Study Plan to Conduct a Sensitivity Analysis of the Factors Affecting Stream Temperature to Assist the Development of Hardwood Conversion Guidelines for Small Forest Land Owners

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Introduction

New forest practices rules (hereafter, rules) took effect July 1, 2001 based on the negotiations in the Forest and Fish Report (FFR 1999). The FFR proposed that "Provisions are made for the conversion of and/or treatment of riparian forests which may be under-stocked, overstocked or uncharacteristically hardwood dominated while maintaining minimum acceptable levels of function" (FFR Appendix B(I)(b)). To incorporate that intent into rules, a new section to the rules that pertains specifically to hardwood conversion was added (Washington Administrative Code (WAC) 222-30-021(1)(b)(i)). Hardwood conversion is more commonly implemented, however, through alternate plans (WAC 222-12-040 and WAC 222-12-0401)[1]. The qualifying criteria for using an alternate plan is that "In all cases, the alternate planning process will result in a plan that provides protection to public resources at least equal in overall effectiveness as provided by the act and rules while seeking to minimize constraints to the management of the affected lands." The Small Forest Landowners Workgroup is developing a hardwood conversion template for small forest landowners in Western Washington that would simplify the regulatory process for small forest

The study aims to provide an analysis of stream temperature dynamics and to derive a matrix of the relative importance of factors affecting stream temperatures that will help the development of forest management guidelines to assist small forest landowners in Western Washington State.

Review of stream temperature variability

Spatial variability of stream temperature can be assessed at different scales (Brown, 1969, Johnson and Jones, 2000, Danehy, 2005, Scholz, 2002). The climate, geographic position, and elevation of the stream dictate the main characteristics of the stream water energy budget behavior. Locally, near stream vegetation provides shade and may affect air movement over the stream while the physical characteristics of the stream itself such as its geometry, bed particle size, width, and depth, influence the spatial and temporal distribution of stream temperatures.

Poole et al., (2001) defines the temperature regime as "the distribution and magnitude of stream temperatures, the frequency with which a given temperature occurs, the time of the day or year where a given temperature occurs and the duration of time for which a stream is above or below a given temperature". The temperature regime is important in describing the temperature pattern of a stream as well as the biological implications

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[1] The DNR (WAC 222-30-021(1)(i)(A)(V)) was tasked with tracking "the rate of conversion of hardwoods in the riparian zone: (1) Through the application process on an annual basis; and (2) at a WAU scale on a biennial basis as per WAC 222-30-120…". So far, these data are not but anecdotal information suggests that hardwood conversion under the current hardwood rule is rarely done.

related to it. The temperature regime has, of course, to be related to the period of time for stream temperature analysis.

Temporal scales for water temperature regime analysis range from annual to daily. An interannual analysis is used to characterize water temperature variations from year to year, to detect extreme values, and to establish specific trends for dry and wet years and influences of any climate change. A seasonal regime assessment characterizes cyclic seasonal patterns. At an even smaller temporal scale, a diurnal variation pattern may be superimposed over the seasonal variations.

For the purpose of this discussion, the physical factors involved in heat exchange processes are grouped here into two categories: 1) factors related to general site conditions and 2) factors related to the uniqueness of the stream itself. The influence of these physical factors on stream temperatures and their relation to forest harvesting activities is discussed below.

Factors affecting stream temperatures

1. Factors affecting stream temperatures related to general site conditions

A. Geographic area

Geographic location influences the amount of direct solar radiation received by a river. Warmer stream temperatures were observed at lower elevations across large spatial scales (Isaak and Hubert, 2001), although local climatic influences (Lewis et. al., 2000) and the extent of the analysis (Danehy, 2005) may influence this. Cross (2002) suggested that managing tree height can be important at lower latitudes, as a higher stand may be required to achieve the same amount of shading as at higher latitudes.

B. Climate

In the PNW high precipitation areas correlate with relatively cool temperatures of high elevation streams. Conversely, low precipitation areas correlate with relatively warm temperatures at lower elevations (Scholz, 2002). Direct precipitation over a stream can be a source/sink of heat. Direct precipitation is more important for winter conditions when snow absorbs a relatively large amount of heat as it melts at 0^{o}C.

Stream temperature mimics air temperature at some lag time and different magnitudes. Air temperature was found to correlate very well with water temperature and regression models have been developed to relate the two variables (Mohseni et al., 1998, Neuman et al., 2003). Both air and water temperatures respond to the major factor affecting them, the incoming solar radiation. Air temperature was considered as a major factor affecting stream temperatures (Edinger, 1968, Sullivan and Adams, 1990), but this statement may be misleading because correlations do not demonstrate causation (Johnson, 2003). Typical formulations of heat exchange processes (Chapra, 1997) include air temperature in the conduction/convection at the air/water interface and atmospheric longwave radiation fluxes. The conduction/convection flux at the air-water interface (also known as sensible heat) is driven by the temperature difference between water and air and by the wind speed. It is related to evaporation flux through the Bowen ratio. Relative humidity is important for evaporation/condensation, while wind speeds influence both evaporation/condensation and conduction/convection processes. The presence or absence of riparian vegetation can alter microclimate conditions (Ledwith, 1996, Brosofske et al, 1997).

