The Influence of In-stream Habitat Characteristics on Chinook Salmon (*Oncorhynchus tshawytscha*)

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Summary of Findings

Influence of fine sediment in spawning gravel on Chinook salmon:

- High levels of fine sediments in stream bed substrate can limit Chinook egg survival.
- Fine sediment loads can reduce inter-gravel water flow which reduces dissolved oxygen and limits embryo survival.

Influence of suspended solids on Chinook salmon:

- Chlorinated and aromatic organic solids can increase mortality.
- High levels of organic solids can result in sub-lethal physiological responses.
- High levels of inorganic solids can result in fine sediment deposition in spawning gravel.

Influence of downed woody debris on Chinook salmon:

- Woody debris can provide refugia from predators and high stream velocities.
- Woody debris, and other cover, is most beneficial during early stages of development and at low temperatures.

Influence of water temperature on Chinook salmon spawning and egg incubation:

- Upstream migration will cease if temperatures are below 3.3 ˚C or above 20 ˚C.
- The majority of spawning occurs between 6 ˚C and 15 ˚C.
- The optimal temperature range for egg survival is 8 ˚C to 12 ˚C.
- The optimal temperature range for development to the alevin (larval stage after hatching before yolk absorption) stage is 4 ˚C to 8 ˚C.

Influence of water temperature on smoltification by Chinook salmon:

- Water temperature above 14 ˚C and below 7 ˚C can cause mortality in fry.
- High (sub-lethal) water temperature accelerates growth of fry, but can also result in increased susceptibility to disease.
- High temperatures can lead to early seaward emigration by influencing physiology.
- Low temperature can act as a behavioral cue to initiate seaward migration.

Influence of dissolved oxygen on Chinook salmon:

- Dissolved oxygen concentrations below 2.5 mg/L can increase egg mortality.
- Juveniles will avoid water with dissolved oxygen concentrations as high as 4.5 mg/L.
- Adults will not migrate through water with dissolved oxygen concentrations below 3.4 mg/L.
- Dissolved oxygen content is inversely related to water temperature.

Influence of stream flow on Chinook salmon:

- Adults can not migrate to spawning streams if the streams contain insufficient water.
- High temperatures associated with low flows can increase mortality.
- Low dissolved oxygen content, resulting from low flows and high water temperature, can increase mortality.
- Low flowing streams remove less waste products from redds (egg nests) and increase egg and alevin mortality.
- Eggs can become desiccated or frozen if a stream is dewatered.
- Spawning habitat can be degraded in streams without naturally occurring peak flow events.
- Low flowing streams are more susceptible to changes in water temperature.

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Introduction:

Endangered Species Act and Chinook Salmon Recovery Planning:

On March 24, 1999 the Puget Sound evolutionary significant unit (ESU) of Chinook salmon (*Oncorhynchus tshawytscha*) was listed as a threatened species[1] by the National Marine Fisheries Service (NMFS). This ESU includes all naturally spawning populations of Chinook salmon in rivers and streams that flow into the Puget Sound[2]. Under threatened status listing NMFS is obligated to review all actions that might harm Chinook salmon. The Puget Sound Technical Recovery Team (TRT), an independent scientific body, was convened by the NMFS to develop technical delisting criteria and guidance for salmon recovery planning in the Puget Sound region. One goal of the TRT is to "Identify factors for decline and limiting factors." of Chinook salmon in the Puget Sound region[3]. Ongoing review of scientific information is being conducted to support this goal.

Role of Science in Recovery Planning:

Habitat degradation, harvests of fish, fish hatcheries and hydropower development are the primary causes of Pacific salmon decline (Anonymous 2002). A scientific understanding of these processes and their affect on Chinook salmon is a necessary step in any restoration planning. The scientific method has been developed to disprove hypotheses and can not be used to unequivocally "prove" relationships. Caution should be used to avoid recklessly extrapolating scientific findings from the temporal and spatial context from which they were derived. Measurement error and stochastic factors limit the ability of scientific theories to model ecosystem scale processes. None the less postulates that are supported by scientific data can provide valuable insights into the realities that the postulates attempt to describe. Scientific insights can be used most effectively for restoration when considered in conjunction with anecdotal observations of immeasurable processes, economic limitations and political realities.

Purpose and Organization of This Document:

This document seeks to summarize scientific research into many in-stream habitat factors that may limit the survival and abundance of Chinook salmon (Scheuerell and Ruckelshaus, personal communication) in non-technical language. Immediately following this introduction are summaries detailing the documented affects of in-stream habitat factors on Chinook salmon. The habitat features examined are:

- Section 1. Fine sediment in spawning gravel.
- Section 2. Suspended solids.
- Section 3. Woody debris.
- Section 4. Water temperature during spawning and egg incubation.
- Section 5. Water temperature during smoltification.
- Section 6. Dissolved oxygen.
- Section 7. Stream flow.

Appendices 1-7 are matrices detailing the relationships found in scientific literature between in-stream habitat characteristics and Chinook salmon responses. Appendices 8-11 summarize data on the relationship between in-stream habitat characteristics and survival of Chinook salmon at various life stages.

[1] A threatened species is defined as one that is likely to become endangered in the foreseeable future.
[2] An Evolutionary Significant Unit (ESU) is a distinctive group of Pacific salmon, steelhead, or sea-run cutthroat trout (www.nmfs.noaa.gov/).
[3] From Puget Sound Salmon Forum (http://www.sharedsalmonstrategy.org/organization.htm).

Section 1. Fine Sediment and Spawning Substrate

General information on fine sediment in spawning substrate

Chinook salmon prefer to spawn in the largest spawning gravel of any Pacific wild salmon. The preferred gravel ranges from 2.6 cm – 7.5 cm in diameter (Groves & Chandler 1999). During the process of redd[4] excavation Chinook females lift fine sediment[5] from the redd stream bed and the sediment drifts downstream with the current. Moving larger gravel is accomplished by repeated flexing of the females body near the stream bed. A large female Chinook may construct a nest that is 1 m long and 46 cm deep (Busch 2000). This process of excavation results in a redd that contains less fine silt and sand than the surrounding substrate (Chapman 1988). After the female has laid eggs in the redd pocket, and a male has fertilized them, she uses her tail to cover the eggs with gravel. Fine sediments, suspended in the stream water, now begin to settle into the redd pocket by gravitational forces.

Fine sediment can reduce the survival rate of embryos, in a redd, through two mechanisms. Fine sediments can entomb eggs by moving between gravel voids and settling to the bottom of a redd. Fine sediments can also settle into the surface gravel voids, sealing the egg pocket (Beschta & Jackson 1979). Both scenarios will result in a reduced flow of water around the developing embryos. Developing embryos require sufficient inter-gravel water flow to complete their development from egg to alevin[6]. Flowing water supplies the embryos with dissolved oxygen and removes waste products. Alevins also require sufficient inter-gravel water flow until they absorb their yolk and emerge as fry from the substrate. Fry reared in hypoxic conditions tend to be smaller and do not compete successfully with larger fry (Chapman 1988).

Fine sediment and egg survival

The percentage of fine sediment alone may not be the best predictor or embryo survival. Tappel and Bjornn (1983) demonstrated that the relative proportions of substrate particle sizes, not exclusively the quantity of fine sediment, can influence the survival of Chinook embryos. They found that the relationship between Chinook embryo survival and sediment size could best be predicted by the following equation:

$$\textbf{Percent Survival} = 93.4 - 0.1116\, S_{9.5}S_{0.85} + 3.87\, S_{0.85}$$

where;
$S_{9.5}$ = the relative proportion of sediment less than 9.5 mm in diameter
$S_{0.85}$ = the relative proportion of sediment less than 0.85 mm in diameter

This equation was able to explain 93 % of the variability in embryo survival. Figure 1 displays the overall relationship between the percentage of sediment less than 9.5 mm in diameter and survival of Chinook embryos. Reiser and White (1988) also found that Chinook egg survival was inversely related to the percentage of fine sediment in spawning substrate. They investigated the influence of two sizes of sediment on egg survival. Sediments were defined as fine if less than 0.84 mm in diameter and coarse if between 0.84 mm and 4.6

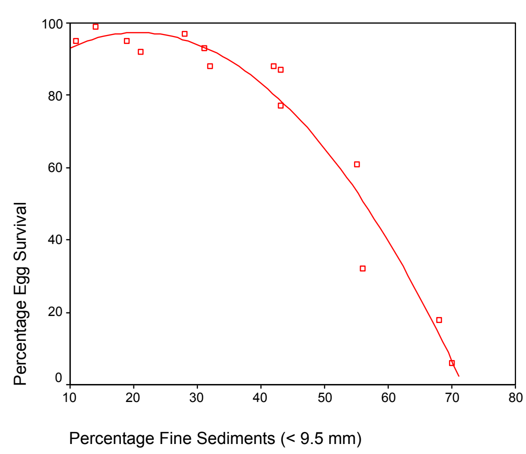

Figure 1. **The relationship between % fine sediments and survival of Chinook eggs (Tappel & Bjornn 1983).**

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[4] A redd is a egg nest excavated into the stream bed by spawning female salmon.
[5] Fine sediment usually includes particles smaller than 6 mm in diameter (Chapman 1988).
[6] The alevin live stage is after egg hatch but before complete yolk absorption.

mm in diameter. They found that no eggs survived when fine sediments made up 50 % of the substrate mixture. Figure 2 displays the relationship between egg survival and the percentage of fine and coarse sediment in the spawning substrate. Chinook egg survival was also positively related to inter-gravel water velocity[7]. Their research could not demonstrate a definitive relationship between the size and composition of sediments and quality of alevins or fry.

