Best Available Science (BAS) and Alternatives Analysis

Presented to the TFW Policy Committee

1. Date	March 4, 2016	
2. Name of TWIG *Include members with affiliations*	Roads Prescription Scale Effectiveness Monitoring TWIG Bob Danehy, NCASI, Julie J. Dieu, Rayonier, Erkan Istanbulluoglu, U of W, Charlie Luce, USFS & Howard Haemmerle, CMER Project Manager	
3. Process Step	*Per the Lean Process revisions approved by CMER 10/26/15, the BAS and Alternatives Analysis document is drafted by the Technical Writing and Implementation Group (TWIG). Upon approval from CMER, the document goes to TFW Policy Committee for approval to begin the study design.* *Other relevant history or information to be added here (if any):* On 2/4/2016 TWIG provided a presentation to Policy outlining 5 alternatives, identifying the TWIG's recommended alterative, and describing the science used in the development of the document.	

4. Decision for TFW Policy Committee	*TFW Policy Committee must approve a study design alternative(s) before the TWIG writes the detailed study design. This document comes before Policy twice:*
	--First meeting: receive document and presentation; Policy questions to TWIG
	--Second meeting: Policy approval of the document
	
	The decision or question for Policy today is:
	The TWIG is requesting Policy:
	    1) approve the BAS/Alternatives document and
	    2) select the alternative for which a study design will be developed.
	
	Once finalized, the Policy decision will be memorialized in the transmittal letter to the Adaptive Management Program Administrator (AMPA).	

5. Content Overview	*The BAS and Alternatives Analysis proposal can be summarized in three sentences by the following:* Alternative #1 (Preferred Alternative): Empirical research on high-traffic, near stream roads focusing on both individual and combinations of BMP. Alternative #2: Do empirical research on high-traffic and other roads focusing on both individual and combinations of BMP. Alternative #3: Develop "plug and play" model components that make WARSEM and GRAIP more effective. Alternative #4: Alternative #1 + Alternative #3; Preferred Alternative of the TWIG Alternative #5: Alternative #2 + Alternative #3.	
6. Budget for Each Alternative *As applicable*	Alternative #1 - $768,000 Alternative #2 - $2,304,000 Alternative #3 - $325,000 Alternative #4 - $1,193,000 Alternative #5 - $2,729,000 Note: Alternative costs do not include site selection.	
7. Rule Group *As applicable*	Roads	

(Not to exceed one page)

Road BMP Effectiveness Best Available Science And Research Alternatives

Context

Washington State Forest Practices are regulated by means of the Forest Practices Act (Title 222 WAC) and Forest Practices Rules adopted by the Washington Forest Practices Board (WFPB). The WFPB is charged with developing rules that protect the state's public resources while maintaining a viable timber industry. Since much of the land regulated under the act contains habitat for aquatic and riparian-dependent species that have been, or may be, listed under the Federal Endangered Species Act (ESA), the Washington Department of Natural Resources (WADNR) has developed a Forest Practices Habitat Conservation Plan (FPHCP) to provide Federal Assurances that the rules will meet the requirements of the ESA.

The WFPB has 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 Forests & Fish Report resource objectives. 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 a research alternatives document and 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 best management practices (BMP).

As stated in the 2015 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.

47
48 It is anticipated the results of this project will inform the forest practices AMP about the
49 effectiveness of BMP in common use, including those used for Road Maintenance and
50 Abandonment Plans (RMAP). These BMP are potentially critical in achieving the FPHCP goals.
51 Should the common BMP used on forest roads prove to be ineffective, Policy and the WFPB
52 may have to revisit the rules and the Forest Practices Board Manual to refine the BMP
53 requirements and application.
54
55 **The Road BMP Effectiveness Project TWIG:**
56 Project Manager: Howard Haemmerle   WADNR
57
58 TWIG Members: Bob Danehy   NCASI
59   Julie Dieu   Rayonier (CMER Representative)
60   Erkan Istanbulluoglu University of Washington
61   Charlie Luce   USFS
62
63 Rule Group: Roads
64
65 Rule Context: WAC 222-24 and Forest Practices Board Manual, Section 3
66
67 Research and Monitoring Program   Road Prescription-Scale Effectiveness Monitoring
68
69 2016 Budget $25,000 (study design development)
70
71
72 **Statement of the Problem**[1]
73 Scientific knowledge of road BMP and prescription effectiveness is insufficient to make sound
74 recommendations. This leads to the potential for:
75   1) Landowners wasting money on ineffective treatments;
76   2) Rule and BMP implementations being inadequate to achieve functional objectives and
77   performance targets (Schedule L-1);
78   3) Overconfidence about the degree of protection landowners can attain (with implications
79   for road construction and maintenance standards); and
80   4) Treatments creating additional environmental risks (e.g., landslides and gullies).
81
82 **General Background**
83 Roads play an important role in our society, providing vital links for transportation of people and
84 materials quickly and efficiently. There are hundreds of thousands of miles of roads in
85 Washington State. Many of these roads are unpaved forest roads, used to access lands managed
86 primarily for timber harvest. Forest roads provide many useful functions such as allowing timber
87 products to be transported efficiently to mills, providing access for recreationalists, hunters and
88 fishermen, and even giving wildlife travel corridors.

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[1] It should be noted that the statement of the problem, project purpose, and the critical research questions may be
refined during the development of the study design.

