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ECOLOGY
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Quality Assurance Project Plan

Type N Experimental Buffer Treatment Study in Incompetent Lithologies: Riparian Inputs, Water Quality, and Exports to Fish-Bearing Waters

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The plan for this study is available on the Department of Ecology's website at www.ecy.wa.gov/biblio/1103109.html.

Data for this project will be available on Ecology's Environmental Information Management (EIM) website at www.ecy.wa.gov/eim/index.htm. Search User Study ID, WEHI0000.

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Quality Assurance Project Plan

Type N Experimental Buffer Treatment Study in Incompetent Lithologies: Riparian Inputs, Water Quality, and Exports to Fish-Bearing Waters

September 2011

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EAP: Environmental Assessment Program.
NWIFC: Northwest Indian Fisheries Commission.

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Abstract

In 2001 the Washington State Forest Practice Board approved a comprehensive set of new forest practice rules (WDNR, 2001), based on the *Forests & Fish Report* (WDNR, 1999). One of the goals of these rules is to protect water quality in streams on non-federal forest lands in Washington State.

The study addresses four critical questions regarding timber harvest along non fish-bearing (Type N) streams:

1. How does harvest of Type N stream basins affect water temperature within and at the outlet of the Type N basin?
2. How does harvest of Type N stream basins affect sediment input to and storage within the Type N channel?
3. How does harvest of Type N stream basins affect suspended sediment and nutrient export to downstream Type F (fish-bearing) waters?
4. How does harvest of Type N stream basins affect benthic macroinvertebrate communities immediately downstream of the harvest unit?

A Multiple, Before-After/Control-Impact (MBACI) design will be used. Up to ten Type N headwater basins will be selected for study in each of two lithologies: unconsolidated glacial till and marine sedimentary. Data collection will be conducted up to two years pre-harvest, two years post-harvest, and during the one-year harvest window for temperature and water quality variables. Monitoring beyond the first two years post-harvest may be necessary to follow recovery to pre-harvest conditions.

Background

In 2001 the Washington State Forest Practice Board approved a comprehensive set of new forest practice rules, based on the *Forests & Fish Report* (WDNR, 2001; WDNR, 1999). One of the goals of these rules is to protect water quality in streams on non-federal forest lands in Washington State. The Cooperative Monitoring, Evaluation, and Research Committee (CMER), directed by the Washington State Department of Natural Resources (WDNR) adaptive management program, commissioned an experimental study to analyze the effectiveness of buffer prescriptions on Type N (non fish-bearing) stream basins in basalt (competent) lithology (Ehinger and Estrella, 2007; Hayes et al., 2006). That study is currently underway and examines the influence of buffer treatments on riparian inputs, stream-associated amphibians, water quality, and exports to downstream fish-bearing waters. The design of this study in incompetent (more easily eroded) lithologies will include many of the elements of the study done in competent lithology so that the results can be compared.

This study is part of the formal adaptive management program for the Washington Forest Practices Habitat Conservation Plan (HCP) and the state forest practices rules and is one component in the Type N Riparian Effectiveness Program in the 2011 CMER work plan (CMER, 2010).

Thermal Processes

There is a growing body of research which has increased our understanding of thermal processes that influence heating and cooling of headwater streams. A one-dimensional energy model for well mixed streams without inflows or outflows (Caissie et al., 2007) is:

$$\frac{\partial T_w}{\partial t} + v\frac{\partial T_w}{\partial x} - \frac{1}{A}\frac{\partial}{\partial x}\left(AD_L\frac{\partial Tw}{\partial x}\right) = \frac{W}{\theta\rho A}H_n \quad (1)$$

where,

- T_w represents the water temperature
- t is the time
- v is the mean water velocity
- x is the distance traveled
- A is the cross-sectional area
- W is the river width
- D_L is the dispersion coefficient in the direction of flow
- θ is the specific heat of water
- ρ is the water density
- H_n is the net heat flux including heat exchange by radiation, turbulent exchange, and conduction across the water surface and bed

For a given time, and excluding the effect of longitudinal dispersion, the equation can be simplified to:

$$\frac{dT_w}{dx} = \frac{1}{v}\frac{H_n}{\theta \rho D} \tag{2}$$

where, D is depth. The model indicates that as water travels through the reach its temperature changes as a function of the net heat flux (H_n), which is the sum of the heat exchange processes including net solar radiation, net long wave radiation, sensible and latent heat exchange, and bed heat conduction (Johnson, 2004; Moore et al., 2005a). For a given heat load, the change in water temperature is proportional to the surface residence time (x/v) and inversely proportional to water depth.

The effect of tributaries depends on the temperature difference between the inflow and receiving stream temperatures and on their relative contribution to discharge, which can be modeled according to a simple mixing equation (Moore et al., 2005a):

$$dT_w = \frac{Q_{trib}}{Q_{main}}\left(T_{trib} - T_{main}\right) \tag{3}$$

where, Q is discharge. This model can be extended to account for the effects of other discrete inflows (e.g., spring). When changes in flow are not discrete, the model becomes:

$$\frac{dT_w}{dx} = \frac{Q_{in}}{Q_{sw}}\left(T_{in} - T_{sw}\right) \tag{4}$$

where, Q_{in} / Q_{sw} is the functional relationship between the diffuse inflow and surface water flow along the reach. This equation can be used to model the effects of diffuse groundwater inputs and direct precipitation to the channel.

Hyporheic exchange is defined as a subsurface flow path along which surface water mixes with subsurface water and then returns to the stream (Gooseff et al., 2003). Water in the hyporheic zone is sheltered from exchanges along the air-water interface and, assuming no groundwater gains or losses, can be modeled in terms of the residence time (Gooseff et al., 2003):

$$\frac{\partial T_{hyp}}{dt} = \int_0^t \frac{\partial T_w(t-\tau)}{\partial t} g^*(t)dt \tag{5}$$

where,

- τ is a lag time
- $g^*(t)$ is a function of the distribution of exchange rates

Because water in the hyporheic zone is sheltered from exchanges along the air-water interface, hyporheic exchange has no affect on the mean stream temperature, but can affect daily minimum and maximum temperatures by desynchronizing heat advection.

These processes can be accounted for using an additive effects model (Moore et al., 2005a) in which the rate of change in water temperature over a reach length (x) is a function of the incoming water temperature, net energy exchange across the air-water surface, and change in temperature associated with inflows, including the desynchronizing effect of hyporheic exchange (Figure 1).

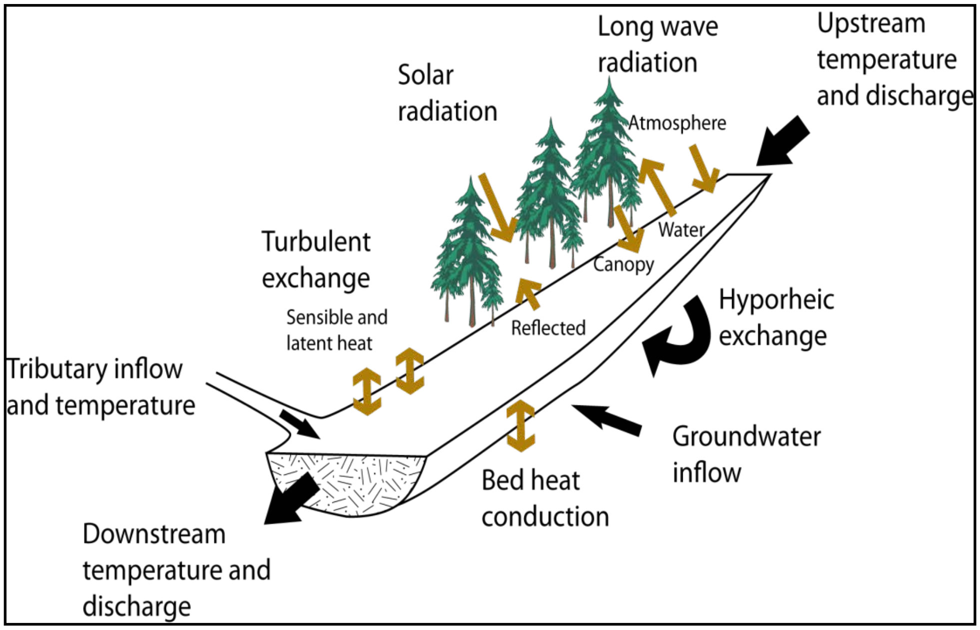

Figure 1. Conceptual model of stream heating and cooling processes (Moore et al., 2005a).

Black arrows indicate energy fluxes associated with water exchanges.

Riparian timber harvest can affect headwater stream temperatures through several mechanisms (Figure 2). Harvest of riparian trees can reduce shading, increasing the solar radiation reaching the stream (Brazier and Brown, 1973; Moore et al., 2005b). Riparian buffers ameliorate the loss of shade from adjacent timber harvest, depending on buffer width, tree height, and tree density (DeWalle, 2010). Clear-cut harvest adjacent to the stream can result in input of logging debris to the stream channel, temporarily offsetting the loss of canopy due to harvest (Jackson et al., 2001). Harvest of riparian vegetation (particularly in conjunction with upland timber harvest) can increase surface water discharge in the drainage basin (and potentially increase groundwater) by reducing evapo-transpiration and changing snow-melt patterns (Jones and Post, 2004). The increase in summer discharge can reduce stream temperature by diluting the heat load in a larger volume of water (Poole and Berman, 2001).

Recruitment of woody debris from riparian buffers over time can affect hyporheic exchange capacity, by creating debris jams and channel steps that provide favorable sites for hyporheic exchange (Wondzell, 2006). Finally, debris flow disturbance (either natural or associated with forest management) alters channel morphology, reduces cover, and decreases hyporheic capacity (Johnson and Jones, 2000).

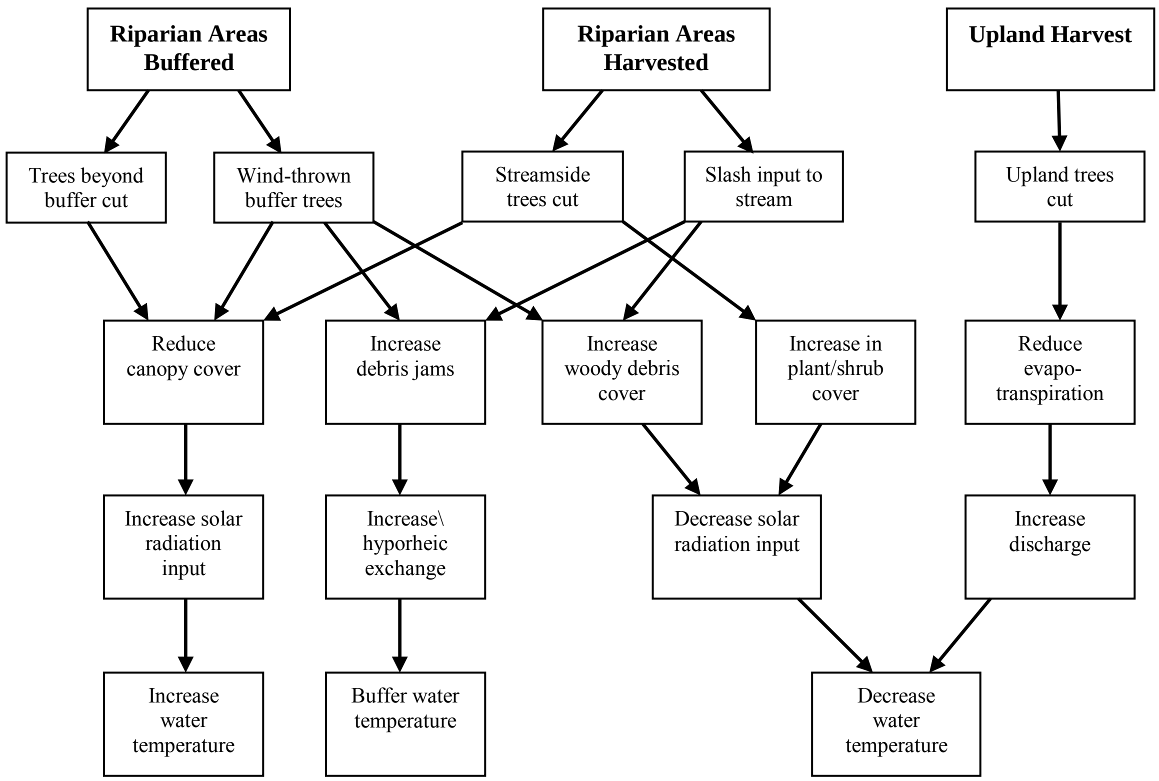

Figure 2. Conceptual model of forest practice effects on heating and cooling processes for water temperature.

