

**Summer Temperatures of Skagit Basin Headwater Streams:
Results of 2001 – 2003 Monitoring**

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Summary of Key Findings

- Skagit headwater streams show a range of sensitivities to thermal inputs from surface processes (e.g. sunlight, air temperature). Some sites located close to channel heads had a stable temperature regime moderated by cool groundwater inputs. However, most sites were responsive to day-night and week-to-week changes in heat inputs, and thus appear to be surface-flux driven.
- Maximum temperatures at Skagit headwater sites were generally similar to those previously recorded in headwater streams monitored elsewhere in western Washington, especially during 2001 and 2002 when summer weather was fairly typical. Skagit tributaries were warmer than other sites during the unusually warm and dry summer of 2003.
- Although the majority of monitoring sites did not exceed regulatory temperature standards, a sizable number did. Of the 97 sites over three years, 24% exceeded the AA standards currently used and 12% exceeded the proposed water temperature system using Core Rearing standards. The less frequent exceedence of the Core Rearing standard suggests that the newer standard is more lenient. This study did not assess which temperature standard is more suitable for supporting downstream fish populations or watershed health.
- Skagit headwater streams, especially those that are surface-flux driven, appear to be sensitive to riparian forest conditions. Clearcut and debris-flow-scoured streams had significantly higher maxima and wider daily ranges during warm periods than did forested or buffered sites.
- Although temperature maxima generally increased in a downstream direction during the typical summers of 2001 and 2002, downstream warming and cooling were both observed during the unusually warm and dry summer of 2003. This appears to contradict the accepted pattern (Beschta et al. 1987, Moore et al. 2005) that streams experience the greatest warming during the lowest flows. We speculate that temperatures during very low flows are increasingly influenced by groundwater inputs and inter-bed exchange, which have a greater relative influence when surface flows are smallest.
- Buffers comprised of 10-30 m of unthinned forest along each side of headwater streams are largely effective at mitigating increases in temperature maxima. Buffered streams have a greater daily range than fully forested streams, a pattern which resembles clearcut streams. Sparse or blown-down buffers appeared to provide little temperature mitigation.
- Regression analysis suggests that lower gradient streams require more shade and thus wider buffers for equivalent temperature mitigation, relative to steeper streams.
- Further research is needed to determine the effects of temperature changes in headwaters affects biological productivity and the extent that warmed water propagates downstream to potentially affect salmonids. This will strengthen the applicability of these results to riparian management strategies.

Introduction and Objectives

The temperature regime of a stream plays a significant role in determining the distribution and productivity of fish, amphibians and other biota living within the stream channel and saturated portions of the bed (Beschta et al. 1987). Because of the mountainous environment and mild temperatures, temperature regimes in Skagit tributaries are relatively cool (<16 C) throughout most of the year and thus support species adapted to this thermal regime. Salmon and trout, the most highly valued aquatic species in the basin, benefit from cool temperatures both within reaches they use and in the many small (i.e. 1st and 2nd order) tributaries that supply cool water and food to downstream spawning and rearing reaches.

Many Skagit tributaries originate in managed forest lands where logging of streamside forests can modify stream temperature regimes, primarily by allowing increased sunlight exposure (Beschta 1987, Johnson and Jones 2000). Temperature changes in headwater streams can influence fish located downstream in two ways: 1. Tributary influx affects the temperature regime of downstream receiving waters (i.e. refugia at inputs, cooling after mixing), and 2. Modified temperatures can affect the productivity of headwater organisms (Johnson and Jones 2000, Moore et al. 2005) that affect the export of insects and other food resources to downstream fish-bearing waters.

Headwater stream temperatures in the Skagit basin were monitored in 2001, 2002 and 2003 to evaluate peak summer temperatures and the response to forest management. More specifically, the objectives were to:

1. Characterize temperature regimes of headwater streams within the basin during the summer peak-temperature period,
2. Compare observed peak temperatures to those measured in headwater streams elsewhere in Washington,
3. Compare observed peak temperatures to both the current and proposed regulatory standards, and
4. Evaluate the role of riparian logging, shade, aspect and channel dimensions in influencing segment-scale temperature change.

Background Studies and Concepts

A sizable body of research has documented temperature regimes and environmental controls for rivers and fish-bearing streams in the Northwest (Beschta et al. 1987). Because headwater streams have received far less attention, the findings from larger streams inform the expectations of temperature dynamics in headwater streams. Because several existing syntheses of stream temperature dynamics are available (Beschta, et al. 1987, Stillwater Sciences 2001), we have not included a detailed literature review. Instead we set the context for our results by summarizing previous temperature studies of headwater streams and listing the key principles of temperature dynamics and assumptions that have shaped the interpretation of our data.

Several studies have investigated temperatures of headwater channels in forested portions of western Washington (i.e. Caldwell et al. 1991, Jackson et al. 2001, Black 2001). Although all three evaluated the effects of riparian logging, the conclusions were mixed. For instance, Caldwell et al. (1991) found that temperature increases in clearcut segments were apparently negated by cooling in downstream shaded reaches (though tributary influx may have contributed). The other two studies, both in the western Olympic Peninsula, found both warmer and cooler stream temperatures below clearcuts. In Jackson's (2001) sites, cooler post-logging temperatures were attributed to shade from post-logging slash cover and the much cooler summer weather the year after logging. Black (2001) found post-harvest temperature increases in channels flowing from small wetlands but not for those originating at springs. Clearly there

are a number of important site-scale and weather factors that affect temperature sensitivity of headwater streams.

These and other temperature studies provided the following key assumptions and expectations that influenced this study:

Temperatures in headwater streams are highly variable over time and between streams (Beschta et al. 1987, Jackson et al. 2001). This supports the benefits of numerous spatially-dispersed monitoring sites with several summers of monitoring.

The warmest temperatures of the year produce disproportionate stress to biota and fish. We assume that changes in the thermal regime from that of a mature forest may lead to changes in biological and chemical processes that could adversely affect salmonids (Johnson and Jones 2000).

Temperature increases that exceed regulatory guidelines are ecologically relevant. Although the relevance of established regulatory thresholds has been debated (e.g. Ice et al. 2005), they provide a useful benchmark for comparison.

Headwater streams may respond to similar physical processes as larger fish-bearing streams:

- **Because direct sunlight is a dominant heating mechanism, logging of riparian forests is potentially an important land use effect upon stream temperatures** (Beschta et al. 1987, Johnson and Jones, 2000). Although stream temperatures are affected by numerous physical mechanisms, sunlight is the one input factor most affected by land use.
- **Groundwater inputs and exchange can strongly affect stream temperatures** (Johnson and Jones 2000, Story et al. 2003).
- **Small streams are constantly adjusting to local energy inputs and losses, which fluctuate at small scales (hourly or 10s of meters).** Because they are very shallow, headwater streams may be particularly sensitive to changes in energy flux (Poole and Berman 2000) and are not likely to reach an equilibrium temperature.

Heat introduced to headwater streams may be routed to fish habitat downstream (Beschta et al. 1987). Although stream temperatures may decrease from intermixing of cooler water into a heated stream, downstream reaches will still receive warmer water than they would have if the warming had not occurred. Specifics of temperature routing from headwater streams are not yet well understood, however.

And finally, we have assumed that standard tools for monitoring stream temperatures, shade and stream attributes are adequate for monitoring. Despite their limitations, recording thermographs, spherical densimeters and other field tools were used because they are the standard instruments for measuring relevant features and processes.

Methods

Study Area

The Skagit basin is located in the northwestern Cascade Mountains in Washington state (Figure 1). The climate is temperate with abundant rainfall (1500-2500 mm or 60-100 inches/year at monitoring sites). Although the majority of rain falls between October and June, occasional summer rains are not uncommon. Maximum stream temperatures occur when extended sunny