89
90 However, roads influence a variety of watershed processes, including sediment production
91 (Megahan and Kidd 1972; Reid and Dunne 1984; Bilby et al. 1989; Luce and Black 1999, 2001a;
92 MacDonald et al. 2001), hydrologic event timing (Wemple et al. 1996; Jones and Grant 1996),
93 and slope stability (Sessions et al. 1987; Montgomery 1994). Of particular concern is road
94 erosion and the locations where it is delivered to streams and rivers. Road erosion can be a large
95 source of anthropogenic sediment in watersheds managed for forest production (Megahan and
96 Kidd 1972; Swanson and Dyrness 1975; Reid and Dunne 1984; Megahan and Ketcheson 1996).
97 The fine-grained sediment produced by road surface erosion has the potential to adversely affect
98 water quality and aquatic resources at the site-scale (e.g., the water quality at a culvert outlet),
99 the reach scale of a channel, and the watershed scale. As noted by Black and Luce (2013):
100 "Forest road runoff and fine sediment delivery are widely acknowledged to have serious impacts
101 on aquatic ecosystems (Cederholm et al. 1981; Platts et al. 1989; Thurow and Burns 1992; Lee et
102 al. 1997; Luce and Wemple 2001)." With rare exception (e.g., Martin 2009 found some square
103 miles of land with forest roads and NO delivery), the potential for adverse effects from forest
104 roads exists across the roaded, forested landscape. As a consequence, water quality regulations
105 and cumulative effects modeling of forest management have frequently focused on forest roads.
106
107 Excessive sedimentation is the most important cause of lotic ecosystem degradation in the
108 United States in terms of stream distance impacted (USEPA 2000). This is a concern to
109 environmental managers because increased inorganic sediment loads alter the natural biotic
110 community (algae, macrophytes, invertebrates and fishes) in streams (Tebo 1955; Cordone and
111 Kelley 1961; Waters 1995; Wood and Armitage 1997; Kaller and Hartman 2004; Suttle et al.
112 2004; Fudge et al. 2008). Increased inorganic sediment loads, beyond quantities or frequencies
113 that occur naturally, can influence the stream biota in a number of ways. Turbidity increased by
114 sediments can reduce stream primary production by reducing photosynthesis, physically
115 abrading algae and other plants, and preventing attachment of autotrophs to substrate surfaces
116 (Van Nieuwenhuyse and LaPerriere 1986; Brookes 1986). Decreasing primary production can
117 affect many other organisms in the stream food web (Izagirre et al. 2009). Sedimentation has
118 been shown to be a major factor in the loss of habitat for mussels worldwide (Poole and
119 Downing 2004; Geist and Auerswald 2007). Minshall (1984) examined the importance of
120 substratum size to aquatic insects and found that substratum is a primary factor influencing the
121 abundance and distribution of aquatic insects. Aquatic macroinvertebrates are adversely affected
122 by habitat reduction and/or habitat change resulting in increased drift, lowered respiration
123 capacity (by physically blocking gill surfaces or lowering dissolved oxygen concentrations), and
124 reducing the efficiency of certain feeding activities especially filter feeding and visual predation
125 (Lemly 1982; Waters 1995; Runde and Hellenthal 2000; Suren and Jowett 2001).
126 Macroinvertebrate grazers are particularly affected as their food supply either is buried under
127 sediments or diluted by increased inorganic sediment load thus increasing search time for food
128 (Suren 2005; Kent and Stelzer 2008). Deposited sediments affect fish directly by smothering
129 eggs in redds (Fudge et al. 2008), altering spawning habitat, and reducing overwintering habitat
130 for fry (Cordone and Kelley 1961), and indirectly by altering invertebrate species composition,
131 thereby decreasing abundance of preferred prey (Suttle et al. 2004). Declines in salamander
132 abundance also were seen with increases in fine sediment inputs (Lowe and Bolger 2002).
133
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136 <u>**Specific Statement of the Problem**</u>
137 Roads are persistent sources of fine sediment to forest streams, which otherwise have
138 characteristically clear water except during significant storm events. While substantial
139 improvements in water quality have been secured in recent decades through diligent application
140 of mitigation measures (usually called best management practices or "BMP") for sediment from
141 forest roads, there are still some locations where noticeable loading occurs related to forest roads
142 (Dubé et al. 2010). Recent work has demonstrated that sediment delivery from forest roads is
143 focused in a small fraction of the road network. Two Washington studies found that only 10-11%
144 of the forested road length is delivering sediment to the channel network (Dubé et al. 2010;
145 Martin 2009). Similar work in Oregon and Idaho, summarized in Figure 1, shows that 90% of the
146 delivered sediment comes from 9.2% of the drainage points (Black et al. 2013). That fraction is
147 primarily comprised of larger, more heavily travelled roads in proximity to streams. Mitigation
148 for these locations has proven more challenging than in other places, and better information is
149 needed to hone our capacity to efficiently handle sediment from these high-traffic, near-stream
150 (HTNS) road segments.
151
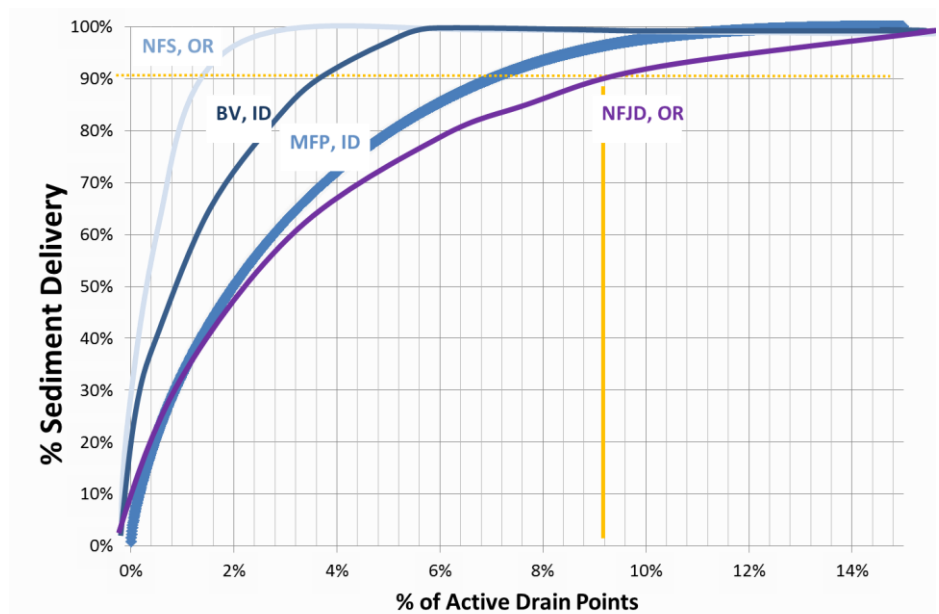
152
153 Figure 1: Pareto analysis of sediment production from four GRAIP watershed surveys (Black et
154 al. 2013).
155
156 There are several reasons why HTNS road segments are particularly challenging for sediment
157 control. Frequent heavy traffic decreases the effectiveness of surfacing roads with quality rock
158 by the crushing of the rock and pumping of fines from the substrate. Drainage modifications that
159 limit delivery are also compromised when water bars are worn and ruts form (e.g., Burroughs
160 and King 1989; Black et al. 2013). Segments carrying frequent heavy traffic may be the most
161 difficult to restrict traffic on during wet weather, increasing the severity of these effects. These

162 roads also need frequent maintenance of the surface (e.g., frequent grading to reduce pot hole
163 development) to maintain their ability to handle traffic. The close proximity to streams makes it
164 difficult to rely on infiltration into the forest floor to disconnect road discharges from streams.
165 The proximity to streams or stream crossings also means that these roads will be the wettest and
166 most affected by groundwater and exfiltration from the hillslope. In technical parlance, these are
167 high production (detachment of sediment from the road surface and ditch), high delivery (greater
168 fraction of produced sediment carried to stream) road segments.
169
170 These HTNS roads present strong technical challenges. Since excessive fine sediment in fish-
171 bearing streams is perhaps the single largest, management-related factor impacting instream
172 biota, including listed fish species, reducing road surface erosion and delivery to stream is of
173 critical importance. Not only are HTNS roads more likely to deliver sediment to streams, they
174 are typically critical to the transportation network as key mainline roads. Therefore, HTNS roads
175 may warrant additional investment by landowners to use enhanced BMP not only to meet
176 stewardship goals, but for operational needs as well. Improved mitigation for erosion of HTNS
177 forest roads may allow better operational flexibility so forest operations can be conducted in a
178 wider range of weather, with improved vehicle-use capacity and potentially reduced
179 maintenance. However, road upgrades and enhanced BMP are a significant cost; therefore,
180 improved knowledge of individual and in-combination BMP is essential for understanding the
181 return on BMP investments.
182
183 Whether from the landowner or regulatory perspective, a central question is what combinations
184 of surfacing, ditch line management, traffic control, and drainage management will most
185 efficiently and effectively mitigate sediment yields and hydraulic effects from HTNS roads? The
186 question pivots on combinations because there is already significant information on what
187 individual treatments such as rocking or traffic changes can do to mitigate sedimentation (e.g., as
188 summarized by Burroughs and King 1989). Such information has been formulated into simple
189 empirical approaches that estimate sediment yield from a road surface based on a number of
190 empirical multipliers similar to the Universal Soil Loss Equation (USLE) (e.g., Dubé et al. 2010;
191 Luce and Black 2001a). These efforts predicate on two assumptions: 1) That the implementation
192 of multiple BMP has the expected positive benefits; and 2) That those positive benefits are
193 multiplicative. Luce and Black (2001a) experimented with BMP combinations and their results
194 do not support these two assumptions.
195
196 BMP treatments are rarely used alone and it is the combination of activities that has been
197 inadequately studied. Some combinations work well together while others may produce little
198 additive improvement at a greater cost. Under certain circumstances, one BMP may even reduce
199 the effectiveness of another one; for example, paving a road reduces production of sediment
200 from the surface, but contributes more water to the ditch line, and if the ditch is bare soil, erosion
201 can increase relative to that expected from a gravel road. Furthermore, safety and operational
202 constraints imposed by one part of a design can impair another part. For example, rocking with
203 high value rock sometimes encourages use of a road grader to retrieve lost rock from the ditch
204 line, which in turn renews the availability of sediment in the ditch (where stream power is high)
205 potentially negating much of the benefit of the rocking.
206

207   Furthermore, these simple models based on empirical, site-specific studies may have very little
208   applicability to locations other than where they were developed (e.g., WARSEM) as they are not
209   process-based representations of the effects of BMP. Therefore, there is a strong need for joint
210   development of extensive field studies and process-based numerical modeling approaches using
211   physical principles to study the effects of single and multiple BMP on water and sediment
212   transport across roads. Models should provide the physical framework for the different pathways
213   of BMP influence on water and sediment flows, while field observations would provide the data
214   to further refine models, and can be used as model input parameters.
215
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Project Objectives
218   The forest practices road rules are designed to protect water quality and riparian/aquatic habitats
219   through road prescriptions (WAC 222-24) and best management practices (BMP – Forest
220   Practices Board Manual, Section 3, 2013)[2]. These prescriptions and BMP, also called
221   "treatments" in this document, are broadly intended to minimize: 1) sediment production and
222   delivery from the road prism; 2) hydrologic connection between roads and the stream network;
223   and 3) the risk of road-related landslides caused by inadequately built and maintained roads and
224   culverts. This project will specifically focus on 1) and 2) – it will take a different study design to
225   evaluate the treatment effectiveness of 3).
226
227   Although an extensive body of research of the performance of individual BMP already exists
228   (e.g., as summarized in Burroughs and King 1989 and Dubé et al. 2004), some individual BMP
229   are not well studied and substantial gaps exist in our understanding of the collective performance
230   of road BMP at the site scale in reducing sediment production, sediment delivery and hydrologic
231   connectivity. Of particular concern is that conceptual models used in the design of road BMP
232   field studies in the literature assume a multiplicative approach such that data collection is
233   focused on observing and measuring factors that are used in multiplicative models. This limits
234   the scalability of those observations using different, more process-based models.
235
236   As landowners work to complete implementation of their RMAP and to meet road sediment
237   performance targets and water quality standards, it is important to provide them and other
238   stakeholders with a more confident technical foundation for determining which BMP are most
239   effective and cost effective at minimizing the discharge of sediment to the stream network and
240   the practical and operational limitations of what can be achieved in certain sensitive
241   environmental settings.
242
243   In summary, our understanding of BMP effectiveness is too incomplete to make sound
244   recommendations based on existing scientific evidence. Therefore, we may not be achieving
245   resource objectives, nor applying BMP in the most cost effective manner with the best risk trade-
246   offs.
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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?