Much of the scientific uncertainty about current riparian management practices is due to the complexity of heating and cooling processes in headwater streams (Poole and Berman, 2001; Moore et al., 2005a). Extensive variation in summer stream temperatures has been observed within stream reaches and across the landscape (Dent et al., 2008), apparently due to extensive variation in physical, hydrologic, and climatic conditions that drive the relative importance of various processes (Poole and Berman, 2001; Johnson, 2004), as well as differences in past riparian management practices and disturbance (Brown and Krygier, 1970; Brosofske et al., 1997; Wilkerson et al., 2006).

Some key points to consider in designing this study based on the literature are:

1. The application of Forest Practices riparian rules can result in differences among the study basins in shading and solar radiation input;
2. Differences in groundwater input, tributary input, and hyporheic exchange capacity among sites could mask treatment effects if not considered in the study design and data analysis;
3. Physical characteristics that affect the sensitivity of headwater streams to forest practices such as elevation, aspect, basin size, steam-associated wetlands and lakes, discontinuous flow, climate, and debris flow disturbance should be documented so they may be considered in the analysis.

We hypothesize that stream temperature response in incompetent lithologies may differ from those seen in competent lithologies. Dent et al. (2008) observed significant differences in summer stream temperature between stream reaches in sedimentary and igneous lithologies, while Hunter and Quinn (2009) observed a difference in summer temperature response between a channel with glacial alluvium compared to a bedrock-dominated channel in sedimentary lithology. Differences in the underlying lithologies and the soils they produce may affect basin hydrology and groundwater regimes by affecting summer baseflow and groundwater input rates. In addition, lithology affects channel morphology (e.g., channel width, water depth, and gradient). This affects the size and composition of bed materials which in turn affect bed conduction and hyporheic exchange capacity.

Sediment Response to Forest Practices in Headwater Streams

Forest management in small forested basins is likely to affect sediment and wood inputs to channels which in turn influences the timing and magnitude of sediment transport (Hassan et al., 2005a, b; Table 1). The removal of forest canopy reduces canopy interception and evapotranspiration. This changes the magnitude and timing of water delivery to the soil (Keim and Skaugset, 2003) and increases soil moisture (Lewis et al., 2001; Johnson et al., 2007). The response to forest harvest is strongly seasonal. In conifer-dominated forest basins, streamflow may increase by several hundred percent during the late summer and early fall period in the first five years after harvest (Jones and Post, 2004).

Table 1. Sediment mobilization and yield from hillside slopes (Hassan et al., 2005a).

Process	Mobilization Rate		Yield Rate to Stream Channels	
	Forested Slopes	Cleared Slopes	Forested	Cleared
NORMAL REGIME				
Soil Creep (including animal effects)	1 $m^3/km/yr$*	2x	1 $m^3/km/yr$*	2x
Deep Seated Creep	10 $m^3/km/yr$*	1x		1x
Tree Throw	1 $m^3/km^2/yr$	-	-	-
Surface Erosion: Forest Floor	< 10 $m^3/km^2/yr$		< 1 $m^3/km^2/yr$	
Surface Erosion: Landslide scars, gully walls	>10^3 $m^3/km^2/yr$		>10^3 $m^3/km^2/yr$	
Surface Erosion: Active Road Surface				
EPISODIC EVENTS				
Debris Slides	10^2 $m^3/km^2/yr$	-100x	10^3 $m^3/km^2/yr$	

*These results reported at m^3/km channel bank. All other results reported as m^3/km^2 drainage area. Results are generalized to order of magnitude from a table that originally appeared in Roberts and Church (1986).

Forest practices may not only increase summer low-flow conditions, but they have the potential to increase the frequency or magnitude of sediment transporting events as well (Alila et al., 2009). Sediment transport is a function of transport capacity and sediment supply (Schumm, 1971) both of which can be altered by forest practices. Transport capacity is a measure of the total sediment that a stream can carry. Competence reflects the size of material that can be moved. Both capacity and competence are altered through changes in the timing or volume of runoff associated with changes in drainage density from roads (Wemple et al., 1996) and the routing of subsurface flow into the surface network (Wemple and Jones, 2003). Bedforms, large wood, or other channel features increase hydraulic resistance (Kaufmann et al., 2009) while the introduction of large quantities of woody slash can trap fine sediment that would otherwise be routed through the network (Jackson et al., 2001).

Hydrologic changes can also affect sediment supply by affecting the processes that deliver sediment. For example, Robert and Church (1986) found that prior to logging: streambank erosion, landslides, soil creep, and tree throw were co-dominant sources of sediment to the stream channel in several disturbed watersheds in the Queen Charlotte Islands. Logging increased streambank erosion and landslides, which accounted for up to 85% of the total sediment delivery. Soil creep, tree throw, and road surface erosion constitute the remaining fraction. Although sediment export was estimated to have increased, the residence time of bed sediment also increased by as much as ten-fold because large quantities of sediment were stored in in-channel sediment wedges.

Episodic mass wasting can deliver large quantities of sediment to stream channels in a short period of time and can mask treatment effects. Grant and Wolff (1991) documented 30 years of suspended and bed load sediment mobility from three small basins with different road building and forest harvest treatments. They estimated that approximately 85% of the total 30-year load was transported in a single event in which a series of debris flows scoured the channel to bedrock. In a review paper, Dunne et al. (2001) noted that one of the main problems with measuring and predicting the influence in forest management on sediment transport is that the monitoring period is typically too short to sample the variability of natural and disturbed hydrologic regimes.

The *Type N Experimental Buffer Study in Basalt*, to which this is a companion study, focused on erosion-resistant volcanic lithologies because the study's target amphibian species tend to be found there, probably because of the small to medium gravel-size stream substrate present. Recent studies conducted in the Pacific Northwest have documented different responses to anthropogenic disturbance between volcanic and sedimentary lithologies in stream temperature (Dent et al., 2008), relative bed stability (Kaufmann et al., 2009), and ecological condition (Kaufmann and Hughes 2006). These differences in response are likely the result of differences in erodability and, therefore, sediment supply to headwater basins (Kaufmann and Hughes, 2006).

Key findings to consider in the design of this study are:

1. Over the timescale of this study (two years post-harvest) changes in sediment transport and storage are likely to be associated with changes in bank erosion and shear stress, e.g., stream discharge and wood loading.

2. Sediment supply and transport is episodic and the full effect of forest harvest on overall sediment transport may not manifest itself at the basin outlet within two years following harvest. Changes in discharge and sediment inputs from wind throw may be offset by increases in roughness elements that cause short-term decreases in transport capacity and increases in sediment storage.

Nutrient Response to Forest Practices in Headwater Streams

The common forms of inorganic nitrogen are nitrate-N and ammonia. Nitrate is the dominant form in forested headwater streams while ammonia tends to be present only at very low concentrations. Pre-harvest concentrations can vary widely. They vary by vegetation type and have been found to be higher in reaches dominated by nitrogen-fixing alder (Triska et al., 1995). Organic nitrogen, both particulate and dissolved, tends to comprise a small proportion of the total nitrogen concentration.

Nitrate-N is soluble and readily transported in surface or groundwater flows. Post-harvest Nitrate-N concentrations can be affected by harvest-associated changes in stream flow and timing (Moore and Wondzell, 2005), soil mineralization rates, and decreased uptake rates (DeLuca and Zouhar, 2000). The result is larger quantities of mobile nitrate in the soils and more groundwater delivered to the stream. The net effect on stream water nitrate concentration depends upon the combined effects of more available nitrate-N and greater groundwater volume, but the total mass of nitrate-N exported from the basin is likely to increase immediately post-harvest.

Unlike nitrate-N, phosphorus tends to bind with sediment particles and is not readily transported via groundwater. Changes in phosphorus concentration and export tend to mirror suspended sediment export described above. Harvest practices that minimize soil disturbance and sediment delivery to the stream will likely minimize any effect on phosphorus concentration and export.

A review of the effects of forest harvest on annual average stream water nutrient concentrations (NCASI, 2001) indicated that nitrate-N increased in 30 of the 43 studies reviewed. Ammonia and phosphorus concentrations generally showed little or no response to harvest although this may have been due to the coarseness of the analysis. Considerable variability in nitrogen and phosphorus concentration was seen based on drainage area, lithology, and season.

Nutrient export, especially nitrate-N, is of interest because dissolved inorganic nitrogen was identified as the primary nutrient limiting phytoplankton growth in Puget Sound (Newton and Van Voorhis, 2002) and is at least partially responsible for the eutrophic conditions noted within Puget Sound (Bricker et al., 2007). Eutrophication is linked to the hypoxia (areas of low dissolved oxygen) noted in southern Hood Canal and south Puget Sound as sinking organic matter (phytoplankton) fuels high microbial respiration rates in the deeper waters. Recent efforts have estimated loads from major rivers and wastewater treatment plants (Mohamedali et al., 2011) and an accurate estimate of loads from different land uses will help to direct efforts toward those sources that can be most efficiently managed.

Macroinvertebrate Response to Forest Practices in Headwater Streams

Water quality regulatory criteria are intended to protect instream biota. Because the streams in this study are fishless, macroinvertebrates will be used as the indicator of biological effects. Headwater streams in mature forests are heavily shaded and stream fauna depend upon allochthonous inputs. Harvest of riparian trees allows increases in autochthonous production because more solar radiation reaches the stream, and decreases the allochthonous inputs through decreased litterfall to the stream (Stockner and Shortreed, 1976).

It is this shift from an allochthonous to autochthonous food base that likely drives many of the changes in macroinvertebrate composition rather than changes in stream temperature or fine sediment (Hawkins et al., 1992; Kedzierski and Smock, 2001; Kreutzweiser et al., 2005). The change is often seen as an increase in total numbers or biomass of organisms and a shift toward grazers and away from shredders (Haggerty et al., 2009; Wilkerson et al., 2010). Observed increases in gatherers have been attributed to increased detritus input to the stream in the form of logging slash (Haggerty et al., 2009; Kobayashi et al., 2010).

Project Description

Goal

This study will evaluate the effects of timber harvest in headwater basins on water temperature, sediment inputs to and storage within the Type N stream channel, exports of suspended sediment and nutrients from the Type N basin, and benthic macroinvertebrate communities.

Critical Questions

1. How does harvest of Type N stream basins affect water temperature within and at the outlet of the Type N basin?
2. How does harvest of Type N stream basins affect sediment input to and storage within the Type N channel?
3. How does harvest of Type N stream basins affect suspended sediment and nutrient export to downstream Type F waters?
4. How does harvest of Type N stream basins affect benthic macroinvertebrate communities immediately downstream of the harvest unit?

Target Population

The target population is perennial, non fish-bearing (Type Np) basins on two types of incompetent lithology (marine sediments and unconsolidated glacial till) in western Washington located on forest lands managed for timber production.

Site Selection

Criteria

This study is meant to be complementary to the *Type N Experimental Buffer Treatment Study in Basalt Lithologies* (Type N Basalt). The Type N Basalt study focused on streams with coarse substrate where coastal tailed-frogs were likely to be present. The presence of coastal tailed-frogs drove many of the site-selection criteria, including: elevation range, gradient range, lithologies, and minimum stream order. We will use similar selection criteria except that we will select lithologies likely to produce a fine-grained stream substrate. The site selection criteria are listed in Table 2 and described below.

