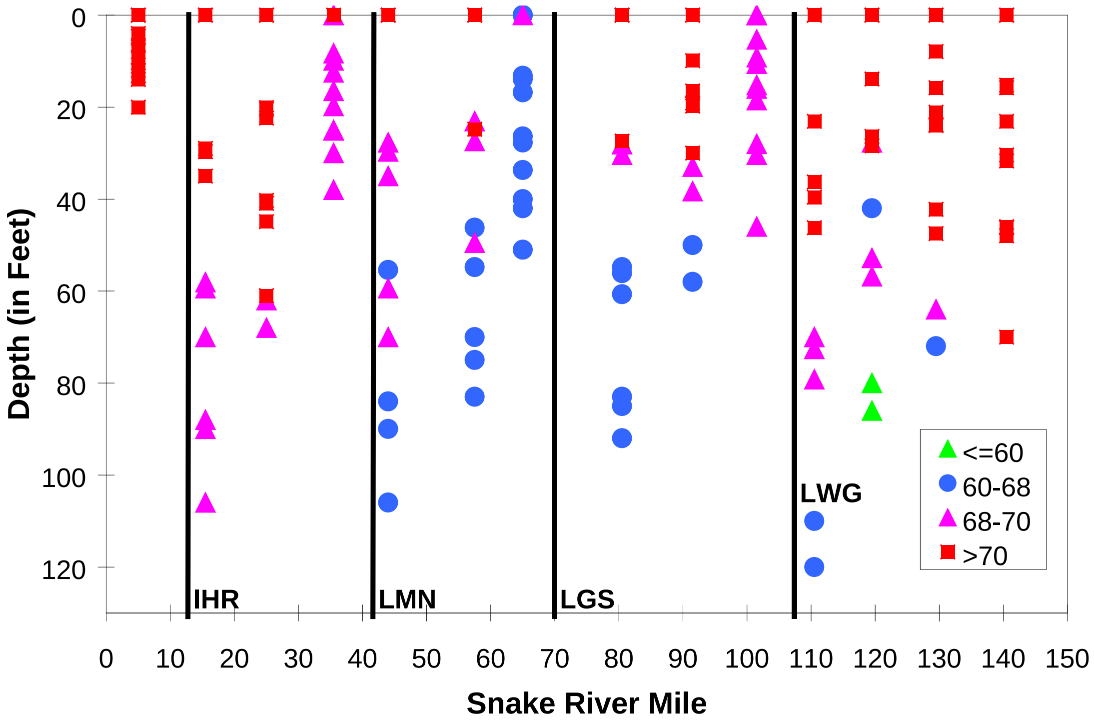
July 21, 1992



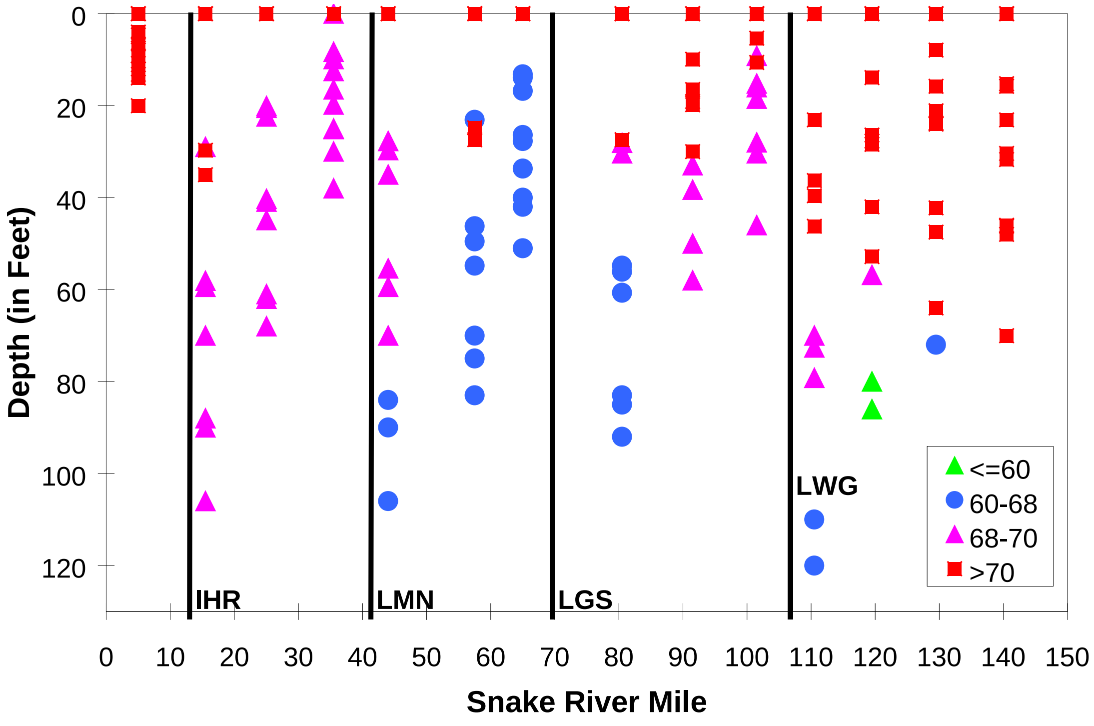

July 23, 1992


July 25, 1992