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

3) Are combinations of individual BMP for the roads and ditches additive, multiplicative, synergistic, or antagonistic?

4) For individual or combinations of BMP, are increases in turbidity minimized? If turbidity increases, at what stream length below the stream crossing does it abate?

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 effect 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?

> **Comment [JD1]:** This proposal by Bob stems from a Doug Martin comment asking what, specifically, we mean by "hydrologic impacts." Please review carefully as it is a critical question.

> **Comment [JD2]:** Additional question stemming from TWIG conversation about sampling design.

Best Available Science Summary
Empirical Research
The generation of fine sediment from road networks in the forested environment has been investigated for more than forty years. The largely unpaved road networks are geographically extensive and therefore cross or lie parallel to many streams across the landscape. Early logging limitations led to high road densities; high rainfall in the coastal region causes high stream density and numerous stream crossings and, thus, road impacts are unusually high. 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. So, it became clear to the early researchers that this juxtaposition had the potential to deliver substantial loads of eroded material to river networks (e.g., Megahan and Kidd 1972; Beschta 1978; Reid and Dunne 1984; Bilby 1985).

The earliest research was conducted in the 1970's and 1980's (e.g., Megahan and Kidd 1972; Reid and Dunne 1984) and served to illuminate how much sediment was being produced from

299   different parts of the road prism under a variety of circumstances. In particular, Walt Megahan
300   and colleagues made numerous contributions to the body of science relating to road prism
301   sediment sources. One of their important contributions was the 1972 effort evaluating the role of
302   subsurface storm flow interception (SSSFF) - SSSFF produced 7.3 times more water than the
303   road's surface; this result fundamentally changed our understanding of roads and their impact on
304   the landscape.
305
306   Subsequent efforts focused on traffic levels (e.g., Luce and Black 2001a and references therein),
307   tread configuration (e.g., Burroughs and King 1989), tread surfacing (e.g., Swift 1984) and
308   cutslope vegetation (e.g., Luce and Black 2001b). The effectiveness of cross-drain spacing has
309   been extensively studied (e.g., Montgomery 1994; Wemple 1996; Croke and Mockler 2001;
310   Luce et al. 2014) as has the benefit of quality rock surfaces (e.g., Foltz and Truebe 1995). It has,
311   in fact, been common to measure sediment production across a variety of situations. Most of this
312   research has focused on the measurement of sediment production or delivery with and without a
313   single BMP application.
314
315   The work by Luce and Black (1999) is particularly important to western Washington because it
316   was conducted in the same ecoregion – the Oregon Coast range. In an intensive study, they
317   examined road design and maintenance at 74 plots where they measured sediment production
318   and road features. Looking at distance from culverts, road slope, soil characteristics, and
319   cutslope height as well as the vegetation condition of cutslopes and ditches, they were able to
320   develop relationships among variables which greatly improve erosion estimates. In both of
321   Megahan and Kidd (1972) and Luce and Black (1999), there was an extensive field program of
322   replicated treatments allowing reasonably powerful statistical tests among site characteristics and
323   treatments. These are only examples of some of the profound work previously completed, but
324   these examples allow us to consider what is still needed, how previously completed work can be
325   built on, and the effort necessary to collect the meaningful data.
326
327   A variety of useful methods for quantifying surface erosion has been described in the literature
328   (Megahan and Kidd 1972; Reid and Dunne 1984; Ice 1986; Bilby et al. 1989; Foltz and Trube
329   1995; Luce and Black 1999; Kahklen 2001; MacDonald et al. 2001 and 2004). This information
330   was briefly summarized in Black and Luce (2013) who point out that "the methods require a
331   range of effort and expense and vary substantially in accuracy." Black and Luce (2013) provide a
332   settling basin and tipping bucket design that measures both water and sediment discharge for
333   individual road plots which can be systematically applied to road sediment and road hydrology
334   studies in the future.
335
336   The sum of the research had grown enough by the early part of this century that researchers
337   could review the combined findings. In 2004 in a CMER-funded project, Drew Coe did a review
338   of the published literature – 35 studies. The review examined projects that looked at both site and
339   basin level responses. While the individual studies focused on specific topics to meet their
340   project's objectives, the body of the science could be summarized into several key findings.
341   Many researchers documented how site-specific conditions dramatically change runoff
342   processes. A few studies highlighted the importance of the interception of surface flow by
343   cutslopes as a dominant mechanism. The magnitude of that interception is dependent on
344   lithological features. Another theme in the reviewed work was the extent of connectivity

345   between the road and stream network and the factors exerting influence on connectivity. The
346   document also provided insights from studies on the hydrologic effects streams have on runoff
347   generation. Much of this work was the basis of the early generations of road models, particularly
348   another CMER-funded project, WARSEM (Dubé et al. 2004).
349
350   In a subsequent publication, MacDonald and Coe (2008) compared sediment delivery from roads
351   in 11 studies from across the world. The work compared research from across the US and other
352   locales such at New Zealand and the US Virgin Islands with a wide range of estimated
353   production rates both within and between studies. They segregated the studies by road prism
354   feature and were able to estimate sediment production by road surface, and cutslopes and
355   fillslopes. In addition, they compared road erosion fine sediment inputs to landslide delivery of
356   fine sediment. When they scaled the road studies to the work focused on landslides, the values
357   were similar and in some cases larger in the road-related erosion. One difference was that road-
358   related delivery was primarily at stream crossings.
359
360   **Model Development**
361   Efforts to develop models of road erosion that could be applied at larger scales has resulted in
362   numerous summaries of the existing body of empirical research (e.g., Dubé et al. 2004;
363   MacDonald and Coe 2008). The development of models became imperative as scientists and
364   managers recognized that given the extent of road networks, tools needed to be developed to
365   better understand potential cumulative impacts and how they might prioritize remediation efforts.
366
367   Road erosion models can be grouped into two categories, empirical and physically-based.
368   Empirical models are based on statistically significant relationships between erosional response
369   (road surface, ditch, cutslope) and independent site variables or factors (e.g., geology, road
370   surfacing and length, rainfall). Effects of independent site variables are incorporated as
371   multipliers to predict total erosion from a road segment, which is then multiplied by a sediment
372   delivery ratio (SDR) to estimate sediment delivered to a nearby stream. Empirical models are
373   used to predict mean annual sediment contribution from roads often at the catchment scale.
374   Physically-based models incorporate conservation equations that describe sediment detachment,
375   transport and delivery processes from road segments which are driven by rainfall and overland
376   flow. Models typically share a relatively standard road surface hydrology component for
377   modeling infiltration and runoff generation, driven by rainfall events, although they disregard
378   interception of surface and subsurface flow from hillslopes by roads.
379
380   Empirical Models
381   Washington Department of Natural Resources (WADNR) developed Watershed Analysis
382   methods (WFPB 1995), which included a series of empirical relationships to estimate road
383   surface erosion based on empirical modeling concepts developed by Megahan and Kidd (1972)
384   and Megahan (1974) and the R1-R4 model (Cline et al. 1981; Ketcheson et al. 1999). A number
385   of similar watershed modeling tools that employ different software have evolved from the
386   Watershed Analysis methods of WADNR to assess impacts of roads on annual sediment yields.
387   The models estimate annual road surface, ditch, and cutslope erosion based on multiplicative
388   empirical site-specific factors (geology, surfacing, traffic, rainfall, sediment delivery), sum them
389   up, and multiply by a road age factor. Among these models, Washington Road Surface Erosion
390   Model (WARSEM) was developed as a Microsoft Access database application. Boise Cascade

