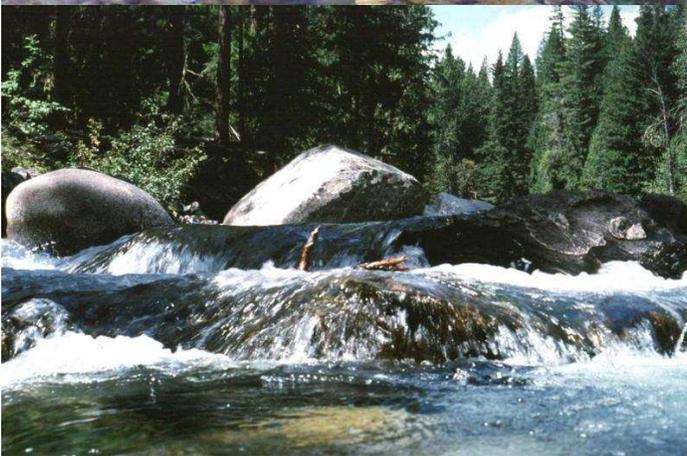


Summer Stream Temperatures in the Olympic Experimental State Forest, Washington.

**Department of Natural Resources Habitat Conservation Plan Stream and
Riparian Monitoring Program. 2004 Report.**



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Executive Summary

- Summer stream temperatures were monitored in 49 forested watersheds on the western Olympic Peninsula, Washington, as part of the Department of Natural Resources Habitat Conservation Plan long-term monitoring efforts. Most of these streams were in DNR's Olympic Experimental State Forest. Because a major aquatic conservation goal of the HCP is to return streams to a natural condition, some natural streams within the adjacent Olympic National Park were also monitored in order to compare them with OESF stream temperatures.
- Twenty four of 49 streams exceeded the state Department of Ecology's temperature criterion for waters defined as "core salmon and trout habitat" (aka class AA waters). For streams that exceeded the class AA temperature criterion, the number of days of exceedance ranged from 1 to 48 and averaged 26. All waters monitored in this study were rated by DOE as class AA or higher. The DOE temperature criterion for class AA waters is any 7 day average of daily maximum temperatures in excess of 16.0 °C.
- All sites with less than 25% of the upstream riparian forest harvested and 85% of sites with less than 50% of the riparian forest harvested, met the class AA water quality standard. Conversely, 61% of sites with more than 50% of the upstream riparian forest harvested exceeded the class AA water quality standard.
- Basin characteristics most strongly correlated with increases in the average daily maximum stream temperature (ADMX) were the percentage of the forest in the basin that had been harvested, the percentage of riparian forest harvested, and the size of the basin. Riparian forest harvest was the single best predictor of ADMX, (followed closely by total basin harvest) while riparian forest harvest and basin size together could explain 53% of the variation in ADMX.
- Pairwise comparisons demonstrated a significant difference in the mean ADMX between sites with less than 5% of the basin forest harvested (Category 1) and all categories of sites binned as either 5-33%, 34-67% or 67-100% of the total forest harvested (categories 2, 3 and 4, respectively). There was no significant difference in the mean ADMX between categories 2, 3 and 4.



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Introduction

The Washington Department of Natural Resources has an approved Habitat Conservation Plan for state-owned forest lands. A conservation objective of the HCP is to “maintain and aid restoration of water to the quantity, quality and timing with which these streams systems evolved” (DNR 1997). The DNR has embarked on a long-term monitoring program to assess the extent to which the HCP is meeting its conservation objectives. The DNR, in consultation with NOAA Fisheries Northwest Fisheries Science Center, chose to monitor stream temperature and use this as an indicator of overall watershed condition. This was done for several reasons, notable among them, the relative ease and economy with which stream temperatures could be measured, and because stream temperature both integrates the impacts of multiple watershed processes and also directly affects the health of instream biota (Hokanson et al. 1977; Beschta et al. 1987; Holtby 1988; Berman and Quinn 1990; Brosofske et al. 1997; Coutant 1999; Torgersen et al. 1999). These features make stream temperature an ideal variable for determining how various watershed activities may be cumulatively affecting instream biota.

Important factors affecting stream temperature include air temperature, stream morphology, groundwater influences, and riparian and basin forest condition (Brosofske et al. 1997). The interaction of stream morphology and riparian forest condition is particularly important. Low-order streams, are usually found in the steeper headwaters, are narrow, have small flows and as such, are sensitive to riparian conditions. Smaller streams have less insulating capacity due to the low flow, and an absence of riparian vegetation can cause large temperature increases and fluctuations (Constantz et al. 1994), but because such streams are generally narrow, they benefit greatly from the shade of riparian vegetation. Mid-order streams are characterized by moderate gradients, being somewhat wider and less easily shaded, and having small tributaries which are often the main sources of inflow, and thus have a great influence on temperature (Beschta et al. 1987). High-order streams usually have the lowest gradients, wider channels and larger flows. Relative to headwater streams, they are generally warmer because they are both wider and lower in elevation. However, the large volume of water they carry modulates temperature changes.

Changes to riparian and watershed vegetation resulting from timber harvest can alter stream temperature regimes. Removing upland or riparian vegetation may increase stream

temperatures by increasing the thermal radiation entering the stream and by increasing surface runoff, which in turn decreases aquifer storage, decreases groundwater inflow, and increases light to the stream (Lynch et al. 1984; Beschta et al. 1987; Li et al. 1994; Brosofske et al. 1997; Coutant 1999). Removal of vegetation may also indirectly increase stream temperatures by contributing to the widening and shallowing of channels, reducing woody debris recruitment and increasing turbidity (Meehan et al. 1979; Holtby 1988). Available evidence suggests the relationship between riparian corridors and stream temperature are non-linear. Relatively narrow buffers produce the largest increases in shade with progressively smaller increases in shade per unit of buffer width occurring as the buffer becomes wider, but still having measurable effects on stream shading more than 50 m from the stream (Steinblums et al. 1984; Brosofske et al. 1997).

