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Modeling the Effects of Riparian Buffer Width on Effective Shade and Stream Temperature

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Modeling the Effects of Riparian Buffer Width on Effective Shade and Stream Temperature

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Abstract

To evaluate the effects of converting riparian hardwood-dominated stands to coniferous-dominated stands on western Washington stream temperatures, we combined a shade model and water quality model to explore the stream heating potentials of three buffer-width scenarios. Changing one variable at a time, we then ran a series of model simulations for various buffer-width (30-75 feet) and harvest-length (500-1500 feet) scenarios. Results of each simulation were expressed as the change in maximum daily temperature relative to the unharvested state (i.e., upstream boundary condition).

When a 500-foot harvest unit and 50-foot buffer were then applied to our model channel, the downstream temperature of the 10-foot-wide stream increased 0.13°C relative to the upstream state. Temperature continued to rise as harvest-unit length increased, with the 1500-feet-long unit showing the most change (+0.36°C, or approximately +0.12°C per 500 feet of harvest length). Wider buffers (75 feet), in contrast, continued to dampen temperature increases for the 10-foot stream, even at a harvest-unit length of 1500 feet. Results for the 20-foot-wide stream showed a similar pattern, but temperature increases in response to harvest-unit length were higher: 0.15°C (500 feet) – 0.60°C (1500 feet), or about 0.18°C per 500 feet of harvest length. Temperature of the 10-foot-wide stream was more sensitive to buffer width than the 20-foot-wide stream. In contrast, all buffer scenarios cooled the 20-foot-wide stream less effectively, with predicted downstream temperatures converging somewhat when harvest-unit length reached 1000 feet. Inferences vary depending on the shade curve used.

Overall, results indicated that, for the stream scenarios analyzed, riparian vegetation and harvest-unit length exerted greatest control on stream temperature at lower flow rates. Conditions favoring high daily maximum stream temperatures include: shallow and wide streams, north-south channel orientation, low groundwater influx or hyporheic exchange with the channel, and low gradient.

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Introduction

The Washington State Department of Natural Resources (DNR) and the Forests and Fish Report (FFR, 1999) provide recommendations, rules, statutes, and programs for forest practices on private forest lands. The intent of this stewardship, hereafter called Forest Practices rules, is to maintain a viable timber industry in Washington State while preserving and protecting natural resources such as waterbodies (and their respective ecosystems) as required by the federal Clean Water Act and the Endangered Species Act.

The Forests and Fish Report's proposal for *"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))"* was written into Forest Practice rules (Washington Administrative Code (WAC) 222-30-021(1)(b)(i)), effective July 1, 2001) as a section specific to hardwood conversion. To date, however, Forest Practice applications have usually prescribed hardwood conversion via alternate plans (WAC 222-12-040 and WAC 222-12-0401) rather the standard Forest Practice rules[1], even though alternate plans are equally (or more) stringent[2]. Under either hardwood conversion route, however, length of channel to which hardwood conversion should be applied is still uncertain.

A workgroup consisting of state agencies and small forest landowners is currently working to resolve these and other questions by developing an alternate plan template for hardwood conversion. This study is thus intended to identify stream temperature control variables to inform that workgroup.

The study combines a shade model and a water quality model to predict stream temperature response to three buffer-width scenarios[3]. The buffer scenarios are applied to two fixed stream widths (10 feet and 20 feet), assumed equivalent to bankfull width (bfw) with channel incision = 0. We recognize that bfw of many streams draining low-elevation forest lands of western Washington is ≤ 3 feet, but the difference in shade provided by a mature hardwood stand to a 3-foot vs. 10-foot bfw channel is negligible. These widths are practical starting points given that the data needed to parameterize some model variables were only available for mainstem rivers.

[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 Watershed Administrative Unit (WAU) scale on a biennial basis as per WAC 222-30-120…". So far, these data are not available, but anecdotal information suggests that hardwood conversion under the current hardwood rule is rarely done.

[2]The qualifying criteria for alternative plans 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."

[3]These models are frequently used by the Washington State Department of Ecology for Total Maximum Daily Load (TMDL) studies such as response of surface waters to thermal loading.

In addition to bfw categories, all model runs assume the following:

- riparian forest and harvest unit consist of mature red alder
- adjacent, downstream harvest unit is also mature red alder
- uniform canopy closure within buffer
- uniform buffer width (no buffer allowance for wetlands, slope stability, etc.)
- harvest unit on one side of stream only
- no tributary inflow to the modeled reach

The study asks three primary questions:

1. What is the relative impact on stream temperature of the modeled harvest scenarios?
2. How much distance to recovery (i.e., what length of intact forest downstream of the harvest unit edge is needed to re-establish thermal equilibrium of the stream similar to that found upstream of the harvest unit)?
3. Which variables are important (i.e., what is the relative temperature-control importance of a list of stream variables identified by a literature search)?

To address these questions a three-stage modeling strategy was used.

In Stage 1, literature was consulted to identify a reference-state buffer width (i.e., wide enough so that angular canopy density (analogous to canopy cover) inside the buffer is similar to an unharvested stand). The reference state (120 feet wide) was then inserted in the shade model to identify the channel orientation (aspect) receiving least daily shade. Using this worst-case orientation, each stream width (10 feet and 20 feet) then received three buffer-width scenarios (bank-to-buffer edge, perpendicular to stream):

- 30-foot, no-cut buffer
- 50-foot, no-cut buffer (current hardwood conversion target)
- 75-foot, no-cut buffer

These scenarios established input shade conditions for Stage 2, the temperature model. Scenarios were selected to bracket the hardwood conversion 50-foot buffer target so that temperature response of narrower and wider alternatives could be compared to effectiveness of the existing Forest Practice regulation. Relevant stream variables (including groundwater/ hyporheic influence, length, width, and upstream temperature) were then combined with five harvest-unit sizes (500-, 750-, 1000-, 1250-, and 1500-foot harvest block edge parallel to channel) in a series of cases for each buffer-width/stream-width combination and evaluated in the temperature model. Baseline conditions were selected to approximate those typical of forested, low-elevation western Washington streams.

Stage 3 was a sensitivity analysis used to evaluate the relative influence of a subset of variables identified as potentially important by the literature review. For the sensitivity cases, each variable was tested individually for selected values while holding remaining model values constant.

The stream temperature metric is daily maximum value. Results are summarized as a matrix of factors affecting stream temperature ranked by relative importance. Finally, the reader should note that model baseline values are initial conditions given freedom to vary during the model simulation (e.g., vary with or without restriction). Thus, for example, though daily average water temperature is a baseline input value, initial diel range is also specified such that the full daily temperature cycle can be simulated.

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Stream Heating Processes and Controls

Heat Exchange Processes in a Stream System

The temperature of a stream reflects the amount of heat energy in the water. Water temperature change within a particular segment of a stream results from heat exchange between the water and the surrounding environment during transport through the segment (Figure 1). If more heat energy enters the water in a stream segment than leaves, the temperature will increase; if less heat energy enters than leaves, the temperature will decrease.

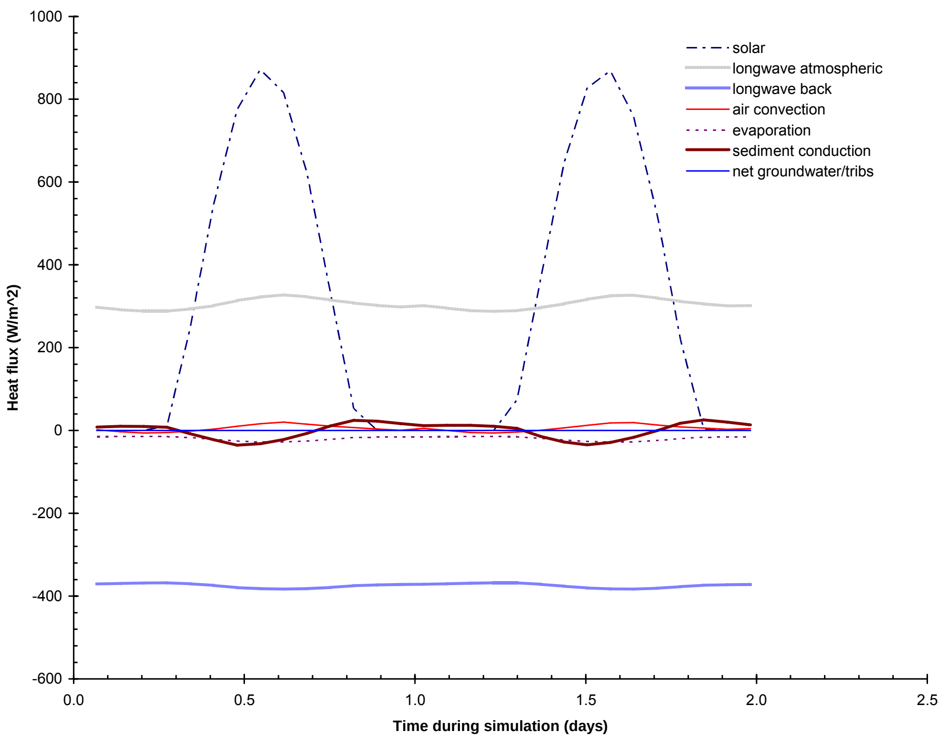


Figure 1. Main components of stream heat balance.

(Net heat flux = solar + longwave atmosphere + longwave back + air convection + evaporation + sediment conduction). Estimated surface heat fluxes are for a 20-foot-wide stream completely exposed to incoming solar radiation. Hyporheic exchange was not simulated.

The complete heat budget for a stream also accounts for mass-transfer processes which depend on the volume of water into and out of a particular segment. Mass transfer processes in open channel systems can occur through advection, dispersion, and mixing with tributaries and groundwater inflows and outflows. Mass transfer relates to downstream transport of volume, instream mixing, and loss or gain of water from a stream. The distinction between reduced heating of streams and actual cooling is important. Shade can significantly reduce the amount of heat flux that enters a stream. Whether water temperature increases, decreases, or remains stable as the stream flows downgradient, however, depends on the balance of all the heat exchange and mass transfer processes in the stream (Figure 2). Small streams are expected to be cooler than mainstems because much of their discharge is provided by groundwater.

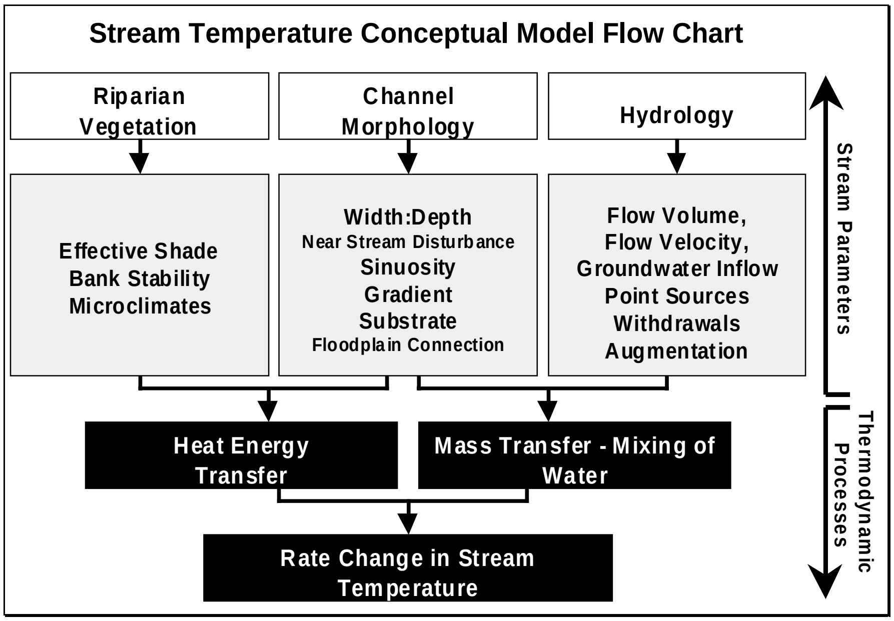


Figure 2. Conceptual model of factors affecting stream temperature.

Microclimate, insulating processes, upstream conditions, and channel morphology also superimpose local variations on the general downstream heating trend (Torgersen et al., 2001; Johnson, 2003). In the Pacific Northwest, high precipitation and high elevation generally correlate with relatively cool temperatures; conversely, low precipitation correlates with relatively warm temperatures at lower elevations (Scholz, 2001; Isaak and Hubert, 2001). There are, however, exceptions to this pattern, subject to local climatic influences (Lewis et al., 2000) and analysis extent (Danehy et al., 2005). Natural features such as small, shallow lakes or swamps acting as headwaters for small streams can result in downstream cooling patterns (Mellina et al., 2002). Forested streams with alluvial beds also usually exhibit low diurnal variation, and those with bedrock beds exhibit higher diurnal variation (Johnson, 2004). Small, shallow streams with reduced shading are more thermally sensitive and exhibit higher diurnal fluctuations than larger streams (Brown, 1969; Sinokrot and Stefan, 1993; Danehy et al., 2005).

Stream Temperature Recovery from Thermal Loading

Spatial (longitudinal) Recovery

The rate of thermal recovery of a stream after solar loading due to loss of riparian vegetation depends on stream width and volume, which drives the rates of the stream heating processes. Small streams have higher temperature recovery potential than large streams because shading of the small stream is more effective and the stream is more responsive to stream cooling processes such as groundwater and cold tributary inputs. Energy balance analyses indicate that groundwater inflows, bed conduction, and hyporheic exchange are key pathways for cooling small streams (Story et al., 2003). Even without groundwater inflow and hyporheic exchange, shading can cool a small stream (Johnson, 2004). By contrast, relatively large streams require longer distances for temperature recovery because thermal inertia is increased and riparian shading is less effective. Thus, some large streams may not recover.

Temporal Recovery

Stream temperatures may recover to pre-harvest conditions after a period of time in which the riparian vegetation has grown enough to provide efficient shading. Small Pacific Northwest streams (basins < $1 km^2$) have returned to a pre-harvest temperature regime in 15 years, coinciding with canopy closure in riparian zones and a change from mostly coniferous to deciduous vegetation (Johnson and Jones, 2000). Smaller streams can recover sooner because early successional vegetation can provide as much shade as wooded buffers for channels of bankfull widths < 2.5 m (Blann et al., 2002). If harvest methods and riparian vegetation regeneration do not favor rapid regrowth, however, modification of maximum stream temperatures can be minimal in the first 5 years after harvest (Johnson and Jones, 2000; Beschta and Taylor, 1988). Windthrow and other disturbance also can increase direct solar exposure, prolonging post-harvest thermal recovery (MacDonald et al., 2003).

Factors Affecting Stream Temperatures

Riparian Vegetation

Riparian vegetation influences sensible and latent heat exchange at the air-water interface by partially blocking direct solar radiation received by the stream, slowing wind speeds above the channel, reducing air and soil temperatures, and increasing relative humidity. As stream width and volume increase, however, riparian vegetation influences diminish (Poole and Berman, 2000). Riparian vegetation restoration has been identified as one of the most important management steps that may improve stream temperatures (Johnson and Jones, 2000; Blann et al., 2002).

Warming as a stream flows downgradient is a natural process, but summer downstream temperatures tend to increase relative to pre-harvest conditions after riparian vegetation is removed (e.g., Holtby, 1988; Lynch et al., 1985; Rishel et al., 1982; Patric, 1980; Swift and Messer, 1971; Brown et al., 1971; and Levno and Rothacher, 1967). Increased daily stream temperature variations and elevated monthly and annual temperatures, as well as daily maxima, have been detected by many studies following loss of riparian vegetation (e.g., Brown and Krygier, 1970; Sullivan et al., 1990; Johnson and Jones, 2000; MacDonald et al., 2003). Maximum increases in mean summer stream temperatures have been associated with low retention of riparian shade or vegetation and patch cut treatments (MacDonald, 2003; Johnson and Jones, 2000). When southeasterly aspect combines with very low retention, increases as high as 6ºC have been reported, with the magnitude of daily temperature fluctuations also increasing.

In contrast, temperature changes for high-retention basins are generally small. Other studies have reported only minor temperature changes following timber harvest (~0.05 – 1.1 ºC; Mellina et al., 2002), but these modest changes were attributed to high streamside-retention treatments (40-60% channel shade remaining), small lakes located at the headwater of the streams, and groundwater. Loss of riparian vegetation may also shift seasonal high temperatures in time, occurring earlier in the summer following clear-cutting, patch cutting, and debris flows (Johnson and Jones, 2000).

