

EVALUATION OF WATBAL: A MODEL FOR ESTIMATING SEDIMENT DELIVERY AND WATER
YIELD RESPONSE TO LAND MANAGEMENT ON THE CLEARWATER NATIONAL FOREST,
IDAHO

Jonathan J. Rhodes, Hydrologist

prepared for

Columbia River Inter-Tribal Fish Commission
729 NE Oregon, Suite 200
Portland, OR 97232

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Executive Summary

This report describes and evaluates WATBAL, a model used to estimate changes in sediment delivery and water yield in response to logging, road activities, and fire on the Clearwater National Forest (CNF) in Idaho. Sources of inaccuracy in WATBAL's estimates of sediment delivery and water yield are of interest for several reasons.

WATBAL is one of the tools commonly used by the CNF to evaluate the impacts of existing conditions and proposed activities on watershed resources that are affected by sediment delivery and streamflow, including stream channels, water quality, and habitats for salmonids. The CNF provides habitats for several species of native salmonids that are imperiled and adversely affected by increases in sediment delivery. Roads and activities associated with logging contribute to increases in sediment delivery. Many streams with fish habitat have already been adversely affected by elevated sedimentation from the cumulative effects of logging and roads.

Because sediment delivery and peakflows are among the primary environmental concerns related to land management activities on the CNF, WATBAL is used as one of the tools to meet regulatory requirements, including:

- Evaluation and disclosure of the environmental effects of proposed activities, including determination of their likely consistency and compliance with Forest Plan standards related to fish habitat conditions, sediment delivery and water quality;
- Evaluation and disclosure of the cumulative effects of proposed activities together with those from existing watershed conditions;
- Evaluation of how the proposed activities affect habitats for species listed under the Endangered Species Act (ESA), such as bull trout and steelhead, and take reasonable measures to ensure that management activities do not adversely affect habitats for ESA-listed species;
- Adequate differentiation among land management alternatives with respect to their environmental effects;
- Determination of land management alternatives' consistency and compliance with federal trust obligations to treaty tribes related to fisheries, salmon run rebuilding efforts, the Clean Water Act, and other regulations.

For these reasons, this report examines WATBAL attributes that may cause it to inadequately differentiate among management alternatives or underestimate the cumulative effects of activities and existing conditions on aquatic systems.

Studies of the WATBAL's accuracy corroborate that, prior to its calibration by the CNF circa 2006, the model generally underestimated measured sediment yield from watersheds on the CNF. This report identifies several aspects of the model that likely cause it to do so, including:

- WATBAL's low erosion rates for older roads and those that are reconstructed or subjected to elevated use; these are likely significant sources of underestimation because the road network on the CNF is primarily comprised of older roads and is a major source of management-induced sediment delivery;
- WATBAL's inability to accurately estimate sediment delivery from activities that are near streams, which is important because a significant portion of the road network on the CNF is hydrologically connected or proximate to streams;
- WATBAL's failure to factor in surface and mass erosion from logging landings;
- WATBAL's inability to consider elevated channel erosion in response to increases in peakflows caused by vegetation removal and roads;
- WATBAL's allowance to use assumed levels of mitigation of sediment delivery that have not been adequately verified by monitoring;
- WATBAL's inability to estimate erosion and sediment delivery from mining and grazing in watersheds subjected to those land uses.

These attributes also likely cause WATBAL to inadequately differentiate among alternatives with different levels of logging and the construction, reconstruction, use of landings and roads on the basis of their impacts on sediment delivery.

The sediment delivery component of WATBAL was calibrated by the CNF circa 2006. While this calibration improved accuracy with respect to the calibration data set, it has not been tested on other data as needed to validate that it robustly reduces the model's proclivity to underestimate sediment delivery from roads and logging in a variety of settings. Additionally, the CNF's calibration may not address actual sources of underestimation in WATBAL that are identified in this report.

An independent, simplified calibration of WATBAL, based on addressing likely sources of model inaccuracy, was performed as part of this report. This independent calibration improved the model's performance with respect to sediment yield to a similar degree as the calibration done by the CNF circa 2006. This corroborates that calibration approaches aimed at addressing the model's limitations can improve accuracy and likely aid in adequately differentiating among proposed land management alternatives.

The CNF's own assessment of WATBAL's sediment delivery component indicates that the model likely has an accuracy of plus or minus 30-40% with respect to watershed scale sediment yields. This level of uncertainty in the model indicates that the impacts of activities on sediment delivery can be substantially greater than forecast by WATBAL. It is critical to completely incorporate this level of uncertainty in assessments of the impacts of activities on sediment delivery and its effects on aquatic systems.

WATBAL's water yield component also has several limitations. Research has shown that the methods used in WATBAL water yield component underestimate changes in water yield in response to logging and roads. Research has also noted that effects of roads and logging on short-duration high streamflows (peakflows) are important to consider. The water yield methods used by WATBAL are unable to estimate the effects of roads and logging on peakflows.

WATBAL's water yield component is also unable to adequately estimate the effects of roads and logging on peakflows generated by rain-on-snow events, which are typically the largest peakflows generated on the CNF. For these combined reasons, it is likely that WATBAL does not adequately differentiate among alternatives with respect to their likely impacts on streamflows.

This report provides several recommendations to improve WATBAL. These include: taking efforts to revamp erosion rates for roads, adjusting the delivery of sediment from roads that are in close proximity or hydrologically connected to streams, treating logging landings as equivalent to roads with respect to their effects on sediment delivery and streamflow, and modifying the water yield component to reasonably estimate changes in peakflows, including those generated by rain-on-snow events.

The limitations identified in this report likely are not peculiar to WATBAL and its use on the CNF. WATBAL is closely related to a number of models used by other national forests in Regions 1 and 4 of the U.S. Forest Service to estimate changes in water yield and sediment delivery. Therefore, it is likely that these models and WATBAL have similar limitations. While the description and evaluation of these related models, including how they compare with WATBAL, is beyond the scope of this report, the limitations identified in this report can be used to help evaluate the accuracy of models related to WATBAL.

TABLE OF CONTENTS

	Page
Introduction.....	1
Model overview.....	1
Ecological and management contexts.....	2
Description of the sediment delivery component of WATBAL.....	4
Likely sources of error in WATBAL estimates of sediment delivery.....	11
Studies of the accuracy of WATBAL sediment delivery estimates.....	40
Description of the water yield component of WATBAL.....	45
Likely sources of error in the water yield component of WATBAL.....	47
Studies of the accuracy of WATBAL's water yield component.....	50
Conclusions and recommendations.....	50
Literature cited.....	54

LIST OF TABLES

Table 1. Surface erosion rates in WATBAL for roads, logging, and fire	8
Table 2. Mass failure acceleration factors in WATBAL for logged and burned areas...9	9
Table 3. Mass failure acceleration factors in WATBAL for roads.....9	9
Table 4. A comparison of surface erosion rates for roads with different use levels in WATBAL and two related sediment delivery models.....	14
Table 5. Surface erosion rates for a reconstructed road in WATBAL and a related sediment delivery model.....	28
Table 6. Watershed attributes, measured sediment yield, and WATBAL estimates of sediment yield in seven watersheds on the Clearwater National Forest.....	42
Table 7. Measured sediment yield vs. sediment yield as estimated by: a) WATBAL prior to calibration; b) WATBAL as calibrated by Jones and Patten (2006); and, c) independent WATBAL calibration as part of this report.....	44

LIST OF FIGURES

Figures 1a and 1b. Cumulative sediment delivery over 10 years from surface erosion from road construction as estimated by WATBAL and a related sediment delivery model.....	19
Figures 2a and 2b. Cumulative sediment delivery over 10 years from surface erosion from 15-year-old roads as estimated by WATBAL and a related sediment delivery model.....	21
Figures 3a and 3b. Cumulative sediment delivery over 10 years from surface erosion from heavily used roads as estimated by WATBAL and a related sediment delivery model.....	24
Figures 4a and 4b. Cumulative sediment delivery over 10 years from surface erosion from reconstructed roads as estimated by WATBAL and a related sediment delivery model.....	27
Figure 5. Natural stream density, road density, and resulting stream density due to integration with the road network in watersheds on the Clearwater National Forest and the Umatilla National Forest.....	29

LIST OF PHOTOS

Photo 1. Elevated surface erosion on an unpaved road in the Pete King watershed.....	16
Photo 2. Another example of elevated surface erosion on an unpaved road.....	16
Photo 3. An example of the impacts of heavy road reconstruction.....	16

Introduction

This report provides a general overview and evaluation of WATBAL, a model used on the Clearwater National Forest (CNF) to estimate changes in sediment delivery and water yield in response to logging, road development, and fires. This report identifies and describes some of the model's more significant limitations. This report also evaluates some of the assumptions involved in the model's use. This report is *not* a detailed description of the model or an exhaustive review of all potential sources of model inaccuracy because that is beyond the scope of this report.

Because WATBAL also provides one of the bases for differentiating among the environmental effects of land management alternatives in environmental analyses on the CNF, this report evaluates aspects of the model that can cause it to inadequately do so. This report also provides some recommendations that may aid in improving WATBAL as tool for assessing watershed impacts on streamflow and sediment delivery.

The limitations identified in this report are not peculiar to WATBAL and its use on the CNF. A number of models used by other national forests in USFS Regions 1 and 4 to estimate changes in water yield and sediment delivery have bases and attributes that are similar to those of WATBAL (Rhodes, 1996). Therefore, it is likely that these models and WATBAL have similar limitations. However, the description and evaluation of these related models, including how they compare with WATBAL, is beyond the scope of this report.

Model overview

Like most of the family of related models employed in USFS Regions 1 and 4 to estimate sediment delivery and water yield effects from logging, roads, and fire, WATBAL is used to provide an indication of how land management has and will affect some stream conditions (e.g., those affected by changes in water yield and sediment delivery).

WATBAL model has two major components, which are described separately in this report. The first component is used to estimate average annual rates of: 1) natural levels of sediment delivery to streams and 2) management-induced sediment delivery from surface erosion and mass erosion from logging, roads, and fire.

The second WATBAL component is used to estimate natural water yield and management-induced changes in water yield attributes in response to logging, roads, and fire.

It is important to note WATBAL estimates only management-induced sediment delivery and changes in water yield from logging, roads, and fire (Patten and Jones, 2005). WATBAL does not estimate sediment delivery and changes in water yield caused by several other potentially prominent management-induced sources, including: mining, grazing, and, apparently, logging landings.¹ Some of the potential effects of ignoring these sources of streamflow alteration and

¹ Patten and Jones (2005) contain no mention of how landings are treated in the model, either with respect to how they are factored into the estimates of disturbed area, or effects on erosion and sediment delivery or water yield. The impacts of landings on vegetation, runoff, and erosion are

accelerated sediment delivery are discussed in this report's evaluation of the model's limitations.

Ecological and management contexts

Sediment delivery is an important ecological and management concern for several reasons. First, management activities, such as logging and roads, significantly increase sediment delivery, as many studies have consistently documented (e.g., Rhodes et al., 1994; USFS and USBLM, 1997a). Roads, in particular, greatly increase sediment delivery in an enduring fashion (USFS and USBLM, 1997a).

Elevated sediment delivery has affected many streams on the CNF in watersheds that have been logged and roaded (Rhodes et al., 1994; Espinosa et al., 1997; Huntington, 1998). Sediment delivery exerts a strong influence on stream channel conditions at scales ranging from the reach to the network (Richards, 1982). Elevated sediment delivery degrades water quality and fish habitats in ways that significantly reduce the survival and production of imperiled salmonids.

The streams on the CNF provide habitats for several native salmonids, including steelhead, spring Chinook salmon, bull trout, and westslope cutthroat trout (USFS and USBLM, 1997a). All of these salmonid species are imperiled due to severe reductions in their abundance and range that threaten their persistence (NMFS, 1996; USFS and USBLM, 1997a; USFWS, 1998; Kessler et al., 2001). Habitat degradation has significantly contributed to this situation (USFS and USBLM, 1997a). Bull trout and steelhead populations on the CNF have been listed under the Endangered Species Act (ESA), while the other native salmonids have been petitioned for listing.

Additional habitat degradation or maintenance of degraded habitat conditions increases the risk that salmonid populations will be extirpated from habitats and trend toward extinction (USFS and USBLM, 1997a) and is inimical to restoring these aquatic populations (NMFS, 1996; Karr et al., 2004). The maintenance of elevated sediment delivery prevents or inhibits the recovery of channel conditions degraded by increases in sediment delivery (Rhodes et al., 1994). Despite existing degradation, aquatic habitats on public lands, such as those on the CNF, are critical cornerstones for the protection and restoration of aquatic populations (Karr et al., 2004).

Salmonid habitats on the CNF and throughout the Snake River Basin are highly susceptible to sedimentation because of their watershed geology, hydrology, and geomorphology. Native salmonids, and especially spring Chinook salmon, spawn and rear in depositional stream environments are highly vulnerable to degradation by sedimentation caused by increased sediment delivery (Rhodes et al., 1994).

Elevated sediment delivery has three major effects on the condition of habitats for these salmonids that reduce their salmonid survival and habitat productivity. These are: increases in the amount of fine sediment in substrate, decreases in pool volumes and frequency via pool in-filling, and channel widening.

typically as great and as persistent as those from roads (Geppert et al., 1984; Menning et al., 1996; Beschta et al., 2004).

Increased levels of fine sediment in substrate significantly reduce salmonid survival, via several mechanisms and effects (Chapman and McLeod, 1987; Meehan, 1991; Rhodes et al., 1994; Waters, 1995). Research indicates that there is no threshold below which exacerbation of fine-sediment delivery and storage in salmonid habitats is harmless (Suttle et al., 2004). While all salmonids are negatively affected by increases in fine sediment, bull trout and cutthroat trout are particularly sensitive, undergoing steep reductions in survival with increases in fine sediment (Weaver and Fraley, 1991). Due to their effects on salmonid survival, elevated levels of fine sediment in the Columbia basin habitats, which include the CNF, increase the likelihood that native salmonid populations will be extirpated from habitats and trend toward extinction (USFS and USBLM, 1997a).

Increases in sediment delivery reduce the quality and volume of pools and impede pool development via several mechanisms. Fine sediment tends to be deposited and sequestered in pools during lower flows (Kappesser, 2002; Buffington et al., 2002). The loss of pool depth from sedimentation has been shown to be correlated with increased levels of fine sediment in streams caused by increased sediment delivery (Kappesser, 2002). Elevated sediment delivery contributes to increases stream width and decreases stream depth in depositional reaches (Richards, 1982; Dose and Roper, 1994). These changes in stream width and depth are also associated with reduced pool dimensions (Buffington et al., 2002).

The regional analysis of McIntosh et al. (2000), which included the upper Snake River basin, documented the consistent loss of large pools over a 50 year period in streams with sediment delivery elevated by management activities, and concluded that elevated sediment delivery was a primary contributing factor. Lisle and Hilton (1992) documented that fine sediments occupied a larger proportion of pools in streams with elevated sediment delivery than in streams with lower levels of sediment supply.

The loss of pool volume and quality negatively affects native salmonids (Meehan, 1991; Rhodes et al., 1994; USFS and USBLM, 1997a). Pools are a habitat feature essential to native salmonids at a variety of lifestages (McIntosh et al., 2000). Studies have repeatedly shown that salmonid production is positively correlated with pool quality, volume, and frequency (Meehan, 1991; USFS and USBLM, 1997a; McIntosh et al., 2000).

Channel widening caused by sedimentation exacerbates seasonal water temperature extremes, even in the absence of changes in other controls on water temperature, such as stream shading (Beschta et al., 1987; Bartholow, 2000). Elevated summer water temperatures have negative effects on native salmonids and many amphibians (Beschta et al., 1987; Meehan, 1991; McCullough, 1999, USFS and USBLM, 1997a; b; c). Bull trout are especially sensitive to increases in water temperature (USFS and USBLM, 1997a; USFWS, 1998). Elevated summer water temperature is a widespread water quality problem afflicting salmonids in streams draining public lands with a history of management disturbance, including those on the CNF (USFS and USBLM, 1997a; USFWS, 1998).

Elevated peakflows also contribute to channel widening, especially when accompanied by increases in sediment delivery (Richards, 1982). Increases in channel erosion and consequent downstream sediment delivery are inevitable with persistent increases in peakflows (Dunne and

Leopold, 1978; Richards, 1982; Dunne et al., 2001). Logging and roads can increase peak streamflows on the CNF (King, 1989).

The foregoing clearly indicates that land management activities increase sediment delivery and peak streamflows, conferring significant negative environmental effects on stream systems and salmonids.

The regulatory framework requires that national forests adequately disclose land management impacts to the public. Existing legal mandates require the CNF to:

- evaluate and disclose the environmental effects of proposed activities, including their likely consistency and compliance with Forest Plan standards related to fish habitat conditions, sediment delivery and water quality;
- evaluate and disclose the cumulative effects of proposed activities together with those from existing watershed conditions;
- evaluate how the proposed activities affect habitats for species listed under the ESA, such as bull trout and steelhead, and take reasonable measures to ensure that management activities do not adversely affect habitats for ESA-listed species;
- adequately differentiate among land management alternatives with respect to their environmental effects;
- determine consistency and compliance with federal trust obligations to treaty tribes,² salmon run rebuilding efforts, the Clean Water Act, and other regulations.

In environmental analyses on the CNF, WATBAL is used as one of the key tools to meet these mandates, because sediment delivery and peakflows are among the primary environmental effects of land management activities. Therefore, it is important to identify potential sources of consistent bias³ in WATBAL. Similarly, it is critical to evaluate WATBAL attributes that may cause it to fail to adequately differentiate among proposed alternatives with respect to their likely environmental impacts on aquatic systems.

Many citizens, organizations, and governmental entities have strong interests in how land management on the CNF affects watersheds, stream conditions, water quality, and fish populations. Identification and explanation of some the WATBAL's model's limitations can help interested parties evaluate the potential accuracy of assessments of watershed conditions or project impact assessments that are partially predicated on WATBAL results.

² The Columbia Basin Treaty tribes have a treaty-reserved the right to take fish at “usual and accustomed” places. The national forests in the Columbia Basin have a federal trust responsibility to these Tribes to manage watersheds consistent with restoring a harvestable surplus of the fish that pass by these “usual and accustomed” places.

³ Throughout this report, the term “bias” is used in solely with respect to modeling results, such as the tendency of a model to underestimate modeled attributes or processes.

