This is not a peer-reviewed article.
Pp. 554-559 in Total Maximum Daily Load (TMDL) Environmental Regulations: Proceedings of the March 11-13, 2002 Conference, (Fort Worth, Texas, USA) Publication Date March 11, 2002. ASAE Publication Number 701P0102, ed. Ali Saleh.

Predicting Sediment TMDLs for Forest Conditions with the WEPP Model

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Introduction

Water quality laws require regulatory agencies to identify the beneficial uses streams and rivers, and to determine the pollutants that may impair those uses. The amount of pollutant that can be tolerated for a given beneficial use is the total maximum daily load (TMDL). In forest watersheds, sediment is generally the greatest pollutant. Sediment sources include surface erosion from forested hillslopes and roads, mass failure, and channel erosion.

One of the questions managers are seeking to answer is how to relate forest practices to sediment loads. The purpose of this paper is to present a tool that can predict daily sediment delivery to forest streams, and to discuss the implications of its application.

Forest Sedimentation Processes

In forests, soil erosion occurs from disturbances such as forest roads, timber harvesting, or fire. These disturbances have major affects on both the vegetation and the soil properties. Soil erodibility depends on both the surface cover and the soil texture (Elliot and Hall 1997).

After a fire or operation, forests are highly susceptible to erosion in the following year. They do, however, recover quickly as vegetation regrowth is rapid when smaller plants do not have to compete with trees for sunlight, nutrients, and water. For example, figure 1 shows the reduction in erosion rates following a wildfire in Eastern Oregon dropped about 90 percent the first year, with no erosion observed in year 4 on any of the slopes (Elliot and Robichaud 2001).

Sediment from upland erosion is frequently deposited in stream channels where it may remain for years to decades, slowly moving through the stream system in response to high runoff events (Trimble 1999). Thus, the scale at which sedimentation is measured becomes important. Smaller scales will show large variations in erosion rates as disturbed sites recover, whereas larger watershed scale observations will tend to reflect long-term trends in erosion and transport rates, with large sediment loads associated with infrequent watershed disturbances or flood events.

Roads add a layer of complexity to streams as they may provide a significant amount of sediment to streams the first few years following construction or reconstruction. With age and/or good management practices, sediment delivery from road networks can be reduced to less than ten percent that of newly-constructed roads (Burroughs and King 1989).

Erosion Prediction

Erosion prediction methods are used to evaluate different management practices and control techniques. One of the prediction tools recently developed is the Water Erosion Prediction Project (WEPP; Flanagan and Livingston 1995). WEPP is a physically-based soil erosion model, and is particularly suited to modeling the conditions common in forests. (Elliot and Hall 1997; Elliot et al. 2000).

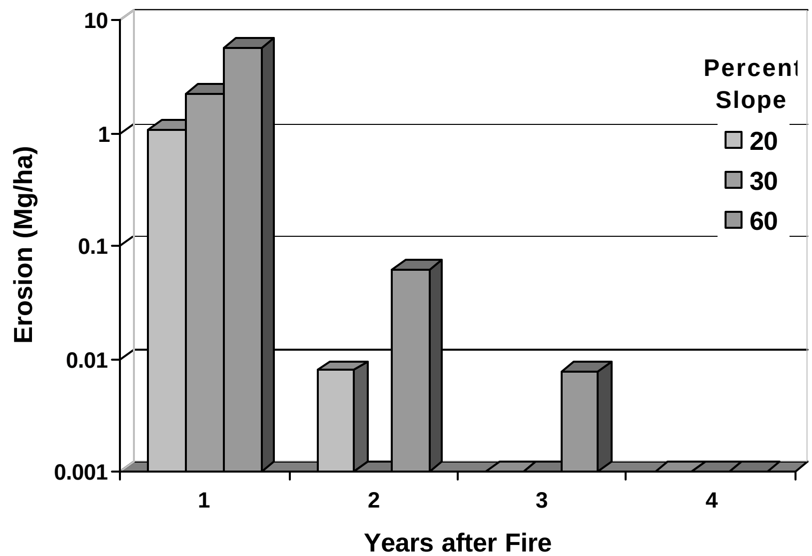

Figure 1. Erosion rates measured following a wildfire in Eastern Oregon. Note log scale on y-axis (Elliot and Robichaud 2001).