Table 2. Site selection criteria.

Criterion	Limit	Information Source
Geographic location	West of the Crest of the Cascade Mountain Range in Washington State	GIS analysis
Elevation	< 1,067 m (3,500 ft) for the Olympic Peninsula < 1,219 m (4,000 ft) for the Cascades and SW Washington	
Gradient	5 – 50% (3 – 27 degrees)	
Lithology	> 80% of basin within lithology classes of glacial till or marine sedimentary	
Basin size	~12 – 49 ha (~30 – 120 ac)	
Stand age	>70% of basin between 30 and 80 years old during harvest treatment window	Landowner
Ownership	>80% owned by single participating landowner	
Harvest timing	Treatment basins: harvest October 2013 – May 2015 Reference basins: no harvest before October 2016	
Landowner commitment	5 years	

GIS: Geographic Information Systems

Geographic location. Study sites will be restricted to the area west of the crest of the Cascade Mountains in Washington State; the geographic area where the prescriptions are designed to be applied.

Lithology. This study will focus on streams with fine-grained substrate to complement the previous study in competent (basalt) lithologies. Therefore, we will include only those basins that are largely comprised of one of two incompetent lithologies - marine sedimentary or unconsolidated glacial till - as identified by the WDNR on the Southwest or Northwest Geologic Maps.

Elevation. This study will use the same criteria as the Type N Basalt study, which limited basin elevation at the N/F junction to less than 1219 m (4,000 ft) in the South Cascades and less than 1,067 m (3,500 ft) in the Olympic Peninsula. No restrictions were needed for the Willapa Hills basins because the maximum elevation was only 948 m (3,110 ft) (McIntyre et al., 2009).

Stream gradient. This study will use the same criterion as the Type N basalt study, which restricted the average stream gradient to between 5 and 50% (3-27 degrees).

Basin size. The entire basin will be harvested, except for areas (sensitive sites) specifically set aside in the rules. This study will use the same basin area criteria as the Type N Basalt study. The lower area limit is largely driven by landowners, who have indicated that they would not typically harvest a unit smaller than 12 ha (30 ac). Forest Practices regulations limit maximum size of harvest units to 49 ha (120 ac) without review by an interdisciplinary team (WDNR, 2001). Since treatments were meant to reflect forest practices as currently implemented, basin size was constrained between 12 and 49 ha (30 and 120 ac).

Stand age. This study will use the same criterion as the Type N basalt study: stand age between 30 and 80 years at time of harvest. Landowners indicated that 30 years was a minimum age for harvest and the maximum stand age was set at 80 years because harvest of stands over 80 years is infrequent in Washington State and would not represent a common rule implementation.

Ownership. Since coordination and implementation of the harvest treatments on schedule would be difficult in basins with multiple landowners, only basins where a single landowner controls at least 80% of the basin area will be selected.

Harvest timing. Treatment basins must be harvested between October 2013 – May 2015, and reference basins must have no management activity until October 2016.

Landowner commitment. In order to participate, landowners must be willing to harvest basins to study specifications and schedule. They must also allow access to their land throughout the study period of 5 years, which would allow for two years pre- and two years post- harvest data collection plus one year to coordinate harvest.

Site Selection Process

The site-selection process will include the following steps described below:

1. **Identify non fish-bearing basins using GIS (Geographic Information Systems).** Type N basins will be identified using the WDNR hydrology layer (http://fortress.wa.gov/dnr/app1/dataweb/metadata/WA_Hydro_Data_Dic.htm#Top), which includes points where the fish occupancy was predicted to end based on the last-fish model. Watersheds contributing to the fish endpoint are identified using a 10-m Digital Elevation Model (DEM) from the National Elevation Dataset (1/3 arc second elevations accessed on March 23, 2009) that are re-projected to 10 m using bilinear interpolation.

2. **Apply the GIS-based site-selection criteria** to the pool of non fish-bearing basins within the study area, including lithology (www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/gis_data.aspx), elevation, gradient, and basin size to identify suitable study basins based on physical criteria.

3. **Site Selection Database.** We will create a GIS data layer coverage to delineate all non fish-bearing basins meeting the site-selection criteria and an Access database to manage and analyze the data generated by the GIS site-selection process. GIS data layers associated with the project are stored in a file geodatabase. The geodatabase contains all the source files, the delineated basins, and ArcGIS model builder scripts used for basin creation. Characteristics related to elevation and stream gradient are derived from the 10-m DEM. The database will include those variables listed in Table 3 below.

4. **Establish Landowner Cooperation and Determine Ownership.** Landowners across the selection area will be contacted for their interest in participating and sharing information about stand age and timber harvest plans. Ownership boundaries within each basin (number of landowners), the stand age distribution, and projected harvest date will be obtained from cooperating landowners.

5. **Field verify the GIS-based and ownership criteria for qualifying basins.** Make field visits to candidate sites to verify basin characteristics including existence of a Type N stream, location of the Type F/N break, basin elevation, stream gradient, stream substrate size, and stand age.

6. **Select basins.** Qualifying basins will be grouped by perennial stream length, basin area, channel morphology and hydrology (Montgomery and Buffington, 1993; Montgomery and MacDonald, 2002); aspect; number of road crossings and their locations; and proximity to other basins (Table 3). Up to ten basins will be selected from the pool of sites for each lithology.

Table 3. Variables used to describe study basins.

Variable	Data Source
Mean channel width	Field measurements
Mean channel slope	Field measurements
Basin aspect	GIS analysis
Basin area	GIS analysis
Solar loading potential	GIS analysis
Mean basin elevation	GIS analysis
Perennial stream length	GIS analysis w/field verification

Organization and Schedule

Table 4 lists the people involved in this project. All are employees of the Washington State Department of Ecology. Table 5 presents the proposed schedule for this project.

Table 4. Organization of project staff and responsibilities.

Staff (all are EAP except client)	Title	Responsibilities
Mark Hicks Water Quality Program Phone: 360-407-6477	EAP Client	Clarifies scopes of the project. Provides internal review of the QAPP and approves the final QAPP.
William Ehinger GWFF Unit SCS Phone: 360-407-6416	Project Manager and Principal Investigator	Writes the QAPP. Manages project. Oversees QA review of data and entry of data into EIM. Analyzes and interprets data. Writes the draft report and final report.
Greg Stewart NWIFC Phone: 360-528-4367	Principal Investigator	Writes the QAPP. Analyzes and interprets data. Writes the draft report and final report.
Dave Schuett-Hames NWIFC Phone: 360-528-4333	Principal Investigator	Writes the QAPP. Analyzes and interprets data. Writes the draft report and final report.
Martha Maggi GWFF Unit SCS Phone: 360-407-6453	Unit Supervisor for the Project Manager	Provides internal review of the QAPP, approves the budget, and approves the final QAPP.
Will Kendra SCS Phone: 360-407-6698	Section Manager for the Project Manager	Reviews the project scope and budget, tracks progress, reviews the draft QAPP, and approves the final QAPP.
William R. Kammin Phone: 360-407-6964	Ecology Quality Assurance Officer	Reviews the draft QAPP and approves the final QAPP.

EAP: Environmental Assessment Program.
EIM: Environmental Information Management database.
QAPP: Quality Assurance Project Plan.
GWFF: Groundwater Forest & Fish.
SCS: Statewide Coordination Section.
NWIFC: Northwest Indian Fisheries Commission.

Table 5. Proposed schedule for completing field work, data entry into EIM, and reports.

Field and laboratory work	Due date	Lead staff
Field work completed	May 2017	Project field lead
Laboratory analyses completed	NA	
Environmental Information System (EIM) database		
EIM user study ID	WEHI0000	
Product	Due date	Lead staff
EIM data loaded	December 2018	Project field lead
EIM quality assurance	March 2019	Project field staff
EIM complete	June 2019	Project field lead
Final report		
Author lead / Support staff	William Ehinger, Greg Stewart, Dave Schuett-Hames	
Schedule		
Draft due to supervisor	December 2017	
Draft due to client/peer reviewer	March 2018	
Draft due to external reviewer(s)	June 2018	
Final (all reviews done) due to publications coordinator	December 2018	
Final report due on web	January 2019	

Experimental Design

Overview

This study will evaluate the effects of the Westside Type N riparian rules on stream temperature, sediment input to and storage within the channel, downstream transport of suspended sediment and nutrients, and benthic macroinvertebrate response in forest lands on marine sedimentary and glacial till lithologies in western Washington. It is designed so the results can be compared with an earlier study on the effects of these rules in basins with competent lithologies.

The experimental unit is the Type N basin, the drainage area above the uppermost point of fish habitat as defined by the Washington Forest Practices rules. The Type N drainage basin is an appropriate unit of study because:

- The Westside Type N riparian prescriptions are designed to be applied on a basin scale with different requirements for different portions of the drainage network.
- A study at the headwater basin scale can examine reach-scale effects within the drainage basin, as well as exports to downstream fish-bearing waters.
- The results will be comparable with the earlier study done in competent lithologies.

Basins harvested using the Westside Type N riparian rules (WAC 222-30-021 (2)) will be compared to unharvested reference basins. In the harvested basins, all trees not precluded from harvest by the forest practices rules will be removed in a single-entry, clearcut harvest. The rules require 50 ft no-cut buffers for 50% of the length of perennial Type N stream network, including a buffer immediately upstream of the junction with the downstream Type F fish-bearing water, extending 300-500 feet, depending upon total stream length (see table "Minimum percent length of Type Np waters to be buffered when more than 500 feet upstream from the confluence of a Type S or Type F water).

In addition the rules call for 50-foot buffers around certain "sensitive sites" designated in the forest practices rules (perennial initiation points, headwall and side-slope seeps), 56-foot buffers around headwater springs and at the junction of two or more Type Np streams and no harvest on alluvial fans. Segments for harvest must be a minimum of 100 feet in length. There is also a 30-ft equipment limitation zone along the entire stream channel intended to prevent soil disturbance near the channel. Riparian stands that occur outside the prescribed buffers will be clear-cut to the stream. The reference basins will have forest stands of similar age to the treatment basins, but no harvest will occur during the study period.

Data will be collected for two years prior to harvest, during harvest, and for two years following harvest [1] in both the treatment and reference basins. A Multiple Before-After/Control-Impact (MBACI) design will be used. The MBACI design differs from the BACI design in that multiple control basins and multiple treatment basins will be monitored and that multiple measurements (years) will be taken pre- and post-harvest. The MBACI design, with its replication of reference

[1] The study may extend beyond two years post-harvest, if the initial findings warrant the extension and funding is available.

basins in space and time, provides an estimate of the natural variability throughout the pre- and post-treatment periods (Underwood, 1994a, 1994b; Downes et al., 2002) and allows a better test of the assumption that any changes detected after harvest are due to the harvest treatment. In addition, having multiple control and treatment basins decreases the likelihood that the study will be severely compromised by the loss of one or more basins due to storm damage, landowner withdrawal from the study, or other unforeseen circumstances.

Ten basins from each lithology will be monitored to evaluate changes in stream temperature; with three basins in each lithology used as references and the other seven receiving the harvest treatment. In addition, two of the ten basins in each lithology group will be monitored to evaluate changes in sediment and nutrient export, with one used as an unharvested reference basin and one receiving the harvest treatment (Table 6). The final number and distribution of reference and harvest treatments among the two lithologies will depend upon the total number of basins available and landowner ability to apply the treatments in a timely manner. Random assignment of specific basins to the treatment or reference group will be followed to the extent possible, given the land managers' constraints on harvest schedules.

Table 6. Distribution of sampling basins.

The study includes two lithologies (marine sedimentary, glacial till), two treatments (reference and harvested), and up to ten sites per lithology of which two will be monitored for downstream exports.