Description of the sediment delivery component of WATBAL

With respect to its methods for estimating sediment delivery, WATBAL is one of a family of models used in USFS Regions 1 and 4 that are based on Cline et al. (1981), which simplify the complex processes of erosion, subsequent sediment delivery to streams, and the routing of sediment through a stream network to specific stream reaches. The sediment delivery estimates in WATBAL consist of discrete methods for estimating average annual sediment delivery from: 1) natural conditions; 2) management-induced surface erosion from logging, roads, and fire, 3) management-accelerated mass erosion from logging, roads, and fire. Although estimated sediment delivery from management-induced surface erosion and management-accelerated mass erosion are estimated separately, they are usually combined to provide an estimate of total sediment delivery from fire, logging, and roads in environmental analyses.

WATBAL provides sediment delivery estimates in terms of the annual average amount per unit watershed area ($T/mi^2/yr$), which can be integrated over the watershed area to provide the total estimated annual sediment delivery from the watershed to a reach (T/yr). WATBAL also provides the total estimated average annual sediment delivery in a form that expresses how much sediment delivery to a reach has been accelerated by management-induced sources. In this case, the total management-induced sediment delivery is divided by the estimated natural sediment delivery; this quantity is multiplied by 100 to express the total increase in sediment delivery from management as percent over natural (% ON). This lattermost form is one of the typical ways that WATBAL outputs are described and discussed in most NEPA documents on the CNF.

In many environmental analyses on the CNF, WATBAL is used as one of the tools to evaluate differences among land management alternatives and some of their cumulative effects on stream channels, salmonid habitat, and salmonid survival. The estimates of relative rates and trends in sediment delivery by WATBAL, and other models based on Cline et al., 1981, have been viewed as fairly reliable for assessing differences among alternatives, while the absolute estimates of sediment delivery are generally taken to be less reliable and represent only indices of sediment delivery (Cline et al., 1981; Potyondy et al., 1991; King, 1993).

The entire area of the CNF has been stratified into landtypes and WATBAL's sediment delivery estimates rely very heavily on assumptions about these landtypes. With respect to WATBAL, areas within a given landtype are assumed to have homogenous topography, drainage density, vegetation, parent material, soil conditions, and vegetation (Patten and Jones, 2005). Areas within a landtype are assumed to have hydrologic and erosional characteristics that respond similarly to perturbation of soils and/or vegetation⁴ (Patten and Jones, 2005).

Within WATBAL, each landtype is assigned a hazard rating for: a) mass failures, including both debris avalanches and rotational failures, and, b) surface erosion for the undisturbed soil

⁴ Basic landtype characteristics (e.g., soil types, drainage density, etc) are based on surveys of conditions on the CNF, but the classification may not be based on rigorous analysis of how these attributes vary within and among landtypes. It is not clear if the hazard ratings assigned to landtypes have been rigorously verified via monitoring.

surface, subsurface and substrata (C-horizon and parent material). These hazard ratings provide one of the bases for estimating erosion and sediment delivery from natural conditions and from logging, roads, and fire in WATBAL (Patten and Jones, 2005).

Natural sediment delivery

WATBAL estimates natural sediment delivery on the basis of the landtype within a watershed. The natural sediment delivery from each land type was developed from some limited monitoring of sediment load in several watersheds with landtypes that have been considered to be “representative” (Patten and Jones, 2005).⁵ Natural sediment delivery for other, unmonitored landtypes was estimated by extrapolating the measured sediment loads and partitioning landtype erosion under the assumption that about 80% of the natural sediment load is from mass erosion and with the remainder from surface erosion related to fire history (Patten and Jones, p. 9, 2005). For each landtype within a watershed, the WATBAL input files contain the estimated average annual rates of sediment delivery ($T/mi^2/yr$) from the following natural sources of erosion: 1) surface erosion; 2) mass erosion; and 3) total erosion (the sum of estimated natural surface and mass erosion).

The total natural sediment delivery for each landtype in the watershed is then calculated by multiplying the natural sediment delivery rate per unit area ($T/mi^2/yr$) for the landtype by the area of the landtype within the watershed. The natural sediment delivery rate for each land type in the watershed is then essentially weighted by the area of the landtype within the watershed and summed to provide the total natural sediment delivery rate on a per unit area basis ($T/mi^2/yr$) for the watershed.

Management-induced sediment delivery from surface erosion

WATBAL estimates the management-induced sediment delivery of surface erosion from three activities: roads, fire, and logging. Basic surface erosion rates for each activity are assumed to decrease with the time since the activity was initiated (age of activity) as shown in Table 1. Although Patten and Jones (2001) state that the basic surface erosion rates in WATBAL are derived from Megahan (unpub.), they are considerably modified, especially for roads, from those in Cline et al. (1981) which are also based on the data of Megahan (unpub.). These modifications are described in greater detail in the section on sources of model error in this report.

These basic surface erosion rates for each activity as a function of age are used to estimate the total sediment delivery from the activity in each landtype as modified by activity area, management practice, land type or parent material, mitigation, sediment delivery efficiency for the land type and, in the case of logging and fire, the surface slope.

⁵ Patten and Jones (2005) does not identify the landtypes monitored or how they were deemed to be “representative.” Similarly, it does not identify the number of watersheds monitored or the length of the monitoring.

Table 1. Assumed basic surface erosion rates in WATBAL per unit area (T/mi²/yr) for roads, logging, and fire as a function of time since the initial impact (after Patten and Jones, 2005).⁶ The equation for basic surface erosion shown for roads more than six years old results in calculated reduction in surface erosion of about 2% per year, for all roads more than four years old.⁷

Age of impact (yrs)→	1	2	3	4	5	6	>6
Roads	67,500	4,050	1,350	1,350	1,336	1,323	1350 * 0.99 ^(road age -3)
Logging	352	187	141	95	46	25	0
Fire	375	100	25	0	0	0	0

Surface erosion from roads is estimated by essentially stratifying the road network into segments with the same age, mitigation practices, and general location⁸ for each landtype in the watershed. In each landtype, the basic erosion rate as function of the age of the road is multiplied by the total area of the homogenous (age, mitigation, location) segments in each landtype. For each road segment with homogenous mitigation and age within a landtype, the estimate of eroded sediment from the total area of these roads in the landtype is then modified to account for the landtype, road mitigation, and routed to the stream via a sediment delivery ratio essentially as follows:

$$S_r = BSER_r * A_r * M_r * G * R_r * D \quad (1)$$

where: S_r = sediment delivered (T/yr) from surface erosion from the road segment to the nearest stream channel; $BSER_r$ = the basic erosion rate (T/mi²/yr) for the road segment as a function of its age (See Table 1) ; A_r = total area (mi²) of the road segment within the landtype, including the cut, fill, prism, and ditches; M_r = a dimensionless user-supplied mitigation coefficient, ranging from 0.0 to 1.0 to account for presumed reductions in erosion and sediment delivery from measures such as graveling of the road surface or riparian buffers; G = a landtype erosion coefficient, in the form of a coefficient ranging from about 0.38 to 1.1 to account for estimated differences in erosion in different landtypes;⁹ R_r = a dimensionless binary coefficient to reduce estimated erosion and

⁶ The method of denoting the age of impact in Patten and Jones (2005) has been converted in this report to be consistent with that in Cline et al. (1981) and Potyondy et al. (1991), both of which demarcate road age with the first year after road construction designated as year “1”. Patten and Jones (2005) demarcate the first year treated as year “0.”

⁷ For simplicity, this equation is shown in Table 1 for roads greater than six years old, but WATBAL uses the equation for all roads five years and older (Patten and Jones, 2005).

⁸ Within WATBAL, the locations of activities within the landtype are essentially ignored in estimating sediment delivery, with one important exception: Roads that are defined as “ridgetop roads” have impacts reduced by 80% in WATBAL (Patten and Jones, 2005). A “ridgetop” road segment is one that has the following attributes: 1) located on the upper third of slopes; 2) no stream crossings; 3) land slope is “significantly” less than the mean slope of the landtype (Patten and Jones, 2005).

⁹ WATBAL calculates surface erosion by means of separate coefficients for surface erosion at the

sediment delivery for ridgetop roads, which is 0.2 for “ridgetop” roads and 1.0 for roads in all other landscape positions ; D = a dimensionless mean sediment delivery coefficient for the landtype, used to estimate the fraction of eroded sediment delivered to the nearest stream channel (Patten and Jones, 2005). The value of D is calculated in WATBAL solely as a function of slope and the average distance to streams within the landtype (Patten and Jones, 2005).¹⁰

Equation (1) is basically used iteratively on each road segment with homogenous age, mitigation, and general location, within each landtype to provide the total surface erosion from all roads in a landtype. These estimates of sediment delivery to streams from surface erosion on roads are then summed to give the total surface erosion from all roads in the watershed.

Sediment delivery from surface erosion from logging is estimated in a somewhat similar manner. Within a given landtype, logged areas are essentially stratified into units with homogenous in age, mitigation, and slope. Then, for each such group of logged units within a landtype, WATBAL’s method of sediment delivery can be conceptualized as follows:

$$S_1 = \text{BSER}_1 * A_1 * Y * L * M_1 * U * G * D \quad (2)$$

where: S_1 = sediment delivered (T/yr) to the nearest channel from surface erosion from logging units with the same age, mitigation, and slope in a landtype; BSER_1 = the basic erosion rate (T/mi²/yr) for the logging units as a function of their age (Table 1); A_1 = area (mi²) of the logging units; M_1 = a dimensionless user-supplied mitigation coefficient, ranging from 0.0 to 1.0 to account for presumed reductions in erosion and sediment delivery from mitigation measures such as riparian buffers (dimensionless); Y = a yarding practice factor, ranging from 0.2 (for aerial yarding) to 1.0 (for tractor yarding), to account for different levels of surface disturbance from different types of logging practices (dimensionless); L = a dimensionless fraction reflecting the amount of crown cover removed (e.g., 1.0 for clearcutting and 0.5 for 50% removal); U = a dimensionless land surface slope factor, ranging from 0.5 (for 0% slopes) to 2.0 (for 75% slopes), to account for the effect of slope on surface erosion (dimensionless); G = a geologic erosion factor, as in equation (1); and, D = a sediment delivery coefficient as in equation (1).

Equation (2) is used iteratively to estimate surface erosion for all logged units that are less than seven years old (Table 1). The sediment delivered to streams from surface erosion in all such logged areas is estimated by summing S_1 for in all landtypes in the watershed.

Sediment delivery from surface erosion caused by fire is estimated by delineating all burned areas of the same age and slope within a given land type. WATBAL’s method of estimating sediment delivery from burned areas can then be conceptualized as follows:

soil surface, subsurface (or substrata), and parent material (or C-horizon), for each landtype, depending on the depth of the disturbance (Jones and Patten, 2005). However, for the sake of simplicity, these can be conceptualized as a single coefficient for the landtype.

¹⁰ The average distance to streams within a landtype is calculated within WATBAL based on the stream density in the landtype as determined from surveys of streams within landtypes on the CNF. It is important to note that this delivery coefficient is based solely on these average conditions within a landtype and not on the actual proximity of the activity to a stream.

$$S_f = \text{BER}_f * A_f * U * G * D \quad (3)$$

where: S_f = sediment delivered (T/yr) to the nearest channel from surface erosion from all burned areas with the same age and slope in given landtype; BSER_f = the basic erosion rate for the burned area as function of its age (T/mi²/yr); A_f = area (mi²) burned within the landtype; U = a land surface slope factor, as in equation (2); G = a geologic erosion factor, as in equations (1) and (2); and, D = a sediment delivery coefficient as in equations (1) and (2).

Equation (3) is used iteratively for all burned areas that are less than four years old in each landtype (Table 1). The sediment delivered to streams from surface erosion from fire is estimated by summing S_f for all burned areas from all landtypes in the watershed.

Management-accelerated sediment delivery from mass erosion

WATBAL estimates the average annual sediment delivery to streams from mass erosion as accelerated¹¹ by fire, roads, and logging. The estimated natural mass sediment delivery rate (T/mi/yr) for the landtype is basically multiplied by the “acceleration factor” for the activity. For fire and logging, the acceleration factor is solely a function of the impact’s age (Table 2).

Table 2. Mass failure acceleration factors for logging and fire used in WATBAL as a function of age (after Patten and Jones, 2005).

Age of fire or logged area	Mass failure acceleration factor ($P_{f,i}$), all soil types
<6	1
6-10	0.5
10+	0

The mass erosion acceleration factor for roads is a function of both road age and parent material in the landtype (Table 3). According to Jones and Patten (2005), these mass failure acceleration factors are based on an extensive study of mass failures on the Boise National Forest and the CNF in the 1970s by Megahan et al. (1978) and a study of mass failures on the CNF that occurred during rain-on-snow events in the winter of '95-'96 by McClelland et al. (1997).

Table 3. Mass failure acceleration factors for roads used in WATBAL as a function of road age and landtype parent material (after Patten and Jones, 2005).

Time since construction (yrs)	Parent material type		
	Granitic	Belt-Series	Border
0	225	23	0

¹¹ WATBAL treats surface erosion as a process induced by management (assumed largely negligible under natural conditions) and mass erosion as a natural process accelerated by management (Jones and Patten, 2005).

1-3	80	80	60
4-10	120	250	100
11-15	80	140	50
16-19	50	40	20
20+	50-0	40-0	20-0

Although mass erosion rates are typically driven by episodic climatic events, WATBAL does not attempt to account for the episodic, climate-driven effects (Patten and Jones, 2005). Instead, WATBAL treats sediment delivery from mass failures in a given year as an expected annual average amount based on the probability of mass failures over multiple years as increased by management. This approach results in fairly smooth and continuous estimates of sediment delivery from mass erosion in WATBAL instead of estimates that are episodically pulsed. Patten and Jones (p. 16, 2005) state that this is likely to reduce the precision and accuracy of WATBAL sediment delivery for any given year, but may provide increased accuracy for over several years.¹²

The way WATBAL estimates average annual sediment delivery from mass failures from roads can be conceptualized as follows:

$$MS_r = NM * A_r * P_r * R_r \quad (4)$$

where: MS_r = sediment delivered (T/yr) from mass erosion from roads within a given landtype that are of ages that have the same mass erosion acceleration factor (Table 3); NM = estimated natural sediment delivery per unit area (T/mi²/yr) from mass erosion for the landtype; A_r = area (mi²) of the roads; P_r = a dimensionless acceleration factor for roads as a function of the age of the road and the parent material of the landtype as in Table 3; R_r = a dimensionless, binary coefficient to reduce estimated erosion and sediment delivery for “ridgetop” roads, which is 0.2 for “ridgetop” roads and 1.0 for all other roads. Equation (4) is iteratively applied to all roads in the landtypes in the watershed and summed to provide the total estimated average annual sediment delivery from mass failures as accelerated by roads in the watershed.

WATBAL estimates sediment delivery from fire and logging in a manner similar to that for roads:

$$MS_{lf} = NM * A_{lf} * P_{lf} \quad (5)$$

where: MS_{lf} = sediment delivered from mass erosion from burned and logged areas within a given landtype that are of ages that have the same mass erosion acceleration factor (Table 2) (T/yr); NM = estimated natural sediment delivery from mass erosion for the landtype, which is zero for some landtypes (Patten and Jones, 2001; 2005) (T/mi²/yr); A_{lf} = area of logged¹³ or burned forest (mi²)

¹² Surface erosion rates are also strongly driven by storm size and precipitation amounts. Thus, surface erosion also exhibits considerable inter-annual variability with annual rates that are pulsed and episodic. Similar to Cline et al., (1981) and other models based on it, WATBAL does not attempt to estimate episodic nature of surface erosion from roads, logging, or fire.

¹³ Logged areas are estimated as the area treated multiplied by the amount of crown cover removed. For instance, an area of 0.10 mi² would be used in equation (5) to represent 0.20 mi² of area with

with the same mass erosion acceleration factor in the landtype; P_{lf} = a dimensionless acceleration factor for fire and logging as a function of their age as in Table 2. This equation is iteratively applied to all logged and burned areas in all of the landtypes in the watershed and summed to provide the total estimated average annual sediment delivery from mass failures accelerated by roads in the watershed.

Sediment routing

WATBAL routes management-induced and accelerated sediment delivery from fire, roads, and logging to a specific point of interest within the watershed. The mouth of watersheds within a project area is often used as the point of interest, but the mouths of smaller watersheds within a larger watershed are also used.

WATBAL intrinsically assumes that the total estimated natural sediment delivered to the stream system is diminished by sediment storage in channels, behind obstructions and in floodplains, as it is routed downstream. This approach is based on watershed data that indicate that sediment yield per unit area of watershed decreases with increasing watershed area (Cline et al., 1981; Jones and Patten, 2005). Based on this relationship between sediment yield and watershed area, WATBAL uses the method of Cline et al. (1981) to estimate a channel routing coefficient as a function of watershed area to account for assumed reductions in sediment delivery caused by storage within channels. This method is largely based on heuristics and tractability, augmented with sparse data (Cline et al., 1981; Potyondy et al., 1993).¹⁴ WATBAL calculates the channel routing coefficient as follows:

$$c=WA^{-0.177} \quad (6)$$

where: c = channel routing coefficient; WA = watershed area (mi^2) at the point of analysis in a stream.

Total management-induced and accelerated sediment delivery from all sources within a watershed area are summed and then routed to a point of interest by multiplying this sum by the channel routing coefficient in equation (6). This total routed sediment amount is then essentially divided by the watershed area to provide an estimate of the total sediment delivery from roads, logging and fire on a per area basis for the watershed above a point of interest in the watershed ($T/mi^2/yr$). This same process is used to route estimated natural sediment delivery to a reach. In NEPA documents on the CNF, this routed sediment from management sources is typically divided by the routed natural sediment delivery at the same point of interest in the watershed to express the estimated average sediment load as a percentage of the natural sediment delivery (% ON). As will be discussed, management thresholds for sediment delivery on the CNF are typically expressed in

50% removal of crown cover.

¹⁴ Cline et al. (1981), Potyondy et al. (1991), King (1993), and Jones and Patten (2005) all note that equation (6) is likely a source of inaccuracy in models based on Cline et al. (1981). Jones and Patten (2005) note that it may be the weakest element in WATBAL.

terms of % ON.