Rates of downstream heating can be dramatically reduced, however, when riparian vegetation is retained (Johnson and Jones, 2000; Blann et al., 2002; Danehy et al., 2005) or channels are artificially shaded (Ebersole et al., 2003), or heat flux from peak solar radiation is otherwise minimized (Adams and Sullivan, 1990; Sinokrot and Stefan, 1993; Johnson and Jones, 2000).

There is, however, a natural maximum level of shade that a given stream is capable of attaining, which decreases as stream width increases. The effectiveness of riparian vegetation to shade streams thus depends on buffer width and canopy cover (Brazier and Brown, 1973; Steinblums et al., 1984), and is subject to natural variability in vegetation structure (Brazier and Brown, 1973; Steinblums et al., 1984). Two published curves relating buffer width to angular canopy density (ACD) differ somewhat (Figure 3). This may reflect the variability of the two old-growth study sites, often characterized by multi-layered, gap-rich canopies. Both curves, however, suggest that 120-foot-wide buffers provide at least 80% angular canopy density.

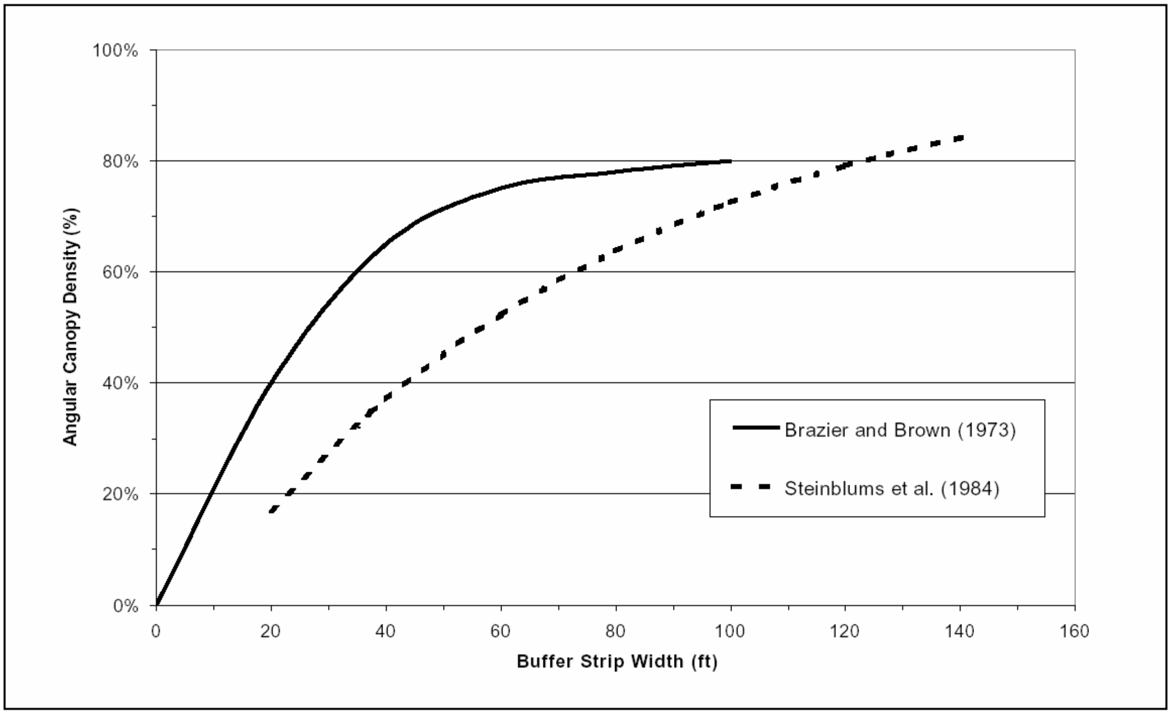


Figure 3. Relationship between angular canopy density (ACD) and riparian buffer width for small streams in old growth riparian stands (after Beschta et al., 1987 and CH2M Hill, 2000).

Other studies found that riparian buffer widths ranging from ~11- 43 meters (m) (36 -142 feet) provided 60% - 100% levels of shading characteristic of riparian forest where no harvest occurred. Most of the potential shade came from the riparian area within about 75 feet (23 m) of the channel (CH2M Hill, 2000; Castelle and Johnson, 2000; Christensen, 2000). These studies have assessed the shading effectiveness of buffer widths (Table 1) over the past 30 years.

Table 1. Shading effectiveness of various buffer widths (literature summary, after CH2M Hill, 2000, and Christensen, 2000).

Reference	Buffer investigated (meters)	Observations
Brazier and Brown 1973	11-24	Provided 60-80% shading. Found that a 79-foot (24-m) buffer would provide maximum shade to streams.
Broderson 1973	15	A 49-foot (15-m) buffer provides 85% of the maximum shade for small streams.
Hewlett and Fortson 1982	15-30	Provided 60-80% shading.
Lynch et al. 1984	30	A 98-foot (30-m) buffer maintains water temperatures within 2°F (1°C) of their former average temperature in small streams (channel width less than 3 m). Provided 50-100% shading (equivalent to mature forest).
Steinblums et al. 1984	17	A 56-foot (17-m) buffer provides 90% of the maximum angular canopy density (ACD).
Corbett and Lynch 1985	12	A 39-foot (12-m) buffer should adequately protect small streams from large temperature changes following logging.
Beschta et al. 1987	30	A 98-foot-wide (30-m) buffer provides the same level of shading as that of an old-growth stand.
Jones et al. 1988	30-43	Provided 50-100% shading.
Sinokrot and Stefan 1994	Tested mechanistic stream temperature model to changes in weather and streambed variables.	Stream temperature was more sensitive to air temperature and solar radiation. Daily average stream temperature is not very sensitive to streambed thermal conductivity.

Air Temperature

Air temperature correlates well with water temperature, and models relating the two variables have been successfully used at daily, weekly, and monthly time scales (Stefan and Preud'homme, 1993; Caissie et al., 1998; Mohseni et al.; 1998, Erickson and Stefan, 2000). The strong correlation results from a common driver, solar radiation (Johnson, 2003). Air temperature also influences water temperature through heat exchange processes such as atmospheric longwave radiation, convection/conduction, and evaporation processes at the air-water interface (Chapra, 1997). Air temperature may play a more important role in the heat budget of a stream during nighttime, influencing daily water temperature minima (Danehy et al., 2005). Upstream conditions that may favor increased diel ranges include low hyporheic exchange (Johnson, 2004), reduced riparian vegetation protection (Brown and Krygier, 1970; Johnson and Jones, 2000), and shallow, low-velocity flow.

Solar Radiation

Solar radiation has a small effect on daily mean water temperatures, but it is important for daily fluctuations (Adams and Sullivan, 1990). Artificial shading of a second-order stream (Oregon) showed that blocking incoming solar radiation reduced daily maximum temperatures in the shaded reach, but minimum and mean temperatures were not substantially affected (Johnson, 2004).

Flow

All water heat exchange processes are influenced by volume of flow (Poole and Berman, 2000). Small, shallow streams are more sensitive to the water-temperature drivers and usually exhibit higher diurnal fluctuations. Small stream (discharges less than 1 m^3/s) temperatures may vary by as much as 20ºC between daily extremes and large streams (discharges more than 142 m^3/s) by as little as 2ºC (Brown, 1969). High summer stream temperatures are typically associated with low flows (Adams and Sullivan, 1990).

Stream Width and Depth

Width-to-depth ratio (i.e., volume-to-surface area) influences stream temperatures (Bartholow, 2000; Poole and Berman, 2000; Blann et al., 2002) because volume-to-surface area relationships affect heat exchange. The ratio is relevant to small forested streams which tend to be wide, considering their small basin areas (relative to watersheds of 10-100 km^2; Anderson et al., 2004). Width of small forested streams is thought to result from interaction between woody debris, shading, understory vegetation, rooting characteristics, and channel size.

Bed Morphology and Channel Orientation

Bed substrate influences daily maximum temperature in multiple ways. For example, a smooth streambed reduces depth, changing the width-to-depth ratio, which affects the stream's heat exchange. Bed conduction processes also vary in magnitude with conductive properties of the parent material and temperature gradient in the streambed. In shallow streams, more heat fluxes through beds composed of rocks compared to those composed of mud (Sinokrot and Stefan, 1993). Channel morphology, in turn, is influenced by riparian vegetation, which stabilizes banks.

Some studies report north-south (N-S) oriented channels are warmer than east-west (E-W) oriented channels (Sridhar et al., 2004). Others found no significant relationship between channel aspect and stream temperature (Lewis et al., 2000).

Groundwater

Because groundwater is both typically cooler than surface water and of near constant temperature throughout the year, groundwater influx can moderate seasonal and diurnal stream temperature variations (Moore and Wondzell, 2005; Mellina et al., 2002; Danehy et al., 2005). Groundwater temperature is usually considered similar to mean regional or elevational air temperature, differing from surface temperatures by as much as ~ 10ºC (Mellina et al., 2002). Magnitude of the groundwater effect depends mainly on the surface vs. groundwater temperature difference and volume of groundwater inputs relative to surface flow (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.

Some authors indicate groundwater levels increased after forest harvest due to decreased interception losses and transpiration (Moore et al., 2005). Others suggested warming of shallow groundwater in clearcuts may result in heat advection to a stream, enhancing the effects of increased solar radiation or decreasing the effect of riparian buffers (Moore et al., 2005).

Hyporheic Exchange

Complex mixing and exchange of groundwater with channel and substrate water occurs in the hyporheic zone (Poole and Berman, 2000), the permeable layer of sediments lining the channel bed. Hyporheic exchange may strongly influence temporal and spatial variability of stream temperature and is a mechanism for buffering and reducing daily- maximum stream temperature (Johnson and Jones, 2000; Poole and Berman, 2000; Johnson, 2004). A hydraulically connected aquifer can also exchange water with the main channel through hyporheic flow, a back-and-forth transfer between the stream and water table.

Hyporheic exchange for small streams has been reported as low [0.6-5% total surface flow/ 100 m, fifth-order streams (Kasahara and Wondzell, 2003)] and only significant when thick sediment is present [~20-300% of stream depth (Harvey and Wagner, 2000; Gooseff et al., 2003)].

Hyporheic exchange can thermally buffer a stream reach but is relatively ineffective for channels lined with basalt or other bedrock and minimal sediment (Johnson, 2004).

Hyporheic exchange is sensitive to channel straightening, simplification of the bed form, loss of woody debris, and other land-management practices. Sedimentation due to forest harvesting can reduce hyporheic exchange via clogging bed materials and changing channel morphology (Moore and Wondzell, 2005). As hyporheic flow declines, stream temperature buffering declines, and daily minimum and maximum temperatures may increase (Johnson, 2004).

Important geomorphic factors affecting hyporheic exchange rates include pool-step sequences (Wondzel, 2004), as well as hyporheic zone heterogeneity, bed-form configuration and sinuosity, and hyporheic zone thickness. Stream features likely to increase hyporheic exchange are large-woody-debris steps (primarily in headwater channels), logjams (primarily in smaller fish-bearing channels), and channel braiding or sinuosity (primarily larger channels). A braided channel with multiple channels at different elevations can trigger intricate hyporheic flow patterns as flow responds to gravity. Subsurface flow paths can also be created by a meandering channel, flowing through point bars.

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.

Microclimate

A recent paper summarizing microclimate effects in Pacific Northwest forests indicated that much of the change in microclimate due to forest harvest takes place within about one tree height (15 to 60 m) of the edge (Moore et al., 2005). Solar radiation, wind speed, and soil temperature adjust to interior forest conditions more rapidly than do air temperature and relative humidity. Nighttime edge temperatures are similar to interior forest conditions while daytime relative humidity was found to decrease from interior to edge in response to the increased air temperature.

Buffers 45 m wide on each side of the stream can preserve the pre-harvest microclimate gradient, although this value can increase up to 300 m, depending on the variables analyzed (Brosofske et al., 1997). The microclimate of the near-channel zone inside riparian buffers has been reported as similar to that of extensive, mature stands (Hagan and Whitman, 2000).

The effects of air temperature and vegetation are discussed above.

Other Modeling Studies

LeBlanc et al. (1997) performed a stream temperature sensitivity analysis investigating the most influential factors affecting stream temperatures using a deterministic stream temperature model. Out of 14 variables evaluated, this study found that riparian vegetation (through partially blocking the incoming solar radiation), groundwater discharge, and stream width (stream size) had the greatest impact on stream temperatures.

For a mechanistic model applied to a 10-km-long stream, the most sensitive factors affecting daily maximum summer stream temperatures were streamside shading (accounting for 40% of the total temperature increase), channel width, weather parameters, groundwater temperature, and stream roughness (Bartholow, 2000). This study, which examined microclimate response to large scale harvesting on daily maximum stream temperature, also found high air temperature increased stream temperature, but increased wind speed and reduced humidity cooled the stream. These results indicate that a complex set of factors, rather than a single factor such as stream shading, influences stream temperature.

A simple, deterministic model simulating daily maximum stream temperatures on both the west and the east slopes of the Cascade Mountains during critical air-temperature and low-streamflow conditions has also indicated stream temperature is relatively insensitive to buffer widths greater than 15 m, and that leaf area index (LAI) effected daily maximum stream temperature most, followed by average tree height (Sridhar et al., 2004). Model scenarios also show early successional buffers provided as much shade as wooded buffers for channels < ~2.5 m bankfull width. High width-to-depth ratio can also offset the benefits of riparian vegetation shading (Blann et al., 2002). Sullivan et al. (1990) ranked a series of model parameters that had a significant impact on the modeled daily maximum stream temperature (Table 2).

Table 2. Ranked sensitivity of model variables in predicting daily maximum stream temperature from Sullivan et al., 1990.

Parameter	Change in Prediction of Maximum Daily Temperature (0°C)
Air Temperature	15.2
Humidity	7.6
Solar Radiation	5.2
Shade	-1.6
Wind Speed	-0.7
Stream Depth	0.7
Travel Time	-0.6
Groundwater	-0.3
Inflow Water Temperature	0.02

Most of the above cited studies indicate that weather-related parameters such as air temperature and relative humidity are sensitive model input data for daily maximum stream temperature prediction. However, the field studies reviewed for this analysis did not establish the direct cause-effect relationship between the altered microclimate due to harvesting and stream temperature response.

Methods

Modeling System

The shade model used for this study was Shade.xls (hereafter, SHADE). SHADE is an Excel/Visual Basic for Applications (VBA) program which estimates effective shade from topography and riparian vegetation (Ecology, 2003). SHADE is an implementation of a method proposed by Chen et al. (1998a,b). The water quality model used was QUAL2K (Chapra and Pelletier, 2003; Pelletier and Chapra, 2004). QUAL2Kw is a version of QUAL2E, programmed in the Windows macro language VBA. Excel is used as the graphical user interface.

These modeling packages are frequently used by the Washington State Department of Ecology (Ecology) for Total Maximum Daily Load (TMDL) studies requiring assessment of effective-shade thermal response under different flow and shade scenarios. The models have been tested on a variety of stream sizes and riparian-vegetation types throughout Washington. Typically, a temperature TMDL requires a model representing scientifically defensible processes, calibration of the model to a particular system by selecting appropriate input data, and validation of the model by testing the calibration with an independent data set.

Both models, along with additional model documentation and user manuals, are available at www.ecy.wa.gov/programs/eap/models/.

Shade Model

Because shade is an input variable to the water quality model, it was calculated first. The model uses relationships between latitude/longitude, day of year, aspect and gradient, solar path, buffer width, canopy cover, and vegetation height to compute hourly, dawn-to-dusk shade for the target stream. Direct radiation to the stream is then estimated with an hourly time step, attenuated by topography, vegetation, and water surface albedo. Diffuse radiation load to the stream, also calculated, is assumed to be a function of constant-sky openness rather than changing hourly with solar position. Final radiation load is calculated as a function of stream width. For a list of key model-variable values, see Table 3.

The shade indicator used in this report is effective shade, defined as the fraction of total possible solar radiation blocked from reaching the water surface, or

$$\text{Effective shade} = (J_1 - J_2)/J_1$$

where J_1 is potential solar heat flux (unattenuated by riparian vegetation and topography) and J_2 is solar heat flux at the stream surface. Differences between effective shade and canopy cover (resulting from channel orientation and other factors) indicate effective shade should be used for this analysis (Kelley and Krueger, 2005).

Table 3. Variables for SHADE and proposed values for model runs.