Number	Temperature/ invertebrates	Sediment/Nutrient export
Lithologies	2-marine sedimentary and glacial till	
Treatments	2-unharvested and harvested	
Sites/ lithology	10	2
Reference / treatment sites	3/7	1/1
Total number of sites	20	4

The remainder of the experimental design section of this document is divided into two parts. The first part presents the analysis and variables for the stream temperature component and the second part describes the analysis and variables for sediment and export components. The sampling plan and data collection procedures are presented in a separate section further back in the document.

Stream Temperature

Introduction

A series of specific research questions will be used to address the critical question for stream temperature: "How does harvest of Type N basins affect water temperature within and at the outlet of the Type N basin?"

1. Is there a change in summer daily maximum water temperature at the outlet (T1), below the clearcut portion of the stream (T2), within the clearcut reach (T3), and at the perennial initiation point (PIP (T4) following harvest (Figure 3)?

One objective of the Westside Type N riparian prescriptions is to prevent changes in water temperature that would exceed water quality standards. The analysis will evaluate changes in summer water temperature at the N/F junction in harvested Type N basins relative to the reference basins.

2. What is the effect of the buffered reaches on post-harvest water temperature?

This analysis will examine reach scale changes in summer stream temperature, within the buffered reaches above the N/F junction. Of special interest is whether the minimum prescribed buffer lengths (300 or 500 feet, depending upon total perennial stream length) are sufficient to prevent an increase in the summer daily maximum water temperature at the basin outlet.

3. What factors appear to drive water temperature response at the basin scale?

Numerous authors have noted that stream temperature response is not only affected by heat exchange across the air-water surface interface, but is also a function of hydrologic conditions (Johnson, 2004; Hannah et al., 2004; Leach and Moore, 2010). This analysis will evaluate the effects of the processes described earlier on stream temperature response at both the reach and basin scale. It will also evaluate how those processes responded to harvest.

4. How does water temperature change longitudinally over the Type N network?

Previous research indicates that there can be substantial variability in stream temperature within the Type N stream network. The analysis for research question 4 will document the longitudinal gradient in stream temperature during the late summer low-flow period.

5. How do the key riparian descriptors (canopy closure, stream cover, woody debris, wetted channel length, stream-adjacent wetlands) change after harvest?

In the forest environment, the amount of solar radiation reaching small streams is typically limited by the vegetation and woody debris which blocks incoming solar radiation. Timber harvest adjacent to streams can reduce canopy cover and increase the amount of solar radiation reaching the stream, while input of logging debris can increase stream cover. Following harvest, growth of trees, shrubs, and understory plants, and also wind throw of buffer trees can affect incoming solar radiation. Harvest could also cause changes in hydrology, which could cause changes in the length of perennial channel and in the surface areas of stream-adjacent wetlands.

Analysis

Analytical frameworks used to answer the Research Questions posed above are presented in turn. Each includes a description of the statistical model or test that will be employed, along with a basic description of the data required. Field methods are described in the Sampling and Measurement Procedures section below.

Research Question 1

Temperature change at the outlet treatment stream will be determined using the paired basins approach advocated by Watson et al. (2001) and Gomi et al. (2006). This method involves five steps:

1. Establish regression relations between treatment and reference basins in the pretreatment period (calibration) then predict treatment stream temperatures in the post-harvest period using the regression coefficients and the measured temperature in the reference stream.

Stream temperature collected at 30-minute intervals will be aggregated to a daily time series to avoid problems associated with sub-daily lags (e.g., hourly) between reference and treatment temperature response and to reduce serial autocorrelation among sequential 30-minute temperature values. The daily time series will be evaluated using the model:

$$y_t = \beta_o + \beta_1 x_t + \beta_2 \sin(2\pi j / 365.25) + \beta_3 \cos(2\pi j / 365.25) + \varepsilon_t \quad (6)$$

where,

- y_t is the maximum temperature at a treatment stream on day t,
- x_t is the corresponding temperature at the control stream,
- β_0, β_1, β_2, and β_3 are the coefficients to be estimated by regression,
- j is the day of the year, and
- ε_t is an error term.

The sine and cosine terms in equation 6 represent a single seasonal term:

$$A \sin(2\pi j / 365.25 + \phi) = \beta_2 \sin(2\pi j / 365.25) + \beta_3 \cos(2\pi j / 365.25) \quad (7)$$

where,

- A is the harmonic amplitude and
- ϕ is the harmonic phase shift of the seasonal variation in temperature response.

For the purpose of model reduction, the sine and cosine terms will be dropped only if both are not significant.

2. Calculate the treatment effect (TE) as the observed daily maximum temperature minus the predicted temperature in the treatment stream.

$$TE = (y_t - \hat{y}_t) \quad (8)$$

where,

- y_t= observed temperature on day t and
- $\hat{y}_t$ = the predicted temperature on day t

For the calibration period, the TE is ε_t, the regression residuals.

3. Adjust daily TE values based on the presence and strength of serial autocorrelation in the regression residuals.

The error term may be expressed as an autoregressive process of order 'k' such that:

$$\varepsilon_t = \rho_1 \varepsilon_{t-1} + \rho_2 \varepsilon_{t-2} + \ldots + \rho_k \varepsilon_{t-k} + \mu_t \quad (9)$$

where,

- ρ_i is the autocorrelation between error terms at a lag of 'i' days,
- ε_{t-1} is the error term 'i' days before day 't', and
- μ_t is the random error (independent and identically distributed normal variables with mean zero and variance σ_t^2).

If the residuals from the calibration regression exhibit significant autocorrelation based on an examination of the partial autocorrelation plots, then the treatment effect will be adjusted to remove the autocorrelation using:

$$\hat{\mu}_t = (TE_t) - \hat{\rho}_1 (TE_{t-1}) - \ldots - \hat{\rho}_k (TE_{t-k}) \quad (10)$$

where,

- $\hat{u}_t$ is the adjusted treatment effect on day t,
- TE_t is the calculated treatment effect on day t, and
- $\hat{\rho}_i$ is an estimate of the lag i autocorrelation coefficient.

4. Test the adjusted values for statistically significant differences between the pre-harvest and post-harvest periods. The adjusted TE values, $\hat{u}_t$, for July-August for all pre-harvest years will be compared to the July-August values for each post-harvest year using a two-sample Kolmogorov-Smirnov test to determine if a significant ($P<0.05$) temperature change has occurred at that location on that stream.

5. A repeated-measures, mixed-effects model using the daily TE values and an autoregressive term in the model will be used to evaluate the effect of harvest on July-August stream temperature due to harvest across all basins in the study.

As with any BACI design, a key assumption of the design is that the treatment vs. reference relationship is stationary over the period of study. The analysis described above will be done comparing two reference basins. If the Kolmogorov-Smirnov test shows no significant difference in the July-Aug adjusted TE values between the first two years and the last two years, then we will assume the relationship is stationary.

Research Question 2

In the buffered reaches, the post-harvest change in solar energy exchange is expected to be relatively small and the temperature effect will likely be determined in part by the incoming temperature. In the buffered reach, sensible and latent heat exchange driven by the energy gradient between air and water are likely to be larger because of the smaller role of solar input.

It is expected that the change in heat energy through the buffered reach should be inversely proportional to the change in water temperature associated with water entering the reach. We shall evaluate the buffer reach temperature using a slightly modified version of Equation 5:

$$y_t = \beta_o + \beta_1 x_t + \beta_2 u_{cc,t} + \beta_3 \sin(2\pi j / 365.25) + \beta_4 \cos(2\pi j / 365.25) + \varepsilon_t \quad (11)$$

where,

- $\hat{u}_{cc,t}$ is the adjusted TE for T2 (bottom of the clear-cut reach) on day *t*, and
- β_2 is a coefficient, expected to be negative, to be estimated.

Research Question 3

The goal of this analysis is to identify the factors that appear to be most correlated with temperature response among the basins, identify the physical processes associated with those factors, and then relate measured temperature changes with those process factors.

In this study, we will use a simple additive effects model (Moore et al., 2005a) to evaluate the relative contribution of different factors to changes in water temperature:

$$\Delta T_{out} = Lith + \Delta T_{in} + \Delta T_{air} + \Delta Q + \Delta Sr + \Delta Hyp + L \times \Delta Q + L \times \Delta Sr + L \times \Delta Hyp + \varepsilon \quad (12)$$

where,

- ΔT_{out} is the post-harvest change in water temperature leaving the reach (See Eq 13.),
- ΔT_{in} is the post-harvest change in water temperature coming into the reach,
- ΔT_{air} is the post-harvest change in air temperature within the buffer,
- ΔQ is the post-harvest change in summer flow,
- ΔS_r is the post-harvest change in surface water residence time,
- ΔHyp is the post-harvest change in hyporheic residence time, and
- *L* is length of the stream reach.

Changes in water and air temperature time series (ΔT_{out}, ΔT_{in}, and ΔT_{air}) will be calculated from the TE values obtained from the paired-basin analysis with daily time series described in Research Question 1, above, as:

$$\Delta T = (\overline{TE}_{post}) - (\overline{TE}_{Pre}) \quad (13)$$

where,

- $\overline{TE}_{post}$ = average July-Aug TE post-harvest and
- $\overline{TE}_{pre}$ = average July-Aug TE pre-harvest.

Air temperature in this context is used as a proxy for net heat exchange across the air-water interface.

Although the regression model (Eq 10) is based on a conceptual model of stream heating and cooling processes, it should not be confused with a deterministic model (Caissie, 2006). In this analysis, we propose to determine which factors appear to be most closely correlated with changes in water temperature in the study basins.

With 14 treatment basins, the maximal model has only four residual degrees of freedom for use in estimating model error (see Table 7 for an example of the data layout), and model reduction will be important. We propose to follow the modeling guidelines of Crawley (2007) and Zurr et al. (2009) which include:

1. Elimination of highly correlated explanatory variables,
2. Use of General Additive Models to evaluate curvature in relationships and determine whether transformations or alternate model approaches are appropriate,
3. Use of single term deletions from a maximal model to arrive at the minimally adequate model.

Table 7. Example database format for evaluation of factors affecting stream temperature response within a given reach.

Basin	Lithology	ΔT_{out} (°C)	ΔT_{in} (°C)	ΔT_{air} (°C)	ΔQ (Ls^{-1})	Length (m)	ΔSr (hrs)	ΔHyp (hrs)
1	MS	3.2	0.1	4.8	41		-2.52	4.5
2	GT							
..	…		…		…		…	…
14	GT							

As noted above, changes in discharge (ΔQ) have the potential to affect stream temperature through changes in the volume, location, and/or timing of groundwater input; and through changes in water depth and velocity. We will not attempt to separate these effects in this analysis, but assume that changes in discharge are uniformly distributed throughout the network.

Research Question 4

Longitudinal variation in stream temperature will initially be addressed by collecting water temperature measurements along the entire main Type N channel of each basin on a single day during the summer low-flow period. Temperature will be plotted as a function of distance from the perennial initiation point. These data will be used to determine whether there is a general form to the change in water temperature as a function of distance to the PIP (i.e., $\Delta T=f(x)$), or whether there are discontinuities in longitudinal temperature profile.

Research Question 5

Stand density and basal area, tree mortality, percent canopy closure, percent slash/woody debris cover, and percent shrub/understory plant cover over the stream will be measured at a network of vegetation plots and channel transects.

At each selected transect, percent of channel obscured by slash/small woody debris, percent of channel obscured by large woody debris, percent of channel obscured by shrub/understory plant cover, and canopy closure will be measured. The surface area of stream-adjacent wetlands will be estimated from a survey of the sample reaches from the channel network. A one-way ANOVA will be used to test for treatment effects in the difference between pre and post-harvest values.

Sediment and Nutrient Export

The stream sediment component of the study is designed to answer Critical Questions 2 and 3 at two basins in each lithology:

2. *How does harvest of Type N stream basins affect sediment input to and storage within the Type N channel?*

   Sediment delivery to the stream channel may increase post-harvest due to higher streamflow, bank erosion, overland flow, landslides, and road runoff. Storage of sediment within the channel is largely a function of woody debris. Small diameter woody debris is likely to increase dramatically with the input of slash from the harvest. Large woody debris may also increase from larger pieces of slash and wind-thrown trees.