391   developed a GIS-based program (SEDMODL) to automate the WADNR road erosion
392   calculations used in WARSEM for landowners with extensive road networks. Version 2 of this
393   model (SEDMODL2) was developed by NCASI in collaboration with Boise Cascade (NCASI
394   2003). The model uses an elevation grid combined with road and stream information layers to
395   produce a GIS version of WARSEM. WARSEM and its interface with SEDMODL2 is a
396   spatially distributed model by road segment, including features for estimating ditch, cutslope,
397   and road surface erosion. WARSEM can be applied at large catchment scales and the effects of a
398   variety of Best Management Practices (BMP) enable the model to be used to aid catchment
399   decision-making (Dubé et al. 2004; Fu et al. 2010).
400
401   GRAIP is a distributed watershed-scale tool that analyzes risks from multiple erosion processes
402   for forest roads, including surface erosion, gullying, landslides, and stream crossing failure, in a
403   GIS environment based on road inventory and terrain data (Prasad et al. 2005). As input, GRAIP
404   requires GIS coverages of road lines and drain points to represent the continuity of water flow
405   paths along and off of the road. The model uses a base erosion rate (A), scales that with
406   multipliers for topographic factors of flow path length (L) and slope (S), a vegetation factor (V),
407   and a road surface factor (R), and estimates mean annual sediment yield from a watershed,
408   SY=A*L*S*V*R (kg/yr) based on the formula of Luce and Black (1999). Sediment production
409   from road segments can be mapped using GIS. The model uses simple rules to route sediment to
410   drain points such as culverts, estimates sediment delivery to streams from culvert outlets, and
411   routes accumulated sediment from culverts through the channel network. The routed sediment
412   gives a long-term average of sediment yield sourced from road surfaces. Sediment delivery from
413   sub-catchments within a watershed can be analyzed and compared in relation to road density and
414   other factors. GRAIP includes a landslide risk component that estimates an index of stability
415   (SI). SI increases in the model at culvert locations where water concentrates at a point outlet.
416   While the representation of roads in GRAIP is based on an empirical equation which needs a
417   baseline erosion rate, the range of integrated processes represented in GRAIP makes it an
418   effective tool to examine relative impacts of road conditions holistically across a watershed.
419
420   Physically Based Models
421   Two physically based models have been applied to modeling road erosion: WEPP and Kineros.
422   Of these, WEPP has a specific module intended to assist users in inputting parameters for roads.
423   That version – WEPP Road – is limited to modeling road segments (Elliot and Hall 1997).
424   WEPP Road is a fairly generic tool that is run online using site and road conditions selected from
425   a menu of default choices developed largely based on empirical observations. Site conditions
426   include climate (obtained from weather stations), soil textural type, rock cover %, and inputs to
427   characterize road geometry such as gradient, length and width of road, fill and buffer, as well as
428   road design conditions. The Road version does not require any site-specific field observations
429   and, therefore, it is relatively easy to implement and can be used directly from the web
430   (http://forest.moscowfsl.wsu.edu/fswepp/). Another interface, WEPP Road Batch, predicts
431   erosion for multiple road segments, currently up to 200 segments in a batch. Both interfaces
432   predict average annual erosion only.
433
434   Site-specific data can be incorporated in the WINDOWS version of the model, which allows
435   users to run both hillslope and 'watershed' configurations (Elliot and Hall 1997; Elliot et al.
436   1999a), where the 'watershed' configuration allows for using shapes beyond the single-plane

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437 representation in WEPP Road. However, the generic WINDOWS version requires a large
438 number of data inputs which are often difficult to obtain in the field and are highly uncertain.
439 WEPP was designed around BMP for farmer's fields, and adaptation to roads has required ad-
440 hoc adjustments to create a road-like simulation. Consequently the web-based version offers a
441 simpler application option for roads. A strong aspect of WEPP is its capacity to develop
442 continuous simulations driven by sequences of rainfall events. While this model can be useful to
443 characterize relative rates of sediment production from different road surfaces for initial design
444 and maintenance purposes, it does not include functionality for road sediment BMP. In addition,
445 the high data intensity makes its implementation difficult and introduces a high degree of
446 uncertainty on model results.

447

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

452

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

461

462 Dubé et al. (2011) compared SEDMODL2/WARSEM, GRAIP, WEPP Road and WEPP
463 watershed models against a large data set of road erosion observations at 9 sites across the US
464 that had sufficient data to run and test the models. The WEPP (PC interface) model which has
465 the ability to predict runoff and erosion from individual storms produced relatively better results
466 for individual storms than for long-term averages. The GRAIP and SEDMODL2 models
467 predicted between-segment variations generally well and were found suitable for relative
468 comparisons of different management conditions. Overall, none of the models showed good
469 performance in predicting actual values of average annual runoff and erosion at all sites. The two
470 main points of the analysis are that the models were reasonably good at discerning relative
471 differences among locations, but poor at predicting actual amounts of sediment delivered. This
472 is both encouraging and disappointing. Encouraging, because they should allow prioritizations
473 of road segments for remediation and possibly be useful in evaluating improvements.
474 Disappointing because with the regulatory process it is necessary to have a reasonable estimate
475 of how much sediment is delivered. Dubé et al. (2011) recommended the use of local data from
476 field observations to calibrate the surface erosion models if estimates of actual values are needed.
477 Therefore, more extensive information could both improve actual modelling estimates in a
478 region and allow enhancements to the model(s).

479

480 In summary, while simple models are thought to be more useful and easily applied for land
481 management purposes, more complex models can conceptually provide a basis for building
482 improved understanding and scientific knowledge. However, both approaches provided in the

11

483 literature have shown significant deficiencies and have very limited utility especially for
484 evaluating the impact of road BMP. Some of the most pronounced limitations of existing models
485 are:
486

487 • Empirical models are driven by data and work best in regions where they were
488 developed.
489 • Spatial and temporal dynamics in the climate are not included in inputs of empirical
490 models.
491 • The effect of each factor on sediment yield is assumed to be multiplicative, following the
492 USLE equation idea, without much physical justification. One publication, Luce and
493 Black (2001a), notes that the multiplicative interaction is in error for independently
494 derived empirical effects of traffic and ditch grading. That documents a need for a better
495 theoretical foundation for mixed BMP effect modeling.
496 • Among models, only WARSEM considers the effects of BMP from a list of 70 different
497 BMP choices. In the WARSEM manual, each BMP is described qualitatively and a
498 deterministic multiplier is assigned to introduce the influence of BMP in the calculated
499 sediment yield (Table C-1, WARSEM manual, Dubé et al. 2004). These multipliers were
500 based on very limited data, and were not systematically obtained by holding other
501 conditions constant while changing one BMP. Because multipliers were obtained from
502 limited sites, inference beyond the local setting is not validated. Nor is there a guarantee
503 that one BMP is not redundant with another. The model does not build physical
504 causalities between BMP and the hydrologic and erosional responses of the road setting.
505 • The WEPP runoff generation component poorly predicts runoff responses in most data
506 sets collected at a range of study sites as reviewed by Dubé et al. (2011). Natural
507 hydrology of a road site, such as base flow and surface flow contributions to ditches and
508 culverts from hillslopes, was not incorporated in the existing physically-based models for
509 roads.
510 • Both physically based models only work on assemblages of planes, so water cannot
511 accumulate in ruts or ditches unless they are explicitly input by the user (they do not exist
512 at all in WEPP Road). Concentrated flow erosion in WEPP is not physically based but
513 essentially input as a parameter by the user. This is an important factor in evaluating rut
514 development and ditch line erosion in forest roads.
515

516

517 **Alternative Research Approaches**
518 <u>Overview</u>
519 Alternatives developed by the TWIG show tradeoffs between doing new empirical research or
520 trying to improve existing models with existing data without doing additional empirical research,
521 between concentrating new empirical research on HTNS roads or doing a wider suite of forest
522 road types, and between doing new empirical research with or without a modeling component.
523 Our preferred alternative, #4 below, proposes empirical research focused on HTNS roads with a
524 modeling component. For each of the five alternatives, we provide details about the approach, a
525 list of products, assessment of benefits and limitations, and estimations of relative time and cost.
526

527 This is step 4 in the TWIG process. If Policy approves follow-up work on one or more of the
528 following alternatives, a study design will be developed. The study design will contain detailed
529 methods for site selection and layout, data collection, and analysis.
530
531 The alternatives we propose are:
532
533 Alternative #1 – Empirical Research of BMP on HTNS Roads
534
535 Alternative #2 – Empirical Research of BMP on HTNS and non-HTNS Roads
536
537 Alternative #3 – Utilize Existing Data to Improve Existing, Segment-Scale Models
538
539 Alternative #4 – Do Empirical Research of BMP on HTNS Roads (Alternative #1) and Utilize
540 New and Existing Data to Improve Existing Models
541
542 Alternative #5 – Do Empirical Research of BMP on HTNS and non-HTNS Roads (Alternative
543 #2) and Utilize New and Existing Data to Improve Existing Models
544
545
546 **Discussion of Alternatives**
547 Alternative #1 –Empirical Research of BMP on HTNS Roads
548 Proposal
549 Alternative #1 comprises measurements of road sediment production from road prisms and
550 delivery below roads. We propose to research road surface erosion by observation and
551 measurement of sediment production from a sample of individual road segments using sediment
552 traps. We propose to research delivery below roads by observing delivery versus non-delivery
553 (success or failure) from a large number of segments. For Alternative #1, we propose to do
554 detailed empirical research on individual BMP and combinations of BMP targeting specifically
555 HTNS roads.
556
557 Details of Approach
558 Opportunities to reduce both sediment production and sediment delivery will be studied. Study
559 sites will be placed in 2-4 distinct regions of climate, lithology and topography in Washington
560 State to address relative effectiveness as a function of regional contexts. During the study design
561 phase, the TWIG will identify potential opportunities to evaluate aquatic effects from differing
562 volumes of road inputs while conducting empirical research on BMP.
563
564 The sampling frame for the sediment production field studies will apply a basic conceptual
565 understanding of the physics of sediment detachment and transport from/through the road tread,
566 cutslope, ditch line, and fill slope to facilitate the exploration of the influences of BMP on
567 sediment production and transport in these different domains. Conceptually, the cutslope and
568 tread generate runoff and sediment, which is then fed to the ditch (or a rut) where concentrated
569 flow transports the sediment. The primary sources of water are the components of the road
570 prism with large areas, the tread and cutslope. The tread generates runoff during relatively
571 intense precipitation events (see Luce and Cundy 1992 and 1994; Luce 2004), whereas the
572 cutslopes produce more runoff from long precipitation events or snowmelt in the Pacific