Raleigh et al. (1986) developed a suitability index curve for survival of Chinook egg challenged with fine sediments of different size classes. Suitability index curves were based on a combination of professional judgment, literature and field data. A suitability index score of 1 indicates perfect suitability of the habitat. Figure 3 displays the suitability index curves for fine sediment less than or equal to 0.8 mm and for fine sediments greater than 0.8 mm.

Fronde numbers can be used to predict the likelihood of sediments settling into stream bed substrate and redds. Low Fronde numbers (Fr < 0.9) can result in rapid sealing of the upper 5 cm of gravel substrates. Higher Fronde numbers (Fr > 0.9) change the flow dynamics and cause deposition to occur within the upper 5-10 cm of substrate gravels (Beschta & Jackson 1979). The Fronde equation is defined as:

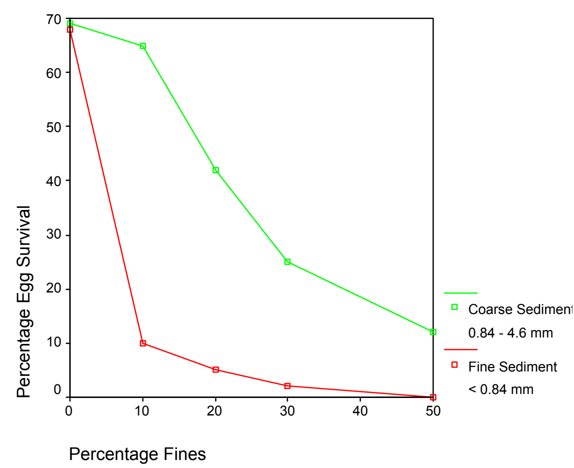

Figure 2. **Percentage fines and survival of Chinook eggs from Reiser & White 1988.**

$$\mathbf{F_r} = \sqrt{\frac{\overline{V}^2}{gy}}$$

where: $\overline{V}$ = mean velocity, m/s, g = acceleration due to gravity (9.8 m/s^2), y = depth of flow, m

This Fronde equation may be used to estimate the intrusion of sediments into redd gravel and the percentage egg survival may then be inferred.

Conclusions

The general relationships between sediment loads, inter-gravel water flow, dissolved oxygen and egg survival are clear. Fine sediment loads can reduce inter-gravel water flow which limits dissolved oxygen and Chinook embryo survival. Lack of empirical research into the influence of fine sediments on Chinook eggs, however is a gap in the scientific understanding of the precise quantities and sizes of fine sediment that can significantly reduce embryo survival. None the less it has been demonstrated that fine sediments in stream bed substrate can limit Chinook egg survival (Tappel and Bjornn 1983, Reiser and White 1988).

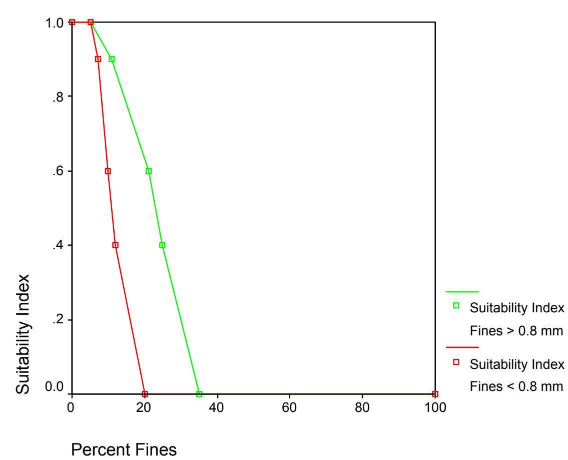

Figure 3. **Suitability index curves for Chinook eggs challenged with fine sediment; data from Raleigh et al. 1986.**

[7] Correlation coefficient of 0.797 (Reiser and White 1988)

Section 2. The Influence of Suspended Sediments on Chinook Salmon

General information on suspended sediments

Most Chinook salmon populations are naturally exposed to high levels of suspended sediments during heavy rainfall and spring freshets (Martens and Servizi 1993). Land use changes in watersheds can change historic hydrology and can increase the sediment supply to streams. Few researchers have conducted empirical studies relating Chinook salmon health to suspended sediments. The physical and chemical characteristics of particular sediments supplied to streams, combined with the quantity, will determine their impact on resident Chinook. Some suspended sediments can directly impact Chinook salmon. Suspended solids can also degrade Chinook rearing habitat by altering prey availability.

Inorganic solids

Gills of salmon are susceptible to damage by suspended inorganic solids. The fine structure of gills may be altered by exposure to suspended solids (Martens and Servizi 1993). Intracellular mineral particles have been found in the gills and spleens of Chinook salmon, but these particles have not been definitively linked to mortality (Martens and Servizi 1993). Suspended inorganic solids move downstream and eventually leave suspension and settle to the stream bed.

Suspended solids also have consequences once they settle onto the stream bed substrate. Heavy sedimentation of spawning substrates can limit survival of eggs as well as post embryonic developmental stages. Bjornn et al. (1977) examined the influence of granitic sediments on the habitat and behavior of juvenile Chinook. The wild juveniles were found to actively avoid streams with fully embedded channels (all inter-gravel space full of sediment). When wild Chinook were placed into a test channels they emigrated from fully embedded streams at much higher rates than from a control channel with no sediment. Figure 4 shows the number of fish remaining in control and test channels over a period of eight days.

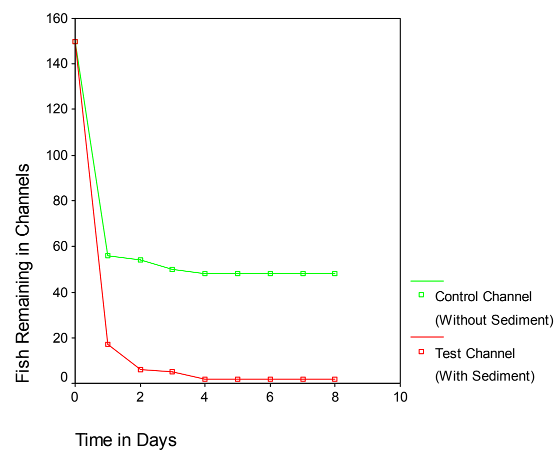

Figure 4. **The time in days that wild age-0 Chinook salmon remained in channels with varied sedimentation levels; recreated from Bjornn et al. 1977.**

Inorganic solids can also influence Chinook salmon indirectly through food web impacts. Bjornn et al. (1977) found that sedimentation of stream beds altered insect population dynamics. Streams with fully embedded stream bed substrate yielded the smallest absolute number of insects per square meter. Stream beds with sedimentation levels of 1/3 to 2/3 had the highest number of insects per square meter, but the relative proportions of species differed.

Organic solids

Organic solids suspended in stream water can influence fish survival and health. Some organic solids such as pulp mill effluent (Eaton et al. 1997), ammonia (Servizi and Gordon 1990), chlorinated compounds and aromatic compounds (Arkoosh et al. 2001) can have lethally toxic effects on Chinook salmon. It should be expected that all of these compounds may also impact Chinook salmon at sub-lethal levels.

Juvenile Chinook exposed to chlorinated and aromatic compounds may have increased susceptibility to pathogens. Arkoosh et al. (2001) found that juvenile Chinook exposed to contaminants associated with urban estuaries in the Puget Sound exhibited an increased susceptibility to mortality caused by a marine pathogen, *Vibriosis anguillarum*. Eaton et al. (1997) documented the effects of pulp mill effluents on juvenile Chinook. They concluded that sub-lethal quantities of effluent led to chromosomal damage of red blood cells. Chromosomal damage to red blood cells can impair oxygen transport functions within the blood stream of fish (Eaton et al. 1997).

Non-toxic organic solids can have indirect impacts on Chinook salmon. Aerobic microbes consume dissolved oxygen as they decompose organic matter. In this way high levels of in-stream organic matter can result in anoxic conditions. The reaction of Chinook salmon to anoxic conditions is discussed in detail in section 3 "Dissolved Oxygen and Chinook salmon".

Conclusions

Few studies have explored the relationship between suspended solids and Chinook salmon survival or health. There is little evidence to support the notion that inorganic suspended solids have direct lethal effects on Chinook, but they can influence the movements of Chinook and the abundance of their food sources. Chlorinated and aromatic organic solids can have direct lethal effects on Chinook at concentrations that vary for the particular compound. High levels of other organic solids can result in anoxic conditions, with resulting sub-lethal responses for all life stages of Chinook salmon.

Section 3. Woody Debris and Chinook Salmon

General information on in-stream woody debris

No direct causal relationship between in-stream woody debris and Chinook salmon survival or health has been found. The correlation found between woody debris and Chinook salmon suggests that in-stream woody debris may enhance habitat for Chinook salmon (Bjornn and Reiser 1991). Woody debris may provide cover from predators and zones of decreased water velocity. Low water velocities allow juveniles access to a larger portion of a stream channel for feeding (Meehan 1991). Studies have found that juvenile Chinook are most abundant in areas with velocity refugia including trees, shoals and the downstream portion of levees (Sommer et al. 2001). The association of juvenile Chinook with in-stream cover varies with season and is the strongest in winter (Allen 2000).

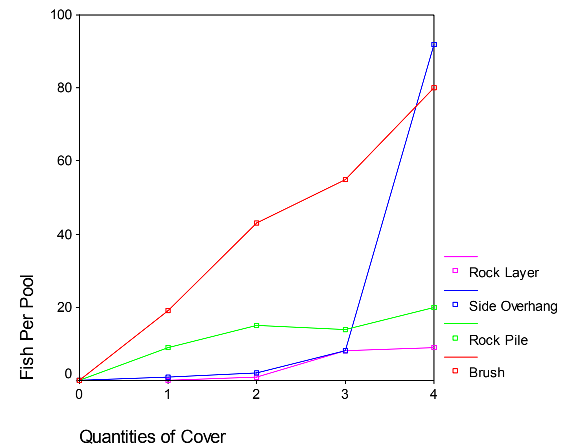

Figure 5. The relationship between quantities of cover and yearling Chinook salmon per pool; recreated from Bjornn & Reiser (1991).

