Empirical and Modeled Evaluation of Forest Road BMP Effectiveness in Western Washington

Executive Summary

Roads play an important role in our society, providing efficient links for transportation of people and materials. Forest roads provide many functions such as allowing timber products to be transported to mills, providing emergency access, and providing access for recreationists, hunters, and fishermen. However, road erosion can be a large source of anthropogenic sediment in watersheds managed for timber production. Fine-grained sediment has the potential to adversely affect water quality and aquatic resources at the site, the channel reach, and the watershed scales.

Increased inorganic sediment loads, beyond quantities or frequencies that occur naturally, can influence the stream biota in a number of ways. Turbidity can reduce stream primary production by reducing photosynthesis, which affects other organisms in the food web. In addition, turbidity impacts gill function and respiration, and limits feeding success of fish. Deposited sediments may affect fish or amphibians directly by smothering eggs in redd or oviposition sites, altering spawning or early rearing habitat, and reducing overwintering habitat for fry. Fish or amphibians may also be affected indirectly by deposited sediments limiting invertebrate species composition, thereby decreasing abundance of preferred prey.

Recognizing that roads are persistent sources of fine sediment to forest streams, forest managers have made substantial improvements in water quality in recent decades through their diligent application of best management practices (BMP). Based on a first-time sampling of road BMP, initial monitoring results in western Washington indicate that 10-11% of the total forested road length directly delivers sediment to the channel network. Cross-drain culverts to relieve ditch water before it reaches a stream crossing have become a common practice. The remaining 10-11% of the total forest road length that continues to deliver to streams is stream-adjacent, cannot be successfully drained onto a hillslope, and, where this situation coincides with heavy traffic, leads to increased delivery of sediment to streams.

A focal question in this project is: *What combinations of surfacing, ditch line management, traffic control, and drainage management will most efficiently and effectively mitigate sediment* *yields from high-traffic, near-stream (HTNS) roads*? Many previous studies have tested individual BMP, but landowners are more likely to implement multiple BMP simultaneously (e.g., it is common to reconstruct an old road by adding better quality rock, increasing the number of cross-drain culverts, putting the tread into a crowned configuration, and grassing the ditch line). Thus, studying multiple BMP as a set is a logical approach. In fact, one BMP may even reduce the effectiveness of another one. For example, paving a road reduces sediment delivered from the surface but contributes more water to the ditch line and, if the ditch is bare soil, erosion can increase relative to that expected from a ditch adjacent to a gravel road.

Not only are HTNS roads more likely to deliver sediment to streams, they are typically critical to the transportation network as key mainline roads. Therefore, HTNS roads may warrant additional investment by landowners to increase BMP beyond those in common use, not simply to meet stewardship goals but also to effectively address operational needs. However, road upgrades and enhanced BMP incur a significant cost. Therefore, improved knowledge of both the effectiveness of individual and integrated combinations of BMP is crucial for understanding the return on BMP investments.

Currently, one of the most significant challenges for evaluating BMP effectiveness experimentally is a lack of theoretical and modeling basis with which to: a) analyze and interpret data, b) generate hypotheses for new locations, and c) explore what-if scenarios for comparison of BMP alternatives on water and sediment budgets. This limitation results in strained applicability to locations other than where BMP effectiveness was empirically tested. Therefore, to advance our understanding and predictive capability, a critical need exists for joint development of extensive field studies and complementary process-based numerical modeling approaches to investigate the effects of single and multiple BMP on runoff and sediment production and transport from roads. To fulfill this need, we propose to investigate sediment production and delivery by conducting extensive empirical field research of BMP impacts on road erosion, complemented by a process-based geomorphic modeling framework developed using a Python-based Earth Surface modeling toolkit called Landlab (http://landlab.github.io/#/). Replicated individual and combinations of BMP treatments will inform model refinement, allowing iterative improvements to predictive capability.

Two related sets of field experiments—the Major Experiment and the Parameterization Experiments—will be conducted. In the Major Experiment, we will observe and measure rainfall, runoff, and sediment production from the road surface and ditch line over several years for a large sample of individual road segments using sediment tubs, tipping buckets, and turbidity tanks. These road segments will be selected so as to avoid stream crossings, and they will require a cross-drain culvert that allows water to flow onto the platform holding the sediment tubs, tipping buckets, and turbidity tanks. Measurements will be repeated over the course of multiple years as different BMP and their combinations are applied to the established research sites. Our field study effort will require 40 road segments in each of two distinct lithologies—one that has a high proportion of fine particles and low permeability, such as siltstone or glacial till, and one that has a lower proportion of fines and is more permeable, such as volcanic bedrock and deposits. Across each set of 40 sites, similar ranges in rainfall that are generally typical of forested Western Washington will be sampled. Six years of data will be collected for each lithology: three to understand relationships between rainfall, traffic, surfacing, and grading, in the context of the distinct lithologic attributes and all with no ditch line BMP present except grass seeding, and three more years with tread and ditch line BMP of interest installed at some of the sites to quantify their benefits, congruent to the aforementioned treatments.

However, not all the sediment production-related critical questions are answerable without additional effort. Existing theory and process-based formulations of runoff hydraulics and sediment detachment and transport mechanics will guide the development of additional Parameterization experiments. Six integral Parameterization Experiments are proposed that will support and augment the basic field results, refine their process-based interpretation, and enhance project modeling by adding indispensable and relevant knowledge. They include: Cost Versus Maintenance Survey, Sediment Trap Efficiency, Ditch Line Hydraulics, Road Micro-Topography Evolution, Short-Time-Scale Interactions, and GRAIP/WARSEM Delivery Analysis and Survey. The Parameterization Experiments will be used to estimate the physical effects of each BMP (e.g., distill each BMP into what it does to the two physical variables of sediment transport: critical shear stress and the grain shear stress). In the context of these smaller experiments, the Major Experiment will examine how those physical effect descriptors (e.g., critical shear stress and shear stress partitioning), in combination with rainfall amounts, affect sediment yield. Collectively, these data sets will facilitate the development of the physical framework for modeling how different BMP influence water and sediment flows on the road surface and ditch line.

Existing physically-based models for road erosion do not represent the interactions of flows between planar and concentrated flow conditions, shear stress partitioning on road surface sediments and obstructions (e.g., vegetation) , or feedback mechanisms between flow, substrate size, and channelization processes. These factors, along with the existing knowledge that all road erosion models require calibration for accurate predictions (Dubé et al., 2011; Black and Luce, 2014), lead to the current paradigm that every BMP effectiveness evaluation needs to be done empirically for every new context. The scope of an experimental study considering the various potential contexts and interaction effects would be overwhelming and prohibitively expensive. Each new BMP proposed would need to be tested in a range of different settings and in combination with a range of other BMP.

The premise of our study is that we can reduce the dimensionality of this problem by collapsing the BMP impacts on sediment generation and transport to a few physical variables, such as shear stress partitioning and critical shear stress, and quantifying these in the field experiments and numerical modeling. The Landlab modeling approach we propose will represent the interactions among hydrologic factors and BMP. This approach will identify the effects of each BMP in terms of what it does to the supply sediment size distribution and what it does to impede flow, erosion, and transport. If successful, this effort would make empirical testing of BMP much more tractable and efficient. Conceptually, a simple level of BMP testing could be reduced to the amount of work shown in the Parameterization Experiments, subject to occasional validation in terms of actual sediment yield results. In reality, certain aspects of the Landlab-based model will likely require calibration at some basic level in different settings across the state. Therefore, we cannot say that the Landlab-based model can be used to make predictions without further experimentation. If, however, we can determine that the simplified descriptions of BMP effects on sediment supply and hydraulics can be independently measured, we can also apply the Landlab-based model to generate estimates of the effects of new treatments.

In our proposed approach, field research design and modeling will be executed synergistically as one will inform the other. Based on the existing understanding of erosion physics, the initial version of "Landlab Roads" will form our null hypothesis for a mechanistic road erosion model. Landlab will first be run on road segments representative of the environmental and topological conditions of HTNS roads in western Washington State. As experimental data become available from field sites, we will calibrate, validate, and refine Landlab theory and assumptions. Results from Years 1-3 of the Major Experiment (for each lithology) and from the Parameterization Experiments will be used to prioritize the types of BMP and their combinations to evaluate during Years 4-6 (for each lithology). Following the development of large datasets comprised of both modeled and observational field data, we will use statistical methods and search for empirical relationships between sediment yield, rainfall, road BMP, road segment characteristics (e.g., slope, length), and lithology. The empirical analysis of the Major Experiment will use the independent variables we develop—the critical shear stress (e.g., fine sediment availability), the grain shear stress, and the flow rate—regressed against observed sediment yields. In the final two years of this project, the improved versions of the model will be used to create detailed simulated datasets using a supercomputer for a range of locations, conditions, and BMP combinations across the HTNS forest roads within Washington State.

These relationships will generate useful qualitative and quantitative information for practitioners. By the end of this project, we expect to provide a number of deliverables. Statistical analyses of empirical and modeled formulations will provide improved parameters that can be used in existing empirically-based tools such as WARSEM and GRAIP. Reports and fact sheets that summarize findings qualitatively and emphasize recommendations and management options will be created with forest policy-makers and forest engineers in mind. Reports that present descriptions of the field experiments, empirical outcomes, statistical analyses, and Landlab model results will be provided to CMER. Finally, peer-reviewed journal publications will be produced. All models will be delivered with tutorials on a website (e.g., http://landlab.github.io/#/). Landlab workshops will be arranged with interested groups to present hands-on examples of the use of the model. However, these new models will not be designed for direct operational use, such as by a forest engineer estimating sediment production, but rather by future researchers who may use the Landlab products to simplify both the field work needed to calibrate road erosion in other locations and the efforts needed to test additional BMP.

In summary, this project is designed to improve our understanding and, ultimately, our capacity to efficiently handle sediment from high-traffic, near-stream (HTNS) road segments. The approach will collect extensive focused field data while simultaneously developing a process-based model, which will later be refined based on the empirical data. This experimental design will determine how individual and combinations of BMP affect sediment supply, sediment transport, and road runoff across a range of environmental conditions. The statistical analysis of the modeled and experimental data will produce empirical formulations that can be implemented in existing road erosion tools used for decision making under a range of environmental and BMP combinations. This project will provide landowners, managers, and regulatory agencies with better information to more cost effectively address delivering road segments.

Context

Washington State Forest Practices are regulated by the Forest Practices Act (Title 222 WAC) and Forest Practices Rules adopted by the Washington Forest Practices Board (WFPB 1995). The WFPB is charged with developing, maintaining, and improving rules that protect the state's public resources. The Washington Forest Practices Regulatory Program is included under the Incidental Take Permit (ITP) issued by the Federal Services (NMFS and USFWS) as part of the Forest Practices Habitat Conservation Plan (FPHCP 2005). The ITP is expected to provide long-term regulatory stability for forest management activities, and allow for the protection of covered species (FPHCP 2005). Much of the land regulated under the FPHCP contains habitat for aquatic and several stream associated and riparian-dependent amphibian species that are "listed" under the Federal Endangered Species Act (ESA). The Washington Department of Natural Resources (WADNR) developed the FPHCP to provide Federal Assurances that the rules will meet the requirements of the ESA.

The WFPB and state legislature set up a formal science-based Adaptive Management Program (AMP) to provide technical information and science-based recommendations that will assist the WFPB in determining when it is necessary or advisable to adjust rules and guidance to achieve the FPHCP resource objectives and performance targets. The resource objectives are to ensure that forest practices will not significantly impair the capacity of aquatic habitat to: a) support harvestable levels of salmonids; b) support the long-term viability of other covered species; or c) meet or exceed water quality standards, including protection of beneficial uses, narrative and numeric criteria, and anti-degradation (WAC 222-12-045).

The WFPB has empowered the Cooperative Monitoring Evaluation and Research committee (CMER) and the T/F/W Policy Committee (Policy) to participate in the AMP (WAC 222-12-045(2)). In 2012, the WFPB directed CMER to pilot a Lean process for developing first a research alternatives document and then study design for the Road Prescription-Scale Effectiveness Monitoring Project. Per the new 'pilot' process, a Technical Writing and Implementation Group (TWIG) was formed to develop options for addressing questions related to the effectiveness of road prescriptions and BMP.

As stated in the 2016 CMER Work Plan, the objectives of monitoring forest roads at the prescription-scale are to:

1) Evaluate the effectiveness of road maintenance categories in meeting road performance targets; and
2) Identify sensitive situations where prescriptions are not effective.

This project will study surface erosion sediment production and delivery reductions from site-specific BMP.

The TWIG submitted the initial scoping of the project to CMER in a draft dated 25 June 2014. The scoping was approved by CMER on 26 August 2014, and was approved by TFW Policy on 2 September 2014 after some editing of the critical questions so that they better matched rule language. The TWIG submitted the 21 July 2015 draft of the Best Available Science and Alternatives document to CMER; extensive comments, particularly related to the lack of actual alternatives, led to major changes. The TWIG submitted the 15 January 2016 draft to CMER, provided a presentation at the 26 January 2016 CMER meeting, and received permission to forward the alternatives to TFW Policy. On 4 February 2016, the TWIG presented the document to TFW Policy, and on 4 March 2016, TFW Policy approved Alternative #4 as supported by the TWIG. This document is the study design for Alternative #4.

The results of this project will inform CMER, TFW Policy and the WFPB about the effectiveness of BMP in common use, including those used for Road Maintenance and Abandonment Plans (RMAP). The identification of effective BMP is critical in achieving the FPHCP goals. Should the common BMP used on forest roads prove ineffective in meeting the FPHCP resource objectives, Policy and the WFPB may have to revisit the rules and the Forest Practices Board Manual to refine the BMP requirements and application.

The Road BMP Effectiveness Project TWIG

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Rule Group:	Roads	
Rule Context:	WAC 222-24 and Forest Practices Board Manual, Section 3	
Research and Monitoring Program:	Road Prescription-Scale Effectiveness Monitoring	

Current CMER Budget

Table 1. Current CMER Budget for Road Prescription-Scale Monitoring Project (after 4/2018 Policy reprioritization)

Year	Total spent so far	FY 2018	FY 2019	FY 2020	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026
Budget	350,239	277,267	538,752	374,500	330,500	403,000	400,500	406,000	291,000	212,000
Total: $3,583,758										

Statement of the Problem

Scientific knowledge of road BMP prescription and implementation effectiveness is insufficient to make the best possible recommendations. This leads to the potential for:

1) Landowners wasting money on ineffective treatments;
2) Rule and BMP implementations being inadequate to achieve functional objectives and performance targets (FPHCP Schedule L-1);
3) Overconfidence about the degree of protection landowners can attain (with implications for road construction and maintenance standards); and
4) Treatments creating additional environmental risks (e.g., landslides and gullies).

General Background

Roads play an important role in our society, providing links for transportation of people and materials quickly and efficiently. Hundreds of thousands of miles of roads exist in Washington State. Many are unpaved forest roads used to access lands managed primarily for timber harvest. Forest roads provide many useful functions such as allowing timber products to be transported efficiently to mills; providing access for recreationists, hunters and fishermen; providing emergency access; and even giving wildlife travel corridors.

However, roads also influence a variety of watershed processes, including sediment production (Megahan and Kidd 1972; Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 1999, 2001a; MacDonald et al. 2001; Sugden and Woods 2007), hydrologic event timing (Wemple et al. 1996; Jones and Grant 1996), and slope stability (Sessions et al. 1987; Montgomery 1994). Of particular concern are road erosion and the locations where sediment from such erosion is delivered to streams and rivers (e.g., Edwards et al. 2016). Road erosion can be a large source of anthropogenic sediment in watersheds managed for forest production (Megahan and Kidd 1972; Swanson and Dyrness 1975; Reid and Dunne 1984; Megahan and Ketcheson 1996). The fine-grained sediment produced by road-surface erosion can adversely affect water quality and aquatic resources at the site scale (e.g., the water quality at a culvert outlet), the reach scale of a channel, and the watershed scale. As noted by Black and Luce (2013): “Forest road runoff and fine sediment delivery are widely acknowledged to have serious impacts on aquatic ecosystems (Cederholm et al. 1981; Platts et al. 1989; Thurow and Burns 1992; Lee et al. 1997; Luce and Wemple 2001,).” With rare exception (e.g., Martin [2009] found individual square miles of forest land with no road delivery), the potential for adverse effects caused by forest roads exists across the roaded, forested landscape. As a consequence, water quality regulations and cumulative effects modeling of forest management have frequently focused on forest roads. Excessive sedimentation is the leading cause of lotic ecosystem degradation in the United States in terms of stream distance impacted (USEPA 2000). Such excessive sedimentation is a concern to environmental managers because increased inorganic sediment loads alter the natural biotic community (algae, macrophytes, invertebrates, amphibians and fishes) in streams (Tebo 1955; Cordone and Kelley 1961; Waters 1995; Wood and Armitage 1997; Welsh and Olivier 1998; Kaller and Hartman 2004; Suttle et al. 2004; Fudge et al. 2008). Increased inorganic sediment loads, beyond quantities or frequencies that occur naturally, can influence the stream biota in several ways. Increased turbidity can reduce stream primary production by reducing photosynthesis, physically abrading algae and other plants, and preventing attachment of autotrophs to substrate surfaces (Van Nieuwenhuyse and LaPerriere 1986; Brookes 1986). Decreasing primary production can affect many other organisms in the stream food web (Izagirre et al. 2009). Sedimentation has been shown to be a major factor in the loss of habitat for freshwater mussels worldwide (Poole and Downing 2004; Geist and Auerswald 2007). Minshall (1984) examined the importance of substratum size to aquatic insects and found that substratum is a primary factor influencing the abundance and distribution of aquatic insects. Aquatic macroinvertebrates are adversely affected by habitat reduction and/or habitat change resulting in increased drift, lowered respiration capacity (by physically blocking gill surfaces or lowering dissolved oxygen concentrations), and reducing the efficiency of certain feeding activities especially filter feeding and visual predation (Lemly 1982; Waters 1995; Runde and Hellenthal 2000; Suren and Jowett 2001). Macroinvertebrate grazers are particularly affected as their food supply either is buried under sediments or diluted by increased inorganic sediment load thus increasing search time for food (Suren 2005; Kent and Stelzer 2008). Deposited sediments affect fish directly by smothering eggs in redds (Fudge et al. 2008), altering spawning habitat and reducing overwintering habitat for fry (Cordone and Kelley 1961), as well as indirectly by altering invertebrate species composition, which decreases the abundance of preferred prey (Suttle et al. 2004). Declines in salamander abundance also were seen with increases in fine sediment inputs (Lowe and Bolger 2002; see also Hawkins et al. 1983).

Specific Statement of the Problem

Roads are persistent sources of fine sediment to forest streams, which otherwise have characteristically clear water except during significant storm events. Substantial improvements in water quality have been secured in recent decades through diligent application of mitigation measures (usually called best management practices or “BMP”) for sediment from forest roads (e.g., Cristan et al. 2016, Edwards et al. 2016). However, there are still some locations where noticeable loading occurs related to forest roads (Bilby 1989, Sheridan and Noske 2007, Dubé et al. 2010, Brown et al. 2014). Recent work has demonstrated that sediment delivery from forest roads is focused in a small fraction of the road network. A Washington study found that only 10-11% of the forested road length is delivering sediment to the channel network (Dubé et al. 2010); similar results are reported in a landowner survey (Martin 2009). Work in Oregon and Idaho, summarized in Figure 1, shows that 90% of the delivered sediment comes from less than 9.2% of the drainage points (Black et al. 2013). That fraction is primarily comprised of larger, more heavily travelled roads in proximity to streams. A survey of over 5,000 drainage points in Western Montana and subsequent sediment modeling found that 76% of road sediment delivery occurred within 10 meters of the stream (Cissel et al. 2014). Mitigation for these locations has proven more challenging than in other places, and better information is needed to hone our capacity to efficiently handle sediment from these high-traffic, near-stream (HTNS) road segments.

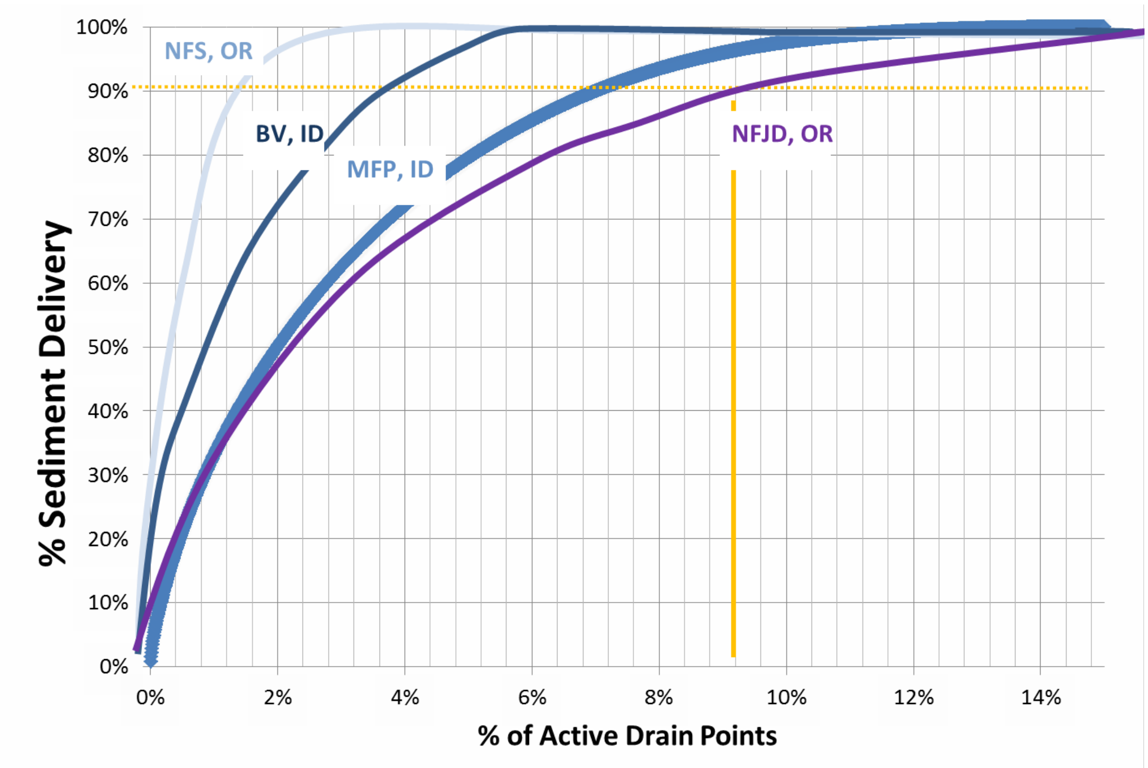

Figure 1. Pareto analysis of sediment delivery from four GRAIP watershed surveys (Black et al. 2013).

For several reasons, HTNS road segments are particularly challenging for sediment control. Frequent heavy traffic decreases the effectiveness of surfacing roads with quality rock by the crushing of the rock and pumping of fines from the substrate. Drainage modifications such as crowning or outsloping that limit delivery are also compromised when ruts form (e.g., Burroughs and King 1989; Black et al. 2013). Segments carrying frequent heavy traffic may be the most difficult on which to restrict traffic during wet weather, increasing the severity of these effects. These roads also need frequent maintenance of the surface (e.g., frequent grading to reduce pothole development) to maintain their ability to handle traffic. The proximity to streams makes it difficult to rely on infiltration into the forest floor to disconnect road discharges from streams. The proximity to streams or stream crossings also means that these roads will be the wettest and most affected by groundwater and exfiltration from the hillslope. In technical parlance, these are high production (detachment of sediment from the road surface and ditch), high delivery (greater fraction of produced sediment carried to stream) road segments.

These HTNS roads present imposing technical challenges. Excessive fine sediment in fish-bearing streams is perhaps the single largest, management-related factor impacting instream biota (e.g., Waters 1995), including listed fish species, so reducing road surface erosion and delivery to stream is of critical importance. Not only are HTNS roads more likely to deliver sediment to streams, they are critical to the transportation network as key mainline roads. Therefore, HTNS roads may warrant additional investment by landowners to use enhanced BMP (e.g., improved road surfacing, better ditch line BMP with rock check dams) not only to meet stewardship goals but for operational needs as well. Additional mitigation for erosion of HTNS forest roads may allow forest operations to be conducted in a wider range of weather conditions, with higher vehicle-use capacity and potentially reduced maintenance. However, road upgrades and enhanced BMP add a significant cost; therefore, improved knowledge of individual and in-combination BMP is essential for understanding the return on BMP investments.