Effects of stream temperature on salmonids

Of particular concern to the conservation goals of the HCP are mitigating the effects of temperature on salmonid populations and the aquatic food web upon which they depend, especially the temperature requirements of salmonids at different life-stages and the implications of change to the natural temperature regime that accompanies them. (Figure 1). Temperature directly influences the metabolic and physiologic processes of salmonids. At optimal temperatures for each life-stage, fish can metabolize at a rate that minimizes thermal stress. This allows more energy to be used for important functions such as growth, development, foraging, and reproduction (Beschta et al. 1987; Coutant 1999; Sullivan et al. 2000). These optimum temperatures usually reflect those temperatures likely found within the natural range of the species' habitats (Hokanson et al. 1977). For salmonids, this optimum temperature is relative, based upon food supply, previous acclimation temperature and duration of exposure, species and life-stage. Specific optimum temperatures are especially important during preparation for and while spawning, as they both require a great deal of energy expenditure that may be spent too quickly with high temperatures (Hokanson et al. 1977; Beschta et al. 1987; Coutant 1999; Hicks 1999; Sullivan et al. 2000).

Lethal temperatures are usually defined as the temperature that results in 50% mortality of a population (LT_{50}). For Pacific coast salmonid species, high LT_{50} s range from 20-27°C, though deaths may occur outside this range. Extremely low temperatures may be lethal due to failure of the nervous system at low metabolic rates but impacts of low temperatures on salmonid mortality have not been as well studied and is generally not considered to be a large problem relative to the concerns about high temperatures (Hokanson et al. 1977; Hicks 1999; Sullivan et al. 2000).

Sub-lethal effects are diverse, occurring at every life-stage. For example, during incubation, temperatures between 3.1-14.4 °C are needed to avoid mortality or premature hatching that may result in smaller, less developed alevins that lack competitive skills to gain food and avoid predation (Heming 1982; Hicks 1999; Torgersen et al. 1999). Stream temperatures during rearing influence the rate of metabolism and with sufficient food supplies, the rate of growth. With insufficient food, increased metabolism, caused by high temperatures, will cause decreased growth rates. These higher temperatures can also cause thermal stress, causing reduced tolerance to other environmental stresses and increased susceptibility to disease (Hicks 1999). As adults, higher temperatures can negatively influence migration and spawning (Hicks 1999; Torgersen et al. 1999). Increased temperatures may also lower fecundity, delay or inhibit ovulation, reduce gamete quality, increase the risk of bacterial infections or allow

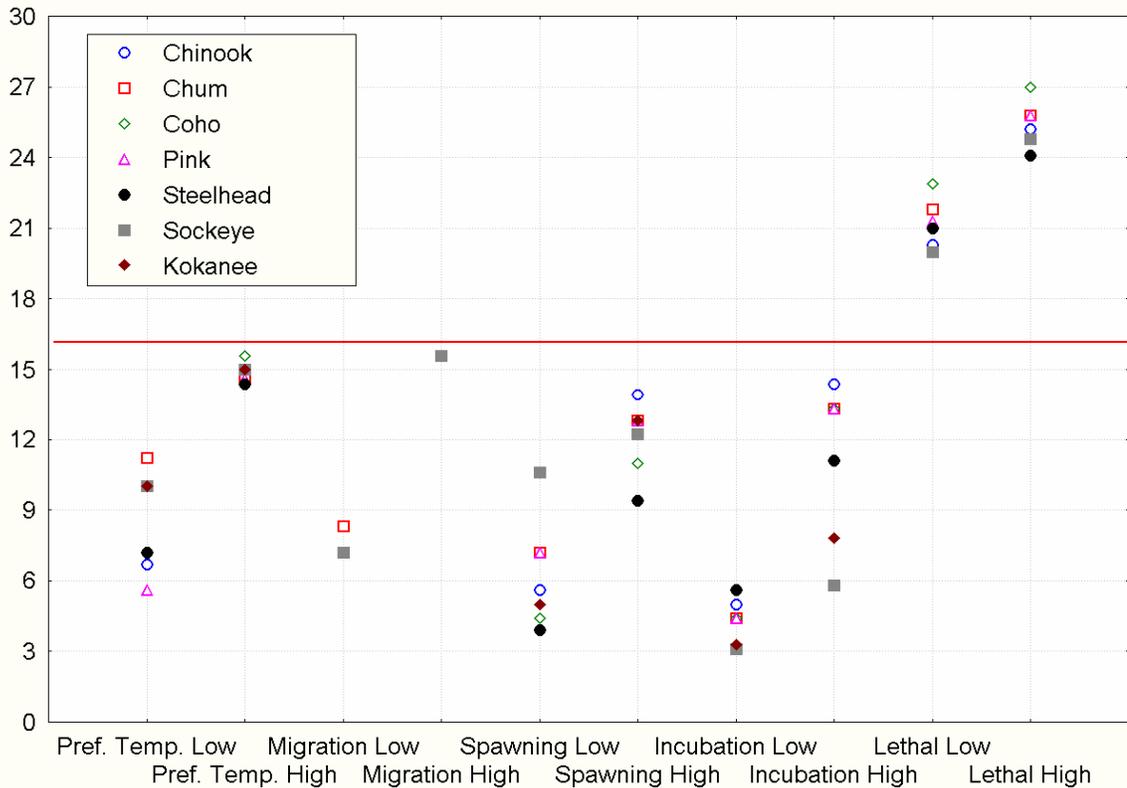


Figure 1. Salmon temperature preferences, by activity. High and low marks bracket the range of preferred temperatures for a given activity and species. Based on Bell (1973), Brett (1952), McConnell and Blahm (1970) and Hicks (1999). Red line marks 16 °C, the DOE temperature standard for core salmon rearing and spawning habitat.

greater uptake of metals (Servizi 1991; Hicks 1999). At near lethal temperatures adults salmonids can experience a loss of equilibrium, which can disrupt an individual’s ability to reach cold water or avoid predators (Hicks 1999).