573 Northwest (Luce 2002). Runoff from both of these sources will carry some fine sediment
574 depending on the characteristics of their surfaces and sediment detachment by raindrops and
575 traffic. Runoff from these areas is generally shallow and diffuse in nature, but when that runoff
576 is accumulated along the ditch line or in ruts, it becomes concentrated flow, and the more
577 powerful flowing water can more actively detach sediment where the soil is exposed.
578 Alternatively, a well vegetated ditch can promote settling of fine sediments from the cutslope or
579 tread. We can think about parallel processes when water runs off of a crowned or rutted surface
580 over the fillslope, as well.
581
582   Empirical Research on Sediment Production Reduction
583 The first approach would use sediment trap technology developed by the USFS (Black and Luce,
584 2013 - see Figure 2 below) to test sediment production differences from several plots applying a
585 few prescribed combinations of BMP, as much to demonstrate the effectiveness of a "best"
586 design as to determine how far it is necessary to go to achieve substantial reductions in
587 production.
588

589
590
591 Figure 2: A sediment trap installed below a road segment.
592
593 Testing of BMP combinations will be done for mixed tread, ditch line, and cutslope treatments in
594 a way that isolates tread and cutslope treatment effects from the concentrated flow treatment
595 effects (see Burroughs and King 1989 for examples of individual effects) as well as how the
596 presence or lack of treatment in the concentrated flow road-element can enhance or limit the
597 effectiveness of tread and cutslope treatments. For example, a graded ditch line can undo
598 sediment reductions from the tread simply because the clean water from a paved road can detach
599 sediment from the bare ditch line to satisfy transport capacity (e.g., Luce and Black 2001a).
600 Although the subject has been approached before for a specific combination (e.g., Luce and
601 Black 2001a), it has not been systematically applied toward the particular end of understanding
602 the general effects of multiple BMP.
603
604 The sediment production tests of BMP will ultimately be stratified by geology and climate, but
605 will initially be applied in a single area with relatively consistent base geology and climate. A

606   sample of about 80 plots was used in the Oregon Coast Range (Tyee Sandstone and weathered
607   volcanics) in the 1990s using a small crew; it offered a reasonable sample size for a number of
608   alternative treatment combinations. The number of suitable sites (HTNS) may be the limiting
609   factor on getting a large sample size; for Alternative #2, obtaining suitable sites for other road
610   types is not expected to be a limitation.
611
612   <u>Empirical Research on Sediment Delivery Reduction</u>
613   The second approach would use a sediment delivery survey like that used in GRAIP (Black et al.
614   2012), a simple sampling approach to estimate short-scale delivery reductions when careful
615   drainage design is applied in these hydrologically challenging locations. The basic question to
616   address is the relationship of sediment transport distances below drainage features with the
617   contributing road length/area. Related survey work on stream connectivity shows an effect of
618   the contributing length or area of road and the probability of delivery at different distances (Luce
619   et al. 2014, Figure 3). There is also a suggestion from analysis of those data (not shown in
620   Figure 3) that the effect of distance is more pronounced for smaller contributing areas, which
621   would be relevant to the use of crowning or water bars to reduce the area of roads contributing to
622   stream crossings. A few surveys during wet weather conditions may be the most efficient
623   approach for this study component.
624
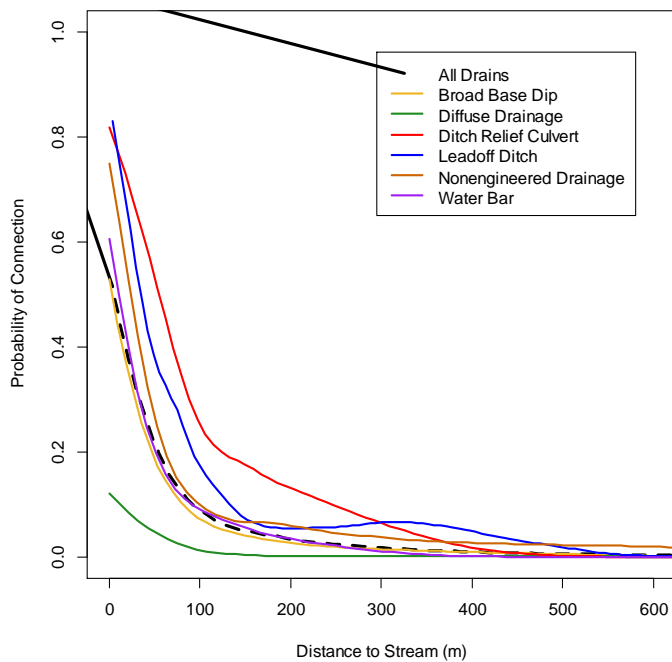
626   Figure 3: Probability of hydraulic connection between a road drainage diversion and a stream as
627   a function of the drain type and distance to stream (Luce et al. 2014).
628

629 <u>Products</u>
630 • Detailed data about individual and combinations of BMP on HTNS roads in the contexts
631 of lithology and topography.
632 • An analysis of the data.
633 • A report about same, including implementation recommendations (i.e., both where and
634 how).
635
636 <u>Benefits and Limitations</u>
637 Alternative #1 will provide information to improve our understanding of road surface erosion
638 and delivery. Doing research across distinct regions of climate, lithology and topography will
639 help develop a better understanding of lithological and topographic controls. That will allow a
640 better understanding of BMP effectiveness for HTNS Roads. In particular, a better
641 understanding of the relationships among BMP and how combinations of BMP relate to each
642 other (e.g., may not be multiplicative as applied in existing operational models). With a focus of
643 HTNS roads, potential gains at the roads most likely to contribute will be evaluated. Not doing
644 research on non-HTNS roads does not mean that these results cannot be applied to non-HTNS
645 roads. Results about lithologic and topographic controls and how BMP interact will be applicable
646 to the rest of the road network, although some special designs for HTNS roads may not be
647 necessary for other road types.
648
649 Modeling is a logical extension of empirical research because of the need to apply expensive,
650 detailed, site-specific results to the landscape. NOT doing modeling, as is proposed in
651 Alternative #1, limits the use of these new data and precludes broader landscape application. In
652 particular, local topographic, geologic, and climatological contexts are important. We have
653 gained considerable knowledge from road surface erosion and delivery field studies. Those
654 studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al.
655 (2011), the field studies have led to the development of models providing reasonably good
656 estimates on relative amounts of material eroded. However, they are only fair to poor in
657 predicting actual amounts of eroded material unless local calibration data are used. Improvement
658 in the existing models is to a large degree limited by available data. Much of the modeling
659 efforts have been using "best available data' which may not be appropriate for many of the road
660 segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be
661 done across all possible scenarios, additional work needs to focus on data collection that will
662 provide the most useful new information to operational prediction of actual amounts. And not
663 proceeding with a modeling effort begs the question: How do we demonstrate meeting WQ
664 standards or TMDL requirements if we don't model?
665
666 While detailed field work is impractical for all roads, a large enough sample size of well
667 replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A
668 primary limitation to gaining more information is the cost associated with such an effort.
669 Treatments will need to be designed to address the various processes and mechanisms for erosion
670 with the treatments and their distribution designed so individual as well as cumulative processes
671 can be quantified. These sampling requirements will drive cost as sites will require both
672 equipment and labor over time. The design will also need substantial site selection effort.
673

674   Depending on the details of the sampling design, Alternative #1 will answer Critical Questions
675   1-7 for HTNS roads for those specific situations included in the sample (e.g., regions, lithologies,
676   topographic positions) and, to a lesser extent, will answer Critical Questions 1-7 for non-HTNS
677   roads for those specific situations included in the sample. However, extrapolation of these results
678   to other situations and stronger answers to Critical Questions 2-4 and 6 will be possible with
679   modeling (Alternative #4).
680
681   Relative Cost/Time Estimates
682   •   Mobilization to Each Region – $4,000
683   •   Estimate of Site Selection – Unknown
684   •   Equipment, Installation – $3,500
685   •   Monitoring per Site – $1500 each year
686   •   Estimate of Number of Sites / Region – 40
687   •   Estimate of Number of Regions – 2-4
688   •   Total (minimum estimate) - $768,000 (assumes only 2 regions; assumes 4 years of
689   sampling; does not include site selection and maintenance; could be expanded by using
690   results to drive changes to design or factors tested)
691
692   Alternative #1 is approximately 1/3rd the cost of Alternative #2 for the same number of regions,
693   and less than 1/3rd the cost of Alternative #5. It is somewhat less expensive than Alternative #4
694   which proposes an equivalent field effort and incorporates a modeling component. It is much
695   more expensive than Alternative #3.
696
697
698   Alternative #2 – Empirical Research of BMP on HTNS and non-HTNS Roads
699   Proposal
700   Alternative #2 comprises measurements of road sediment production from road prisms and
701   delivery below roads. We propose to research road surface erosion by observation and
702   measurement of sediment production from a sample of individual road segments using sediment
703   traps. We propose to research delivery below roads by observing delivery versus non-delivery
704   (success or failure) from a large number of segments. For Alternative #2, we propose to do
705   detailed empirical research on individual BMP and combinations of BMP on both HTNS roads
706   and other forest roads.
707
708   Details of Approach
709   See above in Alternative #1 – research efforts would be extended to additional road types, but
710   techniques would be the same. The minimum cost estimate has tripled (see below) because three
711   traffic levels would be sampled in each region.
712
713   Products
714   •   Detailed data about individual and combinations of BMP on both HTNS roads and other
715   forest roads in the contexts of lithology and topography.
716   •   An analysis of the data.
717   •   A report about same, including implementation recommendations (i.e., both where and
718   how).
719