Whether from the landowner or regulatory perspective, a central question is what <u>combinations</u> of surfacing, ditch line management, traffic control, and drainage management will most efficiently and effectively mitigate sediment yields and hydraulic effects from HTNS roads? The question pivots on combinations because significant information on what individual treatments such as rocking or traffic changes can do to mitigate sedimentation already exist (e.g., as summarized by Burroughs and King 1989). Such information has been formulated into simple empirical approaches that estimate sediment yield from a road surface based on several empirically-derived multipliers similar to the Universal Soil Loss Equation (USLE) (e.g., Dubé et al. 2010; Luce and Black 2001a). Importantly, these efforts depend on two pivotal assumptions: 1) That implementation of multiple BMP has the expected positive benefits; and 2) That those positive benefits are additive, multiplicative or synergistic. Luce and Black (2001a) experimented with BMP combinations, and their limited results contradict these two assumptions. These key issues of most previous research and the simple, multiplicative nature of existing models fundamentally drive the sample design of this project.

Particular BMP treatments are rarely used in isolation; it is the combination of multiple BMP that has been inadequately studied. Some combinations may work well together while others may improve little at a greater cost. Under selected circumstances, one BMP may even reduce another's effectiveness. For example, paving a road reduces production of sediment from the surface, but contributes more water to the ditch line, and if the ditch is bare soil, erosion can increase relative to that expected from a gravel road. Furthermore, safety and operational constraints imposed by one part of a design can impair another part. An operational example is that rocking with high value rock sometimes encourages use of a road grader to retrieve lost rock from the ditch line, which in turn renews the availability of sediment in the ditch (where stream power is high) potentially negating much of the benefit of the rocking. A safety example is that outsloping a road may greatly reduce its delivery, but this cannot be done in steeper ground where a truck sliding off the road could have catastrophic results.

These simple models are parameterized by empirical, site-specific studies. It has been demonstrated that none of the existing models accurately predict sedimentation at individual sites (Dubé et al. 2011); those authors believe this is because the BMP parameters represent only the site conditions where they were collected. At issue is that BMP are parameterized solely by site-specific sediment measurement without process-based representations of their effects. Development of an improved model would provide the physical framework for understanding how different BMP influence water and sediment flows, while field observations would provide the data to further refine models and can be used as model input parameters.

Project Objectives

The forest practices road rules are designed to protect water quality and riparian/aquatic habitats through road prescriptions (WAC 222-24) and best management practices (BMP – Forest Practices Board Manual, Section 3, 2013). These prescriptions and BMP, also called "treatments" in this document, are broadly intended to minimize: 1) sediment production and delivery from the road prism; 2) hydrologic connection between roads and the stream network; and 3) the risk of road-related landslides caused by inadequately built and maintained roads and culverts. This project will specifically focus on 1) and 2) – evaluating the treatment effectiveness of 3) will take a different study design.

An extensive body of research on the performance of individual BMP already exists (Burroughs and King 1989; Dubé et al. 2004), and the most recent summaries (Cristan et al. 2016; Edwards et al. 2016) provide comprehensive information regarding the effectiveness of these BMP. However, not all BMP are well studied and gaps exist in our understanding of road BMP at the site scale in reducing sediment production, sediment delivery, and hydrologic connectivity. Of particular concern is that conceptual models used in the design of road BMP field studies in the literature assume a multiplicative approach such that data collection is focused on observing and measuring factors that are used in multiplicative models. This limits the scalability of those observations using different, more process-based models.

As landowners work to complete implementation of their RMAP and to meet road sediment performance targets and water quality standards, it is important to provide them and other stakeholders with a more complete technical foundation for determining: a) which BMP are most effective at minimizing the discharge of sediment to the stream network; b) which BMP are most cost effective; and c) the practical and operational limitations of what can be achieved in sensitive environmental settings.

In summary, gaps in our understanding of BMP effectiveness may compromise our ability to mitigate delivery from those HTNS road segments that contribute sediment to waters of the State. Because of this, we may not be achieving resource objectives, nor applying BMP in the most cost effective manner with the best risk trade-offs.

Critical Questions

CMER Work Plan Critical Question

- *Are road prescriptions effective at meeting site-scale water quality standards and performance targets for sediment and water? (Exclusive of mass wasting prescriptions, which are covered in the Unstable Slopes Rule Group.)*

Study Design Critical Questions

1) How effective are road sediment BMP, individually and in combination, at minimizing production and delivery of coarse and suspended sediments from forest roads to streams (DNR Typed Waters)?

2) What is the comparative effectiveness of BMP in minimizing the production, routing, and delivery of sediment to streams (defined as DNR Typed waters)? And what are the comparative installation cost effectiveness, and maintenance cost effectiveness and frequency, of these BMP?

3) For individual or combinations of BMP, are increases in turbidity minimized?

4) Are the effects of combined BMP for the road surface and ditch lines additive, multiplicative, synergistic, or antagonistic with respect to runoff and sediment production from road segments?

5) To what extent do road BMP affect water storage and erosion potential at site-scale road segments?

6) How do different characteristics of topography and lithology affect the selection and design of road BMP?

7) How quickly after installation or removal of BMP does the post-construction disturbance that temporarily increases sediment production and delivery abate?

Proposed Alternative Research Approaches

History of the Alternatives

Alternatives were developed by the TWIG to show tradeoffs between doing only empirical research or only modeling, as well as combinations of the two approaches (BAS/Alternatives Document dated 15 January 2016). The alternatives also incorporated an emphasis on the development of alternative approaches on high-traffic, near-stream (HTNS) roads versus entire road networks.

Five alternatives are listed below – the TWIG's preferred alternative, #4, proposes empirical research focused on HTNS roads with a modeling component. This alternative was approved by Policy on 3 March 2016 and has guided subsequent development of this study design.

1. Empirical Research of BMP on HTNS Roads;
2. Empirical Research of BMP on HTNS and non-HTNS Roads;
3. Utilize Existing Data to Improve Existing, Segment-Scale Models;
4. Do Empirical Research of BMP on HTNS Roads (Alternative #1) and Utilize New and Existing Data to Improve Existing Models (Alternative #3);
5. Do Empirical Research of BMP on HTNS and non-HTNS Roads (Alternative #2) and Utilize New and Existing Data to Improve Existing Models (Alternative #3).

Overview of Alternative #4

The Alternative #4 approach involves (A) measurements of road sediment production from road prisms and delivery below roads; and (B) development of a geomorphic model to understand road prism erosion in the context of multiple contributing and transporting elements and integrate field and modeled data statistically to make inferences about the critical questions. Figure 2, a simplified version of Figure 8, shows the interactions of this combined field work and modeling proposal. Several key aspects of the proposed research are introduced below and elaborated later in the proposal.

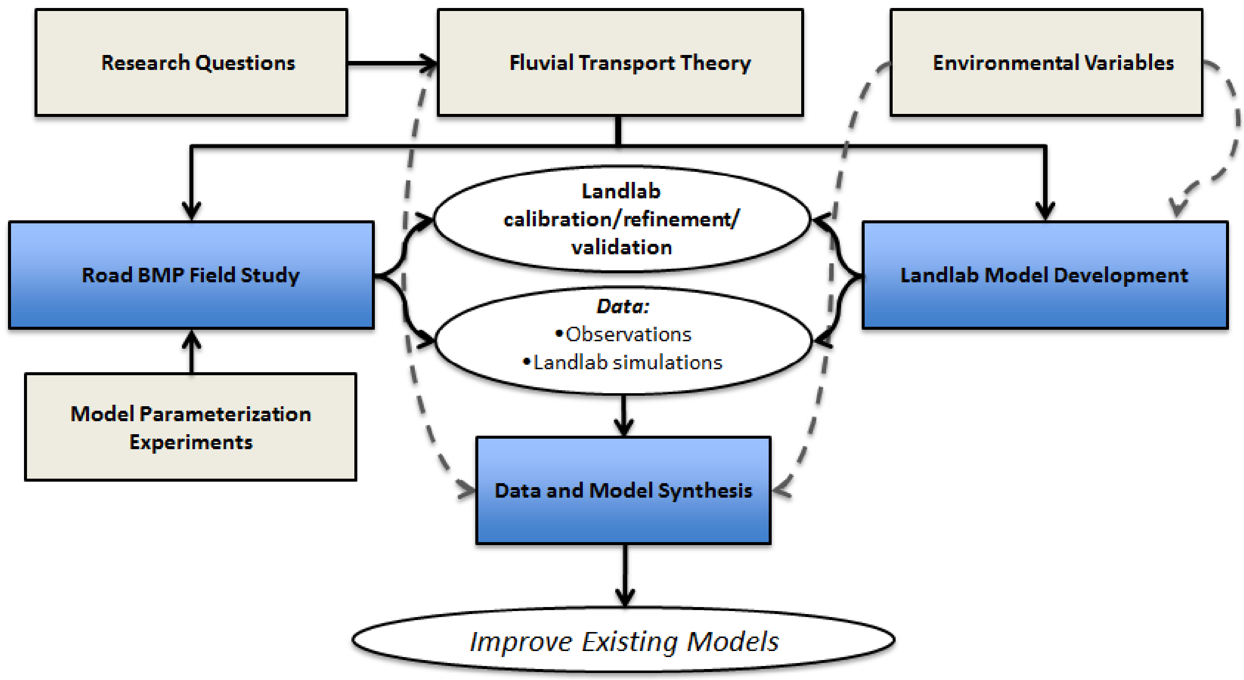

Figure 2. Diagram showing feedbacks between the empirical studies and the process-based model development. Blue boxes show main study tasks.

Our field experiment and modeling design are synergistically related. The design of our field experiments will be guided by sediment transport theory, conservation of mass principle and their application for modeling road erosion and BMP effects on flow and transport. This approach is chosen over strictly empirical sampling approaches in order to: 1) Take advantage of the wealth of knowledge in sediment transport theory and roles of environmental factors that control sediment production, detachment, and transport; 2) Develop physics-based causal linkages between sediment yield and climate, road surfacing, the hydrologic and sedimentation influences of lithology, and ditch line conditions and BMP effects by adapting and refining formulations from mechanistic erosion and sediment transport literature; 3) Use theory and models as a framework to relate observations of sediment yield to categorical and physical variables such that process-based understanding gain in one location can guide predictions in others. With this process-based research strategy our approach is summarized as below.

(A) We propose to research road erosion and transport from the tread and ditch line with and without application of BMP by setting up field experiments to monitor and quantify runoff and sediment production and transport to address the research questions listed above. Study sites will be placed in two distinct lithologies chosen for their broad representation of Western Washington geology and for their differing hydrologic and sedimentation characteristics while having overlapping rainfall ranges. In each lithology, 40 individual road segments will be equipped with sediment collection tubs and other collection devices. The sampling frame for the field studies will create a basic conceptual understanding of the physics of sediment production, detachment, and transport from/through the road tread and ditch line.

(B) We propose to apply a distributed grid-based geomorphic model based on fluvial transport theory and conservation principle to understand road tread and ditch line erosion in the context of multiple processes that detach and transport sediment (e.g., traffic and rainfall). This model will be used at the scale of road segments and include estimates of hillslope hydrologic processes that contribute ditch water from the cutslopes. As field observations become available, model predictions will be compared against observations to refine model theory, calibrate parameters, and improve model predictions. We will then use the model as a numerical laboratory across other locations in the regions we have identified to develop a large modeled data set using a supercomputer to study effects of BMP combinations, as well as the role of local conditions and initial conditions (e.g., road location, topography and lithology). Our experimental monitoring and modeled data will offer a unique and rich data set which will be grouped, analyzed and synthesized using existing statistical techniques to address CMER Work Plan and Study Design critical questions as elaborated in the Expected Results Section.

Strategic Motivation for Modeling Efforts and Use of Landlab

Currently, one of the most significant challenges for evaluating BMP effectiveness experimentally is a lack of theoretical and modeling basis with which to a) analyze and interpret data, b) generate hypotheses for new locations, and c) explore what-if scenarios for comparison of BMP alternatives on water and sediment budgets. The current suite of "physically-based" road erosion modeling tools do not separately consider erosion and transport processes in channelized locations (e.g., ditch or wheel track) versus planar contributing features of the road. Some BMP are designed to prevent generation of fine sediments on the planar features with shallow flow (e.g., surfacing quality); other BMP affect the capacity of concentrated water flowing along the road ditches and wheel tracks to pick up and transport sediment. Within these subsets of BMP, some alter the particle size distribution available for transport, effectively altering the critical shear stress, while others partition available shear stress into immobile features like large rocks, hydraulic loss in steps, or grass stems. The latter prevent the flowing water from moving such sediment as is available. Existing physically-based models do not represent the interactions of flows between planar and concentrated flow conditions, shear stress partitioning on erosion and transport, or feedback mechanisms between flow, substrate size, and channelization processes.

Without such theoretical and modeling basis, supported by observations designed to explore process couplings, any evaluation of data on altered sediment yield from BMP can be only partially mathematically described. While altered surfacing quality could be reasonably described in one of the planar sediment models, actual observations would depend on the farther transport of that material through the longitudinal transport system on the monitored road segment. Any calibration done for a given surfacing treatment, without information about or the capacity to model the interaction of that surface sediment supply with the ditch or wheel tracks, would attribute all of the effect of those features to the quality, or lack thereof, of the surfacing. Treatments in the ditch line or to mitigate flow down wheel tracks cannot be physically represented in the models, requiring a parameter adjustment that would not be equivalent to the actual treatment effect in a highly nonlinear and dynamic system. These factors, along with the existing knowledge that all road erosion models require calibration information for accurate predictions (Dubé et al., 2011; Black and Luce, 2014), lead to the difficult realization that every BMP effectiveness evaluation needs to be done empirically for every new context. The scope of an experimental study considering the various potential contexts and interaction effects would be overwhelming and prohibitively expensive. Each new BMP proposed would need to be tested in a range of different settings and in combination with a range of other BMP.

The proposed modeling approach using the Landlab earth surface modeling toolkit (https://landlab.github.io/#/) will identify the effects of each BMP in terms of a) what it does to the supply sediment size distribution and b) what it does to impede flow, erosion, and transport. The prediction we are testing in the current study is whether these features of each BMP, which can be independently measured per the Parameterization Experiments and represented as BMP components in Landlab, can be related to sediment supply changes from road plots empirically.

The empirical analysis of the Major Experiment will use the independent variables we develop—the critical shear stress (e.g., fine sediment availability), the grain shear stress, and the flow rate—regressed against observed sediment yields. The Parameterization Experiments will be used to estimate the physical effects of each BMP (e.g., distill each BMP into what it does to the critical shear stress and the grain shear stress). The Major Experiment will examine how those physical effect descriptors (e.g., critical shear stress and shear stress partitioning), in combination with rainfall amounts, affect sediment yield. To test if this dimensionally simplified set of predictors is adequate for the task, we will examine whether we estimate equivalent reductions in sediment yield from different BMP that have equivalent critical shear stress and fractional reductions in shear stress. If successful, the reduced dimensionality of the problem would make empirical testing of BMP much more tractable and efficient in this and future studies. Conceptually, a simple level of BMP testing could be reduced to the amount of work shown in the Parameterization Experiments, subject to occasional validation in terms of actual sediment yield results.

Because certain aspects of the Landlab-based model (e.g., the hydrology of different geologic, precipitation, and seasonality details) and their effects on sediment yields will likely require calibration at some basic level in different settings across the state, we cannot say that the Landlab-based model can be used to make predictions without further experimentation. However, the hope is that with better theory and a model framework, the dimension of those experiments will be much smaller, and substantial hypothetical development can be made to isolate specific questions for testing by using other hydrologic process information. In this sense, conditional projections for different locations can be made. If we can determine that the simplified descriptions of BMP effects on sediment supply and hydraulics can be independently measured, we can also apply the Landlab-based model to generate estimates of the effects of new treatments.

Study Design Proposal

The major experiment measuring sediment production and transport in response to a set of covariates and BMP is the focus of the project; statistical analyses of these results will provide direct information on BMP effectiveness for stakeholders and policy makers as well as support model development and refinements. This effort will require 40 road segments in each of two lithologies with different hydrologic and sedimentation characteristics (see Location below). Six years of data will be collected in each lithology – three to understand relationships between rainfall, traffic, surfacing rock types, and grading and three with ditch line and other site-specific BMP installed or removed to quantify their benefits. However, not all the critical questions are answerable without additional effort. Six parameterization experiments are proposed to augment the basic field results and enhance the modeling component of the project. Each of these efforts is a component of the full project, aiding in adding to the overall statistical results, improving model accuracy, and gaining additional relevant knowledge.

Below, we present details about the design, implementation, maintenance, and intent of the components of the experiments. We also discuss how we will evaluate the basic data and build and use datasets to inform the modeling framework and theory. The Sections are titled: Major Experiment - Best Management Practices; Parameterization Experiments; Empirical Analyses and Statistics; Modeling Framework; Modeling Theory - Road Prism Erosion and Surface Dynamic Model; and Expected Results and Limitations. The Major Experiment Section has subtitles: Context; Plot Design; Covariates; BMP - Implementation and Schedule; Location; and Site Criteria. Modeling Theory has subtitles: Sediment Mass Balance; Overland Flow; Erosion Model; and Sediment Yield.

The Major Experiment - Best Management Practices

Context

On forest roads, the cutslope and tread generate runoff and sediment, which are then fed to the ditch or a rut where concentrated flow transports the sediment (see Figure 3). The primary sources of water are the components of the road prism with large areas, the tread and cutslope. The tread generates runoff during relatively intense precipitation events (Luce and Cundy 1992, 1994; Luce 2002), whereas the cutslopes produce more runoff from long precipitation events or snowmelt in the Pacific Northwest (Luce 2002). Runoff from these areas is generally shallow and diffuse in nature, but it carries the fine sediment that is detached by raindrops and traffic. When that runoff is accumulated along the ditch line or in ruts, it becomes concentrated flow, and the more powerful flowing water can more effectively transport sediment, as well as actively detach sediment where the soil is exposed.

Tread BMP focus on reducing sediment production or limiting the delivery of sediment to the ditch line. The use of high quality surfacing rock to reduce the production of fine sediment is a common BMP, particularly on high-traffic forest roads; however, actual quality is influenced by local availability, so “high quality” is a relative term. A crowned tread, such as is displayed in Figure 3, is also a common BMP. Regular maintenance by grading results in diffuse flow of water off the tread which limits sediment detachment. It also limits sediment delivery to the ditch line because approximately one-half of the tread surface does not contribute sediment or water to the ditch. However, too much maintenance can result in excessive sedimentation (Luce and Black 2001B, Sugden and Woods 2007, Swift 1984). In addition, more site-specific and specialized tread BMP have been used in situations of high delivery. These include the application of sediment binders, the elevation of individual stream crossings, and the addition of truly high quality surfacing rock (e.g., unweathered basalt in a 3-inch minus sort) at individual stream crossings.

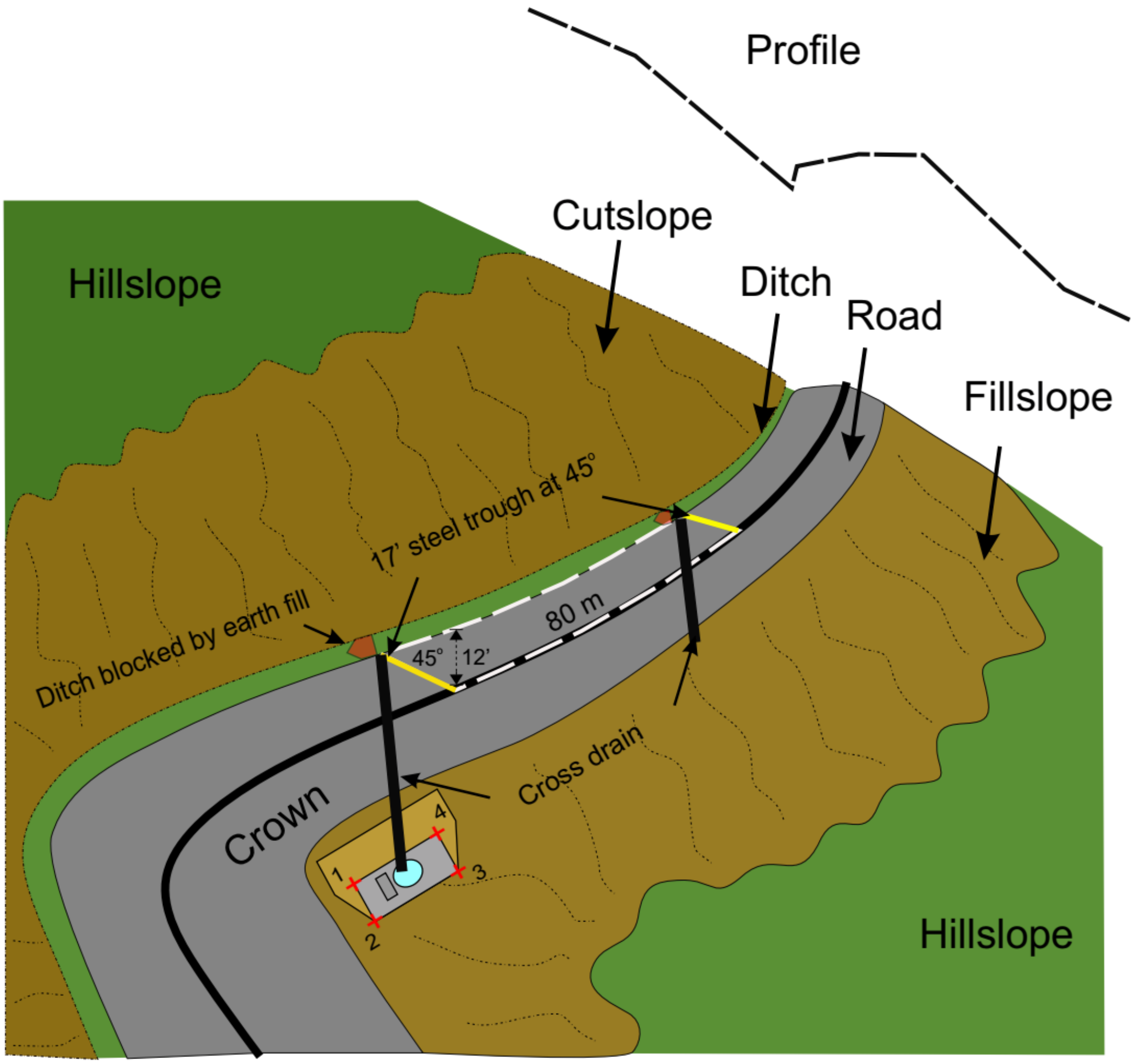

Figure 3. A schematic diagram showing hillslope and road prism that includes cutslope, ditch road surface and fillslope. White rectangle shows an example of road surface area to be studied. Ditch line BMP cause the ditch water to slow and drop the coarser particles transported from the tread. Some have a filtering effect as well (e.g., hay bales and silt fencing) while others stabilize the bottom of the ditch so that erosion of the ditch does not occur and does not contribute additional sediment to that derived from the tread (e.g., rock check dams). Although not well studied, many stakeholders of the forest industry have visually observed that a well-grassed ditch is an effective BMP. As simple as this sounds, grass is an inexpensive BMP that provides all three functions (i.e., slows water, filters and stabilizes the ditch).