Likely sources of error in WATBAL estimates of sediment delivery

As with any model that simplifies complex processes, WATBAL has many potential sources of inaccuracy and bias. Some of these are intrinsic in the simplification of exceedingly complex phenomena for the sake of model tractability. Increasing model complexity is not always the antidote to such defects, because complex models not only increase the number of potential sources of error, but can perform more poorly than simple models and at far greater operational expense (e.g., Grayson et al., 1992). Other sources of error in WATBAL include some of the assumptions embedded in the model, the data used, and context for use. Since an exhaustive description and discussion of these potential sources of error is beyond the scope of this report, only the most significant sources of likely inaccuracy and bias in WATBAL with respect to its *uses* are covered in the following.

In a management context, WATBAL estimates of sediment delivery are primarily used to:

- a) examine and disclose the effect of existing watershed conditions on sediment delivery and its cumulative effects of streams and aquatic habitat and salmonid survival;
- b) differentiate among proposed land management alternatives with respect to their effects on sediment delivery, stream conditions, and salmonid survival; and
- c) determine the ecological and legal significance of existing and likely future cumulative effects of land management activities on the CNF

Therefore, this report focuses only on those aspects of WATBAL that cause consistent *bias* in these three uses of WATBAL results, which are likely to lead to consistently inaccurate conclusions about a), b), and c) above. These sources of error are described and discussed in order of the magnitude of bias and error they likely incur in WATBAL results and the decisions, assessments, and disclosures that are based on WATBAL results.

Basic surface erosion rates for roads

WATBAL's basic surface erosion rates for roads (BSE_{r} in equation (1)) likely cause WATBAL to significantly and consistently underestimate surface erosion on roads that are: 1) more than one year old and, especially, roads more than two years old; 2) significantly reconstructed; and/or, 3) subjected to significant increases in haul traffic. This causes WATBAL to consistently underestimate surface erosion from roads, because the BSE_{r} values exert a pronounced effect on sediment delivery estimates from surface erosion in WATBAL. As will be discussed in greater detail, this underestimation of surface erosion by WATBAL is significant ecologically and from a management perspective for the following reasons:

- 1) Surface erosion from roads is a significant source of management-induced sediment delivery to streams; in many watersheds, roads are typically the largest source of management-induced source of sediment delivery to streams;

- 2) The vast majority of the road network on the CNF is more than two years old;
- 3) Many projects analyzed via WATBAL commonly involve road reconstruction and/or increased road traffic.
- 4) Elevated sedimentation of salmonid habitats from roads is a significant constraint on the survival and production of imperiled salmonids in many watersheds on the CNF (Rhodes et al., 1994; Espinosa et al., 1997).

As will be discussed in greater detail, the foregoing effects of WATBAL surface erosion rates on estimates of sediment delivery are accentuated by the pattern of road development on the CNF. In aggregate, watershed conditions and the problems with the BSE_{r_t} values often cause WATBAL to significantly underestimate the effects of existing land management conditions on sediment delivery and consequent effects on streams and salmonids. These likely sources of error also likely cause WATBAL to consistently underestimate the likely future cumulative effects of proposed land-disturbing activities on sediment delivery and its resulting impacts on aquatic resources. The latter problem hinders assessment of compliance with obligations and regulations, as well as reasonable differentiation among various proposed alternatives in terms of their likely cumulative aquatic effects.

Basic surface erosion rates from roads over time

The WATBAL's BSE_{r_t} values for roads that are more than a year old are quite low, due to unrealistic assumptions about the rate of reduction in surface erosion on roads over time. As shown in Table 4, the assumed rates of surface erosion on roads as a function of time in WATBAL depart considerably from those in Cline et al. (1981), which is the basis for WATBAL. The WATBAL values for BSE_{r_t} are also vastly lower than those used in BOISED (Table 4), a sediment delivery model used on the Boise National Forest (BNF), which is also based on Cline et al. (1981).

These differences in BSE_{r_t} are far from trivial. In Cline et al. (1981) the annual surface erosion rate on roads that are two years old is 13,950 T/mi, or about 4.4 times greater than in WATBAL (Table 4). For roads that are six years old, the average annual surface erosion from roads in Cline et al. (1981) is almost 4 times greater than in WATBAL (Table 4). The significant difference between the models' surface erosion rates on roads increases with road age for roads more than 4 years old, because WATBAL assumes that surface erosion rates on roads continue to decline over time, while those in Cline et al. (1981) do not (Table 4).

As shown in Table 4, the differences in BSE_{r_t} between WATBAL and BOISED for roads that are more than two years old are similar in magnitude to the differences between WATBAL and Cline et al. (1981). However, for heavy use roads, the differences between BOISED and WATBAL are even greater (Table 4).

Notably, the basic surface erosion rates for roads in BOISED and Cline et al. (1981) were validated for roads one to four years old on the BNF (Ketcheson et al., 1999). There was fairly good agreement between predicted and measured surface erosion rates in all four years after

construction and cumulatively over the four years of study (Ketcheson et al., 1999). BOISED underestimated surface erosion on some years on some roads, but overestimated on other roads in other years, resulting in a mean error of zero for the three roads over the four years analyzed (Ketcheson et al., 1999). Therefore, comparison of WATBAL's surface erosion rates with those in BOISED provides an indication of the likely veracity of WATBAL's surface erosion rates for roads. Because BOISED uses basic erosion rates that are several times greater than WATBAL for roads more than two years old in areas with similar climate and vegetation, the results of Ketcheson et al. (1999) indicate that WATBAL's basic surface erosion rates for roads are likely exceedingly low.

Table 4. Basic surface erosion rates for roads, $BSER_r$ as function of road age from WATBAL (Patten and Jones, 2005), Cline et al (1981) and BOISED (Potyondy et al., 1991). Unlike WATBAL, BOISED $BSER_r$ values reflect some of the expected differences in surface erosion caused by elevated road traffic.

Road age (yrs)→	1	2	3	4	5	6	6+
WATBAL Road $BSER_r^{15}$ (T/mi ² /yr)	67,500	4,050	1,350	1,350	1,337	1,323	1350*0.99 ^(road age⁻³)
Cline et al (1981) Road $BSER_r$ (T/mi ² /yr)	67,500	18,000	5000	5000	5000	5000	5000
Difference in $BSER_r$ between Cline et al. (1981) and WATBAL (T/mi ² /yr)	0	13,950	3,650	3,650	3,664	3,677	3,690
Ratio of $BSER_r$ in Cline et al. (1981) /WATBAL	1.00	4.44	3.70	3.70	3.74	3.78	3.82
BOISED $BSER_r$ Heavy use ¹⁶ road (T/mi ² /yr)	67,500	18,000	7,000	7,000	7,000	7,000	7,000
Difference between BOISED $BSER_r$ Heavy use road and WATBAL $BSER_r$ Heavy use road (T/mi ² /yr)	0	13,950	5,650	5,650	5,664	5,677	5,690
Ratio BOISED $BSER_r$ Heavy use road/WATBAL $BSER_r$ (T/mi ² /yr)	0.00	4.44	5.19	5.19	5.24	5.29	5.34
BOISED $BSER_r$ closed road ¹⁷ (T/mi ² /yr)	67,500	18,000	5,000	3,000	2,000	1,250	1250
Difference between BOISED $BSER_r$ closed road and WATBAL $BSER_r$ (T/mi ² /yr)	0	13,950	3,650	1,650	664	-73	-60
Ratio BOISED $BSER_r$ closed road/WATBAL $BSER_r$ (T/mi ² /yr)	1.00	4.44	3.70	2.22	1.50	0.94	0.95

¹⁵ The basic surface erosion rate for roads in WATBAL does not vary with the level of road use. The basic surface erosion rate is for roads that open, maintained, and used (Patten and Jones, 2005).

¹⁶ BOISED's basic surface erosion rate for light use roads is the same as in Cline et al. (1981)

¹⁷ The erosion rates are for a new road, which after construction is closed to traffic with fills and culverts in place and not subject to surface maintenance.

It is possible that the actual rates of surface erosion from roads on the BNF or those measured in Cline et al. (1981)¹⁸ are higher than those on the CNF, due to differences in soils, but, it is highly unlikely that they are four to five times higher than on the CNF. Unlike much of the BNF, many areas on the CNF have ash cap surface soils that can limit surface erosion in response to disturbance (e.g., CNF, 2002). However, these ash cap soils are highly unlikely to reduce surface erosion on roads, because road construction removes surface soils. Road surfaces are typically comprised of subsoil. WATBAL surface erosion rates are calculated based on the assumption that surface erosion on roads occurs on subsurface soils rather than surface soils (Patten and Jones, 2005). The BNF and CNF have fairly similar parent materials, and, thus, fairly similar subsoils.

Further, the CNF does not appear to have road erosion data that indicate that surface erosion on roads on the CNF is significantly lower than on the BNF. In aggregate, the foregoing indicates that surface erosion rates on roads on the BOISED and as measured in Cline et al. (1981) are unlikely to be four times higher than on roads in the CNF. Therefore, the comparisons among WATBAL, Cline et al., and BOISED (Potyondy et al., 1991) indicate that the basic surface erosion rates for roads in WATBAL underestimates surface erosion and sediment delivery from roads on the CNF.

WATBAL's basic surface erosion rates from roads that are one year old is the same as for BOISED and Cline et al. (1981), as shown in Table 4. This implies that heavily disturbed areas on the CNF undergo a similar level of surface erosion, at least initially, as on the BNF. The divergence between the surface erosion rates for roads in WATBAL and BOISED are confined to roads more than one year old, because WATBAL assumes rapid and major reductions in surface erosion on roads, which is highly unlikely as long as roads are maintained and remain in use.

There is no sound basis for assuming that surface erosion continues to significantly decline with time on roads that are maintained and remain in use,¹⁹ as assumed in WATBAL. Patten and Jones (2005) provides no scientific information or data to support this assumption.

The primary causes of elevated erosion from roads are the vast reductions in infiltration rates and soil cover on roads, coupled with mobile fine sediment produced by road traffic. These causative factors do not abate as roads age, if the roads continue to be used and maintained. Many older roads on the CNF show clear diagnostic signs of significant surface erosion on cuts, fills, and unpaved road surfaces, including rilling, sediment transport in ditches, sediment deposits below culverts and other drainage relief features, and dry soil ravel on roadcuts (See Photos 1 and 2).

¹⁸ The estimated basic surface erosion rates in Cline et al., 1981 are based on measurements on the Payette and Boise National Forests.

¹⁹ Notably, the surface erosion rates for roads in WATBAL are based on the assumption that roads are open, used, and maintained (Patten and Jones, 2005).

Photo 1. Elevated surface erosion on roadcuts and the main travelway of an unpaved road in the Pete King watershed on the CNF circa 2005. Although this road is much more than 25 years old, the steep roadcut in the left of the photo still has abundant levels of bare, highly erodible soils on steep slopes which cause elevated surface erosion. Road traffic has disrupted gravel/rock surfacing on the road and created ruts, both of which increase road erosion, as discussed in the text. The road erosion has deposited high levels of fine sediment in the ditch along the road in photo. These fine sediments are easily mobilized during runoff events and are deposited directly to streams when roads are hydrologically connected to streams, a situation which is not uncommon on the CNF, as discussed in the text.



Photo 2. Another example of elevated surface erosion on the main travelway of an older, unpaved road on the CNF taken circa 1997.



The low rates of surface erosion on roads more than a year old, as assumed in WATBAL, are a likely significant source of consistent underestimation of the cumulative effects of existing road networks on sediment delivery and the consequent impacts on streams and salmonids. There are several reasons why this likely undermines the veracity of assessments of compliance with regulations that are based on WATBAL estimates in watersheds that have a significant road network.

First, the basic surface erosion rates exert considerable influence on sediment delivery estimates (see equation (1)), even as modified by landtype, mitigation, etc. Second, there is an extremely significant network of roads in most watersheds on the CNF. According to the CNF's Roads Analysis Report (CNF, 2003), many watersheds have road densities of more than 3 mi/mi.².

Third, the overwhelming majority of roads on the CNF are more than four years old. At the scale of the entire forest or any given watershed, it is extremely likely that more than 95% of the road network is more four years old, and this is the age class of road for which WATBAL most significantly underestimates surface erosion (Table 4).

Fourth, much of the road network is in fairly close proximity and hydrologically connected to streams due to the historic pattern of road development on the CNF. These roads typically have relatively high rates of sediment delivery to streams.

CNF (2003) noted that roads within 300 feet of streams have an increased likelihood of supplying streams with eroded sediment and runoff from roads. About 43% of the 4,254 miles of classified roads²⁰ on the CNF are located within 300 feet of stream channels (CNF, 2003).

Based on detailed road network surveys, Rhodes and Huntington (2000) documented that

²⁰ This analysis does not include "unclassified roads," such as jammer roads (CNF, 2003), which may be in close proximity or hydrologically connected to streams.

about 59% of “valley bottom” roads near streams were hydrologically connected to streams in the Squaw Creek watershed on the CNF. Roads in other slope positions also had a significant percentage of their length hydraulically connected to the stream network (Rhodes and Huntington, 2000). Road segments that are hydrologically connected to streams supply road runoff and eroded sediment directly to the streams.

Roads are hydrologically connected to streams at road crossings where sediment delivery from roads is especially high and little can be done to prevent sediment delivery from roads (Kattleman, 1996). On the CNF, there are 6,666 stream crossings by classified roads (CNF, 2003).²¹ This equates to roughly 1.4 stream crossings per mile of classified system road on the CNF or about one road crossing for every 0.7 miles of classified road.

The frequency of stream crossings by roads is especially high in some watersheds. For instance, the Pete King watershed has 112.7 miles of road and 301 stream crossings by roads in the 27.6 square mile watershed (CNF, 2003). This equates to roughly 2.7 stream crossings per mile of classified road in the Pete King watershed.

Road crossings are not the only place that roads are hydrologically connected to streams. Roads are also connected to streams via other drainage features, such as gullies (Wemple et al., 1996; Rhodes and Huntington, 2000). The proximity and stream connectivity of the road network on the CNF indicate a significant amount of sediment eroded from roads is delivered to streams with relatively high efficiency.

Therefore, the road network’s proximity to and connectivity with streams together with WATBAL’s unrealistically low basic surface erosion rates cause WATBAL to underestimate sediment delivery from roads. This affects both the estimates of existing conditions and likely future effects from sediment delivery, including differentiation among proposed alternatives in environmental NEPA documents that are partially based on WATBAL estimates.

Figures 1a and 1b illustrate the proclivity of WATBAL to underestimate sediment delivery from newly constructed roads. They display the results of a simplified application of WATBAL and Cline et al. (1981), respectively, to estimate sediment delivery from surface erosion from the construction of 4 miles of new road in 6.5 mi² watershed without any other roads, using equation (1) and assumed, reasonable values for some of the variables in equation (1).²² As mentioned,

²¹ Again, this does not include unclassified roads which often have a high frequency of road crossings.

²² Total mean road width was set at 20 feet. The sediment delivery coefficient for the landtype, D , was assumed to be 0.45. The landtype erosion hazard coefficient, G , and the road position coefficient, R_r were both assumed to be 1. Natural sediment delivery from the land type was assumed to be 25 T/mi²/yr. These assumed values roughly approximate the values provided in WATBAL for landtype “23G20” in Patten and Jones (2005). The mitigation coefficient was set at 0.9, which equates to a 10% reduction in sediment delivery. For the sake of simplicity, it was assumed that the example scenario watershed was comprised of only one landtype with the WATBAL attributes described above. This simplified modeling examined only sediment delivery from surface erosion, S_r as in equation (1) and natural sediment delivery to the stream network (e.g., sediment was not routed from the stream network to a specific reach via equation (6)). All of these coefficients and variables

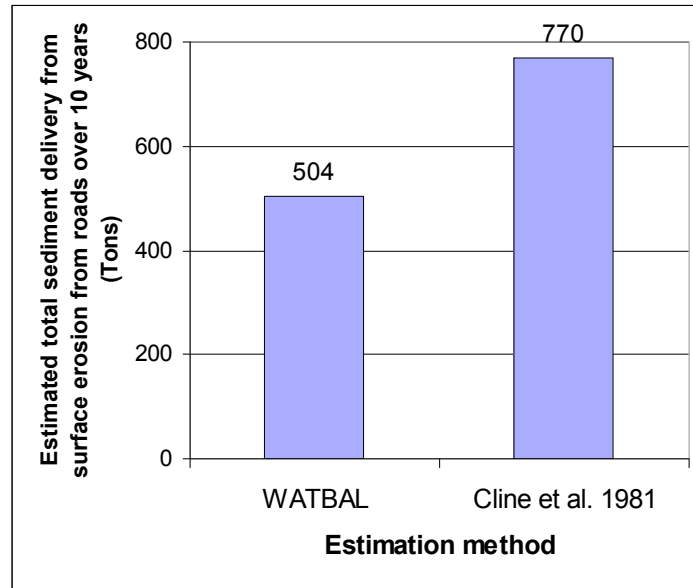
comparisons of sediment delivery calculated from the surface erosion rates in WATBAL, Cline et al. (1981), and BOISED provide a reasonable indication of the propensity of WATBAL to underestimate sediment delivery from surface erosion on roads.

As shown in Figures 1a and 1b, WATBAL's basic surface erosion rate (BSER_r), for roads likely results in exceedingly low estimates of sediment delivery from surface erosion from the construction of roads. The use of Cline et al. (1981) indicates that sediment delivery from surface erosion over a 10-year period is at levels that are more than 50% greater than estimated by WATBAL (Figures 1a and 1b). This indicates that WATBAL likely fails to properly differentiate among alternatives involving different levels of new road construction with respect to their different adverse effects on sediment delivery, streams, and salmonids.

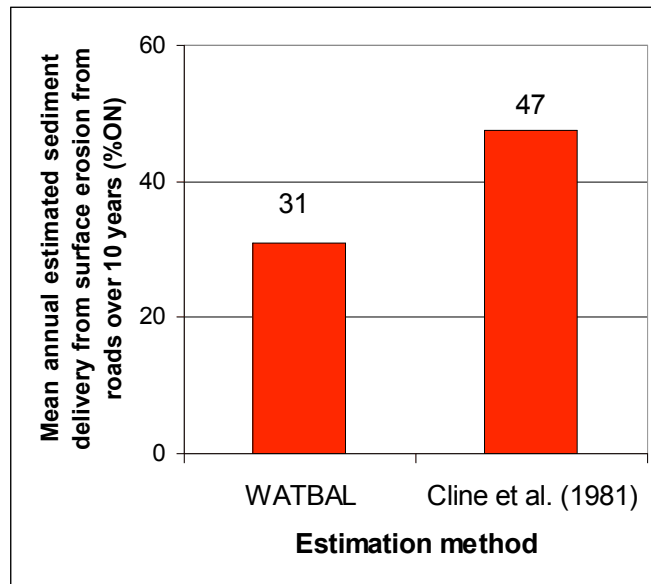
were the same in analysis of the scenario via both WATBAL and Cline et al. (1981).