3. *How does harvest of Type N stream basins affect suspended sediment and nutrient export to downstream Type F waters?*

   Higher post-harvest flows and increased sediment delivery could increase suspended sediment (and associated phosphorus) export post-harvest. Reduced nitrogen uptake plus increased flows and mineralization may increase nitrogen (total and nitrate-nitrogen) export from the basin.

Analysis

Critical Question 2

An ANOVA will be used to compare post-harvest changes in sediment delivered to the bankfull channel via surface erosion, bank erosion, and mass wasting, and changes in sediment delivery via forest road surfaces. An ANOVA will also be used to compare post-harvest changes in in-channel sediment storage as calculated from sediment wedges and bed elevations measured at channel transects.

Critical Question 3

Suspended sediment export will be calculated using the Turbidity Threshold Sampling methodology (Lewis and Eads, 2008). Regression-based models will be constructed to calculate daily, monthly, and annual suspended sediment yield. Ordinary Least Squares (OLS) regression models will be used for the monthly data, where serial autocorrelation of the data is unlikely. Generalized Least Squares regression will be used for the daily data to account for the serial autocorrelation in the residuals. The following regression model will be used:

$$y_t = \beta_o + \beta_1 x_t + \beta_2 \sin(2\pi j / 365.25) + \beta_3 \cos(2\pi j / 365.25) + \varepsilon_t \quad (14)$$

where,

- y_t is the sediment yield from the treatment basin on day (month) t,
- x_t is the sediment yield on day (month) t at the control stream,
- β_0, β_1, β_2, and β_3 are the coefficients to be estimated by regression,
- j is the day of the year, and
- ε_t is an error term.

The adjusted treatment effects ($\hat{\mu}_t$) will be calculated as in Equations 6-8 if significant serial autocorrelation is present.

Prediction intervals about the treatment effect will be calculated as:

$$0 \pm 1.96\sqrt{Var(\hat{\mu}_t)} \qquad (15)$$

where, Var($\hat{\mu}_t$) is the estimated variance.

Using a significance level of $\alpha < 0.10$ and assuming no difference between pre- and post-harvest sediment yield, approximately five percent of the random disturbances are expected to exceed the 95% prediction intervals. If more than five percent exceed, we will assume a statistically significant change has occurred.

Changes in nutrient (nitrate-N, total nitrogen, total phosphorus) export will be evaluated in a similar manner.

Macroinvertebrates

Critical Question 4

4. *How does harvest of Type N stream basins affect macroinvertebrate communities immediately downstream of the harvest unit?*

The analyses will focus on three dependent variables: the number of intolerant taxa, proportion of intolerant taxa, and the EPT index using a repeated-measures ANOVA (Winer, 1971) with measurements taken in both pre-harvest years and both post-harvest years.

Sampling and Measurement Procedures

Water and Air Temperature Measurements

Water temperature (Table 8) will be recorded year-round at 30-minute intervals using TidBit dataloggers (Onset Computer Co) at fixed stations within each Type N stream through two years pre-harvest, the harvest year, and two years post-harvest. Measurement of temperature during the harvest is important, since changes in temperature, if they occur, are expected to be rapid and recovery may follow over a relatively short time. In the FFR buffer treatments, temperature dataloggers will be placed and labeled as follows (Figure 3):

- T4- near the highest point of perennial flow (*i.e.,* PIP).
- T3- near the midpoint of the clearcut reach.
- T2- at the upstream end of the Type N buffer (downstream end of the clearcut reach).
- T300- 300’ below the upstream end of the Type N buffer.
- T500- 500’ below the upstream end of the Type N buffer.
- T1- at the Type F/Type N junction.
- T100D- 100 meters below the Type F/Type N junction, if suitable field conditions exist.

Air temperature will also be recorded at 30-min intervals at each water temperature site. The data logger will be placed approximately one meter above the soil surface, adjacent to the stream bank, and sheltered from direct sun.

Data loggers will be placed at comparable locations in the reference stream allowing comparison along the longitudinal channel gradient. The data will be downloaded each spring and fall to a portable data shuttle, then the dataloggers will be placed immediately back in the stream.

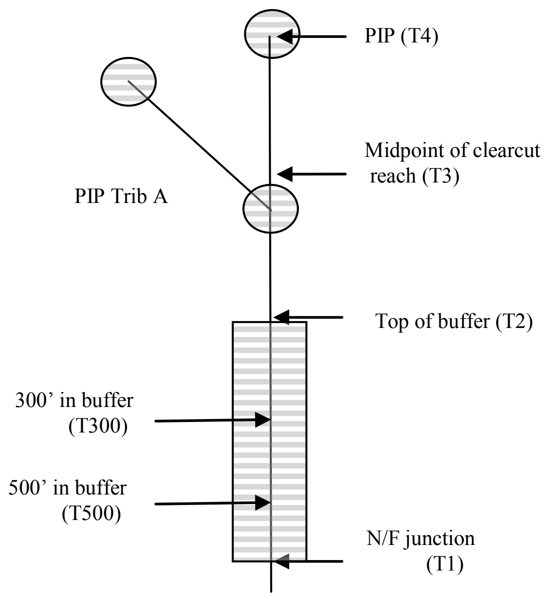

Figure 3. Buffer and sampling layout.

Gray shaded areas indicate the unharvested riparian buffers. There is a 30-ft equipment exclusion zone along the entire perennial stream length. A sensor will be placed 100 meters downstream of the N/F junction (T100D-not shown), if landowner permission and channel length allow. Temperature sensors will be placed at comparable positions along the stream in the unharvested reference basin for comparison.

Table 8. Variables measured in the study.

Parameter	Methodology/instrument	Resolution	Frequency
Water temperature	StowAway TidbiT -5°C to 37°C	0.20°C	0.5 hour
Air temperature	StowAway TidbiT -20°C to 50°C	0.40°C	0.5 hour
Summer Flow Characteristics			
Point flow measurements	Portable flume or dam	NA	1-pre, 1-post
Surface water residence time	Conservative tracer	NA	1-pre, 1-post
Hyporheic residence time	Model air-water temperature phase shift	NA	NA
Transect Measurements			
Slash cover	Line intercept	10% cover categories	Annual
Woody debris < 10 cm diameter		1 piece	Annual
Stream cover	Densiometer	NA	1-pre, 1-post
Bankfull width, depth, profile	Measure down from monumented point	1 cm	2-pre, 2-post
Substrate size class	Platts et al., 1983	NA	2-pre, 2-post
Riparian Vegetation			
Trees/ha, BA/ha	Fixed area strip plot	NA	1-pre
mortality	Fixed area strip plot	NA	1-pre, 2-post
Channel Segment Data			
Step frequency associated sediment volume	Sample of stream reaches, 25% of total perennial channel with minimum of 1 0 and maximum of 50 reaches	NA	2-pre, 2-post
Large woody debris tally, volume, and function			2-pre, 2-post
Stream Network Surveys			
Extent and distribution of wetted channel	Survey of entire channel system	10-m reach	1-pre, 1-post
Road Surface Erosion			
Sediment delivery	Washington Road Surface Erosion Model	NA	1-pre, 1-post
Suspended Sediment and Nutrient Export			
Stream flow	Flume with pressure transducer	NA	Continuous
Turbidity	DTS 12 Digital Turbidity Sensor	0.01 NTU	Continuous
Nitrate-nitrite	SM 4500-NO3-Ia	0.001 mg/L	8/yr plus storm events
Ammonia	SM 4500-NH3-Ha	0.001 mg/L	
Total persulfate nitrogen	SM 4500-NO3-Ba	0.001 mg/L	
Total phosphorus	EPA 200.8	0.001 mg/L	
Soluble reactive phosphorus	SM 4500-P Ga	0.001 mg/L	
Suspended sediment concentration	ASTMD3977B	1 mg/L	
Macroinvertebrates	D-frame kick net	NA	3 times/ yr; 2 yrs pre, 2 yrs post

Summer Low-Flow Characteristics

Low-flow point discharge measurements. Low-flow discharge will be determined in all streams near the N/F junction one time in late summer during both the pre- and post-harvest periods by installing a temporary flume or by routing stream flow through a corrugated drain pipe, into a container of known (20-30 L) volume, and measuring the time needed to fill the container. A low (30-40 cm), temporary dam will be constructed to route the water into the pipe. The pool will be lined with plastic and the dam height kept as low as possible to minimize losses to hyporheic flow. Site conditions will determine which method is used.

Surface water residence time. Surface water residence time is a measure of how long water is exposed to atmospheric thermal loading, and the change in surface water residence time (ΔSr) over a reach of fixed length should be a function of water velocity. As noted above, surface water residence time is not independent of discharge, but the effect of changes in discharge on velocity are expected to be relatively small compared to the changes in roughness in the uppermost, clearcut portions of the network. We propose to quantify changes in surface water residence time as:

$$\Delta Sr = \sum_{i=1 \ldots n} \Delta\left(\frac{x_{surf\,i}}{\bar{v}_i}\right) \qquad (16)$$

Where,

- n is the number of reach segments with relatively constant discharge,
- x_i and v_i are the representative lengths and velocities of segment *i*, respectively, and
- ΔSr is the sum of the changes in residence time along the upstream channel.

We will use a conservative tracer (NaCl) to estimate surface velocity for individual reaches at a given point in time (Kilpatrick and Wilson 1989), and the Manning equation, fit to discharge and velocity estimates, to determine a representative discharge over the period of interest. Measurements will be made in late-summer in all streams pre- and post-harvest.

Hyporheic residence time. Changes in the hyporheic residence time distribution (ΔHyp) will be estimated by the change in lag (τ in Eq. 5) between air and water temperature. The proposed method is similar to that used by Sebehi et al. (2009) and involves using linear regression with harmonic variables to quantify the phase of air and water temperature change associated with the diel and annual cycles. If we assume that daily and seasonal temperature cycles can be approximated by a sine wave, then:

$$T = A\sin[c(t+\phi)] \qquad (17)$$

where,

- *t* is the time (e.g., day),
- A is the amplitude of temperature fluctuation,
- *c* is the cycle which equals 2π/L, where L is the period (e.g., L_{season}=365.25), and
- ϕ is the phase shift.

The parameters in equation 13 are not linear, so we use a trigonometric identity to write:

$$A\sin[c(t+\varphi)] = U_1 \cos(c \cdot t) + U_2 \sin(c \cdot t) \qquad (18)$$

where,

- $U_1 = A\cos(\varphi)$ and
- $U_2 = -A\sin(\varphi)$.

Equation 18 is linear and, assuming that U_1 and U_2 are normally distributed random variables, we can write a model of sub-daily temperature measurements expressed as a function of time (decimal days) with daily and seasonal cycles using the following linear model:

$$T_t = \beta_1 \cos(2\pi t) + \beta_2 \sin(2\pi t) + \beta_3 \cos\left(\frac{2\pi}{365.25} t\right) + \beta_4 \sin\left(\frac{2\pi}{365.25} t\right) + \varepsilon \qquad (19)$$

where,

- t is time (decimal day) and
- β_1, β_2, β_3 and β_4 are estimated coefficients.

Using the same trigonometric identity:

$$\varphi = \tan^{-1}(-\beta_2 / \beta_1) + \tan^{-1}(-\beta_4 / \beta_3) * 365.25 \qquad (20)$$

where, φ is the daily phase.

The lag (τ) between air and water response is estimated as the difference between the two phases ($\varphi_{air} - \varphi_{water}$) and ΔHyp is the difference in estimated lag for the pre-treatment and post-treatment periods (τ_{pre}-τ_{post}).