The common tread BMP, such as improved quality of surfacing rock and a crowned configuration, have been individually studied or modeled by numerous researchers (e.g., Foltz and Truebe 2003; Dubé et al. 2004). A specific combination of BMP has been previously studied (traffic and ditch maintenance—Luce and Black 2001a), but such an effort has not been systematically applied toward understanding the general effects of multiple BMP. Furthermore, little research has been done on ditch line BMP, causing Dubé et al. (2004) to report limited ability to parameterize any ditch line BMP in WARSEM. Overall, little is known about how BMP interact with each other, how their efficacy is affected by varying traffic and rainfall levels, and how the hydrologic properties of distinct lithologies influence transport capacity. As has been explained above in Project Objectives, it is the testing of combinations of BMP and the evaluation of that testing in the context of physical and environmental covariates that drive this study design. Incorporating basic physical principles about sediment detachment and sediment transport—information currently lacking in all empirical road erosion models—is also critical.

The context of the preceding four paragraphs has been the basis of the design of the Major Experiment.

Plot Design

We propose to examine 80 sites, targeting specifically HTNS roads—40 in each of two lithologies with overlapping ranges of rainfall generally typical of forested land in Western Washington (see Location below). Each site will be an 80-meter segment of road with a cutslope, a ditch line, and a tread surface, where the downhill end of each site must have a suitable location just below the road for the sediment collection equipment (Figure 3). Additional details of site criteria are provided below (see Site Criteria).

The tread surface of each 80-meter segment of road will be isolated by steel troughs. The upper end of the ditch line of each segment will be isolated by a cross-drain culvert with an earthen headwall that passes the ditch water and the tread water captured by the upper steel trough under the forest road and onto the forest floor. At the lower end of each 80-meter segment, the lower steel trough will direct the water from the ditch-side tread crown (always 12 ft.) into the ditch. Water collected in the ditch from the cutslope and the 80 meters of crowned tread will pass through the lower cross-drain culvert under the road to the sediment collection equipment (Figure 4). (Note: Installation of steel trough, cross-drain culvert and earthen headwall at the upper end of the ditch line will look exactly like Figure 4, but will drain onto the forest floor unless it is the lower end of the next segment.)

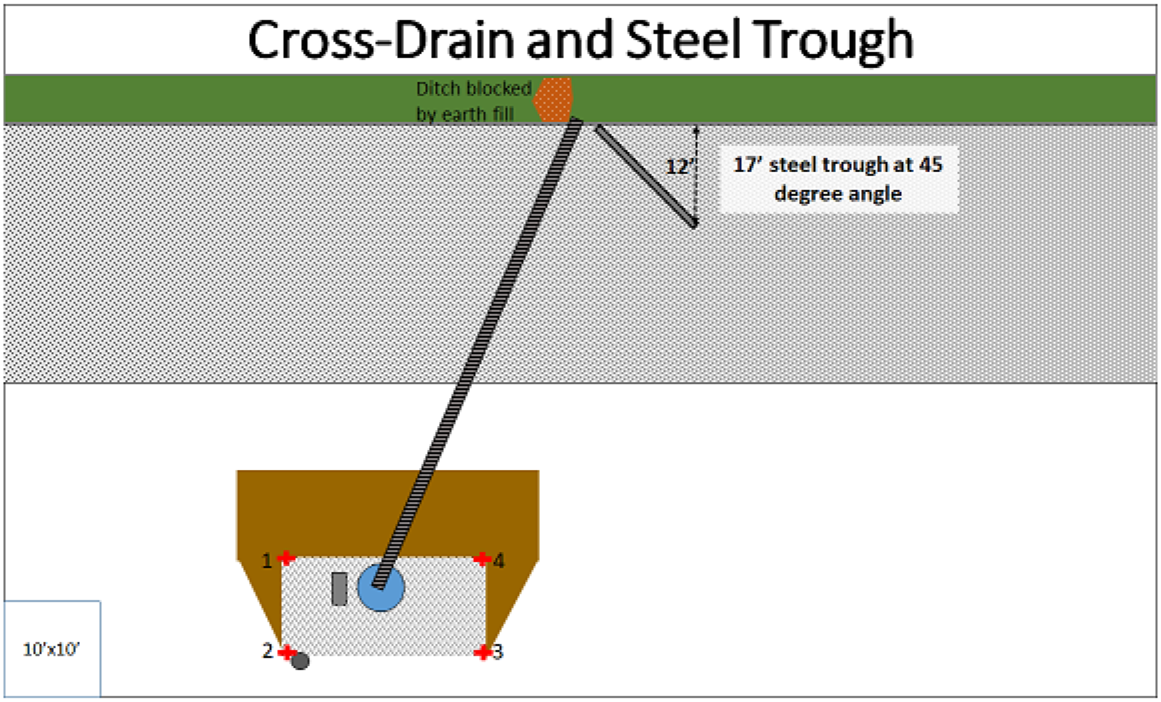

Figure 4. Configuration of bottom end of an 80-meter segment. Ditch (in green) is blocked below cross-drain culvert by earthen headwall. Steel trough is 17-feet-long and placed on a 45-degree angle up the road to capture 12 feet of the tread and drain into the ditch line 1 foot above the cross-drain culvert inlet. The cross-drain culvert is on a strong skew to create a 5% gradient in the pipe and it extends several feet beyond the edge of the tread (in gray) to a platform that holds equipment.

On a 200 ft^2 platform dug into the fillslope or hillslope below the road, road sediment collection equipment will collect both larger sized sediment (i.e., primarily sand) and finer material (i.e., the turbid fraction) with different methods. From the cross-drain culvert outlet, larger particles will accumulate in the sediment tub technology developed by the USFS (Black and Luce 2013—see Figures 5, 6 and 7). Water exiting the sediment tub will pass through a tipping bucket with a data logger, measuring total water flow from the sediment tub (Figures 5 and 6). Finer suspended sediment escaping the sediment tub will be sampled when a calibrated "splash" from alternate tips is captured in a small pipe with holes mounted on one wall of the tipping bucket. The "splash" will then be routed to the suspended solids tank. It is anticipated that the contents of the sediment tubs will need to be measured and emptied twice annually. The collected sediment from the tub and estimated sediment volume from the total number of tips and the average suspended-sediment concentration for each month can be expressed as total weight per year (kg/yr) or divided by road surface area for $kg/m^2/yr$.

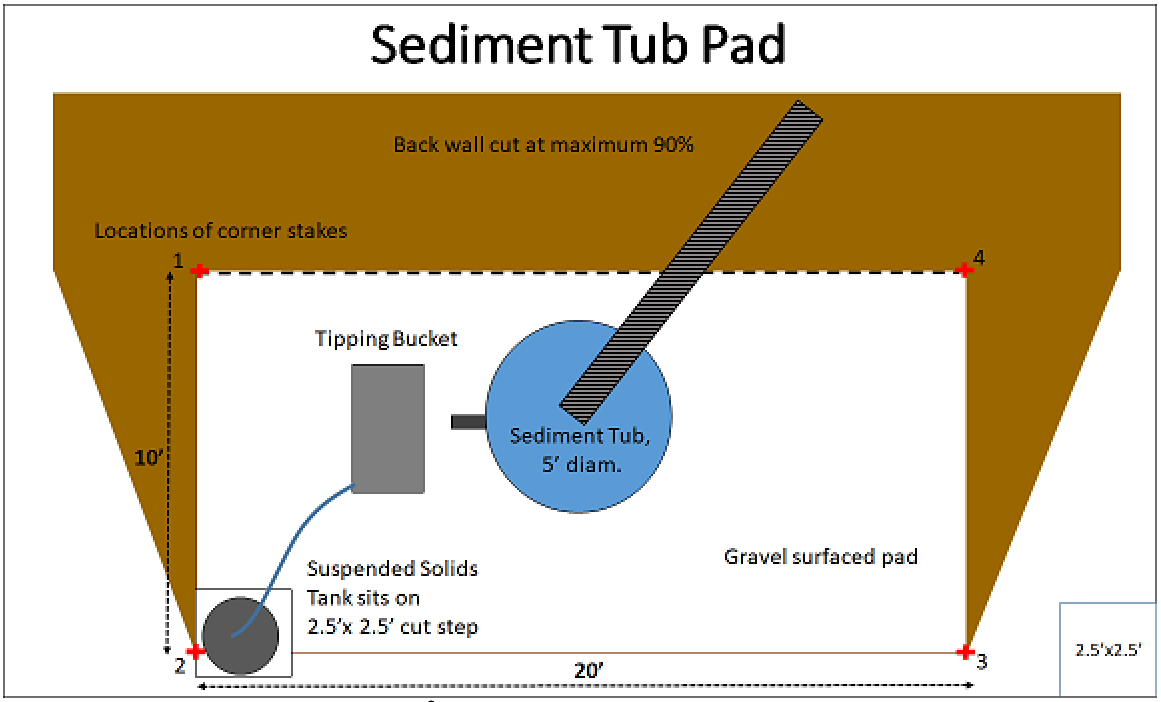

Figure 5. Plan view of the 200 ft^2 platform with the cross-drain culvert outlet, the sediment tub, the tipping bucket, and the suspended solids tank. Extra space to the right provides space for the maintenance crew to measure the tub's collected sediment.

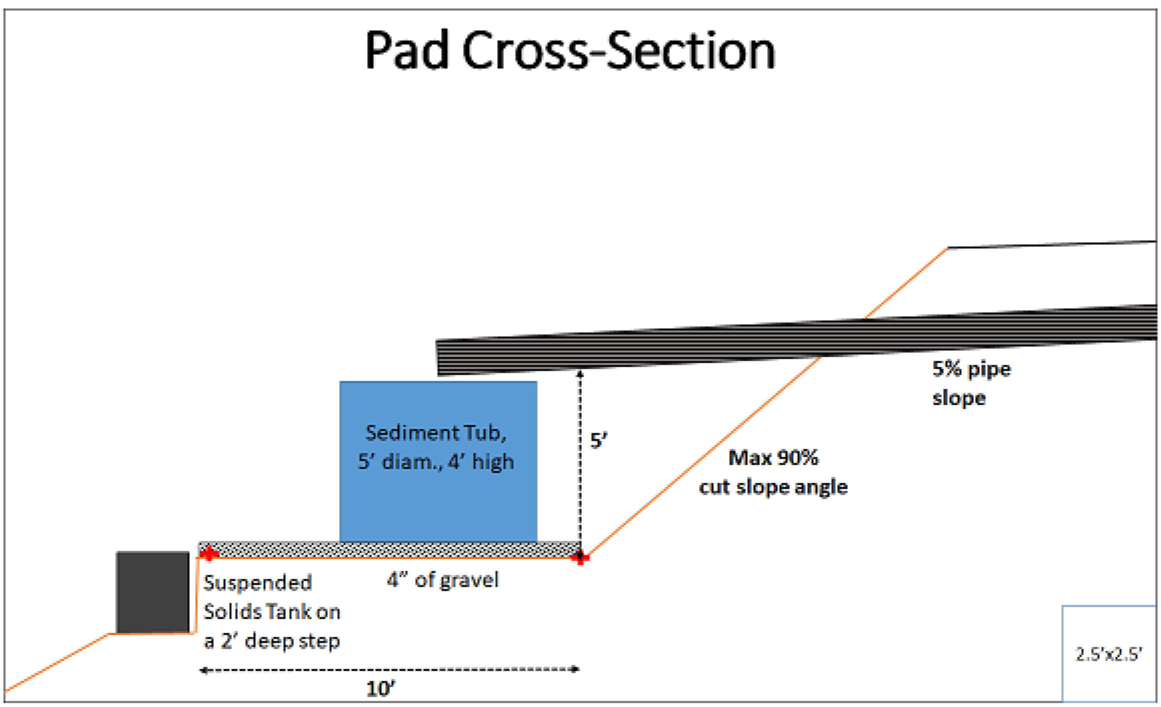

Figure 6. Cross-sectional view of the platform components.

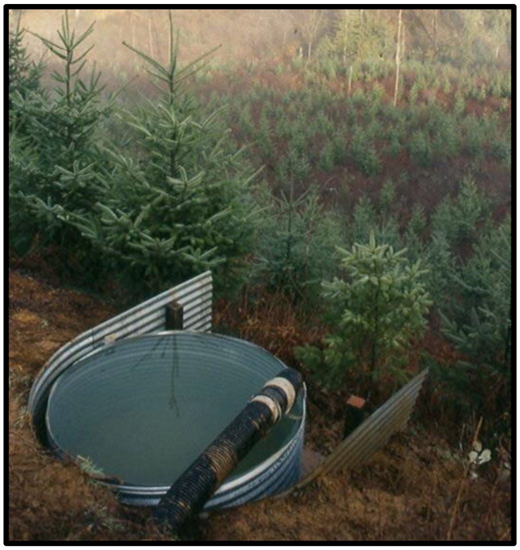

Figure 7. A photograph of a sediment tub installed below a road segment.

Covariates

A discrete set of covariates will be controlled or measured for the length of the experiment (Table 2). The controlled covariates for the road prism include road length (80-meters), road configuration (crowned), and road width (crowned 12-feet from the ditch). Road gradient will be measured (once), and it is limited to the range of 2-10% because sediment transport in a ditch of less than 2% may be sporadic and rilling of the tread may be too extreme at greater than 10% to represent normal detachment processes. And lithology is controlled by having 40 segments in each of two lithologies.

To best distinguish the influences of the common BMP, we will measure those covariates that are impossible or infeasible to control (Table 2). Traffic counting will be accomplished with the use of motion-sensor cameras. These cameras will allow the size of the vehicles to be determined, as well as allow us to distinguish between loaded haul traffic, unloaded haul traffic (e.g., log trucks and dump trucks), and recreational or working "pick-up" traffic. These will be strategically placed so that each arterial road that may contribute traffic to the road with our sample segments will be counted from its intersection.

Frequency of grading will be documented and will occur at the discretion of the landowner unless there is some specific reason for the TWIG to call for grading (e.g., the Road Micro-Topography Evolution Parameterization Experiment described below).

Weak subgrades increase flexing and plastic deformation of the road surface (e.g., Boston et al. 2008), increasing rutting, pothole formation, and pumping of fines from the subgrade. These effects ultimately increase erosion, and, as a result, ensuring adequate subgrade strength or reinforcement is a recognized BMP for forest roads. Because we are working with established, high-traffic roads, which have had substantial modification over time to reinforce weak points in the road, we have little opportunity to experimentally modify the subgrade. However, we have some opportunity to measure the strength of the subgrade during plot installation. As excavations are made to install plot drainage under the road, a space will be cleared at the contact between the subgrade and surfacing material to apply a calibrated Clegg Hammer test (Pattison et al. 2010) to the subgrade surface and to note layering and construction of the road. Specific locations that preferentially develop ruts and potholes may require additional Clegg Hammer testing as the experiment proceeds. If variability is high, it may be necessary to perform continuous plot-scale testing by ground-penetrating radar to determine surfacing depth or by using larger deflectometers on the road surface to determine subgrade strength. As with the other measured covariates, the strength measurement will be used as a covariate in the sediment yield analyses.

Rainfall will be measured by placing six rain gauges across the rainfall gradient in each lithology with consideration to coverage across the 40 road segments and to the validation of the local PRISM estimates. The rainfall range sampled in each lithology will be similar across the two lithologies (Table 7). Cutslope hydrologic inputs will be determined, with uncertainty, by mapping the catchment area above each segment and utilizing ditch line flow observations (i.e., water volume through the tipping bucket) compared to hourly rainfall minus estimated tread contribution.

Table 2. Potential covariates in the examination of BMP performance.

Covariate	Measured/ Controlled	Measurement	Range/Condition
Segment Length	Controlled	---	Steel troughs and cross-drains isolate 80-m road segment
Tread Configuration	Controlled	---	Graded to crowned
Road Width	Controlled	---	Crest graded 12’ from ditch line
Road Gradient	Controlled	---	Limited to 2-10%

Lithology	Controlled	---	Limited to 2
Traffic	Measured	Motion-sensing cameras	Heavy traffic (4+ trucks per day)
Grading	Measured	Landowner reporting and motion-sensing cameras	---
Subgrade Strength	Measured	Clegg Hammer; Deflectometer measurements along plot lengths	Hammer, notes, and samples once during cross-drain installation; Deflectometer once
Rainfall	Measured	Rain gauges	Hourly Precipitation
Catchment Area	Measured	Mapping catchment area above segment cutslope	---
Cutslope Interception	Measured/ Estimated	Ditch line flow observations compared to hourly rainfall minus estimated tread contribution	---

BMP - Implementation and Schedule

Road surfacing is the first BMP to be studied (Table 3). For the first three years of data collection on 40 sites in each lithology, 20 of the sites will be surfaced with “good” rock (i.e., the best locally available) and 20 sites will be surfaced with “marginal” rock (i.e., a lower quality that is locally available but that a landowner would use on a forest road with significant haul) (Table 4). Identification of surfacing currently on the road will occur through conversation with the local landowner(s). Surfacing will be tested for aggregate hardness by submitting samples from the contributing rock pits to the Washington State Department of Transportation (WSDOT). Subject to their recommendations, they will conduct basic testing which may include the Los Angeles Abrasion Test, the WSDOT Test for Degradation, and the Sand Equivalency Test. If we decide to do the Micro-Deval Test, this would have to be contracted to a different facility. It is most likely that some of the 40 sites in each lithology will have to be surfaced with the local surfacing identified as “marginal.”

Four of the 20 sites in each lithology with “good” surfacing will have one or more ditch line BMP installed; these will be monitored the same as the other 36 sites except for the one week each summer when the Ditch Line Hydraulics Parameterization Experiment is conducted (see Ditch Line Hydraulics below). Two of the 40 sites in each lithology, one each with “good” and “marginal” surfacing rock will be monitored the same as the other 38 sites except during the winter season Short-Time-Scale Interactions Parameterization Experiment (see Short-Time-Scale Interactions below). As Table 4 summarizes, the six sites in each lithology that are described in this paragraph will not have a grassed ditch line. Grass will be mechanically removed and then chemically suppressed if it exists in the 6 sites. Grass will be established where it does not exist or where the installation process disturbed it in the remaining 34 sites, in each lithology. These conditions will be maintained as needed during Years 1-3 (for each lithology).

The first three years of data collection in each lithology will provide the data needed to apply a basic conceptual understanding of the physics of sediment detachment and transport from/through the road tread and ditch line (Table 6). Such an understanding will facilitate the exploration of the influences of BMP on sediment production and transport in these different domains and will allow us to observe the influences of the two lithologies on both sediment production and hydrology in the context of varying traffic and rainfall levels. In addition to the Major Experiment data collection during the first three years, the Cost Versus Maintenance Survey and the Ditch Line Hydraulics Parameterization Experiments will be completed. These experiments will inform the final choice of elevated BMP in the ditch line and spacing thereof for later experiments. A third Parameterization Experiment, Short-Time-Scale Interactions, will also be initiated at that time (Table 6).

The first three years of data collection will inform the details of the design of the second three years. Currently, we predict that during the second three years of data collection in each lithology, Years 4-6, 16 sites will remain surfaced with “marginal” rock. Four of these will be unchanged from the first three years of data collection (i.e., with a grassed ditch line and no additional BMP)—these are controls (Table 5). Another four sites in the “marginal” surfacing will have the ditch line grass removed by mechanical means and then chemically suppressed, with no other change. Four "marginal" surfacing sites will have a ditch line BMP installed, two of which will be installed after the grass is removed. The final four "marginal" surfacing sites will have another BMP installed, to be identified by the Cost Versus Maintenance Survey, two of which will be installed after the grass is removed. Twelve sites will retain "good" surfacing, of which there will be four controls, four without grass, and four with the additional BMP installed, two with and two without grass (Table 5). Finally, 12 sites will be surfaced with "quality" rock (i.e., a crushed and well-sorted, hard material)—a BMP utilized at individual stream-crossings. The same "quality" material will be used in both lithologies regardless of trucking distances. Of these 12, four will have a grassed ditch line, four will have the grass removed, and four will have the ditch line BMP installed, two with and two without grass (Table 5). Selection of controls and changed sites will be based on variance among traffic and rainfall.

Maintenance of the equipment and steel troughs will be as often as needed for continuous valid data collection. It is anticipated that a field visit to each site will be necessary two or more times each month during the wet months (October–March), with less frequent visits during the dry months. Sediment production may be sufficiently high to require that the sediment tubs are emptied and measured twice each year. Suspended sediment grab samples will be taken every month to keep the suspended solids tank empty. The grab samples will allow for a composite suspended-sediment concentration to be determined and will ultimately allow for yearly suspended-sediment load values to be determined. We recognize that severe storms will require unscheduled field maintenance. Any dramatic changes to road function, such as a cutslope landslide that blocks the ditch line, will be immediately corrected.

Table 3. Three primary BMP treatments will be examined. One additional approach will be added in Years 4–6, testing another BMP to be determined.

BMP Treatment	Treatment	Maintenance	Years 1–3	Years 4–6
Surfacing Rock Types · Marginal · Good · Quality	Hardness testing of rock source	Rock and crown road	Marginal and good surfacing	Quality surfacing added to other rock types
Ditch Line BMP · No grass · Grass	Maintain or clear ditch grass	Seed and maintain as necessary	Grass seed most sites of each rock type	Remove grass from ½ sites in each lithology.
Elevated BMP in Ditch Line · Check dam · No check dam	Install small dams or similar BMP per specification	Maintain	---	Ditch line BMP added to rock and grass treatments

Table 4. In first three years, for the 40 sites in each lithology, two BMP (surfacing type and ditch grass) will be examined. The Short-Time-Scale Interactions and Ditch Line Hydraulics parameterizations experiments will be conducted in the no grass sites.

BMP for Years 1–3		
Surfacing Type	*Grassed Ditch*	*No Grass*
Marginal (20)	19	1 (Short-Time-Scale)
Good (20)	15	1 (Short-Time-Scale) 4 (Ditch Line Hydraulics)

Table 5. In Years 4–6, for the 40 sites in each lithology, the proposed layout and replication of BMP of experimental sites at each lithology includes “quality” surfacing, the removal of ditch line grass, an elevated BMP in the ditch line, and an additional tread or ditch line BMP (to be identified).

BMP for Years 4–6				
Surfacing Rock Type	*Grassed Ditch*	*No Grass*	*One Elevated BMP in Ditch Line*	*One Additional BMP*
Marginal (16)	4 (controls)	4	4 (2 grass; 2 no grass)	4 (2 grass; 2 no grass)
Good (12)	4 (controls)	4	NA	4 (2 grass; 2 no grass)
Quality (12)	4	4	4 (2 grass; 2 no grass)	NA

Table 6. Timeline of Major Experiment BMP tests and individual Parameterization Experiments on high-traffic roads.

	Major Experiment		**Parameterization Experiments**	
Water Year (approx. FY)	*Activity*	*BMP*	*Experiment*	*Analysis Approach/Result*
Year 0 (FY 2017-2018)	Identify and mark 1-80 sites; Excavate 1-40 sites and apply treatment	34 sites = grassed ditch line; 20 "good" surfacing and 20 "marginal" surfacing	---	---
Year 1 (FY 2019)	Equipment installation for 1-40 sites; Excavate 41-80 sites and apply treatment	Maintain 1-40 sites; 34 sites = grassed ditch line; 20 "good" surfacing and 20 "marginal" surfacing	- Ditch Line Hydraulics - Micro-Topography	- Inform model on ditch flow characteristics
Year 2 (FY 2020)	Equipment installation for 41-80 sites; Collect data for 1-40 sites	Maintain	- Sediment Trap Efficiency - Ditch Line Hydraulics - Micro-Topography - Cost Versus Maintenance Survey	- Compare between BMP - Inform model on ditch flow characteristics - Inform model on surface tread erosion

Year 3 (FY 2021)	Collect data for 1-80 sites	Maintain	- Ditch Line Hydraulics - Short-Time-Scale Interactions	- Inform model on ditch flow characteristics - Inform model on surface tread erosion - Traffic turbidity production
Year 4 (FY 2022)	Collect data; Apply new BMP to 1-40 sites	Maintain 41-80 sites; 8 sites elevated BMP in ditch line; 8 sites one additional BMP; 12 sites "quality" surfacing	- Ditch Line Hydraulics - Short-Time-Scale Interactions	- Inform model on ditch flow characteristics - Traffic turbidity production
Year 5 (FY 2023)	Collect data; Apply new BMP to 41-80 sites	Maintain 1- 40 sites; 8 sites elevated BMP in ditch line; 8 sites one additional BMP; 12 sites "quality" surfacing	- GRAIP/WARSEM Analyses	- Refine model
Year 6 (FY 2024)	Collect data	Maintain	- GRAIP/WARSEM Analyses	- Refine model
Year 7 (FY 2025)	Remove sites 1-40; Collect data for sites 41-80	Maintain	---	---
Year 8 (FY 2026)	Remove sites 41-80	---	---	---

Location

This project will be implemented on two lithologies, distinct in their particle size distribution and permeability. Geologic materials with a high proportion of silt-sized particles also have low permeability and represent a worst-case situation with respect to both sediment production and sediment transport. Poorly indurated silt deposits, siltstone and glacial till meet these requirements and all occur in Western Washington. The second lithology should have a much lower proportion of silt-sized particles and a higher, but not extremely high, permeability. Extremely high permeability materials, such as pure sandy-gravelly glacial outwash, would result in ditch line water being rarely observed, making implementation unfeasible. The dominant type of lithology in Western Washington that is distinct from a high silt lithology is Oligocene-Eocene volcanics, which includes submarine basalt, basalt and andesite flows, and pyroclastics. Additional considerations are: 1) The two locations must have a similar range of annual precipitation, preferably rain-dominated because winter haul is limited in snow-dominated precipitation zones; 2) The rainfall range should represent commercial timberland in the lowlands of Western Washington where rainfall ranges from 40 to 140 inches per year (1,000-3,500 mm/yr), but values of 60 to 85 inches are typical across wide geographic areas; 3) Two to three townships of the desired lithology must exist to have sufficient length of heavy haul routes to select from; and 4) There must be merchantable timber to ensure high traffic. It would also be convenient if the two locations were one area with two inter-fingered lithologies or at least two areas in near proximity. In Table 7, we present preliminary location options. In Appendix C, we present map clips of these preliminary locations.