720   <u>Benefits and Limitations</u>
721   Alternative #2 will provide information to improve our understanding of road surface erosion
722   and delivery. Doing research across distinct regions of climate, lithology and topography will
723   help develop a better understanding of lithological and topographic controls. As with Alternative
724   #1, this alternative will improve our understanding of BMP effectiveness for HTNS Roads. Of
725   particular importance in both Alternative #1 and #2, we will develop a better understanding of
726   the relationships among BMP and how combinations of BMP relate to each other (e.g., may not
727   be multiplicative as applied in existing operational models). Doing both HTNS and non-HTNS
728   roads would incrementally improve our knowledge of the entire road network (i.e., relative
729   sediment production and delivery between road types).
730
731   Modeling is a logical extension of empirical research because of the need to apply expensive,
732   detailed, site-specific results to the landscape. NOT doing modeling, as is proposed in
733   Alternative #2, limits the use of these new data and precludes broader landscape application. In
734   particular, local topographic, geologic, and climatological contexts are important. We have
735   gained considerable knowledge from road surface erosion and delivery field studies. Those
736   studies have been conducted throughout the US and elsewhere and, as detailed in Dubé et al.
737   (2011), the field studies have led to the development of models providing reasonably good
738   estimates on relative amounts of material eroded. However, they are only fair to poor in
739   predicting actual amounts of eroded material unless local calibration data are used. Improvement
740   in the existing models is to a large degree limited by available data. Much of the modeling
741   efforts have been using "best available data' which may not be appropriate for many of the road
742   segments where the models may be used (Dubé et al. 2011). Since empirical work cannot be
743   done across all possible scenarios, additional work needs to focus on data collection that will
744   provide the most useful new information to operational prediction of actual amounts. And not
745   proceeding with a modeling effort begs the question: How do we demonstrate meeting WQ
746   standards or TMDL requirements if we don't model?
747
748   While detailed field work is impractical for all roads, a large enough sample size of well
749   replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A
750   primary limitation to gaining more information is the cost associated with such an effort.
751   Treatments will need to be designed to address the various processes and mechanisms for erosion
752   with the treatments and their distribution designed so individual as well as cumulative processes
753   can be quantified. These sampling requirements will drive cost as sites will require both
754   equipment and labor over time. The design will also need substantial site selection effort.
755
756   Depending on the details of the sampling design, Alternative #2 will answer Critical Questions
757   1-7 for HTNS roads and for other traffic levels for those specific situations included in the
758   sample (e.g., regions, lithologies, topographic positions). However, extrapolation of these results
759   to other situations and stronger answers to Critical Questions 2-4 and 6 will be possible with
760   modeling (Alternative #4).
761
762   <u>Relative Cost/Time Estimates</u>
763   •   Mobilization to Each Region – $4,000
764   •   Estimate of Site Selection – Unknown
765   •   Equipment, Installation per Site – $3,500

18

766 • Monitoring per Site – $1500 each year
767 • Estimate of Number of Sites / Region – 120
768 • Estimate of Number of Regions – 2-4
769 • Total (minimum estimate) - $2,304,000 (assumes only 2 regions; assumes 4 years of
770   sampling; does not include site selection and maintenance; could be expanded by using
771   results to drive changes to design or factors tested)
772
773 Alternative #2 is approximately three times the cost of Alternative #1 for the same number of
774 regions, and almost three times the cost of Alternative #4. It is somewhat less expensive than
775 Alternative #5 which proposes an equivalent field effort and incorporates a modeling component.
776 It is much, much more expensive than Alternative #3.
777
778
779   Alternative #3 – Utilize Existing Data to Improve Existing, Segment-Scale Models
780   Proposal
781 We present a modest proposal to apply a geomorphic model to understand road prism erosion in
782 the context of multiple contributing and transporting elements. The proposed model is not
783 intended as an operational tool, rather as a theoretical support tool to place new and existing
784 empirical information into a context that can better be incorporated into the existing operation
785 tools such as WARSEM and GRAIP. This model will be developed at the scale of road
786 segments, and it will include the hillslope hydrologic processes that contribute to road cutslopes.
787 While the model will be capable of predicting water and sediment dynamics in the road prism
788 (tread, cutslope, ditches, and fillslope) under the influence of single and combined BMP, it will
789 also provide capability to conceptually interface with existing operational empirical models to
790 extrapolate their estimates to different environments (topography, lithology, soils) and time
791 scales.
792
793   Details of Approach
794 Substantial modeling capacity of road erosion already exists. A review of models available for
795 road erosion estimation is provided above in the Best Available Science Summary. However,
796 these models do not provide a robust theoretical framework to merge information from multiple
797 empirical studies done in different environments. There is no existing model that embodies the
798 necessary features to study the impacts of road BMP alternatives. Empirical models focus on
799 mean annual response using simple linear equations based on multipliers and neglect physical
800 processes, nonlinearity, and climatic variability, while physical models are often over
801 parameterized, adapted from agricultural literature. Representation of hillslope hydrology and
802 lithologic and topographic controls on runoff generation are not included in any model. Models
803 lack proper representations of the continuum of water and sediment generation, transport and
804 storage dynamics across the road prism and the influence of BMP on these processes.
805
806 We propose a model to contextually place and extend existing and planned empirical studies into
807 a valid framework for applications using combinations of BMP in operational models like
808 WARSEM or GRAIP. Existing physically based models are too constrained in topology and
809 hydrology to reasonably represent many road BMP. However, a combination of existing
810 software applications can lead to a theoretically rigorous tool to evaluate combinations of BMP

19

811 and design smaller empirical studies to provide local calibration parameters for physically-based
812 relationships.
813
814 We envision a modular and component-based numerical model that can be used to investigate
815 the effectiveness of individual and collective uses of a range of forest road BMP within road
816 segments integrated to watershed flow paths. A new landscape modeling framework called
817 Landlab is suitable for this purpose (http://landlab.readthedocs.org/en/latest/index.html). Landlab
818 is a Python software package that supports numerical modeling in earth science, and especially
819 those fields that deal with earth-surface dynamics including geomorphology, hydrology,
820 glaciology, stratigraphy, and related areas. Landlab is actively being developed by collaborations
821 among University of Colorado, University of Washington (Istanbulluoglu), and Tulane
822 University.
823
824 Landlab is a modeling environment in which scientist can build a numerical landscape model
825 without having to code all of the individual parts (e.g., Tucker et al., 2015). Landlab provides
826 four main resources and capabilities:
827
828   1) A library of *code resources* for building two-dimensional numerical models from scratch.
829   The Landlab library includes a powerful "gridding engine" for creating, managing, and
830   iteratively updating data on structured or unstructured grids. The library also includes
831   support for input and output, including input of digital elevation models (DEM) in
832   ArcInfo ASCII format, handling of parameter inputs using formatted text files, and
833   netCDF-format input and output.
834   2) A set of pre-built *components*, each of which implements a numerical representation of a
835   particular process.
836   3) A *framework for building models* by assembling and linking process components.
837   4) A *library of models* that have already been created from component(s).
838
839 In this project we would use Landlab functionalities of spatial representation of model domains
840 and flow generation and routing. Our modeling efforts would initially focus on processes within
841 a road segment while representing incoming flows of water and sediment from the defined
842 boundaries of the road segment (i.e., hillslope contribution and flows from upslope road
843 segments) as external inputs from other models, linking models, or as specified contexts. Such a
844 model will support the planning of experimental field studies by means of developing what-if
845 scenarios and hypothesis testing of BMP design alternatives to note where results of a given
846 empirical study likely depend strongly on other contexts; this powerful model result is only
847 realized by this project if one of Alternatives #4 or #5 is chosen.
848
849 Representation of hillslope hydrology and long-term (seasonal to annual) hydrologic memory is
850 critical in the PNW to obtain realistic hillslope runoff contribution into ditches. For this purpose
851 we would delineate catchment areas that contribute flows into a road segment and use a separate
852 hydrology model to represent hydrological dynamics on slopes (see Figure 4). We envision using
853 an existing watershed hydrology model suitable for the PNW conditions, such as the Distributed
854 Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994), and feed off-line DHSVM
855 predictions as input to the road model. The watershed model predictions will provide surface