Association of juvenile Chinook salmon and cover

Overhanging vegetation or undercut banks at the sides of streams are preferred habitat for juvenile Chinook. Juvenile Chinook prefer habitat with cover over similar habitat without cover (Richards et al. 1992). Figure 5 displays the relationship found between quantities of cover types and yearling chinook. Both in-stream brush and side overhangs were preferentially selected (Bjornn and Reiser 1991). Raleigh et al. (1986) also found that juvenile chinook preferred woody debris and undercut banks to other in-stream habitat features, as can be seen in Figure 6. Brusven et al. (1986) found similar results when studying the behavior of juvenile Chinook in an experimental channel. They found that on average 82% of the juvenile Chinook preferred covered sections of the channel to uncovered sections throughout the year. The also noticed that the degree of preference for cover types varied with the time of day and the season.

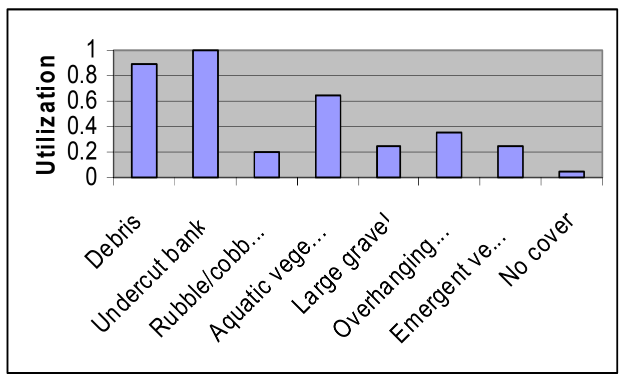

Figure 6. Relationship between cover type and utilization for juvenile Chinook salmon; recreated from Raleigh et al. (1986).

The importance of woody debris and other in-stream cover varies with season and time of day. Tabor and Piaskowski (2001) found that use of overhanging structures and woody debris by juvenile Chinook salmon, in Lakes around the Puget Sound region, varied by time of day and season. In February and March juvenile Chinook were found using overhead structures as cover primarily during the day but in April and May they never used overhanging structures as cover. The use of woody debris decreased over the same time period, but remained in limited use as refugia from predators. This might be explained by the fact that juveniles did not make extensive use of the any near shore areas after mid-May. In a similar study Allen (2000) found that juvenile Chinook, in the Yakima River Basin, varied in their preference for woody debris and other cover types across seasons. The highest frequency of juvenile Chinook associated with woody debris was during the Spring and Fall. The strong association of fish with woody debris may be due in part to their association with the stream margin in the Spring (Allen 2000). Figure 7 shows the difference in association of juveniles with woody debris across seasons as observed by Allen (2000). Temperature differences across seasons may act as cues to stimulate cover seeking by juvenile Chinook.

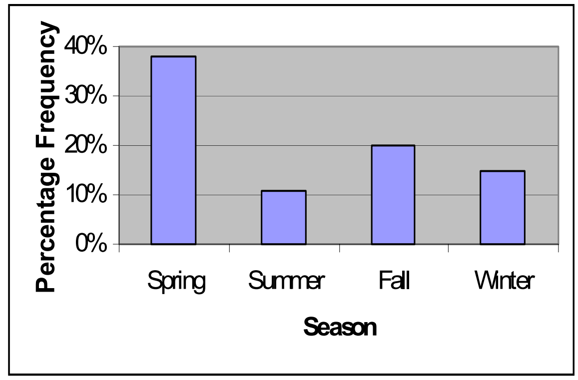

Figure 7. **Use of woody debris as cover according to season; data from Allen (2000).**

Taylor (1988) found that temperature was a more important cue than water velocity in promoting cover seeking by juvenile Chinook. He found that more juveniles were associated with cover at 2 ˚C than at 12 ˚C. Swales et al. (1986) found that stream-type juvenile chinook were primarily associated with pools containing large woody debris during the winter. This is similar to the finding by Bjornn et al. (1977) that Chinook fry use inter-gravel space for cover when exposed to cold water temperatures.

Conclusions

In-stream woody debris can enhance habitat for juvenile Chinook in several ways. Woody debris (and other cover types) can provide refugia from predators and high stream velocities. Cover is preferentially sought during early stages of juvenile development and at low temperatures.

Section 4. Temperature During Spawning and Egg Incubation

General information on Chinook salmon migration and spawning

Chinook salmon like other species of Pacific salmon are anadromous[8]. The majority of Pacific salmon return to spawn in the exact natal stream from which they originated (Busch 2000). Of all the Pacific salmon species, Chinook spend the longest time in the ocean prior to spawning. They may grow in the ocean from three to seven years prior to returning to freshwater streams for spawning (Busch 2000). The exact time spent at sea depends on the evolutionary history of any particular Chinook stock. Historically Chinook salmon have migrated as far up stream, from the Pacific Coast, as western Montana and central Idaho (Brownell 1999).

The massive postglacial expansion of Pacific salmon species so far into fresh water streams would not have been possible if adult fish continued to feed while migrating through fresh water (Brett 1995). Chinook have evolved to refrain from eating for the duration of upstream migration thereby minimizing their ecological impact on the freshwater environment. Completing migration requires adequate storage of lipids and protein to swim upstream and complete reproductive functions (Brett 1995)[9]. The metabolic rate of a fish will determine how long it takes to consume these energy reserves.

Water temperature can influence the survival of migrating adults directly by changing the pace of their metabolic rate. Fish are cold-blooded animals and their metabolism is influenced by ambient water temperature (Bell 1986). The metabolic rate of Pacific salmon can increase "almost exponentially" over the range of livable temperatures (Brett 1995). Such metabolic rate increases may cause adults to exhaust energy reserves prior to completion of reproductive processes.

Temperature during migration and spawning

Studies of the migration timing and survival of adult Chinook support the notion that high water temperatures can limit migration success. Temperature ranges above optimal may cause fish to cease migration. Research has shown that it takes longer for Chinook to loose heat than to gain heat. Temperature equilibration time also increases with the size of the individual fish (Berman and Quinn 1991). Not all populations of Chinook salmon respond identically to absolute water temperature. Burger et al. (1985) studied the migration of tagged adult Chinook through the Kenai River of southern Alaska. They found that fish entering the river during the relatively cooler period of May to June primarily spawned in small tributaries. Fish that migrated during the warmer period from late June to August spawned in the main stem of the river. They concluded that adults began migration such that spawning would commence, in the main stem, as water temperatures were declining from a maximum of 12˚ C. Columbia River Chinook that migrate to sea during the summer (fall spawning), preferentially select progressively lower water temperatures as the season progresses. Low water temperature may serve an orientation cue that guides them to the marine environment. Columbia River Chinook, that emigrate during the spring (spring spawning), do not exhibit such a progressive preference for lower water temperatures (Sauter et al. 2001). Bell (1986) summarized the average temperature tolerances for migrating salmon in western Washington. Table 1 summarizes the tolerance ranges for Chinook stocks that spawn at

	Migration Temperature in ˚C				Spawning
	Spring	Summer	Fall	Optimal	Optimal
Lower limit	3.3	13.9	10.5	9.4	5.6
Upper limit	13.3	20	19	14.2	10.6

Table 1. Temperature range for migrating adult Chinook salmon in western Washington, from Bell (1986).

[8] Anadromous fish spawn and incubate eggs in fresh water habitat after spending most of their adult lives in the marine environment (Busch 2000).

[9] Fish can not store carbohydrates (Brett 1995).

different times of the year. The optimal temperature estimates, for fish in western Washington (Bell 1986), were higher than those of Burger et al. (1985). This should be expected for stocks adapted to migration at lower latitudes with higher average temperatures.

Once adult Chinook reach spawning streams the process of redd construction, egg laying and fertilization can begin. Spawning may cease if water temperature falls below the lower tolerance level (Bell 1986). Since stocks have varied spawning locations and seasons, the optimal temperature range for spawning would also be expected to be variable for different stocks. This notion is supported by the higher optimal spawning ranges reported for stocks from progressively lower latitudes. Groves and Chandler (1999) found that Chinook in the Hells Canyon reach of the Snake River (in Eastern Washington) began redd construction at temperatures, up to 16 ˚C. Figure 8 displays the frequency of redd construction for varied water temperatures in the Snake River from 1993-1995. Groves and Chandler (1999) concluded that the water averaged 13.6 ˚C during the week when spawning began and 7.5 ˚C during the week when spawning ended. This range is higher than that reported by both Bell (1986) and Burger et al. (1985) for stocks originating at higher latitudes. Individual stocks of Chinook have evolved to spawn at different seasons through out the year.

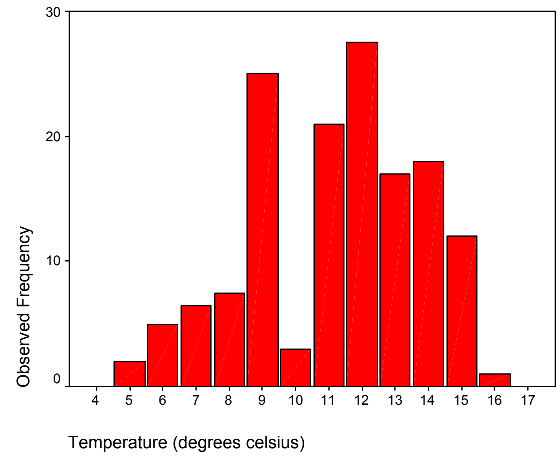

Figure 8. **Frequency distribution of mean weekly temperature during redd construction by Chinook salmon; recreated from Groves and Chandler (1999).**

Fish which are adapted to survive will lay their eggs at the time of year that coincides with optimal temperature ranges for development of embryos. Fish that lay eggs when the water temperature is not suited for embryo survival will not pass on their genetics to subsequent cohorts.