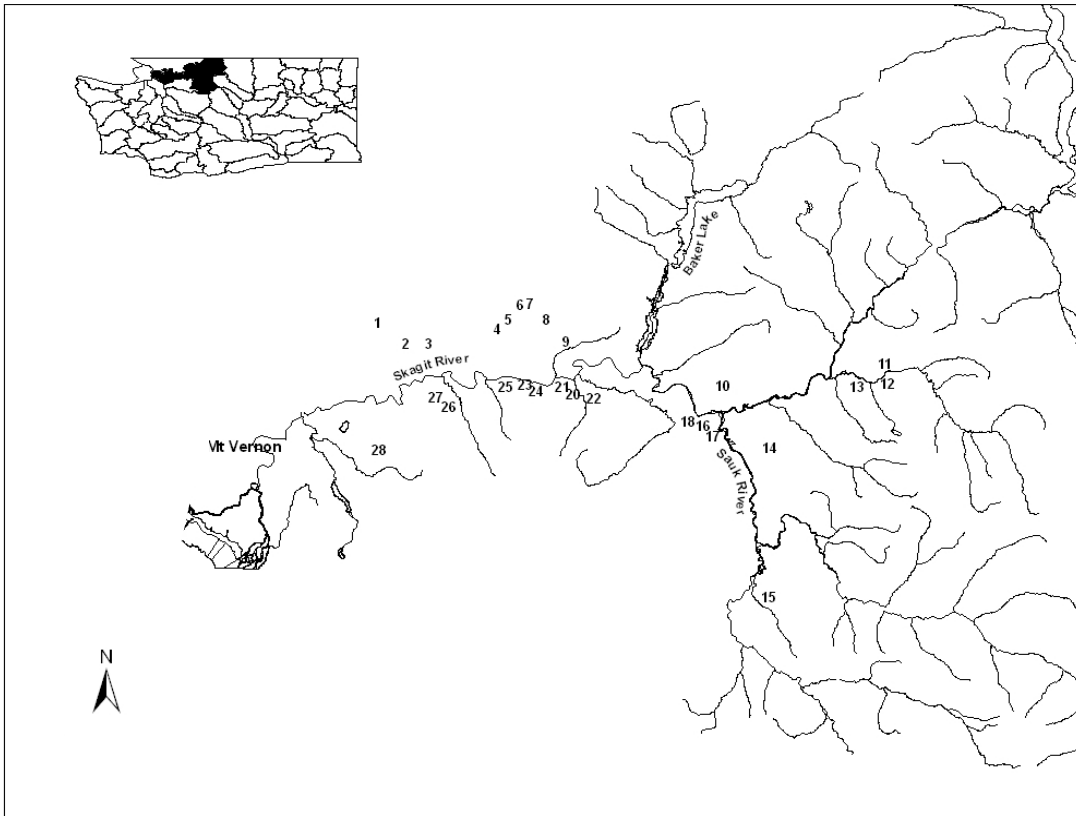


Figure 1. Location of headwater temperature monitoring sites in the Skagit basin in northwestern Washington. Monitoring sites were concentrated in the middle and lower portions of the basin where most state and privately-owned timberlands are located.

and hot periods coincide with low flows, normally between late June and early-September, depending on the year.

Temperature monitoring was performed in the western and central portions of the Skagit basin which have been managed over the past century for timber production using primarily clearcut methods. Since the early 1990s, it has been common to retain “buffer strips” of unlogged timber within 20-50 feet on either side of all fish-bearing and larger (>~3 m) non-fish-bearing streams. Smaller tributaries typically receive no buffer except where within unstable terrain. Study streams are located between 100 and 800 m in elevation (300-2600’). Although all sites are within the Western Hemlock Climax Zone (Franklin and Dyrness, 1978), Douglas-fir, western redcedar, and red alder are also prevalent riparian tree species.

Monitoring Designs

Temperature monitoring occurred during the summers of 2001, 2002 and 2003, though the thermographs placement strategies differed between years. The 2001 effort involved 2-3 probes each at a handful of clearcut and buffered sites (Table 1). The monitoring in 2002 and 2003 included a wider distribution of tributaries (Figure 1) across the basin.

In 2002, 20 segments were monitored at upstream and downstream ends to evaluate riparian forest conditions and basin aspect (North vs. South). In 2003, an adjacent segment design was used to evaluate

temperature changes within 150 m segments with differing riparian forest conditions (Figure 2). Stream channel and riparian forest attributes were documented to assess the roles of channel width, gradient, buffer width and shade (Table 1). Weather conditions at local weather stations were slightly cooler than the long-term average in the summer of 2001, near average in 2002 and unusually warm in 2003 (Appendix 1).

Table 1. Summary of headwater stream temperature monitoring in the Skagit basin in 2001, 2002 and 2003.

Year	No. of thermographs	Sites monitored *	Criteria for thermograph location	Site characteristics documented
2001	12	#1, 2, 20, 21, 22	Top and bottom of buffered and clearcut segments (variable length)	Channel width at thermographs
2002	40	#1, 2, 4-8, 10-13, 18, 17, 22-27	Top and bottom of segments (variable length) that were clearcut (6 segments), buffered (7), forested (5) and debris flow (2) – sites split between N & S aspects	Channel width at thermographs
2003	44	#1-3, 5-9, 13-17, 28	Top and bottom of upstream/downstream segments (150 m) with contrasting riparian canopy (Figure 2): forest (13), buffer (11), clearcut (3).	Bankfull and wetted channel dimensions, tributaries, buffer widths and shade within each segment.

* - Site locations are shown in Figure 1

Field Methods

Recording thermographs (Onset Stowaways) were calibrated according to TFW standards (Schuett-Hames, et al. 1999) and programmed to record maximum hourly values. Thermographs were housed in protective PVC tubes placed in relatively deep pools to maximize submersal. Dates of operation are shown in Appendices 2, 3 and 4.

Site conditions were documented at monitoring sites. In 2001 and 2002, bankfull channel widths were measured at each probe location. Riparian forest categories - clearcut, buffer or mature forest - were determined from visual reconnaissance and aerial photography.

In 2003, channel and riparian conditions were measured at each probe site and at four equally-spaced locations within each segment (Figure 2). Shade was measured using a concave spherical densiometer (four readings averaged). Channel dimensions (bankfull width, wetted width and depth) were measured during low flow conditions as was the width of riparian forest buffer (where present) on each side. Tributaries and seeps were recorded and characterized by bankfull width and surface flow category (e.g. continuous flow, patchy flow, dry).

Data Analysis

Once thermographs were recovered and data downloaded, data was imported to Excel for analysis. Data from each site were screened to look for evidence that the channel had temporarily gone dry or other anomalies. For each year, data were trimmed to the operating season common to all thermographs, except as noted in appendices. For all statistical tests, observed temperatures were compared only between sites for the same year, due to inter-annual weather differences noted previously (Appendix 1).

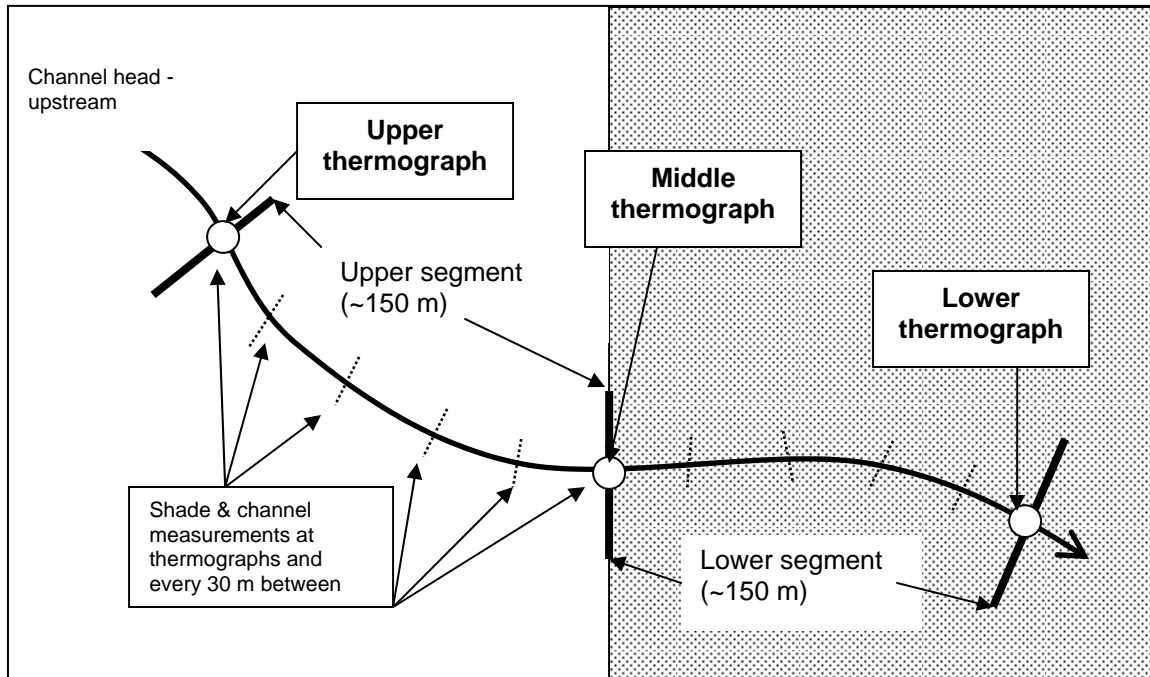


Figure 2. Arrangement of temperature and channel monitoring locations in a 2003 monitoring site. Shading portrays different forest conditions for adjacent segments. Some sites included three stream segments and four gages.

The series of hourly temperature values from each site were reduced to produce three statistics (Table 2) used for most analyses. The “instantaneous maximum” is the highest temperature recorded during the study period and is a statistic commonly cited in temperature literature and regulatory standards. We also calculated the “7-day average daily maximum” (7-DAD maximum), by finding the maximum value of the 7-day running average of daily maxima. The 7-DAD maximum is presently used for state temperature standards in Oregon and is proposed for Washington. The 7-day average daily range was calculated by averaging the daily range (daily

Table 2. Key temperature statistics used in this study.