Figures 1a and 1b. Estimated cumulative sediment delivery over 10 years from management-induced surface erosion from 4 miles of road construction in a 6.5 mi watershed (see text for additional details), as estimated by WATBAL and Cline et al. (1981). Figure 1a shows cumulative sediment delivery (Tons) over the 10 year period as estimated by the two methods. Figure 1b displays mean annual sediment delivery in terms of percent over natural (%ON) over 10 years for the same scenario as in Figure 1a. WATBAL estimates of sediment delivery from surface erosion from newly constructed roads in this scenario are less than 66% of that estimated by Cline et al. (1981), indicating that WATBAL surface erosion rates for roads are too low, contributing to underestimation of sediment delivery.

a)



b)



Figures 2a and 2b provide an indication of how WATBAL likely underestimates sediment delivery from existing road networks comprised primarily of older roads, due to WATBAL's low basic surface erosion rate for roads that are more than 4 years old. Figures 2a and 2b display the results of the use of WATBAL and Cline et al. (1981) to estimate surface erosion over a ten-year period from a 6.5 mi² watershed with a road density of 2.5 mi/mi² comprised of roads that are 15 years old at the beginning of the analysis.²³ As shown in these figures, in this situation, WATBAL estimates less than 25% the level of sediment delivery from surface erosion from roads over 10 years estimated by Cline et al. (1981).

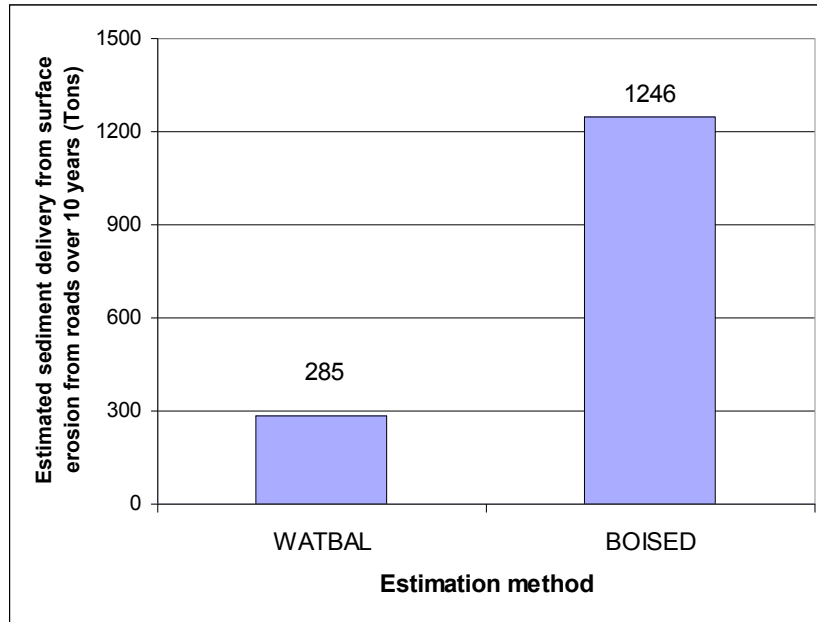
These results indicate that the low basic surface erosion rates for roads more than 4 years old in WATBAL cause it to significantly underestimate sediment delivery from roads and its cumulative effects on streams and fish. In a data-driven retrospective of the impacts of land management to fish habitats on CNF, Espinosa et al. (1997) concluded that WATBAL's failure to accurately assess sediment delivery from older roads was a primary contributor to the CNF's failure to protect and restore salmonid habitat on the CNF.

Together with the character and nature of the existing road network, this aspect of WATBAL likely introduces consistent bias in assessments and disclosures of cumulative effects on streams and salmonids in CNF environmental analyses that are predicated partly on WATBAL estimates of sediment delivery. This underestimation of sediment delivery from roads by WATBAL will tend to be to greatest in watersheds where: a) road density is relatively high; b) much of the road network is proximate to the stream network; c) stream crossings by roads are frequent and numerous; and/or; d) the road network is primarily comprised of older roads.

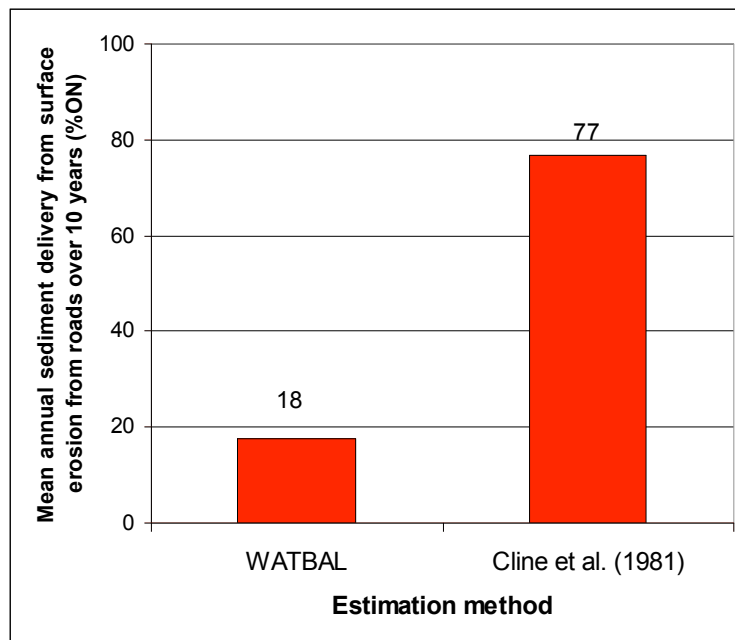
²³ In this analysis, watershed attributes and other variables and coefficients were as described in the previous footnote.

Figures 2a and 2b. Sediment delivery from management-induced surface erosion over 10 years in 6.5 mi² watershed with a road density of 2.5 mi/mi² comprised of roads 15 years old, as estimated via by WATBAL and Cline et al. (1981) (See text for additional details). Figure 2a displays cumulative estimated sediment delivery (Tons) over 10 years. Figure 2b displays mean annual sediment delivery in terms of percent over natural (%ON) over 10 years period for the same scenario as in Figure 2a. The estimate of sediment delivery from Cline et al. (1981) are more than 4.3 times greater than that of WATBAL, indicating that WATBAL likely underestimates sediment delivery from roads that are more than 4 years old, as discussed in greater detail in the text.

a)



b)



Basic surface erosion rates for roads with different levels of use

The basic surface erosion rates for roads, BSER_r, in WATBAL do not account for the increased surface erosion caused by increased road use and maintenance on unpaved roads. Logging and many other land management activities inherently involve the increased use of roads, which significantly elevates soil impacts and surface erosion from unpaved roads (Wald, 1975; Reid et al., 1981; Foltz, 1996; Gucinski et al., 2001; Ziegler et al., 2001). The USFS's summary of scientific information on roads (Gucinski et al., 2001) concluded that "rates of sediment delivery from unpaved roads are...closely correlated to traffic volume."

The increases in surface erosion caused by elevated road use are significant. Reid et al. (1981) documented that unpaved roads used by more than four logging trucks per day generated more than seven times the sediment generated from roads with less use. Elevated traffic on previously unused or abandoned roads reverses whatever soil recovery has accrued through non-use. Reid et al. (1981) documented that roads subjected to use by more than 4 logging trucks/day generated more than 100 times the sediment from abandoned roads.

Even with a road surface of crushed rock aggregate, which is often used with the intent to reduce sediment production on road surfaces, Foltz (1996) documented that elevated truck traffic increased sediment production by 2 to 25 times that on unused roads in western Oregon. Foltz (1996) noted that a similar range of increases in sediment production in response to elevated road traffic was likely in other regions because the primary causes are the same across regions. Primary mechanisms for increased erosion and sediment production from road use are the production of highly mobile fine sediment on road surfaces, bare soil surfaces, road prism damage, disruption of gravel or aggregate surfaces, and the creation of ruts on roads (See Photo 2).

Road use during wet periods magnifies the effect of road use on surface erosion. Wet weather haul causes rutting, documented by USFS research to increase sediment delivery from surface erosion on roads by about 2-5 times that occurring on unrutted roads (Foltz and Burroughs, 1990). Sediment from road erosion from wet weather use is delivered to streams with elevated efficiency. The USFS's summary of scientific information on roads (Gucinski et al., 2001) noted "As storms become larger or soil becomes wetter, more of the road system contributes water directly to streams."

Increased road use typically requires increased road maintenance. A significant increase in road maintenance to facilitate increased road use is a common component of vegetation management proposals on USFS lands (e.g., Bitterroot National Forest, 2001; CNF, 2002). Road maintenance activities increase surface erosion from roads by removing vegetation and disturbing road prisms and ditches (RRSNF, 2004). Black and Luce (1999) found that road grading elevated sediment production for at least a year. Luce and Black (2001) documented that ditch maintenance also elevated erosion.

The increases in sediment production caused by increased road use are ecologically significant. Sediment production remains greatly elevated on roads, even in the absence of

increased road use.

However, WATBAL does not provide any means of accounting for increased surface erosion in response to elevated road use and maintenance. The surface erosion rates for roads in WATBAL are the same regardless of level of road use and maintenance (Table 4). This likely causes WATBAL to underestimate sediment delivery from heavily used roads. Further, this situation makes WATBAL unable to properly differentiate among proposed alternatives with differing levels of road use.

In contrast, BOISED (Potyondy et al., 1991) provides basic surface erosion rates that reflect that increased road use elevates road erosion (See Table 4). The basic surface erosion rate for heavily used, older roads in BOISED are more than 5 times that of WATBAL (Table 4).

Notably, BOISED very likely underestimates the relative difference in surface erosion between heavily and lightly used roads, because it only estimates a 40% increase in response elevated road use. In contrast, studies have consistently documented a greater than 200% increase in road surface erosion in response to elevated road use (Reid et al., 1981; Foltz, 1996). Therefore, it is likely that WATBAL underestimates surface erosion from heavily roads to greater degree than indicated by the difference between WATBAL's and BOISED's estimates of surface erosion from heavily used roads (Table 4.)

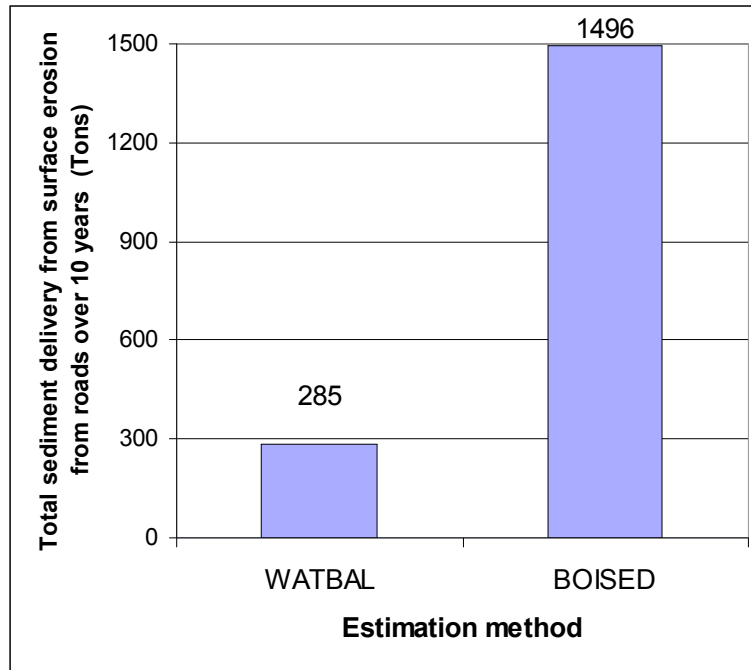
Figures 3a and 3b provide an example of the magnitude of the difference in WATBAL estimates for sediment delivery from heavily used roads in comparison to those from BOISED. For the situation illustrated in these figures, BOISED and WATBAL BSER_r values for heavily used roads were used to evaluate the same scenario as Figures 2a and 2b, but with the additional assumption that half of the roads in the watershed are heavily used. Under this scenario WATBAL estimates less than 20% of the sediment delivery from surface erosion from roads estimated by BOISED. This indicates that WATBAL consistently underestimates sediment delivery from heavily used roads. This indicates that with respect to sediment delivery, WATBAL likely does not adequately differentiate among alternatives with significantly different levels of elevated road use.

These are significant defects, because major logging or mining projects can greatly increase road traffic, sometimes for several years. The increased traffic is typically most pronounced on the older roads that are major haul routes out of watersheds. These major haul routes are often in close proximity to streams and with a significant percentage of road surfaces hydrologically connected to streams. Roads with these attributes are where WATBAL most significantly underestimates sediment delivery from roads in response to elevated traffic.

The basic surface erosion rate in WATBAL for open, maintained roads that are more than five years old is roughly the same as the basic surface erosion rate in BOISED for roads that have been closed to vehicular use for several years and are not maintained (Table 4). While this indicates that WATBAL's basic surface erosion rates for open and used roads may be adequate for closed roads, assuming that BOISED surface erosion rates for closed roads are applicable to conditions on the CNF, it provides another indication that WATBAL's surface erosion rates for open and maintained roads is low. This is because roads that have been closed for several years typically undergo some degree of vegetative recovery with non-use, resulting in reduced surface erosion (See Photo 3), while open roads that are used and maintained do not.

Figures 3a and 3b. Estimated sediment delivery by WATBAL and BOISED for a 10-year period from management-induced surface erosion roads in a 6.5 mi² watershed with a road density of 2.5 mi/mi² comprised of roads 15 years old, 50% of which are heavily used (See text for additional details). Figure 3a displays the total estimated sediment delivery (Tons) from surface erosion from roads under this scenario. Figure 3b displays mean annual sediment delivery in terms of percent over natural (%ON) for the same scenario as in Figure 3a. In this situation, BOISED estimates are more than 5.2 times the level estimated by WATBAL, indicating that WATBAL underestimates surface erosion and sediment delivery from heavily used roads (See text for additional details).

a)



b)

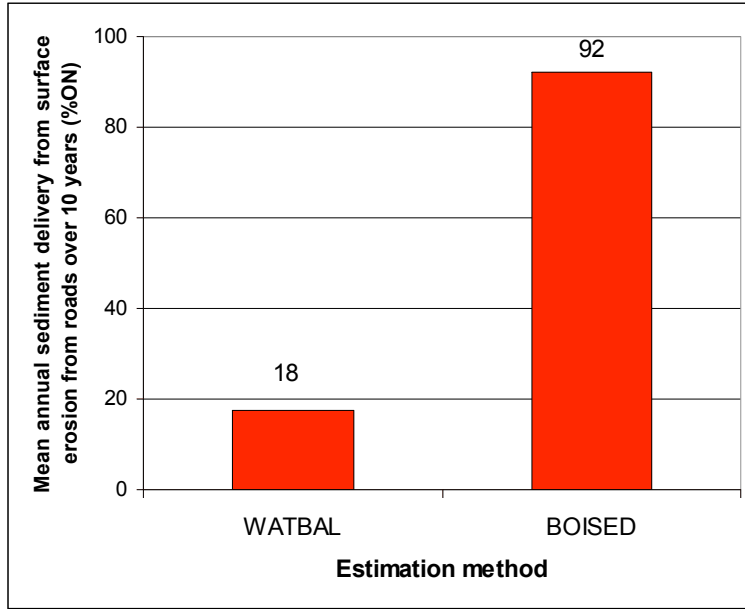


Photo 3. An example from Karr et al. (2004) of some typical impacts of reconstruction and heavy use of unused roads on vegetation, soils, road runoff, and sediment production. Top photo shows an unused road in 1996 on the Malheur National Forest, Oregon which had undergone some recovery of vegetation and soil conditions through non-use, resulting in reduced erosion and runoff. Bottom photo shows how reconstruction of the same road in 1999 reversed this recovery, increasing soil erosion and delivery of the eroded sediment in surface runoff.



Basic surface erosion rates for road reconstruction

Road reconstruction increases surface erosion through several mechanisms. It creates mobile fine sediments at the road surface, fills, and ditches. It can disrupt roadcuts that have had some degree of recovery over time. It can also involve sidecasting. It typically reverses whatever vegetative and soil recovery may have occurred, especially with major reconstruction of roads that have been unused for several years (Beschta et al., 2004; Karr et al., 2004), as shown in Photo 3. All of these impacts increase erosion and sediment delivery from roads.

Logging or major vegetation management projects on national forests often include road reconstruction and grading to expedite log haul, typically along the major haul routes. On the CNF the major haul routes tend to parallel streams in close proximity and with a high degree of hydrologic connectivity to the streams.

To account for increases in surface erosion from road reconstruction, WATBAL uses a second set of surface erosion rates as a function of time since reconstruction. This second set of surface erosion rates are added to the initial basic surface erosion rate that is a function of time since construction (Table 1 and 5).

The surface erosion rates in WATBAL for reconstructed roads are another likely source of underestimation of sediment delivery. Table 5 displays the two basic surface erosion rates in WATBAL and their summed values for a road reconstructed 15 years after initial construction. These rates are likely low because they assume that rates of elevated surface erosion on reconstructed roads, especially older ones, rapidly taper off over time (Table 5). As previously discussed, this rapid reduction in rates of surface erosion rates on roads is highly unlikely because the primary causes of elevated surface erosion on roads do not recover rapidly as long as roads remain open, are used, and periodically maintained.

Table 5 also displays the surface erosion rates for reconstructed roads in BOISED. Several years after reconstruction, the basic surface erosion rate for heavily reconstructed roads in BOISED is more than five times that of WATBAL. Several years after reconstruction, BOISED's basic surface erosion rate for lightly reconstructed roads is more than 3.5 times that of WATBAL (Table 5). Again, this indicates that WATBAL likely underestimates surface erosion on roads in response to reconstruction, especially on older roads.