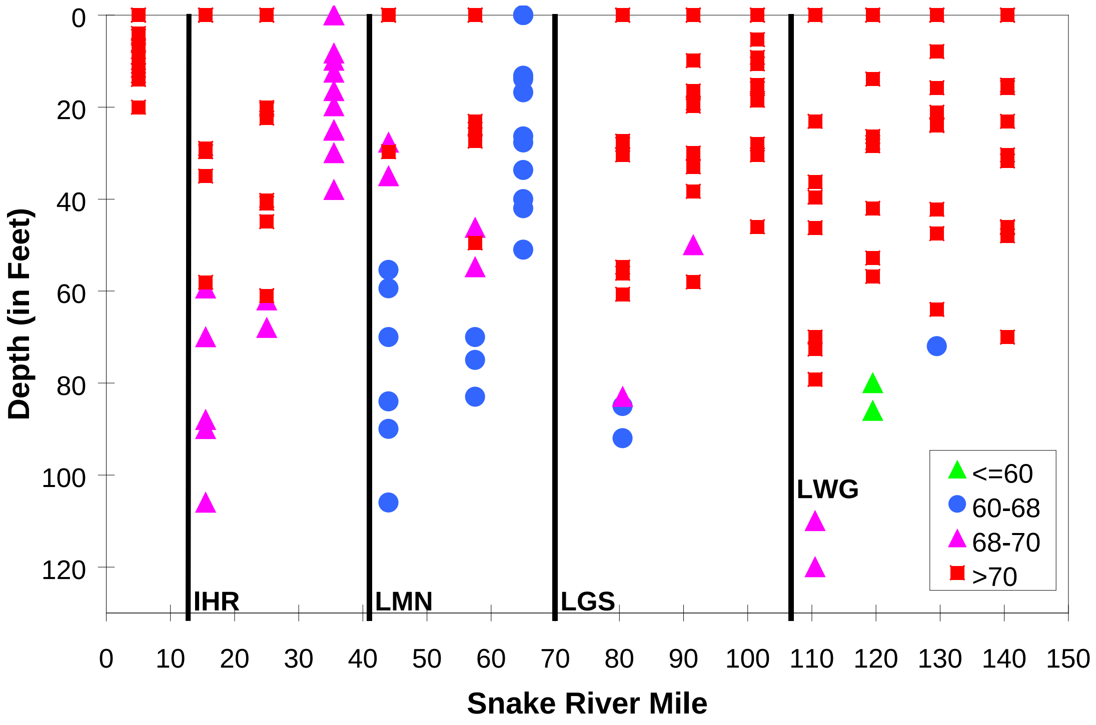
July 28, 1992



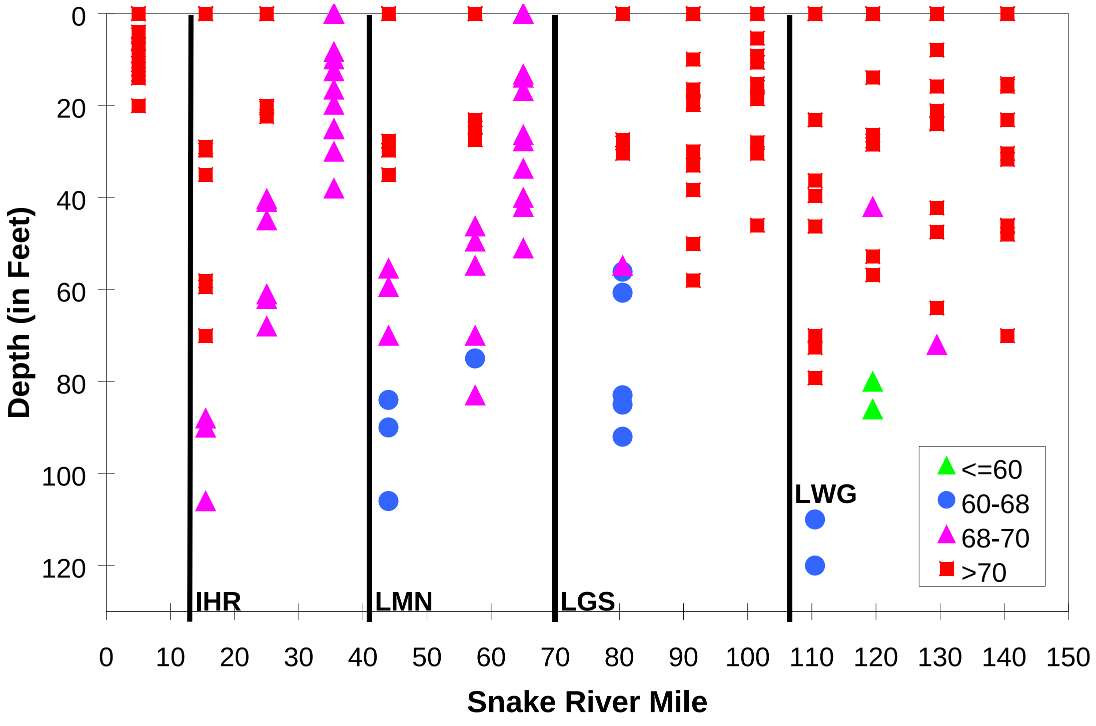
July 30, 1992



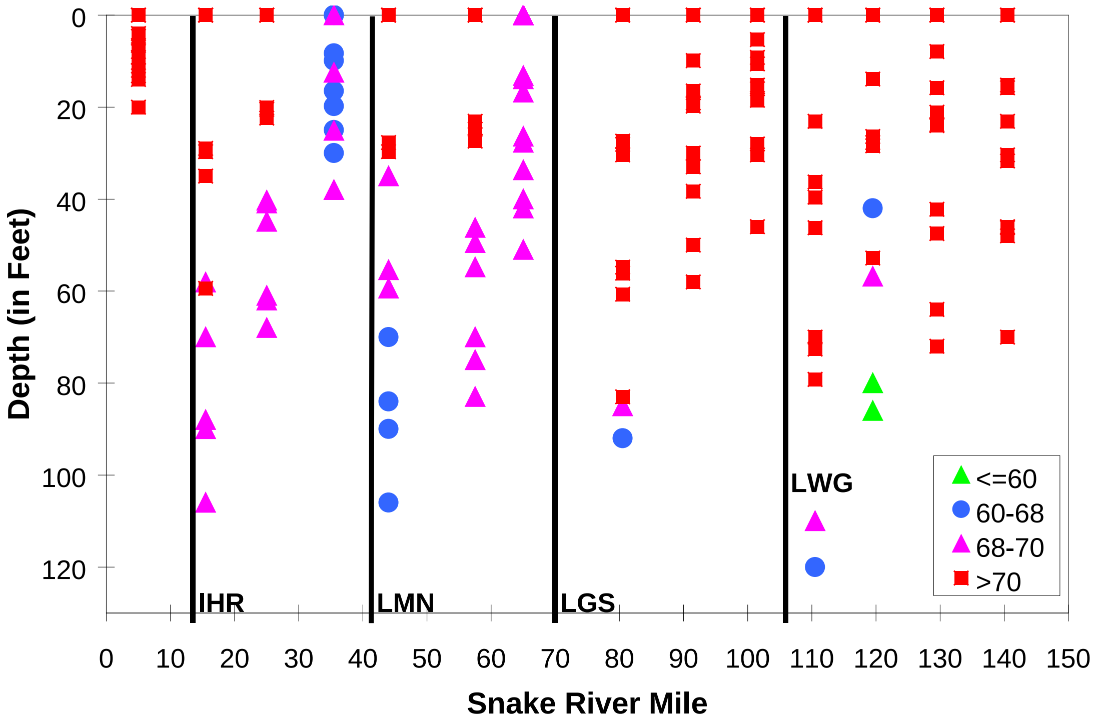