Coutant (1999) outlines how some of these sub-lethal effects are having detrimental impacts on Snake River fall-run Chinook salmon. These temperature stresses are a result of the adjusted timing of the natural temperature regime caused by dams. The pre-spawning temperatures are higher than they would be without the dams, which is especially hard on the fish as this is a time that they require low temperature to avoid metabolization of fat stores. During spawning these high temperatures persist. This results in small eggs susceptible to mortality, with insufficient yolk and poor incubation conditions (Heming 1982). Smaller, immature alevins result from these circumstances and are less able to compete and avoid predation. Colder waters occur during rearing in this shifted temperature regime, leading to smaller, slower development and later migration. Migration temperatures then approach 20 °C, a lethal level for most Chinook. Smolts survive this temperature if acclimated but would nevertheless be energy-deprived due to poor food supplies. They may be emaciated and disoriented and very susceptible to predation (Coutant 1999).

In stream areas with sub-optimal temperatures, fish may avoid harmful effects by seeking thermal refugia (Berman and Quinn 1991; Gries and Juanes 1998; Torgersen et al. 1999; Sullivan et al. 2000; Ebersole et al. 2001). Sub-optimal temperatures that support salmonids for brief excursions between refugia have been termed the “zone of resistance” (Sullivan et al. 2000,

see Figure 2). Thermal refugia consist of areas of groundwater upwelling, deep pools, shaded areas and junctions with colder tributary inflows. Some deep pools can be as much as 5-10 °C cooler than the surface water (Beschta et al. 1987). Salmonids will thermoregulate behaviorally by moving to these areas to slow metabolism in order to conserve energy. A decrease of 2.5 °C can produce a 12-20% decline in basal metabolic rate (Berman and Quinn 1991). This adaptation is used especially prior to and during spawning when salmonids are fasting and must conserve energy for gonad growth, gamete maturation, spawning migration and release of gametes (Coutant 1999). However, in order for thermal refugia to be useful, they must be large and frequent enough to support the densities of fish present. Infrequent refugia may also be difficult to locate and thus inhibit exploratory behavior in individuals (Beschta et al. 1987). Competition for thermal refugia may limit the density of salmonids supported in certain reaches as well (Ebersole et al. 2001).

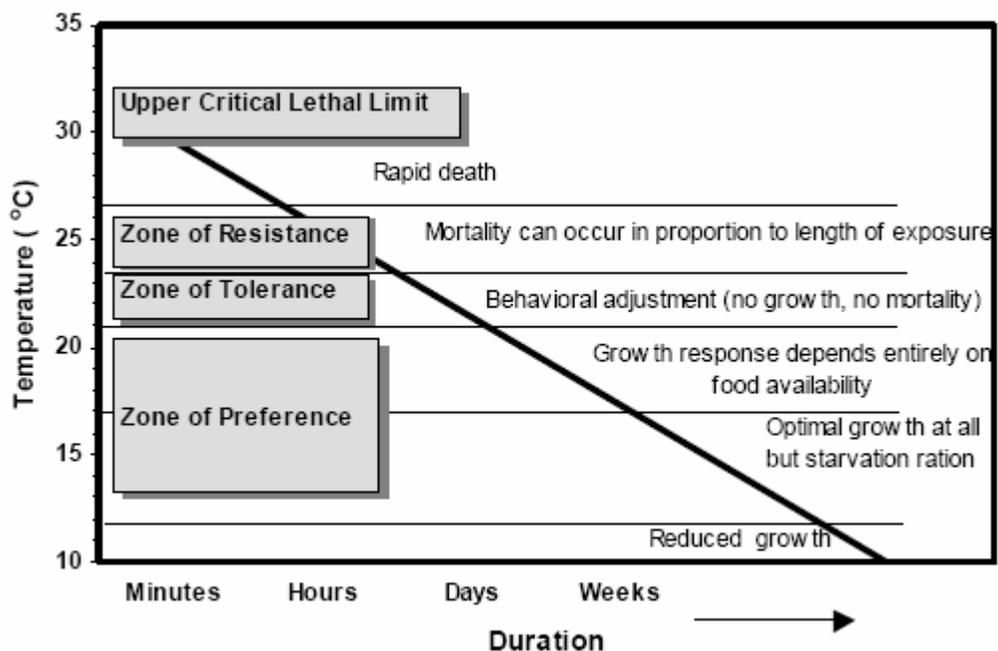


Figure 2. Generalized effects of temperature on salmonids (from Sullivan et al. 2000).

Changes to other trophic levels may also occur with increased thermal radiation from canopy removal. Stream temperature changes may alter the microbial community, algae and invertebrates, which form the energy base for salmonids. However, not all of these changes are necessarily bad for salmonids, depending on changes in light and temperature. Beschta et al. (1987) summarize some of these changes. With additional light, decomposition by microflora increased, promoting increased invertebrate production and thus food for salmonids. However, this benefit would only persist if the input of material to the stream remains constant, as organic matter could continue to be consumed at an accelerated pace. Algal growth and species composition were also accelerated with additional light and warmer temperatures. In warmer streams another effect was a shift to filamentous green algae, resulting in higher levels of trapped fine sediment. The fine sediment allowed for greater levels of oligochaete worms but which were not consumed by the fish in the study (Beschta et al. 1987).

Overall, stream temperature increases can negatively effect salmonids, but the magnitude and extent of these effects can vary. Factors influencing temperature effects include the species

and life history stages involved and the magnitude and timing of changes in the stream temperature regime. Because a major purpose of the DNR HCP is to protect stream habitat for salmonids, direct monitoring of temperature regimes in DNR streams is important outside of the fact that stream temperature is being used as an overall integrator of stream condition.