	Variable	Type	Value
Stream	Channel orientation	Fixed	North-south [1]
	Bankfull width	Variable	bankfull width = 10 ft bankfull width= 20 ft
	Near stream disturbance	Fixed	0- vegetation assumed to begin at bankfull width
	Channel incision (vertical drop from bankfull edge to water surface)	Fixed	0
Shade	Topographic shade	Fixed	assume no topographic shade
	Buffer width	Variable	120 ft (reference state) [2] 50 ft (baseline condition) 30 ft 75 ft
	Buffer height [3]	Fixed	80 ft
	Canopy cover [4]	Fixed	85%

[1] result of SHADE orientation trials, see below.
[2] field studies indicating 120-foot buffers approximate an unharvested angular canopy density (Table 1 and Figure 3)
[3] estimated height of mature red alder
[4] Brazier and Brown (1973) and Steinblums et al. (1984) shading curves and field studies (Table 1)

Temperature Model

QUAL2Kw treats stream channels as a series of adjacent segments of set length. The heat balance takes into account heat transfers from upstream reaches, loads, abstractions, the atmosphere, and sediments (Figure 4). Input variables are summarized in Appendix B. Using an hourly time step, diel temperatures for each segment at steady flow conditions were simulated using mathematical formulations of heat exchange processes described in Chapra (1997). These processes included shortwave solar radiation, longwave atmospheric radiation, longwave radiation from the water, conduction/convection at the air-water interface, evaporation, bed conduction, and hyporheic exchange.

Hydraulic parameters (mean velocity, depth, and width) were estimated using either established rating curves or Manning's equation. Air temperature, relative humidity, and effective shade levels were treated as diurnally varying input. Differences in daily maximum temperature between the downstream and the upstream end of each modeled channel were then calculated for each case. Model scenarios were repeated for two different shade curves because, though both curves are suitable to the region and forest type of this study (i.e., Western Cascades), they predict somewhat different relationships between angular canopy density and buffer width.

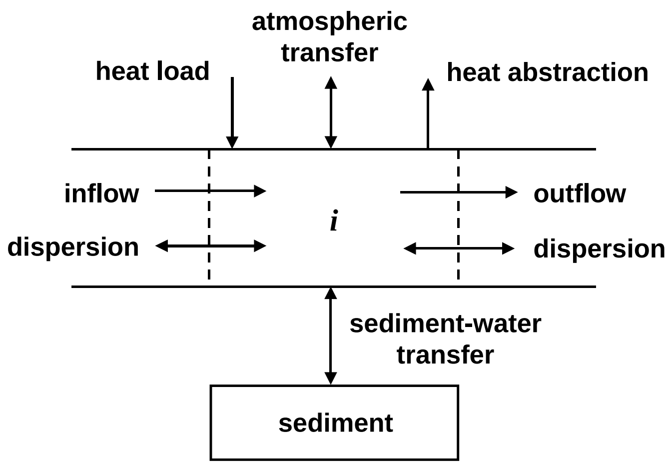


Figure 4: Heat balance and stream segmentation in QUAL2Kw

Model uncertainty was evaluated as in Department of Ecology temperature TMDL studies using the root mean square error (RMSE) criterion. The RMSE assesses overall model performance and was calculated as:

$$RMSE = \sqrt{\sum \frac{(T_{measured} - T_{calculated})^2}{n}}$$

where:

$T_{measured}$ =measured temperature metric of interest from a representative set (i.e., daily mean maximum or minimum)

$T_{calculated}$ =simulated correspondent temperature metric

n = number of pairs

Sensitivity Analysis

QUAL2Kw was used to examine the temperature influence of a subset of variables, including flow, groundwater input, and hyporheic exchange. These variables were changed by a fixed percent or step, based on literature values or previous TMDL work, while holding other scenario values constant. Results were expressed relative to the baseline scenario (discussed below).

Baseline Conditions

The baseline model system was a simple box-shaped channel bordered by a uniform 50-foot riparian buffer on one bank. The opposite bank was unharvested. No buffer allowance was made for wetlands, slope stability, residual conifers, etc. Riparian overstory was assumed to be mature red alder 80 feet in height with 85% within-stand canopy closure. The shading effect of the 50-foot riparian buffer was based on published shading curves (Figure 3) and shade modeling results (see below). Key baseline model variables and starting values are discussed below and fully described in Appendix B.

Upstream Boundary Condition, Water Temperature

The upstream temperature boundary condition was set as the median condition found at the CMER Hardwood Conversion Study sites. Daily average stream temperature was set to 13.8°C, corresponding to the median, mid-July to end-of-August temperature at these sites (Hunter, 2006, personal communication).

Sensitivity test: One higher diel range of temperature was compared to the baseline (Table 4).

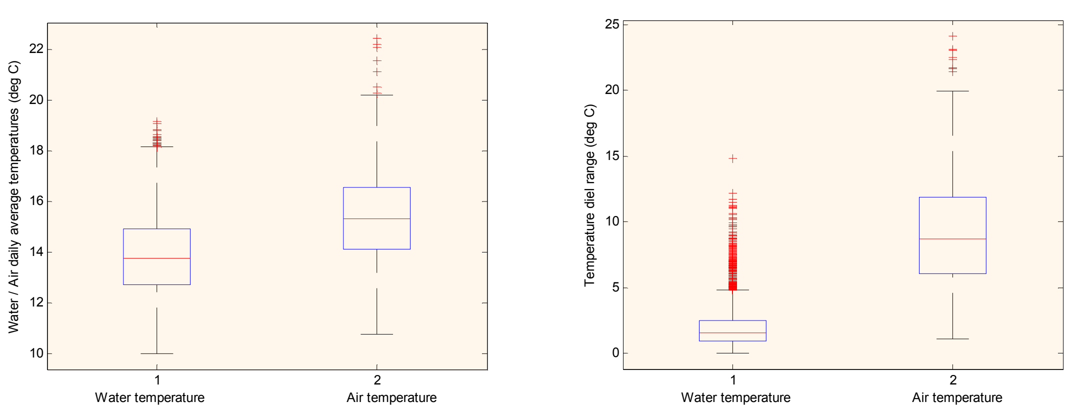
Table 4. Boundary temperature (deg C) condition (upstream of harvest unit)

Condition	T_{max}	T_{mean}	Diel range
Baseline	14.6	13.8	1.6
Sensitivity	14.6	12.2	5

Microclimate

Baseline air temperature and diel range were 15.4°C and 9°C, respectively (Hunter, 2006, personal communication; Figure 5). Wind speed was set to 0.4 m/s. A relative humidity (RH) baseline value of 85% was used given RH at Western Cascade foothill sites (93.8-97.2%) declined 2.5-13.8% after harvest (Brosofske et al., 1997; Dong et al., 1998). Air and dew point temperatures were treated as fixed.

Sensitivity test: Wind speed was set to 1 m/s (Pelletier and Chapra, 2004) to evaluate the influence of evaporation and convection processes at the air-water interface.



(a) (b)

Figure 5: Box and Whisker plots of (a) daily average and (b) diel range of water and air temperature recorded at eight Hardwood Conversion Study sites in 2003 and 2004.

Volume, Depth, and Velocity

Baseline flow regime for the 10-foot-wide stream was set at 0.2 m^3/s. To better account for the shading effect, the baseline flow condition for the 20-foot-wide stream was set to 0.4 m^3/s. Flow was assumed constant for all stream segments. An average depth of 9 cm and average velocity of 0.7 m/s was used for all runs.

These values were empirically-derived from modeled relationships between discharge and hydraulic parameters (width, depth, cross sectional area, and mean velocity). The sources of these data were Ecology stream temperature TMDL studies of western Washington streams less than about 10 m bankfull width. Width (B_0), is related to discharge (Q) by a power function (Leopold, 1994) as

$$B_0 = aQ^b, \qquad \textit{Eq. 1}$$

where "a" is a constant of proportionality and "b" is the estimated exponent, averaged for many stream types at 0.26 (Leopold, 1994).

Manning's equation was used in the model to solve for depth (y) given flow (Q), Manning's roughness coefficient (n), wetted width (B_0), and channel slope (S_e).

Manning's equation for a rectangular channel (side slope s = 0) is as follows (Chapra 1997)

$$Q = \frac{1}{n}\frac{[(B_0 + sy)y]^{5/3}}{\left(B_0 + 2y\sqrt{s^2+1}\right)^{2/3}}S_e^{1/2} \qquad \textit{Eq. 2}$$

Sensitivity test: Flow rates were increased sequentially by 0.04 m^3/s and 0.08 m^3/s for the 10-foot and 20-foot-wide streams respectively. Maximum values were 0.36 m^3/s and 0.72 m^3/s. To illustrate the effect of sub-baseline flow, cases varying in both flow rates and vegetation shading as per two shading curves (Figure 3) were added.

Groundwater and Tributary Inputs

Baseline condition assumed no groundwater or tributary inputs.

Sensitivity test: Groundwater input to the channel was assumed uniformly distributed at rates of 0.01, 0.012, 0.014, 0.016 and 0.018 m^3/s per 100 m. Average mean air temperature for western Washington lowlands (about 10°C, Appendix C) was used as groundwater temperature. This is because (1) groundwater temperature typically varies around regional mean annual air temperature and (2) property owned by small forest landowners is likely to be located at lower elevations. For the 0.01 m^3/s case, groundwater temperature was varied between 6 and 14°C with a 2°C step increment. Tributary inputs were assumed to be none.

Stream Roughness and Channel Slope

Channel slope was assumed 2%, and Manning's roughness coefficient (*n*) was set to 0.04 for both stream widths (Zalewsky and Bilhimer, 2004).

Sensitivity test: Manning's *n* was varied between 0.04 and 0.16 using a 0.02 step. Channel slope was varied between 2-8% using a 2% step.

Hyporheic Exchange

Baseline condition assumed no hyporheic exchange.

Sensitivity test: One thick sediment case was investigated, assuming hyporheic zone thickness to be 300% of stream depth and hyporheic flow volume to be 80% of surface flow/100m.

Effective Shade

The baseline effective shade state was a pure red alder buffer 80 feet tall and 50 feet wide, with 85% cover (see discussion below). Using the reference state, SHADE was used to simulate how effective shade from a 120-foot buffer varies with channel aspect as a function of channel width. This was done to identify which orientation is most prone to thermal loading (worst case). Four orientations were considered: N-S (0 and 180 deg), E-W (90 and 270 deg), and NE-SW or SE-NW (45, 135, 225 and 315 deg). The buffer scenarios were then applied to the worst-case orientation (least effective shade during the daily cycle).

Because the two published shading effectiveness curves considered differ (Figure 3), all channel width and buffer combinations were modeled for each curve using QUAL2Kw (Table 5).

Table 5. Canopy cover values used for effective shade simulations.

Buffer width (feet)	Canopy cover (%)	
	Brazier and Brown, 1973	Steinblums et al., 1984.
30	55	30
50	70	45
75	75	60

Sensitivity Test: Buffer canopy cover was varied from 25% to 85%, in 10% increments. Tree height was varied for a N-S orientation channel for the same 25% to 85% range.

Results and Discussion

SHADE Model

Channel Orientation: Baseline State Identification

Overall, north-south (N-S) channels over the width range examined received the least shade, so N-S orientation was selected as a baseline (i.e., worst-case) condition. However, channel width and orientation interacted to determine effective shade. For channels less than ~10 meters wide, the orientation effect was small (about 5% or less) and fairly uniform. Narrow N-S oriented channels received slightly less shade than other orientations. In contrast, effective shade declined by ~25% as channel width increased from 0-10 m, suggesting width exerts greater control on channel shade than orientation (Figure 6). For channel widths greater than ~ 10 m, however, effective shade for east-west (E-W) oriented channels declined sharply relative to other orientations. Streams less than ~3 m wide receive the maximum daily average effective shade (90% or more); streams 16-18 m wide receive about one-half this value.

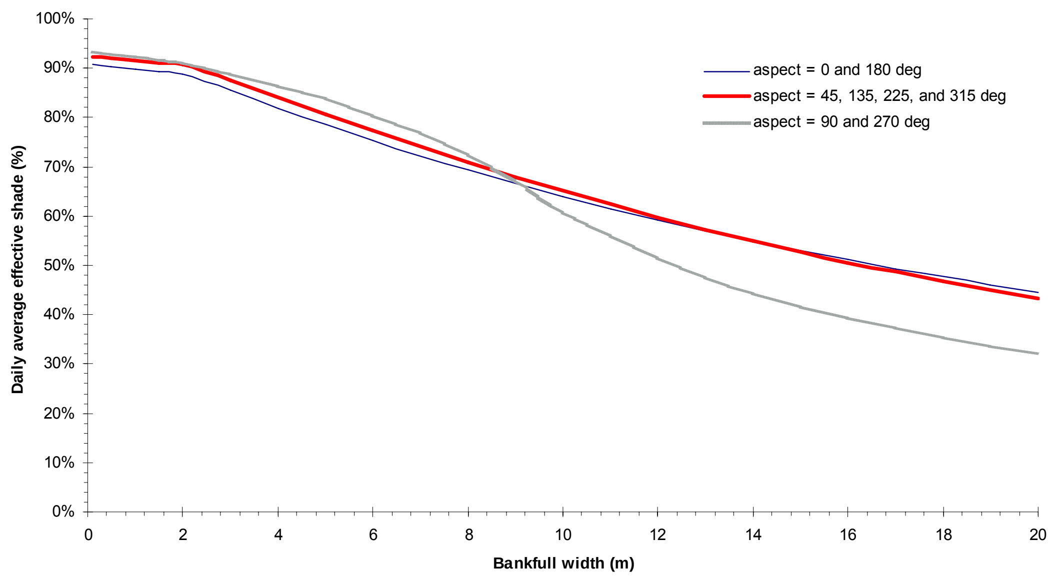


Figure 6. Simulated daily average effective shade as a function of bankfull width for various stream aspects (120-foot buffer)

Varying Canopy Cover: Evaluating 85% Canopy Cover

Varying canopy cover of the reference-buffer width reduced effective shade but did not greatly affect the shape of the daily shade curve for either the 10-foot-wide (Figure 7) or 20-foot-wide (Figure 8) channel, regardless of channel orientation. The model predicted canopy cover of 85% provided ~80-90% shade. Though effective shade varies throughout the day for all orientations, narrow N-S oriented channels had the highest overall daily maximum water temperature potential. Such channels are shaded least around midday, when air temperature and solar radiation are near peak daily values.

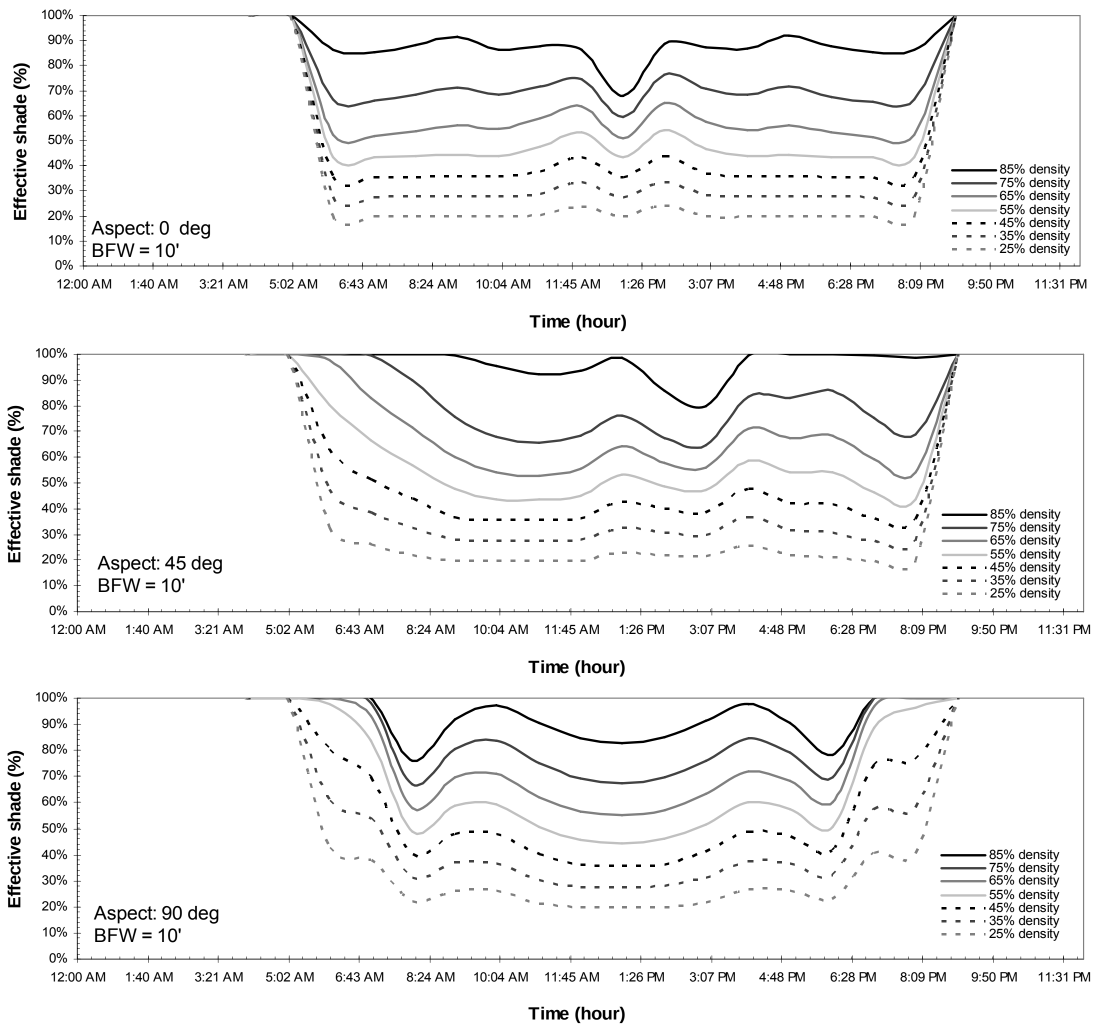


Figure 7. Daily effective shade for three channel orientations provided by a 120-foot buffer of canopy cover varying from 25% to 85%. Channel width is 10 feet.