August 1, 1992



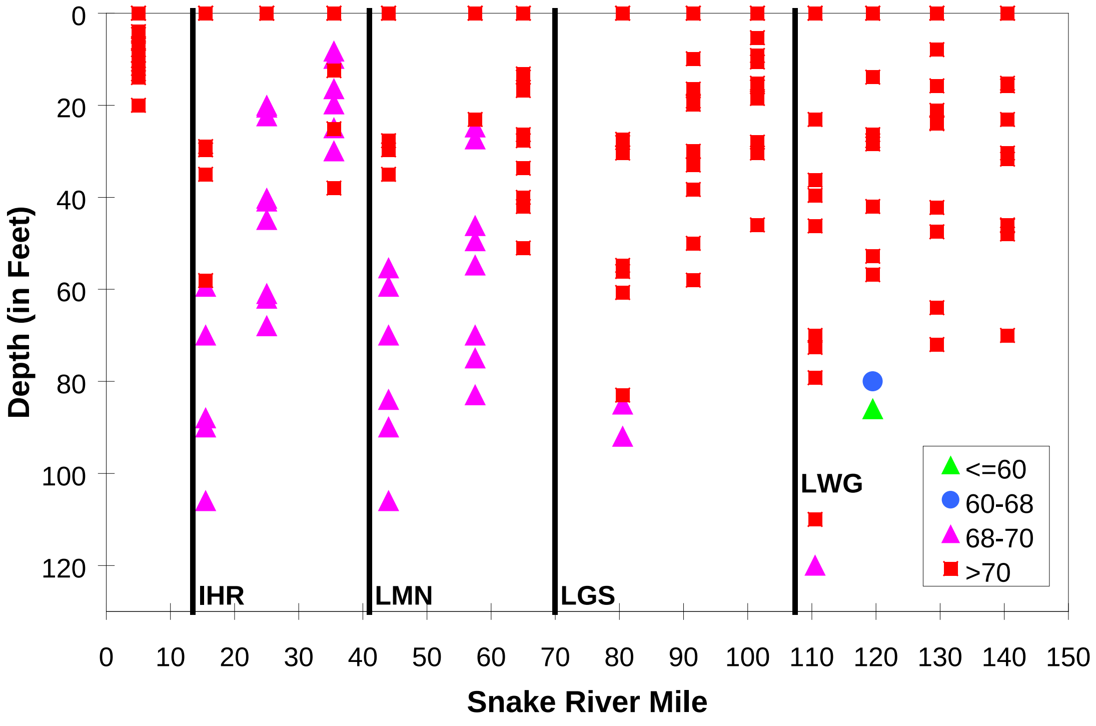
August 4, 1992



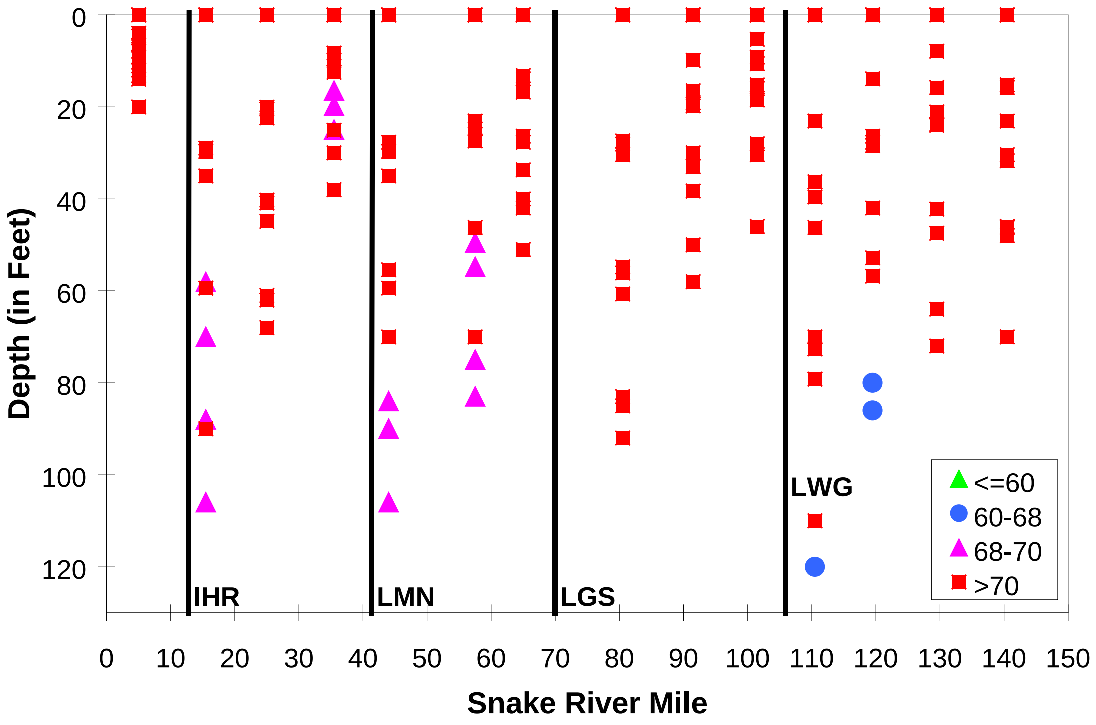