Figures 4a and 4b provide an example of the difference between WATBAL estimates for sediment delivery from reconstructed roads and those from BOISED. In these figures, BOISED and WATBAL BSER_r values for heavily used roads were used to evaluate the same scenario as Figures 2a and 2b (i.e., a 6.5 mi² watershed with a road density of 2.5 mi/mi² comprised of roads 15 years old), but with the additional assumption that 10 miles of road are heavily reconstructed. Under this scenario BOISED estimates more than 3.3 times the sediment delivery from surface erosion from reconstructed roads than that estimated by WATBAL.

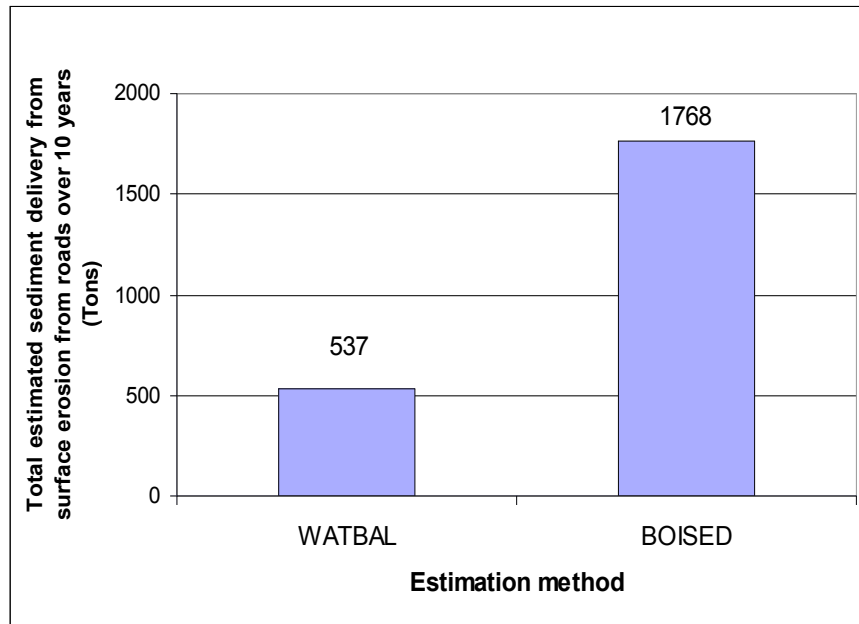
WATBAL's underestimation of sediment delivery from reconstructed roads will tend to be to greatest for projects with road reconstruction of:

- a) a significant portion of the road network;
- b) older roads;
- c) roads that are proximate to stream network and/or are hydrologically connected to streams at crossings or via other drainage features.

As discussed, major haul routes commonly exhibit these attributes. Therefore, WATBAL underestimates the effect on sediment delivery of reconstructing such roads. Similarly, WATBAL also very likely fails to adequately differentiate among alternatives with significantly different levels of road reconstruction. This is a significant limitation in environmental assessments that are partially based on WATBAL, because many projects evaluated via WATBAL involve alternatives that include significant levels of road reconstruction (e.g., CNF, 2002).

Figures 4a and 4b. Sediment delivery from management-induced surface erosion over 10 years in a 6.5 mi² watershed with a road density of 2.5 mi/mi² comprised of roads 15 years old, 10 miles of which are heavily reconstructed, as estimated via by WATBAL and BOISED. Figure 4a displays the cumulative sediment delivery (Tons) from surface erosion from roads under this scenario. Figure 4b displays mean annual sediment delivery in terms of percent over natural (%ON) over 10 years for the same scenario as in Figure 4a. In this situation, BOISED's basic surface erosion rates estimate about 3.3 times the sediment delivery estimated by WATBAL, indicating that WATBAL likely underestimates sediment delivery from heavily reconstructed roads. See text for additional details and discussion.

a)



b)

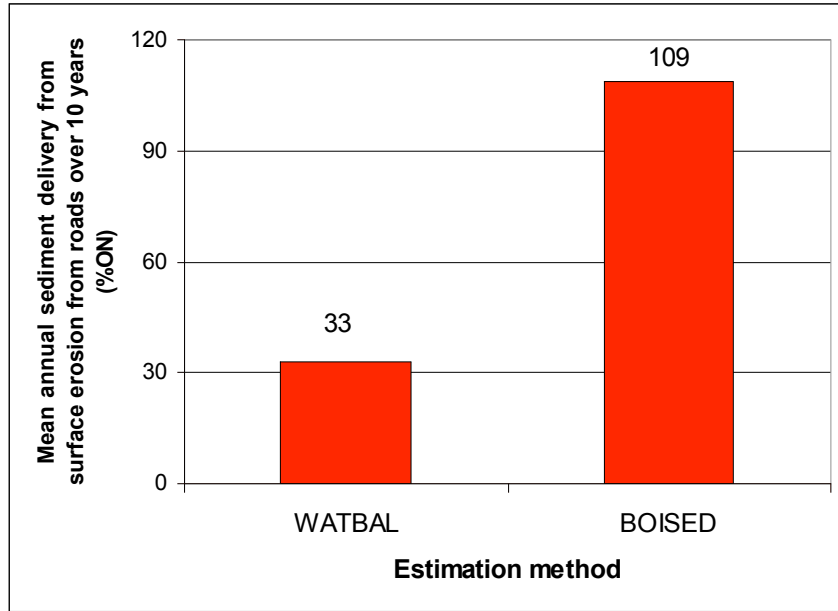


Table 5. Basic surface erosion rates for road reconstructed 15 years after initial construction in WATBAL (Patten and Jones, 2005) and BOISED (Potyondy et al., 1991). All basic surface erosion rates are in units of T/mi²/yr.

Years since reconstruction	1	2	3	4	5	6	7	8	9	10
WATBAL basic surface erosion rate for road 15 years old road at time of reconstruction	1,197	1,185	1,173	1,161	1,149	1,138	1,127	1,115	1,104	1,093
WATBAL road surface erosion rate reconstruction ²⁴	13,500	810	270	270	267	265	262	260	258	256
WATBAL total surface erosion rate reconstructed road	14,697	1,995	1,443	1,431	1,416	1,403	1,389	1,375	1,362	1,349

²⁴ Patten and Jones (2005) only provides surface erosion rates for reconstruction through the eighth year after reconstruction. In this table, the rates for the ninth and 10th year were estimated by linear extrapolation.

BOISED: basic surface erosion rate for road heavy reconstruction and use	18,000	10,000	7,000	7,000	7,000	7,000	7,000	7,000	7,000	7,000
Ratio between BOISED/ WATBAL: heavy reconstruction	1.2	5.0	4.9	4.9	4.9	5.0	5.0	5.1	5.1	5.2
BOISED: basic surface erosion rate for road light reconstruction and use	9,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000
Ratio Between BOISED/ WATBAL: light reconstruction	0.6	2.5	3.5	3.5	3.5	3.6	3.6	3.6	3.7	3.7

Estimated average sediment delivery efficiency by landtype

Like Cline et al. (1981) and many other models based upon it, WATBAL does not use the actual position of a sediment-producing activity or its actual proximity to a stream channel to estimate the efficiency of delivery of eroded sediment to stream systems. Instead, WATBAL estimates the average sediment delivery efficiency coefficient, D in equation (1), by landtype based on stream density inventories and mean distance to streams.

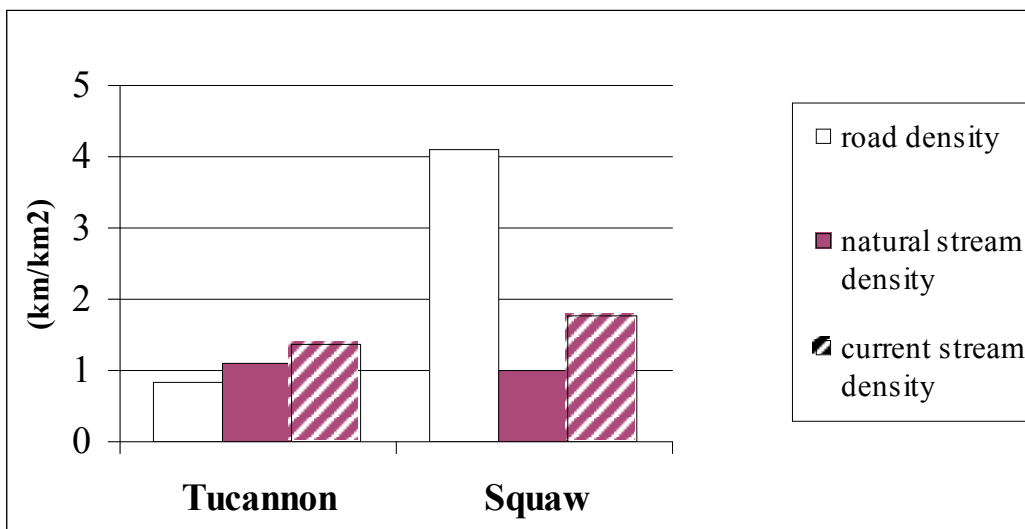
This simplified approach to estimating the efficiency of sediment delivery over slopes, via the coefficient D, has not been validated. This aspect of models based on Cline et al. (1981) is generally considered to be among the weakest model attributes (Cline et al., 1981; Potyondy et al., 1991; King, 1993).

This approach is a likely source of bias because logging and roads are not randomly and evenly distributed over the landscape or within landtypes. As previously discussed, much of the road network is in relatively close proximity to streams or connected streams so that they effectively act as an extension of the stream network. Sediment delivery efficiency on these road segments and at stream crossings is very likely far higher than the average sediment delivery coefficient for a landtype based on the mean distance to streams within the landtype as derived from stream density estimates, as is done in WATBAL.

WATBAL's use of mean sediment delivery coefficient for landtypes based on estimates of their natural stream density ignores that the road networks typically increase stream densities

(Wemple et al., 1996, Rhodes and Huntington, 2000). This change in stream density is not trivial, especially in watersheds with higher road densities. Based on the amount of road connected to streams in the Squaw Creek watershed on the CNF in Rhodes and Huntington (2000), the road network in Squaw Creek nearly doubled the natural stream density (Figure 5).

Figure 5. Natural stream density, road density, and current stream density due to integration with the road network in Squaw Creek watershed, CNF and Tucannon River watershed, Umatilla NF, based on detailed survey of road connectivity with streams (Rhodes and Huntington, 2000).



The effect of road network on increasing stream density is not restricted to a single watershed. It has been verified in all watersheds where such data have been collected (Wemple et al., 1996; Rhodes and Huntington, 2000; Wemple et al., 2001; Coe, 2006). The increase in stream density by roads tends to increase with increasing road density (Figure 5), other factors remaining equal.

WATBAL’s method of estimating the efficiency of sediment delivery from slope to streams intrinsically assumes that sediment is delivered to streams overland via non-channelized flow (Cline et al., 1981; Patten and Jones, 2005). This is not always the case, because channelized flow from roads to streams is fairly common (Wemple et al., 1996; Rhodes and Huntington, 2000; Coe, 2006). Channelized transport typically delivers sediment to streams more efficiently over longer distances than non-channelized flow (O’Laughlin and Belt, 1994; Coe, 2006).

This aspect of WATBAL likely causes it to underestimate sediment delivery and effects on streams and fish under existing conditions in watersheds with a significant road network. It also serves as a source of underestimation of the impacts of alternatives that reconstruct, construct, or increase traffic on roads that are near or cross streams. These defects undermine the ability of WATBAL to adequately differentiate among alternatives with respect to sediment delivery. They also cause WATBAL to significantly underestimate likely future cumulative effects caused by alternatives that reconstruct, construct, or increase traffic on roads that are closer than average to the stream system.

Mitigation coefficients for roads and logging

WATBAL allows user-defined input of mitigation levels that reduce sediment delivery erosion from roads and logging as calculated in equations (1) and (2). Although Patten and Jones (2005) states that mitigation values should “...reflect validated modifications...” (emphasis in original) to logging and road practices, it provides no criteria for how mitigation measures should be validated with respect their rate of reduction in erosion and sediment delivery. The validation of the quantitative effectiveness of mitigation measures requires detailed quantitative monitoring of sediment production and delivery from a variety of practices, including no-treatment controls, from an array of activities in a variety of land types over a reasonably long period time. This requisite validation of the quantitative effectiveness of mitigation practices is seldom done for any practice in any landtype by any national forest, including the CNF.

Patten and Jones (p. 19, 2005) states that mitigation values are used to reduce “...sediment from surface erosion sources...regardless of site-specific conditions and characteristics of the land involved” (emphasis added), indicating that the actual effectiveness of mitigation measures has not been determined on a site-specific basis.

Patten and Jones (2005) includes an Appendix for mitigation values that can be input into WATBAL. These values were “developed on the Clearwater National Forest using research, [“Best Management Practices”] BMP observations, and professional judgment” (Patten & Jones, p. 19, 2005). However, “professional judgment,” and “BMP observations” cannot adequately determine the actual quantitative effectiveness of specific mitigation measures reducing erosion and sediment delivery from logging and roads.

BMP audits rely solely on visual assessment of BMPs. They are subjective and lack experimental rigor. Stanford and Ward (1992) labeled the assignation of mitigation effectiveness on the basis of visual BMP inspections as “the illusion of technique,” because such are conjectural and without any scientific merit.

Therefore, user-supplied mitigation in WATBAL is fraught with potential for error and abuse, because it allows inclusion of mitigation levels which are not grounded in reality. Because the level of mitigation applied in WATBAL is determined by the user, the magnitude of error caused by this factor likely varies among users as well as terrain.

There is reliable evidence from the CNF that BMPs fail to protect aquatic resources from sediment delivery from land disturbance. Espinosa et al. (1997) provided a detailed review of in-stream data from watershed case histories that clearly indicated that BMPs fail to protect fish habitat and streams. Espinosa et al. (1997) concluded that BMPs may actually increase habitat damage because they have been blindly relied upon instead of avoiding the implementation of damaging watershed actions. Studies have repeatedly shown that habitat damage increases as the amount of disturbance from logging and road construction increases, even when BMPs are applied. Such habitat damage includes elevated turbidity, suspended sediment, and sedimentation (Chapman and McLeod, 1987; Rhodes et al., 1994).

Most mitigation measures and BMPs do little to reduce erosion and sediment delivery when activities are in close proximity to streams or during major storm or flood events. Kattleman

(1996) concluded that BMPs cannot eliminate the aquatic impacts of stream crossings. These limits on BMP effectiveness are seldom factored into mitigation effectiveness estimates.

Patten and Jones (2005) suggest using user-defined mitigation values in WATBAL to account for the effect of PACFISH/INFISH buffers. However, this also poses problems. Many areas within PACFISH buffers are no longer completely functional due to past logging and roads. Many roads are within PACFISH buffers. For example, as previously noted, about 43% of all classified roads on the CNF are within 300 feet of streams (CNF, 2003). In such cases, claiming a fixed mitigation level based on the existence of PACFISH buffers is not valid.

The WATBAL analysis in the CNF DEIS for White Sands project (CNF, 1995) provides an example of how the use of implausible levels of mitigation in WATBAL leads to spurious results. In this case, it was predicted that logging, together with the construction of 3.9 mi. of roads with 15 road crossings in a roadless area would not cause any increase in sediment delivery to streams. This is spurious because it is known that the construction of road crossings elevate sediment delivery by many times the natural rate and cannot be effectively mitigated (Kattleman, 1996). Further, regional assessments have repeatedly concluded that there is no reliable empirical evidence that the application of BMPs can reduce the impacts of logging and road construction at the watershed scale to an ecologically insignificant level (Rhodes et al., 1994; Ziemer and Lisle, 1993; ISG, 1996; USFS and USBLM, 1997c). Megahan et al. (1992) and USFS and USBLM (1997c) stated that it was not possible to conduct logging activities without generating sediment to streams, no matter how carefully the activities were implemented.

In sum, the allowance for user-defined mitigation coefficients in WATBAL can significantly usurp the disclosure of cumulative effects and credible differentiation among alternatives with vastly different effects on anthropogenic sediment delivery. In some cases, such as CNF (1995), this can be the largest source of error in WATBAL analyses of the effects of activities on sediment delivery.

Reduction factors for ridgetop roads

WATBAL reduces sediment delivery from mass failures and surface erosion by 80% for all roads that meet the criteria for ridgetop roads, via R_r in equations (1) and (4). Patten and Jones (2005) provides no rationale for this level of reduction. Ridgetop roads can have pronounced effects on sediment delivery.

Rhodes and Huntington (2000) documented that ridgetop roads had a higher fraction of their length that initiated gullies >10m in length than midslope and valley bottom roads. Therefore, even where ridgetop roads do not cross streams, they can be hydrologically connected to streams and contribute to gullying, which is yet another source of sediment delivery from roads. Montgomery (1994) documented that ridgetop roads can contribute to headward channel erosion and increased rates of mass failure. This information indicates that the ridgetop road reduction factor in WATBAL likely causes it to underestimate sediment delivery from ridgetop roads.

The ridgetop road factor in WATBAL also skews the aggregate analysis of sediment delivery from roads. While this factor quite significantly reduces estimated sediment delivery from

ridgetop roads in WATBAL estimates, there is no equivalent approach that boosts sediment delivery from roads segments that cross streams, are in close proximity to streams, or have a high degree of hydrologic connection to streams. This likely injects significant error into WATBAL estimates where there is a significant amount of “ridgetop” road, especially when they are on unstable and erosive land types, or where significant construction or reconstruction of ridgetop roads is proposed.

Sediment delivery from landings

The construction, reconstruction and use of landings have impacts to soils, vegetation, runoff, and sediment flux that are akin to those from roads in persistence and intensity (Geppert et al., 1984, Menning et al., 1996; Karr et al., 2004; Beschta et al., 2004). Like roads, landings effectively “zero out” soil productivity for many years (Geppert, 1984). The USFS Region 5 method for cumulative effects analysis (Menning et al., 1996) treats landings as equivalent to roads with respect to their adverse watershed cumulative effects on erosion and runoff. Per unit area, landings erode at rates similar to roads. They also contribute sediment over considerable distances. Ketcheson and Megahan (1996) found that sediment from landings traveled up to 348 feet in settings similar to much of the CNF.

Landings also often involve a significant area in many projects. For instance, based on the analysis of several logging projects, landings typically occupy about two per cent of an area slated for logging. Thus, a 5000 acre vegetation management project would construct about 100 acres of landings, assuming that two per cent of the area is occupied by landings. This level of landing construction would occupy the same area as about 41.2 miles of road with a mean width of 20 feet. This is extremely significant, because landings have impacts on soil erosion and sediment delivery that on par with those from roads in their severity and persistence. There is no question that 41.2 miles of new road construction would have significant impacts on sediment delivery to aquatic systems. Given their impacts, there is also no question that an equivalent area of landing construction would have similarly adverse impacts.