Stream Monuments and Sampling Point Location Procedure

A network of monumented stream transects will be established at 10-m intervals along the Type Np (perennial) stream network, including tributaries to create a sampling framework (Figure 4). The monumented transects will be numbered sequentially working upstream from the N/F junction along the main channel (Tributary A). When the top of the main channel is reached, the numbering will continue from the bottom to the top of the lowest tributary (Tributary B) and so forth, until all transects in all tributaries have be numbered sequentially. This framework will be used to select sampling locations for measurements taken in series of channel transects and in associated vegetation plots.

Twenty-five percent of the transects will be systematically selected for monitoring by randomly selecting a starting point between 1 and 4 and sampling every fourth transect. A minimum of 10 transects will be sampled to ensure an adequate sample in very small basins. A maximum of 50 transects will be sampled in very large basins due to limited field time.

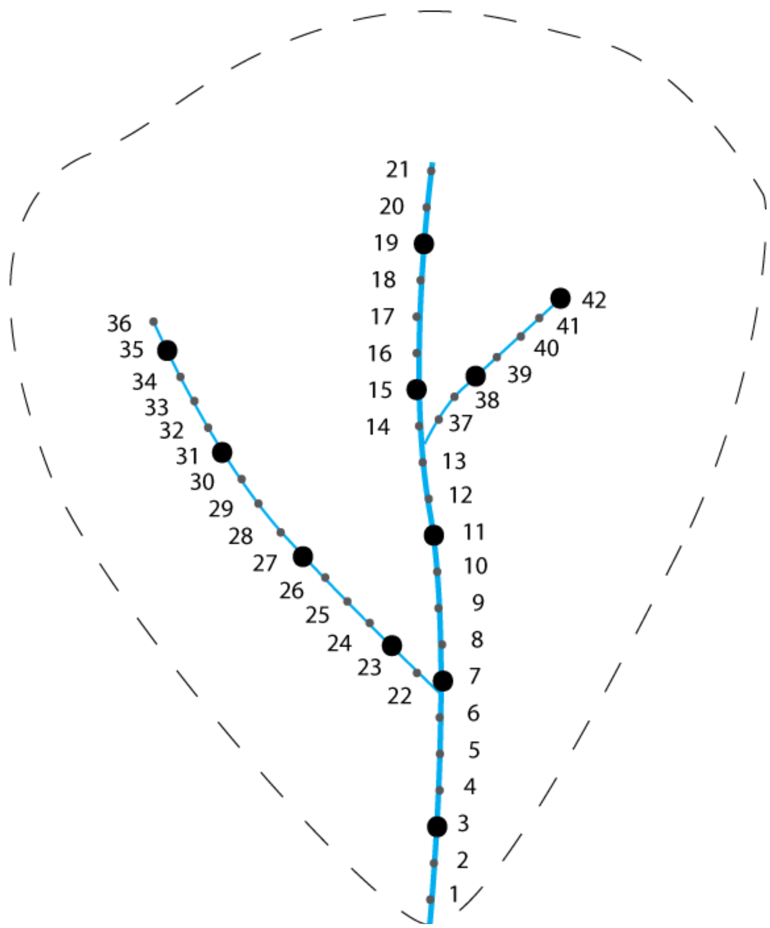

Figure 4. Stream transect layout.

Transects will be established at 10 m intervals. In this example, every fourth transect is sampled (bold dot), beginning with transect 3.

Transect Measurements

At each selected transect the channel will be permanently monumented using rebar stakes. A series of channel and cover data will be collected at each transect.

Slash/wood and shrub cover. A tape will be stretched horizontally between the rebar stakes and used to measure the proportion of the distance within the bankfull channel obstructed by various types of cover, including a) slash and small wood, b) large wood, and c) shrub and understory plant cover. Data on small (diameter ≤10 cm) woody debris frequency and volume will be collected using the line intercept sampling method (Wallace et al., 2000).

Canopy closure and stream cover. Canopy closure will be measured at the selected sampling points using a densiometer held one meter above the water surface and midstream. To measure cover provided by low understory or slash, densiometer measurements will be taken at the same transects but at the water surface.

Bankfull width and depth. One piece of steel rebar will be installed outside the bankfull width on each bank so that a horizontal bar can be leveled across them. Measurements will be taken from the bar to the bankfull surface and every 30 cm across the channel to establish a channel cross-sectional profile from bank to bank. These profiles will be used to evaluate changes in sediment storage (deposition and scour) over the course of the study.

Substrate. Substrate size class will be noted at 0.1 m intervals along the transect to provide data on substrate size need for question 2 of the sediment analysis (Platts et al., 1983).

Riparian Vegetation

Riparian Vegetation. Riparian stand data will be collected at a series of fixed-area strip plots. A plot will be established at each transect selected for measurement (see above), including tributaries, however riparian data will not be collected on those portions of the treatment basins where clear-cut harvest will occur, since all trees will be removed. Each plot extends for 7.6 m (25 ft) parallel to the channel azimuth and extends out 15.24 m (50 ft) in a perpendicular direction on each side of the stream, corresponding to the width of the buffer, for an total area of 232 m^2 (2500 ft^2). At each sampling event, all standing trees ≥10 cm (4 in) diameter breast height (DBH) will be counted, and the condition (live/dead), species, and DBH will be recorded.

Canopy class will be recorded for live trees; decay class and mortality agent will be recorded for dead trees. All counted trees will be marked with paint or tree crayon to aid in identifying them in subsequent surveys. The riparian surveys will be conducted once prior to harvest and in each post harvest year. In the post-harvest surveys trees that have died since the previous survey will be identified. Data will be collected on trees that have fallen since the last sampling event, including species, diameter, distance-from-stream, fall direction, and recruitment class. Evidence of sediment delivery from root-pits will be noted. In addition, the diameter, length, and recruitment class of large wood (≥10 cm diameter and ≥1 m in length) recruited to the stream will be recorded.

Channel Segment Data

Channel step frequency and sediment wedge volume. In each selected segment, channel steps ≥ 20 cm will be tallied and the dominant and subdominant step-forming materials will be documented for each step. Length, width, and depth of the sediment wedge will be measured and used to calculate the volume of sediment deposited behind each step.

Large woody debris. Each piece of large woody debris (≥10 cm diameter and ≥1 m in length) that intrudes into the plane of the bankfull channel (instream and suspended) will be tallied following a modified Timber-Fish-Wildlife (TFW) protocol (Schuett-Hames et al., 1999). Each piece will be identified to species, if possible, and the level of decay (decay class). For each piece, the length and midpoint diameter of the portion within the bankfull channel will be recorded. The distance from the stream to the root wad will be measured and channel functions associated with each piece (pool formation, step formation, sediment retention) will be noted.

Stream Network Surveys

Wetted channel length. During the summer low-flow period, July-August, the entire length of channel network will be surveyed to determine the length of the channel with surface flow. The length and average width of each stream adjacent wetland in contact with the bankfull channel will be recorded.

Streambank and landslide erosion. A survey of the entire network will be conducted annually to identify sources of sediment delivery to the channel, including: bank erosion, surface erosion, landslides, and soil disturbance from uprooted trees. The length, width, and depth will be measured and the volume calculated based upon the feature's approximate shape. The location (reach) of each erosion feature and its probable cause will also be noted.

Large woody debris recruitment. Each year post-harvest the diameter of the midpoint of the portion of the tree over the channel, length, distance from channel to center of the root pit, and species will be recorded for all riparian trees recruited to the channel since harvest. This will include all large woody debris recruited to the stream or suspended over the bankfull width.

Road Surface Erosion

The network of roads in each basin will be surveyed once before and once after harvest to run the Washington Road Sediment Model (Dube et al., 2004), which will be used to estimate the volume of sediment from road surface erosion delivered to the stream network. Information on road usage intensity will be obtained from the landowner.

Suspended Sediment and Nutrient Export

Suspended sediment export will be estimated at two basins within each lithology at a sampling station located near the Type N/F junction.

Continuous stream flow. A 12 to 24 inch (depending upon basin area and estimated average annual precipitation) Montana flume will be installed near the Type N/F junction with a pressure transducer to measure stage height. Flow will be calculated from stage height using the appropriate equation for the flume.

Suspended Sediment and nutrient loads. Turbidity Threshold Sampling (Lewis, 1996; Lewis and Eads, 2008) will be implemented using a Forest Technology Systems DTS-12 turbidity sensor, recording at 10-minute intervals, located as near the Type F/N junction as practicable in the four basins selected for export estimates. An ISCO Model 3712C automatic pump sampler, activated at a specific turbidity threshold values on both the rising and falling limbs of the turbidigraph, will collect discrete samples during high turbidity events. These samples will be analyzed for suspended sediment concentration (SSC) that will be used to develop a regression model to estimate SSC from the continuous turbidity record. The product of the estimated SSC and the associated flow, estimated from stage height at the flume, will be summed to calculate daily and monthly suspended sediment loads. Loads may also be evaluated over other time intervals to describe suspended sediment transport seasonally or during specific events.

Nutrient samples will be collected up to eight times per year during routine sampling events. High-flow events will be sampled using the pump sampler described above. Pump sample bottles will be acid washed and prepped with sample preservative. Bottles will be retrieved immediately after a storm event and submitted to the lab for analysis the next day. Bottles not collected within the required holding times will not be submitted for analysis.

Macroinvertebrate

Macroinvertebrate samples will be collected from six riffles near the N/F junction using a Surber sampler with 500-micrometer net. Coarse substrate in the enclosed area will be removed and scrubbed to dislodge clinging invertebrates into the collection net. After scrubbing, all remaining substrate in the enclosed area will be agitated to a depth of 15 cm. The six samples will be composited for analysis. The macroinvertebrate field samples are preserved in 85% ethanol. Samples will be collected spring, summer, and fall in each of the two pre-harvest and each of the two post-harvest years.

Samples will be sub-sampled using a 500-organism count. Macroinvertebrates are removed from a minimum of two randomly chosen squares in a sub-sampling grid containing 30 squares. The dimension of each square is 6 cm x 6 cm and the tray has an overall dimension of 30 cm x 36 cm. The sample material from a field container is spread evenly on the base of the grid tray. All organisms are removed from randomly chosen squares until a minimum of 500 macro-invertebrates are picked and the process is continued to include all remaining organisms in the selected squares. Larger macroinvertebrates are removed from the sample square prior to use of a dissecting scope. Invertebrates will be identified to lowest practical taxonomic level and grouped by functional guild.

Quality Control Procedures

Field

All water temperature data loggers will be checked for accuracy prior to use in the field by comparing them with NIST thermometers across a range of temperatures from near zero to 20°C. Those that are not within the manufacturers' specifications for accuracy will be replaced. Turbidity sensors will be returned to the manufacturer for calibration each year. Pressure transducers will be checked against staff gage measurements on each site visit. Corrections for instrument drift will be made if the offset measurement (transducer stage height minus flume stage gage height) changes by more than 0.5 centimeter between sampling events.

Field crews will undergo a sampling methods review each year under the supervision of the Principal Investigator or the Field Lead. The stream monuments will ensure that samples are collected at the proper locations within the stream. Datasheets will be checked for accuracy and completeness before leaving the study basin and the field lead will keep a record of all sampling activities in the study basins.

Data calculations will be reviewed by a Principal Investigator. All analyses will be done by or under the guidance of one of the Principal Investigators.

Laboratory

Nutrient and SSC samples will be analyzed at Manchester Environmental Laboratory. The standard quality control protocols, outlined in the Manchester Laboratory *Lab Users Manual* (2008), and the chosen analytical methods will be used for this work (Table 9).

Five percent of the macroinvertebrate samples will be reanalyzed each year following identification. Errors in identification should be less than five percent of the total macroinvertebrate taxa in the sample (Plotnikoff and Wiseman, 2001).

Table 9. Water chemistry, holding times, and reporting limits are listed below.