August 6, 1992



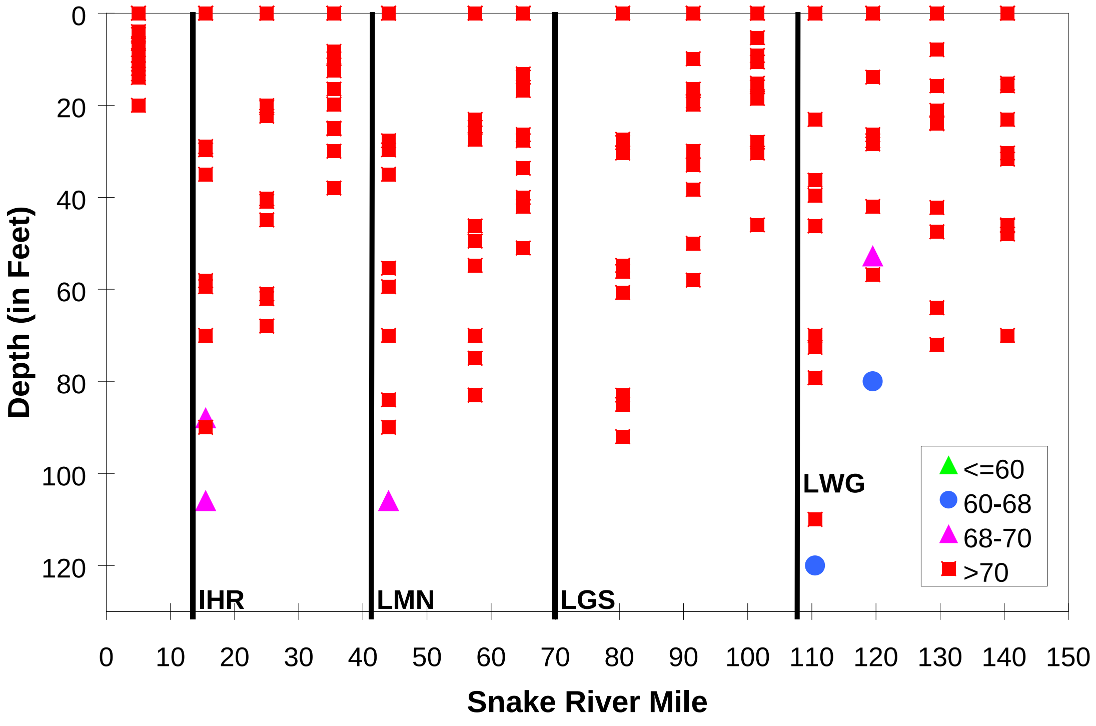
August 10, 1992



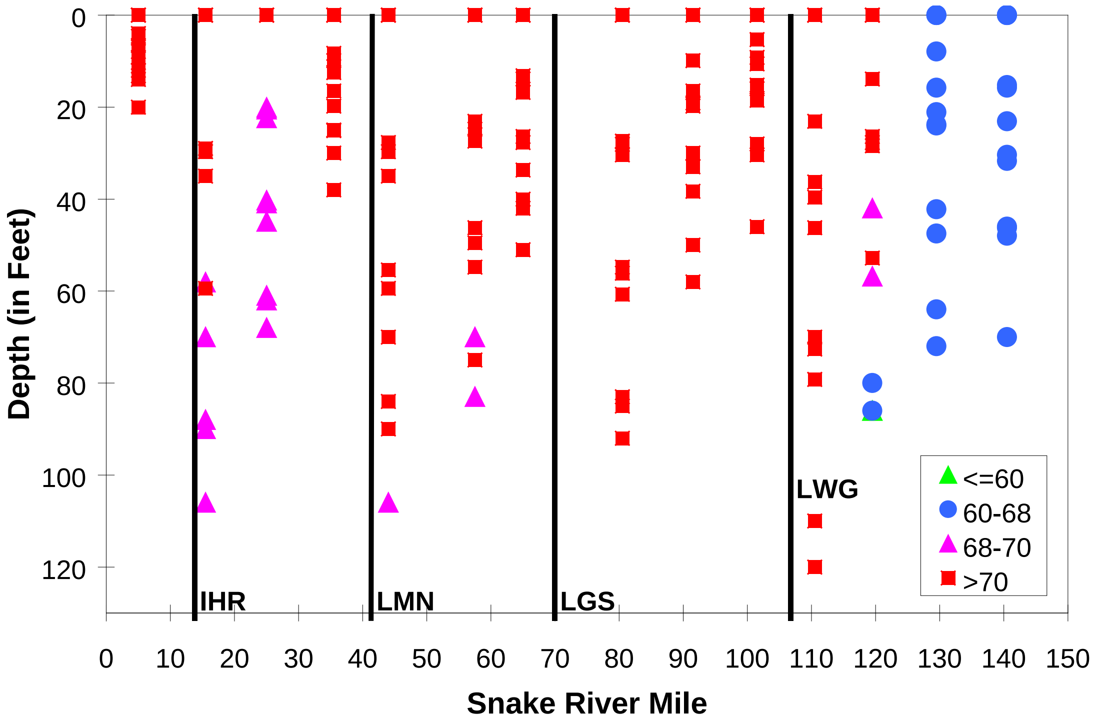
August 17, 1992