Purpose of study

The purposes of our study were to 1) continue to collect baseline data on stream temperature conditions in DNR's Olympic Experimental State Forest for the purpose of assessing the long term stream temperature regimes changes within the OESF as the DNR HCP continues to be implemented, and 2) compare the temperature regimes in the OESF streams relative to streams in natural (unharvested) basins.

Methods

Study Area

This study was conducted on the west side of the Olympic Peninsula, Washington, primarily on tributaries to the Clearwater and Hoh Rivers (Figure 3). The rivers originate in the Olympic Mountains and flow westward through glacially carved valleys, across a coastal plain composed primarily of glacial materials, and empty directly into the Pacific Ocean. Elevation ranges from sea level to 2428 m at the peak of Mount Olympus.

Most of the low-lying areas are within the Sitka spruce (*Picea sitchensis*) vegetation zone (Franklin and Dyrness 1979). Common tree species in addition to Sitka spruce include western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), big leaf maple (*Acer Macrophyllum*) and red alder (*Alnus rubra*), with black cottonwood (*Populus trichocarpa*) and willow (*Salix* sp.) common in riparian areas. The bedrock geology of the region consists mostly of uplifted sedimentary rocks formed in the Miocene and Eocene, with a layer of uplifted oceanic basalt in the northern, eastern and southern parts of the Peninsula. Much of the area was glaciated during the Pleistocene. Glacial deposits from alpine glaciers are present in all the major west trending river valleys to an elevation of about 250 m, and are present across most of the coastal plains and foothills to the west. Continental glacial deposits are found on the northern edge of the Peninsula, but our sites were not in this area. The low-elevation coastal climate is very wet with cool summers and mild but cloudy winters. Annual rainfall in the area ranges from 400 mm to 3500 mm, the majority of which falls as rain and snow during the months between October and March. Afternoon air temperatures during the summer months range from 18-27°C, with night temperatures dropping to 7°C. Winter temperatures are cooler with afternoon temperatures around 4°C and decreasing to near freezing at night (National Park Service 1997).

The rivers and streams of this region provide important habitat for several species of salmonids. These include summer and winter steelhead (*Oncorhynchus mykiss*) spring, summer and fall chinook (*O. tshawytscha*), chum (*O. keta*), coho (*O. kisutch*), pink (*O. gorbuscha*), and sockeye (*O. nerka*) salmon, Dolly Varden char (*Salvelinus malma*), and resident/sea-run cutthroat trout (*O. clarki*) (WSCC 2000). Land ownership on the western Peninsula is a mix of public and private owners, including the National Park Service, the United States Forest Service, the Washington Department of Natural Resources (DNR), and a number of large timber companies. Outside of Olympic National Park, most land is actively managed to produce timber.

Site selection

We selected 52 streams for temperature monitoring. Twenty two sites were located on tributaries to the mainstem Hoh River, 10 sites in the South Fork Hoh River basin, 19 sites in the Clearwater River basin and 1 site on small a small tributary to the Bogachiel River, just outside the Hoh basin. Sites were selected to represent a range of conditions typical of tributaries to the Clearwater and Hoh River basins owned by the DNR. Such conditions included basin size, elevation, aspect, geology and forest harvest levels. Because of time constraints and the large number of data loggers needed deploying over a wide geographic area, site selection was generally limited to streams that could be reasonably accessed from a road.