Statistic	Definition
Seasonal Maximum	Maximum temperature recorded during the operating season.
7-DAD Maximum	Highest 7-day average of daily maxima during the operating season.
7-DAD Range	7-day average of differences between daily maxima and minima over the same period for which the 7-DAD Maximum was recorded.

maximum minus daily minimum for each day) for the 7 days when the 7-DAD maximum was recorded. This statistic is intended to document the daily temperature fluctuations during the period of greatest overall temperature stress, but may not reflect the period with the widest daily ranges. Focusing on daily ranges during this 7-day period, rather than the entire season, was intended to avoid cool and cloudy portions of the summer when water temperatures are moderate and daily ranges are relatively narrow.

Comparison between riparian treatments (e.g. clearcut, buffer, forest) were made using 2002 temperature data because they offered the best balance of sites in each treatment category. We compared between categories using the non-parametric Mann-Whitney test which does not require a normal distribution. One-sided tests were used to determine whether temperatures were warmer in the category with less riparian canopy. A threshold p-value of 0.10 was used to identify statistically significant differences using the Mann-Whitney tests.

The effect of various contributing factors (riparian shade, channel width, etc.) on temperatures was tested using the 2003 sites because the data collected that year included quantitative documentation of key conditions of the upstream segments (Table 1). The relationship between temperatures and segment conditions were tested using multiple regression analysis (p-value < 0.10 to identify significant predictors). We analyzed all segments, including adjacent segments, together (e.g. Figure 2) to maximize the sample size, even though this pooled non-independent sites. This limitation was accepted because the analysis tested the influence of local (<150 m) upstream conditions regardless of conditions further upstream. Because the variability introduced by conditions more than 150 m upstream was unaccounted for in the analysis, the influence of the local conditions analyzed was, if anything, underestimated.

Results and Discussion

Summary of Monitoring Site Characteristics

The 28 temperature monitoring sites are distributed through state and private timberlands in the Skagit basin (Figure 1). Sites were chosen that: 1. Represented several typical canopy categories (i.e. clearcut, forested, buffered) and, 2. Had been observed to have continuous surface flow during previous summers. Randomized site selection was not possible because available stream maps (i.e. DNR hydro layer) show only a small proportion of existing headwater streams and thus provide an incomplete representation of potential sites. Secondly, we preferentially chose streams known to have surface flow through the summer season to avoid monitoring intermittent segments likely to go dry prior to summer peak temperatures. An advantage of monitoring perennial streams is that they are more likely than intermittent streams to influence stream temperatures in fish-bearing reaches downstream.

Sites categorized as 'clearcut' or 'buffer' had been logged within ten years prior to monitoring. Buffers vary in width (ranged from 6-30 m each side) and had minimal to moderate windthrow impacts since harvest. The 'clearcut' category in 2002 included three segments that were logged to the stream edge and three with thin buffers (<10 m) that had mostly blown down. Riparian forests aged 10-30 years were categorized as 'plantation' due to extensive riparian regrowth that provided more than 50% shading. 'Forest' sites had mature forest aged 50 years or older. Two sites monitored in 2002 had been scoured by debris flows the previous winter so were placed into a separate category due to increased temperature sensitivity (Johnson and Jones 2000).

All streams appeared to be non-fish bearing on the basis of small flow, high gradient and/or lack of observed fish. Judging by the channel sizes and local experience with headwater channels, we interpret most, if not all, to be first or second-order streams. Channel bankfull widths average about 2 m (range =

0.4 – 4.8 m) and summer wetted widths were roughly half the bankfull widths. Channel gradients measured at the 2003 sites ranged from 8 to 44% and averaged 28%.

Observed Temperature Regimes

The headwater streams monitored showed a range of temperature patterns. One observed temperature pattern involved sites with consistently cool temperatures (see Figure 3, Upstream gage) assumed to reflect a close proximity to a spring or major groundwater source. All such potentially “groundwater-driven” patterns were observed at uppermost monitoring stations. Seasonal changes were slight and the daily changes at these sites were generally less than 0.5 C.

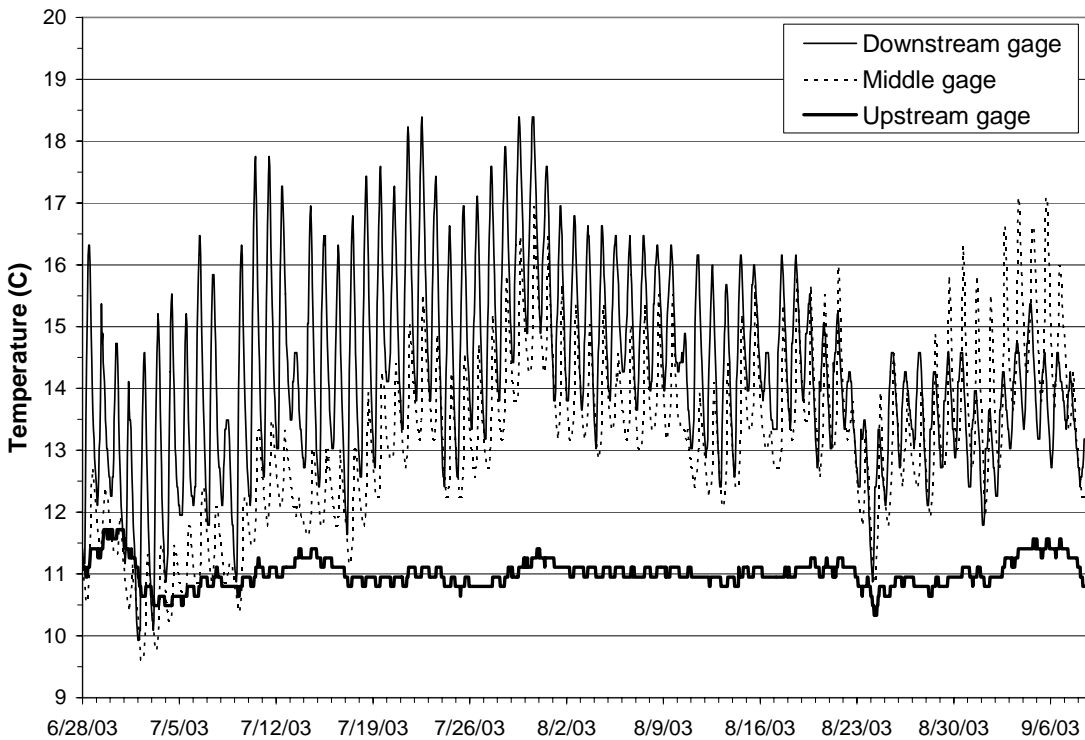


Figure 3. Hourly temperatures for summer 2003 at three gages at the Site #14 (Figure 1) illustrate the two temperature regimes observed. The upstream gage has a narrow daily and seasonal variation that suggests a groundwater-driven thermal regime. In contrast, the middle and downstream gages show greater temperature fluctuation that indicates moderate and strong levels of surface energy influx, respectively. The moderately surface-driven middle gage resembles the greatest number of monitoring sites from this study.

The other observed temperature regime was at streams which changed by 3 C or more from pre-dawn lows to hot summer afternoons (Figure 3, Downstream gage). These “surface-influenced” sites likely reflect a rapid response to surface energy inputs, which change greatly through the daily cycle. Most monitoring sites display a moderately surface-driven regime with daily swings of 1 to 3 C. Readers can infer the general temperature regime of individual sites by comparing the 7-DAD Range values documented in the Appendices with these ranges. Riparian forest canopy appears to influence daily temperature ranges, as discussed later in this report.

From our data in 2001, 2002 and 2003, the seasonal maxima and 7-day-average-daily maxima for most (66%) sites were recorded in the latter half of July. Nearly all of the remaining sites peaked in either August or the first half of September. In virtually all cases, the seasonal maximum and the 7-DAD maximum occurred in the same period. From this, we recommend that monitoring projects designed to document summertime maxima in similar streams deploy thermographs from mid-June through late September.

Comparison to Other Headwater Temperatures in Western Washington

We compared the temperatures recorded in Skagit headwaters to results from three previous headwater studies elsewhere in western Washington (Figure 4). Most of the other data were collected in the western Olympic Mountains and Willapa Hills, which are climatically similar to the Skagit basin but perhaps slightly milder due to closer proximity to the Pacific coast. Still, the Skagit headwater temperatures were similar to observations elsewhere, especially temperatures recorded in 2001 and 2002 which had relatively cool and typical temperatures, respectively. This similarity suggests that temperature regimes and management sensitivities of Skagit headwater streams are not dissimilar to those in other parts of western Washington.