Solar exposure was identified as the most influential factor in stream heating processes (Sinokrot and Stefan, 1993, Johnson and Jones, 2000, Danehy, 2005). Adams and Sullivan (1990) indicated that solar radiation (direct or diffuse) has a small effect on daily mean water temperatures, but it was important for daily fluctuations. Following an artificial shading experiment on a second order stream in the Oregon Cascade Range, Johnson (2004) concluded that blocking the incoming solar radiation reduced maximum temperatures in the shaded reach, but minimum and mean temperatures were not substantially affected. As summarized in Cross (2002) several researchers agreed that diffuse solar radiation (e.g. radiation passing through a forest canopy) has no influence on stream temperatures.

C. Location within the watershed

A typical water temperature pattern, associated with both natural and human-impacted rivers, is lower stream temperatures at the headwaters increasing at lower elevations. Microclimatic conditions, insulating processes, and channel morphology alter the stream temperature longitudinal profile, superimposing local variations over the general trend of downstream heating (Torgersen et al., 2001). However, there are exceptions to this pattern and the natural or human caused occurrence of downstream heating is still debated in the literature. Stream temperature at a certain location is influenced not only by its specific surroundings, but also by the upstream conditions (Johnson, 2003). Natural features such as small shallow lakes or swamps acting as headwaters for small streams can cause a downstream cooling pattern (Mellina et al., 2002).

Small headwater streams are expected to have cooler temperatures than the mainstems, because much of their discharge is provided by groundwater. Forested streams with alluvial beds usually exhibit low diurnal variation patterns, while a bedrock bed can determine higher diurnal fluctuations (Johnson, 2004).

2. Local factors affecting stream temperatures

A. Hyporheic exchange

Hyporheic exchanges recently have received increased attention as an important mechanism for stream cooling (Johnson and Jones, 2000, Poole and Berman, 2000, Johnson, 2004). The hyporheic zone is defined as the region located beneath the channel and is characterized by complex hydrodynamic processes mixing stream water and groundwater. The resulting fluxes can have significant implications for stream temperature at different spatial and temporal scales.

Because each stream setting is different, the relative proportion of stream water and groundwater in hyporheic exchange processes and the hyporheic exchange flow patterns are unique to that system. The most important geomorphic factors that affect hyporheic exchange rates are the hyporheic zone heterogeneity, bed form configuration and sinuosity, and hyporheic zone thickness. Studies based on hydrochemical gradients between surface and subsurface water indicated increasing groundwater influence with depth into the hyporheic zone (Malcolm, 2004). A braided channel with multiple channels at different elevations can trigger intricate hyporheic flow patterns as the water flows gravitationally from higher to lower channels. Subsurface flow paths can also be created by a meandering channel, as the water tends to flow through the point bars created by the stream. Recent research on the influence of the bed substrate on small streams temperature (Johnson, 2004) indicated that maximum temperatures in an upstream bedrock reach of a second order stream in the Oregon Cascade Range were up to 8.6ºC higher and minimum temperatures were 3.4ºC lower than downstream in the alluvial reach. The distance between the two stream temperature monitoring locations was about 550 m.

For small size forested streams the heat exchange rates with the surroundings are increased as the volumes of water transported are small. In small streams, pool-step sequences were found to be the dominant feature driving the hyporheic exchange (Wondzel, 2004). Pool-step sequences can influence the hyporheic exchange rates at a smaller time scale (hours) than the complexity of flow paths created by a meandering stream (days) (Wondzel, 2004).

The hyporheic zone is responsive to the land management activities such as channel straightening, simplification of the bed form, and loss of woody debris that affects the hyporheic exchange rates. Reduced hyporheic flows can increase the difference between the daily minimum and maximum temperatures, as the intensity of this buffering process is diminished (Johnson, 2004).

B. Role of the stream width – wide streams vs. narrow streams

Blann et al. (2002) assessed the role of near stream riparian vegetation for controlling stream temperatures in a study that assessed the possibility of the reintroduction of brook trout *Salvelinus fontinalis* into Wells Creek, a tributary of the Mississippi River in southeastern Minnesota. Current condition of the stream was assessed using the U.S. Fish and Wildlife Service’s Stream Temperature Model and simulations scenarios were used to estimate the thermal behavior under different shade scenarios, buffer widths and width-to-depth ratios. The study found that channel shape can be as important as shade in moderating summer water temperatures in small streams. The simulation scenarios showed that early successional buffers (grasses and forbs) provided as much shade as wooded buffers in streams with bankfull widths less than 2.5 m. Model simulations assuming reduced width-to-depth ratio indicated that early “successional buffer vegetation mediated mean temperature as well as the wooded buffer when discharge was held constant".

Near stream vegetation is important for stream width and bank stabilization. Width to depth ratio can play an important role in controlling stream temperatures (Blann et al., 2002). A study that assessed the most influential factors affecting stream width using over 1,100 locations found that for streams with watersheds greater than 10 to 100 km^2 widths are narrower for streams with woody riparian vegetation while smaller streams tend to be wider for the same riparian conditions(Anderson et al., 2004). This behavior of smaller streams was thought to be influenced by the interactions between woody debris, shading, understory vegetation, rooting characteristics and channel size. Channel morphology along wooded buffers can have a higher width-to-depth ratio that offsets the benefits of riparian vegetation shading (Blann et al., 2002).

C. Riparian vegetation

Riparian vegetation may act as an efficient insulating barrier, where the vegetation influences heat exchange rates with the atmosphere and the surrounding environment. Riparian vegetation may cause changes in microclimatic conditions; decreasing air temperature, ground temperatures, and wind speeds, and increasing the relative humidity. It also plays an important role in bank stability and channel morphology. As the river enlarges and widens, riparian vegetation influences become less important (Poole and Berman, 2000). Shade is an index of the amount of solar energy that is obscured or reflected by vegetation or topography above a stream. Effective shade is defined as the fraction or percentage of the total possible solar radiation heat energy that is prevented from reaching the surface of the water.