Table 7. Preliminary Location Options

Lithology	Location	Center Twn/ Rng	Combination	Proximity	Rainfall Gradient (mm)
Low Permeability Alternatives					
Siltstone	Satsop/Little North River	T16N R7W		Capitol Forest Basalt	2100-2500
Till (?)	South of Mossy Rock	T11N R3E	Combo 1	Tilton	1600-2500
Till	South of Sultan/Goldbar	T26N R8E	Combo 2		1300-3500
Till	Issaquah South	T22N R6E			1000-1500
Silt Deposits	Lower North River	T16N R10W			1900-2500
High Permeability Alternatives					
Basalt	Capitol Forest	T17N R3W		Satsop/Little North River	1400-3000
Volcanics	South of Mossy Rock	T11N R3E	Combo 1		1300-2600

Volcanics	South of Sultan/Goldbar	T26N R8E	Combo 2		1300-3500
Volcanics	Tilton	T14N R3E		South of Mossy Rock	1300-2800
Volcanics	Cowlitz County	T7N R1E			1200-3700

The best option is the Satsop and Little North River siltstone and its proximal Capitol Forest basalt. Both lithologies cover large areas, are adjacent, and have overlapping rainfall ranges. They are also easily accessed from Olympia. However, we will need to verify that Capitol Forest is experiencing sufficient haul to meet our experimental conditions. An additional issue-of-concern for Capitol Forest is the heavy recreational use which may increase equipment maintenance costs. If the best option is not viable, more investigation regarding the specifics of the lithologic units and of the haul levels will be investigated for Combinations 1 and 2, and then for the other options.

Site Criteria

Within each lithology, site selection should achieve:

- Sites in clusters of 10 -
    - across the range of annual precipitation,
    - for the lithology with the narrower range;
- Sites where road gradient is 3-7%; and
- Stream-adjacency.

Site criteria must include:

- 80 meters of road whose tread and ditch can be separated from the road above a specified point by a steel trough and a cross-drain and then captured in a cross-drain culvert at the bottom (see Figure 4);
- A cut-and-fill road design (i.e., a cutslope and a ditch);
- A low to moderate gradient or benched hillslope below the cross-drain culvert so that installation of the sediment tub and other equipment is possible;
- A relatively low topographic position so that cutslope interception is occurring; and
- Heavy traffic, which is defined by Reid (1981) as roads that experience more than four loaded trucks per day.

An additional consideration is that annual precipitation levels may result in such high channel density that sites that can be effectively cross-drained and captured may be too few to implement—if this occurs in the areas of highest annual precipitation within one of the lithologies, then those levels of annual precipitation should not be studied within either lithology.

Parameterization Experiments

Alone, the Major Experiment cannot answer all the critical questions, nor will it provide all data needed for the proposed modeling effort. Furthermore, effectiveness of some BMP *can* be assessed in separate experiments, saving time and money. Six parameterization experiments are proposed to augment the basic field results and enhance the modeling component of the project by establishing new relationships for processes that will not be quantified in the Major Experiment. By establishing new relationships for processes that will not be quantified in the Major Experiment. These are summarized immediately below and in Table 8, and are described in more detail in the sections to follow.

1) The Ditch Line Hydraulics will parameterize the physical effectiveness of ditch line BMP identified by the Cost Versus Maintenance Survey and will also allow for simple testing of future ditch line BMP designs.
2) The Road Micro-Topography Evolution will parameterize the development of rills on heavy haul routes to better understand how sediment detachment and transport changes between grading events.
3) The Sediment Trap Efficiency experiment will directly inform our understanding of the efficacy of ditch line sediment traps. We will measure particle sizes and proportions of total sediment captured for sieved soil samples of the two lithologies at varying flow rates, allowing for extrapolation to other soils and climates.
4) The Cost Versus Maintenance Survey will inform the TWIG about commonly used, and potentially innovative, tread and ditch line BMP that will inform the selection of those to be tested starting in Year 4.
5) The Short-Time-Scale Interactions will improve our understanding and ability to model traffic impacts during discrete rain events. Knowledge about the short-time scale will inform our choices about seasonal haul restriction.
6) The GRAIP/WARSEM Delivery Analysis and Survey will utilize existing data (Dubé et al. 2010) and conduct additional road surveys, as needed, to create a hydraulic connectivity relationship between road drainage diversions and distance to streams as a function of the drain type for western Washington (i.e., diagram equivalent to Figure 6 for Idaho). Quantifying likelihood of delivery from a road drainage feature is not a component of the Major Experiment but is of critical importance to evaluation of BMP that alter delivery locations or water accumulation and drainage along the road.

We admit that with limited field observations some of the parameterization experiments may produce parameters with high variance. The propagation of errors in sediment yield predictions due to the uncertainty in parameters will be evaluated as part of our model test and validation as discussed in the Model Sensitivity and Validation Section.

Table 8. Objective and year(s) of experiment for the six parameterization experiments.

Parameterization Experiment	Year	Objective
Ditch Line Hydraulics	1-4	Measure hydraulic characteristics of flow through ditch lines and parameterize physical efficacy of in-ditch BMP
Road Micro-Topography Evolution	1-2	Examine tread surface conditions, such as particle size distribution and road tread elevation, and the changes seen over time
Sediment Trap Efficiency	2	Determine efficacy of in-ditch sediment traps
Cost Versus Maintenance Survey	2	With landowner input, better understand operational costs of mainline road maintenance.
Short-Time-Scale Interactions	3-4	Examine sediment detachment and transport from the road tread under various traffic conditions
GRAIP/ WARSEM Delivery Analyses	5-6	Use results to support landscape-scale model refinements by better estimating delivery from all drainage structures

Ditch Line Hydraulics

Shear stress is one of the driving forces of sediment transport from forest roads to nearby streams. The total shear stress acting on the road surface or the bottom of the ditch line is a function of the hydraulic radius of flowing water. A controlled experiment in which the hydraulic radius can be measured will help us look further into the component of the shear stress causing sediment to be transported. Understanding the underlying mechanisms of such sediment transport will allow us to better determine which BMP will be the most effective at mitigating sedimentation to streams.

To better understand this grain shear stress, we propose a natural flume experiment to look at shear stress partitioning. The basic concept of shear stress partitioning can be explained through the work of Einstein and Barbarossa (1952). They proposed to partition shear stress into two separate components: the shear stress that acts upon forms in the channel, such as bed forms and vegetation, and the shear stress that acts upon the sediment itself.

$$\tau = \tau_f + \tau_s = \rho_w g R_f s + \rho_w g R_s s$$

where τ_f and τ_s are shear stresses and R_f and $R_s$are effective hydraulic radii due to channel forms and sediment grains, respectively. ρ_w is the density of water, g is the acceleration due to gravity, and s is the sine of the channel slope.

In this parameterization experiment, we are interested in only the shear stress due to sediment grains, τ_s. One of the most common methods used to calculate the grain shear stress, τ_s, from the total shear stress, τ, is to write τ_s as a function of a shear stress partitioning ratio, f_p.

$$\tau_s = \tau \cdot f_p$$
$$f_p = (\frac{n_s}{n_t})^{1.5}$$

where n_s and n_t are the sediment grain Manning's roughness value and the total Manning's roughness value, respectively. n_s and n_t can be approximated by

$$n_s = k \cdot {D_{50}}^p$$
$$n_t = \frac{R^{2/3}\sqrt{s}}{\frac{Q}{A_f}}$$

where k and p are parameters (Yen 1992); R is the hydraulic radius; Q is the discharge; A_f is the cross-section; and s is the sine of the slope. The hydraulic radius is calculated from

$$R = \frac{A_f}{P_w}$$

where P_w is the wetted perimeter of the cross-section. Both A_f and P_w are measured. Multiple other ways of calculating the grain shear stress, τ_s, from the total shear stress, τ, are presented in Le Bouteiller and Venditti (2015). We plan to utilize more than one of the methods presented to develop the best relationship between grain shear stress and transported sediment. (See below for modeling theory details.)

For the calculation of grain shear stress to come to fruition, values for the hydraulic radius, the D_{50}, a grain size distribution of the sediment in-situ, and a grain size distribution of the sediment transported from the roads are needed for the best results. This parameterization experiment will allow us to obtain these values.

Ditches to be used as flumes will be selected at 4 sites in each of the different lithologies (i.e., a total of 8 sites) and will be utilizing different BMP. Because each of the ditches will have different BMP, we will be able to determine how each BMP affects sediment transport, and therefore shear stress acting on the system. This parameterization experiment will utilize the sediment collection tubs (see Figure 4) already in place from the overall project; however, tubs will be emptied before this parameterization experiment and sediment captured during these experiments will be analyzed separately.

Under certain conditions, this parameterization experiment can be further utilized to test and refine sediment detachment and transport theory and validate our model, in addition to estimating n_t and f_p. For the purpose of this experiment, we will assume that sediment supply from the road tread is negligible during a short summer experiment.

This parameterization experiment will be conducted in each lithology for the first three years that the plots are installed; overall this means Years 1 through 4 for one week during the summer. Conducting this parameterization experiment over the course of multiple years will allow us to determine the temporal effects of the BMP being used at each site. Water will be hosed to the selected ditches once a day for a week to collect multiple data points at each site. The water will be hosed using a tanker at a few different flow rates to match the range of hydrologic conditions observed at the site. While water is flowing, the water depth will be measured using a meter stick, and the cross section will be measured using a tape measure and meter stick. Using the measurements of the cross section of the ditch and the flowing water depth, hydraulic radius can be obtained. Once the run is finished for the ditch, sediment will be collected from the sediment tubs and sieved to obtain a grain size distribution.

In summary, to obtain the value of f_p we will use observations of Q, measured flow area, wetted perimeter (A_f, P_w), and calculated R to calibrate a value of n_t for each experiment. Relating roughness of sediment grains to D_{50} of the in-situ channel sediments and using the assumption of n_t being an additive of roughness due to grains and obstructions, one can quantify n of BMP and calculate f_p. Through measurement of the hydraulic radius, as well as collection and analysis of transported sediment, we will be able to partition shear stress so that we can look at the relationship between the grain shear stress and the concentration of sediment that is transported. We will also be able run our model at the scale of the ditch line for same duration as this parameterization experiment to obtain sediment yield predictions. These predictions, as well as the sediment size distribution from the model, will be compared with properties of the sediment collected in the sediment tub. Such analysis will quantify the efficacy and efficiency of ditch line BMP being used at each site, as well as further develop and validate our model.

Budget

Water tanker $4000/year × 4 years (Years 1-4)
Graduate Student (already in Modeling Budget)

Road Micro-Topography Evolution

Water flow on roads is shallow, and small topographic features affect which way it flows. This is important to the ultimate disposition of water and the sediment it carries. If water flows diffusely, it causes little erosion, but if it concentrates in rills and ruts, it is more effective at moving sediment. If it flows off the tread into the ditch, ditch line BMP can act to moderate the sediment, but if it flows down the tread, it may deliver to the stream untreated. These changes over time are topographically subtle but critical to BMP effectiveness in the real world. Fortunately, theories, models, and instrumentation exist that can be applied to make these changes more predictable and observable.

In landscape evolution theory, model parameters that set the nonlinearity of sediment transport to flow shear stress directly control the spatial patterns of erosion and channelization of the modeled domain, as well as sediment yield at the outlet (e.g., Tucker and Whipple 2002; Hancock and Willgoose 2001). Understanding and accurately modeling micro-topographic evolution of the road surface, particularly the formation of concentrated flow patches (i.e., rills), is critical for the following reasons: (1) The formation of rills amplifies erosion and transport due to the development of much higher shear stress in concentrated flow than that which occurs in diffuse overland flow before rill development; (2) Higher shear stress in rills more effectively entrains and transports both fine and coarse sediment in greater volumes, altering the size distribution of sediment at basin outlet; (3) Representing the links between micro-topographic evolution and sediment characteristics of the road surface material, grading, traffic, climate, and lithology will have direct implications on road maintenance and traffic control. Therefore, having the capacity to realistically model micro-topographic features and sediment yields concurrently will enhance the model performance and credibility for producing large modeled data sets.

In the Modeling Theory Section, we outline a preliminary theory for the proposed numerical model for predicting topographic evolution and sediment routing. Model equations use median sediment size for sand, gravel, and fines, as well as their corresponding proportions on the road material as input. This Road Micro-Topography Evolution study will refine, calibrate, and test the model using high-resolution maps of road surface elevation (i.e., micro-topography) and road surface sediment characteristics.

We propose an experiment that will characterize changes in micro-topography and sediment properties over time using repeated measurements of surface elevation and sediment characteristics. In the past, erosion models have been tested with laboratory-scale experiments involving close-range photogrammetry and LIDAR mapping (Hancock and Willgoose 2001; Jomaa et al. 2010; Cuomo et al. 2016). To our knowledge, micro-topographic mapping on forest road surfaces and using them to confirm erosion predictions is unprecedented. The finest spatial resolution of interest for micro-topographic elevation mapping is the median size of gravel used in the road substrate because sediment transport theory uses median grain size as input to estimate transport rates.

We will take advantage of existing high-resolution surface mapping technologies available at the University of Washington. The Riegl VZ-4000 terrestrial laser scanner offers measurements of surface topography with approximately 1-3 centimeter accuracy and resolution. Unmanned aerial vehicles (UAVs) can be used for Structure from Motion (SfM) photogrammetry surveys which offer orthoimage mosaics and digital elevation models (DEM) with millimeter-scale resolution. Both technologies will provide elevation products with sufficient spatial resolution to precisely measure changes in road surface elevation and sediment size distribution.

Our goal is to produce multiple maps for micro-topographic change and patterns for 2 to 3 experimental sites. Weather conditions (e.g., rain and wind speed) and site conditions (e.g., road slope, surrounding tree canopy height/density, and turning radius of road curves) will be considered when selecting suitable field sites and mapping technology. At each site, we will map road micro-topography and ditch line conditions (e.g., ditch slope, elevation, and vegetation), as runoff and sediment from roads and rills may settle in the ditch. Measurements will be made during four periods: 1) Once at the end of the dry season; 2) Once after grading of the road surface; 3) Once during the wet season (twice if roads are graded in the wet season); and 4) Once at the end of the wet season. High-resolution image mosaics with resolutions ranging from centimeter to as low as millimeter scales will be generated in ASCII or netCDF formats and used for several different purposes. Sediment particle size and surface roughness will be estimated using grid resolutions commensurate with median sediment size observed in the field (e.g., millimeter-scale), as well as with direct sampling sieve analysis. Such high resolution gridded data (sediment grids) will be used to represent the spatial variability of sediment particle size. Digital elevation models (DEM) will be developed for modeling erosion and transport in Landlab with resolutions sufficient to resolve the formation of road rills and road micro-topography. For each modeling DEM grid, the grain size distribution will be assigned by averaging the grain size information contained in the finer-resolution sediment grids. DEM derived from repeated high-resolution measurements will be used to determine changes in patterns of erosion/deposition, density of drainage lines, surface roughness, and particle-size distribution over the study period. Differences observed in the DEM will also be used to make estimates of the amount of sediment production by roads.

Model simulations with Landlab will use micro-topographic maps and surface sediment size distribution from the beginning of the wet season. The model will be forced with observed rainfall for the same period as the field mapping. We will compare modeled elevation and sediment yield from Landlab against empirical sediment yield and micro-topographic observations from the end of the wet season. Sediment from cutslopes can be introduced as background soil creep rates, using existing geomorphic literature (e.g., Luce and Black 1999;

Reid and Dunne 1984). Model parameters will be calibrated as needed to match modeled sediment yields, as well as spatial details of micro-topographic change.

Micro-topographic mapping will be conducted under the supervision of Dr. David Shean, a research associate at the University of Washington Applied Physics Laboratory (APL), who will soon join the Civil and Environmental Engineering Department as an assistant professor. Dr. Shean has expertise in photogrammetric techniques and mapping landscape change using time series of high-resolution DEMs from satellite, airborne, UAV, and terrestrial platforms. The estimated budget with salary and fringe benefits, vehicle rental, and equipment use is $15,000 per year. Field data collection will occur over two years, for a total cost of $30,000. The work is currently planned for Years 1 and 2.

Sediment Trap Efficiency

A common BMP is the use of sediment traps in ditch lines to collect transported sediment and be periodically cleaned. These are usually dug at the end of a ditch line as a final treatment of water quality before water is released to a water body. Little is known about the efficacy of sediment traps. Fortunately, the basic principle is the settlement of particles as the velocity of water is temporarily slowed—it is conceptually a particle-settlement-time versus water-residence-time design. While such a design could be tested in a real ditch with trials over the course of several years, a more cost-effective approach can be used for bounding expected performance. We propose a more active experimental format to rapidly and inexpensively test the bounds of likely performance from this treatment.

The basic design will use half of an oil barrel on its side as the sediment trap (approx. 25 gallons or 3.3 cubic feet). This approximates a maximum practicable size considering ditch width, excavator scoops (i.e., common installation is two scoops, side-by-side, parallel to the ditch axis) and road safety (i.e., sediment traps on the scale of settling ponds that are immediately road-adjacent may be a hazard). Furthermore, there is no competing interest to make sediment traps any smaller. The experiment will utilize three flow rates, which changes the mean residence time of water in the trap. The experiment will also evaluate two source soils with varying particle size distributions, representative of the two lithologies chosen for the Major Experiment.

Flow rates will be varied through 75, 50, and 25 gallons per minute (gpm). These flow rates reflect the maximum flow rate expected for an 80-meter road segment (based on simple hydrologic calculation for 10-minute precipitation intensity) and two-thirds and one-third of that rate, respectively, as well as mean residence times of 20, 30, and 60 seconds in the trap, respectively. Water will be supplied from a sediment-free source (e.g., a portable fire pump with 90-100 gpm maximum flow rate).

Two sediment sources will be used, one from each of the two lithologies used in the Major Experiment. The samples will be sieved, and the fraction of sediment finer than 2 millimeters will be used to feed the traps. We expect the two lithologies to have relatively strong contrasts in clay and fine silt content. About 3 cubic feet of sieved material will be used in each replicate.

Operationally, the half-barrel will be set on the ground nearly level with a 10- to 15-foot length of a double-wall, 18-inch plastic culvert acting as a flume set on a 3% grade feeding it. The culvert will be fed water by the pump. A baffle will be placed to prevent direct flow-through of sediment laden water. Sediment will be placed in the approach trough for the water to carry to the trap. Outlet water from the trap will be run through one of the tipping bucket gages used in the Major Experiment with tipping bucket outflow being subsampled (a few milliliters per tip) and placed in a composited water sample.

At the end of the experiment, the sediment in the trap will be weighed. The concentration of sediment in the outflow water will be measured and multiplied by the total flow to estimate overflow sediment. The total mass of sediment from the trap and the outflow water will be compared to the input sediment mass placed in the flume to check mass balance. Mass placed in the flume will be based on the weight of the sediment along with the moisture content taken from 5 samples (placed in soil tins for lab analysis). The ratio of the trapped mass to the total mass is the trap efficiency. Additionally, particle size analysis will be done on the input soils, trapped sediment, and overflow sediment to calculate the trap efficiency by particle size range so that results can be extrapolated to other soils with different particle size distributions. These particle sizes will also be compared to the observed particle sizes of sediment from the Major Experiment to estimate sediment trap efficacy.

We envision this experiment as being ideal for a research experience for undergraduates (REU) where an undergraduate student will carry out the experiment and lab work under the tutelage of a graduate student.

Costs:

- Equipment:
  - Pump: $5,000
  - Pipe: $300
  - Barrel: $100
  - Tipping Bucket and Logger: $1200
- Student intern, 1 Quarter: $4,000

Cost Versus Maintenance Survey

This sub-project is a small and inexpensive survey that will be conducted by the TWIG. The survey will be distributed to road engineers that are members of the Washington Forest Protection Association, employees of WADNR State Lands, and to any other forest road engineers who are interested in participating. The survey will ask road engineers:

1) Which tread or ditch line BMP or combinations of BMP they are utilizing for road segments that cannot be disconnected from the channel network by cross-drain culverts;
2) How frequently these BMP have to be maintained for different traffic levels;
3) What the cost of installation of each BMP for an individual stream crossing location is; and
4) If they can provide a diagram or photos for unique BMP.

The cost question will specify that we want the cost for a "normal" BMP installation—if four rock dams in a ditch line down to a stream-crossing is the norm, then that is a BMP installation. The cost question will also assume broader maintenance efforts in the area so that cost estimates are specific to the BMP and are not inflated by mobilization. The road engineer will understand that he may have to consult with one or more of his road contractors for an accurate cost estimate. At issue is that hourly rates for road contractors and equipment may be proprietary. State or federal agencies must pay federal rates, but industrial timberland owners may choose to do a competitive bid process and may be unwilling or unable to reveal direct costs due to potential anti-trust issues. To sidestep this issue, and to obtain more directly comparable "costs" among BMP, we will consider asking for equipment and personnel time for each BMP rather than asking for actual monetary costs.

This effort will occur in Year 2 because it will inform the tread and ditch line BMP installation within the 80 sites in Year 4 (not to be confused with the installation of ditch line BMP in 4 sites within each lithology starting in Year 1 for purposes of the Ditch Line Hydraulics). Common BMP or combinations of BMP will be identified and utilized within the 80 sites. It will not be possible to test every tread and ditch line BMP within the 80 sites, but potentially effective BMP that are unique or rarely used could be added to the Ditch Line Hydraulics Sub-Project so that some information is acquired. Ultimately, this sub-project informs Critical Question #2.

Direct costs are limited to incidentals such as printing, postal fees, and meeting supplies (<$500).

Short-Time-Scale Interactions

Sediment production and transport from a forest road surface in short-time scales are controlled primarily by road surface characteristics including soil properties, contributing length and gradient, as well as triggering factors including traffic frequency and size, and rainfall intensity and duration (Fu et al. 2010; Reid and Dunne 1984; Van Meerveld et al. 2014). The processes that produce fine sediment are understood to be disturbance of the armor layer, pumping of fines from subgrade, and crushing of rocks on the surface. In combination with these processes, precipitation can lead to increases in sediment production during rainfall events that persist for tens of minutes following a passage of trucks (Luce and Black 2001a; Van Meerveld et al. 2014; Ziegler et al. 2001b). For example, a study on Honna Watershed, Haida Gwaii, British Columbia, Canada showed that the total mass of the sediment increases linearly with precipitation intensity (Van Meerveld et al. 2014). Similarly, Van Meerveld et al. (2014) showed that elevated sediment concentrations in road surface runoff persisted for 30 minutes following the passage of loaded logging trucks during low intensity (<8mm/h) rainfall events and for much shorter periods at higher rainfall intensities. However, the study showed no significant sediment pulses during the passage of empty trucks, except during very high rainfall intensities.