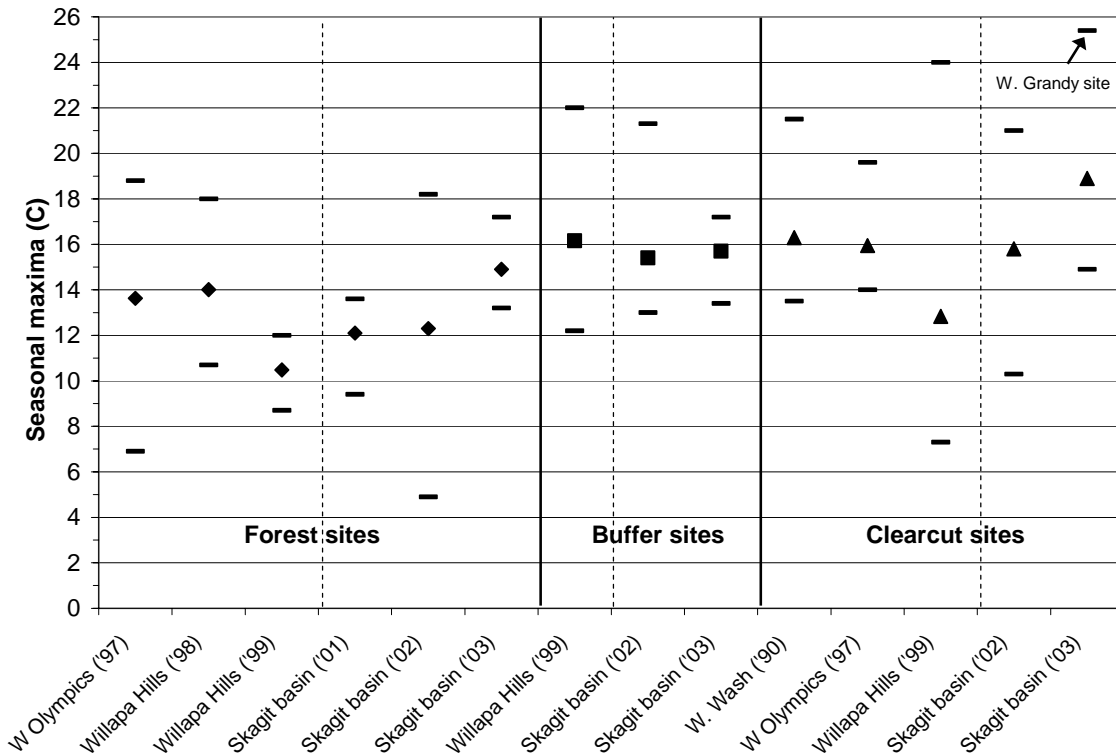


Figure 4. Comparison of seasonal maximum stream temperatures observed in this study (Skagit basin) with previous headwater temperature studies in western Washington. Central symbol indicates average within each location/category; dashes indicate minima and maxima. Data sources: Western Olympics – Black 2001, Willapa Hills – Jackson et al. 2001, Western Washington - Caldwell et al. 1991. Note that Willapa Hills data were collected between mid-June and mid-August (Rhett Jackson, personal communication) and thus may have missed the seasonal maxima if it occurred outside this period.

However, the stream temperatures we documented during the unusually warm summer of 2003 were warmer overall than previous studies. The seasonal maxima for the Skagit sites were warmer than for similar categories elsewhere in terms of averages and minima, but not maxima (Figure 4). It is noteworthy that the 2003 maximum at the West Grandy site (25.4 C) is warmer than any of the temperatures recorded among the other western Washington studies (Figure 4). Because this site is considerably warmer (6 C) than even the next warmest 2003 Skagit site (Figure 4), we suspect that atypical site conditions contributed. During a field visit in mid-summer 2003, low flow volumes and the relatively low gradient (9%) combined to produce very slow water velocities that maximized solar exposure. Perhaps 2003 temperature data from other parts of western Washington will become available to help determine whether unusually high temperatures were recorded elsewhere as well.

Comparison of Maxima to Regulatory Standards

Comparing the observed headwater stream temperatures to Washington state standards was complicated a proposal to change the structure of water quality standards as this report was being written. Given this transitional situation, we compared observed values to both the existing and proposed standards. This allows temperature performance to be compared to both past and future studies here and elsewhere. It also allows comparison between compliance relative to the two standards for the same monitoring data.

Prior to 2003, maximum temperatures were determined on the basis of “Use Classes”. Under this system, maximum temperatures are not to exceed 16 C for Class AA (“extraordinary”), and 18 C for Class A (“excellent”). By virtue of their locations, all streams in this study were classified as “AA” except for the two western-most sites (#1 Handy 4 and #23 Hellgrammite), which are classified as “A”. These streams are rated “A” simply because they flow into tributaries that enter the Skagit below River Mile 25. Otherwise, the “A” sites are sufficiently similar to the “AA” sites in terms of elevation, climate, and land use such that they would be no less likely to meet the “AA” temperature standards. For the sake of simplicity, all headwater streams were compared against the “AA” standard.

The new standards (see WAC 173-201A-200) are based on aquatic life uses (fish species and life stages) and each use category has a threshold for the highest 7-day average of daily maxima (AKA “7-DAD maximum”). Among our study sites, streams that were formerly Class AA are now termed “core spawning and rearing”, and the threshold for the 7-DAD average is 16 C. Former Class A streams are termed “rearing habitat” and have a target of 17.5 C. Although none of our headwater sites are thought to provide fish habitat, we understand that upstream tributaries receive the same rating as downstream waters. All sites were compared to the “core spawning and rearing” standard for the reasons mentioned in the previous paragraph. Data from all stream monitoring stations and years were assessed. Figure 5 illustrates that numerous headwater sites were warmer than the AA standard (left portion of Figure 5), especially in 2002 and the unusually warm summer of 2003. Most (78%) sites that exceeded 16 C have upstream areas affected by timber harvest (clearcuts with or without forest buffers) and the effects of reduced shade are examined in detail later in this report. The sites that did not exceed 16 C include 87% of forested sites and 52% of managed streams. Caution should be used in extrapolating these percentages across the landscape because sites are not independent and sample sizes differ between treatments over the three monitoring years.

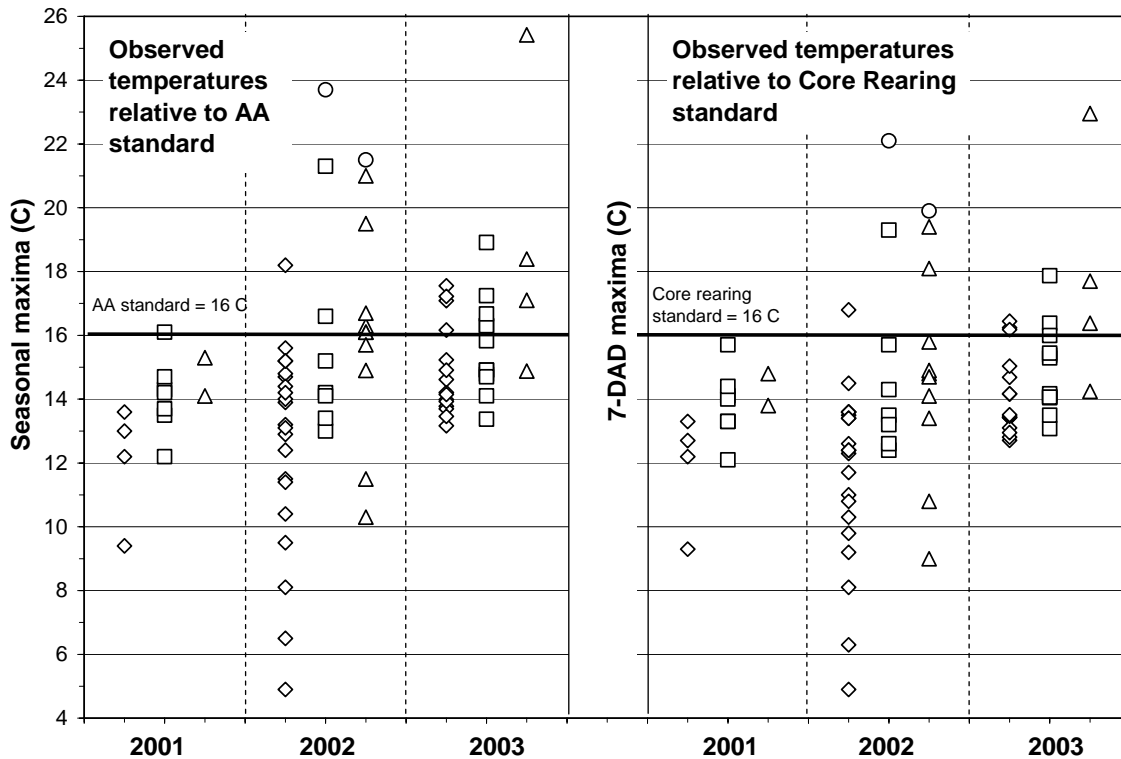


Figure 5. Observed maximum temperatures at Skagit headwater sites compared to regulatory Class AA and Core Rearing standards. Diamonds are forested sites, squares are buffers, triangles are clearcut and circles are debris flows.