The effects of removal of near stream vegetation on stream temperatures and the biological implications for fish affected of increased water temperatures were observed as early as 1926 by Titcomb (Story et al., 2003). Brown and Krygier (1970) indicated that loss of riparian vegetation results in larger daily temperature variations and elevated monthly and annual temperatures. Daily temperature maxima of small streams increase the most in response to vegetation removal (Sullivan et al., 1990).

Clearcut logging resulted in higher temperature of intragravel water in salmon and trout spawning beds and decreased concentrations of dissolved oxygen Ringler and Hall (1975). Ebersole et al., (2003) analyzed the influence of shading over cold water patches such as side channels, alcoves, lateral seeps and floodplain spring brooks for their relevance in fish biology. Experimental shading was found to decrease daily maximum stream temperatures within cold water patches 2 to 4^{o}C indicating that the near-stream vegetation affects the temperature patterns of the cold water patches.

Riparian vegetation restoration was identified as one of the most important management steps that may improve stream temperatures (Johnson and Jones, 2000, Blann et al, 2002). However, due to the complexity of the stream heating processes, other factors can determine the thermal patterns of a given stream, limiting the effectiveness of the riparian restoration efforts.

Effects of forest activity on stream temperatures of first order streams in the interior sub-boreal forests of northern British Columbia were assessed in a study aimed to estimate possible timber harvesting prescriptions and their implications for stream temperatures (Macdonald et al., 2003). Eight creeks (bankfull widths 0.6 – 3.2 m) were included in the analysis. Five of them were affected by harvesting activities and were compared against 3 control streams outside of the cutblock boundaries. Three riparian prescriptions were assessed to determine their effectiveness to prevent postharvest stream temperature increases: (1) low retention – removal of all merchantable timber (>15 or >20 cm diameter at breast height (DBH) within 20 m of the stream; (2) high retention – removable of large merchantable timber >30 cm DBH within 20-30 m of the stream; and (3) patch cut – a high retention along the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed. Stream temperature data were recorded hourly throughout the year 18 and 27 months prior to harvesting and 5 years after harvesting. Summer stream temperatures increased following timber harvesting, mostly for low retention and patch cut conditions, where as much as 4ºC (from 8ºC to 12ºC) in summer maximum mean weekly temperatures were observed. This difference increased to about 6ºC for a stream with a southeasterly aspect and where the least amount of understory vegetation remained after harvesting. For the small streams investigated, the high-retention treatment provided small temperature changes (< 1ºC increase vs. 2-4ºC increase) compared to the low-retention treatments in the first year of postharvest. Daily stream temperature fluctuations increased following timber activity (1.0-1.3ºC before harvesting became 2.0-3.0ºC after harvesting), mostly in areas with little riparian vegetation, compared to the more vegetated areas. Windthrow was observed in the first 3 years of the study for both low and high retention conditions and likely impacedt stream temperatures. During this period, temperature differences between pre and post harvesting conditions rose in 3 of the streams with riparian treatments.

Johnson and Jones (2000) analyzed historic data in three small basins (< 1 km^2) in western Oregon to assess the effects of streamside harvesting on stream temperatures. Increases in stream temperatures resulted from timber harvesting were observed in daily and weekly maximum and minimum temperature values. Maximum stream temperatures increased 7ºC and occurred earlier in the summer after clear-cutting and burning in one basin and after debris flows and patch cutting in another. Timber harvesting was also found to affect daily extremes, as diurnal fluctuations in June were observed to increase 2 to 8ºC.

Mellina et al. (2002) assessed the effect of timber harvesting on water temperature of small streams (< 2m bankfull width) with headwaters in small lakes located in British Columbia for 1 year before and 3 years after clearcut logging. Their study confirmed that timber harvesting impacted stream temperatures, but reported minor changes, averaging 0.05 – 1.1 ºC following logging with respect to summer daily maximum and minimum temperatures, diurnal fluctuations and downstream cooling. These modest changes were attributed to the harvesting treatments that still allowed the streams to receive 40-60%

shade during the post harvest years and to the influence of small lakes, located at the headwater of the streams. Groundwater was also found to play a significant role in stream cooling.

D. Channel orientation

Channel orientation is the aspect of the channel with respect to the position of the sun (Scholz, 2002). Sullivan et al. (1990) suggested that both riparian vegetation and topography may provide more shade to north-south oriented streams than to east-west oriented streams. Lewis et al., (2000) found no significant relationship between channel aspect and stream temperature and suggested it probably plays a minor role.

E. Microclimate conditions

Harvesting effects on riparian microclimate conditions was assessed for five small streams 2-4 m wide in Western Washington (Brosofske et al., 1997). Riparian buffer widths ranging from 17 to 72 m were left intact after harvesting at all sites. The study investigated the pre-harvest microclimatic gradients from the stream to the upland, the effect of harvesting on these microclimate conditions and the effects of buffer width and near-stream microclimate on stream microclimate. The authors concluded that microclimate pre-harvest gradients approached upland forest interior within 31-47 m from the stream. Surface temperature and humidity gradients were found to extend even further; 31-62 m.. Harvesting influenced the near stream microclimate conditions. Buffers of at least 45 m wide on each side of the stream were found to preserve the microclimate gradient, although this value can increase up to 300m, depending on the variables analyzed. No change in wind speeds were found at stream locations within the buffer strips adjacent to clearcuts. Wind speed measurements indicated that the wind increased at distances of approximately 15 m from the edge of the riparian buffer, and then declined to preharvest conditions, approaching upland conditions toward the edges of the buffers.