Incubation temperature and egg survival

Once eggs have been laid they require tolerable water temperatures for successful incubation. In general the time required for Chinook egg incubation is inversely related to the water temperature (Allen 1986). This effect likely results from the increase in metabolic rate that accompanies a water temperature increase. Excessively high or low water temperatures will result in egg mortality. Optimal temperatures for particular stocks are likely to vary with the evolutionary history of salmon stocks. Raleigh et al. (1986) indicate that the tolerable range of temperatures for Chinook egg incubation is between 4.5 ˚C and 14.0 ˚C. Figure 9 displays the results of empirical studies conducted by Beacham and Murray (1988), Olson et al. (1970) and Olson and Foster (1955). The genetic sources for the eggs examined were British Columbia, Washington and Idaho respectively. Although the magnitude of mortality differed for individual stocks the overall trend was the same. Mortality was lowest between 8 ˚C and 12 ˚C for all stocks. The stocks from British Columbia suffered higher mortality as temperatures climbed. This difference in egg

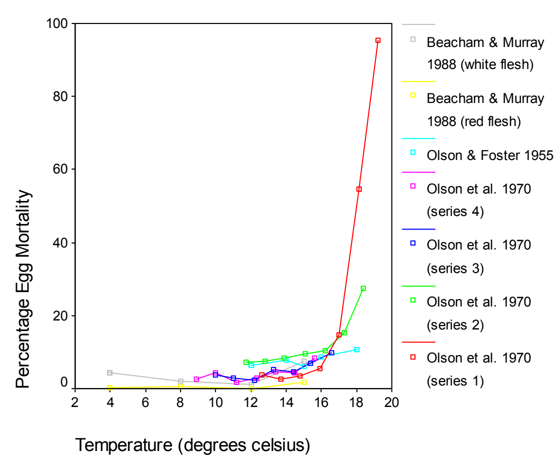

Figure 9. **Survival rates for Chinook eggs incubated at varie water temperatures; data from Beacham and Murray (1988), Olson et al. (1970), and Olson & Foster (1955).**

mortality at high temperatures between stocks may be due to the average annual temperature differences faced during prior evolution by the individual stocks. The influence of temperature on embryo survival also depends on an interaction between temperature and stage of embryo development.

Water temperature is most important during the initial stage of egg incubation. Once a Chinook embryo has reached the early blastula[10] stage its tolerance for sub-optimal temperatures begins to increase (Weatherley and Gill 1995). In an empirical study Murray and Beacham (1986) found that once epiboly[11] was complete, survival rates of embryos were independent of incubation temperatures between 4 ˚C and 12 ˚C. Metabolic changes induced by water temperatures during egg incubation can also influence the morphological characteristics of later life stages.

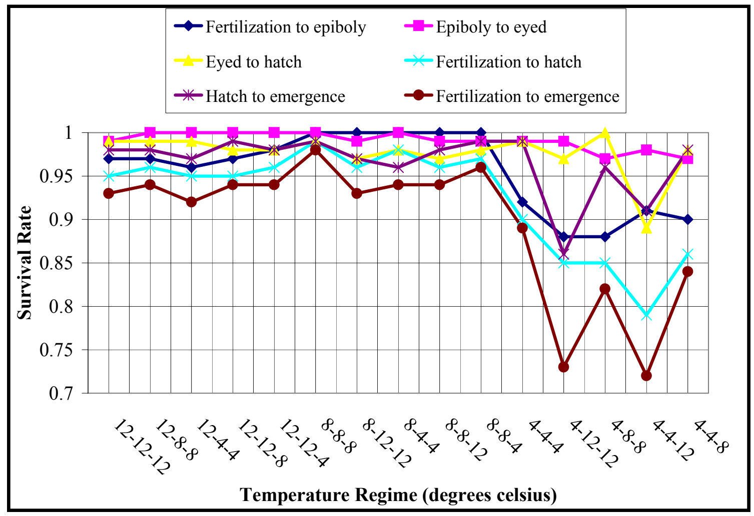

Figure 10. **Survival rates for embryos challenged with temperature regimes consisting of T_1, T_2, and T_3; data from Murray & Beacham 1986.**

Incubation temperature and morphological development

Temperature regimes during initial incubation can result in predictable morphological changes at later developmental stages. After fertilization eggs develop through several distinct stages. Once eggs hatch the Chinook is classified as an alevin. Alevins continue to develop in gravel interstices as they absorb the remaining yolk sac. When the alevins emerge from the gravel, usually after complete absorption of the yolk sac, they are classified as fry. In a study performed by Murray and Beacham (1986) Chinook eggs were subjected to consecutive temperature regimes (T) such that: T_1= fertilization to epiboly, T_2 = epiboly until complete eye pigmentation and T_3 = eye pigmentation until fry emergence. Figure 10 displays the results of temperature regimes (Murray and Beacham 1986) on developmental stages from egg fertilization through fry emergence. They found that later morphological characteristics of Chinook alevins and fry were related to incubation temperatures. The size of individual alevin and fry was greatest for Chinook which had been initially incubated at 12 ˚C. Conversely Murray and Beacham (1986) found that yolk weight declined with increasing incubation temperature. Morphological differences due to high temperature incubation regimes clearly continued to manifest at later developmental stages.

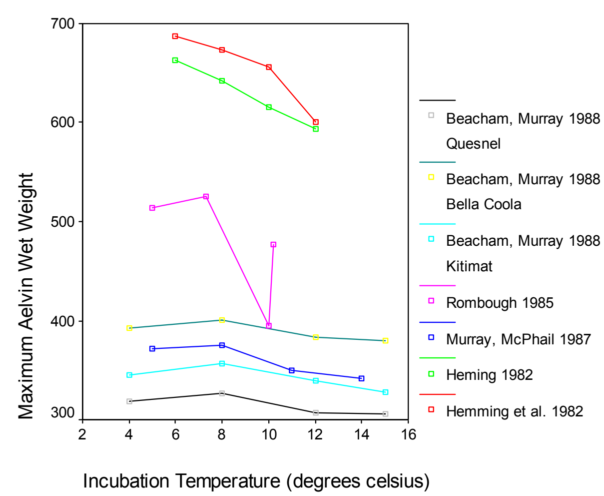

Figure 11. **The relationship between incubation temperature and maximum alevin wet weight; data from Beacham and Murray (1988), Heming et al. (1982), Heming (1982), Murray and McPhail (1988), and Rombough (1985.)**

[10] The blastula stage is defined by the development of 128 cells in the egg (Weatherley and Gill 1995).
[11] Epiboly is the developmental stage characterized by tissue formation in the egg (Weatherley and Gill 1995).

Chinook embryos grow most efficiently at temperatures between 4 ˚C and 8 ˚C, but the precise relationship depends on the particular stock (Beacham and Murray 1988). Embryos exposed to higher, but sub-lethal, incubation temperatures reach their maximum alevin wet weight faster than embryos exposed to lower incubation temperatures, however embryos that develop in relatively cooler water reach a greater maximum alevin weigh (Rombough 1985). Figure 11 displays the results of empirical studies conducted to determine the relationship between incubation temperature and maximum alevin wet weight. All of the studies used eggs from genetic sources in British Columbia. The maximum weights achieved differed for particular stocks. This may be due to the smaller initial egg size of interior-spawning stock when compared to coastal-spawning stocks (Beacham and Murray 1988). The overall trend is essentially the same for all studies. Incubation temperatures between 4 ˚C and 8 ˚C consistently produced the heaviest alevins. This finding is further supported by a study that found relative growth of alevins to be greater at a control incubation temperature of 7.4 ˚C – 9 ˚C when compared to an experimental incubation temperature of 9.0 ˚C – 11.1 ˚C (Heath et al. 1993).

Conclusions

Water temperatures can influence migration, spawning success, egg survival and later morphological development of Chinook salmon. The range of tolerable water temperatures, for different life stages, varies with the evolutionary history of particular stocks. In general no stocks will migrate upstream if temperatures are below 3.3 ˚C or above 20 ˚C. The majority of spawning will occur between 6 ˚C and 15 ˚C. Highest egg survival will occur between 8 ˚C and 12 ˚C. Some Chinook eggs will still survive at temperatures between 4 ˚C and 14 ˚C. The highest mortality for developing Chinook, as a result of extreme incubation temperatures, will occur at the alevin and fry stages. Chinook develop most efficiently to the alevin stage when eggs are incubated at temperatures between 4 ˚C and 8 ˚C.