Of the temperatures recorded, fewer sites (14 relative to 23) exceeded the proposed Core Rearing standard than the “AA” standard (Figure 5, right portion). Even though the target temperature is the same for both standards, the 7-DAD maximum was generally about 1 C cooler than the instantaneous maximum for the sites in this study and the differences were greater for the warmest streams. This 1 C difference between the seasonal and 7-DAD maxima is similar to findings for headwater streams in the western Olympics (Black 2001).

It appears that both regulatory standards reasonably describe the upper range of temperatures observed among the forested headwater streams in this study, at least for summers with near normal temperatures. Among the 24 total forested sites monitored in the typical summers of 2001 and 2002, only one exceeded both the AA and Core Rearing standards. The unusually warm temperatures at that particular site (#23, “Round Again”) could be because it is one of the widest channels in this study and is located downstream of an immature plantation which provides only partial shade. Although numerous forested sites exceeded both standards in the unusually warm 2003 summer, the majority (75-83%) still did not (Figure 5).

Differences Between Riparian Forest Categories

A key objective of this monitoring project was to determine whether headwater stream temperatures are affected by riparian logging. Although many studies have shown that stream temperatures increase after logging, it is argued that headwater streams are less sensitive because they are “groundwater driven”. We

used the 2002 data to test for differences between forest categories because a sufficient number of clearcut, buffer and forested sites were monitored (Table 2).

Among the 2002 monitoring sites, buffers appeared to mitigate maximum temperatures such that they were not significantly warmer ($p < 0.10$ for one-sided Mann-Whitney test) than forested streams (Table 3). In contrast, maxima in clearcut and debris flow scoured channels were significantly warmer than the either forested or buffered sites in all cross-category comparisons. The ranking of categories from coolest to warmest was identical for both the instantaneous and 7-DAD maxima: forest and buffered sites were cooler than clearcut sites ($p < 0.10$), which were cooler than debris flow scoured sites ($p < 0.10$).

Table 3. Results of Mann-Whitney test for differences (one-sided) between riparian categories among 2002 Skagit headwater sites. Shaded cells indicate statistically significant ($p < 0.10$) differences; the darker shading indicates highly significant ($p < 0.01$) differences. For instance, the upper right shaded cell indicates that there is a less than 10% probability that maximum temperatures in debris flow sites are not warmer than for clearcut sites.

Temperature statistic:	p-value for difference between riparian categories:					
	Forest < buffer	forest < clearcut	forest < debris flow	buffer < clearcut	buffer < debris flow	clearcut < debris flow
Instantaneous maxima	> 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
7-DAD Max	> 0.10	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
7-DAD Range	< 0.10	< 0.01	< 0.10	< 0.01	< 0.10	> 0.10
Number of sites: Forest – 5, Buffer – 7, Clearcut - 6, Debris flow – 2.						
Due to small number of debris flow sites, the minimum p-value for comparisons is 0.10.						

The buffered streams in this study, however, had a significantly greater ($p < 0.10$) daily temperature 7-DAD range than forested streams during periods of warm temperatures (Table 3, Figure 6). Clearcut and debris-flow-scoured streams had significantly greater daily ranges than those in buffers or forest. More interestingly, the daily temperature ranges of debris flow sites were not significantly greater ($p > 0.10$) than clearcut sites, a pattern that differs from the maxima. This expanded temperature range in clearcut and debris flow scoured channels presumably represents the response to the greater heat influx from increased sunlight exposure relative to forested streams, and is consistent with previous studies of forest streams (Beschta et al. 1987, Johnson and Jones 2000).

Daily low temperatures during warm periods, which affect the daily ranges, do not appear to differ much between forest categories (forest, buffer, or clearcuts), suggesting that the physical processes by which heat is lost during the night are not greatly affected by forest canopy. The exception involves the two debris flow scoured channels monitored in 2002, where daily lows were 4-6 C warmer than non-scoured streams, including clearcuts. We suspect that this results from heat conduction through the night from sun-warmed bedrock, perhaps in conjunction with reduced opportunities for heat conduction into an alluvial streambed, which was scoured by the debris flow (Johnson and Jones, 2000).

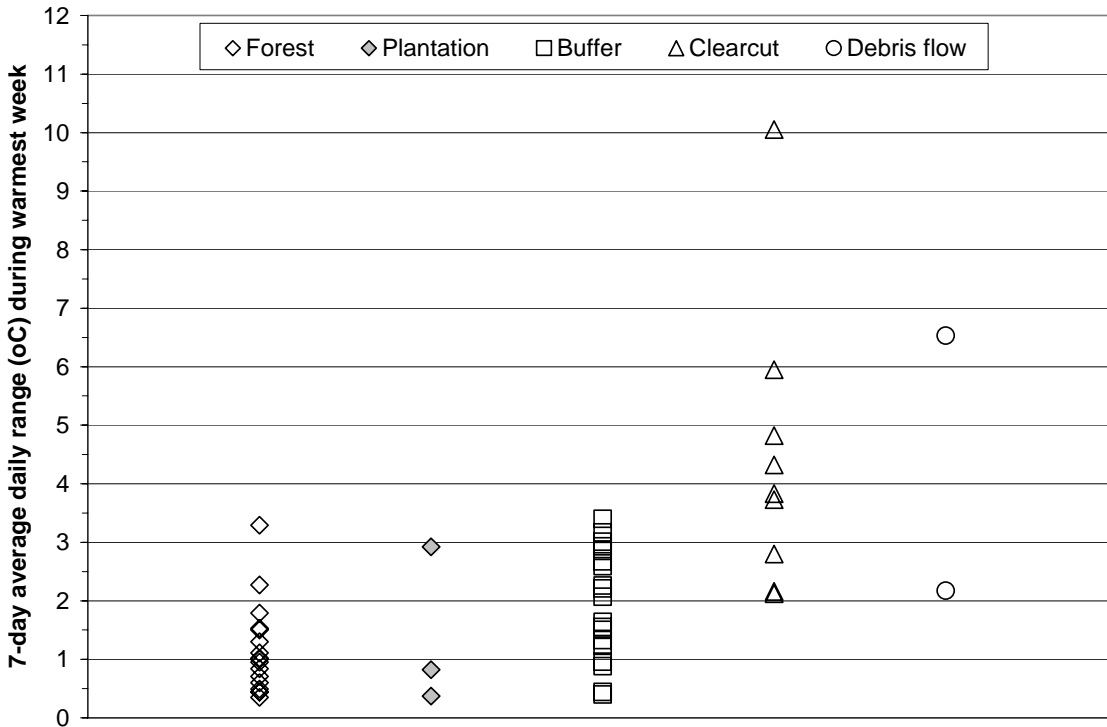


Figure 6. Seven-day average daily ranges at 2002 monitoring sites, displayed by riparian category. Statistical differences were found between most categories, as detailed in Table 3.

Effects of Site Conditions on Segment Changes

The 2002 sites were selected to test between temperature responses on north and south aspects. No differences were noted between aspects among non-scoured (i.e. forested, clearcut and buffered) streams. The single debris flow-scoured stream on a south aspect had a much larger 7-DAD range than the comparable north aspect site (6.5 vs. 2.2 C), though the lack of replication precluded statistical testing.

Regression models were developed for 2003 data using the three temperature statistics in Table 2 and the downstream difference in instantaneous maxima within monitored segments. Significant multivariate models were identified for seasonal maxima, 7DAD maxima and the 7-DAD ranges (Table 4). The optimal models for these three statistics have similar predictive value and include shade, elevation and channel gradient as significant predictor variables. Upstream shade was the strongest predictor and gradient was significant in both the simple and quadratic forms, suggesting a non-linear response.

The finding that greater shade is associated with cooler maximum temperatures and smaller daily ranges is consistent with past studies of larger forest streams (Beschta et al. 1987, Johnson 2004). The inverse effect of elevation on maxima has also been noted elsewhere, presumably because it is a primary control of groundwater temperature. The inverse response between high temperatures and channel gradient is reasonable but not well documented elsewhere. Flow rates are slower in lower gradient channels, which results in longer exposure to heat inputs. This suggests that temperature sensitivity varies between streams and can be evaluated on the basis of measured channel gradient (evaluated further in the following section).

Unlike the 2002 sites, which nearly all warmed downstream (Figure 7A), many of the 2003 segments had cooler maxima at the lower end than at the top (Figure 7B). The relatively weak relationship between measured segment attributes and the downstream change in maxima (Table 4) was surprising, especially because the 2003 monitoring design (Figure 2) was designed to evaluate segment-scale influences. Shade was inversely but weakly correlated ($R=0.37$) with temperature change, which could explain the apparent cooling within shaded reaches invoked by Caldwell et al (1990). However, the majority of heavily shaded segments in 2003 still experienced net warming, suggesting other site-scale cooling mechanisms.

Table 4. Summary of multiple regression models that predict 2003 temperature statistics on the basis of upstream segment attributes. Sample size is 30 for all analyses.