Hagan and Whitman (2000) found that uncut riparian buffer strips 75’ wide provide at least a narrow (10m) strip of forest cover with a microclimate very similar to that of extensive mature forest cover.

Ledwith (1996) examined the effects of riparian buffer width on air temperature and relative humidity in riparian areas. Microclimate monitoring was performed during the summer of 1994 at 2 sites located in Six Rivers National Forest, California, where buffer widths were 150 m, 90 m, 30 m, 15 m and 0 m (clearcut). A 6.5ºC increase in mean air temperature was recorded along the riparian zone between the 150 m and 0 m buffer width. Mean air temperature increased by 1.6ºC/10m for buffer width 0-30 m wide and by 0.2ºC/10m for buffer strips 30-150 m wide. Relative humidity was inversely proportional to air temperature. A 19% decrease in relative humidity was recorded between the 150 m and 0 m buffer width collection sites. Mean relative humidity dropped by about 3.8%/10m for buffer width 0-30 m wide and by 0.6º%/10m for buffer strips 30-150 m wide.

F. Groundwater

Groundwater can dampen daily fluctuations by providing near constant temperature inputs throughout the year. The relative magnitude of the groundwater effect depends mostly on the temperature differences between the surface and groundwater, and the amount of groundwater inputs relative to the surface streamflow (Sullivan et al, 1990). Hydraulic properties of the aquifer and streambed topography, and the relative contribution of groundwater to hyporheic processes can also determine the groundwater influence on stream temperatures. The relative importance of groundwater accretion varies with stream size (Sullivan et al., 1990), smaller streams being more sensitive to groundwater inputs than larger streams.

During summertime, groundwater inputs were found to decrease stream temperatures (Mellina et al., 2002). Groundwater temperatures were found to differ significantly from the surface temperatures by as much as ~ 10ºC and are usually considered to be close to the mean annual air temperature (Mellina et al., 2002). The influence of groundwater on the daily extremes depends also on the relative fractions of groundwater and surface water in the hyporheic exchange zone as well as the dynamics of hyporheic flows and heat exchange processes. Silliman and Booth (1993) found that bed temperature gradients are greater in areas with groundwater accretion, enhancing bed conduction and hyporheic exchange processes.

G. **Flow**

This is one of the most important factors affecting the stream temperature regimes. All heat exchange processes are influenced by the volume of the flowing water (Poole and Berman, 2000). Small, shallow streams are more sensitive to the water temperature drivers and usually exhibit higher diurnal fluctuations. In Brown (1969) small stream temperatures (discharges less than $1m^3/s$) varied by as much as 20ºC between daily extremes and large streams (discharges more than 142 m^3/s) by as little as 2ºC. The insulating role of the near stream vegetation and topography diminishes with stream size increasing (Poole and Berman, 2000). Seventy kilometers and further from their source, most streams in northwestern California were too wide to be affected by canopy cover (Lewis et al., 2000).

3. Stream temperature recovery

A. Spatial (longitudinal) recovery

The potential of a stream to recover after warming in clearings is important for forest management. Recovery rate depends on the stream size which drives the rates of the stream heating processes. Small streams have higher temperature recovery potential than larger streams, because shading is more effective and the stream is more responsive to stream cooling processes such as groundwater and cold tributary inputs. By contrast, relatively large streams require longer distances, if any, for temperature recovery, as the thermal inertia is increased, and the riparian vegetation shading is less important.

Story et al. (2003) estimated the thermal behavior of two small streams (mean bankfull widths at 1.3 -1.4 m) in shaded reaches downstream of a clearing. Stream temperature data recorded during July-August 2000 showed downstream cooling of about 4ºC for both reaches observed over distances of approximately 200m. Energy balance estimates indicated that groundwater inflows (40%) and bed conduction and hyporheic exchange (60%) are responsible for stream cooling. In one stream, the effects of cooling were increased for small flows (under 5L/s) when it was estimated that upstream surface water was lost by infiltration, enhancing the cooling effect determined by groundwater inflows.

B. Temporal recovery

Stream temperatures may recover to preharvest conditions after a period of time in which the riparian vegetation has grown enough to provide efficient shading. Stream temperatures in small creeks (basins < $1km^2$) in western Oregon returned to preharvest levels in 15 years, coinciding with canopy closure in riparian zones (Johnson and Jones, 2000) and a change from mostly conifer to deciduous vegetation.

Small streams can recover sooner, because early successional vegetation can provide as much shade as wooded buffers in streams with bankfull widths less than 2.5 m (Blann et al., 2002). As summarized in Johnson and Jones (2000), Beschta and Taylor (1988) suggested that the effect of riparian vegetation on maximum stream temperatures is not noticeable in the first 5 years postharvest, but linear decreases are expected over the next 15 years.