To better understand how to control this sediment source efficiently, we need to study the contribution of fines on these short-time scales in the context of overall annual plot sediment production. The focus of this experiment is to measure sediment detached and transported from the road tread under variable surfacing rock quality, truck frequency, and rainfall intensity. This experiment will determine how much sediment is produced from the road surface and where the sediment goes during a rain event after a truck pass. In addition, we will examine the within-plot contribution of sediment from traffic relative to that from ditch and cutslope by sampling water from: a) the tread as it enters the ditch from the road side; b) the ditch upstream of the tread contribution; and c) the outlet of the cross-drain culvert after the first two have combined. If possible, we will also try to sample water flowing from the cutslope. A combination of photography and videography using a digital camera and physical samples of the traffic-generated fines in the tread will be used to examine evolution of the tread sediment particle size distribution and supply of mobile sediment at very short time scales. A digital recording turbidimeter placed on the plot outlet will give fine temporal scale data on how plot turbidity contributions change over time while flow variations are being recorded by plot equipment.

Figure 8. An example of a wet forest road surface after trucks have passed. The sediment in the upraised patterns are fine sediments that were pressed into tire sipes and would be easily transported if it were raining.

The study will develop a large number of sediment production datasets associated with variable surfacing rock qualities, rainfall intensities, and passes of trucks. Statistical analyses of these datasets will help identify factors that contribute to sediment yield and transport and provide specific information to policy makers about sediment production at differing haul levels and rainfall rates. The results will also help to calibrate and refine the proposed Landlab-based erosion modeling.

If most sediment is generated by individual truck passes, then predicting the production of sediment from each truck pass can become a key focus of future research. The questions would turn specifically to the influences of surfacing, subgrade design, country rock, tire pressure, traffic frequency, and antecedent rainfall on the amount of sediment produced by each truck pass. Fortunately, sediment produced by an individual truck pass can be sampled on short-time scales and small plots, leading to very high sampling rates and relatively low cost measurements. Such a sampling scheme also allows for algorithmic statistics to rapidly learn from a large number of samples. A benefit of the short-time-scale Parameterization Experiment will be in building the background and logic needed to support a more-efficient high-sample-rate means of measuring road impacts on water quality.

Field methods will include:

1. Selection of two sites in each lithology, one in "good" surfacing rock and one in "marginal" surfacing rock. These will not be grassed.
2. Conduct experiments during variable conditions of natural rainfall following average winter conditions (i.e., not after a big storm event and not after an extended dry spell such that antecedent conditions are typical of most weeks during the winter).
3. Collect road runoff and sediment after each passage of a loaded 10 yd^3 dump truck. Additional collection of road runoff and sediment after passage of unloaded trucks or recreational/work "pick-ups" may be needed to understand their contributions.
4. Vary timing of truck passes, maybe 15-minute and 30-minute intervals during different collection periods. Skip dump truck pass if a loaded log truck or dump truck drives through the segment.
5. Photographs and videos will be taken using a digital camera on a stand with a macro lens to document disturbance of the wheel tracks and as a means to measure sediment sizes remaining afterwards. The camera will visually document the armoring of the surface as rainfall removes fines, providing a basis for visual monitoring of road condition and susceptibility to erosion.
6. Continuous turbidity monitoring at the cross-drain outlet will occur.

This is currently planned for Years 3-4. Total cost for four plots (16 samples) is $60,000.

Budget:

Crew (16 days/yr)	$6000/yr X 3yrs
Travel	$6000/yr X 3yrs
Traffic for hire (dump truck)	$8000/yr X 3yrs

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GRAIP/WARSEM Delivery Analysis and Survey

This parameterization experiment evaluates the degree to which the distance of a forest road from a stream affects the probability of sediment from a drainage structure (e.g,, cross-drain culvert or steel trough) reaching the stream. Several factors in addition to absolute distance may influence the results and will be evaluated as covariates. The length of road draining to the drainage structure and total drainage area of that road segment are closely related and have been shown to strongly influence the probability of delivery. For example, related survey work on stream connectivity shows an effect of the contributing length of road on the probability of delivery at different distances for a large Idaho dataset (Luce et al. 2014, Figure 6). Other factors, such as hillslope gradient, did not strongly influence the Luce et al. (2014) results, but greater soil development, particularly greater accumulation of the humus layer, may cause western Washington results to be different from those observed in Idaho. In addition to contributing road length, contributing drainage area, and hillslope gradient below the drainage structure, ditch line gradient and lithology will be evaluated for potential influence. Emphasis will be placed on data collection along HTNS roads. These will be evaluated as a subset because large volumes of fine sediment produced by high-traffic road segments may travel farther than is generally observed in other circumstances. This is partially because high-traffic roads are wider and, for a given length of road, contribute more water to a cross-drain culvert. Delivery distances are shorter for smaller contributing road lengths, which is relevant to the use of crowning, outsloping, or steel troughs to reduce the area of roads contributing to stream crossings. These results will help landowners identify those segments of HTNS roads that cannot be disconnected from the channel network with just the installation of drainage structures (i.e., usually cross-drain culverts in western Washington) and focus the use of tread and ditch line BMP to those road segments with the most critical need. The data will also inform future landscape-scale modeling efforts (see the Expected Results Section).

For this analysis, we will use a sediment delivery survey developed in a manner that facilitates comparisons with pre-existing datasets such as the Luce et al. (2014) which was collected using the GRAIP methodology (Black et al. 2012). It may also be possible to augment our dataset with the Washington Road Sub-Basin Scale Effectiveness Monitoring First Sampling Event (2006-2008) dataset (Dubé et al. 2010) which was collected using the WARSEM methodology (Dubé et al. 2004). An example of how simple it is to simultaneously use both methodologies is that GRAIP is a simple Yes/No delivery answer whereas WARSEM has 25%, 50%, 75% and 100% delivery estimates if delivery is occurring—any percentage of delivery in WARSEM is a “Yes” in GRAIP for purposes of data comparison. We can also apply a multinomial statistical model with the WARSEM data to statistically test data in a similar way.

Crews will travel down a road, measuring the spacing and nature of road drainage features and follow the outlets of road drainage to see where evidence of sediment transport, such as scouring of the hillslope or deposition of fresh sediment, stops and whether it reaches the stream. They will measure hillslope and ditch line gradient, and map three points—top of the road segment, drainage feature, and last sediment/scour observed. Lithology and contributing drainage area will be GIS evaluations and will not be field measured.

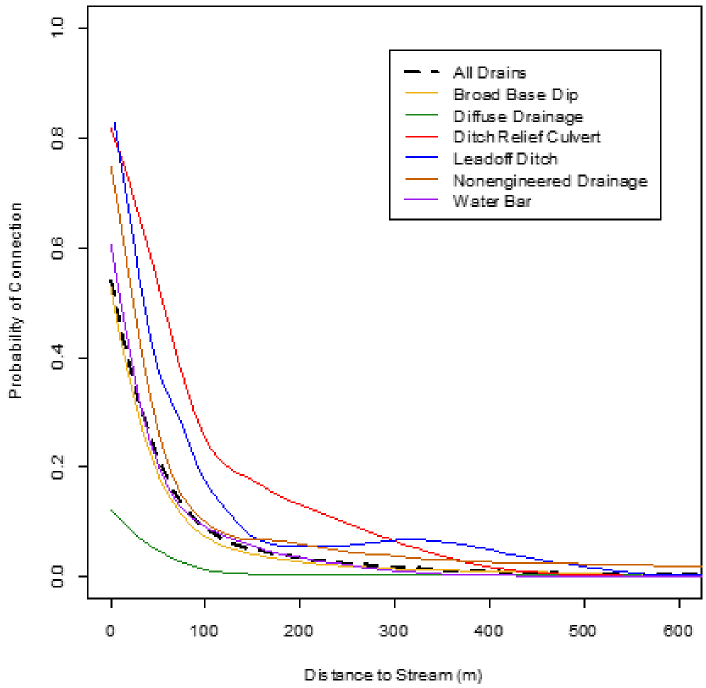

Figure 9. Probability of hydraulic connection in Idaho State between a road drainage diversion and a stream as a function of the drain type and distance to stream (Luce et al. 2014).

We propose to carry out this parameterization experiment during Years 5 and 6 with a crew of two people surveying about 100 miles of road split across the study areas, focusing on the high-traffic roads. This work will occur during the winter months when evidence of sediment transport will be the most visible both because the evidence will be fresh and because grasses and leaves on brush will be minimal.

Costs for a seasonal crew, their transportation, and travel are about $30,000. Cost for 7 days of wet weather sampling including travel by non-seasonal crews would be about $5,000. Data analysis, including summary of the Dubé et al. (2010) dataset, will cost about $12,000. The work is currently planned for Years 5 and 6. The total cost for this study element is therefore estimated to be $47,000.

Empirical Analyses and Statistics

The empirical analysis of the Major Experiment, in combination with that of the Parameterization Experiments, will use the independent variables we develop—the critical shear stress (e.g., fine sediment availability), the grain shear stress, and the flow rate—regressed against observed sediment yields. The Parameterization Experiments will be used to distill each BMP into what it does to the critical shear stress and the grain shear stress, and the Major Experiment will examine how critical shear stress and shear stress partitioning affect sediment yield. In this regression analysis, each BMP or combination of BMP resolves into these two independent variables rather than being analyzed as a unique entity unto itself. Because each BMP affects sediment yield through how it contributes to decreasing fine sediment availability (as measured by critical shear stress) and reducing the shear stress of the flowing water acting on sediment particles (shear stress partitioning), this is a powerful and cost-effective way to estimate the benefits of individual BMP (or combinations thereof) without actually measuring each in the Major Experiment.

We will also analyze the Major Experiment dataset to report on BMP effectiveness directly. Its design allows for interpretation of BMP applications in a Before-After-Control-Impact (BACI) design, considered one of the most powerful bases for logical inference. For the Major Experiment, specifically tested BMP include: 1) Three surfacing rock types, "good" and "marginal" from local rock pits and "quality" which will be truly high quality aggregate; 2) Grassed ditch lines; 3) An elevated BMP in the ditch line; and 4) Another BMP to be identified before its installation in Year 4. These BMP will be tested in the context of several covariates (see Table 2 above) including two lithologies selected to have different proportions of fine sediment and different hydrologic properties, across a range of rainfall typical of western Washington forest land, with varying traffic and grading regimes.

Statistical approaches will need to include multiple BMP treatments and multiple years in some cases. An analysis of variance (ANOVA) will test BMP combinations, and an analysis of covariance (ANCOVA) will test covariate influence of BMP treatments. However, even with 80 plots, the power of these tests will be fairly low because the number of samples in a given cell of the ANOVA/ANCOVA design will be small. We will use a variety of tools for different questions as the data set expands through time to identify groups for comparison that will best leverage the restricted number of plots available. For example, the resulting first-year data set will compare surfacing BMP with up to 20 replications and allow prediction equations with a suite of covariates developed at each road segment (Table 2). In addition, first year tests of differences in surfacing performance can robustly use t-tests in Year 1 (e.g., coarse sediment metric - kg/yr). Similarly, robust relationships of the covariates with a dependent variable (e.g., mean monthly suspended-sediment concentration) will be developed.

Tread and ditch line BMP additional to those tested in the Major Experiment will be tested in Parameterization Experiments. Each experiment of an individual BMP will be a strong test/measure of effectiveness, but each is also strongly conditional on how the experiment is set up, such that a full range of real world circumstances will not be tested. This limits broad generalization of these results and necessitates thoughtful modeling as a basis for extrapolation to other conditions.

We will combine these different sources of statistical information through the use of the Landlab-based modeling to generalize the results of the Parameterization Experiments to the full scope of conditions covered in the Major Experiment, and we will compare the Landlab-based modeling to the statistical regression model from the Major Experiment. Following the development of large datasets comprised of both modeled data and observational field data, we will apply statistical methods to Landlab-generated data and search for relationships between sediment yield, rainfall, road BMP, road segment characteristics (e.g., slope, length), and lithology. Specifically, these modeling experiments will help us quantify the variability of sediment production and the influence of storm events in driving annual sediment yields within the scope of climate and lithology measured in the Major Experiment. The empirical formulations from the statistical analysis will provide alternative formulations that can be used in existing empirically-based tools such as WARSEM and GRAIP, particularly for framing consequences of multiple BMP installations. Our experimental field monitoring and numerical model results will offer a uniquely rich dataset to investigate and address CMER Work Plan and Study Design critical questions listed in the Critical Questions Section.

Table 9. List of the Study Design Critical Questions and which parts of the study design will answer each question.

Critical Questions	**Answered By:**	
How effective are road sediment BMP, individually and in combination, at minimizing production and delivery of coarse and suspended sediments from forest roads to streams (DNR Typed Waters)?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	**X**
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	
	Short-Time-Scale	**X**
	GRAIP/WARSEM	**X**
What is the comparative effectiveness of BMP in minimizing the production, routing, and delivery of sediment to streams (defined as DNR Typed waters)? And what are the comparative installation cost effectiveness, and maintenance cost effectiveness and frequency, of these BMP?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	**X**
	Short-Time-Scale	**X**
	GRAIP/WARSEM	
For individual or combinations of BMP, are increases in turbidity minimized?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	
	Short-Time-Scale	**X**
	GRAIP/WARSEM	

Are the effects of combined BMP for the road surface and ditch lines additive, multiplicative, synergistic, or antagonistic with respect to runoff and sediment production from road segments?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	**X**
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	
	Short-Time-Scale	**X**
	GRAIP/WARSEM	
To what extent do road BMP affect water storage and erosion potential at site-scale road segments?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	
	Short-Time-Scale	
	GRAIP/WARSEM	
How do different characteristics of topography and lithology effect the selection and design of road BMP?	Major Experiment	**X**
	Ditch Line Hydraulics	**X**
	Road Micro-Topography	**X**
	Sediment Trap Efficiency	**X**
	Cost vs. Maintenance	
	Short-Time-Scale	**X**
	GRAIP/WARSEM	**X**
How quickly after installation or removal of BMP does the post-construction disturbance that temporarily increases sediment production and delivery abate?	Major Experiment	**X**
	Ditch Line Hydraulics	
	Road Micro-Topography	
	Sediment Trap Efficiency	
	Cost vs. Maintenance	
	Short-Time-Scale	**X**
	GRAIP/WARSEM	

Modeling Framework

Because of the complexity of processes that govern BMP performance and the large number of factors that influence them, it is difficult to extrapolate findings of local field studies of road erosion, hydrology, and BMP performance to other locations. A wide range of treatments for reducing erosion from forest roads exist (Burroughs and King 1989; Dubé et al. 2004), and combining them all into an experiment as unique and individual treatments would be overwhelming. Therefore, a theoretical modeling framework that is based on the principle of continuity of water and sediment across the road prism, and that integrates road prism processes with hillslope hydrology and sediment input/output across its boundaries (see Figure 7), is needed. In addition, this theoretical modeling framework can help interpret and merge findings from past field studies and guide future field research and design of road BMP. However, it is imperative to keep in mind that this modeling framework will not be designed for direct operational use, such as by a forest engineer estimating sediment production, but rather by future researchers who may use the Landlab products to simplify both the field work needed to calibrate road erosion in other locations and the efforts needed to test additional BMP.

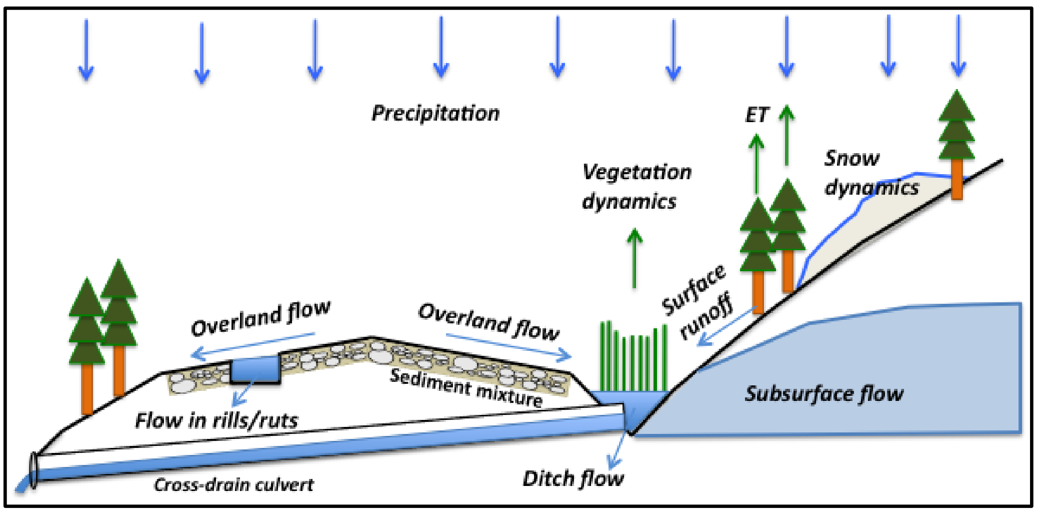

Figure 10. Forest road cross-section with some of the proposed model components indicated in text.

Limited modeling capacity of road erosion already exists. A review of models available for road erosion estimation is provided below in Appendix B – Best Available Science Summary. However, these models do not provide a robust theoretical framework upon which to merge information from multiple empirical studies across different environments. No existing model embodies the features and processes of the environment necessary to study the impacts of road BMP alternatives. Empirical models focus on mean annual response at the scale of road segments using simple linear equations based on a set of multiplicative factors that relate to road, environment and BMP conditions, and neglect physical processes, nonlinearity, local lithology, and climatic variability. Physical models are often over-parameterized and adapted from agricultural and rangeland literature. Representation of hillslope hydrology and lithologic and topographic controls on runoff generation are not included in any model. Current models lack proper representations of water and sediment generation, transport, and storage dynamics across the road prism and the influence of BMP on these processes.

One of the overarching questions of this project is: *How do road BMP affect sediment supply, sediment transport, and road runoff in different environments*? To address this question, we aim to improve the predictions of existing road erosion models and develop capacity to assess the influence of road BMP on runoff and erosion. This research question, as well as the study design critical questions posed earlier, will guide the development of our field and modeling approach. Inherent in this is the premise that some of the well-developed and tested theoretical concepts in fluvial geomorphology, sediment transport, and hydrology can be applied to modeling road surface processes and BMP performance (Figure 8).

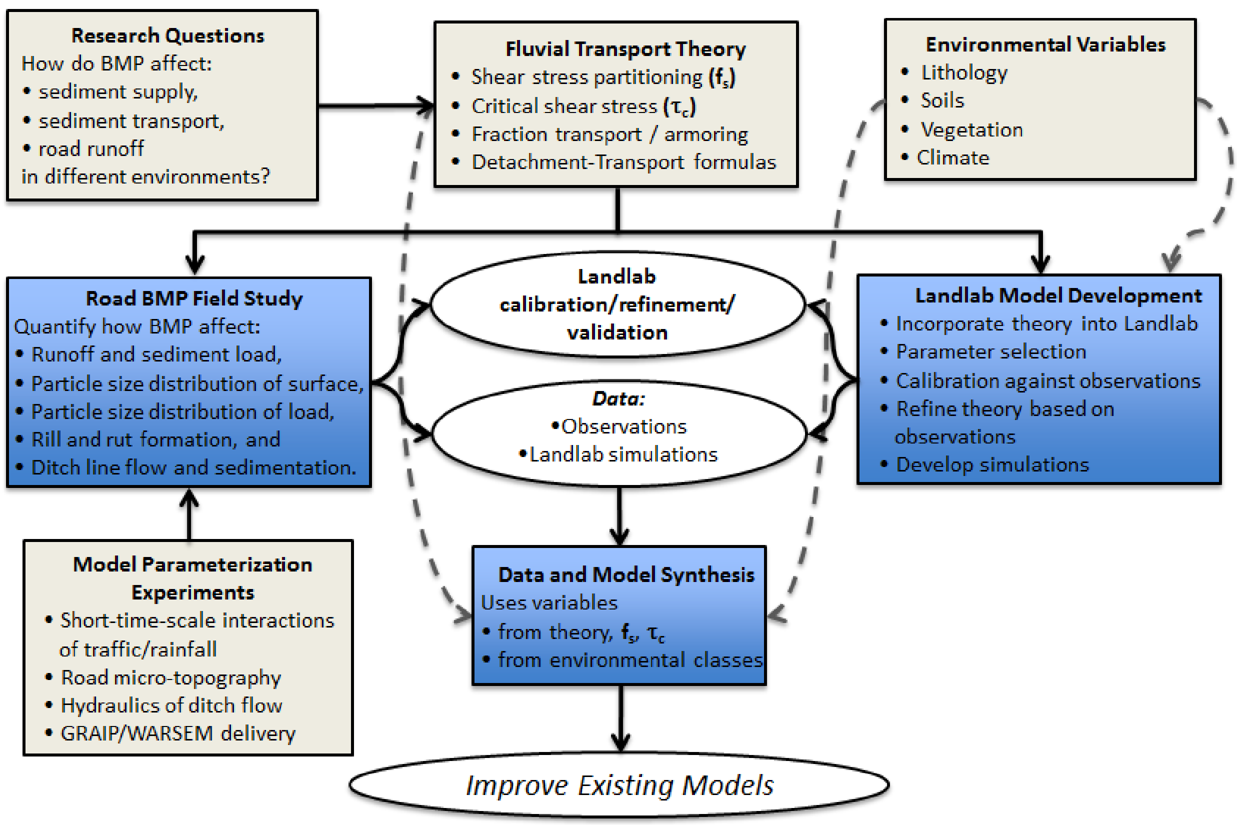

Figure 11. Diagram of Interactions between Road BMP Field Study Design, Landlab Model Development, and synthesis of observational and modeled data to improve existing models.

To guide model development and field studies, we will first adapt existing fluvial geomorphic concepts for overland flow sediment detachment and transport based on shear stress of flow, critical shear stress of eroding substrate, and shear stress partitioning ratio due to biomass and surface coarsening (e.g., Istanbulluoglu et al., 2003, 2004; Istanbulluoglu and Bras, 2005). We will also conceptualize models for sediment production and fining on road tread as created by traffic and runoff. In the next section, we present theory that will be used to develop the first version of the model (i.e., null hypothesis model). These formulations will be corroborated with field observations—refined, or in some cases refuted, for modeling road surface processes. The fluvial theory adapted for roads and conceptualizations of sediment production on the road prism will be implemented in an existing grid-based geomorphic modeling framework called Landlab (Hobley et al., 2017). Landlab development for watershed modeling has been funded by the National Science Foundation to University of Colorado, University of Washington, and Tulane University. In this project, Landlab will be adapted and implemented on forest roads and new components will be developed to represent forest road BMP and hillslope hydrologic processes. Landlab will predict water and sediment dynamics of the road surface and ditch line driven by individual storms and traffic, under the influence of single and combinations of BMP.

Initially we will construct representations of BMP and theoretical forms of shear stress, critical shear stress, and shear stress partitioning concepts in Landlab. This initial model will first be run on road segments representative of the environmental and topologic conditions of HTNS roads in select regions of Washington State. Numerical model simulations will be driven by local climatology observed in regional observational networks such as COOP stations or gridded data sets used to drive numerical models of hydrology (e.g., Livneh et al., 2013; 2015). Istanbulluoglu and his group recently developed Landlab routines to automatically download and extrapolate weather data from regional historical gridded data sources to use in any given location in the country. Results from numerical experiments will be used to prioritize the types of BMP and their combinations for developing field experiments.

Our field studies are designed to collect observational data that quantify the variables outlined in the theoretical modeling approach (e.g., runoff, sediment yield, and road surface sediment size distribution and micro-topography) and implement combinations of BMP in the field guided by a series of numerical Landlab experiments. Experimental data from field sites will enable calibrating, validating, and refining Landlab theory and assumptions. For each of the 40 experimental sites with and without BMP combinations, Landlab will be run continuously as observational data becomes available. Multiple variables—elevation, rut forms, sediment size distribution, runoff, and sediment yields—will be used in model evaluation. We aim to optimize model parameters so that the model can be run for different lithologies using only parameters that can be measured *in situ* (e.g., median sediment size) or parameters that can be obtained from maps (e.g., soil texture and rock type).