Temperature statistic	Model significance (F-statistic)	Model R ²	Predictor variables (p-value)
Seasonal maxima	<0.001	0.73	Shade (<0.01), Elevation (<0.01), Gradient ^{0.5} (<0.01), Gradient (0.02)
7-DAD maxima	<0.001	0.77	Shade (<0.01), Elevation (<0.01), Gradient ^{0.5} (<0.01), Gradient (0.02)
7-DAD range	<0.001	0.72	Shade (<0.01), Gradient ^{0.5} (0.02), Gradient (0.06)
Change in maximum from upstream	0.013	0.27	Elevation (0.03), Shade (0.04)
Non-significant ($p > 0.10$) predictors: bankfull width, wetted width & depth, buffer width.			

We hypothesize that flows in 2003 were so low that temperature changes were dominated by heat exchange driven by groundwater inputs and transfer with saturated alluvium. Although the 2003 field protocol attempted to identify seeps and tributary junctions, spatially dispersed hyporheic inputs and losses from the channel are very hard to quantify during a one-day field survey (R. Dan Moore, Forest Hydrologist, University of British Columbia, personal communication). It would be interesting to see if shade, gradient or other readily measurable attributes would be related to segment-scale temperature changes during a more typical flow year when hyporheic exchange was not such a dominating influence. The inverse relationship between elevation (a surrogate for the temperature of groundwater influx) and temperature change provides additional support to this cooling mechanism.

Implications for Headwater Riparian Management

As discussed above, our monitoring data suggest that buffers are effective at mitigating increases in peak temperatures in headwater streams (Table 3). However, daily temperature ranges in managed stands appear to be significantly wider (Table 3), which may be undesirable. Individuals designing buffers or evaluating buffering strategies may wish to know how wide buffers need to be to mitigate temperature effects. Shade and buffer widths recorded in 2003 were used to plot the relationship between buffer width and percent shade. This curve (Figure 8) indicates that although a 10 m buffer (on each side) provides about 70% of the shade of a mature forest, a buffer 20 m or wider is needed to be equivalent to a forest. The curve in Figure 8 is

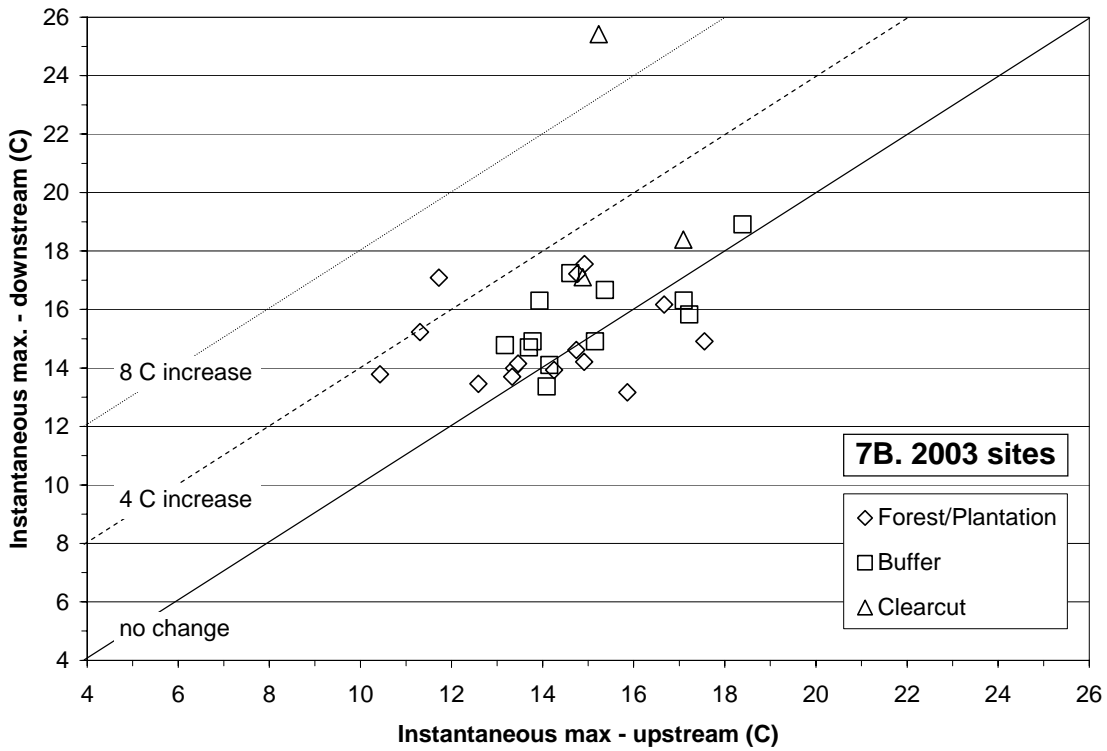
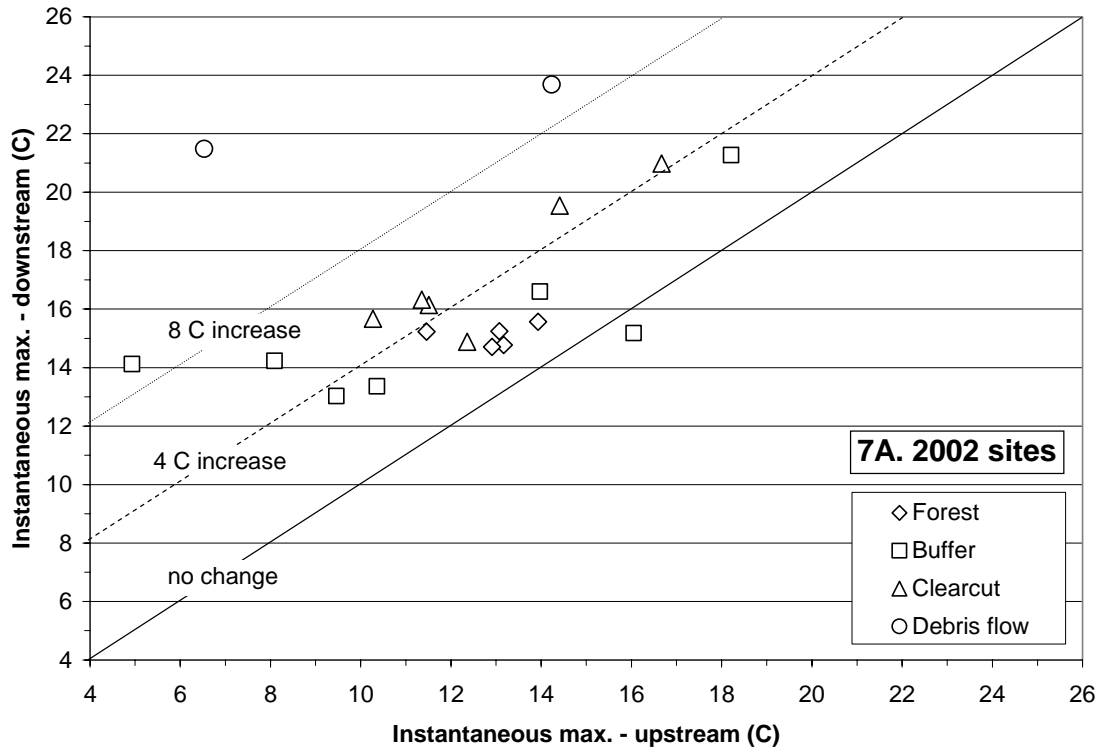


Figure 7. Relative change in seasonal maxima between upstream and downstream gages at sites monitored in 2002 (above) and 2003 (below). Downstream temperature increases were considerably more prevalent in 2002 than in 2003.

similar to shade relationships developed elsewhere in the Northwest (see Figure 8 in Beschta et al. 1987). It should also be noted that several buffers that were largely blown down experienced sizeable temperature increases due to lack of shade.

We observed that clearcut riparian stands can regenerate considerable shade within a decade or two, especially where red alder is dominant. Shade levels along the three 10-20 year old plantations monitored in 2003 averaged 80%. Significant slash was noted in three of the four clearcut sites (i.e. #1, 13, 14) monitored in 2003. Although logging slash has been observed elsewhere to mitigate canopy reduction due to logging (Jackson et al. 2001), stream temperatures at these sites were still generally warmer than forested streams.