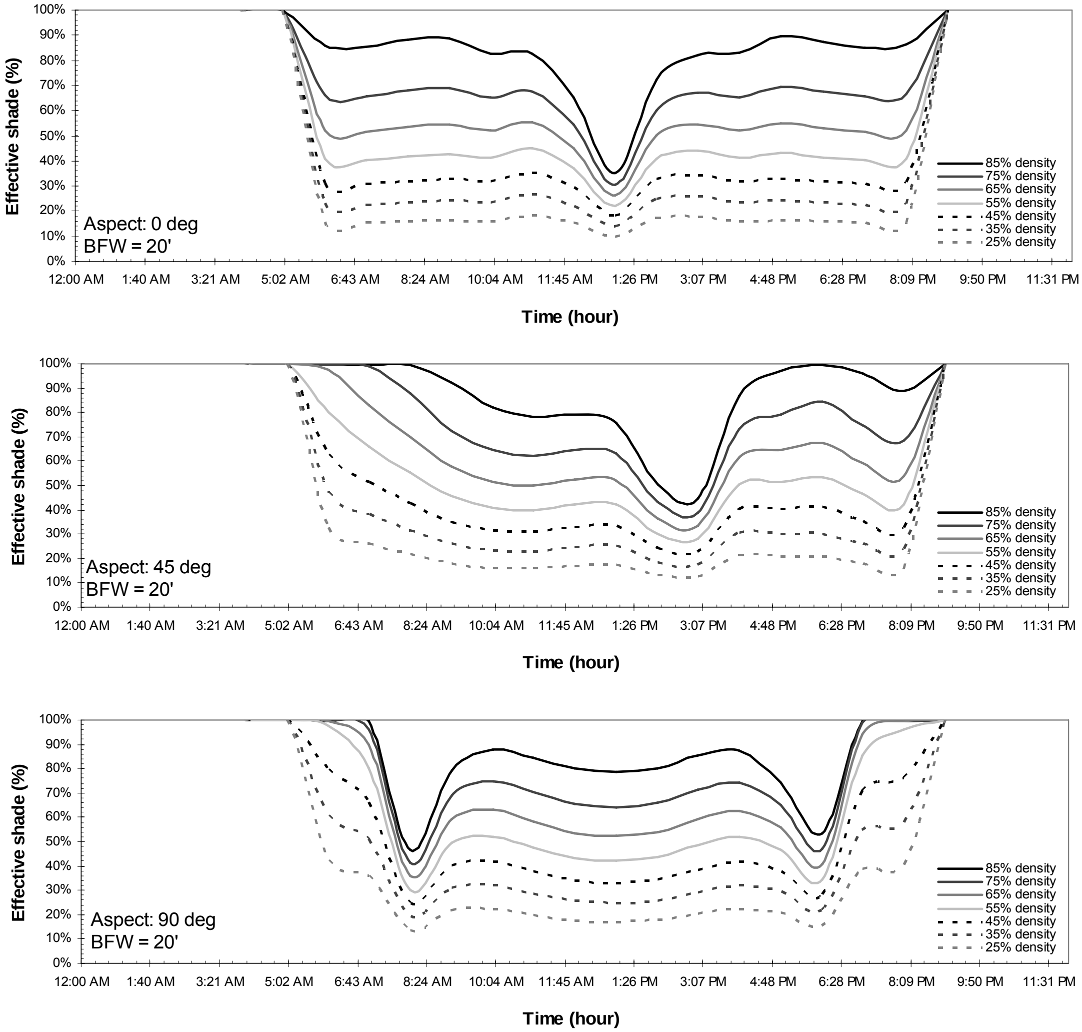


Figure 8. Daily effective shade for three channel orientations provided by a 120-foot buffer of canopy cover varying from 25% to 85%. Channel width is 20 feet.

Varying Vegetation Height: Effective Shade Changes

For the 10-foot-wide channel, channel shading efficiency declined when riparian vegetation height fell below 5 m (Figure 9). This corresponds to roughly 1.4 times the modeled channel width (treated as bankfull width). Similarly, shading efficiency for the 20-foot-wide channel begins to decrease when vegetation height declined below about 10 m, also roughly 1.4 times the modeled channel width (Figure 10). For riparian vegetation shorter than 1.4 times the bankfull width, shading effectiveness declined regardless of canopy cover.

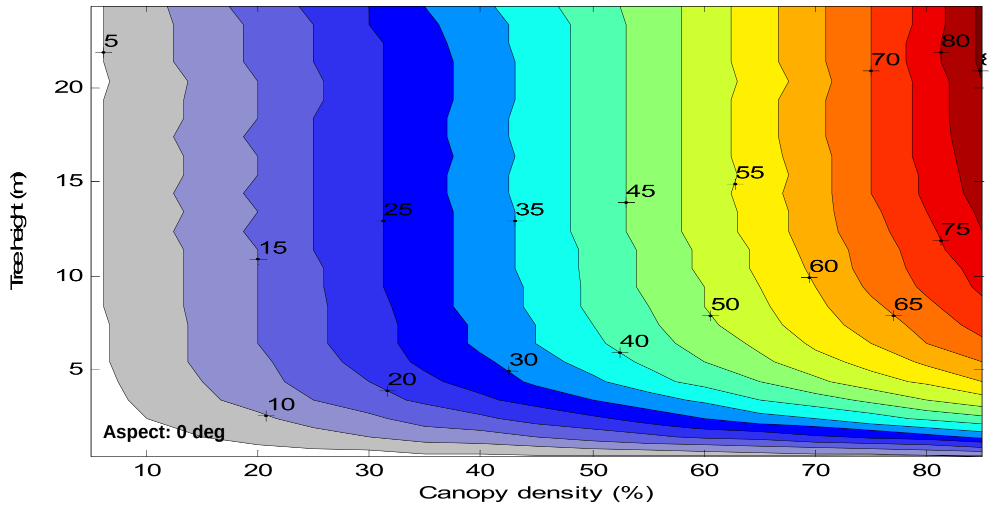


Figure 9. Contour lines of equal effective shade as a function of varying tree height and canopy cover for a single-sided, 120-foot buffer (opposite bank unharvested) and 10 feet wide, north-south oriented channel. At 85% canopy density, 10-meters-tall riparian vegetation provides ~75% the effective shade provided by 25-meters-tall vegetation.

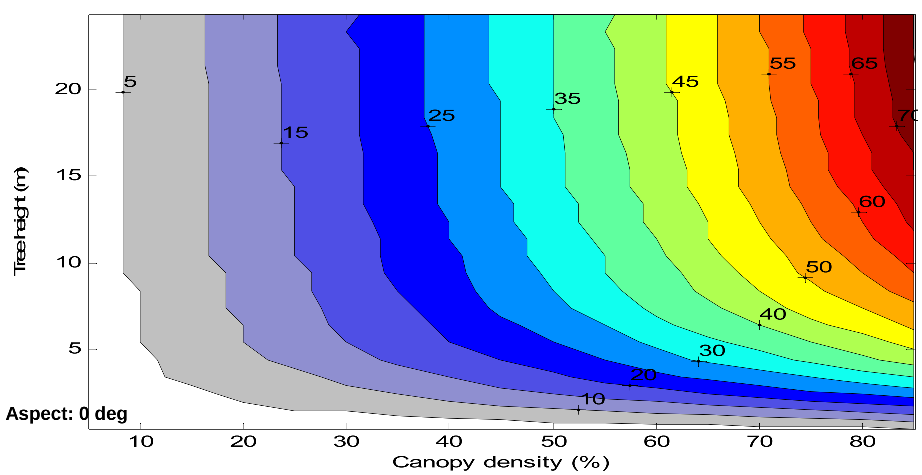


Figure 10. Contour lines of equal effective shade as a function of varying tree height and canopy cover for a single-sided 120-foot buffer (opposite bank unharvested) bordering a 20-foot-wide, north-south oriented channel.

Effective shade: Buffer-width Scenarios

The two shade curves used predicted different levels of effective channel shade for equivalent channel width and buffer combinations, resulting in a range of values (Table 6). The relationship between angular canopy density (ACD) and buffer strip width is stronger for the Brazier and Brown (1973) curve (r^2=0.87) than the Steinblums et al. (1984) curve (r^2=0.61).

Table 6. Daily average effective shade by buffer width and stream width relative to daily effective shade for an undisturbed stream. The lower shade limit resulted from applying the shade curve published by Steinblums et al. (1984); the upper limit is the value predicted by Brazier and Brown's (1973) shade curve.

Channel Width (feet)	Riparian Buffer	Modeled Daily Average Effective Shade (%) *Relative to Undisturbed Streams*
10	75 ft (23 m)	81-90
	50 ft (15 m)	73-86
	30 ft (9 m)	65-78
20	75 ft (23 m)	79-88
	50 ft (15 m)	69-83
	30 ft (9 m)	61-72

QUAL2K Model

For each model simulation, a single variable was changed while holding the remainder constant. Results were then calculated as difference in daily maximum temperature between downstream and upstream ends of the modeled reach relative to baseline conditions (Tables 7, 8). Additional simulations were added as needed to better quantify effects of individual variables on stream temperature.

Overall, for the 10-foot-wide channel, daily maximum water temperature increased most as buffer width declined (Table 7), but predicted temperature changes varied depending on the shade curve used. For many variables examined, temperature changes ≥ 0.3 °C relative to the baseline were few until harvest-unit length approached 1000 feet. Generally water temperature increased with increasing harvest-unit length. Only groundwater influx reduced daily maximum temperature relative to the baseline, but it was not always effective. Patterns were similar for the 20-foot-wide channel (Table 8), with generally larger increases in daily maximum temperature. Specific variables are discussed below.

Table 7. Stream temperature simulations results (channel width = 10 ft). Shaded columns are differences between upstream and downstream temperature for the stated conditions. Values rounded to two decimals.

Stream width = 10 ft			Temperature response / harvest unit									
			500'		750'		1000'		1250'		1500'	
Parameter investigated	***Baseline value***	Model run	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)
		Baseline condition ($T_{max\ upstream} =$ 14.6°C)	**14.73**	**0.13**	**14.79**	**0.19**	**14.86**	**0.26**	**14.91**	**0.31**	**14.96**	**0.36**
Riparian buffer	50' (Brazier and Brown, 1973)	50' (Steinblums, 1984)	14.81	0.21	14.90	0.30	15.01	0.41	15.11	0.51	15.21	0.61
		30' (Brazier and Brown, 1973)	14.78	0.18	14.86	0.26	14.96	0.36	15.04	0.44	15.12	0.52
		30' (Steinblums, 1984)	14.86	0.26	14.96	0.36	15.13	0.53	15.25	0.65	15.37	0.77
		75' (Brazier and Brown, 1973)	14.69	0.09	14.73	0.13	14.78	0.18	14.81	0.21	14.85	0.25
		75' (Steinblums, 1984)	14.76	0.16	14.83	0.23	14.92	0.32	14.98	0.38	15.04	0.44
Flow	Q = 0.2 m^3/s (7.1 cfs)	Q = 0.24 m^3/s (8.5 cfs)	14.71	0.11	14.76	0.16	14.82	0.22	14.86	0.26	14.91	0.31
		Q = 0.28 m^3/s (9.9)	14.69	0.09	14.73	0.13	14.79	0.19	14.82	0.22	14.86	0.26
		Q = 0.32 m^3/s (11.3 cfs)	14.68	0.08	14.72	0.12	14.76	0.16	14.80	0.20	14.83	0.23
		Q = 0.36 m^3/s (12.7 cfs)	14.67	0.07	14.70	0.10	14.75	0.15	14.78	0.18	14.81	0.21
Stream roughness	n=0.04	n = 0.06	14.73	0.13	14.79	0.19	14.86	0.26	14.91	0.31	14.96	0.36
		n = 0.08	14.73	0.13	14.78	0.18	14.85	0.25	14.91	0.31	14.96	0.36
		n = 0.10	14.73	0.13	14.78	0.18	14.85	0.25	14.90	0.30	14.95	0.35
		n = 0.12	14.73	0.13	14.78	0.18	14.85	0.25	14.90	0.30	14.95	0.35
		n = 0.14	14.73	0.13	14.78	0.18	14.85	0.25	14.90	0.30	14.95	0.35
		n = 0.16	14.73	0.13	14.78	0.18	14.85	0.25	14.90	0.30	14.95	0.35
Groundwater input, constant temperature T = 10 deg C	No groundwater input was assumed	0.01 m^3/s/100m (0.35 cfs), T=10 deg C	14.55	-0.05	14.53	-0.07	14.51	-0.09	14.49	-0.11	14.47	-0.13
		0.012 m^3s/100m (0.42 cfs), T=10 deg C	14.52	-0.08	14.49	-0.11	14.44	-0.16	14.41	-0.19	14.38	-0.22
		0.014 m^3/s/100m (0.49 cfs), T=10 deg C	14.49	-0.11	14.44	-0.16	14.38	-0.22	14.34	-0.26	14.30	-0.30
		0.016 m^3/s/100m (0.56 cfs), T=10 deg C	14.45	-0.15	14.40	-0.20	14.32	-0.28	14.27	-0.33	14.22	-0.38
		0.018 m^3/s/100m (0.63 cfs), T=10 deg C	14.42	-0.18	14.35	-0.25	14.26	-0.34	14.20	-0.40	14.14	-0.46
Constant groundwater input, variable T	No groundwater input was assumed	0.01 m^3/s/100m (0.35 cfs), T = 14 deg C	14.70	0.10	14.75	0.15	14.80	0.20	14.83	0.23	14.87	0.27
		0.01 m^3/s/100m (0.35 cfs), T = 12 deg C	14.63	0.03	14.64	0.04	14.65	0.05	14.66	0.06	14.67	0.07
		0.01 m^3/s/100m (0.35 cfs), T = 10 deg C	14.55	-0.05	14.53	-0.07	14.51	-0.09	14.49	-0.11	14.47	-0.13
		0.01 m^3/s/100m (0.35 cfs), T = 8 deg C	14.48	-0.12	14.43	-0.17	14.36	-0.24	14.32	-0.28	14.27	-0.33
		0.01 m^3/s/100m (0.35cfs), T = 6 deg C	14.40	-0.20	14.32	-0.28	14.22	-0.38	14.14	-0.46	14.07	-0.53
Hyporheic exchange	No hyporheic exchange was assumed	hyporheic zone (d) = approx 300% stream depth Q = 80% of surface flow / 100m	14.73	0.13	14.78	0.18	14.85	0.25	14.90	0.30	14.95	0.35
Reach gradient	2%	4%	14.73	0.13	14.79	0.19	14.86	0.26	14.91	0.31	14.97	0.37
		6%	14.73	0.13	14.79	0.19	14.86	0.26	14.91	0.31	14.97	0.37
		8%	14.73	0.13	14.79	0.19	14.86	0.26	14.92	0.32	14.97	0.37
Increased headwater temperature diel range	Tmin = 13 deg C Tmax = 14.6 deg C Tmean = 13.8 deg C	Tmin = 12.2 deg C, Tmax = 14.6 deg C, Tmean = 12.2 deg C	14.72	0.12	14.77	0.17	14.83	0.23	14.88	0.28	14.93	0.33

'-' sign indicates a decrease in temperature; '+' sign indicates an increase in temperature

Table 8: Stream temperature simulations results (channel width = 20 ft). Shaded columns are differences between upstream and downstream temperature for the stated conditions. Values rounded to two decimals.