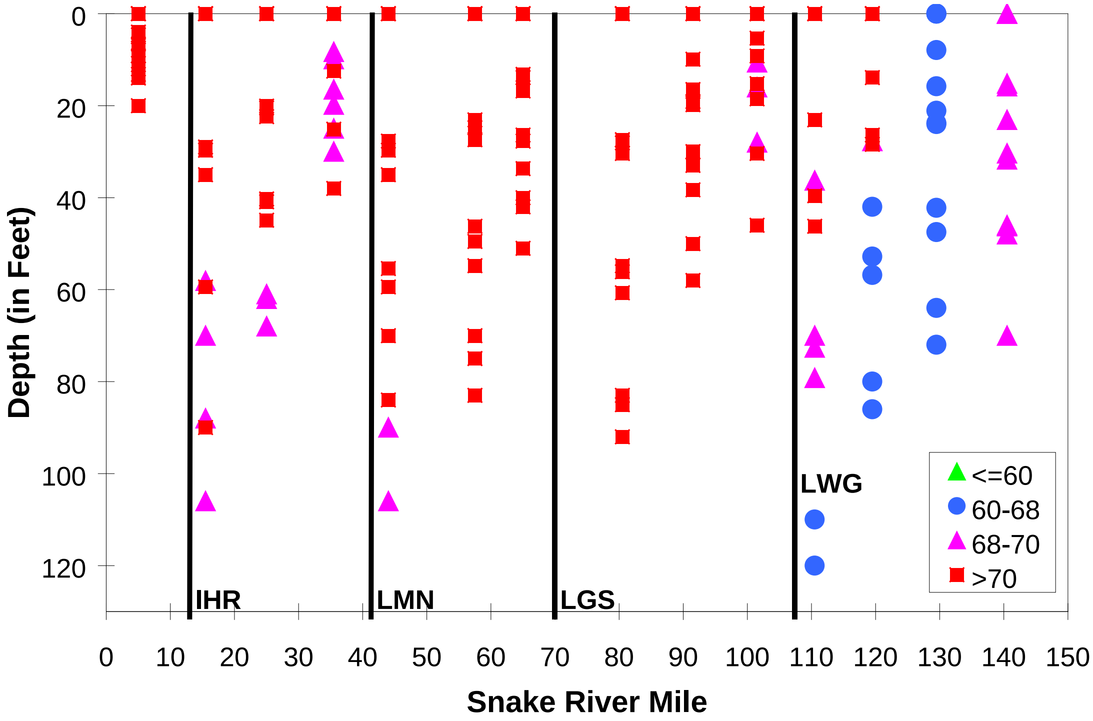
August 19, 1992

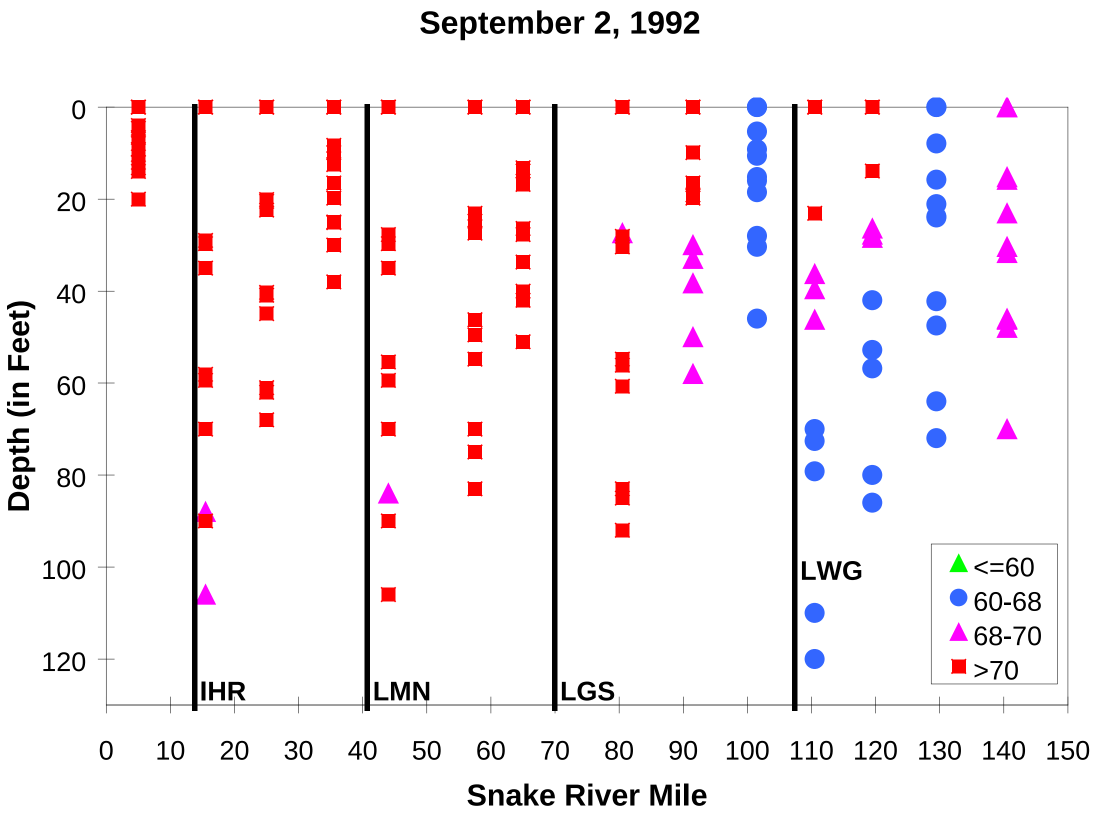


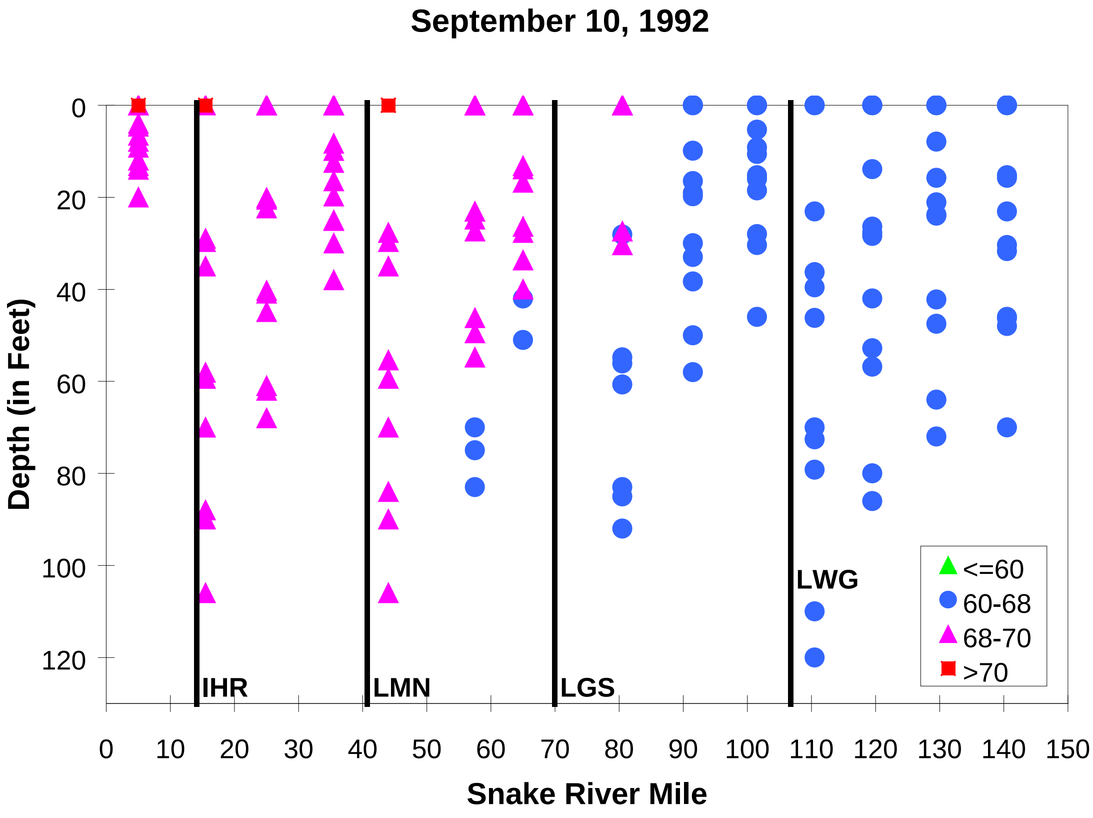