An initial set of model runs will use base parameter values and coefficients from existing literature. We will group site conditions, such as lithology and BMP. With each model run, in each group, we will explore the components of the model that may be calibrated, staying within realistic ranges of parameters. We will group final model parameters from each run and compare parameters across different field settings. We expect that each model calibration will inform the selection of model values in subsequent runs within each group. This thorough model calibration, evaluation, and refinement will result in a final set of model formulations and parameter ranges that best represent road erosion processes as well as the effects of single and combined BMP.

The improved versions of the model will be used to create simulated data sets for locations and conditions across forest roads within Washington State. Following this process, the proposed model will be able to predict water and sediment dynamics in the road tread and ditch line under the influence of single and combined BMP. We will then use the model across other selected locations to develop a large modeled dataset to study effects of BMP combinations, as well as the role of local conditions and initial conditions (e.g., road location, topography and lithology). Our experimental monitoring and modeled data will offer a unique and rich data set which will be grouped, analyzed, and synthesized using existing statistical techniques to address the CMER Work Plan and Study Design critical questions as elaborated in the Expected Results section.

Modeling Theory - Road Prism Erosion and Surface Dynamics Model

In this section, we describe the proposed road prism erosion and surface dynamics model that will be implemented using the Landlab earth surface modeling framework (Hobley et al. 2017). The theory presented here will be calibrated and refined using observations from field experiments. The model will use fine-scale spatial representation of the road prism elevations. Initial simulations will be run at 10-20 cm grid resolutions and will be made finer as model stability is tested and improved.

Sediment Mass Balance

Sediment depth and size distribution (gravel, sand, and finer proportions) will be modeled on the actively eroding road surface and ditch. This layer of active erosion will be taken as surface layer of a few centimeters (e.g., 2-5 cm). Changes in the substrate depth, h_s, and the elevation of the road prism, z, in length units [L] can be written using conservation of mass:

$$h_s(x,y,t) = h_s(x,y,t-\Delta t) + \Delta h_s(x,y,\Delta t) \qquad (1a)$$

$$z_s(x,y,t) = z\ (x,y,t-\Delta t) + \Delta h_s(x,y,\Delta t) \qquad (1b)$$

$$\Delta h_s(x,y,\Delta t) = S(x,y) - U(x,y) - E(x,y) + D(x,y) \qquad (1c)$$

where x and y represent the location of a point on the Cartesian plane; Δh_s is change in substrate depth [L] over a duration of Δt; S is new sediment supply by surfacing material [L], if any, over Δt; U is a local fine sediment production term by traffic and disturbances [L]; E is erosion by water [L]; and D is the deposition of sediment through the settlement of fines pumped out of surrounding areas or deposition of sediment transported by overland flow [L]. In ditches with vegetation growth, D would be particularly high. The mass balance equations presented above are written using discrete time steps to conceptualize the model.

The two variables that make this general mass balance model unique for unpaved forest roads are S and U terms introduced in equation (1c). Sediment supply by surfacing, S, will be a discrete process in time and will add material on the road crown through a user-specified interval in the model with a given substrate size distribution. This will be one of the BMP options in the model. The sediment production term, U, will represent the pumping of fine sediment from the sediment mixture due to vehicle traffic, disturbances, and road maintenance during the rainy and non-rainy seasons (Megahan 1974). We will test different formulations to relate U to the frequency of traffic as well as disturbance caused by each vehicle passage. We will also relate U to time since surfacing or disturbances use an exponential-decay model (e.g., Megahan 1974; Luce and Black 2001b; Ziegler et al. 2001b). The sediment made available by U will settle in the surrounding areas and will be treated as D, and will add more fine sediment on the surface (e.g., the "active layer"). Our initial model for settling of sediment will relate the fraction of fines settled to distance from the source. We will develop field experiments to characterize the rates of U for different road BMP, lithology, and traffic conditions (see Parameterization Experiments Road Micro-Topography Evolution and Short-Time-Scale Interactions). Data gathered from the experiments will be used to develop empirical formulations for local rates of U and its dependence to environmental conditions, traffic, and road maintenance.

Overland Flow

Rainfall in excess of infiltration becomes overland flow on the road tread. Following the work of Luce and Cundy (1994), the physical-based parameters of existing infiltration equations will be estimated. The ditch line will collect runoff from both surface overland flow from roads and subsurface flow from the hillslope above the cutslope. Hillslope contribution (i.e., antecedent moisture) will be modeled based on existing subsurface flow models such as TOPMODEL (Beven and Kirkby 1979), which is relatively well developed and tested in mountainous landscapes.

Generated runoff from the road surface and ditch line will be used as input to a flow routing component in Landlab. Landlab contains several surface water flow models, including an explicit two-dimensional solution for the shallow water equations. The OverlandFlow component has been adapted from the flood inundation model described by de Almeida et al. (2012). Water discharge is calculated on each active link that connect cells within the model domain, simulating a hydrograph at each link location. This will give a simulated hydrograph between model grid cells that make up the road surface. A set of simulations that explicitly change the micro-topography on the road surface and ditch line will be developed over scales consistent with actual rill and channel lengths. If numerical stability cannot be obtained over that scale, we will use simpler kinematic wave approximations. In some cases, sub-grid parameterizations of channel properties (such as channel shape or hydraulic radius) may be used, especially in ditch lines. The overland flow component will provide a spatial field of water depth, h_w [L], and/or hydraulic radius, R, and discharge, q [L^2/T], per unit width of flow. In a generic form of function, *f*( ) these can be written as:

$$
\begin{aligned}
h_w(x,y) &= f(q,n_t,s) \\
R(x,y) &= f(q,n_t,s)
\end{aligned}
\qquad (2)
$$

The total Manning's hydraulic roughness of the composite surface is n_t which may include additive contributions from the roughness of substrate (n_s), vegetation (n_v), and other elements used for BMP materials such as straw material (waddle, bale, fencing) and rocks. Local slope of the land surface and/or water surface, s, will be calculated in the model by $s = -\nabla z$ with each iteration of the model modifying the elevation field.

On road tread, n_t can be much lower than n_t in the ditch line and will be almost exclusively controlled by the median diameter of the road material. Several empirical equations for calculating overland flow hydraulic roughness due to sediment size are of the following general form (Yen 1992):

$$n_s(x,y) = k \cdot D_{50}(x,y)^p \tag{3}$$

where D_{50} is the median sediment size of the substrate (road or ditch line) at a given location on the road system, and k and p are empirical parameters.

In ditches, hydraulic radius of the flow can be obtained from the Manning's equation for flow velocity, using flow discharge and the total Manning's roughness of the ditch, $n_t = n_s + n_v + n_{BMP}$:

$$R = \left(n_t \frac{Q / A_f}{\sqrt{s}} \right)^{1.5} \tag{4}$$

where, Q and A_f are the ditch line discharge and wetted flow area of the ditch, respectively. Hydraulic radius is a ratio of the wetted flow area of the ditch to the wetted perimeter of the flow (i.e., $R = A_f/P_w$, where P_w is wetted perimeter of the flow). Testing of the impact of different BMP materials on n_t will be included in our experiments for ditch lines (see Ditch Line Hydraulics) by measuring A_f, P_w for given Q. When n_s is approximated by (3), contribution of vegetation and other BMP elements can be estimated by obtaining n_t from (4) and subtracting n_s.

Erosion Model

In the erosion model, we will use shear stress-dependent formulations for local detachment of sediment and its transport by overland flow. At each grid element of the modeled domain, shear stress acting on the road crown and ditch line will be calculated either by water depth or hydraulic radius as:

$$\tau = \rho_w g h_w s$$
$$\tau = \rho_w g R s \tag{5}$$

where, τ is boundary shear stress [Pa: kg/(ms^2)], ρ_w is the density of water [kg/m^3], g is acceleration due to gravity [m^2/s^2], s is sine of local slope angle [-]. The use of h_w versus R is dependent on the scale of the simulation. We will use R in ditch lines.

Besides its contribution to surface overland flow depth, the size distribution of sediment also contributes to sediment transport rates. We propose to model proportions of gravel, sand, and finer than sand sediment sizes such as silt (as a lumped category) within the active sediment layer in space and time over the road tread and ditch line. Because traffic produces fine sediments and soil wash, rill incisions often transport fine particles, leading to the coarsening of the surface sediments during runoff events (Luce and Black 2001a, 2001b). Road surfacing is a widely-used BMP to maintain and reduce erosion from roads. It also changes the size distribution of available sediment on the road surface. Our goal is to keep track of changes in the sediment size distribution on the road surface during and after sediment transport and erosion events caused by overland flow. Keeping track of such changes will allow us to model the fluxes of fine and coarse sediment size fractions from the road system into channels. For sand- and gravel-sized sediment, we propose to start our modeling experiments using fractional sediment transport capacity equations for sand and gravel proposed by Wilcock (2001) and modified by Wilcock and Crowe (2003):

$$q_{s,i} = \frac{W^* F_i \left(\tau / \rho_w\right)^{1.5}}{(s-1)g} \tag{6}$$

where $q_{s,i}$ is volumetric transport rate per sediment size *i*, F_i is the proportion of sediment size *i* in the mixture, and s is specific gravity of sediment. W* is a non-dimensional fractional transport rate that scales highly nonlinearly with the ratio of τ to reference shear stress of sediment size i, $\tau_{r,i}$, as described by Wilcock and Crowe (2003). $\tau_{r,i}$ is the value of shear stress that causes a small "reference" amount of sediment transport, and it is conceptually the same as critical shear stress. For a given τ, W* is much smaller for gravel than for sand sizes. Equation (4) can also be parameterized for the fractional transport of sand and gravel given their respective median grain sizes, $D_{50,sand}$ and $D_{50,gravel}$, in a sediment mixture represented by the D_{50} of the substrate (Wilcock 2001).

The total volumetric sediment transport rate leaving a model grid cell is composed of the transport of gravel, sand, and finer than sand (fines)-sized sediment:

$$q_s = q_{s,sand} + q_{s,gravel} + q_{s,fines} \tag{7}$$

Given the rate of sediment flux, q_s, above, changes in the thickness of the substrate caused by overland flow erosion or deposition can be modeled by

$$\frac{\partial h_s}{\partial t} = \frac{\sum q_s^{in} - q_s^{out}}{w} \tag{8}$$

where $\delta h_s/\delta t$ is the rate of change in substrate thickness. The first term on the right is the sum of incoming sediment flux into a model grid cell and the second term is outgoing sediment flux, typically taken as the sediment transport capacity from (7), and w is the model grid cell width. This formulation assumes transport-limited conditions, which implies that sediment is always available for detachment on the surface and it is cohesionless. When a need to introduce limitations in detachment arises, a detachment capacity equation can be included in this formulation (e.g., Istanbulluoglu and Bras, 2005). The input of sediment from cutslopes and erosion from fillslopes can be modeled with the fluvial model outlined above using D_{50} of natural sediments. Soil creep and rain splash processes can be implemented as needed for cutslopes and fillslopes (e.g., Istanbulluoglu et al. 2004).

The model will use previously documented relationships between sediment transport and flow to estimate various sources of sediment based on the characteristics of those areas. This will give a physically-based theoretical expectation, which will then be tested using measurements and simple statistical approaches. Comparison of estimates with measurements will give an objective estimate of uncertainty. Separating sources of uncertainty between cutslopes and other areas may be assisted through the Short-Time-Scale parameterization experiment.

Removal of fines and sand by overland flow erosion, addition of gravel by surfacing, or deposition by overland flow will all change the median diameters of the substrate as well as the fractions and median diameters of sand and gravel in the mixture. A few examples of tracking median sediment size and fractions of sand and gravel on eroding surfaces exist in literature (Gasparini et al. 1999; 2004). A linear averaging approximation will be our first hypothesis for the spatial evolution of the substrate:

$$D_{50} = D_{50,sand} F_{sand} + D_{50,gravel} F_{gravel} \qquad (9)$$

As the proportion of sand and gravel changes with erosion and deposition, the variables in the equation above can be calculated spatially in the model (Gasparini et al. 1999; 2004).

On insloped and crowned forest roads, sediment eroded from road tread deposits in the ditch line. Common ditch line BMP used to stabilize these deposits include vegetation such as grass and the spreading of straw. The influence of such BMP on local sediment deposition, local sediment erosion, and net sediment yield from a road prism to streams can be evaluated using the concept of shear stress partitioning. Considering the relative contributions from sediment and channel form on flow roughness, Einstein and Barbarossa (1952) proposed to partition the boundary shear stress into grain and form roughness components.

$$\tau = \tau_s + \tau_f = \rho_w g R_s s + \rho_w g R_f s \qquad (10)$$

where, τ_s and τ_f are shear stress, and R_s and R_f are effective hydraulic radii due to sediment grains and form resistance components, respectively. In this project, τ_f and R_f will represent the shear stress and effective hydraulic radius due to different BMP. In the following example, however, τ_f and R_f represent the shear stress and effective hydraulic radius due to vegetation. Utilizing the concept of shear stress partitioning, the shear stress acting on sediment grains (sand/gravel) can be written using a partitioning ratio, f_p:

$$\tau_s = \tau \cdot f_p$$

$$f_p = \left(\frac{n_s}{n_s + n_v + ...} \right)^{1.5} \tag{11}$$

Data from published field experiments (Istanbulluoglu and Bras 2005) related n_v to vegetation biomass. In our proposed field experiment, n_v and n_{BMP} for other BMP will be obtained by solving equation 4 for n_t.

Sediment Yield

The erosion theory outlined above will predict spatial patterns of erosion and deposition on the road prism. Road erosion models currently being used give mean annual road sediment yield. Our model can be cast as a mean annual, annual, or seasonal tool for predicting sediment yield from road surfaces and may be simplified in an empirical form and tested against data. At the outlet of a road segment, the flux of sediment that leaves the road can be integrated over a long timescale, T, to estimate sediment yield (eq. 12, first term). Based on the conservation of mass principle used in the model, this would be the same as adding the net erosion, E_{net}, at each model grid cell over space and time (eq. 12, second term):

$$Q_s = \int^{T} q_s^{out} dt = \int^{T} \int^{A} E_{net}(x, y, t) dadt \tag{12}$$

where A is the area of the road surface and a is the area of a model grid cell. Eq. (12) can be written in a generic "empirical" form of an unknown function that relates the key model variables to modeled Q_s:

$$Q_s = f(P, HL, L_r, W_r, S_r, D_{50}, F_{sand}, F_{gravel}, W^*, f_p) \tag{13}$$

where, P is the rainfall over the duration of T, HL is the hillslope lithological controls for runoff generation, and L_r, W_r, and S_r are road length, width, and slope, respectively. D_{50} is the median sediment size for the substrate mixture as well as sand and gravel components of the mixture, F is the proportion of sand/gravel in the mixture, W* is a non-dimensional transport coefficient which may vary with different road surfacing treatment, and f_P is the shear stress partitioning ratio of the ditch line which will vary with different BMP. In an empirical model, substrate related variables may be given as initial conditions and erosional response can then be related to other variables. Multiple ways exist to explore observations using the variables listed above. A statistical approach will be used to develop empirical formulations from process-based modeling results and sediment-yield observations in the field.

Model Sensitivity and Validation

The proposed Landlab components for road runoff generation, sediment detachment, and sediment transport will be tested and cross-validated using observations from both the Major Experiment and Parameterization Experiments. Sediment production and transport models require several empirical parameters that will be calibrated and validated using observations. These may include, but are not limited to: the rate of local fine sediment production in relation to trafficking and rainfall conditions; non-dimensional transport rate coefficients in the Wilcock and Crowe (2003) sediment transport formulations (W*); and simple source-discharge dependent suspended sediment formulations. The following two general strategies will be used in our model parameterization, sensitivity analysis and validation.

(1) All-data parameterization: Our study will be the first effort to apply the mechanistic sediment transport and landscape evolution theory outlined in this proposal. Therefore, several parameters in the general forms of equations for runoff generation, sediment detachment, and sediment transport may require revisions to represent road surface conditions impacting runoff hydrology and hydraulics. As discussed in the Parameterization Experiments, aspects of the proposed model (e.g., production of fines due to traffic) will rely on our field experiments. In such cases, our approach will help revise theory for roads using all relevant data available to enhance the predictive power of a generalized road model. Here, we give an example for such model revision in relation to the sediment transport theory. Wilcock and Crowe (2003) proposed empirical relations to estimate a non-dimensional transport parameter, W*, for streams and flumes based on sediment size and shear stress. One could anticipate that detachment and transport of sediment on roads may show different characteristics than those observed in streams. If this is true for the data we collect, then we will develop methods to parameterize W* in relation to road substrates, shear stress, and discharge following the studies in available literature. This approach for W* will lead to a general model that may be used for sediment detachment and transport from roads. We will not calibrate this parameter from experiment to experiment.

Some of the Parameterization Experiments could potentially produce highly variable results due either to the limited number of experiments or the complex nature of process interactions and measurement uncertainties. In such cases, our approach will be to first identify the environmental and physical conditions that may lead to high-variance results, and if needed, repeat experiments to the extent feasible given budgetary and time constraints. We will also develop model sensitivity and model error propagation analysis (e.g., Bevington 1969). Such analyses will quantify the response of model predictions to select model parameters and estimate how prediction error and variance grow over time with respect to the variability in the input parameters. Cross-parameter interactions will be considered when selecting parameters to be examined. Methods for error analysis are well-developed in the literature (e.g., Taylor 1982). We will use the Hyak computer cluster at the University of Washington for the large volume of numerical simulations that will be required for error analysis.

(2) Model calibration and cross-validation: Following the step above, our initial approach for model calibration and validation will be to run the model at each study location without calibration, while using physical model parameters consistent with site-specific and experiment-

specific environmental conditions and BMP properties. Model performance in predicting runoff and sediment yields will be measured using the Nash Sutcliffe model efficiency measure (NSE) and zero-intercept regression (Nash and Sutcliffe 1970), both of which use pairs of modeled and observed data. We anticipate NSE greater than 0.7 for annual model predictions. The model will be calibrated to improve NSE as needed, using parameters that the model is sensitive to, as well as parameters that show high variability across sites. We will calibrate and validate the model using subsets of the data. We will avoid calibrating the model for individual sites and BMP, but rather calibrate the model based on geology and climate to improve the generality of the model parameters. Experimental data will be divided into calibration and validation subsets (e.g., leave-one-out calibration and validation). Model performance (i.e., NSE) will be calculated and reported based on the validation subset. In addition to this approach, a more rigorous jackknife re-sampling procedure where all years of data are shuffled and used for both calibration and validation in groups can be used as deemed appropriate (e.g., Tukey 1958).

Expected Results and Limitations

The overarching goal of this study is to gain a firm understanding of physical controls relating to road runoff and sediment yield, and how different BMP, both individually and in-combination, will mediate these controls. Our end goal is twofold: (1) To disseminate this understanding to landowners, managers, and regulatory agencies in ways that can be used for decision making to cost effectively address sediment-delivering road segments; and (2) Provide a process-based numerical modeling framework that can be used to generate field-testable hypotheses, as well as open future avenues for road sediment and BMP research. A greater process-based understanding, rooted in scientific evidence, will ensure that the most effective BMP are being applied.

Information and improved tools will be provided to landowners and collaborating stakeholders in a variety of ways. Basic empirical relationships from statistical analyses will provide alternative formulations that can be used in existing empirically-based tools such as WARSEM and GRAIP. For example, if the implementation of two BMP (e.g., improving surfacing and grassing the ditch line) are not simply multiplicative but rather have a synergistic response, then the existing models can be adjusted to better estimate the overall reduction in both sediment production and sediment transport. With our model developed in Landlab, we will be able to determine seasonal haul restrictions, both at the basic level of, “What are the sedimentation improvements from ceasing haul during the winter months?” and potentially at the more detailed level of, “What are the sedimentation improvements from ceasing haul on individual days of high rainfall?” These results can be directly provided through the deliverables described below, and it might be possible to build a component for WARSEM and GRAIP to answer additional what-if questions related to haul decisions.

While the proposed geomorphic model is not intended as an operational tool for landowners, it will have applications in future research of BMP in other regions. Initially, the model will be used as a theoretical framework to represent forest road BMP using measurable variables to develop a relationship between road sediment response, climate forcing, and environmental and management conditions. Ultimately, the model will be able to be used in other locations using only parameters that can be measured *in situ* (e.g., median sediment size), parameters that can be obtained from maps (e.g., soil texture and rock type), or parameters that can be obtained via smaller experiments (i.e., Parameterization Experiments). This would eradicate the need for large-scale field experiments to estimate sediment yield. Applications such as what we propose here are unprecedented in road erosion literature.

Our experimental field monitoring and numerical model results will offer a uniquely rich dataset to investigate and address CMER Work Plan and Study Design critical questions listed in the Critical Questions Section. By the end of this project, we expect to provide a number of deliverables. Reports and fact sheets that summarize findings qualitatively and emphasize recommendations and management options will be created with forest policy-makers and forest engineers in mind. Reports that present descriptions of the field experiments, empirical outcomes, statistical analyses, and Landlab model results will be provided to CMER. Finally, peer-reviewed journal publications will be produced. All models will be delivered with tutorials on a website (e.g., http://landlab.github.io/#/). Landlab workshops will be arranged with interested groups to present hands-on examples of the use of the model.

Below, we describe in more detail three of the main results, as well as limitations, that we expect from this project.

<u>1) How effective are BMP? Statistical analysis of empirical data:</u> There will be direct results statistically demonstrating the differences in sediment production and transport for different BMP and covariates. For the Major Experiment, specifically tested BMP include: 1) Three surfacing rock types, “good” and “marginal” from local rock pits and “quality” which will be truly high quality aggregate; 2) Grassed ditch lines; 3) An elevated BMP in the ditch line; and 4) Another BMP to be identified before its installation in Year 4. These BMP will be tested in two lithologies selected to have different proportions of fine sediment and different hydrologic properties, across a range of rainfall typical of western Washington forest land, with varying traffic and grading regimes. The Major Experiment allows for interpretation of BMP applications in a Before-After-Control-Impact (BACI) design. BACI is considered one of the most powerful bases for logical inference. (Note: We acknowledge that the removal of ditch line grass before Water Year 5 may cause a sediment spike that confounds data analysis for Years 5-7, particularly in the context of BACI-appropriate statistics. If so, we expect the excess sediment to be ameliorated by Year 6, but we may have to collect one additional year of data.)

Additional tread and ditch line BMP will be tested in parameterization experiments. Seasonal evolution of tread in a regime of traffic and grading during winter rainfall will be measured using micro-topographic analysis. Sediment production during short time scales of intense haul and varying rainfall rates will also be measured. These experiments will address questions about the efficacy of seasonal haul restrictions and optimal frequency of grading. For ditch line BMP, several elevated BMP will be tested to characterize their hydraulic radius, and sediment traps will be tested to characterize their efficacy under a range of ditch line flow rates for two soils. Each piece will be a strong test/measure of effectiveness, but each also has strong contextual framing, which limits broad generalization of these results and necessitates thoughtful modeling as a basis for extrapolation to other conditions.

<u>2) Spatial modeling experiments to extrapolate field-scale results:</u> We described in the modeling section how the proposed model will be refined and validated in each of the 80 field sites. We will use the model as a numerical laboratory across selected locations to extrapolate the understanding gained from field plots over a larger space and time dimension. Modeling locations will include road segments sampled from two lithologies, and varying drainage areas and rainfall regimes within the general region of our study. We will use single and combinations of BMP (e.g., ditch line vegetation and BMP, rock surfacing type, and traffic) and develop scenarios based on our direct field measurements. We will also be able to model hypothetical BMP scenarios with consideration given to our Cost Versus Maintenance Survey. To investigate the long-term response of road sediment yields and BMP under varying weather conditions, we will run our model continuously using gridded historical datasets starting as early as 1915 (e.g., Frans et al. 2016; Livneh et al. 2013, 2015). These model experiments will provide a detailed dataset, which we will use to summarize our findings through statistical analysis, as outlined above for field experiments. We expect that our model results will show broad ranges of response from individual storm-based response to annual and mean annual runoff and sediment yields. Specifically, these experiments will help us quantify the variability of sediment production and the influence of storm events in driving annual sediment yields.