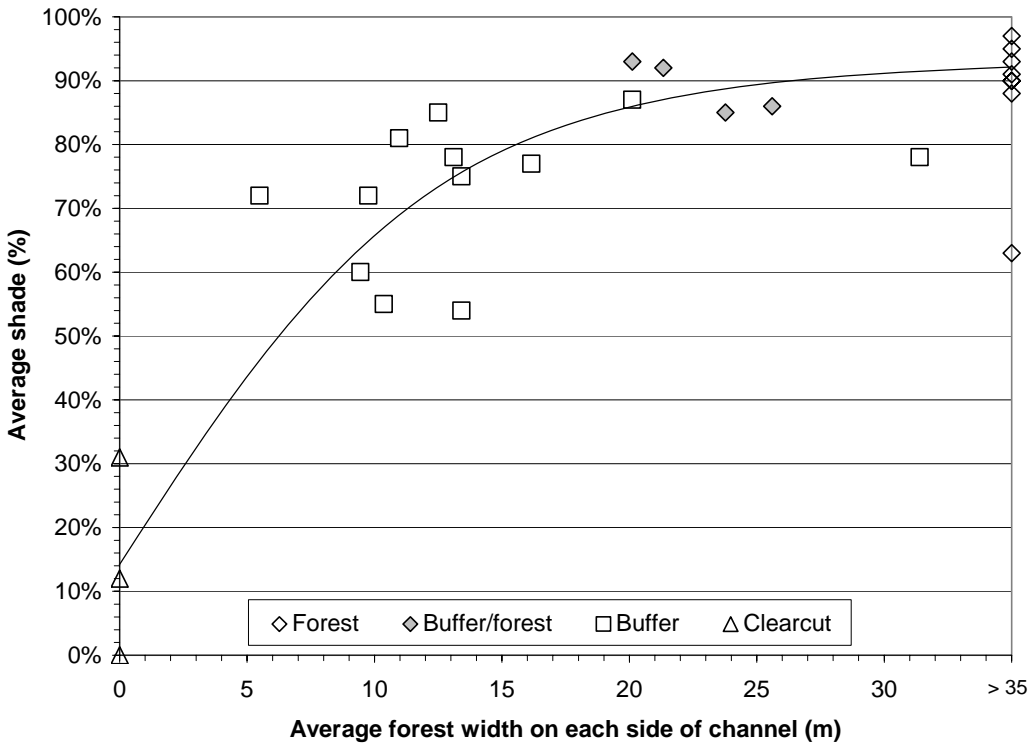


Figure 8. Relationship between average shade (densitometer) and average buffer width for Skagit headwater sites (curve fitted by eye).

The regression equations documented in Table 4 were used to estimate the level of riparian shade required to maintain maxima below regulatory standards. The lines in Figure 9 illustrate that greater shade is required for channels gentler than 25% than for steeper streams. Because there is variability among data points on both sides of the regression line, a buffer that provides the exact amount of shade shown in Figure 9 still has a risk of exceeding the temperature threshold. For this reason, Figure 9 may be more appropriate as an illustrative tool than for guiding levels of riparian harvest.

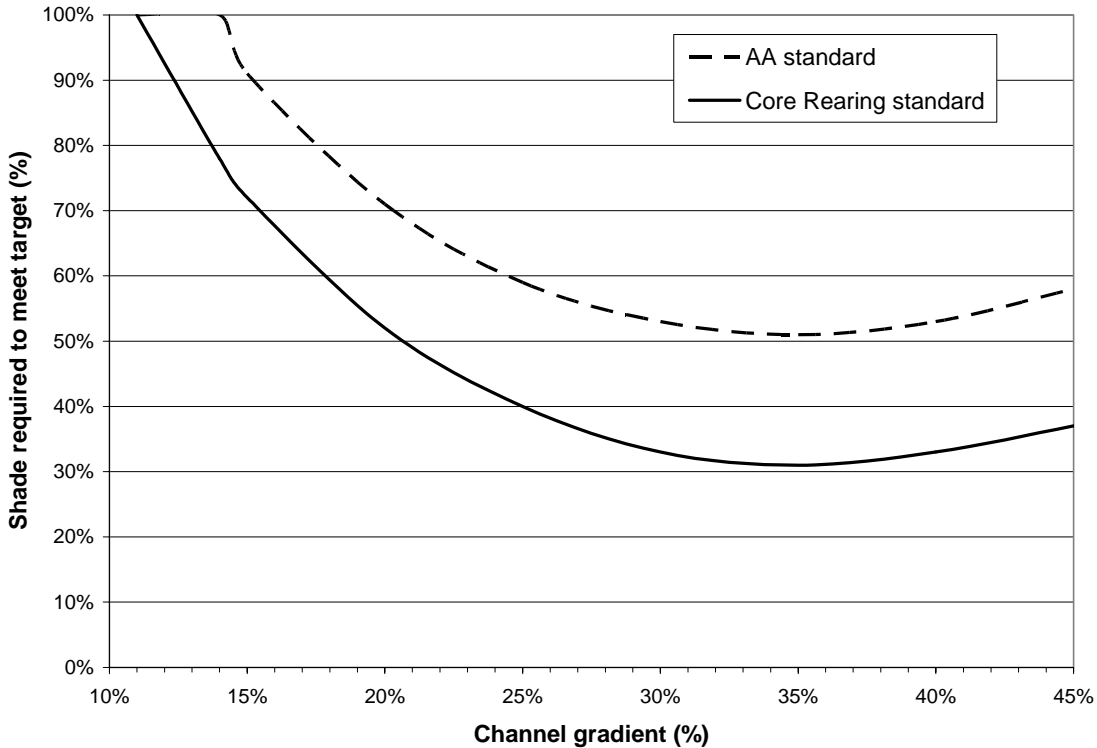


Figure 9. Percent riparian shade required to avoid exceeding regulatory temperature maxima (AA: max < 16 C, and Core Rearing: 7DAD maximum < 16 C). Note that less shade is required for channels with gradients steeper than 25%. These curves were developed from regression analysis of Skagit headwater data collected during the unusually warm and dry summer of 2003.

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Appendix 1. Comparison of monthly air temperatures during monitoring study to long - term temperature distributions.

Method: Monthly average values for daily mean and max during study were compared to long term averages for station and placed into one of five categories described below:	
Temperature category:	Symbol
much cooler than average (<mean - standard deviation)	-- --
cooler than average (between 0 and -- -- category)	--
near average (within +/- 1 C)	0
warmer than average (between 0 and + + category)	+
much warmer than average (>mean + standard deviation)	+ +

Location	Statistic	June	July	August	September
		2001			
Sedro Woolley	mean*	-- --	--	0	0
	max**	-- --	--	0	0
Concrete	mean	-- --	-- --	0	0
	max	-- --	--	--	--
		2002			
Sedro Woolley	mean	+	0	0	0
	max	+	0	0	0
Concrete	mean	0	0	--	--
	max	--	--	0	0
Darrington	mean	+ +	+	+	0
	max	+ +	+	+ +	+
		2003			
Sedro Woolley#	mean	+ +	+ +	+ +	+
	max	+ +	+ +	+ +	+
Concrete	mean	+	+	0	+
	max	+	+ +	+	+
Darrington	mean	+ +	+ +	+	+ +
	max	+ +	+ +	+ +	+ +

* Mean is the average of daily average temperatures

** Max is the average of daily maximum temperatures

2003 had second lowest summer (June+July+Aug) rainfall at Sedro Woolley since record-keeping began in the early 1930s.

Note: Darrington not shown for 2001 because no monitoring sites in area that year.

Source: Western Regional Climate Center web site:

<http://www.wrcc.dri.edu/summary/climsmwa.html>

Appendix 2. Characteristics and Temperatures at 2001 Monitoring Sites.

Site no.	Site name	Up-stream forest	BF width (m)	Grad. (%)	Elev. (m)	As-pect	Stream temperature (C)			Comment
							Max	7-DAD max	7-DAD range	
1	Handy 4	CC	1.3	20	776	SW	15.3	14.8	3.8	
		CC	0.9	16	774	S	14.1	13.8	1.3	downstrm of prvs
		BU	1.4	8	755	S	14.3	14.1	1.6	downstrm of prvs
		BU	3.0	23	735	SW	14.2	14.0	1.7	downstrm of prvs
2	Powell Cr.	FO	3.8	51	534	S	13.6	13.3	0.6	
		BU	2.8	36	347	SE	16.1	15.7	1.6	downstrm of prvs
20	Cougar	BU	1.1	25	256	N	12.2	12.1	0.4	Tributary
		BU	1.0	22	253	N	14.7	14.4	1.2	Tributary
		BU	0.9	18	226	NW	13.5	13.3	0.6	downstrm of jct
21	Savage	FO	4.3	19	373	NW	12.2	12.2	0.3	
		BU	4.5	5	86	NE	13.7	13.3	1.8	downstrm of prvs
22	Long Tom	FO	1.3	42	459	E	9.4	9.3	0.4	
		FO	2.0	15	258	N	13.0	12.7	1.3	downstrm of prvs

Note: All sites monitored from July 20 through September 28. Most began on July 9 but had no high temperatures prior to July 20.

Appendix 3. Characteristics and Temperatures at 2002 Monitoring Sites.