Section 5. Water Temperature and Smolt Migration

General information on the Chinook salmon smoltification

Young Chinook that survive the fry life stage begin to undergo physiological changes in preparation for their journey to the marine environment as smolts. The first visible manifestation of smolitification occurs when the young salmon changes from a dull to a shiny silver appearance. The initiation of smoltification is triggered by photoperiod but the rate and duration is regulated by water temperature (Giorgi et al. 1997). The period of time from hatch to smolt emigration varies for particular stocks. Two general life histories types have been documented by researchers. Chinook that spend less than three months, after hatching, in their natal streams are referred to as ocean-type. By contrast stream-type life history is defined by Chinook that spend over one year in streams before migrating to the ocean. There is a clear pattern to the occurrence of these two life history types along the major streams of the west coast of North America. Ocean-type stocks predominately spawn in streams south of the Columbia River. This includes populations of coastal Oregon and the Sacramento-San Joaquin Rivers. Stocks above 56˚ N (Skeena River) are predominately stream-type. Streams between the Columbia River and Skeena River are used by both ocean-type and stream-type stocks (Taylor 1990). Stream-type Chinook that spend two or three years in their natal streams become more common with increasing latitude and distance from the sea while stream-type that spend only one year in natal streams are more common at lower latitudes. This distribution pattern may be the result of isolated refugia during the Wisconsinan glaciation[12]. Such distributional patterns may have been reinforced by the superior adaptability of larger smolts to longer migrations and colder water (Taylor 1990). These distributional patterns highlight some of the relationships between water temperatures, distance to the ocean and successful smolt migration.

Water temperature and fry mortality

Water temperatures between 7 ˚C and 14 ˚C are ideally suited for Chinook fry survival (Raleigh et al. 1986). Brett (1952) narrowed the preferred range of temperatures for juvenile Chinook to between 12 ˚ C and 14 ˚C. Figure 12 shows the relationship found between temperature and percentage fry mortality in several empirical studies. As can be seen in Figure 12, the specific mortality rate for given temperature varies with the particular stock, but mortality in excess of 50 percent tends to occur at temperatures over 17 ˚C. The upper limit of water temperature that juvenile Chinook can survive for even short periods of time is between 24 ˚C and 24.5 ˚C (Brett 1952). The variability in response by the study populations may be due to genetic differences or the responses may vary as a function of acclimation temperature.

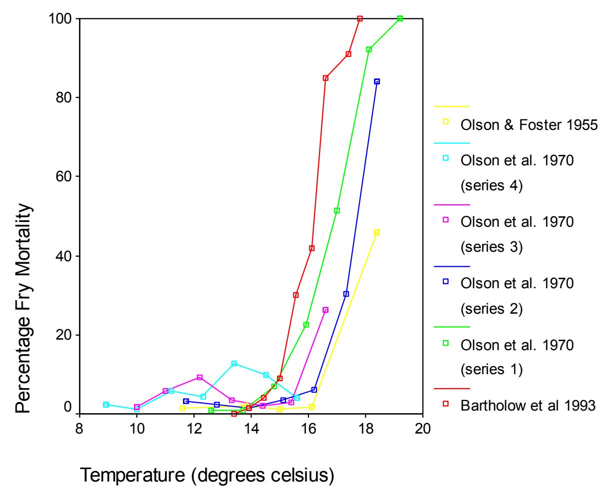

Figure 12. **The relationship between temperature and fry mortality for different stocks; data from Bartholow et al. (1993), Olson et al. (1970) and Olson & Foster (1955).**

Acclimation temperature can influence the amount of time that fry will survive when challenged with higher than optimal and lower than optimal temperatures. The upper lethal limit for Chinook fry varies from 21.5 ˚C to 25.1 ˚C and is positively related to acclimation temperature (Brett 1952). The lower lethal limit for fry varies from 7.4 ˚C to 0.8 ˚C and is inversely related to acclimation temperature (Brett 1952). Figures 13 and 14 show the relationship between

[12] The Wisconsinan glaciation stage of the Pleistocene period occurred between 80,000 and 10,000 years ago.

acclimation temperature and resistance time for juvenile Chinook exposed to high lethal temperatures to low lethal temperatures.

Water temperature and growth rate

Juvenile Chinook salmon grow the fastest at 19 ˚C (Weatherley and Gill 1995), but this may not maximize health and survival. Clarke and Shelbourn (1985) found that young fry growth rate increased over the range of 7 – 17 ˚C, but so did descaling and subsequent mortality. Similarly Banks et al. (1971) found that growth rate of Chinook fingerling groups increased consistently between 10 ˚C and 15.6 ˚C, but varied in their growth rates at 18.3 ˚C. The variability in growth rate at 18.3 ˚C was influenced by increased disease prevalence at the higher rearing temperature (Banks et al. 1971).

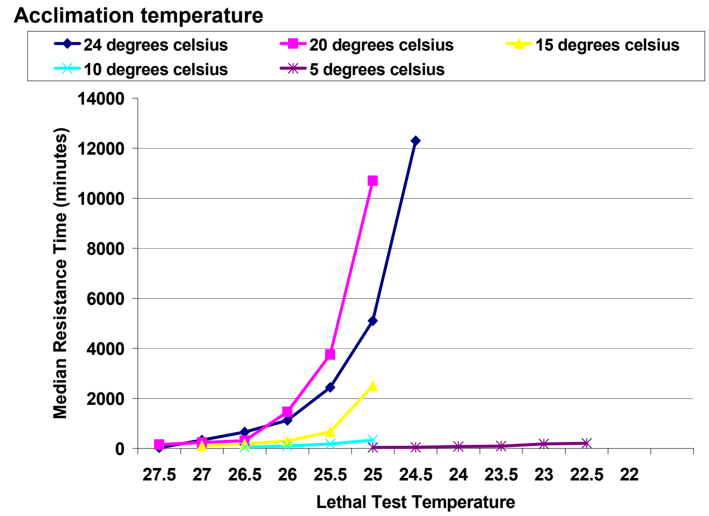

Figure 13. **Variation in median resistance time to lethally high temperatures for juvenile Chinook acclimated to different temperatures; data from Brett (1952).**

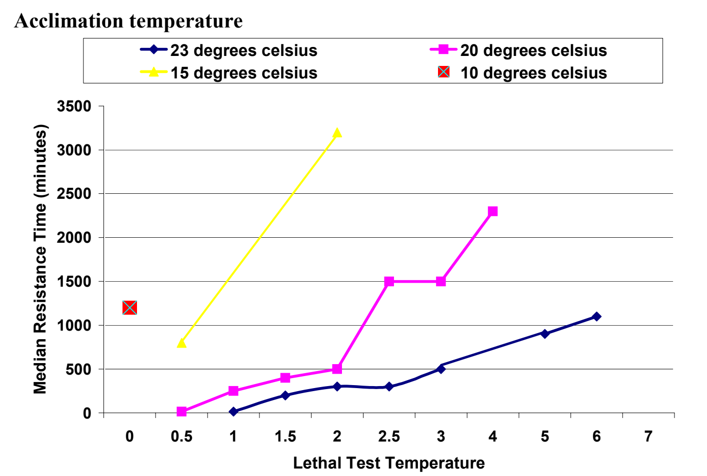

Figure 14. **Variation in median resistance time to lethally low temperatures for juvenile Chinook acclimated to different temperatures; data from Brett (1952).**

Water temperature and smolt emigration timing

Higher than optimal water temperatures can result in early emigration by Chinook fry initiated by physiological change (Giorgi et al. 1997). Temperature may indirectly influence emigration timing by influencing growth of juvenile Chinook. High, but sub-lethal, water temperatures accelerate growth rate. Beckman et al. (1998) concluded that larger Chinook migrate downstream sooner than smaller ones. Faster growth rate may result in early recruitment of endocrine mechanisms that initiate emigration by juvenile Chinook (Beckman et al. 1998). Through this mechanism juvenile Chinook reared in higher temperature streams can migrate earlier in the year than Chinook reared in lower temperature streams.

Temperature may also accelerate emigration by influencing the behavior of Chinook salmon. Roper and Scarnecchia (1999) found that higher than average stream temperatures were associated with an earlier median emigration date for wild Chinook smolts. They found that seaward emigrations were greatest when the water temperatures were between 12.5 ˚C and 15 ˚C, and nearly ceased when the water temperature reached 20 ˚C. The influence of temperature can also interact with other variables such as photoperiod or evolutionary adaptation to influence emigration rate. Muir (1994) found that high temperature (11 ˚C) combined with accelerated photoperiod resulted in increased metabolic rate and the shortest travel times for Chinook fry. Beacham and Withler (1991) demonstrated that juvenile Chinook salmon from a southern British Columbia stock were able to survive for longer periods when exposed to lethal temperatures than juveniles from a northern British Columbia stock. This difference in resistance was attributed to genetic differences resulting from evolutionary history.

Conclusions

Water temperature significantly over 14 ˚C can cause high mortality rates in Chinook salmon fry. Water temperature significantly below 7 ˚C can also cause mortality. The ability of fry to withstand lethal temperatures is related to acclimation. Fry that have been acclimated to high temperatures survive longer in lethally high temperature water. Fry that have been acclimated to low temperatures survive longer in lethally low temperature water. Higher water temperature accelerates growth of fry, but can also result in increased susceptibility to disease. Water temperature can accelerate the timing and rate of seaward migration. High temperatures will accelerate growth and can lead to hormonal changes that initiate early emigration. Low temperatures can interact with photoperiod and act as cues to begin seaward migration. The reaction of Chinook stocks to absolute temperatures varies by the genetic constitution of the stock.

Section 6. Dissolved Oxygen Requirements of Chinook Salmon

Background

Chinook salmon have the highest reported tissue oxygen supply to of any salmonids (Gallaugher et al. 2001). The exact oxygen requirement may vary for different life stages of Chinook salmon, but all life stages depend on aerobic respiration for survival. Inadequate dissolved oxygen can limit growth or cause mortality at all life stages. Oxygen dissolves into stream water through two mechanisms. In still water gaseous oxygen will dissolve into the water through diffusion. In flowing, turbulent water gaseous oxygen can also be entrained and mixed into deep, less oxygenated water (Bell 1986). Organic matter can arrive in stream water from natural, domestic or industrial causes (Whitmore et al. 1960). Oxygen deficiencies can be created by microbial decomposition of organic matter in stream water. Streams without sufficient flow to rapidly foment deep water can become anoxic (Waldichuk 1993). Cold liquid water can hold more dissolved oxygen that warm water can. Since warm water also increases metabolic activity Chinook salmon are particularly susceptible to the damaging effects of anoxic conditions in high temperature water. Elliott (1969) found that the oxygen requirement of Chinook fingerlings increases in direct proportion to rising temperature. Larger fingerlings had lower oxygen demands than smaller ones.