Objectives of the final report

The purpose of this study is to illustrate the impact of harvesting alder-dominated riparian stands to within 30’ of bankfull width on stream temperature assuming a 500’, 750’, 1000’, and 1250’ length of stream harvested. These impacts will be assessed on a range of stream conditions (size, width, upstream temperature, groundwater/hyporheic influence, etc) representing probable candidates for hardwood conversion. Specific objectives that will be addresses are listed below.

a. Model the effect of the prescribed harvest (to 30’ of bfw) compared to preharvest conditions on stream temperature as a function of harvest unit length from 500 to 1250 feet.
b. Model the length of stream required below the harvest unit for maximum stream temperature to equilibrate with ambient conditions.
c. Identify the variables that most influence stream temperature under the matrix of stream conditions identified above.
d. Identify the stream conditions most sensitive with respect to stream temperature to the riparian harvest prescribed.

Study approach

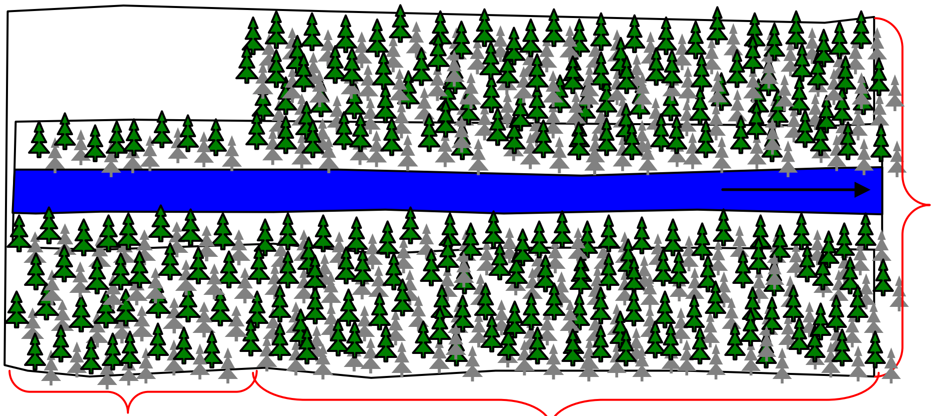
Stream temperature modeling and effective shade simulations

A sensitivity analysis will be carried out using the Qual2Kw model (Pelletier and Chapra, 2004; Chapra and Pelletier, 2003) to simulate a range of environmental conditions where hardwood conversion harvests are likely to occur. QUAL2Kw simulates diurnal variation in stream temperature for a steady flow condition. QUAL2Kw uses the kinetic formulations for the components of the surface water heat budget described in Chapra (1997). Diurnally varying water temperatures at constant intervals along the streams will be simulated using a finite difference numerical method. The model is routinely used by the Washington State Department of Ecology (Ecology). For temperature simulation, the solar radiation, air temperature, relative humidity, headwater temperature will be specified as diurnally varying functions. Effective shade levels will be simulated using Ecology's shade model, an Excel VBA application. The effective shade levels thus estimated will be input in the QUAL2Kw model to simulate the effect of riparian vegetation on stream temperature.

The models and their documentation are available on the Ecology website at http://www.ecy.wa.gov/programs/eap/models/.

The study is comprised of four steps.

1. Determine the site and harvest criteria that apply to all modeling scenarios
2. Develop a matrix of site condition scenarios that will be modeled based upon where hardwood conversions may be considered and populate the model input parameters for each scenario using data from the Hardwood Conversion Study and other data sources.
3. Run models comparing temperature change post harvest on all scenarios developed in Step 2.
4. Summarize the results to meet the objectives listed above.



Riparian buffer used for effective shade estimations = 50' (15.2m) on the each side of

Harvest unit =
500', 750', 1000, 1250, 1500 ft
Riparian buffer = 30'

Downstream recovery reach (length determined by distance to equilibration)

Figure 1. QUAL2Kw model setting for the stream temperature sensitivity analysis.

Site and harvest Criteria

All sites will be assumed to have:

- Mature red alder stands 80 ft in height with 85% canopy closure measured within the stand.
- One-sided harvest only.
- Pre harvest buffer width of 50’
- Post harvest buffer width of 30’ with no other buffers for wetlands, slope stability, etc.
- Downstream buffer similar to pre harvest buffer (80 ft red alder)
- No tributary inflows to the modeled reach
- Groundwater inputs are uniformly distributed to the modeled reach

This relatively conservative scenario, assuming a 100% red alder stand, translates into maximum shade removal because there are no residual conifers to be left after harvest and the consistent 30’ buffer is unaffected by other buffer requirements.

Develop a matrix of site condition scenarios

The range of stream conditions modeled will be described in terms of the input parameters needed for the shade and temperature models reflecting, to the extent possible, the range of stream conditions where hardwood conversion is likely to occur.

Two representative stream sizes will be investigated: 10’ and 30’ bankfull width, respectively. For each of them, the five harvest unit lengths conditions will be evaluated (500, 750, 1000, 1250, and 1500 ft). The baseline stream temperature model for each of these settings (Figure 1) will be tested for sensitivity to model headwater conditions (temperature), groundwater inputs, hyporheic exchange, and stream gradient. The baseline condition, the model descriptions and the parameters selected for the sensitivity analysis are presented in Table 1.

Preliminary effective shade model runs for a condition representative for the postharvest unit reach show that for a bankfull width of less than about 42’ (13m), a N-S oriented stream receives the least amount of shade (Figure 2). A N-S (0 and 180º) is considered therefore a conservative approach for this parameter and it will be used for both effective shade levels and stream temperature simulations.