20

856 runoff and subsurface flow input in the upper boundary of a road cutslope over sub-daily or daily
857 time scales throughout simulations.
858
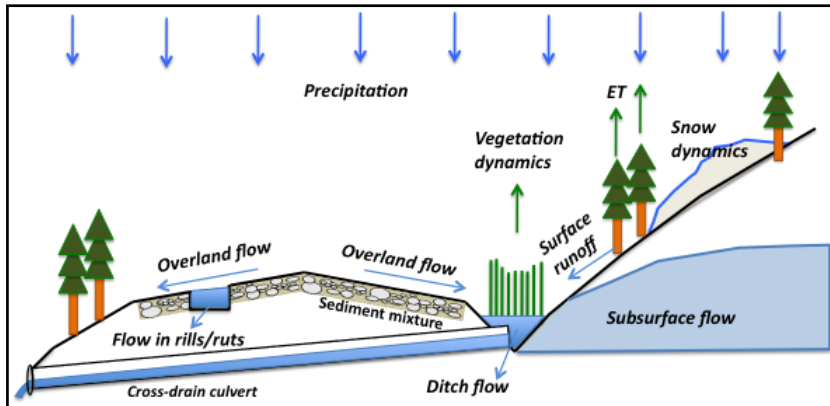
859
860
861
862 Figure 4. Forest road cross-section with some of the proposed model components indicated in
863 text.
864
865 Rainfall-driven infiltration, runoff generation and overland flow routing will be represented on
866 the road surface, ditches and cutslopes, following the model of Luce and Cundy (1994).
867 Overland flow will be routed as diffused or concentrated depending on the flow lines dictated by
868 the surface topography. In the ditches, flow will always be in the form of channel flow. The
869 model will be built to allow for sediment detachment, transport, and deposition using fixed and
870 dynamic grid representations. The latter will deform the initial elevation field as rills form.
871 Because runoff erosion is highly nonlinear to concentrated discharge, representation of surface
872 dynamics will improve predictions. Routing flows on the road surface will show the implications
873 of the evolving nature of road surface on the contribution of runoff overland flow on fillslopes.
874 In the ditch slopes, we will also represent the influence of vegetation (e.g., grass, shrub, bush,
875 etc.) on flow depth, velocity, shear stress, detachment and transport. Storm processes will be
876 modeled in hourly or sub hourly time scales, which will depend on model stability conditions
877 and intensity of rainfall input. Such short time scales will allow developing hydrographs at
878 culvert outlets and ditches. Continuous hydrological processes will be simulated on contributing
879 cutslopes at daily or sub daily time scales as needed. Model forcing can be obtained from
880 gridded climate data used for regional hydrologic models (e.g., Livneh et al. 2013) or local
881 weather stations as available.
882
883 Each BMP will be coded as an individual module. BMP will be geographically placed on the
884 desired location on the road surface, cutslopes, ditches or fillslopes, and will use flows of water
885 and sediment as inputs. Storage dynamics of water and sediment will be represented in each
886 BMP, and BMP will provide outflows at their outlets (either point or as continuous boundary).
887 The modular structure of the proposed model will allow testing of BMP off-line of the road
888 model, using necessary inputs and outputs as time series.   When multiple BMP are used, the
889 influence of each BMP on runoff and sediment discharge and storage will be linked along the

21

890   flow paths of integrated hillslope and road prism domains. All BMP will provide outputs to the
891   road segment. Simulations using a combination of BMP will illustrate their cumulative effects on
892   or downstream of the road prism.
893
894   Products
895   This project will deliver a forest roads BMP component in Landlab with applications and a
896   users' manual. The tools will be made available to public through the Landlab web-based model
897   repository (http://landlab.readthedocs.org/en/latest/).
898
899   Benefits and Limitations
900   The proposed modeling approaches in Alternative #3 may be able to improve our use and
901   interpretation of existing data sets and thereby lead to better understanding of road surface
902   erosion and delivery. For example, using improved DEM, considering hillslope hydrology
903   above road cutslopes in HTNS roads, and forcing the road surface processes with actual
904   climatologic input will lead to improved interpretation of existing data and models.
905
906   An important advantage of using the Landlab modeling framework in this project will be that the
907   proposed forest roads component will be readily compatible with other processes in Landlab,
908   such as landslides, and hillslope and stream erosion and transport processes. This will facilitate
909   watershed and regional scale evaluations of the impacts of roads on watershed hydrologic and
910   geomorphic processes and the potential improvements that can be achieved by road BMP.
911
912   There will be a number critical limitations of developing new model components without new
913   field studies designed consistent with model theory. Several important drawbacks in relying only
914   on existing data will include differences and inconsistencies in the qualitative and quantitative
915   data and descriptions of site conditions such as climate, topography and lithology, as well as
916   differences in data collection methods and instrumentation among sites. As models become more
917   process-based there is a need for detailed characterization of experimental conditions at field
918   sites where models are evaluated, and have a good representation of model forcing conditions as
919   well as hillslope hydrology. Lack of empirical data systematically collected by focusing single
920   and collective effects of BMP over similar space and time scales would hamper the level of
921   fundamental understanding that can be achieved from this modeling effort.
922
923   Relative Cost/Time Estimates
924   • Estimated Cost of Literature Review for Existing Data, gathering data in different
925   formats and geo-referencing the data – $25,000
926   • Estimated Cost of Model Development – $ 300,000 (assumes 3 years of graduate student
927   time)
928

929
930   <mark>Alternative #4 – Do Empirical Research of BMP on HTNS Roads (Alternative #1) and</mark>
931   <mark>Utilize New and Existing Data to Improve Existing Models (preferred alternative of the</mark>
932   <mark>TWIG)</mark>
933   Proposal
934   Alternative #4 will combine Alternatives #1 and #3 and synthesize co-developed data from field
935   observations and model applications to recommend regional BMP alternatives and suggest
936   approximate relative changes in sediment and water yield predictions in space and time.
937
938   Details of Approach
939   See above in Alternative #1 for details of the proposed field work on HTNS roads. For the
940   remainder of this section, we present this alternative from the perspective of combined field and
941   modeling effort.
942
943   The road surface model inter-comparison study of Dubé et al. (2011) showed large uncertainties
944   in model predictions and suggested that most models can only be used at best for relative
945   comparisons of model scenarios for decision making. Among the models they used, only
946   WARSEM included an empirical BMP component. Datasets obtained from field measurements
947   used to develop and evaluate such models focused on quantifying the effects of single BMP at a
948   time and, therefore, are not suitable for testing and evaluating models that can simulate multiple
949   BMP. There is need for developing a theoretical modeling framework for road hydrology and
950   sediment yield modeling with functionality for BMP which could guide the design of empirical
951   field studies in different regions; those results could then be used improve model theory. Figure 5
952   below illustrates how a theoretical model and fieldwork design can be used in a feed-back loop
953   to improve our understanding of road BMP effectiveness in a region and develop targeted
954   recommendations for stakeholders.
955
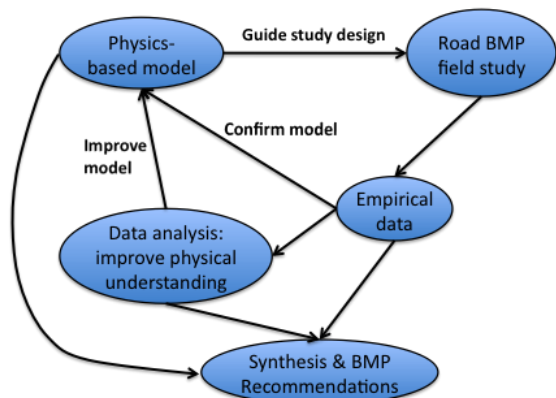
956
957
958
959   Figure 5. Conceptual framework to improve understanding of the effects of road BMP through
960   the feedback loop of physically-based modeling, field work design, empirical measurements and
961   use of field data.
962