A study was carried out with the WEPP model to gain a better understanding of the temporal variability of sediment loads entering streams in forested watersheds (Elliot and Robichaud 2001). WEPP was parameterized to compare erosion rates following wildfire to rates following forest operations, prescribed fire, and road erosion. The study compared two different ecosystems. One was for Montana conditions, with a relatively dry forest, a 40-year fire cycle, an 80-year harvest cycle, 30 percent slopes and tractor logging. The other site was in Oregon with a 200-year fire cycle, a 40-year harvest cycle, 60 percent slopes and a cable logging system.

Figure 2 shows the sediment yields of these two hillslope conditions assuming an average climate. Figure 2a is for the wetter climate in the Oregon Cascade range, and figure 2b for the drier climate in the Bitterroot Mountains in Montana. There are several striking features on these two figures. On both graphs, the vertical axis is logarithmic. The erosion following wildfire is more than 2 magnitudes greater than before the fire, and more than a magnitude greater than following a major forest operation with a buffer. Also, the erosion rate in the Cascades is about two magnitudes greater than the erosion rate in the Bitterroots, even though the difference in precipitation is only about a factor of 2. The majority of the precipitation in the Bitterroots comes as snow, and snowmelt rates (typically 1 mm h^{-1}) are generally much lower than rainfall rates (typically up to 25 mm h^{-1}).

Figure 2 shows the sediment yield values assuming that every year had average weather. The year following a fire or other disturbance may be wetter than normal, increasing sediment yields considerably, or may be drier than normal, so that sediment yields are low to none. Table 1 shows the probability that the sediment yield will be nonzero, the sediment yield for an average year's weather, and the sediment yield that may occur if the year following the disturbance is the wettest year in 5. There is a much greater likelihood that there will be sediment delivered in the Cascade scenario, and sediment delivery rates are much higher.