Stream width = 20 ft			Temperature response / harvest unit									
Parameter investigated	***Baseline value***	Model run	500'		750'		1000'		1250'		1500'	
			Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)	Daily max	ΔT (deg C)
		Baseline condition ($T_{max\ upstream}$ = 14.6°C)	**14.75**	**0.15**	**14.81**	**0.21**	**14.96**	**0.36**	**15.08**	**0.48**	**15.20**	**0.60**
Riparian buffer	50' (Brazier and Brown, 1973)	50' (Steinblums, 1984)	14.84	0.24	14.94	0.34	15.07	0.47	15.17	0.57	15.27	0.67
		30' (Brazier and Brown, 1973)	14.83	0.23	14.93	0.33	15.06	0.46	15.15	0.55	15.24	0.64
		30' (Steinblums, 1984)	14.89	0.29	15.02	0.42	15.18	0.58	15.31	0.71	15.44	0.84
		75' (Brazier and Brown, 1973)	14.70	0.10	14.79	0.19	14.95	0.35	15.07	0.47	15.19	0.59
		75' (Steinblums, 1984)	14.77	0.17	14.85	0.25	14.98	0.38	15.11	0.51	15.23	0.63
Flow	Q = 0.4 m^3/s (14.2 cfs)	Q = 0.48 m^3/s (16.9 cfs)	14.72	0.12	14.78	0.18	14.86	0.26	14.96	0.36	15.06	0.46
		Q = 0.56 m^3/s (19.8 cfs)	14.71	0.11	14.75	0.15	14.81	0.21	14.88	0.28	14.96	0.36
		Q = 0.64 m^3/s (22.6 cfs)	14.69	0.09	14.73	0.13	14.78	0.18	14.82	0.22	14.89	0.29
		Q = 0.72 m^3/s (25.4 cfs)	14.68	0.08	14.72	0.12	14.76	0.16	14.80	0.20	14.83	0.23
Stream roughness	n=0.04	n = 0.06	14.75	0.15	14.81	0.21	14.95	0.35	15.07	0.47	15.19	0.59
		n = 0.08	14.75	0.15	14.81	0.21	14.95	0.35	15.06	0.46	15.18	0.58
		n = 0.10	14.75	0.15	14.81	0.21	14.94	0.34	15.06	0.46	15.17	0.57
		n = 0.12	14.75	0.15	14.81	0.21	14.94	0.34	15.05	0.45	15.17	0.57
		n = 0.14	14.74	0.14	14.80	0.20	14.93	0.33	15.05	0.45	15.16	0.56
		n = 0.16	14.74	0.14	14.80	0.20	14.93	0.33	15.04	0.44	15.16	0.56
Groundwater input, constant temperature T = 10 deg C	No groundwater input was assumed	0.01 m^3/s/100m (0.35 cfs), T=10 deg C	14.57	-0.03	14.56	-0.04	14.60	0.00	14.64	0.04	14.68	0.08
		0.012 m^3s/100m (0.42 cfs), T=10 deg C	14.54	-0.06	14.51	-0.09	14.53	-0.07	14.56	-0.04	14.59	-0.01
		0.014 m^3/s/100m (0.49 cfs), T=10 deg C	14.50	-0.10	14.46	-0.14	14.47	-0.13	14.49	-0.11	14.50	-0.10
		0.016 m^3/s/100m (0.56 cfs), T=10 deg C	14.47	-0.13	14.42	-0.18	14.41	-0.19	14.41	-0.19	14.42	-0.18
		0.018 m^3/s/100m (0.63 cfs), T=10 deg C	14.44	-0.16	14.37	-0.23	14.35	-0.25	14.34	-0.26	14.34	-0.26
Constant groundwater input, variable T	No groundwater input was assumed	0.01 m^3/s/100m (0.35 cfs), T = 14 deg C	14.72	0.12	14.77	0.17	14.89	0.29	14.98	0.38	15.08	0.48
		0.01 m^3/s/100m (0.35 cfs), T = 12 deg C	14.64	0.04	14.66	0.06	14.74	0.14	14.81	0.21	14.88	0.28
		0.01 m^3/s/100m (0.35 cfs), T = 10 deg C	14.57	-0.03	14.56	-0.04	14.60	0.00	14.64	0.04	14.68	0.08
		0.01 m^3/s/100m (0.35 cfs), T = 8 deg C	14.49	-0.11	14.45	-0.15	14.45	-0.15	14.47	-0.13	14.48	-0.12
		0.01 m^3/s/100m (0.35cfs), T = 6 deg C	14.42	-0.18	14.35	-0.25	14.31	-0.29	14.29	-0.31	14.28	-0.32
Hyporheic exchange	No hyporheic exchange was assumed	hyporheic zone (d) = approx 300% stream depth Q = 80% of surface flow / 100m	14.74	0.14	14.80	0.20	14.93	0.33	15.04	0.44	15.15	0.55
Reach gradient	2%	4%	14.75	0.15	14.82	0.22	14.97	0.37	15.09	0.49	15.21	0.61
		6%	14.76	0.16	14.82	0.22	14.97	0.37	15.10	0.50	15.21	0.61
		8%	14.76	0.16	14.82	0.22	14.98	0.38	15.10	0.50	15.22	0.62
Increased headwater temperature diel range	Tmin = 13 deg C Tmax = 14.6 deg C Tmean = 13.8 deg C	Tmin = 12.2 deg C, Tmax = 14.6 deg C, Tmean = 12.2 deg C	14.73	0.13	14.79	0.19	14.89	0.29	15.00	0.40	15.10	0.50

'-' sign indicates a decrease in temperature; '+' sign indicates an increase in temperature

Buffer width and canopy cover interaction affected stream thermal response, with shading effectiveness decreasing as stream width increased (Figure 11). For the narrow channel case (10 feet), rates of stream heating varied widely with buffer width and the shading curve used (Brazier and Brown vs. Steinblums et al.). Differences in the shading curves also resulted in different conclusions. For example, the 50-foot Steinblums et al. (1984) buffer was almost as protective as the 30-foot Brazier and Brown (1973) buffer (Figure 11b). Figure 11 also indicates that smaller streams are protected more efficiently by the streamside buffers. Narrow buffers with low canopy cover were least protective (30-feet, Steinblums et al., 1984); wide buffers with high canopy cover were most protective (75-feet, Brazier and Brown, 1973). The difference in temperature response between the 30-foot and 50-foot buffers is generally higher than that between the 50-foot and 75-foot buffers, with the 30-foot buffers being the least efficient.

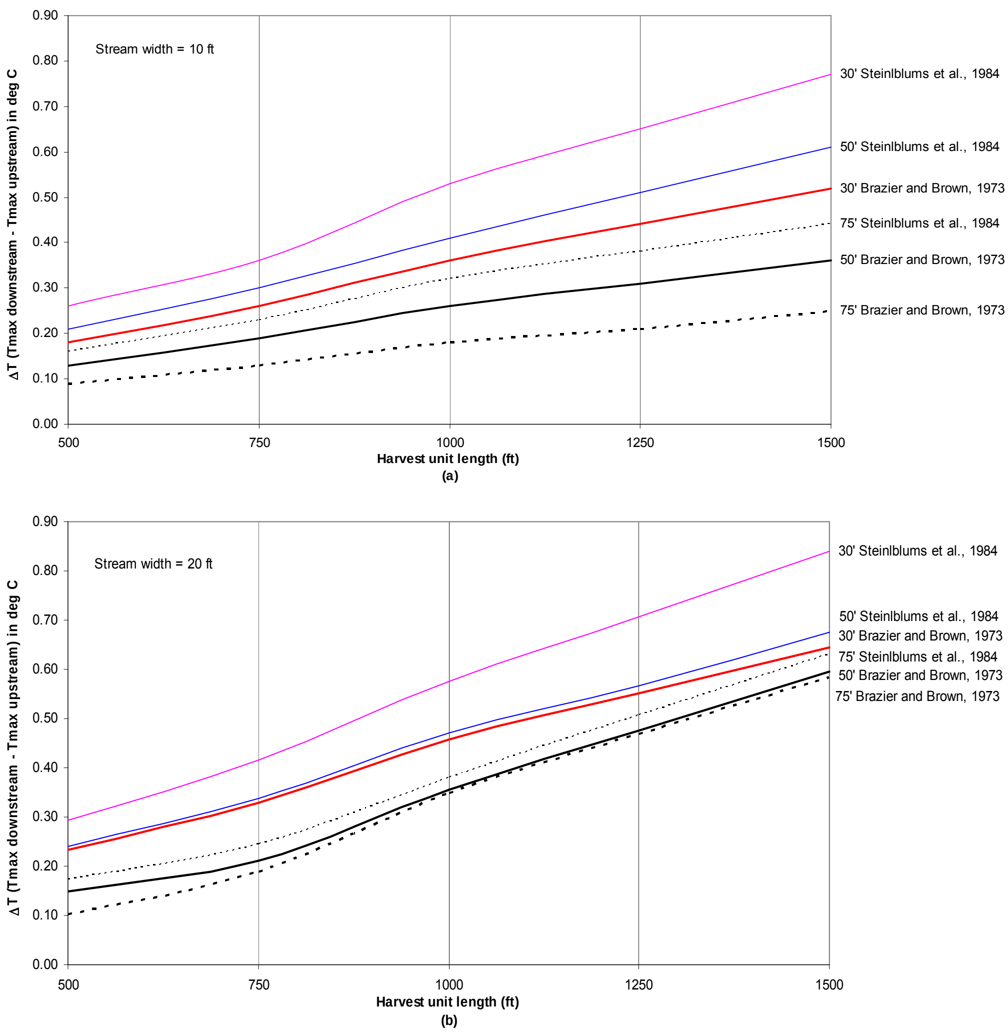


Figure 11. Stream temperature response in the (a) 10-foot-wide and (b) 20-foot-wide streams for different buffer widths and shading curves.

Flow

Increased upstream flow generally reduced downstream heating rates by increasing water depth (i.e., reduced depth-to-flow ratio) (Tables 7 and 8). Sub-baseline flow simulations indicated a much higher tendency for increased downstream heating (Appendix D). These results suggest that, as depth declines, channels with reduced riparian canopy are more likely to warm than those with intact riparian canopy.

Groundwater

Groundwater influx cooled streams, but was less effective as the volume and area of surface flow increased (Figures 12a, 13b). As the temperature differential between groundwater and surface waters declined, the influence of groundwater also declined, failing to offset downstream heating for the 20-foot-wide stream.

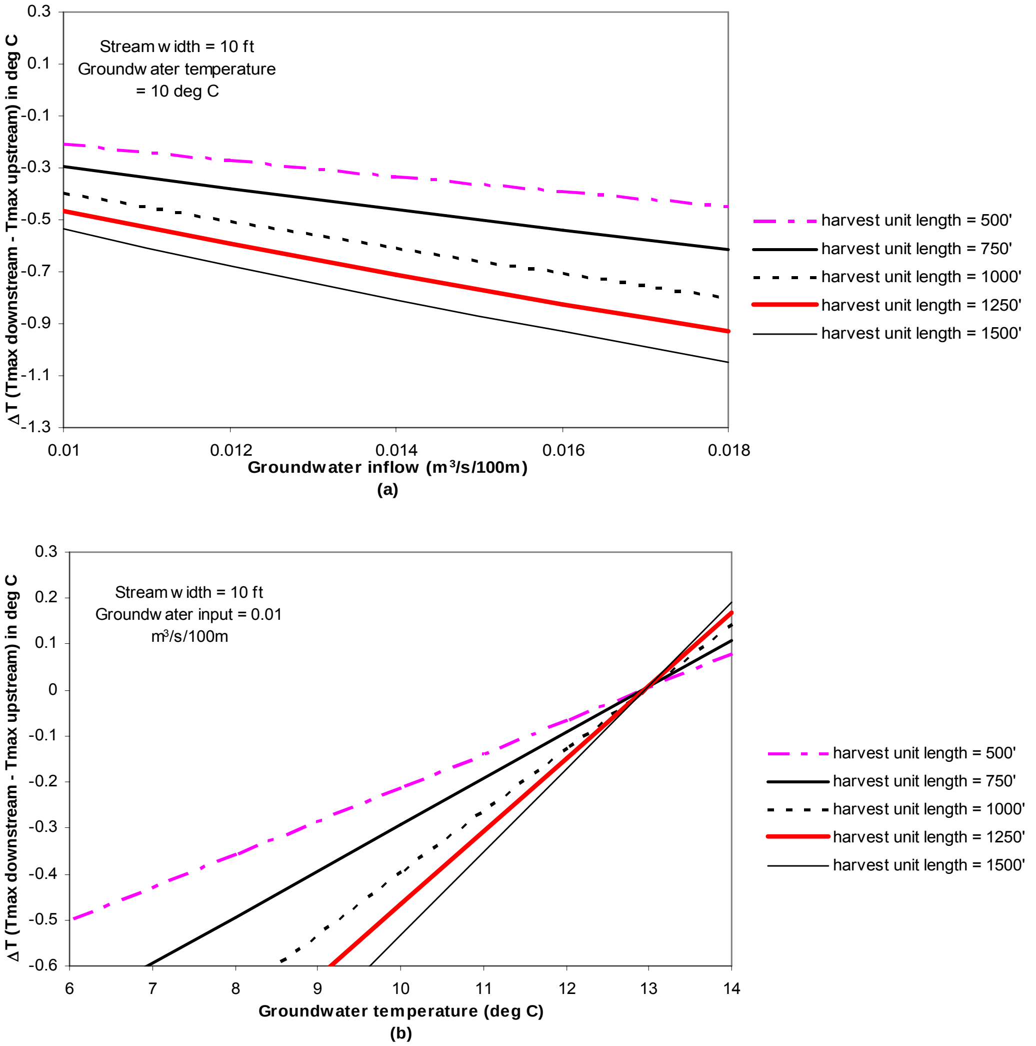
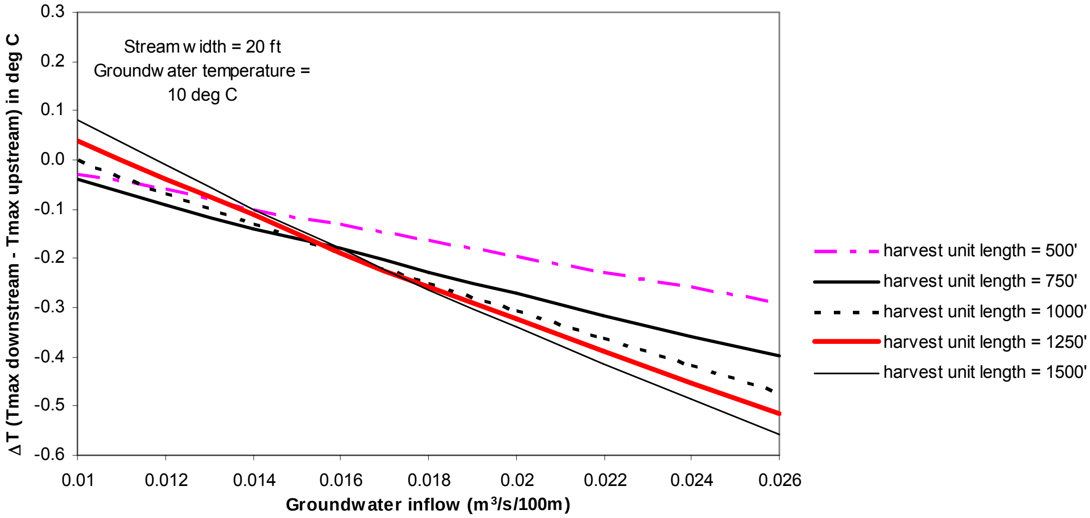
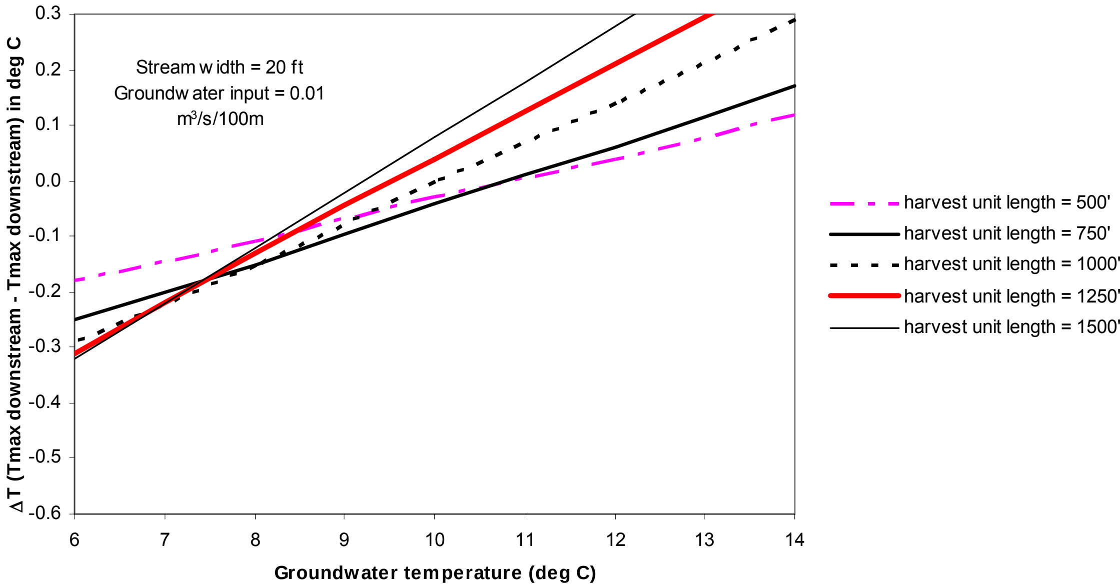


Figure 12. Stream temperature response at the end of each harvest unit for (a) variable groundwater input at constant temperature, and (b) constant groundwater input and variable temperature in a 10-foot-wide stream.