Table1. The proposed baseline condition and the selected model parameters/inputs for the stream temperature sensitivity analysis

	Preharvest baseline **Bankfull width (BF)**	**Harvest unit (HU)**	**Sensitivity analysis: vary one parameter at a time while maintaining the others constant at baseline condition**			
Preharvest baseline	**BF = 10’** - **Mature riparian vegetation on both banks (preharvest condition)** - **Headwater temperature (daily variation) – daily max at 16 deg C, prescribed diel variation (from site measurements)** - **No groundwater input** - **No hyporheic exchange** - **Low gradient** - Fixed representative meteorology - No tributaries - Fixed elevation - NS aspect - Fixed hydraulic coefficients	**HU = 500’**	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed temperature (~annual air temperature), fixed % of flow	Hyporheic exchange – fixed % of instream flow (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 750’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1000’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1250’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1500’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
	BF = 30’ - **Mature riparian vegetation on both banks (preharvest condition)** - **Headwater temperature (daily variation) – daily max at 16 deg C, prescribed diel variation (from site measurements)** - **No groundwater input** - **No hyporheic exchange** - **Low gradient** - Fixed representative meteorology - No tributaries - Fixed elevation - NS aspect - Fixed hydraulic coefficients	**HU = 500’**	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 750’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1000’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1250’	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline
		HU = 1500’ Harvest unit is assumed 1500’ on one bank only (Figure 1)	Headwater temperature: >16 deg C, daily max and < 16 deg C max	Groundwater input – fixed prescribed temperature (~annual air temperature), prescribed % of instream flow	Hyporheic exchange – fixed % of instream flow for two streambed types (alluvial and bedrock)	Gradient - assume a higher gradient than the baseline

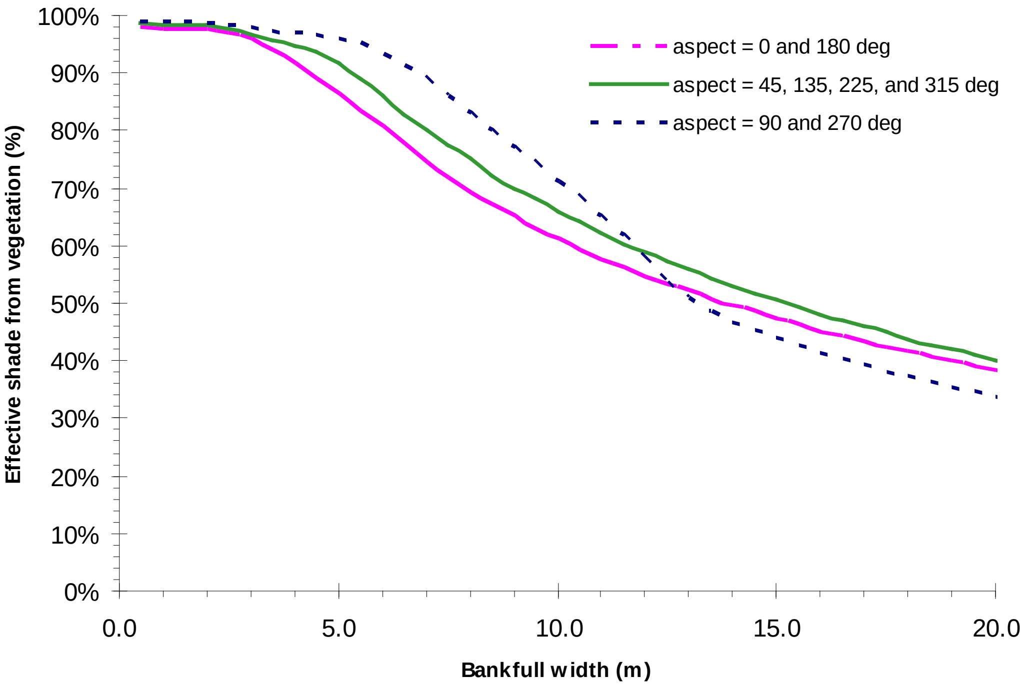


Figure 2. Effective shade levels as a function of bankfull width. No topographic shade was simulated. Trees were assumed at bankfull width, with 2.0 overhang.

A sensitive analysis will be carried out in the standard fashion: varying one parameter at a time while maintaining the others constant (Table 1). The results will be compared to the baseline condition. Period of model simulation will be assumed one day – August 1, considered critical for the evaluation of solar radiation and effective shade, because it is the midpoint of the period when water temperatures are typically at their seasonal peak.

A more detailed description of shade and stream temperature model parameters that will be used in the sensitivity analysis is presented in Appendix A, Tables 1 and 2. The input variables have been categorized as Fixed, same value(s) are used for all model scenarios, or Variable, where the values reflect different stream conditions that will be modeled. Suggested values for some input variables are listed, but these should be developed in consultation with the Riparian Science Advisory Group.

The results of the sensitivity analysis are expected to provide information on the most sensitive factors affecting stream temperatures in Western Washington, the effects of the near stream timber harvesting and the efficiency of the riparian buffers. The analysis is expected to provide information about the possible harvesting lengths (500’, 750’, 1000’, 1250’) and the corresponding downstream temperature recovery lengths.

Deliverables

A report will be produced which describes and justifies the input variables used in each model run. Results of the sensitivity analysis will be presented in a table similar to Table 2, with the temperature response at each of the five specified harvest unit lengths as well as the distance to recovery below the harvest unit. These results will be interpreted with respect to identifying specific stream types or environmental conditions that correlate with stream temperature response (i.e. where stream temperature is sensitive or resistant to the proposed harvest scenario.