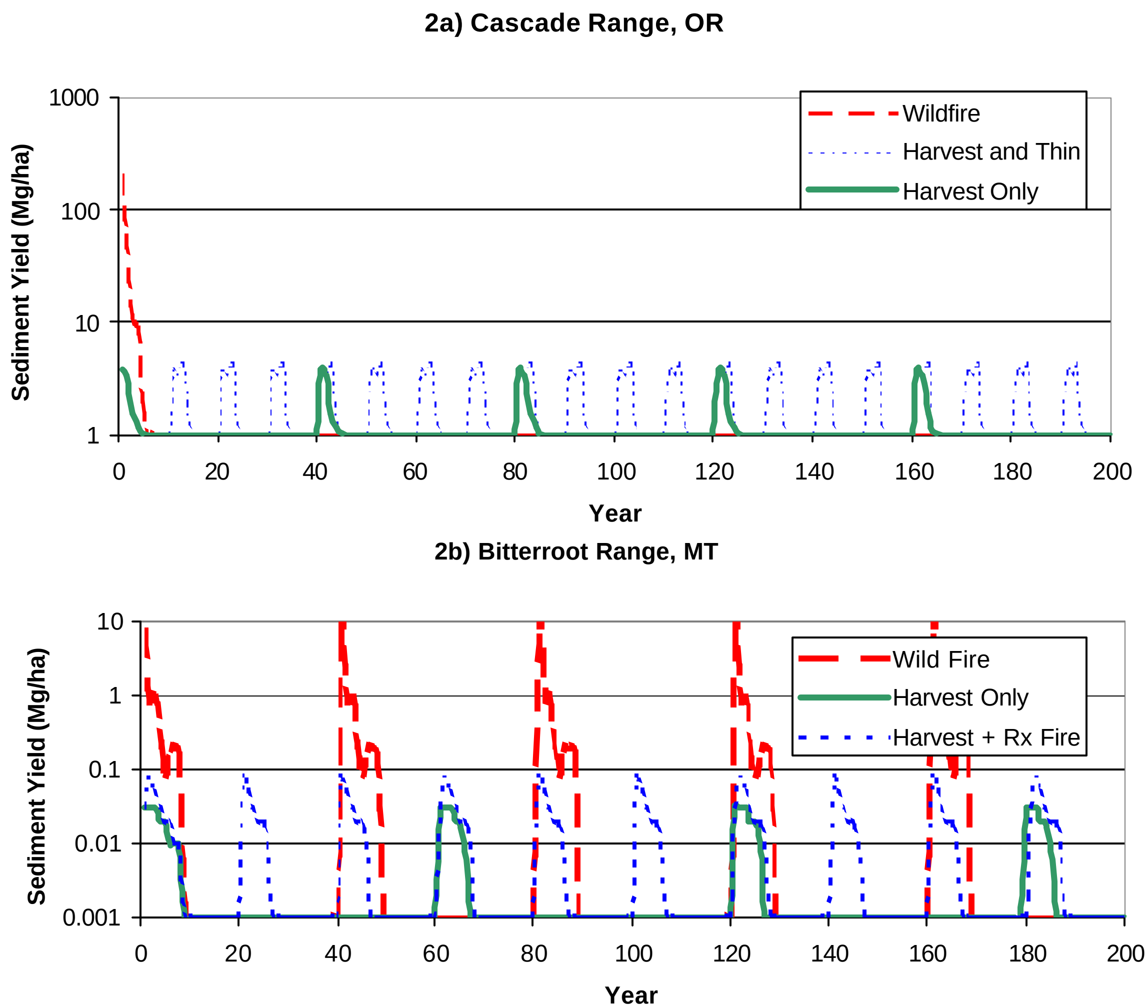

Figure 2. Hillslope sediment yield for an "average" weather pattern versus year for different management conditions for the two scenarios described in Table 3. Note the log scales on the vertical axes, and the difference in scales between the two graphs.

In the Bitterroot Range, the study predicted that there is only an 8 percent chance that there will be any sediment yield in the year following a forest operation. This means that if monitoring is set up to measure sediment yields following a forest operation, there is a 92 percent chance that there will be no observed sediment yield. In the wetter and steeper Cascade Range Scenario, there is an 80 percent chance that there will be sediment delivered across a buffer in the year following the disturbance.

Discussion

Figure 2 and table 1 raise a number of issues for further discussion. Erosion from wildfire is a natural phenomenon, which has driven the development forest ecosystems. Occasional high upland erosion rates and large sediment yields play an important role in shaping landscapes and introducing fresh material into stream systems.

Table 1. Sediment yields the year following a disturbance if the first year has average weather, and if it experiences the most erosive year in 5.

	Bitterroot Range	Cascade Range
Precipitation (mm)		
Average	1548	2816
Greatest in 5 years	1702	3046
Sediment Yield first year after harvest (Mg ha^{-1})		
Probability > 0 (%)	8	80
Average	0.03	4.5
Greatest in 5 years	0.0	9.9
Sediment Yield first year after wildfire (Mg ha^{-1})		
Probability > 0 (%)	100	100
Average	8.1	203.6
Greatest in 5 years	12.6	339.8

One issue arising in figure 2 and table 1 is about the validity of using an average erosion rate. Following a forest disturbance, the overwhelmingly greatest amount of sediment is delivered in the first year, and after several years, the delivery is near zero. The amount of sediment delivered is highly dependent on the climate that first year, as shown in table 1.

Table 2 shows the sediment yield rates presented in figure 2 averaged over the 200-year period. If a manager's goal is to simply reduce the sediment delivery to the stream systems, then the management strategies analyzed may achieve that goal. However, one must also include the erosion from roads, which was not included in this analysis, to estimate the total impact of management activities (Conroy 2001). In a current study, we estimate that typical watershed sediment yields from roads are about 0.4 Mg ha^{-1} in the Cascades and 0.2 Mg ha^{-1} in the Bitterroots, depending on the road network design and level of traffic (Burroughs and King 1989). It appears that roads generate less sediment than wild fire, but greater than harvesting or prescribed fire with a buffer.

An additional modeling study was carried out to look at the variation of loads following individual events. The probabilities of daily sediment loads were predicted from a steep hillslope in the Stanislaus National Forest in California that experienced a severe wildfire in 2001. On the average, there were 2.5 runoff events per year predicted from a forested hillslope, 4.5 events from a harvested hillslope with a 60-m buffer, and 8.5 events from a hillslope that had experienced a high severity fire. Figure 3 shows the distribution of these events for 100 different yearly weather sequences. This demonstrates that disturbances cause more runoff events of greater magnitude than in an undisturbed forest. Note the x-axis is a logarithmic scale. As shown in figure 1, the difference in daily sediment delivery between two natural systems (forested and burned) can easily vary by a factor of a hundred. Figure 3 also shows that there is a likelihood that individual erosion events from an undisturbed forest may exceed erosion from a harvested hillside, and may even exceed erosion following a severe wildfire, depending on the weather the year after the disturbance!