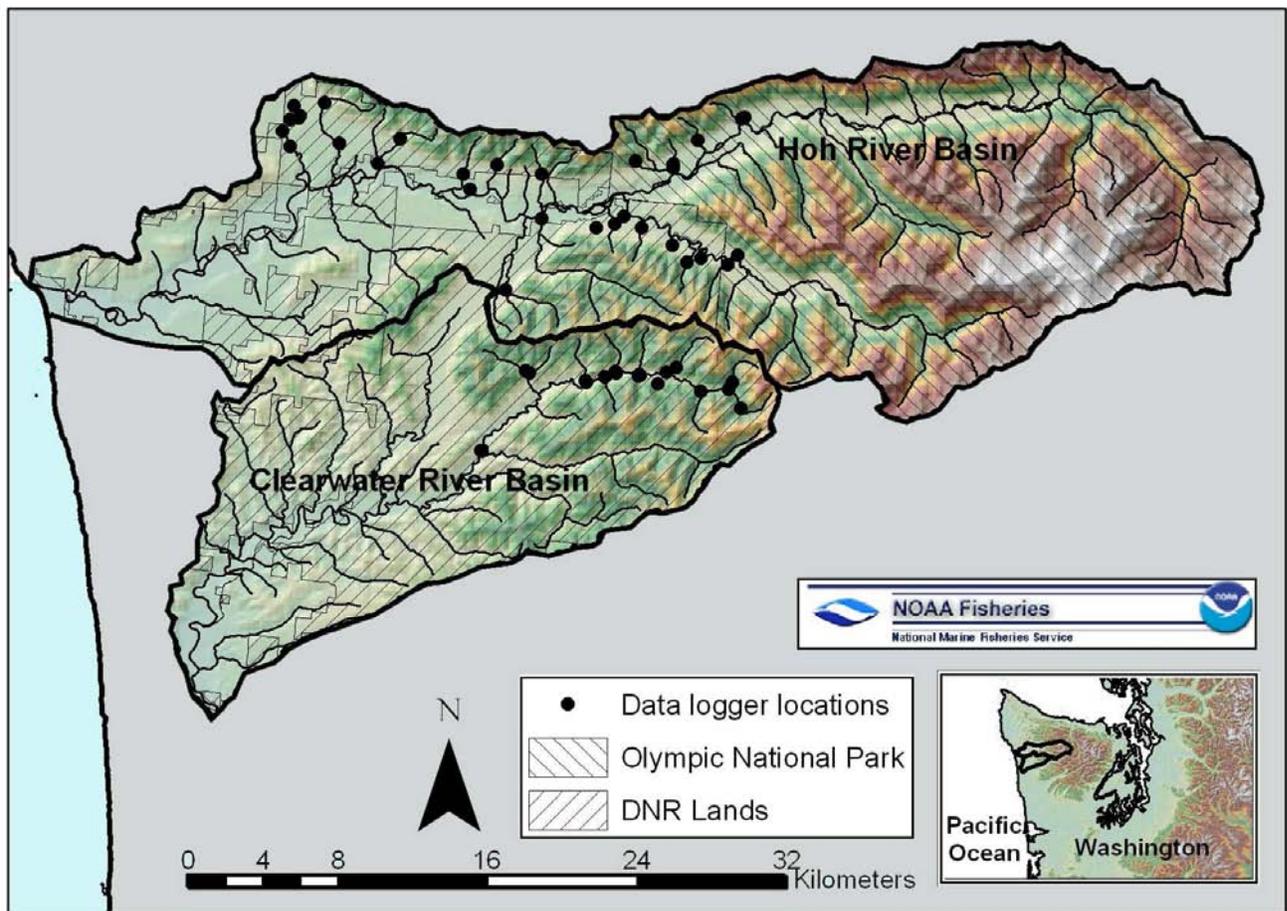


Figure 3. Site map showing tributaries in the Hoh and Clearwater basins where temperatures were monitored.

Because the primary purpose of this study was to compare the temperature regime of streams within actively managed DNR lands with unharvested watersheds, site locations were further restricted to watersheds predominantly owned by DNR or within the Olympic National Park. Sites were selected to sample the range of conditions that exist on actively managed DNR lands and unharvested reference areas owned by the National Park and DNR. Most DNR lands in this region were logged for the first time in the past four decades, leaving two dominant age classes, < 40 years and > 150 years.

Table 1. List of GIS-derived independent variables and various dependent variables related to stream temperature that were examined for correlative relationships.

<u>Independent variables</u>	<u>Dependent variables</u>
<i>Basin parameters</i>	average daily maximum temperature (°C)
sedimentary rock (%)	average daily temperature range (°C)
glacial rock (%)	average daily temperature (°C)
permeable rock (%)	maximum daily temperature (°C)
harvested in last 20 years (%)	total temperature range (°C)
harvested in last 40 years (%)	
harvested in last 100 years (%)	
unharvested (%)	
basin area (km ²)	
 <i>Riparian condition (30 m), basinwide</i>	
harvested in last 20 years (%)	
harvested in last 40 years (%)	
harvested in last 100 years (%)	
unharvested (%)	
 <i>Conditions at datalogger</i>	
elevation (m)	
aspect (degrees)	
 <i>Riparian condition, 30 m wide, 0-200 m upstream from datalogger</i>	
harvested in last 20 years (%)	
harvested in last 40 years (%)	
harvested in last 100 years (%)	
harvested in last 150 years (%)	

Data Collection and Analysis

Stowaway Tidbit submersible data loggers (Onset Computer Corporation, Pocasset, MA) were programmed to store temperature readings every 15 minutes and placed in 52 streams beginning July 1, 2004 and ending August 31, 2004 for a total of 62 days. The accuracy of the Tidbit data loggers is +/- 0.02° C . Data loggers were placed in protective coverings of either hard plastic mesh or perforated PVC pipe, weighted and placed in a pool with good flow. They were then tied with rope to a stationary object such as a root, overhanging tree, or large rock and flagged for reference. When near a road, they were placed upstream of the road crossing. Only data loggers remaining in the stream for the entire time period were used for analyses. Data from 3 of the data loggers could not be used because the data loggers were not submerged at low flows. Thus, data from 49 of the loggers were available for analyses. Microsoft Excel (Microsoft, Redmond Washington) was used to calculate temperature summary statistics for each site (Table 1). Additional statistical analyses were performed using SPSS software, version 13.0 for windows (SPSS, Inc., Chicago, Illinois).

Most watershed characteristics were determined using ArcGIS v.9.0 Geographic Information System (GIS) software (ESRI, Redlands, California) and GIS data layers provided by the DNR. We used TOPO! topographic map software (Evergreen, Colorado) to estimate elevation, stream gradient and aspect for the monitoring locations.

Results

Of all basin characteristics examined, three showed strong correlations to temperature parameters: 1) percent of forest in basin that has been harvested, 2) percent of harvested riparian forest and 3) basin size. All other variables were weakly correlated with temperature parameters. The strongest correlation observed was between the the average daily maximum temperature and the percentage of harvested riparian forest ($r^2 = 0.35$, $p < 0.001$, $n = 49$, Figure 4). A multiple regression including both the amount of unharvested riparian forest and the basin size predicted about half the variation in the average daily maximum temperatures ($r^2 = 0.53$, $p < 0.001$, $n = 49$). Substituting total harvested forest for harvested riparian forest yielded slightly lower but similar predictive power ($r^2 = 0.50$, $p < 0.001$, $n = 49$).