August 25, 1992



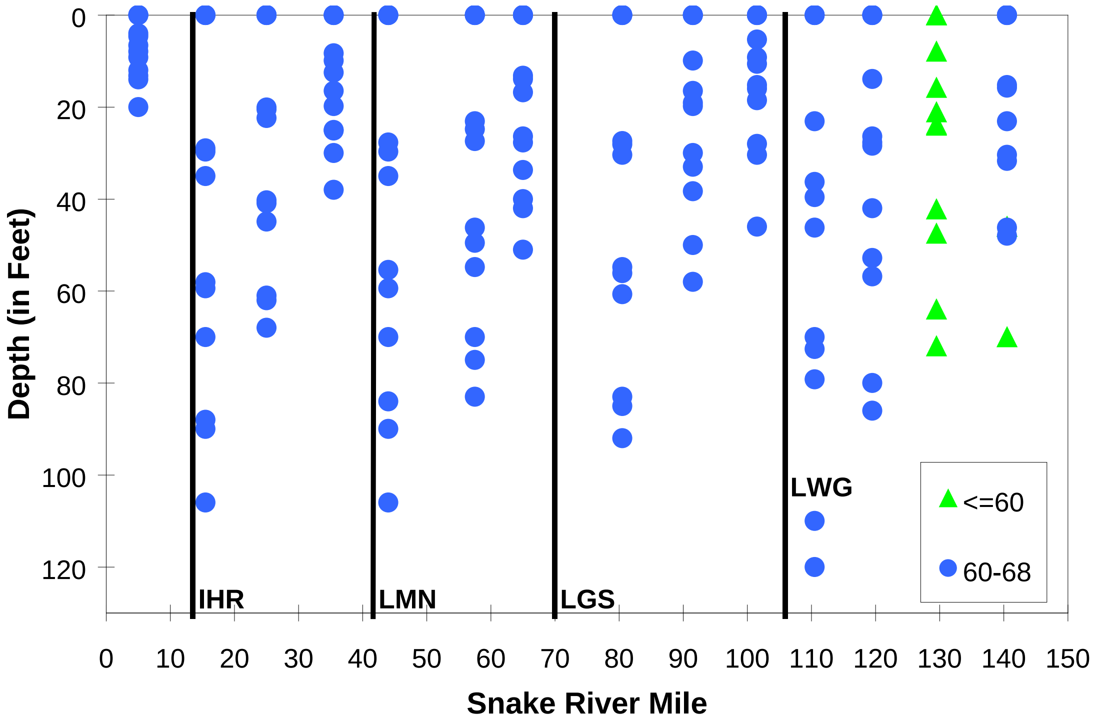
August 29, 1992



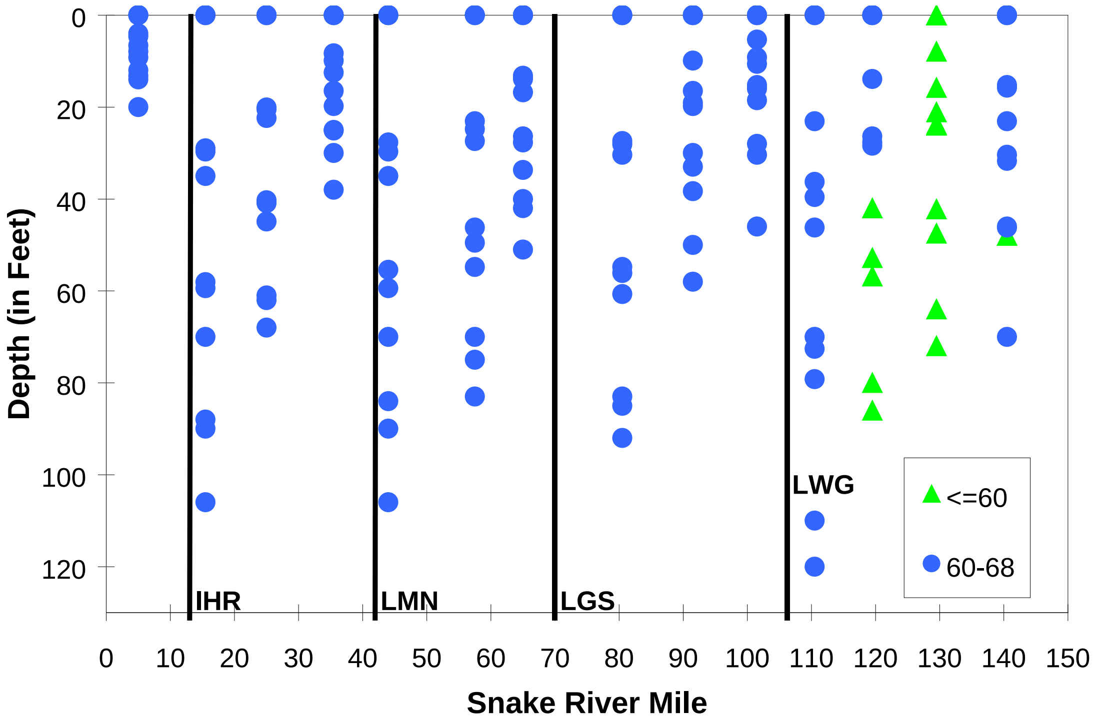

September 2, 1992