This paper presents the challenge in establishing TMDLs for forested conditions. The natural or background rate appears to be extremely low for a number of years, or even decades. Inevitably, a wild fire will occur, resulting in extremely high sediment delivery values. The longer the time since the last major fire and subsequent erosion event, the lower the background sediment generation rate will appear from watershed sampling. In a similar manner, the longer it is since a

Table 2. Average annual erosion rates over 200 years for the scenarios presented in Figure 2.

	Average annual delivery rate during 200 years (Mg ha^{-1})	
	Bitterroot Range	Cascade Range
Wild fire	0.27	2.4
Harvest Only	0.003	1.15
Harvest with thinning	0.007	1.22
Harvest with prescribed fire	0.011	1.51

road has been constructed in a watershed, the lower the sediment delivery from that road (Burroughs and King 1989). This is further complicated from severe logging or farming operations during the last century, which in some cases generated so much sediment that many rivers are still routing that legacy sediment many decades after the disturbance (Rice et al. 1979; Trimble 1999).

This dynamic variability in sediment generation and routing makes simple TMDL values difficult to establish. The time since the last major disturbance and the severity of that disturbance both influence the sediment loads for many years in forest streams. The sediment load may appear to be well below the TMDL one year, but well above the next, depending on the weather during the year. Erosion may be dominated by only one or two major events in a decade. In preparing figure 3, it was noted that the greatest rainfall events do not necessarily correspond to the greatest sediment delivery rates, nor the greatest sediment concentrations so trying to link weather records to runoff, sediment loads, and sediment concentrations, is not easily accomplished.

It appears that for forested watersheds, regulators may need to consider the past history of a watershed before establishing TMDL values that are achievable. Locally developed watershed models such as WATSED and the Washington Forest Practices may be useful in predicting sediment loads after considering past history. Models such as the WEPP watershed model can

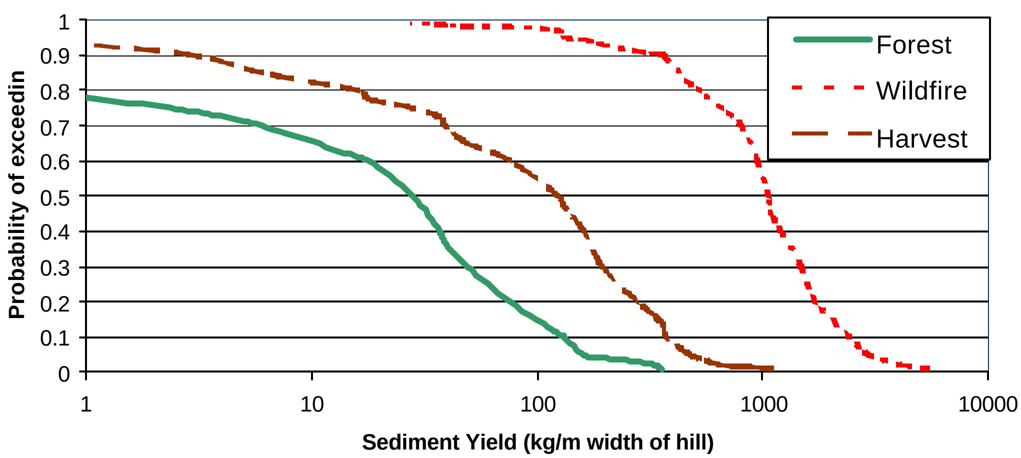

Figure 3. Probability of a runoff event exceeding a given daily sediment yield from a forested hillslope on a 40 percent, 300-m long slope in the Stanislaus National Forest

also assist in developing a picture of the impact of past disturbances on present day sediment loads. Such methods are not simple, but they are likely to be a better approach to developing TMDLs for sediment than simply setting a value based on perceived current levels.

Summary

We used the WEPP model to compare the sediment yields from forested hillslopes following wildfire to sediment yields from the same slopes following forest operations. Sediment yields following forest operations are much lower than following wildfire both the year following the disturbance, and when averaged over two centuries. They are also much lower for daily sediment delivery values and single event sediment concentrations. Because of the large natural variation in sediment yields coming from forested watersheds, establishing a fixed sediment TMDL may not be appropriate.

Conclusions

The following conclusions can be drawn from this paper:

- Sediment delivery following forest operations and prescribed fire with forested buffers are a magnitude or more lower than following wildfire.
- The increased number of disturbances from active forest management result in lower long-term average sediment delivery rates than would occur following less frequent wildfire disturbances.
- It is not appropriate to establish a TMDL without giving due consideration to watershed history, and without providing some consideration for extreme events.

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