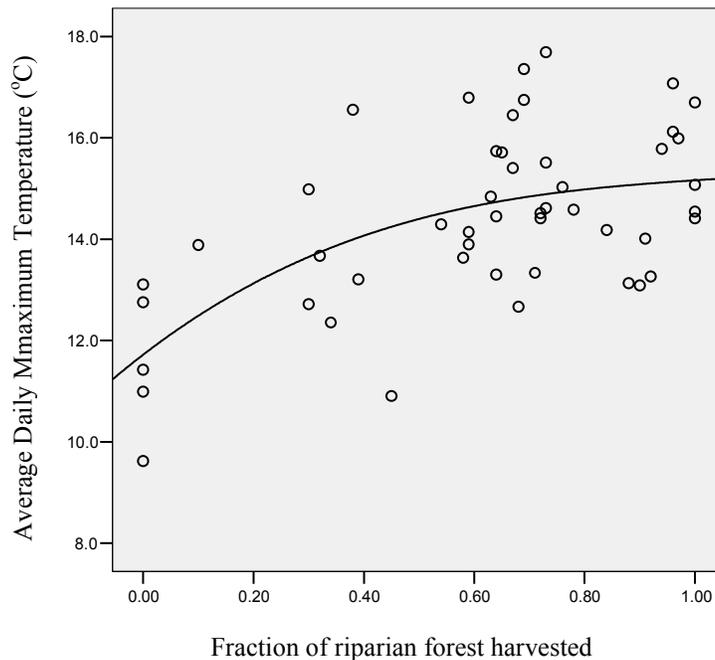


Figure 4. The fraction of riparian forest harvested is the single strongest correlate with average daily maximum temperature ($r^2 = 0.35$, $p < 0.001$, $n = 49$, cubic regression: $\beta_0 = 11.722$, $\beta_1 = 8.372$, $\beta_2 = -7.127$, $\beta_3 = 2.197$).

Measures of temperature fluctuations, such as the average daily temperature range (ADR), were also most strongly correlated with the same three independent variables, with the strongest correlation between average daily temperature range and the percent of harvested riparian forest ($p < 0.001$, $r^2 = 0.21$, $n = 49$). Unharvested basins had stable stream temperatures, with average daily temperature ranges of around 1 °C (Figure 5). Basins that had more than 5% harvest showed a wide range of ADRs. Many harvested basins showed very moderate daily fluctuations of less than 1 °C, similar to unharvested basins, while other harvested basins showed ADRs close to 4 °C.

There was a significant difference in average daily maximum stream temperatures (ADMX) between basins that are unharvested (<5% harvest) and all three classes of basins that have some degree of harvest (0-33%, 34-66% and 67%-95% harvest). There were no significant differences in ADMX between the three classes of basins with some harvest (Dunnetts T3 test, Table 2, Figure 6).

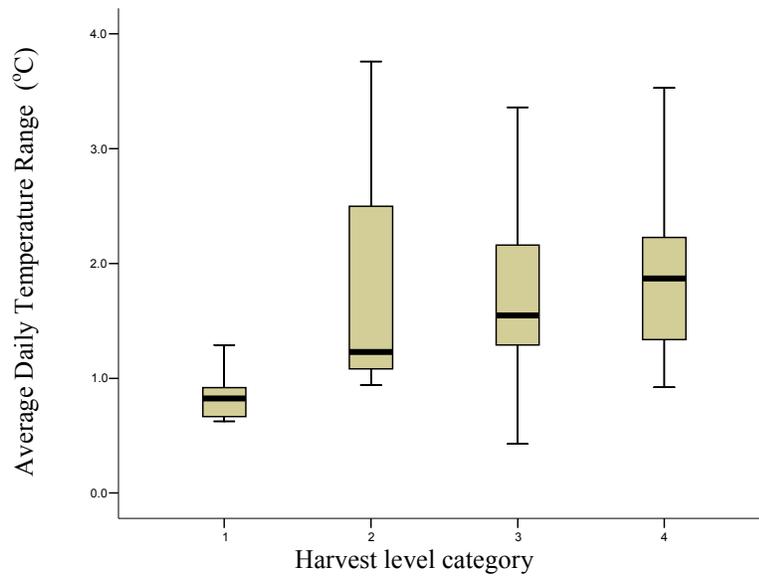


Figure 5. Box and whiskers plot of median and quartiles, comparing average daily temperature ranges of four classes of harvest levels within a basin. Class 1 < 4% harvest (unharvested); 32% < Class 2 \geq 96% harvest; 64% < Class 3 \geq 32% harvest; Class 4 \geq 64% harvest.

Table 2. Dunnett T3 nonparametric pairwise test of means for four classes of harvest levels within a basin. Class 1 < 4% harvest (unharvested); 32% < Class 2 \geq 96% harvest; 64% < Class 3 \geq 32% harvest; Class 4 \geq 64% harvest.

OGC(i)	OGC(j)	mean ADMX	Mean difference (i-j)	Std. Error	Sig.	lower bound	upper bound
4	3	15.08	0.8413	0.505	0.473	-0.593	2.275
	2		0.4996	0.694	0.969	-1.934	2.933
	1		3.4979*	0.686	0.013	0.916	6.079
3	4	14.24	-0.8413	0.505	0.473	-2.275	0.593
	2		-0.3417	0.769	0.998	-2.814	2.131
	1		2.6567*	0.761	0.042	0.097	5.216
2	4	14.58	-0.4996	0.694	0.969	-2.933	1.934
	3		0.3417	0.769	0.473	-2.131	2.814
	1		2.9983*	0.898	0.046	0.054	5.942
1	4	11.58	-3.4979*	0.686	0.013	-6.079	-0.916
	3		-2.6567*	0.761	0.042	-5.216	-0.097
	2		-2.9983*	0.898	0.046	-5.942	-0.054

Twenty four streams had at least one seven day average maximum temperature that exceeded 16.0 °C, and thus did not meet the Washington State Department of Ecology water quality standards for temperature for core salmon rearing and spawning habitat (aka class AA streams; WAC 173-201A-200(1)(c)). All streams that had less than 25% of their riparian forest harvested met the class AA water quality standard, while 85% of streams that had less than 50% of their riparian forest harvested met the class AA water quality standard. In contrast, 61% of all streams that had more than 50% of their total upstream riparian forest harvested did not meet class AA water quality standard for temperature. For streams that exceeded the class AA temperature criterion, the number of days of exceedance ranged from 1 to 48 and averaged 26. All waters monitored in this study were rated by DOE as class AA or higher. A few streams we monitored are also classified as bull trout habitat, meaning that the seven day average maximum temperature should not exceed 12.0 °C. however, we did not analyze streams to assess whether they met this more rigorous standard.