963 For example, the model we outlined in Alternative #3 can aid in the planning of field
964 instrumentation, such as sediment traps and flow measurement, by providing runoff hydrographs
965 with estimated contributions of hillslope runoff, subsurface flow and road surface runoff.
966 Preliminary model runs showing active erosion and deposition areas can be used for identifying
967 monitoring sites. Field data will also be used to: 1) Identify the relative roles of local (road
968 features and design) and global (lithology and geomorphology of contributing areas) controls at a
969 field site; 2) Reevaluate model conceptualization and theory to improve the representations of
970 such controls; 3) Update model parameter values; 4) Regionalize model performance; and 5)
971 Identify model limitations in relation to local and global controls. At each field site, other
972 existing modeling tools will be evaluated as potentials for improving existing tools, and
973 interfacing them with Landlab will be considered. In the final year of the project, field data and
974 modeling at all sites will be synthesized, and BMP recommendations will be developed in
975 different regions and with examples of model implementation. We expect that this modeling
976 tool, based on a component-based Landlab landscape modeling framework, can dramatically
977 reduce model coding and development time and costs for future improvements. A graphical user
978 interface (GUI) can be developed in the future to facilitate both research and operational use of
979 the modeling framework.
980
981   Products
982 • Detailed data about individual and combinations of BMP on HTNS roads in the contexts
983   of lithology and topography.
984 • An analysis of the data.
985 • A report about same, including implementation recommendations (i.e., both where and
986   how).
987 • This project will deliver a forest roads BMP component in Landlab with applications and
988   a users' manual. The tools will be made available to public through the Landlab web-
989   based model repository (http://landlab.readthedocs.org/en/latest/).
990
991   Benefits and Limitations
992 Alternative #4 will provide information to improve our understanding of road surface erosion
993 and delivery. Doing research across distinct regions of climate, lithology and topography will
994 help develop a better understanding of lithological and topographic controls. That will allow a
995 better understanding of BMP effectiveness for HTNS Roads. In particular, a better
996 understanding of the relationships among BMP and how combinations of BMP relate to each
997 other (e.g., may not be multiplicative as applied in existing operational models). With a focus of
998 HTNS roads, potential gains at the roads most likely to contribute will be evaluated. Not doing
999 research on non-HTNS roads does not mean that these results cannot be applied to non-HTNS
1000 roads. Results about lithologic and topographic controls and how BMP interact will be applicable
1001 to the rest of the road network, although some special designs for HTNS roads may not be
1002 necessary for other road types.
1003
1004 Modeling is a logical extension of empirical research because of the need to apply expensive,
1005 detailed, site-specific results to the landscape. In particular, local topographic, geologic, and
1006 climatological contexts are important. We have gained considerable knowledge from road
1007 surface erosion and delivery field studies. Those studies have been conducted throughout the US
1008 and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the

24

1009 development of models providing reasonably good estimates on relative amounts of material
1010 eroded. However, they are only fair to poor in predicting actual amounts of eroded material
1011 unless local calibration data are used. Improvement in the existing models is to a large degree
1012 limited by available data. Much of the modeling efforts have been using "best available data'
1013 which may not be appropriate for many of the road segments where the models may be used
1014 (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional
1015 work needs to focus on data collection that will provide the most useful new information to
1016 operational prediction of actual amounts.
1017
1018 While detailed field work is impractical for all roads, a large enough sample size of well
1019 replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A
1020 primary limitation to gaining more information is the cost associated with such an effort.
1021 Treatments will need to be designed to address the various processes and mechanisms for erosion
1022 with the treatments and their distribution designed so individual as well as cumulative processes
1023 can be quantified. These sampling requirements will drive cost as sites will require both
1024 equipment and labor over time. The design will also need substantial site selection effort.
1025
1026 Depending on the details of the sampling design, Alternative #4 will answer Critical Questions
1027 1-7 for HTNS roads for those specific situations included in the sample (e.g., regions, lithologies,
1028 topographic positions) and, to a lesser extent, will answer Critical Questions 1-7 for non-HTNS
1029 roads for those specific situations included in the sample. Extrapolation of these results to other
1030 situations and stronger answers to Critical Questions 2-4 and 6 will be possible with the
1031 modeling effort proposed in this alternative.
1032
1033   Relative Cost/Time Estimates
1034 - Alternative # 3 Lit Review and Modeling Effort for Existing Data – $325,000
1035 - Additional Modeling Efforts for New Data, Data Analysis and Synthesis – $100,000
1036   (assumes another year of graduate student time)
1037 - Mobilization to Each Region – $4,000
1038 - Estimate of Site Selection – Unknown
1039 - Equipment, Installation – $3,500
1040 - Monitoring per Site – $1500 each year
1041 - Estimate of Number of Sites / Region – 40
1042 - Estimate of Number of Regions – 2-4
1043 - Total (minimum estimate) - $1,193,000 (assumes only 2 regions; assumes 4 years of
1044   sampling; does not include site selection and maintenance; could be expanded by using
1045   results to drive changes to design or factors tested)
1046
1047 Alternative #4 is approximately 1/3rd the cost of Alternative #5 for the same number of regions.
1048 It is approximately the cost of Alternatives #1 and #3 combined because it is the combination of
1049 those two alternatives. It is much more expensive than Alternative #3.
1050

1051
1052   Alternative #5 – Do Empirical Research of BMP on HTNS and non-HTNS Roads
1053   (Alternative #2) and Utilize New and Existing Data to Improve Existing Models
1054   Proposal
1055 Alternative #5 will combine Alternatives #2 and #3 and synthesize co-developed data from field
1056 observations and model applications to recommend regional BMP alternatives and suggest
1057 approximate relative changes in sediment and water yield predictions in space and time.
1058
1059   Details of Approach
1060 Details of the field sampling are discussed above in Alternative #1; this alternative also samples
1061 non-HTNS roads as discussed in Alternative #2. Modeling efforts are described in Alternative #3
1062 and the power of combining field and modeling efforts is described in Alternative #4.
1063
1064   Products
1065   • Detailed data about individual and combinations of BMP on both HTNS roads and other
1066   forest roads in the contexts of lithology and topography.
1067   • An analysis of the data.
1068   • A report about same, including implementation recommendations (i.e., both where and
1069   how).
1070   • This project will deliver a forest roads BMP component in Landlab with applications and
1071   a users' manual. The tools will be made available to public through the Landlab web-
1072   based model repository (http://landlab.readthedocs.org/en/latest/).
1073
1074   Benefits and Limitations
1075   Alternative #5 will provide information to improve our understanding of road surface erosion
1076 and delivery. Doing research across distinct regions of climate, lithology and topography will
1077 help develop a better understanding of lithological and topographic controls. That will allow a
1078 better understanding of BMP effectiveness for HTNS roads and for other traffic levels. In
1079 particular, a better understanding of the relationships among BMP and how combinations of
1080 BMP relate to each other (e.g., may not be multiplicative as applied in existing operational
1081 models).
1082
1083 Modeling is a logical extension of empirical research because of the need to apply expensive,
1084 detailed, site-specific results to the landscape. In particular, local topographic, geologic, and
1085 climatological contexts are important. We have gained considerable knowledge from road
1086 surface erosion and delivery field studies. Those studies have been conducted throughout the US
1087 and elsewhere and, as detailed in Dubé et al. (2011), the field studies have led to the
1088 development of models providing reasonably good estimates on relative amounts of material
1089 eroded. However, they are only fair to poor in predicting actual amounts of eroded material
1090 unless local calibration data are used. Improvement in the existing models is to a large degree
1091 limited by available data. Much of the modeling efforts have been using "best available data'
1092 which may not be appropriate for many of the road segments where the models may be used
1093 (Dubé et al. 2011). Since empirical work cannot be done across all possible scenarios, additional
1094 work needs to focus on data collection that will provide the most useful new information to
1095 operational prediction of actual amounts.
1096

1097   While detailed field work is impractical for all roads, a large enough sample size of well
1098   replicated treatments across 2-4 regions will improve the inferential capacity of the data set. A
1099   primary limitation to gaining more information is the cost associated with such an effort.
1100   Treatments will need to be designed to address the various processes and mechanisms for erosion
1101   with the treatments and their distribution designed so individual as well as cumulative processes
1102   can be quantified. These sampling requirements will drive cost as sites will require both
1103   equipment and labor over time. The design will also need substantial site selection effort.
1104
1105   Depending on the details of the sampling design, Alternative #5 will answer Critical Questions
1106   1-7 for HTNS roads and for other traffic levels for those specific situations included in the
1107   sample (e.g., regions, lithologies, topographic positions). Stronger answers to Critical Questions
1108   2-4 and 6 will be possible with the modeling effort proposed in this alternative.
1109
1110   Relative Cost/Time Estimates
1111   • Alternative # 3 Lit Review and Modeling Effort for Existing Data – $325,000
1112   • Additional Modeling Efforts for New Data – $100,000+ (expect more $ than for
1113   Alternative #4)
1114   • Mobilization to Each Region – $4,000
1115   • Estimate of Site Selection – Unknown
1116   • Equipment, Installation per Site – $3,500
1117   • Monitoring per Site – $1500 each year
1118   • Estimate of Number of Sites / Region – 120
1119   • Estimate of Number of Regions – 2-4
1120   • Total (minimum estimate) - $2,729,000 (assumes only 2 regions; assumes 4 years of
1121   sampling; does not include site selection and maintenance; could be expanded by using
1122   results to drive changes to design or factors tested)
1123
1124   Alternative #5 is approximately three times the cost of Alternative #4 for the same number of
1125   regions. It is approximately the cost of Alternatives #2 and #3 combined because it is the
1126   combination of those two alternatives. It is much, much more expensive than Alternative #3.

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