September 10, 1992

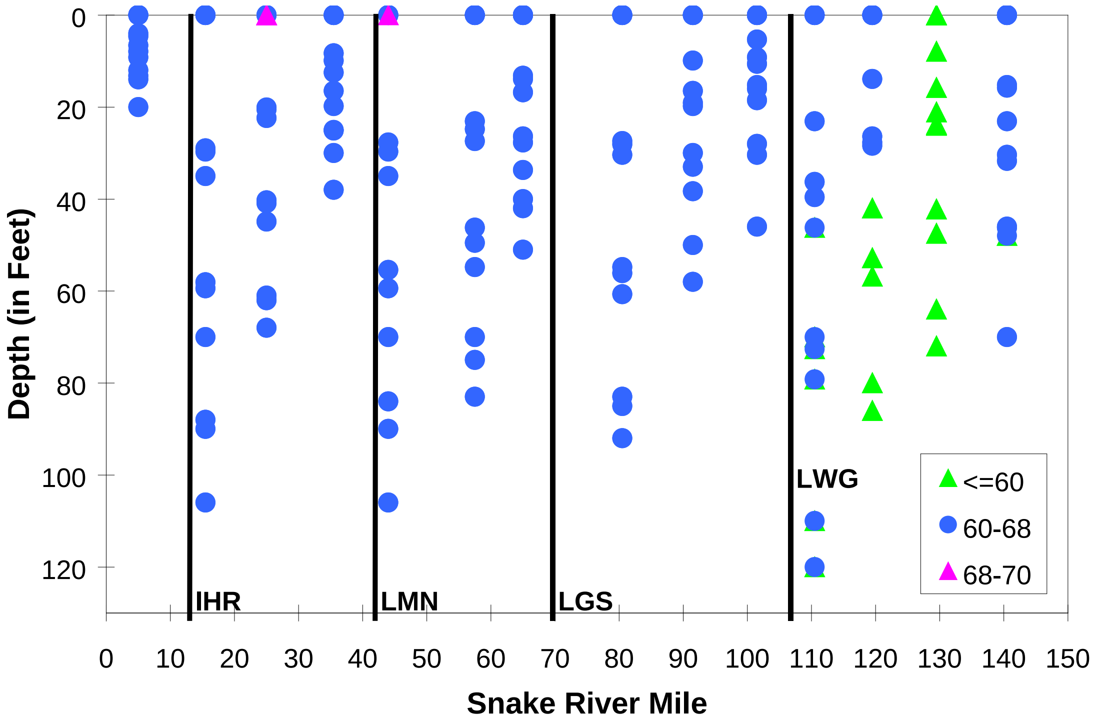
September 12, 1992



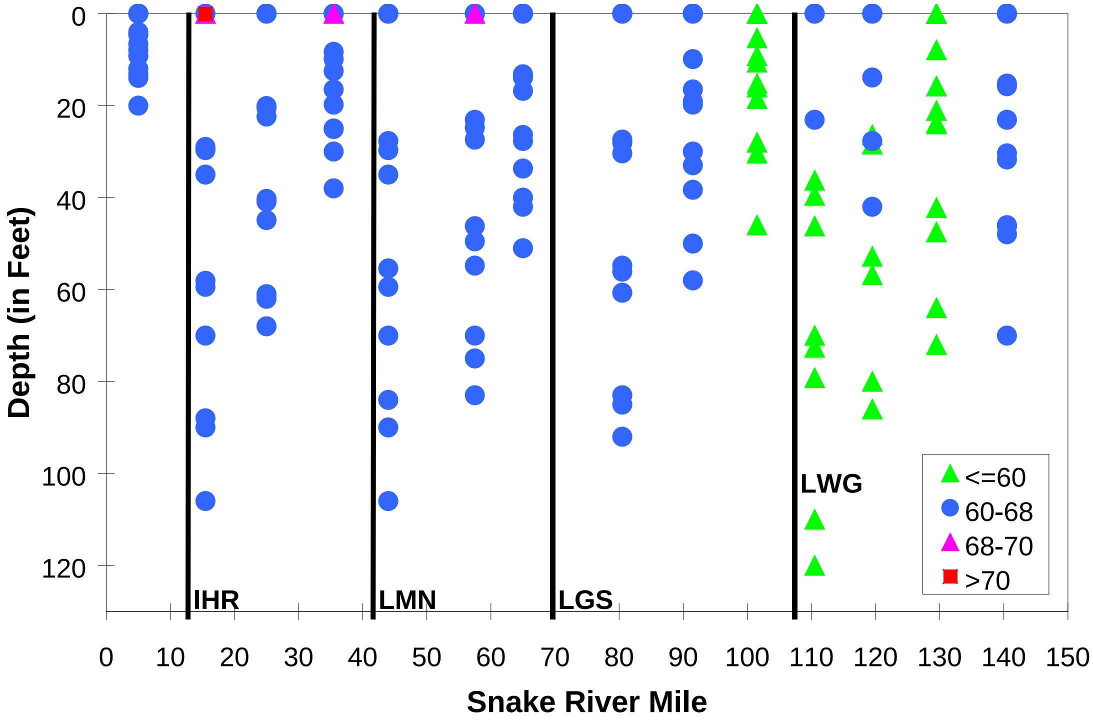