Dissolved oxygen and survival

Chinook eggs incubated in low oxygen conditions suffer abnormal development and high mortality. Post hatching survival is significantly depressed by dissolved oxygen concentrations below 2.5 mg/L. Most embryos will suffer abnormal development if incubated at dissolved oxygen concentrations below 1.6 mg/L (Silver et al. 1963). Depressed oxygen levels also result in hatching delays and retarded growth (Silver et al. 1963). Figure 15 shows the relationship between dissolved oxygen concentration and the percentage of Chinook eggs successfully hatched.

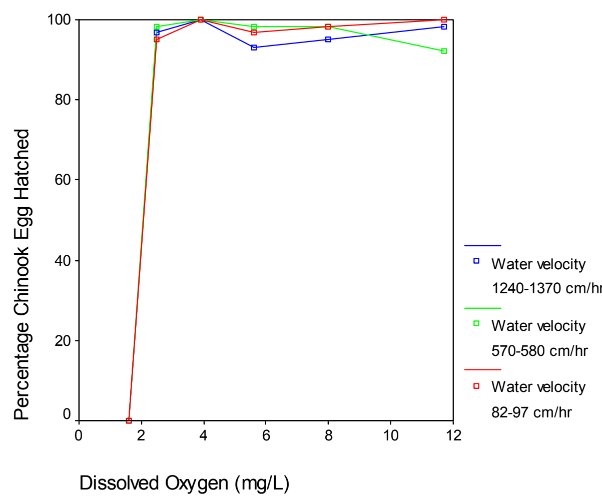

Figure 15. The relationship between dissolved oxygen (mg/L) and the percentage of Chinook eggs hatched; data from Silver et al. (1963).

Anoxic water conditions can repel Chinook from otherwise suitable streams. In a laboratory study Whitmore et al. (1960) found that juvenile Chinook will avoid water with oxygen concentrations as high as 4.5 mg/L. Chinook were more likely to avoid waters with progressively lower oxygen concentrations. They also found that seasonal differences in water temperature influenced channel avoidance. Chinook were more likely to avoid water with low oxygen concentration at high water temperatures (Whitmore et al. 1960). Similar results were found on the Willamette River in Oregon with migrating adult Chinook.

Alabaster (1989) estimated that adult Chinook would cease migration at dissolved oxygen concentrations of 3.4 mg/L. The exact dissolved oxygen concentration that would inhibit migration was inversely related to water temperature. The avoidance of higher oxygen concentrations at high water temperature probably results from metabolic increases, and oxygen requirements, of fish in high temperature water.

Conclusions

Dissolved oxygen concentrations below 2.5 mg/L can significantly increase Chinook egg mortality and developmental abnormalities. Juvenile Chinook salmon will avoid water with dissolved oxygen concentrations as high as 4.5 mg/L. Migrating adult Chinook salmon will not swim through water with dissolved oxygen concentrations of less than 3.4 mg/L.

Section 7. Flow Regimes and Chinook salmon

General information of river flow and Chinook salmon

As early as the nineteenth century dams were being built on streams in the Pacific Northwest. After the great depression of the 1930s hydropower dam construction rapidly accelerated. Dams that restricted access to spawning streams had a devastating impact on many wild Pacific salmon populations (Lichatowich 1999). Empirical data indicates that upstream wild Chinook populations were impacted more severely by hydropower dams than downstream populations. Dams had a major effect on the decline of upriver Chinook stocks on the Snake and Columbia Rivers. Even lower Columbia River stocks have been seriously impacted by hydropower (Schaller et al. 1999). The indirect influence of altered river flow regimes on Chinook salmon stocks is predictably more complicated.

The conclusions by researchers on the relationship between stream flow and Chinook salmon survival do not always agree. Some authors have concluded that there is a weak and variable relationship between survival and mean stream flow (Smith et al. 2002). Using average flow rates for an entire river may limit the power to detect statistical differences for rivers with variable microclimates and subsequent survival rates along their length (Bradford 1994).

Low stream flow and survival

Low flowing streams can influence survival at all in-stream life stages of Chinook salmon. Low flows accumulate sediment in spawning gravels, which degrades spawning substrate[13]. Nelson et al. (1987) documented that reduced flow degraded stream habitat for Chinook salmon in the Trinity River drainage system of northwestern California. The lack of naturally occurring annual flushing flows accelerated sediment loading, and prevented the downstream mobilization of gravels and cobbles. Low flows failed to uproot stream channel vegetation and allowed plant roots to grow into spawning gravels further increasing stream bed sedimentation. Low stream water depth can interact synergistically with fine sediment in spawning gravel to further reduce inter-gravel water velocity, dissolved oxygen and egg survival in redds (Reiser & White 1988). Figure 16 shows the relationship between water depth and egg survival in simulated spawning riffles with Chinook from an Idaho hatchery.

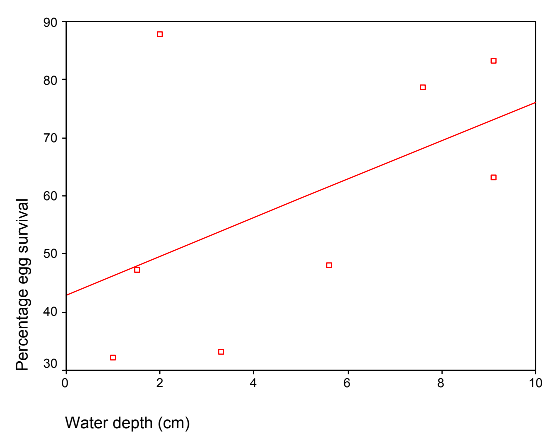

Figure 16. The relationship between water depth in cm and percentage Chinook egg survival; data from Reiser and White (1990).

Low flows can also alter Chinook survival by changing in-stream temperature dynamics. Reduced water volumes in streams allow water temperature to fluctuate more easily with ambient air temperature. Evidence suggests that prior to ESA listing of Chinook salmon on the Snake River, low flows and high temperature contributed to juvenile Chinook mortality. This is supported by evidence that in the Lower Grande Reservoir, below the Snake River, low summer flows were strongly associated with high temperatures.[14]

Low water levels can also lead to Chinook mortality from cold temperatures. Conventional wisdom has held that dewatering of Chinook salmon eggs can result in mortality from freezing or desiccation (Waldichuk 1993). A study of dewatered

[13] See Section 1 "Influence of fine sediment in spawning gravel on Chinook salmon".
[14] Mean summer flows and maximum summer water temperatures were highly correlated, R = -0.999 (Connor et al. 1998).

eggs by Reiser and White (1983), conducted in an Idaho stream between September and October, showed that Chinook eggs may be more resilient to dewatering then previously thought. They found no significant difference in the percentage hatch of dewatered eggs compared to watered eggs over a five week period. The major difference between the study groups was that the dewatered eggs hatched earlier and produced alevins that were longer. Reiser and White (1983) concluded that the difference was due to the elevated rearing temperature for the dewatered eggs. Since temperatures never dropped below 5 ˚C during their study mortality due to freezing could not be addressed by the results. Their results do suggest that Chinook eggs can resist desiccation if dewatered at temperatures ranging from 11.4 ˚C to 5 ˚C.

High flows and survival

High flowing stream can have negative consequences for eggs and fry. Hydrological changes resulting from reduced upstream ground permeability or diversion of water from other sources can result in artificially high flows in streams. Eggs may become silted over or washed out of redds. Fry may be displaced downstream or washed out to sea before smoltification, and the necessary fitness for salt water (Waldichuk 1993).

High flows can reduce predation on juvenile Chinook by increasing water turbidity. High flows also increase the habitat available for foraging (Stevens and Miller 1983). In regulated rivers high flows should be released prior to spawning. Such flushing flows can help to remove fine sediment from spawning gravels and reduce subsequent egg mortality (Nelson et al. 1987). In damned rivers the upstream supply of small gravels and cobble is most likely eliminated. In such a stream flushing flows can result in the progressively unsuitable coarsening of spawning substrates, if suitable sized gravels are not regularly supplied. In such a situation high flows can degrade Chinook spawning habitat (Kondolf et al. 1996). The precise flows needed to flush spawning gravel will vary with the dynamics of any particular stream.

Seiler (2000) found that egg to migrating adult survival, for wild Chinook, from 1989 to 1998 was inversely related to annual high flow in the Skagit River. Severely high flows during incubation caused a significant reduction in egg to migrant adult survival. He concluded that flow has a dominant effect on survival to downstream migration.

Stevens and Miller (1983) found that survival of Chinook salmon, from the Sacramento-San Joaquin River system, increases as flow increases during and shortly after spawning. In this system survival is most influenced by flows during December and January, when fall run Chinook adults spawn.

Stream flow and juvenile Chinook movement

Stream column mean flows between 0.4 ft/s and 0.7 ft/s are ideally suited to juvenile Chinook (Raleigh and Miller 1986). Figure 17 displays the suitability of stream column flows for juvenile Chinook. Observations by Everest and Chapman (1972) agree that juvenile Chinook usually inhabit streams with water velocities less than two feet per second.