The impact of groundwater temperature on stream temperature also varied with channel width and harvest-unit length (Figures 12b, 13b). The mitigating effect of low groundwater temperature increased as harvest-unit length increased. Higher groundwater temperature showed the opposite pattern.



(a)



(b)

Figure 13. Stream temperature response at the end of each harvest unit for (a) variable groundwater input with constant temperature and (b) constant groundwater input and variable temperature in a 20-foot-wide stream.

Hyporheic

Relative to baseline conditions (no hyporheic exchange), hyporheic exchange modestly decreased daily diel range for both stream widths (Tables 7 and 8; Figure 14) downstream of the harvest unit. Hyporheic exchange exerted more downward effect on daily maximum stream temperature than on daily minimum. Assuming uniform hyporheic flow at a constant rate, the mitigating effect of hyporheic exchange increased with increasing stream length. Sub-baseline flow cases indicated that, as flow declined, the importance of hyporheic exchange for mitigating stream temperature sharply increased.

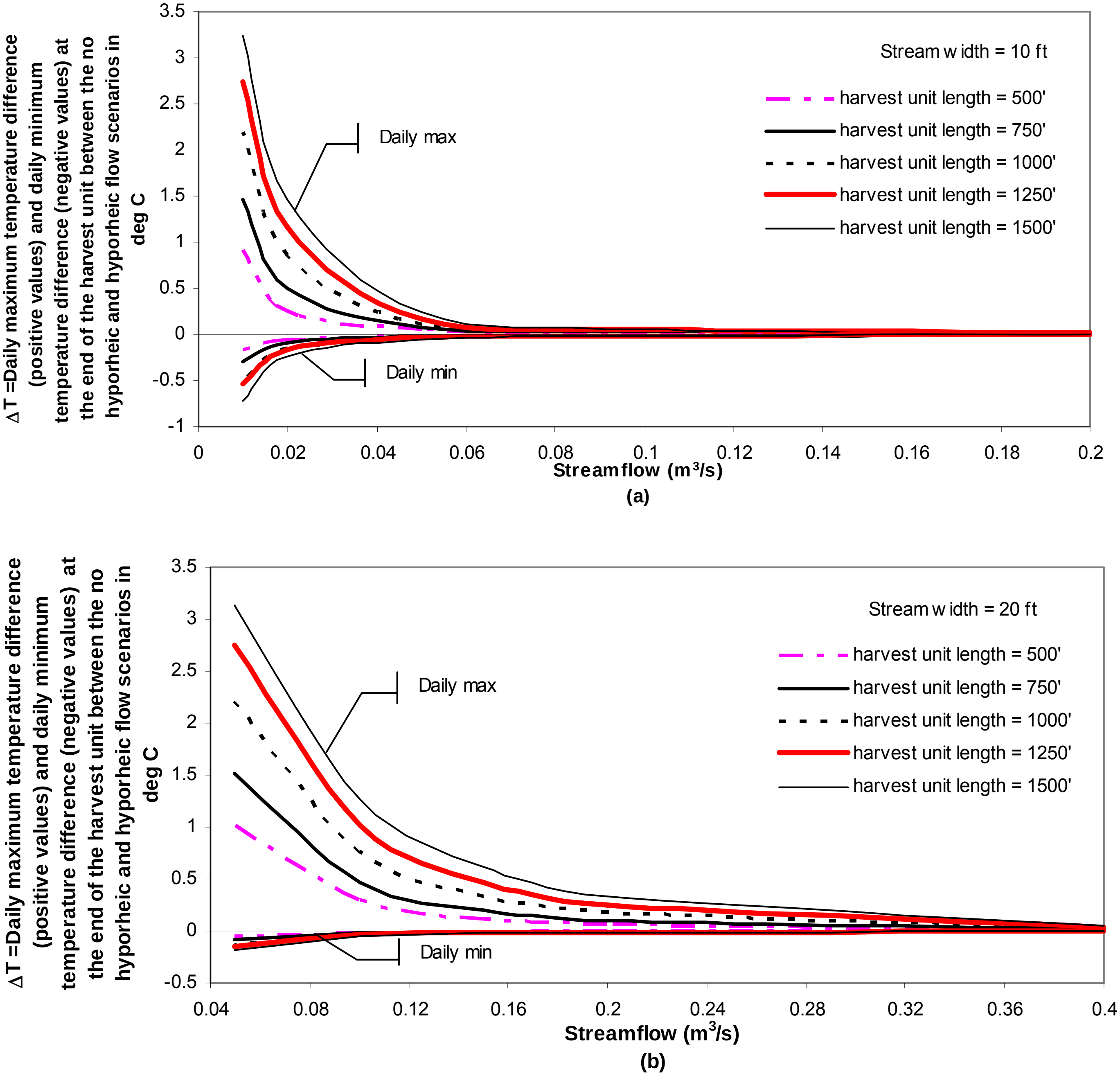


Figure 14. Differences in daily maximum temperature and the differences in daily minimum temperature at the end of the harvest unit between the no hyporheic and hyporheic exchange scenarios for a range of simulated low-flow conditions in the (a) 10-foot-wide and (b) 20-foot-wide streams.

Gradient and Roughness

Increasing gradient reduced stream depth, but downstream heating expected due to shallower water was almost negligible because water was transported more rapidly through the reach (Tables 7 and 8). The model indicated slightly increasing downstream heating rates as gradient increases, but channel sections must be longer than those modeled here for substantial effects to emerge. Increased stream roughness reduced flow velocity and increased water depth. Downstream heating rates declined as a result of increased roughness, but the effect was very small at the scale of the analyzed harvest-unit lengths (Tables 7 and 8).

Wind Speed

No changes in the simulated results were detected (<0.01 °C) compared to the 0.4 m/s scenario, indicating this process plays a small role at this scale.

Increased Diel Range

Increased diel range for the upstream reach boundary condition (same daily maximum temperature, but lower daily average and daily minimum temperatures) resulted in lower downstream heating rates relative to the baseline condition. This effect was similar in magnitude to the effect of stream roughness.

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Conclusions

Riparian buffer width, canopy cover, and harvest-unit length were the most important controls on stream heating. Dense, wide, and tall riparian buffers most effectively shaded channels. Low streamflow was also important because of changing surface-area-to-volume ratios and effects on heat fluxes. Hyporheic exchange and groundwater effects were dependent on harvest-unit length and surface-water-to-groundwater volume. Ten-foot-wide channels warmed less than 20-foot-wide channels for all combinations of buffer widths and harvest-unit lengths examined, but this could be a consequence of constant depth for all simulations. Effects of wind speed, channel roughness, and increasing gradient were generally negligible.

When a 500-foot harvest unit and 50-foot buffer were applied to our model channel, downstream temperature of the 10-foot-wide stream increased 0.13°C relative to the unharvested state. Temperature continued to rise as harvest-unit length increased, with the 1500-feet-long unit showing the most change (+0.36°C, or approximately +0.12°C per 500 feet of harvest length). Results for the 20-foot-wide case show a similar pattern, but temperature increases in response to harvest-unit length were higher: 0.15°C (500 feet) to 0.60°C (1500 feet), or about 0.18 per 500 feet of harvest length.

Other combinations of buffer widths and harvest-unit lengths indicated that temperature of the 10-foot-wide stream was more sensitive to buffer width than the 20-foot-wide stream, the latter having more thermal inertia. As a consequence, the widest buffers (75 feet) continued to dampen temperature increases for the 10-foot stream even at harvest-unit length =1500 feet. A 75-foot buffer reduced downstream heating rates of the 10-foot stream by ~1/3-1/2 relative to other buffer widths. Thus, 10-foot, and by implication, narrower, streams, are highly sensitive to buffer width, with each width tested setting the stream on a slightly different trajectory.

In contrast, the buffer widths examined cooled the 20-foot-wide stream less effectively, and temperature changes began to converge somewhat when harvest-unit length reached 1000 feet. Thus, for 20-foot streams, temperature response to 50-foot and 75-foot buffers was similar.

Shade Evaluations

- *Solar loading potential is highest for north-south oriented channels < ~10 feet wide.* For wider channels, solar loading potential is highest for an east-west orientation.

- *Prior to harvest, streams 10 to 20 feet wide receive about 85-95% of interior forest shade levels*. Narrow streams would receive similar or greater amounts of shade. Small streams therefore are potentially very sensitive to riparian canopy removal.

Conditions Favoring High Daily Maximum Stream Temperatures

- *Relatively shallow and wide streams* (increased width-to-depth ratio). Model simulations indicated that as flow decreased, downstream heating increased.

- *Reduced riparian vegetation.* Generally, stream temperature protection increased as buffer width and density increased. Riparian vegetation as short as ~1.4 times bankfull width can provide about 75% of the shade provided by taller vegetation of similar canopy density. Below this height, however, shading effectiveness begins to decrease regardless of canopy density. Small streams are most sensitive to riparian vegetation removal.

- *North-south oriented streams.* These channels receive minimal shade during the daily direct solar radiation peak (from 10:00 AM to 4:00 PM).

- *Streams located at lower elevations.* Higher air temperatures and lower relative humidity are more likely to occur at low elevations. Field studies indicate that warmer stream temperatures were observed at lower elevations across large spatial scales (Isaak and Hubert, 2001).

- *Streams with low groundwater input and little hyporheic exchange.* The effect of groundwater input and hyporheic exchange is more important at low streamflow rates for the investigated stream types.

- *Low-gradient streams.* Low velocities increase travel time, favoring downstream heating.

Interpretation of our results should consider uncertainties associated with the shade and stream temperature models. Model assumptions and simplifications, estimation of internal model parameters, and input data influence the relative effects. Some important thermal phenomena acting over relatively short distances also were not modeled (for example, pool and riffle sequences, and complex surface and subsurface flow paths).

Recommendations

Discussions about hardwood conversion harvest scenarios should consider the following:

- For the 10-foot-wide channel and harvest-unit length of 750 feet, the predicted downstream temperature change for one 30-foot buffer scenario exceeded 0.3°C, but several other scenarios equaled or approached this value. For harvest-unit length of 1500 feet, the predicted temperature change for all buffer-width scenarios was > 0.3°C, with one exception (buffer width of 75 feet; shade curve from Brazier and Brown, 1973).

- For the 20-foot-wide channel and harvest-unit length of 500 feet (the shortest case considered), the predicted downstream temperature change for several buffer scenarios approached 0.3°C. For harvest-unit length of 1000 feet, the predicted downstream temperature change for all buffer widths was > 0.3°C.

- The modeled flows were high compared to most streams 10 to 20 feet wide. The effects on stream temperature at lower flows are even greater than modeled (Appendix D, all figures).

- Groundwater can cool streams, but effects vary with groundwater temperature and input rates. While this is predictable, groundwater contribution is not easily measured.

- Hyporheic flow effects are similar to the effects of groundwater and would be greater at lower streamflows. Hyporheic benefits were also, predictably, tied to channel length. This variable is difficult to measure.

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Appendices

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Appendix A. Glossary

- **Angular Canopy Density (ACD) is** a reference variable describing the percentage of time that "*a point on the ground receives shade from 10 am-2 pm*" (Teti and Pike, 2005). Blocking the incoming solar radiation between 10 am and 2 pm has the highest impact on stream temperatures. The question of how well this parameter represents actual attenuation of solar energy is still to be determined (Teti and Pike, 2005). Average ACD of a stream reach is estimated by sampling it over the width and length of the reach. ACD was first defined by Brazier and Brown (1973) and refined by Wooldridge and Stern (1979) and Beschta et al. (1987).

- **Bankfull width (bfw)** is the lateral extent of the water surface when the channel is completely filled.

- **Baseline condition** refers to the range of values assumed typical of system variables for riparian buffers of mature red alder 50-feet-wide and the channel widths considered.

- **Bed conduction flux and hyporheic exchange** component of the heat budget represents the heat exchange through conduction between the bed and the waterbody and the influence of hyporheic exchange. The magnitude of bed conduction is driven by the size and conductance properties of the substrate. The heat transfer through conduction is more pronounced when thermal differences between the substrate and water column are higher and usually affects the temperature diel profile.

- **Buffer** is the forested area adjacent to stream left in place to provide shade to the stream.

- **Canopy cover or canopy density** is defined as the percent of sky covered by the riparian vegetation within a given portion of the sky (Kelley and Krueger, 2005). Canopy cover is a function of stand composition, affected, in turn, by crown morphology of the individual trees in the stand.

- **Conduction/convection flux at the air-water interface (also known as sensible heat)** is driven by the temperature difference between the water and air and by the wind speed. It is related to evaporation flux through the Bowen ratio.

- **Diel** refers to a 24-hour period, usually encompassing 1 day and 1 night.

- **Evaporation flux at the air-water interface** is influenced mostly by wind speed and the vapor pressure gradient between the water surface and the air. When the air is saturated, evaporation stops. When vapor pressure at the water surface is less than the vapor pressure of the air, condensation occurs and this term then becomes a gain component in the heat balance.

- **Harvest length** is the length of the harvest unit edge adjacent to the channel (i.e., modeled-channel length for a given scenario).

- **Harvest unit** is the area from which trees were harvested.

- **Hyporheic zone** is the layer of saturated sediment adjacent to and underneath the stream. This zone is hydraulically connected to the stream and continually exchanges flow with the main channel flow and surface water dead zones, with lags due to transient storage.

- **Leaf Area Index** (LAI) is the ratio of green-leaf area to unit of ground area. One-sided leaf area is used for broadleaf canopies. Needle area projections are used for conifers.

- **Longwave atmospheric radiation (**~4 to 120 μm) is determined by various atmospheric components but depends primarily on air temperature and humidity, and increasing as both of those increase. It is most significant during warm cloudy conditions and at night. The daily average heat flux from longwave atmospheric radiation typically ranges from about 300 to 450 W/m^2 at mid latitudes (Edinger et al., 1974).

- **Longwave radiation from the water** is the radiation (~4 μm to 120 μm) emitted by the waterbody to the atmosphere. Back radiation accounts for a major portion of the heat loss from a body of water, increasing as water temperature increases. The daily average heat flux out of the water from longwave back radiation typically ranges from about 300 to 500 W/m^2 (Edinger et al., 1974).

- **Reference state** refers to the range of values assumed typical of system variables for riparian buffers of mature red alder 120-feet wide and the channel widths considered. Effective shade to the channel from the reference state buffer is similar to that provided by an unharvested stand.

- **Shade** is the amount of incoming solar radiation obscured or reflected by vegetation above a stream. Field measurements on small streams (bankfull widths of 3-9.9 meters) in Oregon indicated that percent canopy cover was lower than percent shade (Kelley and Krueger, 2005)*, with similarities observed between canopy cover and shade on east-west oriented streams, and significant differences between canopy cover and shade on north-south oriented streams.

  *Canopy cover derived from clinometer, densiometer, and hemispherical imaging were compared. Shade was estimated from hemispherical images.

- **Shortwave solar radiation** is the difference between direct solar energy and that reflected by the waterbody. Shortwave solar radiation is the most significant input in the heat balance when the sky is clear. However, vegetation and topographic shading can reduce shortwave radiation by 100%.