September 14, 1992



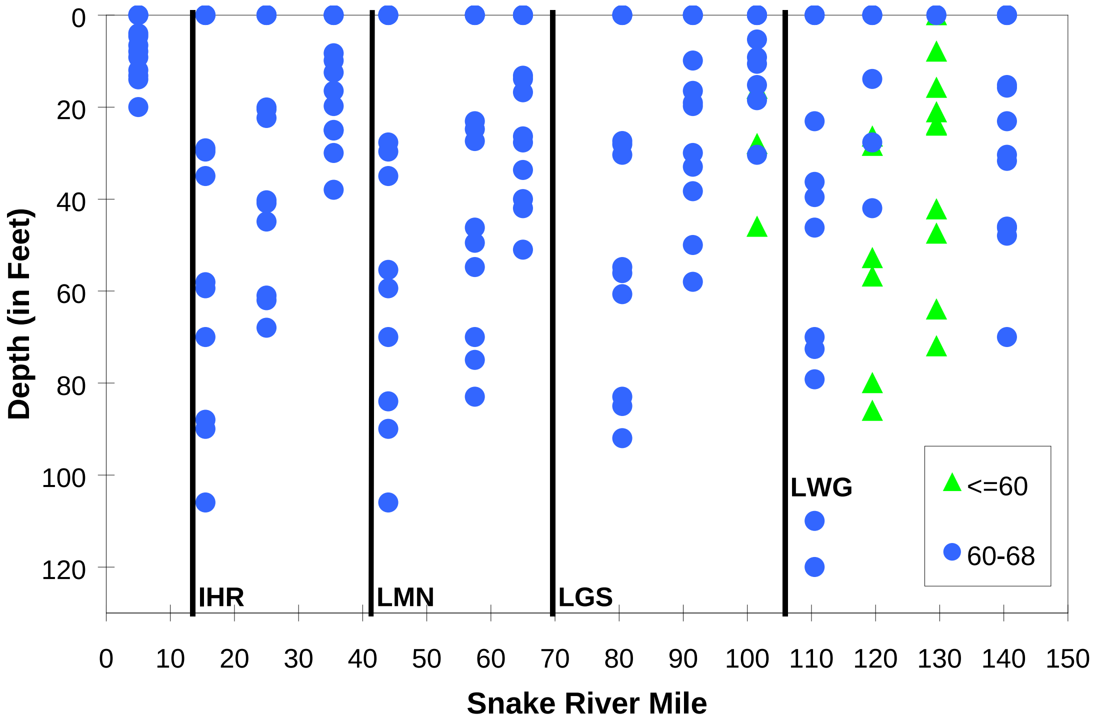
September 16, 1992



September 20, 1992



September 25, 1992



October 7, 1992