Parameter	Container	Preservation	Holding time	Reporting limit
Nitrate-nitrite	125 mL clear wide-mouth polyethylene, pre-acidified with H2SO4	H2SO4 to pH<2; cool to <4°C	28 days	0.01 mg/L
Ammonia	125 mL clear wide-mouth polyethylene, pre-acidified with H2SO4	H2SO4 to pH<2; cool to <4°C	28 days	0.01 mg/L
Total persulfate nitrogen	125 mL clear wide-mouth polyethylene, pre-acidified with H2SO4	H2SO4 to pH<2; cool to <4°C	28 days	0.025 mg/L
Total phosphorus	60 mL clear narrow-mouth polyethylene, pre-acidified with HCl	1:1 HCl to pH<2; cool to <4°C	28 days	0.001-0,005 mg/L
Soluble reactive phosphorus	125 mL amber wide-mouth polyethylene; 0.45 um pore size filters	Filter in field; cool to <4°C	48 hours	0.003 mg/L
Suspended sediment concentration	1000 mL clear wide-mouth polyethylene	Cool to <4°C	7 days	1 mg/L

GIS Data

All GIS data will meet the Washington State Geographic Information Council Geospatial Data Guidelines or FGDC Content Standards for Digital Geospatial Metadata and National Map Accuracy Standards (Table 10). The Washington State Department of Ecology (Ecology) uses the following data storage and import standards.

Table 10. GIS data standards used in the study.

Horizontal Datum	NAD 83 HARN*
Vertical Datum	NAVD-88**
Projection System	Lambert Conic Conformal
Coordinate System	Washington State Plane Coordinates
Coordinate Zone	South (or zone-appropriate if not statewide)
Coordinate Units	U.S. Survey Feet
Accuracy Standard	+/-40 feet or better
Vector Import Format	ArcExport E00 file, Shapefile, File Geodatabase, Personal Geodatabase
Raster Import Format	TIFF, BIL/BIP, RLC,GRID, ERDAS
Metadata	Federal Geographic Data Committee (FGDC), Metadata Content Standards*

* More information is available on the Washington Geographic Information Council (WAGIC) website at http://wagic.wa.gov/Techstds2/standards_index.htm.

** North American Vertical Datum 1988 (NAVD88) as defined by the National Geodetic Survey (NGS) is the official civilian datum for surveying and mapping in the United States. The Washington State Department of Ecology (Ecology) is adopting NAVD88 as the agency standard vertical datum. All elevation data created by or submitted to Ecology should be collected in or converted to NAVD88. The collection method used to determine elevation should be specified. Elevations may be recorded in either feet or meters as long as the unit of measure is explicitly stated in the metadata.

The GIS data was developed and maintained by state and federal agencies (Table 11) and comply with the Washington State Geographic Information Council Geospatial Data Guidelines or FGDC Content Standards for Digital Geospatial Metadata and National Map Accuracy Standards (Geospatial data and map: http://nationalmap.gov/gio/standards/). The accuracy of this information is the responsibility of the agencies and organizations that disseminate the data.

Table 11. The GIS data in this project are listed.

All have metadata that meets the Washington State Geographic Information Council Geospatial Data Guidelines or FGDC Content Standards for Digital Geospatial Metadata.

Data	Source/ custodian	Scale/ resolution
Washington State Watercourse Hydrography	DNR	1:24k
Washington State Geology	DNR	1:100k
Digital Elevation Model 10 m	UW/USGS	24k
Public Land Survey Township, Range, section	DNR	1:24k

DNR: Washington State Department of Natural Resources
UW: University of Washington
USGS: U.S. Geological Survey

Data Management Procedures

The data collected can be put into three distinct categories with respect to data management (Table 12):

- Data collected automatically, at pre-determined intervals by in-situ recording devices.
- Measurements taken in the field and recorded directly into notebooks, then transferred to digital databases.
- Samples collected in the field, then processed in a lab to produce the values that are then transferred to a digital database.

Table 12. Data management procedures for in-situ data collection, field measurements, and lab measurements.

	In-situ data collection	Field measurements	Lab measurements
Examples of type of data collected	Water and air temperature, stage height, turbidity	Channel metrics, riparian stand, densiometer	Water chemistry, canopy photos, macroinvertebrates
Data transfer	Digital storage devices	Waterproof data sheets	Electronic download from laboratory, direct entry into database
Databases used	Temperature-Access database; stage height and turbidity-StreamTrac database	Entered into individual tables within an Access database	Water chemistry is stored in StreamTrac database with flow and turbidity

Water and air temperature data will be collected using Tidbit monitors (Onset Computer Co.). Data will be downloaded in the spring and fall to a data shuttle and then transferred to a network server at Ecology. These data will be imported into one of several Access databases, where suspect data will be manually flagged. The most common reasons for suspect data are exposure of water temperature sensors during low flows or following stream channel movement.

Stage height and turbidity data will be downloaded directly to a laptop computer in the field. The data are uploaded to StreamTrac with the database housed on a network server at Ecology. Downloads are done six to ten times per year. Data will be screened and individual data points flagged if data quality is suspect, following the recommendations in Lewis and Eads (2008).

Data collected during field surveys, including channel, riparian stand, and densiometer measurements, will be recorded on waterproof notebooks and then entered into a database housed on a network server at Ecology.

Measurement of samples analyzed at Ecology's Manchester Environmental Laboratory will be downloaded directly from the lab, including a summary of quality control results, a case narrative discussing any problems with the analyses, corrective actions taken, changes to the referenced method, and an explanation of data qualifiers. After review, these data will be entered in the appropriate database. Samples analyzed at the Operations Center in Lacey will be recorded in lab notebooks entered into the appropriate database.

All databases are stored on servers and backed up daily. At the end of the project all pertinent data summaries will be entered in Ecology's Environmental Information Management system.

Audits and Reports

Quarterly reports will be produced by the principal investigators and sent to the Washington State Department of Natural Resources to ensure conformance to the Quality Assurance (QA) Project Plan. The reports include: progress made in implementing the QA Project Plan, an assessment of data completeness, and any significant problems with implementation as well as substantial QA issues and corrective actions taken.

Semi-annual progress reports will be made to EPA via the Financial and Ecosystem Accounting Tracking System.

Data Verification and Validation

Data Verification

Data collected via in-situ devices (temperature, turbidity, stage height) will be verified by graphically examining the data record for completeness and signs of a) malfunctioning equipment (obviously erroneous readings or missing values) and b) improper placement (e.g., anomalously high water temperature values or erratic turbidity values during low flows). Using the database programs, the data can be verified on a measurement-by-measurement basis (Table 13).

The data sheets on which field measurements are recorded will be checked against the values entered into the database. Lab measurements will be examined graphically for completeness and for lab-based qualifiers.

All databases will be kept on a secure server at Ecology and will be backed up daily.

Data Validation

We will visually compare the water and air temperature patterns at each site to identify and flag data where the water sensor may have been exposed. As a water temperature sensor is exposed (due to dropping water level), the diel temperature pattern begins to resemble the air temperature pattern. This transition can occur over several days.

We will follow Lewis and Eads' (2008) suggested methodology to identify and flag poor quality turbidity data. Because turbidity and suspended sediment concentration are usually strongly correlated, we will use this relationship to identify suspect suspended sediment values due to improper placement of the pump sampler tubing. This typically occurs when the stream bed aggrades so that the tube is too near the stream bottom or the water level drops so that air is drawn into the sample tube.

All field measurements will be examined graphically and anomalous values will be flagged.

Lab measurements will be examined and data qualifiers noted. Five percent of macroinvertebrate samples will be reanalyzed (counted and identified).

Table 13. Data verification and validation procedures.

	In situ data	Field measurements	Lab measurements
Data type	Water and air temperature, stage height, turbidity.	Channel metrics, riparian stand, densiometer	Water chemistry, canopy photos, macroinvertebrates
Data verification	Graphical examination of data for completeness and range of values. Look for signs of equipment malfunction and improper placement (e.g., exposure of temperature sensor or pressure transducer).	Check of field sheets against database values	Graphically examine for completeness and lab-based qualifiers
Data validation	Comparison of turbidity and suspended sediment concentration values. Comparison of water temperature and air temperature. Flag suspect data. Stage height data will be compared to staff gage measurements to ensure they are accurate and consistent.	Graphical examination for anomalous values	Flag lab measurements outside quality control limits, reanalyze 5% of macroinvertebrate samples

Data Quality Assessment

Data that were flagged as poor quality in the data validation process will not be used in any analysis.

Data completeness will be assessed as follows:

Water temperature. The water temperature analysis requires:

- A pre-harvest data record at the reference and treatment sites spread relatively uniformly across the range of recorded water temperatures. Gaps in the data record, e.g., relatively few data at the upper or lower range of the data, will affect the pre-harvest regression relationship and could produce spurious results, if used as the basis for post-harvest effects.
- A nearly complete data record for the July-August period in each post-harvest year because this is the period when high water temperature is likely to occur.

The data will be considered adequate for a given location if these conditions are met.

Stream flow, turbidity, nutrients. The analysis of downstream exports requires sufficient data to build regression models to predict suspended sediment and nutrient loads on a daily basis. The data will be adequate if loads can be calculated on a daily basis for 90% of the storm events over the course of the study.

Macroinvertebrates. A comparison of the reanalyzed samples will be used to evaluate the quality of the macroinvertebrate counts and identification. A coefficient of variation between the repeated analyses of total number of organisms and EPT index of less than 50% will be considered adequate.

Field and laboratory data will be adequate if 90% complete.

References

Alila, Y., Kura, K., P., Schnorbus, M., and Hudson, R., 2009. Forests and floods: A new paradigm sheds light on age-old controversies. Water Resour. Res. 45(8): W08416.

Bricker, S., Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks, and J. Woerner, 2007. Effects of nutrient enrichment in the nation's estuaries: a decade of change. National Centers for Coastal Ocean Science, Silver Spring MD.

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

Brown, G.W. and Krygier, J.T., 1970. Effects of Clear-Cutting on Stream Temperature. Water Resour. Res. 6(4): 1133-1139.

Caissie, D., 2006. The thermal regime of rivers: a review. Freshwater Biology 51(8): 1389-1406.

Caissie, D., Satish, M.G., and El-Jabi, N., 2007. Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada). Journal of Hydrology 336(3-4): 303-315.

CMER, 2010. Fiscal Year 2011 CMER Work Plan. The Cooperative, Monitoring, Evaluation, and Research Committee. Washington State Department of Natural Resources, Olympia, WA.

Crawley, M.J., 2007. The R book. Wiley, Hoboken N.J.

DeLuca, T.H., Zouhar, K.L., 2000. Effects of selection harvest and prescribed fire on the soil nitrogen status of ponderosa pine forests. For. Ecol. Manage. 138, 263–271.

Dent, L., Vick, D., Abraham, K., Schoenholtz, S., and Johnson, S., 2008. Summer Temperature Patterns in Headwater Streams of the Oregon Coast Range1. Journal of the American Water Resources Association 44(4): 803-813.

DeWalle, D.R., 2010. Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width. Journal of the American Water Resources Association 46(2): 323-333.

Downes, B.J., L.A. Barmuta, P.G. Fairweather, D.P.Faith, M.J. Keough, P.S. Lake, B.D.Mapstone, G.P Quinn, 2002. Assessing ecological impacts: application to flowing waters. Cambridge University Press.

Dube, K., W. Megahan and M. McCalmon, 2004. Washington Road Surface Erosion Model (WARSEM) Model. Forest Practices Division. Washington State Department of Natural Resources. Olympia, WA.

Dunne, T., Agee, J.K., Beissinger, S., Dietrich, W.E., Gray, D., Power, M., Resh, V., and Rodrigues, K., 2001. A scientific basis for the prediction of cumulative watershed effects. University of California Wildland Resource Center Report No. 46. University of California Wildland Resource Center, Berkeley, CA.

Ehinger, W. and S. Estrella, 2007. Quality Assurance Project Plan: Type N Experimental Buffer Treatment Study: Addressing Buffer Effectiveness on Riparian Inputs, Water Quality, and Exports to Fish-Bearing Waters in Basaltic Lithologies. Washington State Department of Ecology, Olympia, WA. 28 pp. + appendices. Publication No. 07-03-103. www.ecy.wa.gov/biblio/0703103.html

Gomi, T., Moore, R.D., and Dhakal, A.S., 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia, Canada. Water Resour. Res. 42(8): W08437.