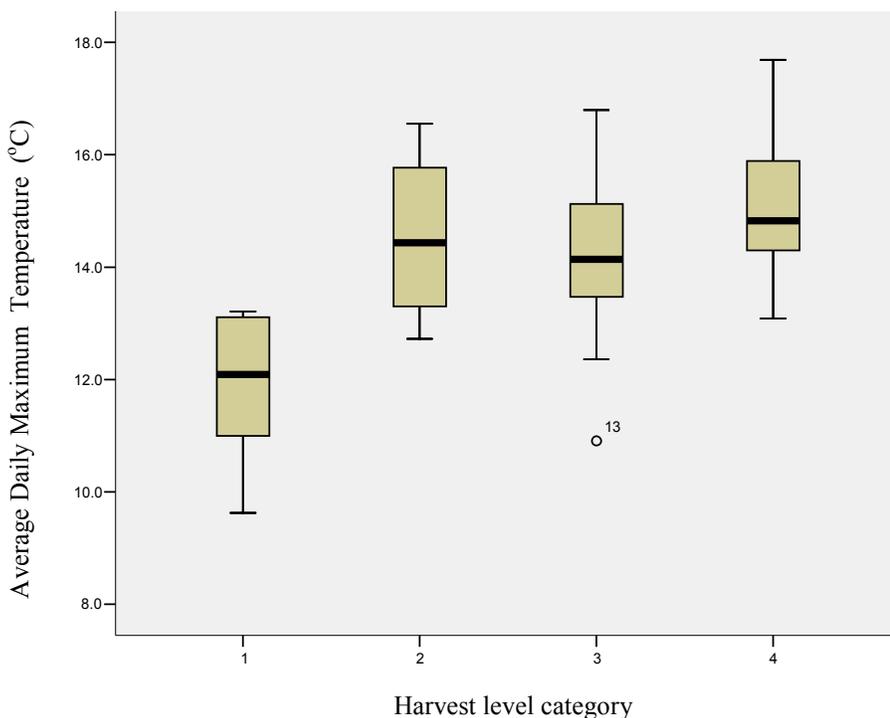


Figure 6. Box and whiskers plot of median and quartiles, comparing average daily maximum temperature (ADMX) of four classes of harvest levels within a basin. Class 1 < 4% harvest (unharvested); 32% < Class 2 ≤ 96% harvest; 64% < Class 3 ≤ 32% harvest; Class 4 ≥ 64% harvest.

Discussion

The results from the 2004 temperature monitoring effort suggest that within the OESF, a majority of streams do not meet DOE water quality standards for temperature, and that stream temperatures in harvested basins are often (but not always) higher and more variable than stream temperatures in unharvested basins. There were a number of streams with high levels of harvest that had temperature regimes similar to natural systems and that did meet DOE water quality standards for temperature. Our analyses showed that the extent of riparian timber harvest or total timber harvest in a basin accounted for about a third of the variation in stream average daily maximum stream temperatures, while riparian timber harvest (or total timber harvest) together with basin size accounted for about half the variation in average daily maximum stream temperatures.

Our findings were similar to results found in other studies comparing temperature changes due to forest management. Hatten and Conrad's unpublished (1995) study concluded that the amount of unharvested forest within a sub-basin was the "best single variable" for predicting mean average hourly and mean daily maximum water temperatures at both managed and unmanaged sites. Similarly, Beschta and Bilby (1987) argue that the immediate riparian environment has less influence on stream temperatures than the cumulative upstream riparian conditions. They suggest that age fluctuations in riparian conditions would not be as effective as consistent older riparian vegetation in keeping stream temperatures cool. Chen et al.'s (1992) study on the relations between old growth patch size and temperature was also consistent with our results. Chen found that the width of an old growth forest patch was extremely influential on internal-patch temperatures. The findings of the study found that temperatures within narrow old growth patches did not mimic those of natural systems due to the amount of solar radiation able to penetrate the vegetation. Only when the patches remained wider than 60 meters were internal temperatures regimes similar to those of large blocks of unlogged forests.

Because of the high degree of overlap between basins that had a high percentage of unharvested riparian forest and total unharvested forest, it is unclear which of the two factors is more important. That is, there were no basins where there was a high degree of riparian protection, but extensive harvest in the uplands. While it might seem intuitively obvious that streams with more unharvested riparian forest upstream are cooler because the bigger trees provide more shade, this is not necessarily the case. For example, Brososke et al. (1997), in a study of 15 small streams in western Washington, could not find a relationship between buffer widths and stream temperatures, but found a strong correlation between stream temperature and soil temperatures outside of the buffer, where harvest had taken place. They concluded this was likely a result of high groundwater inputs to the stream relative to upstream sources, and that the high soil temperatures in clearcuts were heating the groundwater before it reached the stream. Beschta and Taylor (1988) observed increases in stream temperatures over a 30 year period in western Oregon, and found that this was strongly correlated to the cumulative effects of timber harvest within the basin, as opposed to just the direct harvest of timber in the riparian zone. They concluded that this might be in part due to the effects of numerous debris flows resulting from timber harvest activities that occurred in their study area, which likely resulted in wider and shallower streams. Many of the streams we monitored had signs of past debris flows, and this may explain high temperatures in some of the streams in our study.