However, Patten and Jones (2005) provides no description of how landings are treated within the sediment delivery component of WATBAL, nor does it mention of landings. Therefore, it does not appear as though the area of landings is included in the area for roads in calculation of sediment delivery in WATBAL. This is likely a serious source of error due to the extent of landings and the severity and persistence of their impacts on sediment delivery.

The locations and nature of landings increases the significance of this source of error in WATBAL. Landings are always part and parcel of the road system because they are physically connected. Landings are often sited in riparian areas for logistical reasons, including ease of haul and slope. A significant percentage of older landings are sited in riparian areas and have relatively high efficiency of sediment delivery. Logging typically requires the construction, reconstruction, or re-use of landings. Helicopter logging typically requires the construction or reconstruction of landings that are significantly larger than those built for ground-based yarding, because the area must accommodate not only logs, loading equipment, and trucks, but also a helipad and helicopter support equipment.

For these reasons, the failure to assess sediment delivery from landings in WATBAL

likely causes it to underestimate the differences among alternatives with different levels of logging, because the extent of landing impacts typically correlates with the amount of logging. It also causes WATBAL to underestimate the cumulative effects on sediment delivery in watersheds with a significant number of landings, especially when the landings are in riparian areas.

Sediment sources ignored in WATBAL: Grazing, mining, and elevated channel erosion

WATBAL ignores some management-induced sediment delivery from grazing, mining, and elevated channel erosion,²⁵ as the model documentation clearly acknowledges (Patten and Jones, 2005). All three can be significant sources of sediment delivery. This likely contributes to underestimation of sediment delivery in watersheds with grazing, mining, or elevated peakflows. This also occludes the ability of WATBAL results to adequately discriminate the aquatic effects of alternatives with differing levels of grazing, mining, and/or increases in peakflows from vegetation removal.

It is extremely well documented that grazing significantly increases surface and channel erosion (e.g., Dunne and Leopold, 1978; Kauffman et al., 1983; Platts et al., 1991; Fleischner, 1994; CWWR, 1996; Belsky et al., 1999). Grazing does so through a variety of mechanisms, including soil compaction and resulting alteration of soil hydrologic properties, removal of groundcover, trampling, browsing, bank breakdown, and the thwarting of vegetative recovery (Platts, 1991, Fleischner, 1994, Belsky et al. 1999; Kauffman et al., 2004). These mechanisms and their adverse effects on watersheds and native salmonids have been long recognized (Leopold, 1937). Notably, assessments from different parts of the country indicate that the effect of grazing on soil erosion and sediment delivery varies in degree, but not in kind, across ecosystems.

In the Bear Valley Creek watershed in Idaho on the Boise National Forest, grazing was estimated to have more than doubled sediment delivery, resulting in high levels of fine sediment and extremely low salmon survival (Boise National Forest, 1993; Rhodes et al., 1994). In northeastern Oregon, Kauffman et al. (1983) estimated that bank erosion within a lightly grazed reach was about three times higher than in adjacent degraded reaches that had been rested. Bank erosion is significant because it delivers fine sediment to streams with great efficiency. Therefore, the inability of WATBAL to estimate sediment delivery from grazing likely results in the significant underestimation of cumulative sediment delivery and its effects on aquatic resources in watersheds subjected to grazing.

Although mining is less pervasive than other activities, where it does occur, it can greatly increase sediment delivery (Nelson et al., 1991). Plainly, the inability of WATBAL to deal with sediment delivery from mining activities makes it impossible to use it to estimate cumulative sediment delivery in watersheds with significant mining impacts.

WATBAL has no mechanism for estimating increased channel erosion and downstream

²⁵ While Patten and Jones (p. 6, 2005) state that WATBAL “does account for channel erosion and deposition in the tributary streams because these characteristics are part of the landtype coverage the model uses,” this is not equivalent to the estimation of elevated channel erosion in response to increases in peakflows.

sediment delivery in response to increased peakflows. King and Tennyson (1984) and King (1989) documented that even relatively low levels of logging and roads increase peakflows in small watersheds in Northern Idaho. This is consistent with a large number of studies on the effect of forest removal on streamflow in areas where snowmelt is the dominant runoff mechanism (McDonald and Ritland, 1989; Rhodes et al., 1994). Although channel adjustment processes are complex, it is indisputable that increases in peakflow increase channel erosion (Richards, 1982; Dunne et al., 2001). Increased peakflows lead to headward channel erosion, expansion of cross-sectional channel area, including channel widening, and elevated bank erosion. Many small headwater channels are especially vulnerable to increased erosion caused by increased peakflows (Rosgen, 1996). King (1989) warned that the increased peakflow documented in watersheds in northern Idaho could increase downstream sedimentation because sediment transport to downstream reaches is highly correlated to peak streamflow magnitude.

For these combined reasons, WATBAL is likely to underestimate sediment delivery in watersheds with significant mining, grazing, or peakflow elevation from the combined impacts of roads and logging.

Sediment delivery from mass failures accelerated by logging and roads

Mass failures are significant source of sediment delivery on the CNF. Roads and logging greatly increase mass failure rates on the CNF (Megahan et al., 1978; McClelland et al., 1997). Roads particularly elevate sediment delivery from mass failure (Megahan et al., 1978). Sediment delivery from mass failures has been, and is, a significant cause of degradation of streams and fish habitats on the CNF (Megahan et al., 1978; Espinosa et al., 1997; Rhodes and Huntington, 2000). While a detailed analysis of WATBAL's acceleration factors for mass failures from logging and roads by landtype and parent material is beyond the scope of this report, there are a few aspects of WATBAL likely cause consistent underestimation of sediment delivery from mass failures.

WATBAL's mass failure acceleration factors for roads as a function of time are a likely source of underestimation of sediment delivery. These acceleration factors for roads in granitic batholith and Border parent materials are assumed to decline significantly for roads more than 10 years old and especially for roads more than 20 years old (Table 3). This likely causes underestimation of sediment delivery from older roads, because roads more than 20 years old had the highest rates of mass failure per mile of road on the CNF from 1995-1996 (McClelland et al., 1997). In their analysis of mass failures in the watersheds of Papoose, Parachute, Squaw and Doe creeks on the CNF, Pipp et al., (1997) also found that roads more than 20 years old had the highest rates of mass failures from 1995-96. Rhodes (unpub.) analyzed the CNF's mass failure data for 1995-96 and found that in the Squaw/Doe Creek watershed, the rate of mass failure per mile of road was roughly the same for roads more than 20 years old and roads less than 20 years old. However, the mass failures on roads more than 20 years old in Squaw Creek delivered roughly three times the amount of sediment to the stream system than roads less than 20 years old.

These data all consistently indicate that the mass failure rates and sediment delivery from roads more than 20 years old do not decline rapidly, as assumed in WATBAL. Instead, contrary to the assumptions in WATBAL, data from the CNF indicate that sediment delivery from mass failure from roads increase with time. Geppert et al. (1984) noted that rates of mass failures from roads

do not decline over time. Therefore, declining acceleration factors for roads as a function of road age in WATBAL (Table 3) are likely to underestimate mass failures from older roads, especially those more than 20 years old. Since a significant amount of the road network on the CNF is more than 20 years old, this likely causes WATBAL to significantly underestimate sediment delivery from mass failures and its cumulative effects in roaded watersheds.

The mass failure acceleration factors in WATBAL for logging are also a likely source of underestimation of sediment delivery. The acceleration factors for logged areas assume that rates of mass failures areas decline rapidly with time, reaching zero 10 years after logging (Table 2). Available data indicate that this latter assumption is incorrect. Rhodes' (unpub.) analysis of mass failures in the Squaw/Doe Creek watershed found that mass failures from the logged areas more than 10 years old were slightly higher than from logged areas less than 10 years old. McClelland et al. (1997) included no analysis of rates of mass failures from logged areas as a function of age, but stated (p. 13) that areas that had been logged 40-50 years prior had mass failures. This information indicates that the mass failure acceleration rates for logged areas in WATBAL underestimates of sediment delivery from logged areas more than 10 years prior.

Most investigations of mass failures from logged areas have found that the rate of mass failure tends to be greatest 6-10 years after logging due to the loss of root strength caused by decay of the dead roots of logged trees. In contrast, WATBAL's mass acceleration factors for logged areas assume a consistent decline in sediment delivery from mass failure with time (Table 2). Therefore, this aspect of WATBAL likely causes it to underestimate sediment delivery from logged areas that are 6-10 years old.

Data on mass failures triggered by large rain-on-snow events during the winter of '95-'96 indicate that WATBAL acceleration factors for mass failures may be low and in need of updating. McClelland et al. (1997) found that the highest rate of mass failures per unit area during the '95-'96 events occurred in "Border" type parent material. The number of mass failures per unit area in Border parent material was almost twice the rate in granitic Batholith parent material (McClelland et al., Table 10, p. 49, 1997). The mass failure rate per mile of road in Border parent material was almost twice that in granitic Batholith parent material (McClelland et al., Table 3, p. 44, 1997).

In contrast to the mass failure data from '95-'96, the WATBAL acceleration factor for roads in the Border parent material is substantially lower than for the Granitic (Batholith) parent material, as shown in Table 3 (Patten and Jones, 2005). This indicates that: a) WATBAL's acceleration factors for roads in Border parent material are not corroborated by McClelland et al. (1997); and b) relative rates of mass failure from roads in the Border parent material are likely significantly underestimated by WATBAL.

McClelland et al. (Table 10, 1997) also found that the number of mass failures per unit area in Batholith parent material during the '95-'96 events was more than double the rate found by Megahan et al. (1978). Similarly, McClelland et al. (Table 10, 1997) found that the number of mass failures per unit on Border parent material during the 1995-96 events was almost double the rate found by Megahan et al. (1978). McClelland (1997) estimated that the overall volume of sediment from mass failures delivered to streams during the '95-'96 events was more than double the amount delivered during the '74-76 period studied by Megahan et al. (1978). Since the Megahan study

(1978) provides the basis for mass failure calculated in WATBAL, the findings of McClelland (1997) indicate a need to adjust WATBAL's mass failure acceleration factors. However, the acceleration factors in Patten and Jones (2005) are the same as in the 1989 Technical Users Guide to WATBAL (Patten, 1989), indicating that the acceleration factors have not been adjusted in response to the mass failure data for the '95-'96 events.

Based on the foregoing, WATBAL mass failure methods have several aspects that likely contribute to underestimation of sediment delivery. In aggregate, the underestimation is likely to be greatest in watersheds with: a) areas logged more than 10 years prior; and/or b) with roads more than 20 years old; and, c) Border landtypes.

Routing of sediment delivery

The simplified approach used by WATBAL to route sediment to a reach via the routing coefficient calculated in equation (6), has never been validated. It has consistently been flagged as one of the weakest and likely most inaccurate aspects of Cline et al. (1981), and other models based on it (USFS, 1980; Cline et al., 1981; Potyondy et al., 1991; King, 1993; Patten and Jones, 2005). However, the error associated with this aspect of WATBAL is not likely to be randomly distributed. Instead, it is likely to introduce some consistent bias into WATBAL estimates of sediment delivery to a specific reach.

The WATBAL method of routing sediment reduces the estimated anthropogenic and natural sediment delivered to a specific analysis point in a stream as it is routed from upstream reaches. This is based on the assumption that some of the sediment delivered to the analysis point is stored upstream within the channel network instead of being transported to the reach of interest. The amount of sediment assumed to go into upstream channel storage, rather than sediment delivery at the point of interest is a function of watershed size, as indicated in equation (6).

Although there is no question that some sediment delivered to stream systems is stored in channels for some period of time, WATBAL's adjustment method is problematic for reasons other than the lack of validation. Channel storage of sediment is not permanent, although WATBAL's routing algorithm essentially treats it as such. WATBAL has no means of accounting for the eventual downstream transport of sediment that is only temporarily stored in the channel network.

The capacity of channel networks to store sediment is finite, while WATBAL's routing method treats it as essentially infinite. The sediment routing method in WATBAL has no means of reducing the amount of sediment estimated to go into channel storage as sediment delivered from previous activities exhaust the channel storage capacity by in-filling pools and storage sites behind LWD and other channel obstructions. Detailed research on channel deposition under high sediment loads has documented that sediment transport and sediment routing become increasingly efficient as channel sediment storage sites become occupied by sedimentation (Lisle, 1982). WATBAL's simplified channel routing method cannot account for this.

The sediment storage capacity in streams also varies among and within streams due to natural conditions and the effects of management. WATBAL's routing method intrinsically assumes that all streams and all reaches of streams have the same sediment storage capacity and

properties. Pools, channel margins, and areas behind in-channel large woody debris (LWD) are primary sites for channel storage (Rhodes et al., 1994). While these attributes naturally exhibit high variability, previous sediment delivery from prior logging and roads diminish the volume and frequency of these available sediment storage sites. Roads and logged areas in riparian areas cause persistent reductions in the size and number of pieces of in-channel LWD, reducing available sediment storage (Rhodes et al., 1994). A significant percentage of the riparian areas on the CNF are occupied by roads or have been subjected to logging. Huntington (1998) found that low gradient streams in roaded watersheds in the CNF consistently had lower levels of LWD than unroaded watersheds. McIntosh et al. (2000) documented dramatic reductions in pools in roaded watersheds in the Snake River basin. Huntington (1998) found that streams in roaded watersheds in the CNF had lower pool frequency than unroaded watersheds. However, WATBAL's sediment routing method has no means of accounting for this variability in sediment storage sites or that available sediment storage is likely to be lower in watersheds affected by roads and logging.

Inaccuracy caused by the sediment routing calculation in WATBAL may not bias the discrimination among alternatives when WATBAL estimates of sediment delivery are expressed as % ON. This is because estimated natural sediment is also subject to the same routing calculation, and, hence, the same degree of error. When % ON is used to express WATBAL results, estimates of anthropogenic sediment delivery are divided by the estimate of natural sediment delivery, thus, the error associated with routing sediment delivery is likely cancelled out since it is embedded in both the numerator and denominator,

However, the sediment routing calculation aspect of WATBAL likely contributes to consistent underestimation of amount of management-induced sediment routed to a reach. This can be significant, because the routing of sediment in WATBAL reduces the sediment delivered to a reach by about 30% for a 6.5 mi² watershed and by about 46% for a 30 mi² watershed. Errors associated with sediment routing are likely to be most significant in larger watersheds that with a history of high sediment loads and/or loss of LWD, resulting in the loss of in-stream sediment storage capacity.

WATBAL and climate-driven rates of sediment delivery

As with other models based on Cline et al. (1981), WATBAL only estimate *mean* rates of sediment delivery and cannot be used to estimate sediment delivery for specific storm or runoff events of a given magnitude (Patten and Jones, 2005). WATBAL does not account for inter-annual fluctuations in precipitation, streamflow, and storm events that strongly affect sediment delivery from both surface erosion and mass failures. The model does not actually estimate sediment delivery for any given year, but rather an “average” year (Patten and Jones, 2005). This causes WATBAL to underestimate sediment delivery during years with above normal precipitation or major storm events. For instance, circa 1994 it was estimated that total sediment delivery in Pete King Creek was about 25% ON based on WATBAL (Rhodes et al., 1994). During the extreme events of 1995-96, McClelland et al. (1997) estimated that sediment delivery solely from mass erosion was seven times the “background” rate, or at least about 700% ON.²⁶

²⁶ McClelland et al. (1997) do not describe how the “background rate” they discuss was estimated. It may be based on: a) WATBAL estimates of natural sediment delivery; b) WATBAL estimates of

In a similar vein, Megahan et al. (1986) found that a major storm event during road construction increased the sediment yield from a basin in the Idaho batholith by about five times the natural rate, or roughly 500% ON. They concluded that the magnitude of erosion from storms during construction depended more on the stage of construction at the time of a storm than the road design (Megahan et al., 1986). The WATBAL model does not account for such variation in sediment delivery caused by storm events.

However, this, alone, does not inject *consistent* bias into WATBAL estimates. Since WATBAL's annual estimates of sediment delivery include mass failures that occur primarily during larger storm events, it is highly likely that WATBAL overestimates sediment delivery from mass failures during drier or more relatively normal water years, while underestimating it during wetter years. Nonetheless, it should be recognized that WATBAL estimates are likely to be most inaccurate during years with abnormal precipitation levels.

Assumptions associated with WATBAL use and interpretation of sediment delivery results

There are issues external to WATBAL's methods of estimating sediment delivery that can influence the accuracy of assessments based on WATBAL modeling. One is the assumption that most streams on the CNF are "sediment-limited" and can transport more sediment than is typically supplied to them in most years (Patten and Jones, p.27, 2005). Field evidence from the CNF contradicts this assertion.

Monitoring on the CNF has demonstrated that elevated sediment delivery has increased fine sediment levels in fish-bearing streams on the CNF. Based on a survey of 1,100 miles of streams on the CNF from 1989-1995, Huntington (1998) found that cobble embeddedness levels (which is related to fine sediment levels) were higher in all channel types in roaded and logged watersheds, which have elevated sediment delivery, than in unroaded and unlogged watersheds. These differences in fine sediment levels were statistically significant in all channel types, but this difference was most pronounced in lower gradient that are prone to sedimentation in response to elevated sediment delivery. These findings from Huntington's (1998) extensive surveys contradict the notion that most streams in the CNF are supply-limited. If streams inventoried by Huntington (1998) were sediment-limited, it is unlikely that there would have been these marked differences in fine sediment levels between streams in watersheds with sediment delivery elevated by roads and streams in unroaded, unlogged watersheds with natural levels of sediment delivery.

Notably, many of the most productive fish-bearing streams are "B" and "C" type channels, in the classification of Rosgen (1996), with channel substrates composed of gravel, sand, and silt. In particular, low gradient C-type channels are not sediment-limited. These channels are *depositional* zones with floodplains developed by sediment deposition that undergo sedimentation in response to elevated sediment delivery.