Gooseff, M.N., Wondzell, S.M., Haggerty, R., and Anderson, J., 2003. Comparing transient storage modeling and residence time distribution (RTD) analysis in geomorphically varied reaches in the Lookout Creek basin, Oregon, USA. Advances in Water Resources 26(9): 925-937.

Grant, G.E. and Wolff, A.L., 1991. Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA. *In* Sediment and Stream Water Quality in a Changing Environment. *Edited by* N.E. Peters and D.E. Walling. International Association of Hydrological Sciences. pp. 31-40.

Haggerty, S.M., D. P. Balzer, and C.R. Jackson, 2009. Macroinvertebrate response to logging in coastal headwater stream of Washington, USA. Canadian Journal of Fisheries and Aquatic Sciences. 61: 529-537.

Hannah, D.M., Malcolm, I.A., Soulsby, C., and Youngson, A.F., 2004. Heat exchanges and temperatures within a salmon spawning stream in the cairngorms, Scotland: Seasonal and sub-seasonal dynamics. River Research and Applications 20(6): 635-652.

Hassan, M.A., Church, M., Lisle, T.E., Brardinoni, F., Benda, L., and Grant, G.E., 2005a. Sediment transport and channel morphology of small, forested streams. Journal of the American Water Resources Association 41(4): 853-876.

Hassan, M.A., Hogan, D.L., Bird, S.A., May, K.L., Gomi, T., and Campbell, D., 2005b. Spatial and temporal dynamics of wood in headwater streams of the Pacific Northwest. Journal of the American Water Resources Association 41(4): 899-919.

Hawkins, C.P., M.L. Murphy, and N.H. Anderson, 1992. Effects of canopy, substrate composition, and gradient on the structure of macroinvertebrate communities in Cascade Range streams of Oregon. Ecology 63(6):1840 –1856.

Hayes, M.P., W.J. Ehinger, R.E. Bilby, J.G. MacCracken, R. Palmquist, T. Quinn, D. Schuett-Hames, and A. Storfer, 2006. Study Plan for the Type N Experimental Buffer Treatment Study: Addressing Buffer Effectiveness on Stream-Associated Amphibians, Riparian Inputs and Water Quality, and Exports to and Fish in Downstream (Type F) Waters in Basaltic Lithologies of the Coastal Areas and the South Cascades of Washington State. Report submitted for the State of Washington Forest Practices Board Adaptive Management Program. 68 pp. [15 July].

Hunter, M.A. and Quinn, T., 2009. Summer Water Temperatures in Alluvial and Bedrock Channels of the Olympic Peninsula. Western Journal of Applied Forestry 24: 103-108.

Jackson, C.R., Sturm, C.A., and Ward, J.M., 2001. Timber harvest impacts on small headwater stream channels in the coast ranges of Washington. Journal of the American Water Resources Association 37(6): 1533-1549.

Johnson, A.C., Edwards, R.T., and Erhardt, R., 2007. Ground-water response to forest harvest: Implications for hillslope stability. Journal of the American Water Resources Association 43(1): 134-147.

Johnson, S.L., 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries & Aquatic Sciences 61(6): 913-923.

Johnson, S.L. and Jones, J.A., 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Science 57(Suppl. 2) (30-39).

Jones, J.A. and Post, D.A., 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. Water Resources Research 40(5).

Kaufmann, P.R. and Hughes, R.M., 2006. Geomorphic and Anthropogenic Influences on Fish and Amphibians in Pacific Northwest Coastal Streams. *In* Landscape Influences on Stream Habitats and Biological Assemblages. American Fisheries Society Symposium 48:429-455. *Edited by* L.W.a.P.W.S. R.M. Hughes, Bethesda, MD.

Kaufmann, P.R., Larsen, D.P., and Faustini, J.M., 2009. Bed Stability and Sedimentation Associated With Human Disturbances in Pacific Northwest Streams. JAWRA Journal of the American Water Resources Association 45(2): 434-459.

Kedzierski, W.M. and L.A. Smock, 2001. Effects of logging on macroinvertebrate production in a sand-bottomed, low gradient stream. Fresh. Biol. 46:821– 833.

Keim, R.F. and Skaugset, A.E., 2003. Modelling effects of forest canopies on slope stability. Hydrological Processes 17(7): 1457-1467.

Kobayashi, S., Gomi, T., Sidle, R.C., and Takemon, Y., 2010. Canadian Journal of Fisheries and Aquatic Sciences, 67:427-444.

Kreutzweiser, D.P., S.S. Capell, and K.P. Good, 2005. Effect of fine sediment inputs from a logging road on stream insect communities: A large-scale experimental approach in a Canadian headwater stream. Aquatic Ecology 39:55-66.

Lewis, J., 1996. Turbidity-Controlled Suspended Sediment Sampling for Runoff-Event Load Estimation. Water Resources Research 32: 2299-2310.

Lewis, J., Mori, S.R., Keppeler, E.T., and Ziemer, R.R., 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. *In* Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas. *Edited by* M.S. Wigmosta and S.J. Burges. American Geophysical Union, Washington, D.C. pp. 85-125.

Lewis, J. and R. Eads, 2008. Implementation guide for turbidity threshold sampling principles, procedures, and analysis. Gen. Tech. Rep. PSW-GTR-212. Arcata, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station.

Manchester Environmental Laboratory. 2008. Lab Users Manual, Ninth Ed. Washington Dept of Ecology. Sept 2008. http://aww.ecology/programs/eap/forms/Lab%20Manual%20update%207-21-11.pdf

Mohamedali, T., M. Roberts, B. Sackmann, A. Whiley, and A. Kolosseus, 2011. South Puget Sound Dissolved Oxygen Study: Interim Nutrient Load Summary. Washington State Department of Ecology, Olympia, WA. Publication No. 11-03-001. www.ecy.wa.gov/biblio/1103001.html

Moore, R.D., Spittlehouse, D.L., and Story, A., 2005a. Riparian microclimate and stream temperature response to forest harvesting: a review. Journal of the American Water Resources Association 41(4): 813-834.

Moore, R.D., Sutherland, P., Gomi, T., and Dhakal, A., 2005b. Thermal regime of a headwater stream within a clear-cut, coastal British Columbia, Canada. Hydrological Processes 19(13): 2591-2608.

Moore, R.D. and Wondzell, S.M., 2005. Physical hydrology and the effects of forest harvesting in the Pacific Northwest: a review. J. Am. Water Res. Assoc. 41, 763–784.

Newton, J. and K. Van Voorhis, 2002. Seasonal patterns and controlling factors of primary production in Puget Sound's central basin and Possession Sound. Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-059. www.ecy.wa.gov/biblio/0203059.html

Platts, W.S., Megahan, W.F., and Minshall, G.W., 1983. Methods for evaluating stream, riparian, and biotic conditions. Edited by I.E. Station. United States Forest Service, Ogden, Utah. p. 70.

Poole, G.C. and Berman, C.H., 2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27(6): 787-802.

Roberts, R.G. and Church, M., 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Canadian Journal of Forest Research 16: 1092-1106.

Schuett-Hames, D.E., A.P. Pleus, J.Ward, M.Fox, and J. Light, 1999. TFW Monitoring Program: method manual for the large woody debris survey. TFW-AM9-99-004. Forest Practices Division. Washington State Department of Natural Resources, Olympia, WA.

Schumm, S.A., 1971. Fluvial geomorphology: Channel adjustment and river metamorphosis. *In* River Mechanics. Edited by H.W. Shen. Water Resources Publications, Fort Collins, CO.

Stockner J.G. and Shortreed K.S., 1976. Autotrophic production in Carnation Creek, a coastal rainforest stream on Vancouver Island, British Columbia. Journal of the Fish Resources Board of Canada, 33, 1553–1563.

Triska, F.J., V.C. Kennedy, R.J. Avanizino, and K.C. Stanley, 1995. Inorganic nitrogen uptake and regeneration in a small stream at summer low flow: Long-term clear cutting and short-term storm related impacts. Pgs. V1-V13 in K.M. Nolan, H.M. Kelsey, and D.C Marron, eds. Geomorphic processes and aquatic habitat in the Redwood Creek Basin, northwestern California. USGS Professional Paper 1454. Denver, CO.

Underwood, A.J., 1994a. On beyond BACI: sampling designs that might reliably detect environmental differences. Ecological Applications 4: 3-15.

Underwood, A.J., 1994b. Spatial and temporal problems with monitoring. In The Rivers Handbook: Hydrological and Ecological Principles. Vol. 2. Eds. P. Calow and G.E. Petts. p. 1010-123. Oxford, UK: Blackwell Scientific Publications.

Wallace, J.B., Webster, J.R., Eggert, S.L., and Meyer, J.L., 2000. Small wood dynamics in a headwater stream. Verh. Internat. Verin. Limnol. 27: 1361-1365.

Watson, F., Vertessy, R., McMahon, T., Rhodes, B., and Watson, I., 2001. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. Forest Ecology and Management 143(1-3): 189-204.

WDNR, 1999. Forests & Fish Report. Washington State Department of Natural Resources, Olympia, WA. 179 p. Available online at: www.dnr.wa.gov/forestpractices/rules/forestsandfish.pdf

WDNR, 2001. Washington Forest Practices Rules: WAC 222-30-021. Washington State Department of Natural Resources, Olympia, WA.

Wemple, B.C. and Jones, J.A., 2003. Runoff production on forest roads in a steep, mountain catchment. Water Resources Research 39(8): 1220-1237.

Wemple, B.C., Jones, J.A., and Grant, G.E., 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Journal of the American Water Resources Association 32(6): 1195-1207.

Wilkerson, E., Hagan, J.M., Siegel, D., and Whitman, A.A., 2006. The Effectiveness of Different Buffer Widths for Protecting Headwater Stream Temperature in Maine. Forest Science 52: 221-231.

Wilkerson, E., Hagan, J.M., Siegel, D., and Whitman, A.A., 2010. The effectiveness of different buffer widths for protecting water quality and macroinvertebrate and periphyton assemblages of headwater streams in Maine, USA. Canadian Journal of Fisheries and Aquatic Sciences 67: 177-190.

Winer, B.J., 1971. Statistical principles in experimental design, 2nd edition. McGraw-Hill, New York, New York, USA.

Wondzell, S.M., 2006. Effect of morphology and discharge on hyporheic exchange flows in two small streams in the Cascade Mountains of Oregon, USA. Hydrological Processes 20(2): 267-287.

Appendix. Glossary, Acronyms, and Abbreviations

Glossary

Allochthonous: Materials (e.g. organic matter and sediment) which originates from outside the stream.

Autochthonous: Materials (e.g. organic matter and sediment) which originates from within the stream.

Bedforms: Physical characteristics of the stream bed.

Hyporheic zone: The area beneath and adjacent to a stream where surface water and groundwater intermix.

Lithology: Used here to categorize geological units based on their origin (e.g., glacial till, marine sedimentary).

Monuments: Fixed position along the stream that will be monitored over time.

Riparian: Relating to the banks along a natural course of water.

Type N stream: Non fish-bearing stream.

Acronyms and Abbreviations

ANOVA	Analysis of variance
BACI	Before-After/Control-Impact
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
EPT	Ephemeroptera, Plecoptera, and Trichoptera
FGDC	Federal Geographic Data Committee
GIS	Geographic Information Systems
MBACI	Multiple Before-After/Control-Impact
Nitrate-N	Nitrate-nitrogen
QA	Quality assurance
WAC	Washington Administrative Code
WDNR	Washington State Department of Natural Resources

Units of measurement

ac	acre
cm	centimeter
ha	hectare
L	liter
m	meter
mg	milligram
ml	milliliter
NTU	nephelometric turbidity units