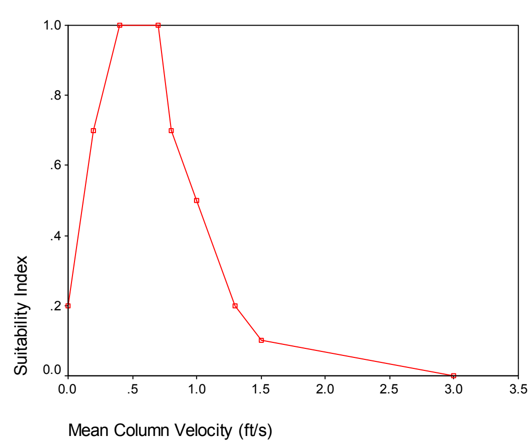

Figure 17. **Suitability of stream column velocity for juvenile Chinook salmon; data from Raleigh & Miller 1986.**

Juvenile Chinook salmon will preferentially select positions, with slower water velocity than the adjacent water, within the water column. Juveniles often reside in concentrated groups near stream edges. Increased flow rate results in the movement of juvenile Chinook perpendicular to the stream flow. This perpendicular movement is unrelated to the magnitude of the flow increase (Scirvell 1994).

Stream water flow can influence the travel time of emigrating Chinook juveniles. Smith et al.

(2002) analyzed the survival and movements of a large number of daily groups of tagged yearling Chinook in the Snake River Basin. They found that median travel time was influenced by a combination of river discharge and degree of smoltification. Travel times tended to decrease throughout the season as flow increased. Empirical data analyzed by Berggren and Filardo (1993) found similar results for juvenile Chinook in key reaches of the Columbia River. The average migration times and their relationship to stream flow differed between Spring-migrating and summer-migrating Chinook, but the trend was the same. They found that smolt migration time for both populations was inversely related to average flow in the stream.

Conclusions

Altered stream flow can influence Chinook salmon mortality and behavior in many different ways. Adult salmon can not migrate to spawning streams if the streams contain insufficient water. High temperatures associated with low flows can increase mortality at all life stages. Low dissolved oxygen content, resulting from low flows and high water temperature, can increase mortality. Low flowing streams will remove less waste products from salmon redds increasing mortality through egg suffocation or premature alevin emergence. Eggs can become desiccated or frozen if dewatered. Streams that have regulated flows, without naturally occurring peak flow events, can accumulate artificially high amounts of fine sediment in spawning gravels. Low flowing stream water can interact synergistically with fine sediment in spawning gravel to further reduce inter-gravel water velocity in redds. Such reduced flows can result in anoxic incubation conditions which will increase mortality.

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Appendices

Appendix 1. Matrix of articles related to fine sediment in Chinook salmon spawning gravel.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
adult, spawning	Substrate	redd location	most redds occurred in med. to large-sized gravel	Groves & Chandler 1999	ID, WA, OR, Snake River
egg	Fine sediment	survival	—, for low and high flow conditions	Reiser & White 1990	ID, Rapid River Hatchery
egg	Heavy sedimentation	survival	—	Allen et al. 1986	general
egg to fry; (a) egg (b) alevins/fry	% fine sediment	(a) survival (b) development index	(a) — (b) inconclusive	Reiser & White 1988	ID, Rapid River Hatchery
egg to fry; (a) egg (b) fry	Fine sediment	(a) survival (b) size	(a) — (b) inconclusive	Tappel & Bjornn 1983	WA, Clearwater River
juvenile, age-0	Fine sediment	density	—	Scrivener et al. 1994	BC, Hawks Creek
juvenile, age-0	Substrate	relative frequency	most fish over sand-gravel substrate	Hillman et al. 1987	ID, Clearwater River

Appendix 2. Matrix of articles related to suspended solids in Chinook salmon habitat.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
adult, spawning	Suspended sediment	homing	nil	Quinn & Fresh 1984	WA, Cowlitz River
eggs	(a) Suspended sediment and (b) amonia	mortality	(a) LC50 at 7 ˚C = 31 g/L (b) LC50 at 7 ˚C = 0.45mg/L	Servizi & Gordon 1990	WA, Quesnel River
juvenile, age-0	Stream bed sedimentation	movement out of test channels	+	Bjornn et al. 1977	ID, Hayden Creek
juvenille	Chlorinated and aromatic compounds	mortality	+ (concentration varied by compound)	Arkoosh et al. 2001	WA, Hylebros waterway
juvenille	pulp mill effluent	chrosomal damage	nil	Easton et al. 1997	BC, Prince George
subyearling & yearling	Water clarity	(a) travel speed (b) time of day movement	(a) + (b) +	Steel 1999	WA, Grande Ronde & Snake Rivers

Appendix 3. Matrix of articles related to woody debris in Chinook salmon habitat.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
juvenile	Overwinter habitat association	catch per unit effort (CPUE)	highest CPUE in ponds with woody debris	Swales et al. 1986	Coldwater & Nicola Rivers, BC
juvenile	Temperature	cover seeking	more cover sought at 2 ˚C than at 12 ˚C	Taylor 1988	BC, Slim Creek
juvenile	Woody debris	% frequency by season	From highest to lowest - Spring, Fall, Winter, Summer	Allen 2000	WA, Yakima River Basin
juvenile	Woody debris, large	(a) Feb. - March, day/night (b) April - May, day/night (c) May-June day/night	(a) nil/nil (b) nil/— (c) nil/nil	Tabor & Piaskowski (2002)	WA, Seattle
juvenile	Woody debris, small	(a) Feb. - March, day/night (b) April - May, day/night (c) May-June day/night	(a) +/nil (b) +/nil (c) nil	Tabor & Piaskowski (2002)	WA, Seattle
juvenile, age-0	(a) Cover (b) water depth	density	(a) + (b) +	Richards et al. 1992	ID, Yankee Fork River
juvenile, age-0	Cover seeking	density	+	Brusven et al. 1986	ID, South Fork Salmon River
yearling	Quantities of cover	fish per pool	+	Bjornn & Reiser 1991	Unknown

Appendix 4. Matrix of articles related to water temperature during spawning and egg incubation of Chinook salmon.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
adult, egg; (a) spawning (b) hatching	Temperature	survival	(a) 42 ˚F (6 ˚C) - 51 ˚F (11 ˚C) (b) 41 ˚F (5 ˚ C) - 58 ˚ F (14 ˚C)	Bell 1986	Western WA
adult, spawning	Average temperature	(a) spawning initiation (b) spawning completion	(a) 13.6 ˚C (b) 7.5 ˚C	Groves & Chandler 1999	ID, WA, OR, Snake River
adult, spawning	Temperature	migration time of year	spawning began with falling temperature	Burger et al. 1985	AK, SE
alevin	Temperature	(a)development stage (b) maximum weight	(a) + (b) ─	Heming 1982	BC, Campbell River
alevin	Temperature	(a) initial feeding (b) development stage (c) max. wet weight	(a) nil (c) + (d) ─	Heming et al. 1982	BC, Campbell River
alevin	Temperature X initial egg weight	time until max. alevin wet weight	─ (96.4% variation by temp. 2% by IEW)	Rombough 1985	BC Vancouver Island
egg	Temperature	survival	─ (heated stream avg. 3.9˚C warmer)	Bisson & Davis 1976	Marion Forks Hatchery, OR
egg	Temperature	(a) fry survival (b) growth	(a) ─ (b) +	Olson & Foster 1955	Priest Rapids, WA
egg	Temperature	development per day	+	Alderdice & Velsen 1977	Nanaimo, BC
egg	Temperature	hatch	+	Allen et al. 1986	general
egg to alevin; (a)egg (b) alevin	Temperature	(a) survival (b) length (c) weight	(a) declined at 14 ˚C and 2 ˚C (b) max. at 8 ˚C (c) max at 5 & 8 ˚C, min at 14 ˚C	Murray & McPhail 1988	BC, Rosewall Creek

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
egg to fry; (a) egg (b) fry	Temperature	(a) survival, growth (b) survival growth	(a) —, + (b) —, +	Olson et al. 1970	Columbia River, WA
egg to fry; (a)egg (b) fry	TU (degree days above O Celsius)	(a) hatch (b) emergence	(a) 256 TU (b) 478 TU	Reiser & White 1988	ID, Rapid River Hatchery
egg, alevin	Temperature	(a) weight (b) relative growth	(a) + (b) —	Heath et al. 1993	BC, Quandra Island
embryo to alevin; (a) red flesh embryo (b) white flesh embryo, (c) to (f) = alevin	Temperature	(a) survival (b) survival (c) length (d) tissue weight (e) total weight (f) yolk weight	(a) + (b) + (c) and (d) highest at 4 ˚C (e) highest at 8 ˚C (f) highest at 15 ˚C	Beacham & Murray 1989	BC, NE
embryo to fry; (a) embryo (b) alevin (c) fry	Temperature	(a) survival (b) survival - size (c) length - yolk weight - tissue weight - wet weight	(a) + (b) —, max. at 12 ˚C, min. at 4 ˚C (c) max. at: 12 ˚C- 4 ˚C - 12 ˚C - nil	Murray & Beacham 1987	BC, Harrison River
juvenile, fingerling	Temperature	growth	+	Banks et al. 1971	Little White Hatchery, WA