The lack of recovery of substrate conditions over significant periods of time also clearly

natural- and management-induced sediment at the time of the landslides; or c) an assumed background sediment delivery rate, independent of WATBAL.

indicates that streams on the CNF are not limited by sediment supply. Rhodes et al. (1994) demonstrated that there had been no statistically significant recovery in fine sediment levels in Pete King Creek on the CNF from 1985 to 1992, based on the CNF's own monitoring data. An updated analysis in the aftermath of the 1995-96 events indicated that this was still the case as of 2000 (Espinosa, pers. comm.). In a similar analysis of Deadman Creek, Rhodes et al. (1994) showed that there was a statistically significant increasing trend in fine sediment levels ($p < 0.10$) from 1985-1992. These data clearly contradict the notion that most streams are supply-limited.

A second unwarranted assumption regarding WATBAL use is that elevated sediment delivery that is below assumed "effect" thresholds does not negatively affect streams (Patten and Jones, 2005). These thresholds vary by stream type, with the "no effect" threshold of 35% ON for C-type channels and 45% ON for B-type channels. Even if WATBAL estimates were accurate, the assumption of "no-effect" thresholds is likely not tenable, for several reasons.

Field research has consistently documented that increases in sediment delivery inexorably lead to increases in fine sediment in channel substrate (Rhodes et al., 1994; Hassan and Church, 2000; Kappesser, 2002). Any increase in fine sediment levels adversely affects salmonid production (Suttle et al., 2004).

Elevated sediment delivery and transport also contribute to the loss of pool volume, depth, and quality through several mechanisms, including increased bed fining and consequent increases in the sedimentation of pools via the sequestering of fine sediments in pools during lower flows (Kappesser, 2002; Buffington et al., 2002). McIntosh et al. (2002) concluded that elevated sediment delivery was one of the primary causes of pool losses documented throughout roaded watersheds in the Snake River basin.

Increased sediment delivery also increases stream width and decreases stream depth in depositional reaches (Richards, 1982). Channel widening and loss of channel depth is associated with reduced pool dimensions (Buffington et al., 2002). Increases in channel width increase summer water temperatures, even in the absence of the loss of stream shade (Beschta et al, 1987; Bartholow, 2001). All of these sediment-related effects significantly reduce the production and survival of salmonids (Meehan, 1991).

These adverse impacts accrue below the thresholds assumed by the CNF for WATBAL estimates of sediment delivery. On Deadman Creek, the WATBAL estimates of sediment delivery averaged less than the assumed "no-effect" threshold of 30% ON from 1985-1992, yet during this same time period fine sediment levels increased in a statistically significant fashion (Rhodes et al. 1994). In Squaw Creek, sediment delivery estimated by WATBAL was less than the assumed "no-effect" threshold of 30% ON at the time of the 1995-1996 storm events that triggered numerous mass failures. In response to the landslides, fine sediments in Squaw Creek underwent a statistically significant increase in cobble embeddedness and surface fine sediment from 1988 to 1998 (Rhodes and Huntington, 2000). This clearly indicates that adverse impacts occur when sediment delivery estimated by WATBAL is well below the assumed "no-effect" thresholds.

Other potential sources of error WATBAL may be a factor in the foregoing. Because WATBAL tends to underestimate sediment delivery, it is likely that actual sediment delivery is often greater than estimated by the model. Hence, in some situations, actual sediment delivery

may be well in excess of assumed “no-effect” thresholds, when WATBAL estimates that sediment delivery is below the threshold.

Studies of the accuracy of WATBAL sediment delivery estimates

Hickey (1997) tested WATBAL accuracy in Pete King and Lolo Creeks on the CNF. Hickey found that WATBAL consistently underestimated measured sediment yield at the mouth of Lolo Creek over nine water years from 1984 to 1994.²⁷ During these nine years, WATBAL estimates of total sediment yield were always less than measured total sediment yield. The difference between measured sediment yield and WATBAL estimates ranged from -0.8 to -65.6 T/mi²/yr,²⁸ with a mean difference of -22.1 T/mi²/yr over nine years (Hickey, 1997).

The differences between WATBAL estimates and measured sediment yield in Pete King Creek exhibited considerably more scatter over 19 water years from 1976 to 1994. WATBAL underestimated sediment yield in Pete King Creek in 9 of these years, but overestimated it in the other 10 years (Hickey, 1997). However, the magnitude of the annual underestimates in Pete King was often much larger than in Lolo Creek. In Pete King Creek, The difference between measured sediment yield and WATBAL estimates ranged from -367.3 to 42.6 T/mi²/yr, with a mean difference of -28.0 T/mi²/yr over 19 years (Hickey, 1997).²⁹ At the watershed scale, the mean annual difference between measured sediment yields and WATBAL estimates was -725.8 T/yr. The largest differences between measured sediment yield and WATBAL estimates in Pete King Creek were in the 1978-79 water year (-133.9 T/mi²/yr) and the 1986-87 water year (-367.3 T/mi²/yr).

These results are consistent with the likely sources of underestimation of sediment delivery in WATBAL identified in this report. As of 1991, about 46.4% of Lolo Creek had been logged or roaded since 1954 (Hickey, 1997). The Lolo Creek watershed has a high road density and much of primary road system parallels streams and is of an older vintage. The watershed has also been subjected to grazing and mining, though these impacts on sediment delivery are believed to be relatively minor in comparison to logging and roads (Espinosa et al., 1997).

WATBAL might have underestimated the sediment yield of Lolo Creek to a greater degree

²⁷ A water year runs from 10/1-9/30. There was one year of data missing from 1984-94, resulting in nine years of data.

²⁸ Throughout this section, the magnitude by which WATBAL underestimated measured sediment yield is designated as a negative number, e.g. the amount is preceded by a minus sign.

²⁹ Hickey (1997) also provided an analysis of the difference between WATBAL estimates and actual sediment yields based on the exclusion of 2 years of data with “catastrophic” sediment delivery from mass failures. The results of this part of Hickey’s analysis is not presented or discussed in this report, because data for years of high sediment delivery should **not** be excluded in tests of WATBAL accuracy. This is because WATBAL’s is structured to incorporate episodic events from mass failures in its annual average estimates of sediment delivery and yield (Cline et al., 1981; Potyondy et al., 1991; King, 1983; Ketcheson et al., 1999; Patten and Jones, 2001). For these reasons, the mean difference between WATBAL and measured sediment yield in these two watersheds provides the best indicator of its biases and accuracy.

if the record had been longer. The entire period analyzed by Hickey in Lolo Creek, 1984-1994, was comprised of drought years on the Boise NF (Ketcheson et al., 1999) and this probably holds for the Lolo Creek area. It is generally acknowledged that WATBAL, and other models of its ilk, are likely to significantly underestimate sediment delivery to the greatest extent during the wettest years (e.g., Hickey, 1997; Ketcheson et al., 1999). Therefore, the results in Hickey (1997) indicate that WATBAL underestimated sediment yield consistently and significantly, even in relatively dry years when it is the least prone to underestimation.

Hickey (1997) estimated that about 36.3% of the Pete King watershed had been disturbed by logging and roads since 1953. The watershed has also been subjected to mining and is grazed (Espinosa et al., 1997). Much of the road system is in close proximity to streams and primarily of an older vintage (Espinosa et al., 1997; CNF, 1999). There is also a high frequency of stream crossings by roads in the watershed (CNF, 1999). These are the very watershed conditions in which WATBAL is likely to consistently underestimate management-induced sediment delivery, and, hence, total sediment delivery. Although the error between WATBAL and measured sediment yields in Pete King Creek exhibited more scatter than in Lolo Creek, the mean difference was larger and negative, indicating that WATBAL, on average, underestimated measured sediment delivery to a greater degree in Pete King than in Lolo.

There are several potential reasons that WATBAL underestimated measured annual sediment yield to a greater degree, on average, in Pete King Creek than in Lolo Creek. Pete King Creek may have greater impacts from grazing and mining impacts. Pete King has higher density of stream crossings by roads (CNF, 1999). Last the period of analysis in Pete King Creek includes some major storm events and is not confined solely to drought years. The record in Lolo Creek was comprised almost solely of drought years (based on extrapolation from Ketcheson et al. (1999)).

Notably, WATBAL would have underestimated sediment yield to greater a degree in Pete King Creek if sediment yield from the 1995-96 water year had been included in the analysis of Hickey (1997). WATBAL estimates for sediment yield would have been in the range of about 20-30% ON (Rhodes et al., 1994), while McClelland et al. (1997) estimated that mass failures, alone, in the absence of surface erosion, increased background sediment yield by about seven-fold or roughly about 700% ON.

The mean accuracy of WATBAL over the period of analysis in both watersheds studied by Hickey (1997) is likely the most important test of WATBAL, because WATBAL, and other models of its ilk, are considered to perform best as estimates of multi-year averages of sediment delivery (Cline et al., 1981; Potyondy et al., 1991; King, 1993; Ketcheson et al., 1999; Patten and Jones, 2005). None of the models based on Cline et al. (1981), including WATBAL, are actually aimed estimating sediment delivery for any given year, but rather average years, based on longer-term estimates (e.g., Potyondy et al., 1991; Patten and Jones, 2005).

Jones and Patten (2006) examined the accuracy of WATBAL in seven watersheds (Table 6), including the two studied by Hickey (1997). These watersheds had differing areas, landforms, and levels of disturbance by past logging and roads. The length of annual sediment yield data for the seven watersheds ranged from 13 to 27 years (Table 6).

Table 6. Watershed attributes, measured mean annual sediment yield, and mean annual sediment yield estimated by WATBAL prior to calibration in study of Jones and Patten, (2006).

Watershed	Area (mi ²)	Road density (mi/mi ²)	Mean measured sediment yield (T/mi ² /yr)	Uncalibrated WATBAL: Mean estimated sediment yield (T/mi ² /yr)	Ratio: mean estimated/mean measured sediment yield	Mean difference: measured minus estimated sediment yield (T/mi ² /yr)	N (yrs)	Ratio: number of years with sediment yield underestimated/ N
Fish Creek	88	0.1	21.9	12	0.55	9.9	14	0.5
Swamp Creek	16	1	19	19.5	1.03	-0.5	15	0.33
Deadman Creek	20	2	28.1	19.1	0.68	9	15	0.6
Elk Creek	35	4	24.3	7.4	0.30	16.9	20	0.95
Pete King Creek	28	5	46.6	29.8	0.64	16.8	27	0.630
Lolo Creek	32	5	27.5	10.3	0.38	17.2	20	0.95
Canyon Creek	20	5	28.9	23.8	0.82	5.1	13	0.461

Jones and Patten (2006) found that WATBAL generally underestimated sediment yield. For all seven watersheds, WATBAL estimates were, on average, only 62.1% of the mean annual measured sediment yields. In six of the seven watersheds, on average, WATBAL significantly underestimated measured sediment yield. In these six watersheds, the ratio of mean estimated sediment yield to measured sediment yield ranged from 0.30 to 0.82 (Table 6). These results generally corroborate the results of Hickey (1997) and are consistent with the sources of underestimation in WATBAL.

Jones and Patten (2006) calibrated WATBAL based on their results. The calibration included: 1) Increasing the mass erosion hazard from “high” (40 T/mi²/yr) to “very high” (80 T/mi²/yr) on five landtypes; 2) increasing the mass and surface erosion coefficients for gneissic granitic and micaceous schist parent materials landtypes; and, 3) increasing the mass and surface erosion coefficients for general granitic parent materials.

The calibration improved overall WATBAL accuracy for the seven watersheds. Post-calibration, on average, WATBAL mean estimates of annual sediment yield were 99% of mean measured annual sediment yield for the seven watersheds over the period of record (Table 7). Linear regression analysis indicated that calibration improved the overall fit of model estimates with measured sediment yield, with an R² value of 0.60. However, post-calibration, WATBAL still underestimated measured sediment yield, on average, in three of the seven watersheds.

Based on this analysis, Jones and Patten (2006) concluded (emphasis added): “The WATBAL-2005 user and land management decision maker **should recognize that the model estimates sediment within a range of 60 percent to 130 percent of long-term measured averages for watersheds similar to the test watersheds.** The model still tends to somewhat under-predict sediment in watersheds with extensive rolling hills and mountain slopeland landforms and over-predict sediment in watersheds with high percentages of breakland landforms.”

While the calibration (Jones and Patten, 2006) improved the accuracy of the WATBAL estimates for the seven watersheds studied, there are several reasons why the calibration may not resolve sources of underestimation of sediment delivery in WATBAL. First, the standard test for the accuracy of model calibrations is to compare them against measurements that were **not** used to develop the calibrations. Jones and Patten (2006) did not test the calibrations to WATBAL in this manner.

Second, it has long been recognized in the field of modeling that there are numerous possible ways to calibrate models, such as WATBAL, that have many coefficients or inputs that can be adjusted. Calibrating just a few of these, as done in Jones and Patten (2006), may not address actual inherent sources of inaccuracy, especially when the calibration is not tested against data that were not used for the calibration.

Because the calibration of Jones and Patten (2006) might not address actual sources of inaccuracy in WATBAL, a very simple independent approach to WATBAL calibration was taken, as described below. This was done to investigate if calibration aimed at addressing inherent sources of inaccuracy in WATBAL might improve estimates to a degree similar to the WATBAL calibration of Jones and Patten (2006).

The independent calibration taken here involved a very simple approach that was **not** iteratively attempted in order to improve the results. As noted previously in this report, it is highly likely that WATBAL basic surface erosion rates for roads are exceedingly low, especially for older roads. Therefore, the independent calibration involved increasing the basic surface erosion rate for roads by 3900 T/mi²/yr in order to bring it closer to the basic surface erosion rate of Cline et al. (1981). This factor was then applied by: a) assuming that the mean width of the roads in all of the watersheds was 20 feet; b) assuming that the mean value for the sediment delivery from roads was 23%; and c) applying it to roads in the watershed, based on the road density data from CNF (1999) and Jones and Patten (2006) for the seven watersheds.

Table 7. Mean measured annual sediment yield and mean annual sediment yield as estimated by: a) WATBAL prior to calibration by Jones and Patten, (2006); b) WATBAL as calibrated by Jones and Patten (2006); and, c) independent calibration of WATBAL via increased surface erosion rate on roads, done as part of this report.

Watershed	Measured sediment yield (T/mi/yr)	Uncalibrated WATBAL: estimated sediment yield (T/mi/yr)	Ratio: Uncalibrated WATBAL estimated sediment yield/ measured sediment yield	Jones and Patten calibrated WATBAL : estimated sediment yield (T/mi/yr)	Ratio: Jones and Patten calibrated WATBAL estimated sediment yield/ measured sediment yield	Road surface erosion calibrated WATBAL : estimated sediment yield (T/mi/yr)	Ratio: Road surface erosion calibrated WATBAL estimated sediment yield/ measured sediment yield
Fish Creek	21.9	12	0.55	22	1.00	13.4	0.61
Swamp Creek	19	19.5	1.03	21.5	1.13	24.9	1.31
Deadman Creek	28.1	19.1	0.68	35.5	1.26	25.9	0.92
Elk Creek	24.3	7.4	0.30	17.8	0.73	21.0	0.86
Pete King Creek	46.6	29.8	0.64	43.4	0.93	43.7	0.94
Lolo Creek	27.5	10.3	0.38	17.6	0.64	25.6	0.93
Canyon Creek	28.9	23.8	0.82	36.1	1.25	40.4	1.40
Mean			0.63		0.99		1.00
R ² - Linear regression of estimated vs. measured sediment yield			0.46		0.60		0.61

Despite the unsophisticated nature of this alternative calibration, it increased the accuracy of WATBAL estimates of annual sediment yield for the seven watersheds to roughly the same degree as that of Jones and Patten (2006) (Table 7). The use of increased surface erosion rates for roads resulted in WATBAL estimates of annual sediment yield that, on average, were 100% of mean measured annual sediment yield for the seven watersheds over the period of record (Table 7). After this simplistic calibration via road erosion rates, WATBAL still underestimated sediment yield, on average, in five of the seven watersheds, but again, the overall accuracy of predictions for the seven watersheds was slightly better than that of Jones and Patten (2006). Linear regression analysis indicated that road surface erosion rate calibration improved the overall fit of model estimates to measured sediment yield, with an R² value of 0.61, slightly higher than that of WATBAL calibration of Jones and Patten (2006).

Because the simplified independent calibration was not verified by testing it against data that had not been used in the calibration, it is uncertain whether this calibration might improve

WATBAL accuracy across many watersheds. However, results of this simplified approach compellingly indicate that there are other ways to tractably calibrate WATBAL besides the route taken by Jones and Patten (2006). These results of the independent calibration indicate that calibrating the model in ways that address likely sources of error in WATBAL, as identified in this report, increase the accuracy of WATBAL to the same degree as the calibration of Jones and Patten (2006) for these seven watersheds.

The analysis of Ketcheson et al. (1999) also provides some indication of the likely accuracy of WATBAL's basic surface erosion rates for roads. Ketcheson et al. (1999) found that over a four-year period, BOISED estimates of surface erosion from three road segments on the BNF were fairly accurate for each year and cumulatively over all four years. BOISED's basic erosion rates for roads are many times greater than those for WATBAL for roads that more than two years old (Table 4). Therefore, this aspect of Ketcheson et al. (1999) indicates that the basic erosion rates for roads that are more than 2 years old in WATBAL are likely low.

Ketcheson et al. (1999) also found that there was fairly good agreement between BOISED estimates of total sediment yield based on mass and surface erosion from roads and measured sediment yield. Although it is more tenuous to extrapolate this to WATBAL, it is consistent with the conclusion that WATBAL's basic surface erosion estimates for roads are a source of its consistent underestimation of sediment yield in roaded watersheds, as documented by Hickey (1997).

Available data on the accuracy of WATBAL (Hickey, 1997) and some of its components (Ketcheson, 1997) corroborate the evaluations in this report, regarding WATBAL. WATBAL's basic surface erosion rates for roads are likely in considerable error. This and other combined error sources cause it to consistently underestimate sediment delivery and yield in significantly disturbed watersheds. This is the case even under climatic conditions that minimize WATBAL's inaccuracy and consistent bias. While the calibration of Jones and Patten (2006) provides a better fit with a calibration data set from seven watersheds, it is uncertain that this improves the model's overall accuracy, because the calibration was not tested against data that were not used in the calibration. It is also uncertain the calibration of Jones and Patten (2006) addresses primary sources of inaccuracy. As shown by this report's independent calibration, increasing in surface erosion rates for roads improves the accuracy of WATBAL to as great a degree as the calibration of Jones and Patten (2006) and may better address likely sources of model inaccuracy.