Sit no.	Site Name	Position	BF Width (m)	Elev. (m)	Aspect	Upstream forest	Stream temperature (oC)		
							Max	7DAD max	7DAD range
Forest									
5	Rally	Upper	1.1	684	S	FO	13.9	12.6	0.7
5		Lower	2.4	517	S	FO	15.6	13.6	1.0
10	Rockport	Upper	2.7	267	S	FO	12.9	11.0	1.1
10		Lower	2	155	S	FO	14.7	12.3	1.5
17	Miller Point	Upper	1.6	712	N	FO&BU	13.1	12.4	0.9
17		Lower	3.1	430	N	FO&BU	15.2	14.5	1.0
18	Finney CT	Upper	2.0	695	N	FO	13.2	12.4	0.4
18		Lower	3.3	420	N	FO	14.8	13.6	0.6
26	Wahlberg CT	Upper	1.2	477	N	FO	11.5	10.8	0.3
26		Lower	1.4	239	N	FO	15.2	13.5	0.8
Buffer									
1	Handy 4 BF	Upper	1.0	774	S	CC	16.1	14.9	3.2
1		Lower	2.6	738	S	BU	15.2	14.3	1.6
2	Powell Creek	Upper	4.8	534	S	FO&BU	14.0	13.4	0.7
2		Lower	3.3	344	S	BU	16.6	15.7	1.5
7	Full Sail	Upper	1.2	771	S	FO&BU	10.4	9.8	0.6
7		Lower	0.9	700	S	BU	13.4	12.6	1.6
12	Jordan/Boulder	Upper	1.5	435	N	FO	8.1	8.1	0.04
12		Lower	1.6	236	N	BU&DF	14.2	13.5	1.3
22	Long Tom	Upper	2.0	464	N	FO	9.5	9.2	0.4
22		Lower	1.8	258	N	BU	13.0	12.4	1.0
23	Round Again	Upper	4.7	467	N	FO	18.2	16.8	2.7
23		Lower	3.4	304	N	BU	21.3	19.3	3.4
25	Single Shot	Upper	1.2	670	N	FO	4.9	4.9	0.1
25		Lower	1.9	224	N	BU	14.1	13.2	2.2
Clearcut									
1	Handy 4 CC	Upper	0.5	807	S	CC	10.3	9.0	1.0
1		Lower	1.0	780	S	CC	15.7	14.7	3.2
4	Wild Rye	Upper	1.3	417	S	CC	16.7	15.8	1.9
4		Lower	1.3	361	S	Sparse BU	21.0	19.4	6.0
6	Red Dog	Upper	1.9	735	S	FO	11.4	10.3	1.2
6		Lower	1.6	657	S	Sparse BU	16.3	14.8	3.7
8	Anchor Steam	Upper	1.9	619	S	FO	12.4	11.7	0.6
8		Lower	2.3	463	S	Sparse BU	14.9	14.1	2.8
13	Donut Hole	Upper	1.3	645	N	CC	11.5	10.8	2.0
13		Lower	1.6	493	N	CC	16.1	13.4	2.1
27	Wahlberg CC	Upper	2.7	165	N	FO	14.4	13.6	0.9
27		Lower	1.4	85	N	CC	19.5	18.1	4.8
Debris flow (scoured in winter 02)									
11	Trillium WT	Upper	1.6	665	S	FO	14.2	13.4	1.6
11		Lower	12.2#	312	S	BU&DF	23.7	22.1	6.5
24	Debris Flow	Upper *	0.4	715	N	FO	6.5*	6.3*	0.3*
24		Lower	12.2#	256	N	FO&DF	21.5	19.9	2.2
All sites monitored from June 15 through October 2 except the upper Debris Flow site, which began August 2. For the lower Debris Flow site the maximum was recorded 7-23; the 7DAD max period ended 8-15. # - Channel "width" enlarged due to debris flow scour.									

Appendix 4A. Characteristics of 2003 Monitoring Sites

Site no.	Site name	Segment		Riparian category	Forest width		Canopy density (%)	BF width (m)	Wetted width (m)	Wetted depth (m)	Channel Grad. (%)
		length (m)	Position		R. bank (m)	L. bank (m)					
1	Handy 4*	150	upper	Plantation	0	0	0	0.9	0.5	0.04	39
1		150	lower	Buffer	10	9	72	2.0	0.7	0.05	21
2	Powell Cr	150	upper	Forest/Buffer	18	>35	86	3.3	1.3	0.07	44
2		150	lower	Buffer	20	12	77	3.6	1.2	0.12	29
3	Upr Childs	150	upper	Buffer	26	14	87	3.4	1.8	0.17	39
3		150	lower	Forest	>35	>35	90	3.3	1.2	0.13	33
5	Rally	150	upper	Forest	>35	>35	95	3.2	1.6	0.14	41
5		150	lower	Plantation	0	0	93	2.1	1.0	0.08	39
6	Red Dog	150	upper	Forest	>35	>35	93	1.7	1.1	0.11	40
6		150	lower	Buffer	16	6	72	1.3	0.8	0.07	22
7	Full Sail	150	upper	Buffer	31	32	78	1.7	0.8	0.07	33
7		150	lower	Forest	>35	>35	63	1.5	1.4	0.10	35
8	Anchor Stm	150	upper	Forest	>35	>35	88	2.0	0.9	0.09	19
8		150	lower	Buffer	7	14	55	1.9	1.1	0.10	14
9	W Grandy	150	upper	Forest	>35	>35	93	0.9	0.5	0.05	31
9		150	lower	Clearcut	0	0	12	0.9	0.6	0.06	9
13	Donut Hole	150	upper	Plantation	0	0	64	1.2	0.5	0.06	34
13		150	lower	Buffer	12	7	60	1.7	0.4	0.06	30
14	White Wash	150	upper	Forest	>35	>35	97	2.2	1.0	0.08	8
14		150	middle	Clearcut	0	0	31	2.0	0.9	0.13	12
14		150	lower	Buffer	12	10	81	3.7	1.0	0.08	8
15	Dan Cr	122	upper	Forest (OG)	>35	>35	90	1.5	0.9	0.11	30
15		150	middle	Plantation	0	0	81	1.7	1.2	0.15	43
15		122	lower	Buffer	13	12	85	1.3	0.8	0.09	25
16	Grisdale	150	upper	Forest/Buffer	17	>35	85	3.3	1.4	0.10	36
16		150	lower	Buffer	21	6	75	4.2	1.6	0.12	25
17	Miller Point	150	upper	Forest/Buffer	>35	12	92	3.0	1.4	0.13	27
17		150	lower	Buffer	10	16	78	3.4	1.3	0.13	20
28	Hllgram*	150	upper	Partial Forest	mixed	mixed	54	1.0	0.5	0.05	21
28		150	lower	Forest	>35	>35	91	1.4	0.7	0.05	22

* - Sites within area covered by "Class A/Rearing Habitat" temperature standards. Others are "Class AA/Core Spawning and Rearing" standard.

Appendix 4B. Temperatures recorded at 2003 Monitoring Sites

Site no.	Site name	Upstream category	Stream temperature (oC)		
			Max	7-DAD max	7-DAD range
1	Handy 4*	unknown	14.88	14.24	3.25
		clearcut	17.10	16.38	4.32
		buffer	16.31	15.38	2.59
2	Powell Creek	unknown	15.86	15.05	0.73
		forest	13.17	12.71	0.44
		buffer	14.78	14.09	0.88
3	Upper Childs	unknown	14.09	13.32	0.88
		buffer	13.37	13.07	0.40
		forest	13.99	13.42	0.71
5	Rally	unknown	14.92	14.08	0.68
		forest	17.55	16.24	2.27
		plantation	14.91	14.17	0.82
6	Red Dog	unknown	10.43	9.66	0.84
		forest	13.78	12.81	1.53
		buffer	14.91	14.17	2.67
7	Full Sail	unknown	15.15	14.36	3.27
		buffer	14.91	14.04	2.21
		forest	14.21	13.43	1.00
8	Anchor Steam	unknown	13.33	12.87	0.71
		forest	13.70	13.10	1.11
		buffer	14.70	14.06	2.26
9	WF Grandy	unknown	11.31	11.06	0.51
		forest	15.23	14.69	1.79
		clearcut	25.42	22.95	10.05
13	Donut Hole	unknown	14.76	14.07	1.17
		plantation	17.22	16.18	2.92
		buffer	15.83	15.29	1.23
14	Whitewash	unknown	11.72	11.39	0.26
		forest	17.09	16.44	3.29
		clearcut	18.39	17.70	3.83
		buffer	18.91	17.87	3.01
15	Dan Creek	unknown	12.59	11.97	0.41
		forest	13.46	12.95	0.49
		plantation	14.15	13.51	0.37
		buffer	14.10	13.50	0.44
16	Grisdale	unknown	14.25	13.68	0.57
		forest	13.93	13.47	0.44
		buffer	16.30	15.44	2.07
17	Miller Point	unknown	14.74	14.21	0.88
		forest	14.61	14.16	0.35
		buffer	17.24	16.38	2.85
28	Hellgrammite*	unknown	15.37	14.52	1.99
		buffer	16.67	15.99	2.93
		forest	16.17	15.04	1.30
* - Sites within area covered by "Class A/Rearing Habitat" temperature standards.					
Others are "Class AA/Core Spawning and Rearing" standard.					