Implications for salmon

Elevated stream temperatures can be harmful for salmon (Beschta et al. 1987; Sullivan et al. 2000). Temperatures over 16.0 °C exceed the upper limit of optimal temperature for most salmon (Figure 1 and Hokanson et al. 1977, but see Sullivan 2000). Studies have also shown that fluctuations in temperature can be harmful to salmon because they increase stress for the fish and inhibit the ability for acclimation to warming temperatures (Hokanson et al. 1977; Coutant 1999; Torgersen et al. 1999). Negative effects of elevated temperatures to salmonids include increased physiological stress, reduced competitive abilities, reduced foraging opportunities, increased susceptibility to predation and disease, delayed or altered migration patterns, habitat abandonment, and death (Groberg et al. 1978, Holt et al. 1978, Reeves et al. 1987, Sullivan et al. 2000). Lethal temperatures for salmonids generally occur at temperatures of 20 °C or higher, well above what was observed in most (but not all) of the streams in the OESF. Available studies suggest one of the most likely effects to salmonids of elevated stream temperatures of the magnitude observed in the OESF are reduced growth rates (e.g. Brett et al. 1969), which can subsequently affect ocean survival rates, and thus potentially have population level effects. For some salmonids, such as coho salmon and steelhead, the elevated temperatures observed might not necessarily be detrimental. At high levels of food availability, modeled results suggest optimal growth rates for coho might be achieved at temperatures near 17 °C (Sullivan et al. 2000, Figure 7). Conversely, measured growth rates for sockeye salmon indicate that when food is not limiting, the optimal growth rate is less than 15 °C, and drops off rapidly as food becomes limiting (Brett 1965, Figure 8).

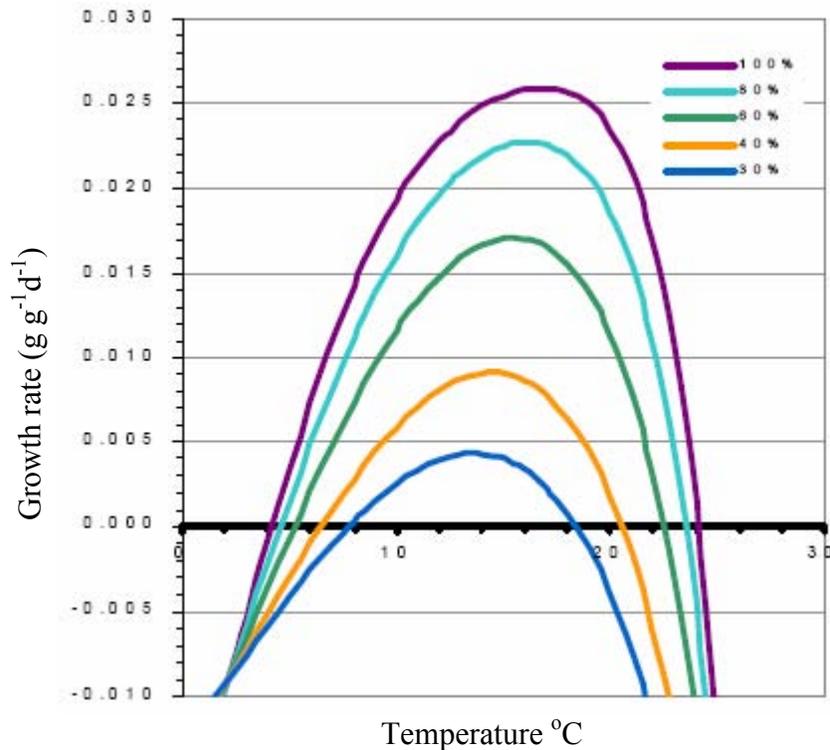


Figure 7. Modeled growth rates of coho salmon as a function of temperature and food availability (from Sullivan et al. 2000). When food availability is 100% of potential food utilization, model results suggest the optimal temperature is near 17 °C. Each line represents a level of food availability relative to saturation levels.

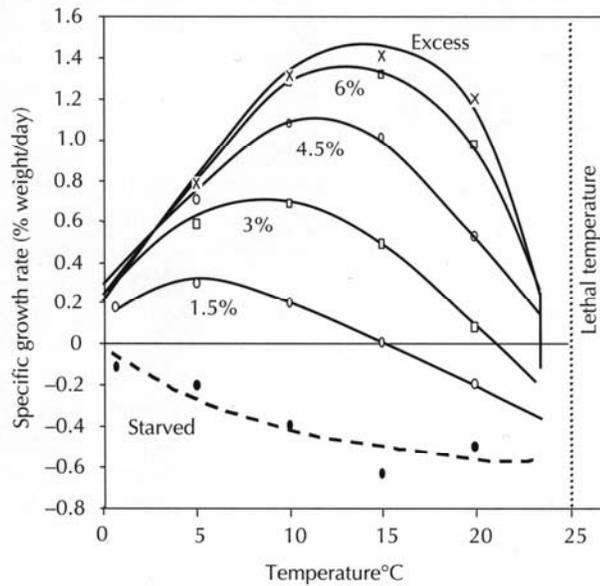


Figure 8. Measured growth rates of sockeye salmon as a function of temperature and food availability (from Brett 1965). When food availability is in excess of growth needs, the optimal temperature is about 15 °C. Each line represents a level of food availability listed as a percentage of body weight. Note that when food is limiting, the optimal growth temperature drops rapidly.

Further, the disease susceptibility of salmonids can go up significantly when exposed to temperatures in the ranges observed in our study. For example, Holt et al. (1975) found that the mortality rate of steelhead, coho and spring chinook from infection by *Flexibacter columnaris* varied from 4-20% among the three species at 12.2 °C and increased progressively to 100% in steelhead and coho salmon at 20.5 °C, and to 70% in Chinook at that temperature. For all three species, as temperature increased, the minimum time to death also increased dramatically. Again for steelhead, coho and spring Chinook, Groberg et al. (1978) found similar relations between temperature and mortality when fish were exposed to the bacteria *Aeromonas salmonicida*, with mortality rates ranging between 18-54% at 12.2 °C and between 86-96% at 20.5 °C.

Given the multiple direct and indirect effects, both positive and negative that stream temperature increases have on salmonids, how these effects vary with both species and life history stage, how stream temperature itself varies both spatially and temporally, and how the physical habitat of streams and the use of that habitat by different salmonids is highly variable, it becomes clear why it is difficult to determine the population-level effects of small (1-4 °C) stream temperature increases. Given the absence of additional data, the DOE temperature standard is probably the best overall criterion for estimating whether stream temperatures in the OESF are likely to negatively affect salmonids.

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