<u>3) Threshold and tipping point experiments:</u> Identifying when and how to make rapid decisions before and during high-precipitation days is critical for sustained management of unpaved forest roads. Such decisions include when to stop road traffic and for how long, as well as when to resurface and grade roads. We will follow two approaches to obtain this information: (1) We will select long-term simulations and examine how road runoff and sediment yields scale with varying rainfall events based on BMP implementation to identify threshold runoff and erosion changes due to BMP differences. (2) We will identify cases that show lowest and highest sensitivity to precipitation intensity and use those locations and BMP conditions to investigate further "what-if" numerical experiments, forcing these systems under the worst and best conditions of management and BMP. Results will be analyzed to obtain critical rainfall intensity and antecedent amount thresholds so that land managers can make rapid and timely decisions based on road and environmental site conditions.

Following the development of large datasets comprised of both modeled and observational field data, we will use statistical methods and search for empirical relationships between sediment yield, rainfall, road BMP, road segment characteristics (e.g., slope, length), and lithology. This effort will provide simple empirical relations to expand equation (13) presented in the modeling section similar to Luce and Black (1999). The empirical formulations from the statistical analysis will provide alternative formulations that can be used in existing empirically-based tools such as WARSEM and GRAIP.

This project is designed to overcome key limitations of previous road BMP experiments and of existing models. These key limitations include: 1) Consideration of hydrologic inputs or hydrologic differences between lithologies; 2) Relationships among BMP, instead of assuming multiplicative improvements; and 3) Characterization of the physical processes of sediment detachment and transport.

Remaining limitations which this project is not designed to overcome fall into three categories. One, there will be BMP that this project does not test, through either the Major Experiment or the parameterization experiments. These include subgrade designs (e.g., varying ballast depths) and road tread stabilization treatments (e.g., soil binders such as oil or magnesium chloride, geotextile fabric treatments). Two, we are not testing across the entire climatic regime of Washington State. Specifically, areas of highest rainfall levels in excess of 100 inches per year, areas of rainfall below 40 inches per year, and snow-dominated areas are not included in this project. The model may extrapolate into areas of higher and lower annual rainfall rates depending on the consistency of the sediment production versus rainfall relationships for our rainfall gradient, and the Short-Time-Scale Interactions Parameterization Experiment results will improve this extrapolation. Idaho research conducted by Luce, Black, and others will bolster snow-dominated modeling efforts. Three, our knowledge of fine sediment production and hydrologic behavior of lithologies other than the two this project is being implemented on will predicate on extrapolating our results. This effort will necessarily be limited to the extent that we understand how the presence of fine sediment in a native material exacerbates road erosion from the tread surface and how the hydrologic properties of the native material affect ditch line water volumes.

Appendix A - References

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Appendix B – Best Available Science Summary

Empirical Research

The generation of fine sediment from road networks in forested environments has been investigated for more than 50 years. The largely unpaved road networks are geographically extensive and therefore cross or lie parallel to many streams across the landscape. Issues are compounded where early logging limitations led to high road densities, and high rainfall in the coastal region causes high stream density and numerous stream crossings. In addition, early engineers largely took a pragmatic approach to railroad and road building by placing the larger "mainline roads" along the mainstem of the principal river and the larger tributaries in a watershed. It became clear to early researchers that this juxtaposition had the potential to deliver substantial loads of eroded material to river networks (e.g., Trimble and Sartz 1957; Megahan and Kidd 1972; Beschta 1978; Reid and Dunne 1984; Bilby 1985).

Some of the earliest research was conducted in the 1970s and 1980s (e.g., Megahan and Kidd 1972; Reid and Dunne 1984) and served to reveal how much sediment was being produced from different parts of the road prism under a variety of circumstances. Walt Megahan and colleagues made numerous contributions to the body of science relating to road prism sediment sources. One of their important contributions was the 1972 effort evaluating the role of subsurface storm flow interception (SSSFF) – SSSFF produced 7.3 times more water than the road's surface; this result fundamentally changed our understanding of roads and their impact on the landscape.

Subsequent efforts focused on traffic levels (e.g., Luce and Black 2001a and references therein), tread configuration (e.g., Burroughs and King 1989), tread surfacing (e.g., Swift 1984; Brown et al. 2013; Rodgers et al. 2014) and cutslope vegetation (e.g., Luce and Black 2001b). The effectiveness of cross-drain spacing has been extensively studied (e.g., Montgomery 1994; Wemple 1996; Croke and Mockler 2001; Luce et al. 2014), as has the benefit of quality rock surfaces (e.g., Foltz and Truebe 1995). BMP to limit sediment production and delivery during and after use of skid trails for harvest near streams have been studied in the southeastern region of the United States (e.g., Wear et al. 2013 and references therein; Vinson et al. 2017). Recent efforts have included detailed studies of stream-crossing designs (Aust et al. 2011), aggregate versus subgrade interactions (Toman and Skaugset 2011), and the effectiveness of sediment trap designs (Grace and Elliot 2011). In addition, van Meerveld et al. (2014) measured road erosion at the scale of individual truck passes in the context of rainfall intensity. Most of this research has focused on the measurement of sediment production or delivery with and without a single BMP application.

In addition to forest road BMP research to understand environmental improvements, a growing body of literature exists with a focus on road construction recommendations that increase road quality and decrease road costs. Sessions et al. (2006) quantified aggregate reclamation from old roads and from new spurs with an underlayment of geotextile to increase reclamation. The authors also provided formulas for estimating cost saving over hauling new rock from greater distances. Compaction of the subgrade to specified standards so that less aggregate is used has been promoted (e.g., Boston et al. 2008) and subsequent papers have offered *insitu* methods for measuring compaction (e.g., Pattison et al. 2010). Recent work has evaluated the bearing capacity (i.e., road strength) improvement of using geogrid under surfacing rock on forest roads in New Zealand, sampling both immediately after construction and after a year of log haul (Visser, et al. 2017). In a broader analysis, Thompson et al. (2010) developed a modeling tool to optimize BMP environmental effectiveness with cost effectiveness.

The work by Luce and Black (1999) is particularly important to western Washington because it was conducted in the same ecoregion, the Oregon Coast range. In an intensive study, they examined road design and maintenance at 74 plots where they measured sediment production and road features. Looking at distance from culverts, road slope, soil characteristics, and cutslope height as well as the vegetation condition of cutslopes and ditches, they were able to develop relationships among variables which greatly improved erosion estimates. In both Megahan and Kidd (1972) and Luce and Black (1999), an extensive field program of replicated treatments allowed powerful statistical tests among site characteristics and treatments. These are only examples of some of the profound work previously completed, but they allow us to consider what is still needed, how previously completed work can be built on, and the effort necessary to collect the meaningful data.

A variety of useful methods for quantifying surface erosion has been described in literature (Megahan and Kidd 1972; Reid and Dunne 1984; Ice 1986; Bilby et al. 1989; Foltz and Truebe 1995; Luce and Black 1999; Kahklen 2001; MacDonald et al. 2001 and 2004). This information was briefly summarized in Black and Luce (2013) who point out that "the methods require a range of effort and expense and vary substantially in accuracy." Black and Luce (2013) provide a settling basin and tipping bucket design that measures both water and sediment discharge for individual road plots which can be systematically applied to road sediment and road hydrology studies in the future.

By the early part of this century, research was substantial such that researchers could review the combined findings. In 2004, in a CMER-funded project, Drew Coe did a review of the published literature – 35 studies. The review examined projects that looked at both site and basin level responses. While the individual studies focused on specific topics to meet their project's objectives, the body of the science could be summarized into several key findings. Many researchers documented how site-specific conditions dramatically change runoff processes. A few studies highlighted the importance of the interception of surface flow by cutslopes as a dominant mechanism. The magnitude of that interception is dependent on lithological features. Another theme in the reviewed work was the extent of connectivity between the road and stream network and the factors exerting influence on connectivity. The document also provided insights from studies on the hydrologic effects streams have on runoff generation. Much of this work was the basis of the early generations of road models, particularly another CMER-funded project, WARSEM (Dubé et al. 2004).

In a subsequent publication, MacDonald and Coe (2008) compared sediment delivery from roads in 11 studies from across the world. The work compared research from across the US and other locales such as New Zealand and the US Virgin Islands with a wide range of estimated production rates both within and between studies. They segregated the studies by road prism feature and were able to estimate sediment production by tread, cutslope, and fillslope. In addition, they compared road erosion fine sediment inputs to landslide delivery of fine sediment. When they scaled the road studies to the work focused on landslides, the values were similar and, in some cases, larger in the road-related erosion. One difference was that road-related delivery was primarily at stream crossings.

Other recent literature reviews summarize the effectiveness of forestry BMP, with both road and harvest emphasis (e.g., Grace 2002; Daigle 2010; Anderson and Lockaby 2011; Cristan et al. 2016; Edwards et al. 2016).

Model Development

Efforts to develop models of road erosion that can be applied at larger scales have resulted in numerous summaries of the existing body of empirical research (e.g., Dubé et al. 2004; MacDonald and Coe 2008). The development of models became imperative as scientists and managers recognized that, given the extent of road networks, tools needed to be developed to better understand potential cumulative impacts and how they might prioritize remediation efforts.

Road erosion models can be grouped into two categories, empirical and physically based. Empirical models are based on statistically significant relationships between erosional response (road surface, ditch, cutslope) and independent site variables or factors (e.g., geology, road surfacing and length, rainfall). Effects of independent site variables are incorporated as multipliers to predict total erosion from a road segment, which is then multiplied by a sediment delivery ratio (SDR) to estimate sediment delivered to a nearby stream. Empirical models are used to predict mean annual sediment contribution from roads often at the catchment scale. Physically-based models incorporate conservation equations that describe sediment detachment, transport, and delivery processes from road segments which are driven by rainfall and overland flow. Models typically share a relatively standard road surface hydrology component for modeling infiltration and runoff generation, driven by rainfall events, although they disregard interception of surface and subsurface flow from hillslopes by roads.

Empirical Models

Washington Department of Natural Resources (WADNR) developed Watershed Analysis methods (WFPB 1995), which included a series of empirical relationships to estimate road surface erosion based on empirical modeling concepts developed by Megahan and Kidd (1972) and Megahan (1974) and the R1-R4 model (Cline et al. 1981; Ketcheson et al. 1999). Several similar watershed modeling tools that employ different software have evolved from the Watershed Analysis methods of WADNR to assess impacts of roads on annual sediment yields. The models estimate annual road surface, ditch, and cutslope erosion based on multiplicative empirical site-specific factors (geology, surfacing, traffic, rainfall, sediment delivery), sum them up, and multiply by a road age factor. Among these models, Washington Road Surface Erosion Model (WARSEM) was developed as a Microsoft Access database application. Boise Cascade developed a GIS-based program (SEDMODL) to automate the WADNR road erosion calculations used in WARSEM for landowners with extensive road networks. Version 2 of this model (SEDMODL2) was developed by NCASI in collaboration with Boise Cascade (NCASI

2003). The model uses an elevation grid combined with road and stream information layers to produce a GIS version of WARSEM. WARSEM and its interface with SEDMODL2 is a model spatially distributed by road segment, including features for estimating ditch, cutslope, and road surface erosion. WARSEM can be applied at large catchment scales and the effects of a variety of Best Management Practices (BMP) enable the model to aid catchment decision-making (Dubé et al. 2004; Fu et al. 2010).

GRAIP is a distributed watershed-scale tool that analyzes risks from multiple erosion processes for forest roads in a GIS environment based on road inventory and terrain data (Prasad et al. 2005). Such erosion processes include surface erosion, gullying, landslides, and stream crossing failure. As input, GRAIP requires GIS coverages of road lines and drain points to represent the continuity of water flow paths along and off of the road. The model uses a base erosion rate (A) scaled with multipliers for topographic factors of flow path length (L) and slope (S), a vegetation factor (V), and a road surface factor (R). It estimates mean annual sediment yield (SY) from a watershed as SY=A*L*S*V*R (kg/yr) based on the formula of Luce and Black (1999). Sediment production from road segments can be mapped using GIS. The model uses simple rules to route sediment to drain points, estimates sediment delivery to streams from culvert outlets, and routes accumulated sediment from culverts through the channel network. The routed sediment gives a long-term average of sediment yield sourced from road surfaces. Sediment delivery from sub-catchments within a watershed can be analyzed and compared in relation to road density and other factors. GRAIP includes a landslide risk component that estimates an index of stability (SI); the model elevates landslide risk at culvert locations where water concentrates at a point outlet. While the representation of roads in GRAIP is based on an empirical equation which needs a baseline erosion rate, the range of integrated processes represented in GRAIP makes it an effective tool to examine relative impacts of road conditions holistically across a watershed.

Physically Based Models

Two physically based models have been applied to modeling road erosion: WEPP and Kineros. Of these, WEPP has a specific module intended to assist users in inputting parameters for roads. That version – WEPP Road – is limited to modeling road segments (Elliot and Hall 1997). WEPP Road is a generic tool that is run online using site and road conditions selected from a menu of default choices that are developed largely based on empirical observations. Site conditions include climate (obtained from weather stations), soil textural type, rock cover percentage, and inputs to characterize road geometry such as gradient, length and width of road, fill and buffer, as well as road design conditions. The Road version does not require any site-specific field observations and, therefore, it is relatively easy to implement and can be used directly from the web (http://forest.moscowfsl.wsu.edu/fswepp/). Another interface, WEPP Road Batch, predicts erosion for multiple road segments, currently up to 200 segments in a batch. Both interfaces predict average annual erosion only.

Site-specific data can be incorporated in the WINDOWS version of the model, which allows users to run both hillslope and ‘watershed’ configurations (Elliot and Hall 1997; Elliot et al. 1999), where the ‘watershed’ configuration allows for using shapes beyond the single-plane representation in WEPP Road. However, the generic WINDOWS version requires many data inputs which are often difficult to obtain in the field and are highly uncertain. WEPP was designed around BMP for farmers' fields, and adaptation to roads has required ad-hoc adjustments to create a road-like simulation. Consequently, the web-based version offers a simpler application option for roads. A strong aspect of WEPP is its capacity to develop continuous simulations driven by sequences of rainfall events. While this model can be useful to characterize relative rates of sediment production from different road surfaces for initial design and maintenance purposes, it does not include functionality for road sediment BMP. In addition, the high data intensity makes its implementation difficult and introduces a high degree of uncertainty on model results.

Another physically-based model that has shown some predictive capability for road erosion is KINEROS2. However, this model does not have an explicit road component, and it was used in a single study that used a road surface hydrology and sediment yield measurements in Thailand (Ziegler et al. 2001a).

Model Limitations

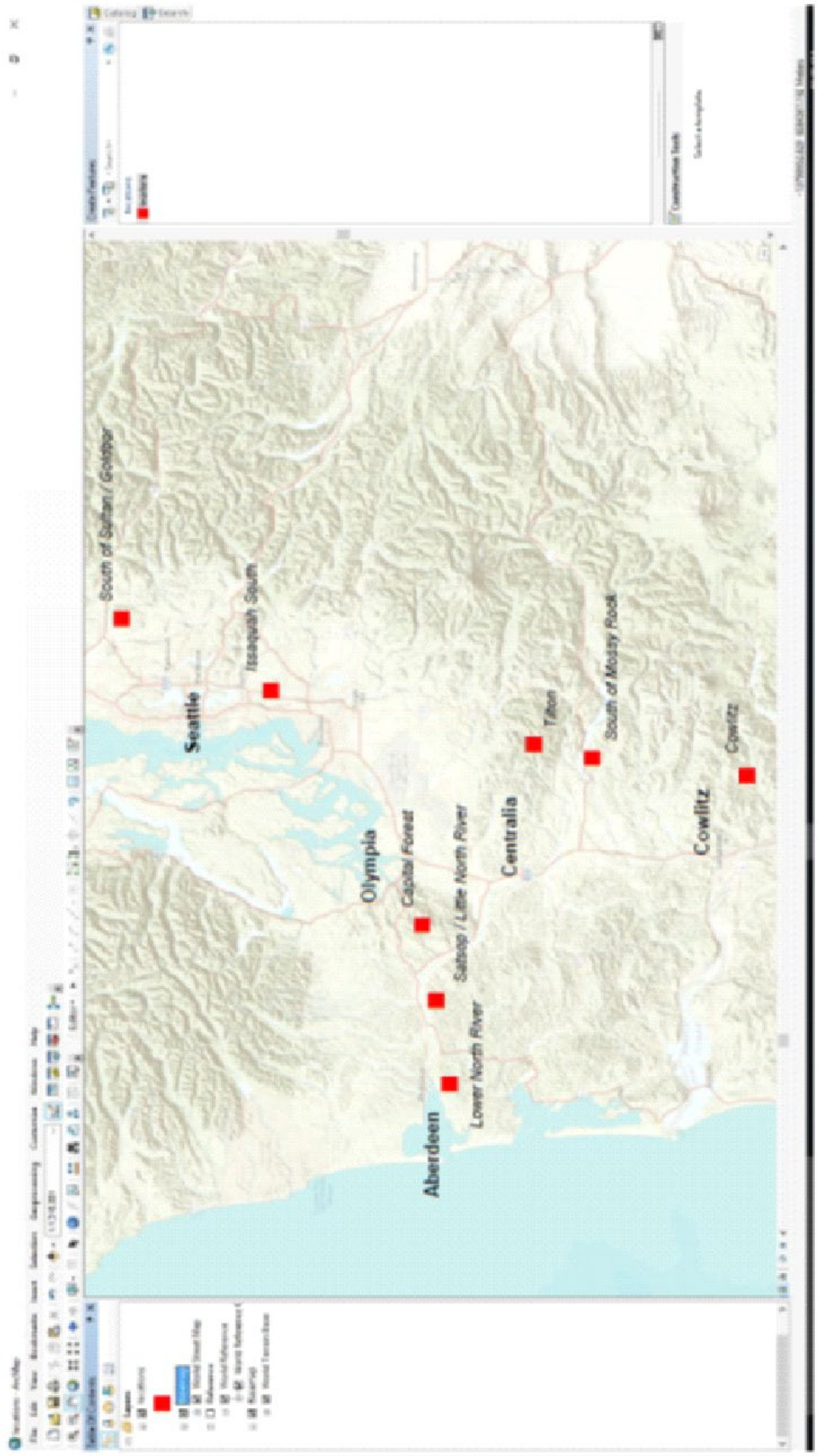
Several studies evaluated and reviewed the performance of empirical and physically based road models against observations (Elliot et al. 2009; Fu et al. 2010; Dubé et al. 2011). Studies that used WEPP Road have shown varying levels of model performance against observed storm runoff and sediment yields from roads. At different sites, both under- (e.g., Peranich 2005) and over-estimations (e.g., Amann 2004) of runoff and erosion have been reported in studies that used WEPP Road. Busteed (2004) had success with model predictions in large storms, and under predicted response driven by small storms.

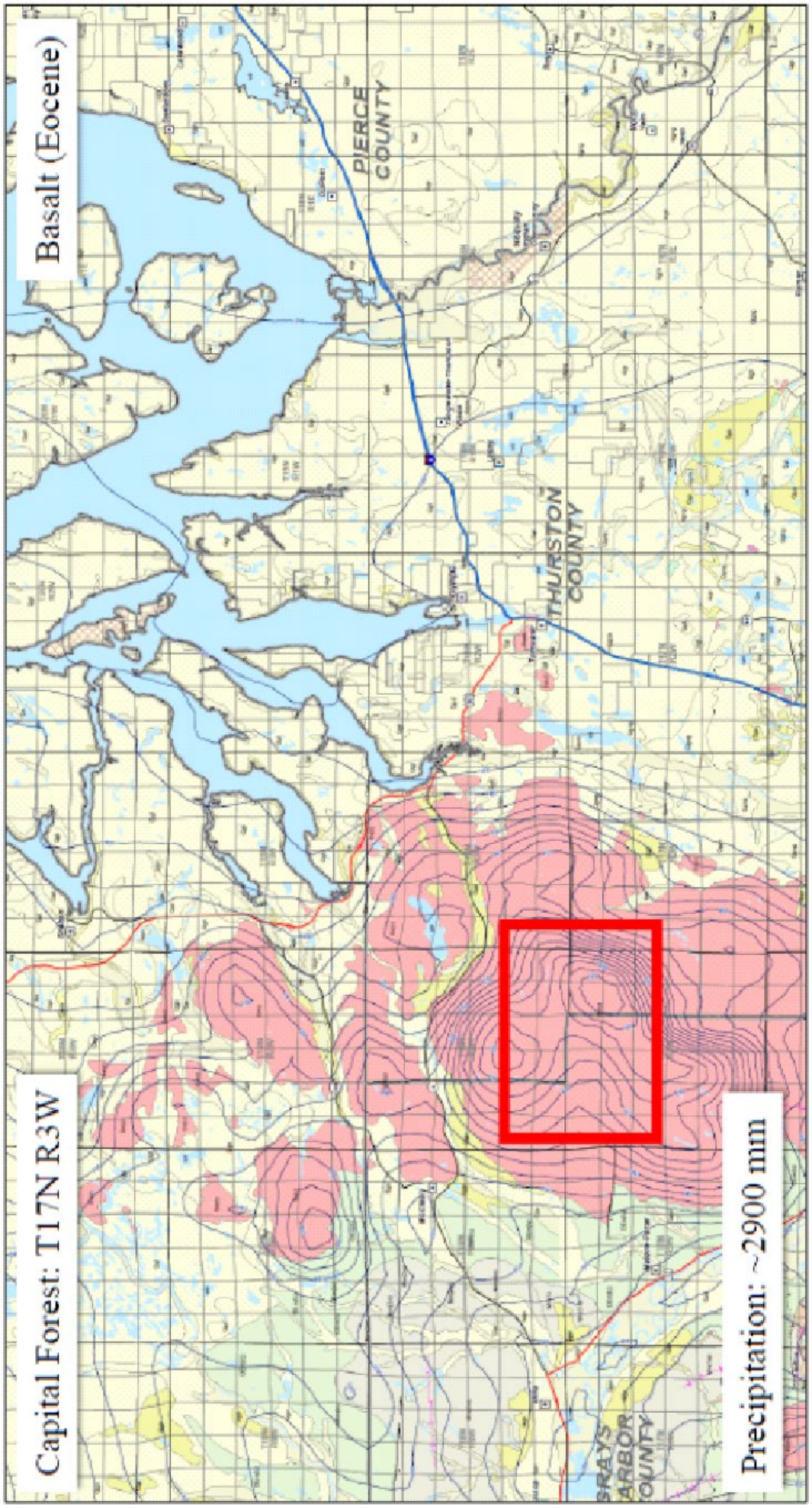
Dubé et al. (2011) compared SEDMODL2/WARSEM, GRAIP, WEPP Road and WEPP watershed models against a large data set of road erosion observations at nine sites across the US that had sufficient data to run and test the models. The WEPP (PC interface) model, which can predict runoff and erosion from individual storms, produced relatively better results for individual storms than for long-term averages. The GRAIP and SEDMODL2 models predicted between-segment variations generally well and were found suitable for relative comparisons of different management conditions. Overall, none of the models showed good performance in predicting actual values of average annual runoff and erosion at all sites. The two main points of the analysis are that the models were reasonably good at discerning relative differences among locations but poor at predicting actual amounts of sediment delivered. This is both encouraging and disappointing. Encouraging because they should allow prioritizations of road segments for remediation and possibly be useful in evaluating improvements. Disappointing because the performance targets in the Forests & Fish Report make it necessary to have a reasonable estimate of how much sediment is delivered. Dubé et al. (2011) recommended the use of local data from field observations to calibrate the surface erosion models if estimates of actual values are needed. Therefore, more extensive information could both improve actual modeling estimates in a region and allow enhancements to the model(s).