Table 2. Example of table with the results of stream temperature sensitivity analysis relevant for small forest sites in Western Washington State

Stream Type	Temperature response / harvest unit					
10’ wide	500’	750’	1000’	1250'	1500’	Distance to recovery
Baseline condition						
Modified headwater temperatures						
Enhanced hyporheic exchange, etc						

Budget

1 FTE (Environmental Engineer) x 4 months= $ 32,416**.**

References

Adams, T.N., Sullivan, K. 1990. The pysiscs of forest stream heating: a simple model. Timber, Fish and Wildlife Report No. TWF-WQ3-90-007, Washington Department of Natural Resources, Olympia, WA.

Anderson, R.J., Bledsoe B.P., Hession W.C., 2004. Width of streams and rivers in response to vegetation, bank material, and other factors. Journal of the American Water Resources Association 40(5):1159-1172.

Blann, K., Frost Nerbonne, J., Vondracek, B., 2002. Relationship of riparian buffer type to water temperature in driftless area ecoregion of Minnesota, North American Journal of Fisheries Management 22:441-451.

Brosofske K.D., Chen, J., Naiman, R.J., Franklin J.F., 1997. Harvesting effects on microclimate gradients from small streams to uplands in Western Washington, Ecological Applications, 7(4), pp. 1188-1200.

Brown, G.W., 1969. Predicting temperatures of small streams. Water Resources Research Vol. 5. No. 1:68:75

Brown, G.W., Krygier, J.T., 1970. Effects of clear cutting on stream temperature. Water Resources Research Vol. 6., No.4:1133-1139

Chapra, S.C. 1997. Surface Water Quality Modeling. McGraw-Hill Companies.

Chen, Y. D. 1996. Hydrologic and Water Quality Modeling for Aquatic Ecosystem Protection and Restoration in Forest Watersheds: A Case Study of Stream Temperature in the Upper Grande Ronde River, Oregon. Ph.D. Dissertation. University of Georgia. Athens, Georgia.

Cross J., 2002. Measuring the impact of harvest intensity on riparian forest functionality in terms of shade production and large woody debris recruitment potential: two models. Master of Science thesis, University of Washington. http://www.ruraltech.org/pubs/theses/cross/index.asp - accessed on April 14, 2005.

Danehy, R.J., Colson C.G., Parrett K.B., Duke, S.D., 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forest setting. Forest Ecology and Management 208 pp 287-302

Ebersole, J.L., Liss, W.J., Frissell, C.A., 2003. Cold water patches in warm streams: physiochemical characteristics and the influence of shading. Journal of the American Water Resources Association, 39(2):355-368.

Edinger, J.E., Duttweiller, D.W., Geyer, J.C., 1968. The response of water temperature to meteorological conditions. Water Resources Research Vol.4, No. 5:1137-1143.

Hagan J., Whitman, A., 2000. Do Riparian Buffer Strips Maintain Interior-Forest Air Temperatures? Forestry and the riparian zone**,** University of Maine Orono, Maine, Conference Proceedings pp 61-62

Harvey, J.W., Bencala, K.E., 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. Water Resources Research, Vol.29, No.1, pp 89-98.

Hetrick, N. J., Brusven, M.A., Bjornn T. C, Keith R. M., Meehan W. R.. 1998: Effects of canopy removal on invertebrates and diet of juvenile coho salmon in a small stream in southeast Alaska**.** Transactions of the American Fisheries Society: Vol. 127, No. 6, pp. 876–888.

Isaak, D.J., Hubert W.A., 2001. A hypothesis about factors that affect maximum summer stream temperatures across montane landscapes, J Amer. Water Resour. Assoc. 37(2): 351-366.

Johnson, S.L. 2003 Stream temperature: scaling of observations and issues for modeling. Invited commentary. Hydrol. Process. 17, 497-499.

Johnson, S.L., Jones, J.A., 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Can. J. Fish. Aquat. 57 (Suppl. 2): 30-39

Ledwith, T., 1996. The Effects of Buffer Strip Width on Air Temperature and Relative Humidity in a Stream Riparian Zone. Watershed Management Council. http://www.watershed.org/news/sum_96/buffer.html - accessed on April 21, 2005.

Lewis, T.E., Lamphear D.W., McCanne, D.R., Webb, A.S., Krieter, J.P., Conroy, W.D., 2000. Regional assessment of stream temperatures across northern California and their relationship to various landscape-level and site-specific attributes. For. Sci. Project, Humboldt State Univ. Foundation, Arcata, CA. 420 p.

Macdonald, J.S., MacIsaac, E.A., Herunter H.E., 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Can. J. For. Res. 33: 1371-1382.

Malcolm, I.A., Soulsby, C., Youngson, A.F., Hannah, D. M., McLaren I.S., Thorne, A., 2004. Hydrological influences on hyporheic water quality: implications for salmon egg survival, Hydrol. Process. 18, pp 1543-1560.

Mellina E., Moore R.D., Hinch, S.G., Macdonald, J.S., Pearson, G., 2002. Stream temperature responses to clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes. Can. J. Fish. Aquat. Sci. 59:1886-1900.

Mohseni, O., Stefan, H. G., Erickson, T. R., 1998. A nonlinear regression model for weekly stream temperatures. Water Resour. Res., 34(10), 2685–2692.

Neumann, D.W., Balaji, R., Zagona, E.A., 2003. Regression model for daily maximum temperature, Journal of Environmental Engineering, Vol. 129, No.7. 667-674.