Appendix B. QUAL2Kw Variables

Table B1. QUAL2Kw variables and proposed model-scenario values. Input variables were classified as "Fixed" (same value(s) for all model runs) or "Variable" (changing among model runs).

	Variable	Type	Value
General	Latitude/Longitude	Fixed	Latitude: 46.65000000 Longitude: -123.65000000
	Channel azimuth/ stream aspect	Fixed	North-south
	Harvest length	Variable	500' (152 m), 750' (229 m), 1000' (305 m), 1250' (381 m), 1500' (457 m)
	Sediment thermal conductivity	Fixed	1.6 W/m/°C
	Sediment thermal diffusivity	Fixed	0.0051 cm^2/s
Hydraulics	Tributary discharge	Fixed	0 (assume no tributary inputs)
	Bankfull width	Variable	Two channel widths were examined • bankfull width = 10 feet (3 meters) • bankfull width= 20 feet (6.1 meters)
	Groundwater inflow rate	Variable	Baseline condition assumed no groundwater input. During sensitivity tests, the groundwater input was assumed uniformly distributed to the modeled reach (at a rate of 0.01, 0.012, 0.014, 0.016, and 0.018 m^3/s per 100 m respectively). Additionally, for the 0.01 m^3/s groundwater input rate, the groundwater temperature was varied between 6 and 14°C with 2°C step increment.
	Manning's *n*	Variable	*n* = 0.04 at baseline condition. n was varied between 0.06 and 0.16 with a 0.02 step increment during sensitivity tests.
	Channel slope (gradient)	Variable	A single value (2%) was used for the baseline condition for the two stream sizes. Streambed slope was varied between 2% and 8% during sensitivity tests.
Temperature	Upstream boundary daily maximum temperature	Variable	Daily average stream temperature was set to 13.8°C and diel range to 1.6°C. The model was tested for a higher diel range. Daily maximum was maintained at the same value as the baseline condition (14.6°C), and the mean value became 12.2°C.
	Upstream boundary temperature – diel range	Variable	A median condition found at Hardwood Conversion Study sites: • 13.8°C daily average • 1.6°C diel range
	Groundwater temperature	Fixed	10°C (groundwater temperature is usually approximated by regional annual average air temperature ± 3 deg C).
	Tributary temperature	Fixed	Assume no tributaries

	Variable	Type	Value
Hyporheic exchange	% of surface flow in the hyporheic area. Depth of the hyporheic exchange region.	Variable	Baseline condition assumed no hyporheic exchange. To simulate increased hyporheic exchange, the thickness of the hyporheic zone was set to 300% of the stream depth and 80% of the total surface flow per 100 meters was assumed.
Meteorology	Air temperature	Fixed	Daily average temperature of 15.4^{o}C and 9^{o}C diel range.
	Relative humidity	Fixed	85%
	Wind speeds	Fixed	0.4 m/s
Model runs	Date	Fixed	August 1
	Duration of simulation	Fixed	1 day

Appendix C. Mean Annual Air Temperature Variability Across Western Washington

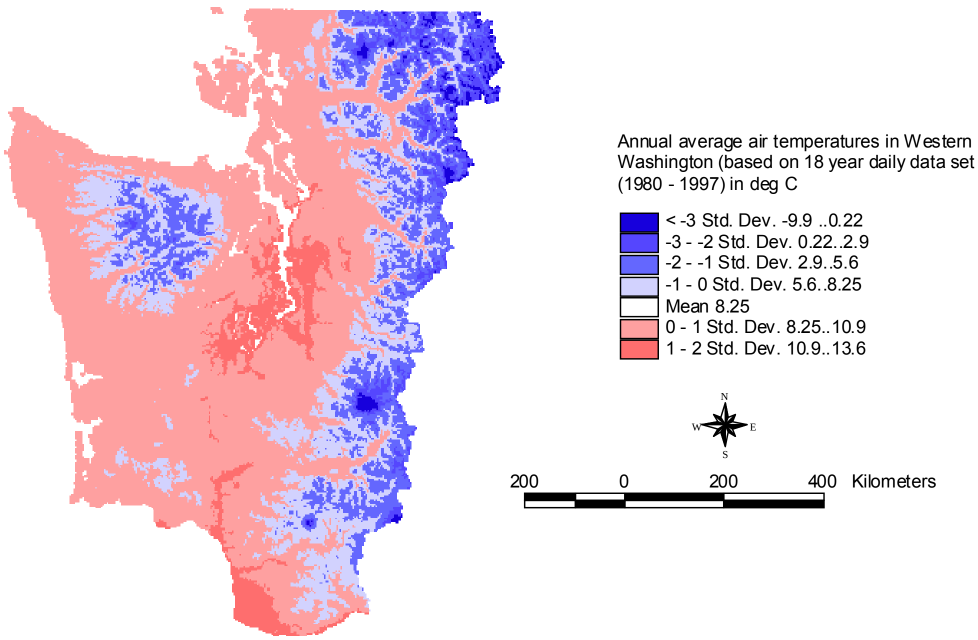


Figure C1. Mean annual air temperature variability in western Washington based on the 18-year data set from www.daymet.org. DAYMET is a University of Montana model. Using a digital elevation model, daily observations of minimum and maximum temperatures, and precipitation from ground-based meteorological stations, an 18-year daily data set (1980 - 1997) of temperature, precipitation, humidity, and radiation has been produced at a 1-km resolution.

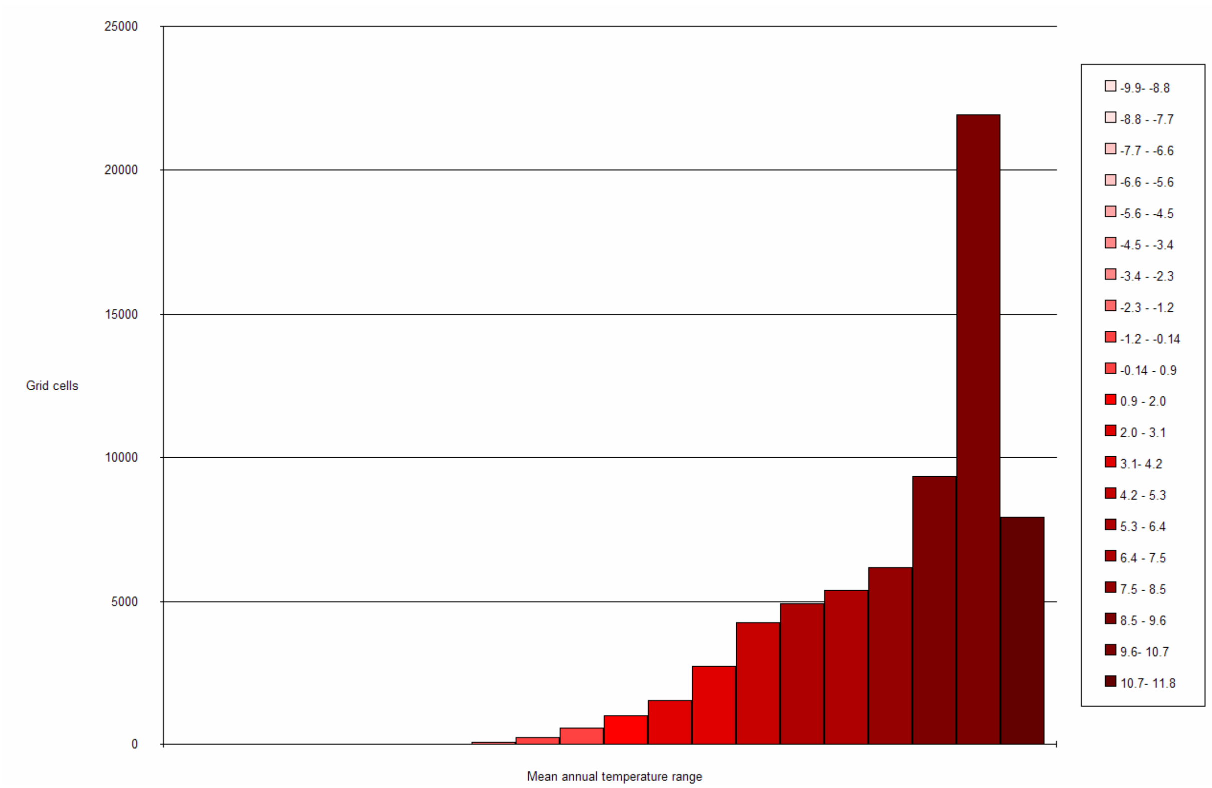
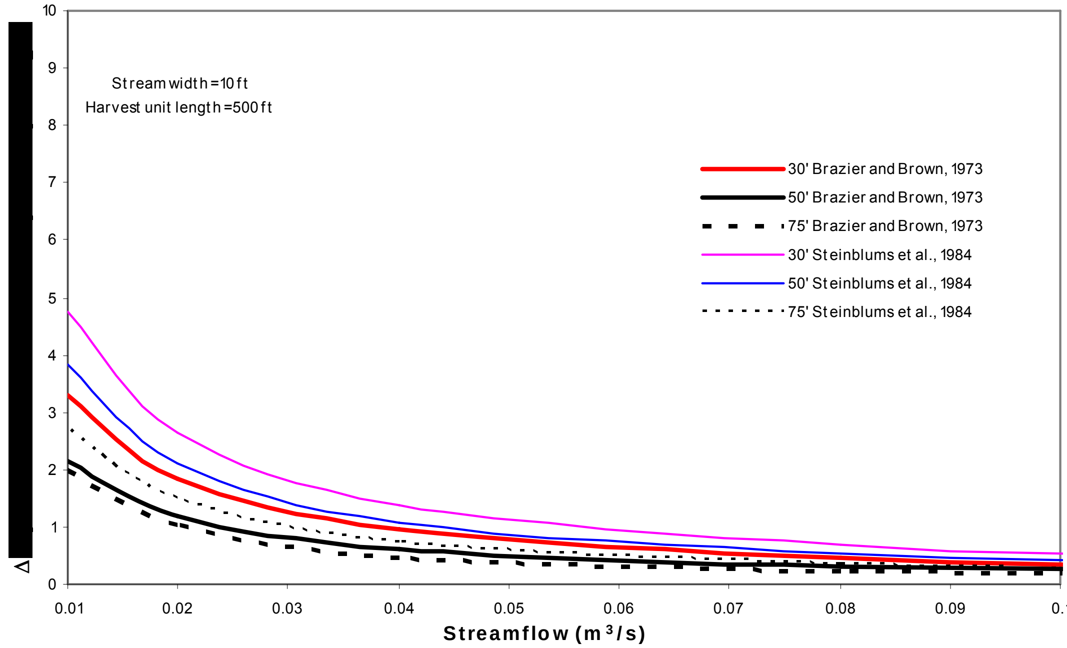
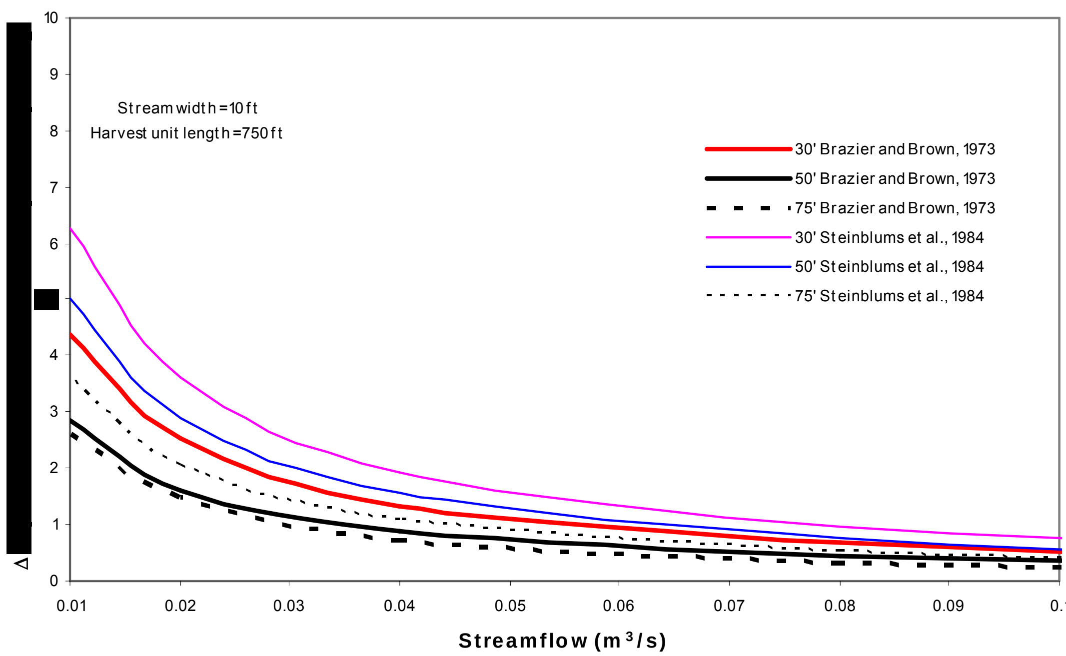


Figure C2. The most frequent mean annual temperature values at low elevations in western Washington vary between 9.6 and 10.7°C.

Appendix D. Daily Maximum Stream Temperature Response to Streamflow for Different Shading Scenarios and Harvest-unit lengths

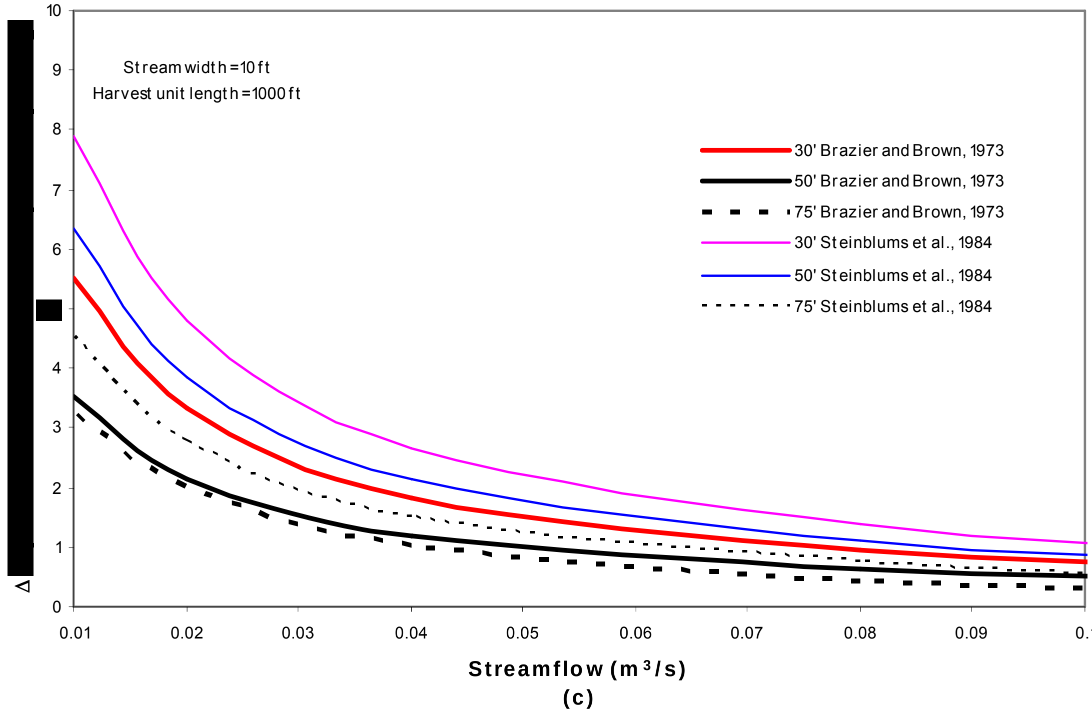


(a)



(b)

Figure D1. Daily maximum stream temperature response with variable streamflow for the 500-ft (a), 750-ft (b), 1000-ft (c), 1250 (d), and 1500-ft (e) harvest-unit lengths in a 10-foot-wide stream.