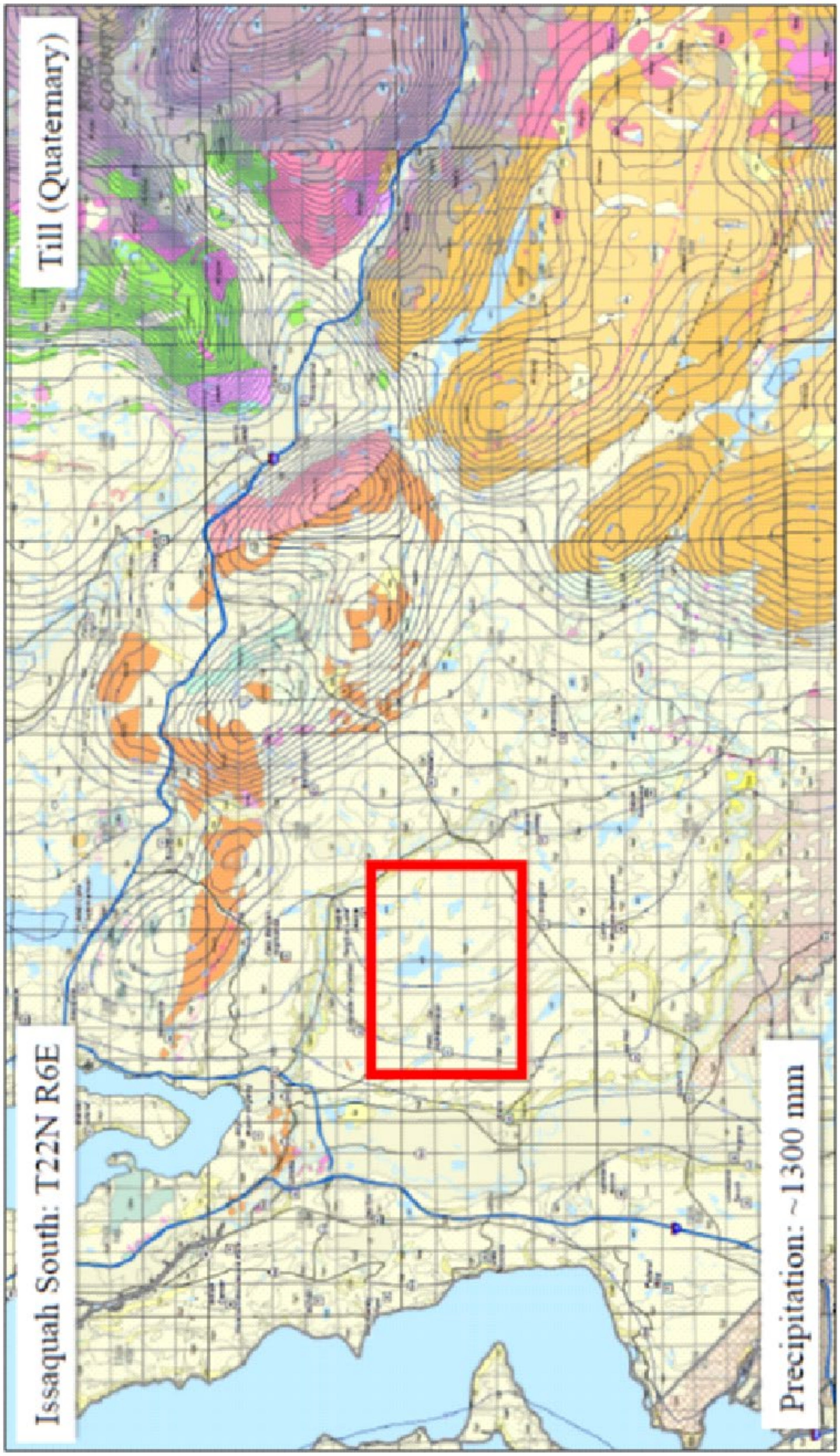
In summary, while simple models are thought to be more useful and easily applied for land management purposes, more complex models can conceptually provide a basis for building improved understanding and scientific knowledge. However, both approaches provided in the literature have shown significant deficiencies and have very limited utility, especially for evaluating the impact of road BMP. Some of the most pronounced limitations of existing models are:

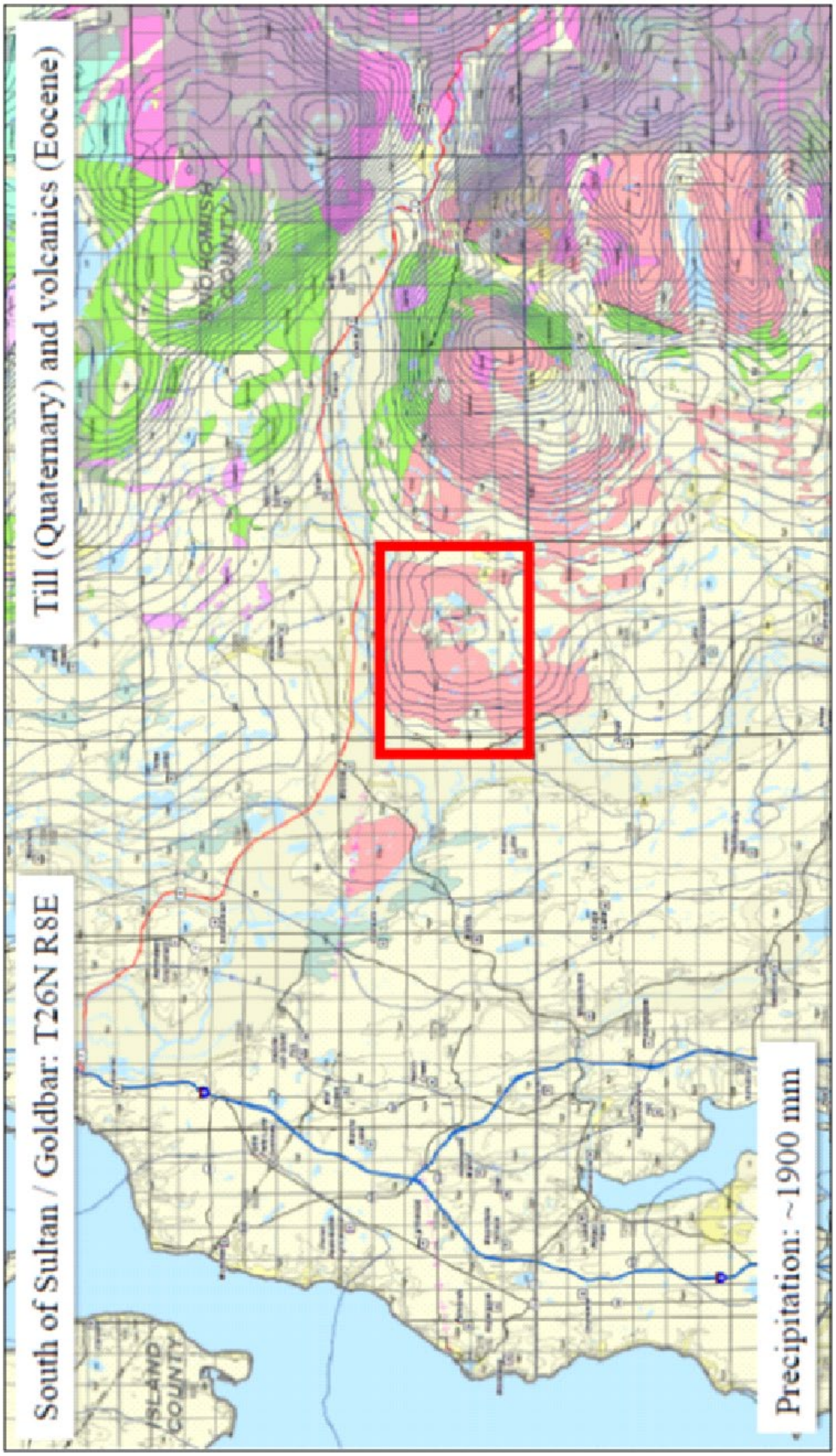
- Empirical models are driven by data and work best in regions where they were developed.
- Spatial and temporal dynamics in the climate are not included in inputs of empirical models.
- The effect of each factor on sediment yield is assumed to be multiplicative, following the USLE equation idea, without much physical justification. One publication, Luce and Black (2001a), notes that the multiplicative interaction is in error for independently derived empirical effects of traffic and ditch grading. This documents a need for a better theoretical foundation for mixed BMP-effect modeling.
- Among models, only WARSEM considers the effects of BMP from a list of 70 different BMP choices. In the WARSEM manual, each BMP is described qualitatively and a deterministic multiplier is assigned to introduce the influence of BMP in the calculated sediment yield (Table C-1, WARSEM manual, Dubé et al. 2004). These multipliers were based on very limited data and were not systematically obtained by holding other conditions constant while changing one BMP. Because multipliers were obtained from limited sites, inference beyond the local setting is not validated; nor is there a guarantee that one BMP is not redundant with another. The model does not build physical causalities between BMP and the hydrologic and erosional responses of the road setting.
- The WEPP runoff generation component poorly predicts runoff responses in most data sets collected at a range of study sites as reviewed by Dubé et al. (2011). Natural hydrology of a road site, such as base flow and surface flow contributions to ditches and culverts from hillslopes, was not incorporated in the existing physically-based models for roads.
- Both physically based models work only on assemblages of planes, so water cannot accumulate in ruts or ditches unless they are explicitly input by the user (they do not exist at all in WEPP Road). Concentrated flow erosion in WEPP is not physically based but essentially input as a parameter by the user. This is an important factor in evaluating rut development and ditch line erosion in forest roads.

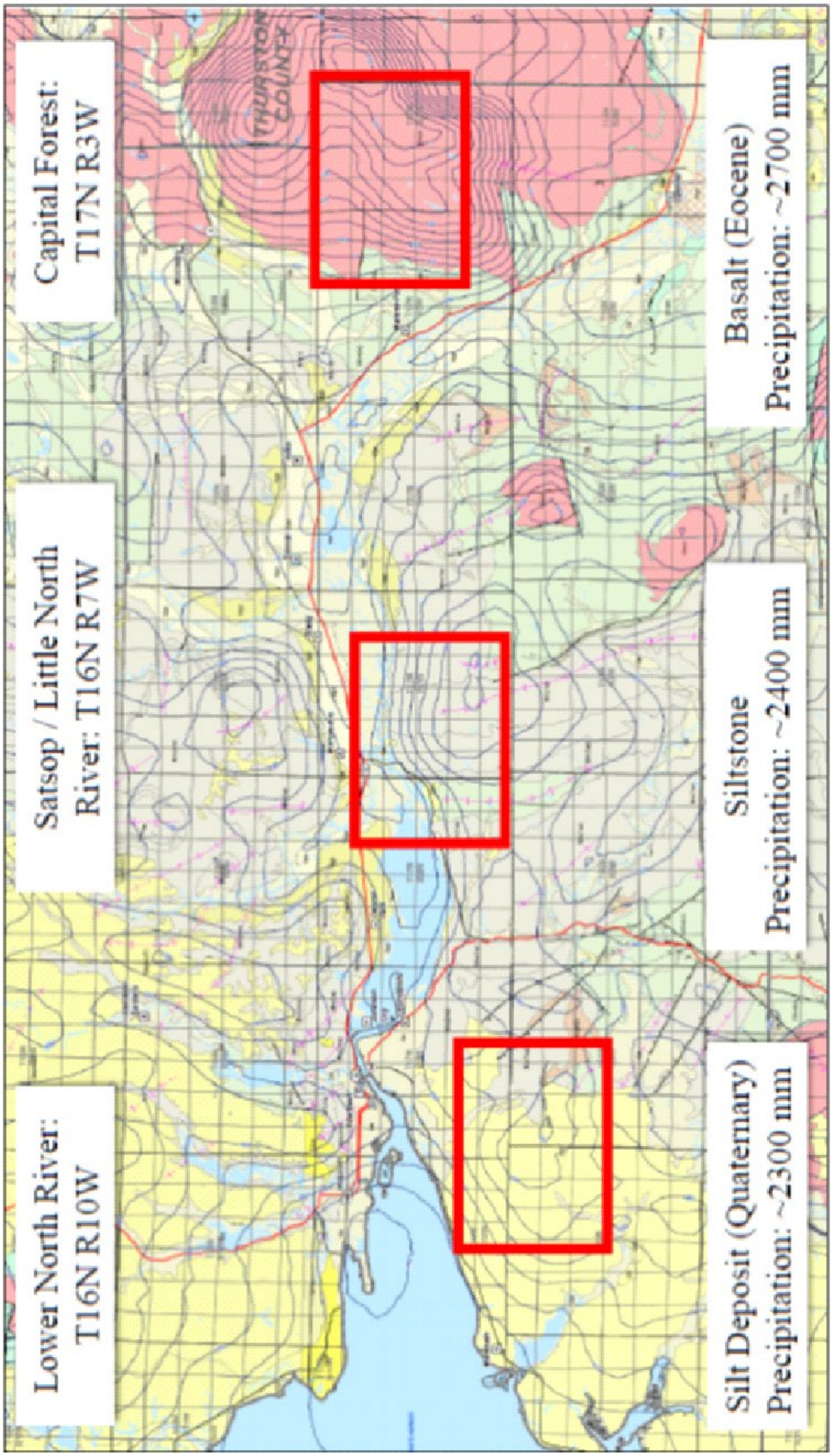
Appendix C – Location Option Maps

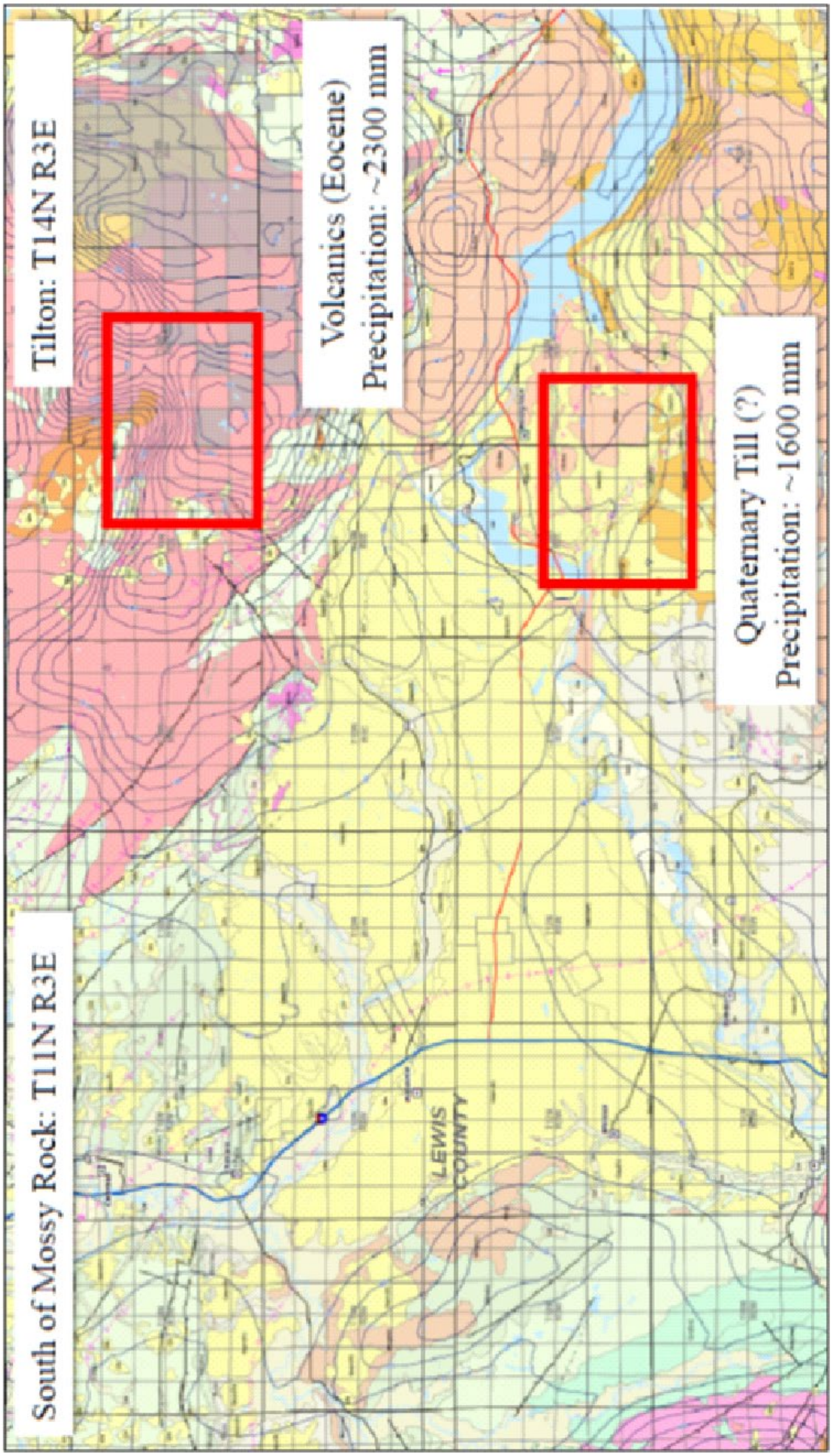


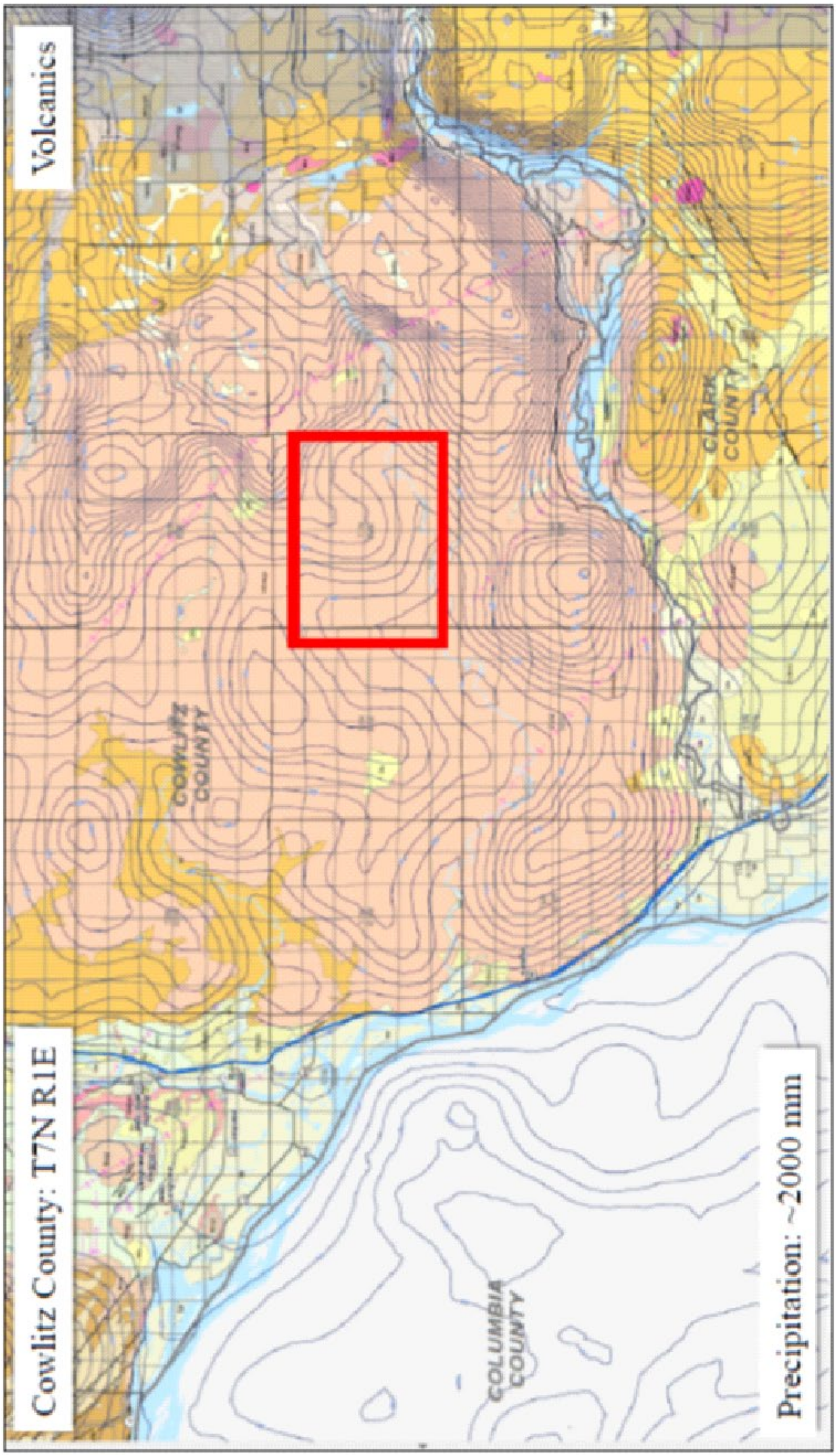

Basalt (Eocene)
Capital Forest: T17N R3W
Precipitation: ~2900 mm
PIERCE COUNTY
THURSTON COUNTY


Till (Quaternary)
Issaquah South: T22N R6E
Precipitation: ~1300 mm


South of Sultan / Goldbar: T26N R8E
Till (Quaternary) and volcanics (Eocene)
Precipitation: ~1900 mm
SNOHOMISH COUNTY
ISLAND COUNTY


Capital Forest:
T17N R3W
Satsop / Little North
River: T16N R7W
Lower North River:
T16N R10W
Basalt (Eocene)
Precipitation: ~2700 mm
Siltstone
Precipitation: ~2400 mm
Silt Deposit (Quaternary)
Precipitation: ~2300 mm
THURSTON
COUNTY


Tilton: T14N R3E
Volcanics (Eocene)
Precipitation: ~2300 mm
Quaternary Till (?)
Precipitation: ~1600 mm
South of Mossy Rock: T11N R3E
LEWIS COUNTY


Volcanics
Cowlitz County: T7N R1E
Precipitation: ~2000 mm
COWLITZ COUNTY
CLARK COUNTY
COLUMBIA COUNTY

Appendix D – Equipment

Table D-1 lists the equipment needed to conduct this project. Estimates of the numbers and costs are provided, and the far-right column provides a cross-walk with the individual experiments.

Table D-1: Equipment List

Item	Number	Unit Cost	Total Cost	Use/Other Information
Steel Troughs	**80-160**	**$450**	**$36,000-72,000**	Tread-surface "waterbar" at start and end of each sample site; some sample sites may be consecutive so all 160 may not be needed.
Sediment Collection Tubs	**80**	**$950**	**$76,000**	Large tub for primary sediment collection.
Cross-Drain Culverts	**80-160**	**$300**	**$24,000-48,000**	Pass ditch and tread water under road to tubs; a few might already be in appropriate locations and some sample sites may be consecutive so all 160 are may not be needed.
Tipping Buckets	**81**	**$1100**	**$88,000**	Measures water flow and captures sub-sample of turbidity fraction below tubs.
HOBO Pendant Event Logger	**110**	**$105**	**$11,550**	These have already been purchased.
Rain Gauges	**12**	**$350**	**$4200***	To document rainfall variance across a location and to collect data needed for Short-Time-Scale Interactions. Have 8 from earlier CMER projects; only buy 4.
Turbidity Meters	**4**	**$2500**	**$10,000**	Data needed for Short-Time-Scale Interactions.
Traffic Counters	**8**	**$425**	**$3420^**	To document traffic variance across a location, backing up the camera system, and to collect data needed for Short-Time-Scale Interactions. These have already been purchased.
Cameras w/ Macro Lens	**2**	**$1000**	**$2000**	To collect "photo sieving" data needed for Short-Time-Scale Interactions.

Motion-Triggered Cameras	**12**	**$250**	**$3000***	To document traffic types across a location and needed if vandalism becomes a problem. Have all these from previous CMER projects; do not buy.
Fire Truck	**1**	**$80/Hour**		Water source for Ditch Line Hydraulics.
Dump Trucks	**1-2**	**$80/Hour**		For installation, maintenance, and to be traffic for Short-Time-Scale Interactions.
Excavator	**1**	**$900/Day**		For installation and maintenance.
Grader	**1**	**$900/Day**		For installation and maintenance.