Description of the water yield component of WATBAL

As with the sediment delivery component of WATBAL, the water yield component is based on a simplification of the complex processes that increase runoff and streamflow in response to land disturbance. WATBAL only estimates changes in annual water yield as affected by the removal of tree canopy by logging, roads, and fire. WATBAL estimates of water yield changes are based solely on the estimate of how canopy removal increases precipitation³⁰ accumulation and snowmelt rates and reduces evapotranspiration. WATBAL completely ignores other impacts that can increase water yield, such as increased surface runoff from soil compaction and reductions in infiltration,

³⁰ Primarily snow.

interception of groundwater at roadcuts, and integration of the channel and road network. Similarly, WATBAL ignores the effects of mining and grazing on changes in water yield.

WATBAL does not estimate peakflows. Instead, WATBAL uses assumptions about the distribution of annual discharge through the year (annual hydrograph) to distribute estimated increases in water yield among the months that typically have the highest monthly flows. A primary assumption is that the all watersheds within a hydrologic region have the similar distribution of flow among months in a year (Patten and Jones, 2005). This distribution of monthly flow amounts is based on mean annual hydrographs that are based on flow records from gages in or near the hydrologic regions that are assumed to be applicable.

The natural annual water yield and mean annual discharge are estimated from a regionalized relationship between runoff and mean precipitation (Patten and Jones, 2005). These methods provide estimates of natural mean annual and mean monthly discharge, Q_{aa} and Q_m , respectively. WATBAL uses the mean annual hydrographs from gauging stations to apportion the mean annual flow among the months of the year as mean monthly flow, Q_m (cfs). This apportionment is also used to identify peak mean monthly flow, Q_{peak} . As part of this distribution of runoff, WATBAL also estimates T_{75} , which is the estimated mean number of days that the estimated mean monthly discharge is greater than 75% of the peak mean monthly flow, Q_{peak} . Ostensibly, this is done via an interpolation program in WATBAL.

As part of the estimation of changes in water yield, WATBAL essentially calculates the equivalent clearcut area (ECA) for areas with fairly uniform aspects and elevations as follows:

$$ECA_b = A_r + \sum(A_f * Q) + \sum(A_l * L * Q) \quad (7)$$

where: ECA_b = the ECA within a uniform aspect and elevation range in WATBAL; A_r = the area of roads, including cut, ditches and fill; A_f is burned area of a given vintage within a uniform aspect and elevation range; Q is an assumed recovery factor as function of age of the burned or logged area, based on ECA recovery curves for different forest types, ranging from 1 in the year after fire or logging to zero at the estimated time of complete recovery; A_l = is area logged in a given year within a uniform aspect and elevation range (2); L is percent of the original crown removed times the original crown cover removed by logging,³¹ ranging from 1 to 0. The product of A_f and Q are summed for all ages of burned areas (A_f) for which Q is greater than zero. Likewise, the product of A_l , L , and Q , are summed for all ages of logged areas (A_l) for which Q is greater than zero.

As indicated in equation 7, WATBAL treats an acre of road as equal to an acre of recent clearcut³² with respect to impacts on streamflow. This is the case even though Patten and Jones (p.

³¹ For example, if an area originally had 50% crown cover and 50% of this is removed, WATBAL calculates L as $= 0.50 * 0.50 = 0.25$. Put another way, if the affected area was one acre with an original crown cover 50% with 50% removal of the original crown cover, WATBAL calculates this as 0.25 acre of ECA in the first year of logging.

³² While roads are treated as equivalent to recent clearcuts on a per unit basis with respect to ECA in WATBAL, open roads are not assumed to undergo any recovery over time with respect to their contribution to ECA, unlike logged areas.

22, 2005) note “In fact, roads can **do far more than alter just the transpiration, snow accumulation, and melt rates**. They can alter the **slope hydrology drastically and often greatly lengthen the stream network**. **The result can potentially be increased peak discharge and decreased duration of flow.**” (emphasis added). Nonetheless, WATBAL treats the areas of roads and logging as having equivalent impacts on a per unit area basis and considers only the effects of roads on transpiration, snow accumulation, and melt rates in estimating changes in water yield

WATBAL uses the values of ECAB to estimate changes in the water yield caused by logging and roads via an “f” factor which has different values in four classes of slope aspect (north, northeast, south, west) as a function of elevation and ECA. These estimated changes are summed over the watershed area to provide an estimate of total change in mean annual water yield.

WATBAL algorithms distribute the total change in water yield solely to the months of March-August as a function of elevations and aspects within the watershed (Patten and Jones, 2005). These estimates are used to calculate the annual water yield, as altered by roads, logging, and fires, in terms of mean annual discharge (Q_{aa}), mean monthly discharge (Q_m), the highest mean monthly discharge (Q_{peak}), and the estimated duration of flow greater than 75% of Q_{peak} (T_{75}).

Likely sources of error in the water yield component of WATBAL

As with the sediment delivery component of WATBAL, this report discusses only major sources of inaccuracy that cause consistent bias in terms of cumulative effects assessment and differentiation among alternatives.

Roads and ECA calculations

A significant source of error in WATBAL is that roads and recently logged areas are treated as equivalent in their effect on ECA and runoff. Notably, the WATBAL documentation explicitly acknowledges that this is not the case (Patten and Jones, 2005). There are a numerous studies that document that roads inexorably alter runoff far more pervasively and persistently than logging. Roadcuts intercept subsurface flows during wet periods and convert it to more rapidly moving surface flow which is eventually routed to streams. This conversion of subsurface flows to surface runoff at roadcuts can contribute to increases in peakflows (Jones and Grant, 1996; La Marche and Lettenmaier, 2001). Subsurface flow interception at road cuts appears to be unavoidable, based on the physics of flow in soils at seepage faces (Rhodes et al., 1994). This effect also appears to be more pronounced when roadcuts are below logged areas (La Marche and Lettenmaier, 2001).

Roads drastically lower infiltration rates, typically by more than 90%. This vastly increases the magnitude, duration, and extent of surface runoff in forested environments, which contributes to increase peakflows. As a result, roads generate elevated surface runoff in response to even minor and frequent rain or snowmelt events.

Roads contribute to peakflows by acting as extensions of stream networks (Jones and Grant, 1996; Wemple et al., 1996; Rhodes and Huntington, 2000; Wemple et al., 2001). The road network almost doubled stream density in Squaw Creek on the CNF (Rhodes and Huntington, 2000) as

shown in Figure 5. This indicates that almost half of the existing stream network by length in Squaw Creek is comprised of roads. The connection between roads and streams rapidly shunts road runoff to the stream network (Wemple et al., 1996), contributing to elevated peakflows (Jones and Grant, 1996; La Marche and Lettenmaier, 2001).

Roads affect surface runoff and peakflows persistently. Hydrologic recovery is negligible for as long as roads are used. Even after abandonment, recovery is extremely slow due to the level of hydrologic alteration. The complete recovery of subsurface flow routing may never occur, even with complete road obliteration.

Therefore, WATBAL's treatment of roads and ECA likely underestimates streamflow alteration in watersheds with significant road networks. This also likely contributes to undermining the ability of WATBAL to properly differentiate among land management alternatives with differing amounts of proposed road construction.

Short duration high flows (peakflows)

The WATBAL model outputs are inadequate to disclose the effects of the alternatives and cumulative effects on peakflows and resultant impacts on aquatic resources because the model only estimates changes in the highest **average monthly** flow generated in response to logging, roads, and fire. In research on flow alteration in Northern Idaho, King (1989) clearly concluded that estimates of highest average monthly flows triggered by logging and roads are not adequate for estimating likely changes in channel conditions and sediment transport caused by logging and roads. King (1989) stated:

“...the largest 7 or 8 days of streamflow account for the majority of the bedload movement... Average monthly streamflows are usually not a good index of bedload transport, and ‘changes in average annual monthly peakflows have no meaningful effect on sediment transport’ (Megahan, 1979) and are thus poor indicators of changes in channel-forming flows.”

WATBAL only estimates changes in the average monthly flows that are cited by King (1989) as poor indicators of channel forming flows.

King (1989) also stated (emphasis added):

*“Thus, it is the relatively few **high flow days** that have the potential for shaping the channel. Increases in **short duration high flows** following harvesting and road building are more important in terms of potential channel erosion and bedload transport than increases in longer duration high flows such as the **maximum mean monthly streamflows**... Therefore, increases in short-duration highflows are more important than longer duration highflows in shaping the channel, and any procedure to estimate streamflow responses and set limits on harvesting should focus on these shorter duration highflows.”*

King (1989) noted that even relatively small changes in short duration peakflows in headwater streams have the potential to significantly increase downstream sedimentation, because channel erosion and sediment transport are exponentially affected by streamflow. Dunne et al.

(2001) came to similar conclusions regarding the effect of relatively small increases in peakflows on channel erosion and sediment transport.

WATBAL's estimation of changes in water yield and mean annual and monthly flows from snowmelt is not a surrogate for estimating the effects on shorter-duration peakflows. This is because roads and logging cause larger percent increases in short-duration peakflows than in annual water yield in areas where snowmelt is the primary source of peakflows, as is the case on the CNF.

WATBAL is unable to estimate changes in short duration high flows, such as instantaneous peakflow, or even the highest mean daily peakflow. Therefore, it is clear that WATBAL is incapable of estimating changes in the most important streamflow attributes with respect to the alteration of channels, sediment transport, and salmonid habitat. King (1989) plainly indicates that WATBAL's estimates of effects on average monthly peakflows are inadequate for determining the effects of the alternatives and cumulative effects on peakflows and resultant impacts on channel erosion, bedload transport, sedimentation, bank erosion, and fish habitat. WATBAL focuses on changes in relatively unimportant and insensitive flow attributes and ignores changes streamflow attributes that are the most ecologically important—short duration high flows, such as the instantaneous or highest mean daily peakflows.

Rain-on-snow events and processes

Rain-on-snow events generate the highest peakflows on the CNF. The highest maximum instantaneous and maximum daily flows in northern Idaho are usually caused by rain-on-snow events (King, 1989). These events also generate the most mass failures in managed watersheds on the CNF, as documented by several studies (Megahan et al. 1978; Pipp et al., 1997; McClelland et al., 1997). Research on the hydrologic alteration by logging and roads has conclusively demonstrated that vegetation removal in areas affected by rain-on-snow events increases accumulation, melt, and runoff (MacDonald and Ritland, 1989; Bowling et al, 2000; La Marche and Lettenmaier 2001).

However, WATBAL does not include rain-on-snow events in its estimates of the effects of logging, roads, and fire on water yield and mean annual and monthly flows. In fact, the major rain-on-snow events on the CNF that cause the greatest stream and watershed damage typically occur between October and March, as they did in 1995-96 (Pipp et al., 1997). WATBAL does not estimate changes in streamflows from October-February. Instead, it apportions all estimated changes in water yield and monthly flows to the period from March-August. Plainly, this causes WATBAL to ignore likely effects on streamflows generated by rain-on-snow events.

For these reasons, WATBAL's water yield estimates do not address the effects of logging and roads on one of the most important processes that generate peakflows: rain-on-snow. This likely causes WATBAL to considerably underestimate the cumulative effects of roads and logging on peakflows.

Grazing

Grazing severely compacts soils and decreases infiltration rates. Both of these effects can

increase surface runoff and peakflows. The effects are not trivial. Based on the data of Kauffman et al. (2004), soil compaction from grazing reduces the water storage capacity of soils by 836,000 cubic feet per square mile of affected area. This loss of water storage capacity likely contributes to peakflows. Kauffman also found that infiltration rates in grazed areas were only 8-30% of rates measured in areas that had not been grazed for about 9-18 years in riparian areas in Central Oregon (Kauffman et al., 2004). WATBAL likely underestimates changes in peakflow in watersheds subjected to grazing because it not only ignores grazing, but ignores all changes in peakflow caused by the effects of increased soil compaction.

Studies of the accuracy of WATBAL's water yield component

King (1989) tested the accuracy of WATBAL's methods for estimating changes in water yield in 11 small watersheds that had been roaded and logged on the Nez Perce National Forest, just south of the CNF. He found that the WATBAL method consistently underestimated changes in water yield caused by roads and logging. WATBAL's methods underestimated the measured increase in water yield by about 38%-116% (King, 1989). Based on these results, King (1989) recommended that the water yield method be revised to increase estimated changes in water yield from logging in northern Idaho, especially in the 4,000-6,000 foot elevation zone.

King's (1989) work indicates that WATBAL systematically underestimates changes in water yield from roaded and logged watersheds. This likely causes WATBAL to underestimate the cumulative effects of logging and roads on water yield and streamflows.

As discussed, King (1989) also demonstrated another major limitation in WATBAL: its failure to account for how logging and roads affect peakflows generated by rain-on-snow events. King found that logging and roads had a pronounced effect on peakflows. For every 10 acres cleared there was an increase in instantaneous peakflows and maximum daily flows of 0.2 and 0.3 cfs, respectively (King, 1989). Based on these results, King noted that limits on the total amount of logging and roads that were aimed at avoiding adverse increases in water yield based on WATBAL methods may not be adequate to avoid adverse increases in peakflows and resulting negative impacts on aquatic resources.

Conclusions and recommendations

There are several aspects of WATBAL that likely cause it to consistently underestimate sediment delivery and peakflow alteration from land use activities and their cumulative effects on water quality, salmonids, and other aquatic resources. These model aspects also likely cause it to inadequately differentiate among alternatives with differing levels of logging and the construction, reconstruction, use of landings and roads with respect to their impacts on aquatic systems. These model features include:

- Assumed surface erosion rates over time for roads, especially for older roads and those that are reconstructed or subjected to elevated use.
- Assumed coefficients of sediment delivery, especially in watersheds with road networks in relatively close proximity to streams and with a high degree of road-

stream connectivity.

- Assumed reduction in the effects of “ridgetop” roads on sediment delivery, without any compensatory increase in sediment delivery from sediment producing activities that are in close proximity to streams.
- Failure to factor in surface and mass erosion from landings.
- Inability to consider elevated channel erosion in response to increases in peakflows.
- Allowance to use assumed levels of mitigation that are not derived from adequate monitoring of quantitative mitigation effectiveness.
- Inability estimate erosion and sediment delivery from mining and grazing in watersheds subjected to those land uses.
- Treating the impacts of roads on streamflow alteration as equal to those from logging on a per area basis.
- Inability to estimate changes in short-duration peakflows and those generated by rain-on-snow events.
- Underestimation of changes in water yield in response to logging and roads.

The sediment delivery component of WATBAL has been recently calibrated. While this calibration improved accuracy with respect to the calibration data set, it has not been tested on other data as needed to validate that the calibration has reduced the model’s documented consistent underestimation of sediment delivery. This calibration may not address actual sources of underestimation in WATBAL. Notably, the results of independent simplified calibration in this report (Table 7) provide a compelling case that calibration efforts aimed at likely sources of model inaccuracy also improve model performance.

Based on the previous, there are several recommendations that are likely to aid in reducing bias in WATBAL and improving its ability to help determine cumulative effects and differentiate among the aquatic effects of alternatives in environmental analyses by the CNF. These are:

- Revamp surface erosion rates for roads to better reflect data on the magnitude and persistence of the effects of roads on surface erosion and sediment delivery.
- Collect data on surface erosion from roads in order to improve the basic surface erosion rates for roads in the model.
- Develop adjustments to coefficients of sediment delivery for roads, based on surveys of their hydrologic connectivity with streams at road/stream crossings and other road drainage features.

- Either eliminate the assumed reduction in the effects of “ridgetop” roads on sediment delivery or develop a factor increasing the impact of roads proximate to streams in order to maintain some degree of parity based on the proximity of activities to streams.
- Treat all landings as equivalent to roads in their effects on streamflow alteration and sediment delivery.
- Develop a method to account for elevated channel erosion in response to peakflow elevation.
- Restrict the use of mitigation in the model only to values that have been verified by adequate quantitative monitoring of the effectiveness of mitigation practices; eliminate visual “audits” and “professional judgment” as a basis for assuming quantitative mitigation effectiveness.
- Develop methods to account for erosion and sediment delivery from mining and grazing in watersheds subjected to those land uses.
- Develop a method to better reflect the actual impact of roads on streamflow alteration by increasing the modeled impacts of roads on streamflow alteration relative to logging on a per area basis; this has already been done for other national forests (e.g., Menning et al., 1996).
- Develop methods to estimate changes in short-duration peakflows and those generated by rain-on-snow events in response to logging and roads, based on research data.
- Update the WATBAL methods to reduce or eliminate the underestimation of changes in water yield in response to logging and roads.
- Test the model accuracy continually; model calibrations should be tested on data that were not used in the calibration in order to test their performance.

The identification of the need to revamp, update, and test WATBAL is neither new nor peculiar to this report. Since the dawn of WATBAL and its antecedents, there have been repeated acknowledgments of the need to test and update the model (Cline et al., 1981; Patten, 1989; King, 1993; Patten and Jones, 2005). The latter has not been done until recently, even though its accuracy and bias have been major sources of contention between the CNF and fishery managers for more than a decade. Major components of WATBAL have not been revamped despite research data that have indicated that some model components likely introduce consistent bias in model’s results. While the need to revamp the model is not new, the need has become pressing due to significant decline in the condition of aquatic habitats and fish populations.

Another key recommendation is related to the interpretation of WATBAL. Various assessments have indicated that the model tends to underestimate the effects of land management

activities on sediment yield and flow alteration. However, the most important indication of the limitations of WATBAL is that many important, but degraded, habitats for imperiled salmonids have not recovered despite assumptions that they would, based on additional assumptions regarding the effects of cumulative sediment delivery as estimated via WATBAL. It is, therefore, key that this be factored into all interpretations of WATBAL results and estimates of their impact on critical aquatic resources.

Similarly, it has been noted that WATBAL estimates are likely only plus or minus about 40% of actual levels of sediment yield after recent calibration (Patten and Jones, 2006). It is critical that this also be concretely factored into interpretations of results. The foregoing has sometimes been conflated to infer that WATBAL estimates of changes in sediment delivery that are close to zero can be assumed to be negligible, as done in some environmental analyses (e.g., CNF, 2002). Instead, WATBAL's resolution is such that estimates of zero change in sediment delivery may be due underestimation, such that the likely actual change in sediment delivery is significant, with substantial aquatic impacts that cannot be quickly reversed once realized. Employing this straightforward and necessary context can greatly improve the quality of the disclosure of environmental impacts from land-disturbing activities.

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