Poole, G.C., Berman, C.H., 2000. Pathways of Human Influence on Water Temperature Dynamics in Stream Channels. U.S. Environmental Protection Agency, Region 10. Seattle, WA. 20 p.
http://www.krisweb.com/biblio/gen_usepa_pooleetal_2000_pathways.pdf - accessed on April 21, 2005.

Ringler, N.H., Hall, J.D., 1975. Effects of logging on water temperature, and dissolved oxygen in spawning beds. Transactions of the American Fisheries Society, Vol. 104, No. 1, pp. 111–121.

Scholz, J., 2001. The variability in stream temperatures in the Wenatchee National Forest and their relationship to physical, geological, and land management factors. University of Washington, M.S. Thesis.

Silliman S.E., Booth D.F., 1993. Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. J. Hydrol. 146: 131-148.

Sinokrot, B. A. and Stefan, H. G.: 1993, Stream temperature dynamics: Measurements and modeling. Water Resour. Res. 29: 2299-2312.

Story, A., Moore, R.D., Macdonald, J.S., 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology, Can. J. For. Res. 33: 1383-1396.

Sullivan, K.J., Tooley, K., Doughty, J.E., Caldwell, J.E., Kenudsen, P., 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Washington Department of Natural Resources Timber/Fish/Wildlife Report TWF-WQ3-90-006.

Wondzel, 2004. in an interview in Science Findings No. 67: Following a river wherever it goes: beneath the surface of mountain streams. Pacific Northwest Research Laboratories http://www.fs.fed.us/pnw/sciencef/scifi67.pdf - accessed on April 21, 2005

Appendix A

Table 1 – Data required by the QUAL2Kw model and proposed values used in the model runs.

	Variable	Fixed / Variable	Value
General	Elevation upstream	Fixed	To be determined; a value representative for the small forest owner sites in Western Washington
	Latitude/Longitude	Fixed	To be determined; a value representative for the small forest owner sites in Western Washington
	Channel azimuth / stream aspect	Fixed	N-S
	Harvest length	Variable	500’ (152 m), 750’ (229 m), 1000’ (305 m), 1250’ (381 m)
Hydraulics	Tributary discharge	Fixed	0 (assume no tributary inputs)
	Bankfull width	Variable	Two stream sizes will be investigated corresponding to: • bankfull width = 10’ (3m) • bankfull width= 30’ (9.1m)
	Groundwater inflow rate	Variable	To be determined (0 and 25 % of Q (tentative))
	Flow coefficients	Fixed	To be determined from the available data representative for the study sites; investigate streamflow regimes and estimate relationships between velocity and flow, wetted width and flow and, depth and flow. Another option would be to use hydraulic coefficients established in Ecology temperature TMDL studies for sites in Western Washington.
	Channel slope (gradient)	Variable	To be determined. A single value will be used for the baseline condition for the two stream sizes (Figure 3).

Table 1 – Data required by the QUAL2Kw model and proposed values used in the model runs (continued).

	Variable	Fixed / Variable	Value
Temperature	Headwater daily maximum temperature	Variable	Two headwater temperature input files will be used: • >16 deg C, daily max • < 16 deg C daily max If possible, these will be selected from the data collected by the Hardwood Conversion Study.
	Headwater temperature – diel range	Variable	See above
	Groundwater temperature	Fixed	To be determined. Approximately annual average air temperature in Western Washington area ± 3 deg C.
	Tributary temperature	Fixed	assume no tributaries
Hyporheic exchange	% of surface flow in the hyporheic area	Fixed	To be determined from the available data or literature; 50% (tentative)
	Bed substrate	Variable	Two types of bed substrate will be simulated: • alluvial • bedrock
	Depth of the hyporheic exchange region	Fixed	100 cm (100 cm is the suggested value in the QUAL2Kw model for areas with intensive hyporheic exchange)
Meteorology	Air temperature	Fixed	Air temperature data collected by the HWC study to determine range of conditions then make recommendation. Or, select a representative weather station for the study sites and determine a median condition based on the historic record.
	Relative humidity	Fixed	Correlate relative humidity data with air temperature data.
	Wind speeds	Fixed	1 m/s Or, correlate with meteorological station data.
Model	Date	Fixed	August 1
	Duration of simulation	Fixed	1 day

Table 2 – Data required by the Ecology shade model and proposed values used in the model runs.

	Variable	**Fixed or Variable**	**Value**
General	Elevation upstream	Fixed	Same as in the QUAL2Kw model.
	Elevation downstream	Variable	Based on streambed slope. To be determined. A single value will be used for the baseline condition for the two stream sizes (Figure 3). For the 30' wide stream a different value than the baseline will be used in the sensitivity analysis.
	Channel azimuth / stream aspect	Fixed	N-S
Stream	Bankfull width	Variable	Two stream sizes will be investigated corresponding to: • bankfull width = 10' (3m) • bankfull width= 30' (9.1m)
	Near stream disturbance zone	Fixed	0- Vegetation assumed to begin at bankfull width
	Channel incision (the vertical drop from the bankfull edge to the water surface)	Fixed	0
Shade	Topographic shade	Fixed	Assume no topographic shade
	Riparian buffer width in the harvested area	Fixed	30'
	Vegetation height below the harvested area	Fixed	80'
	Vegetation density below the harvested area	Fixed	85% or derived from HWC Study
	Vegetation height in the riparian reserve	Fixed	80'
	Vegetation density below in the riparian reserve	Fixed	85% or derived from HWC Study
	Buffer width used for effective shade estimations above and below the harvested area	Fixed	50' (15.2 m)