Appendix 5. Matrix of articles related to water temperature and smolt migration by Chinook salmon.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
juvenile	Latitude	stream type vs. ocean type	stream type N, ocean type S	Taylor 1990	BC, AK, Yukon
juvenile	Temperature	survival	lethal temp. was 24 ˚C - 24.5 ˚C	Brett 1952	Dungeness, WA
juvenile, age-0	Mean temperature	migration rate	—	Giorgi et al. 1997	WA, Columbia River
juvenile, fingerlings	Temperature	growth	+ between 10 ˚C and 15.6 ˚C, variable between 15.6 ˚C and 18.3 ˚C	Banks et al. 1971	Little White Salmon Hatchery
juvenile, fry	Fall vs. spring type	temp. preference during smolitifcation	fall type decreased, spring type n/c	Sauter et al. 2001	Little White Salmon Hatchery
juvenile, fry	Temperature	mortality	+ between 13-18 ˚C	Bartholow et al. 1993	unknown
juvenile, fry	Temperature	growth	+ for 7-17 ˚C	Clark & Shelbourn 1985	BC, Vancouver Island
juvenile, sub-yearling	Rearing temperature	migration rate	+	Beckman et al. 1998	WA, Yakima River
juvenile, sub-yearling	Temperature	survival probability	optimum survival at 14 ˚C	Connor et al. 2000	WA, Snake River
juvenille	High temperature	(a) survival (b) time to death	(a) — (b) + effect varied by population	Beacham & Withler 1991	BC, Vancouver Island
juvenille	ice (aufeis)	survival	over-winter survival was 22%	Bradford et al. 2001	AK, Croucher Creek
juvenille	Temperature	(a) migration travel time (b) ATPase activity	(a) + (b) +	Muir et al. 1994	ID, Clearwater River

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
juvenille	Temperature	emigration date	—	Roper et al. 1994	OR, Jackson Creek
smolt	High temperature	survival	—	Baker et al. 1995	CA, San Joaquin Delta
smolt	Temperature	emigration date	—	Roper & Scarnecchia 1999	OR, South Umqua River
subyearling & yearling	Temperature	(a) fish speed (b) time of day movement	(a) — (b) + for avg. temp.	Steel 1999	Grande Ronde & Snake Rivers, WA

Appendix 6. Matrix of articles related to dissolved oxygen and Chinook salmon.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
adult, migrating	Dissolved oxygen	% of total run	most migration began at 3.5 mg/L	Alabaster 1988	OR, Willamette River
adult, migrating	Dissolved oxygen	migration	no migration at 3.5 mg/L, 21 ˚C, no migration at 3.9 mg/L, 22.4 ˚C	Alabaster 1989	CA, San Joaquin Delta
adult	Max. arterial oxygen transport	max. oxygen uptake	+	Gallaugher et al. 2001	BC
egg	Dissolved oxygen	survival	+	Allen et al. 1986	general
egg	Dissolved oxygen	hatching	+	Silver et al. 1963	OR, Oxbow Hatchery
juvenile	Low dissolved oxygen water	avoidance	+	Whitmore et al. 1960	OR, Hatchery unknown
juvenile, fingerling	Temperature	oxygen consumption	+	Elliott 1969	WA, Longview

Appendix 7. Matrix of articles related to stream flow and Chinook salmon.

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
adult, spawning	Bottom flow velocity	deep vs. shallow water redds	no significant difference	Groves & Chandler 1999	ID, WA, OR, Snake River
adult	Habitat	% use	pools most used	Torgersen 1999	OR, John Day River
egg	Dewatering X fine sediment	(a) survival (b) incubation time	(a) ─ (b) ─ (avg. temp. higher in dewatered sed.)	Reiser & White 1983	ID, Dworshak Hatchery
egg	Fine sediment X flow	survival	─, for low and high flow conditions	Reiser & White 1990	ID, Rapid River Hatchery
egg to migrant	Peak flow	survival	─	Seiler 2001	Cedar River, WA
juvenile	Mean flow (Oct. - Feb.)	abundance	+ (57% of var. accounted for)	Stevens& Miller 1983	CA, San Joaquin River
juvenile	Mean summer flow	(a) max. temp. (b) detection rate	(a) ─ (b) +	Connor et al. 1998	OR, Hell's Canyon
juvenile	Stream flow quantity	distance above streambed	─	Shirvell 1994	BC, Kloiya Creek
juvenile	Water discharged into river	(a) survival during incubation (b) survival during rearing	(a) nil (b) nil	Bradford 1994	BC, Nechako River
juvenile, age-0	Habitat	% use	glide and lateral scour pool preferred	Hillman et al. 1987	ID, Clearwater River
juvenile, age-0	Mean flow	migration rate	+	Giorgi et al. 1997	WA, Columbia River
juvenile, age-0	Water velocity	density	─ bottom & surface velocity	Everest & Chapman 1972	ID, Crooked Fork & Johnson Creek

Stage of Development	Factor	Response Parameter	Type of Response	Reference	Genetic Source
smolt	Turbine operating efficiency	survival	highest survival was at lowest turbine efficiency	Mathur et al. 2000	WA, Snake River
smolt, yearling	Flow exposure	(a) migration travel time (b) survival	(a) ─ (b) + (weak correlation)	Smith et al. 2002	WA, Snake River
smolt; (a) spring-migrating smolt (b) summer-migrating smolt	Water flow	(a) downstream travel time (b) downstream travel time	(a) ─ (b) ─ (both smoltification and flow decreased travel time)	Berggren & Filardo (1993)	WA, Columbia River

Appendix 8. Data relating fine sediment to Chinook salmon survival.

Study and population	% sediment less than 9.5mm	% fine sediment less than 0.8mm	% fine sediment greater than 0.8mm	% fine sediment less than 0.84mm	% egg survival	% egg survival (eyed)
Tappel & Bjornn 1983 (Clearwater, WA)	14				99	
	28				97	
	42				88	
	56				32	
	70				6	
	19				95	
	31				93	
	43				77	
	55				61	
	68				18	
	11				95	
	21				92	
	32				88	
	43				87	
Reiser & White 1988 (Idaho)		0			68	
		10			10	
		20			5	
		30			2	
		50			0	
			0		69	
			10		65	
			20		42	
			30		25	
			50		12	
Reiser & White 1990 (control)				0.3	83.3	99.3
				7.2	78.7	98
				8.7	63.2	96.8
				12.4	48	97.8
Reiser & White 1990 (low flow)				0.9	87.8	98.2
				5.1	47.2	87
				7.4	33.2	95.8
				14.7	32.2	99

Appendix 9. Data relating temperature to Chinook salmon egg survival.

Study and population	Mean temperature	Total % Mortality
Olson et al. 1970 (Handford Reach, WA)		
series 1	12.6	3.86
	13.7	2.52
	14.8	3.54
	15.9	5.45
	17	14.72
	18.11	54.71
	19.2	95.34
series 2	11.7	7.29
	12.8	7.62
	13.9	8.52
	15.1	9.68
	16.2	10.48
	17.3	15.45
	18.4	27.37
series 3	10	3.85
	11	2.85
	12.2	2.19
	13.3	5.07
	14.4	4.54
	15.4	6.9
	16.6	9.85
series 4	8.9	2.5
	10	4.36
	11.2	1.72
	12.3	2.78
	13.4	4.56
	14.5	4.26
	15.6	8.29
Olson & Foster 1955 (Idaho)	12	6.4
	14	7.9
	15	6.2
	16	8.7
	18	10.8

Study and population	Mean temperature	Total % Mortality
Beacham & Murray 1988 (red-British Columbia)	4	0.3
	8	0.5
	12	0.1
	15	1.6
Beacham & Murray 1988 (white-British Columbia)	4	4.4
	8	1.9
	12	1.1
	15	7.6
Murray & McPhail 1988 (British Columbia)	14	52
	11	10
	8	6
	5	17
	2	86

Appendix 10. Data relating water temperature to juvenile Chinook salmon survival.

Study and population	Mean temperature	Total % Mortality	Mean time until death in days	Day Terminated
Bear River (northern Pop) [Beacham & Withler 1991]	22.4	86.5	1.9	2
	21.5	78.8	3.4	16
	20.3	85.3	4.9	17
Robertson Creek (southern) [Beacham & Withler 1991]	22	73.9	13.3	18
[Bartholow et al. 1993]	13.4	0		
	13.9	1.5		
	14.45	4		
	15	9		
	15.55	30		
	16.1	42		
	16.6	85		
	17.4	91		
	17.8	100		
Olson et al. 1970 (Handford reach area, WA)				
series 1	12.6	0.74		
	13.7	0.86		
	14.8	6.82		
	15.9	22.65		
	17	51.48		
	18.11	92.16		
	19.2	100		
series 2	11.7	3.18		
	12.8	2.17		
	13.9	1.36		
	15.1	3.5		
	16.2	5.95		
	17.3	30.39		
	18.4	84.21		
series 3	10	1.76		
	11	5.87		
	12.2	9.38		
	13.3	3.56		
	14.4	1.99		
	15.4	2.84		
	16.6	26.29		

Study and population	Mean temperature	Total % Mortality	Mean time until death in days	Day Terminated
Olson et al. 1970 (Handford reach area, WA)	8.9	2.35		
series 4	10	1.04		
	11.2	5.92		
	12.3	4.29		
	13.4	12.61		
	14.5	9.8		
	15.6	4.02		
Olson & Foster 1955 (Priest Rapids, WA)	11.6	1.5		
	13.8	2		
	15	1.1		
	16.1	1.8		
	18.4	45.9		

Appendix 11. Data relating dissolved oxygen to Chinook salmon egg survival.

Study and population	Dissolved oxygen (mg/L)	Velocity (cm/hr)	Percentage Hatching
Silver 1963 (Oxbow Hatchery, OR)	1.6	82	0
	1.6	570	0
	1.6	1310	0
	2.5	88	95.1
	2.5	590	98.3
	2.5	1330	96.7
	3.9	94	100
	3.9	580	100
	3.9	1240	100
	5.6	97	96.7
	5.6	580	98.4
	5.6	1370	93.1
	8	97	98.3
	8	580	98.3
	8	1360	95
	11.7	94	100
	11.7	580	92.3
	11.7	1360	98.2