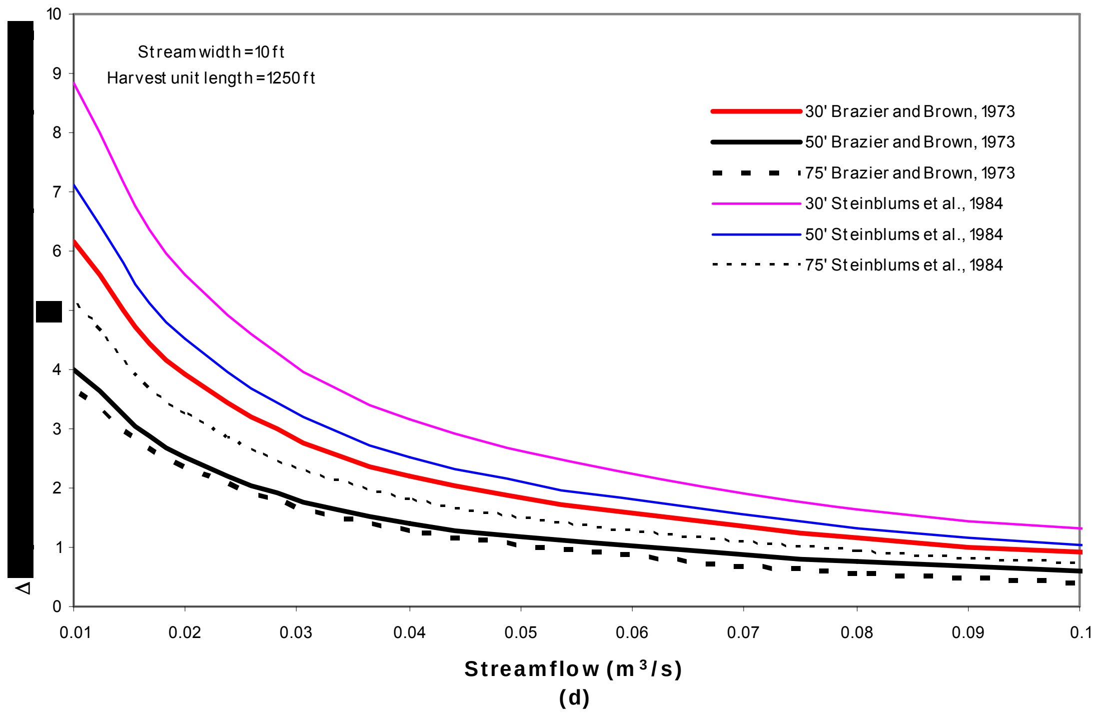
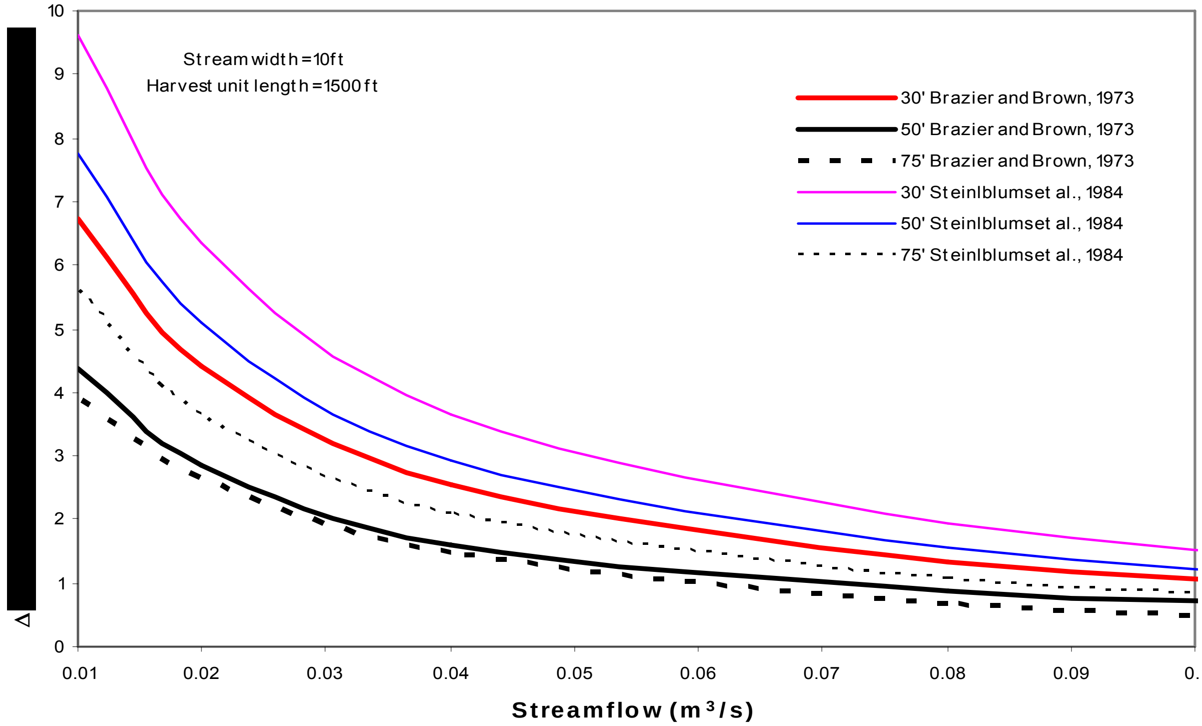
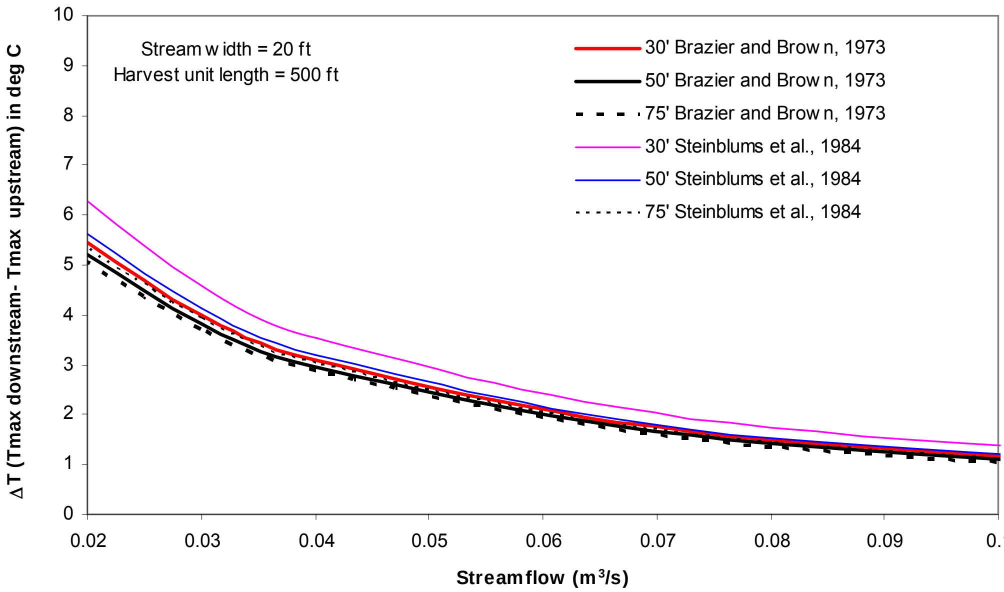


Figure D1 (cont.)

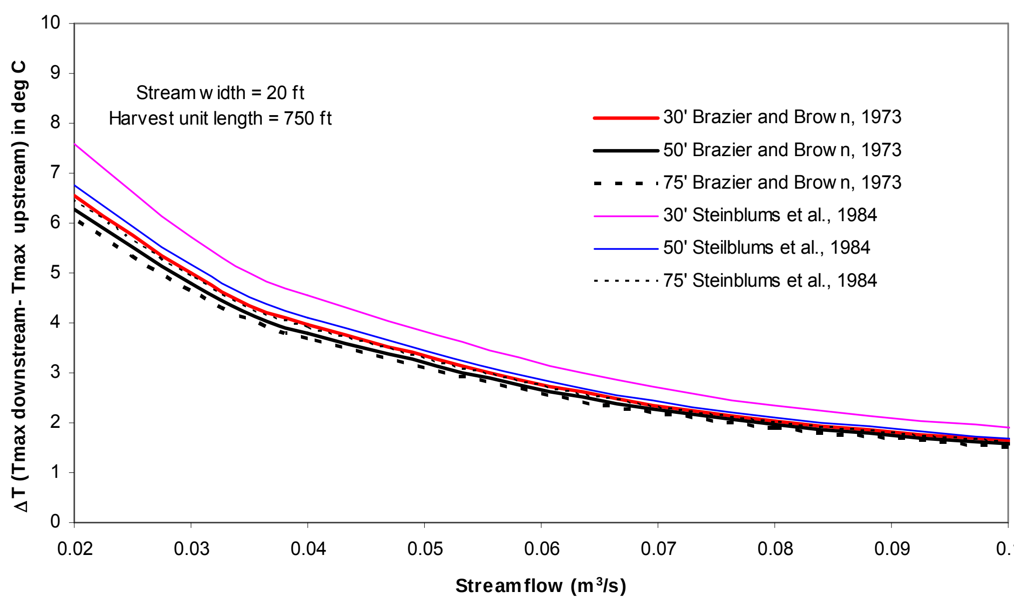


(e)

Figure D1 (cont.)

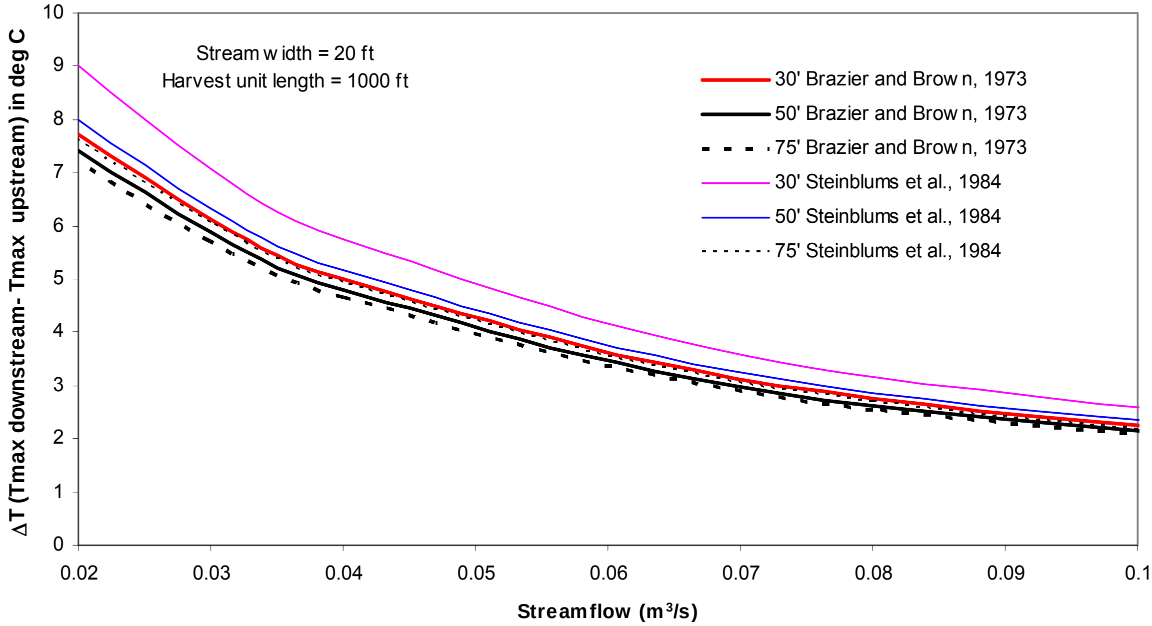


(a)

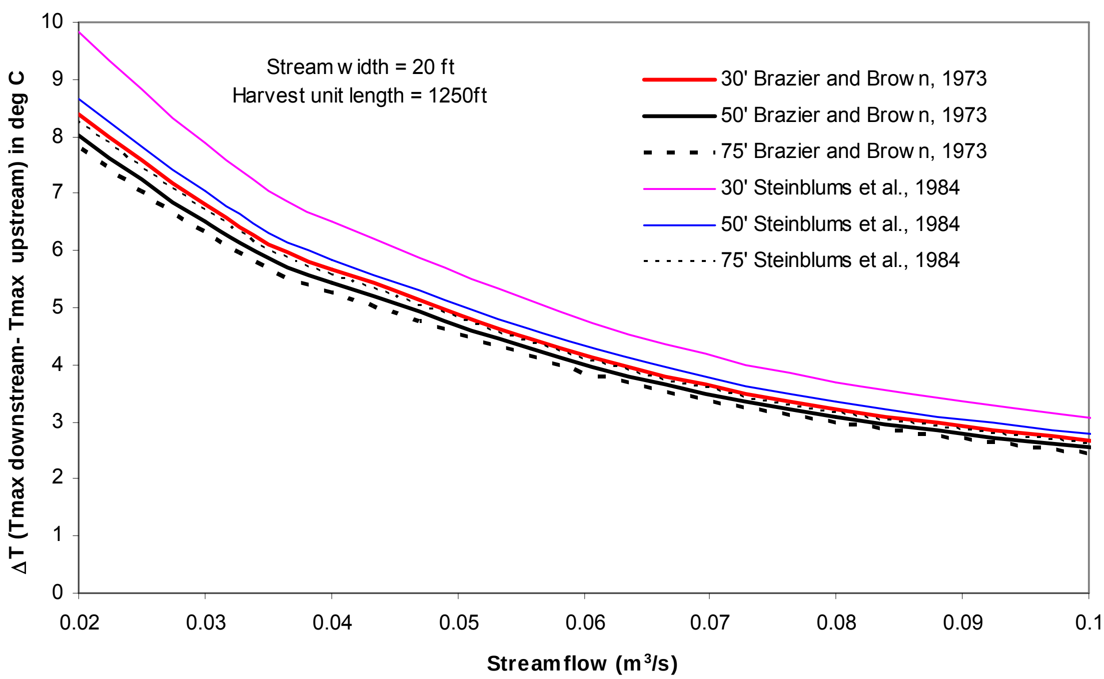


(b)

Figure D2. Daily maximum stream temperature response with variable streamflow for the 500-ft (a), 750-ft (b), 1000-ft (c), 1250 (d), and 1500-ft (e) harvest-unit lengths in a 20-foot-wide stream.



(c)



(d)

Figure D2 (cont.)

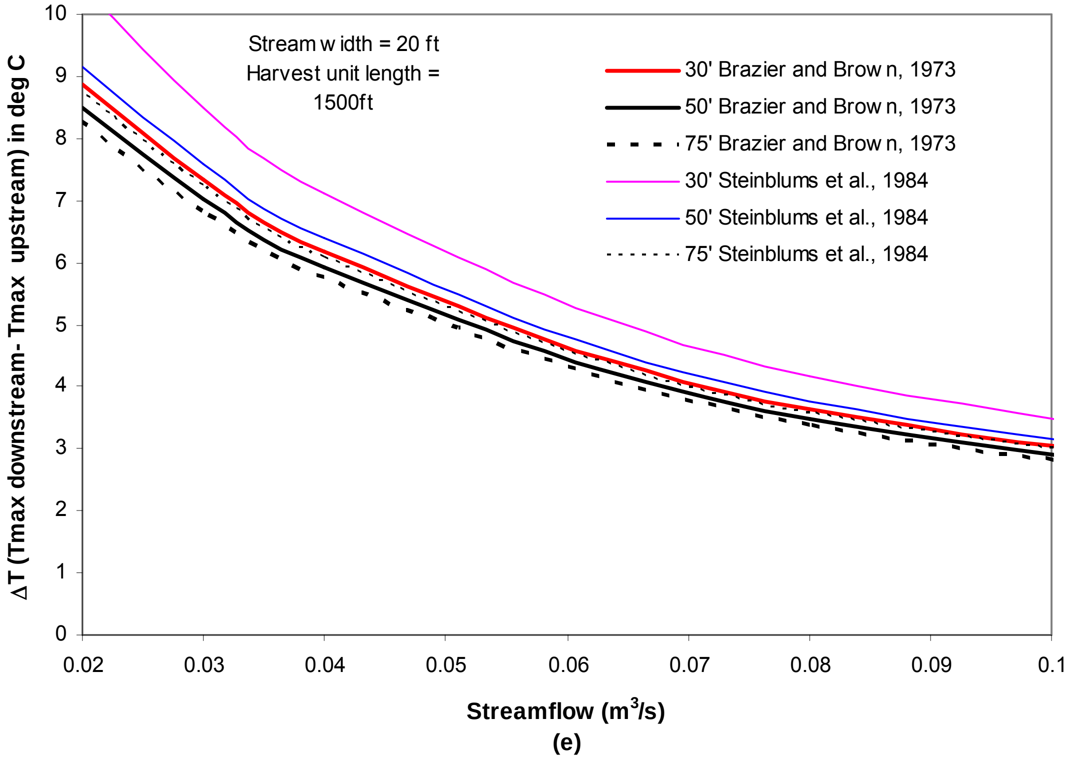


Figure D2 (cont.)