Modeling Soil Erosion from Insloping Forest Roads with Impoundment or Surface Cross Drain Structures

ABSTRACT

Soil erosion is one of the key concerns in forest resource management. Human activities often aggravate sediment production and transport, leading to significantly elevated sediment levels in forest streams and adversely impacting stream water quality, channel stability, and aquatic habitat. Presently, the health and viability of fish stocks in the northwest US is becoming a critical issue for the government and the general public. Improvement of our understanding of forest soil erosion is of pressing importance. The main purpose of this study is to evaluate forest road erosion processes using a modeling approach. A refined version of WEPP (Water Erosion Prediction Project), a physically-based, distributed-parameter erosion prediction model, was chosen as the foundation for the modeling effort. A segment of an insloping forest road with an impoundment or surface cross drain structure, together with the roadside ditch channel and a waterway channel below the drainage structure, was conceptualized and modeled as a small watershed. WEPP was applied to simulate gross sediment yield within the watershed and sediment delivery at its outlet. Different road system configurations with respect to the density of the drainage structures along a road and downslope road gradient were examined under climate and soil conditions for a representative forest watershed in Idaho State. Soil erosion and delivery ratios resulting from the two road drainage system designs were compared. In addition, cost analyses based on the standard information about material and labor cost were performed to identify road drainage structure designs that can lead to minimized soil erosion and sediment delivery, while proving economically justifiable. Results from this study show that WEPP is a useful tool in predicting water erosion from insloping forest roads with impoundment or cross drain structures as well as in helping establish optimum road drainage system designs.

INTRODUCTION

Soil erosion is one of the key concerns in forest resource management. Under natural conditions, forest soil erosion rates are regarded low and the resulting sedimentation is negligible (Croke et al., 1999). For disturbed forests, however, sediment production and the subsequent downslope transport aggravated by human activities—road construction in particular—can lead to significantly elevated sediment levels in forest streams, adversely impacting stream water quality, channel stability, and aquatic habitat (Morfin et al., 1996). It has been estimated that 50–90 percent of excess sediment from forest activities originate on the road system (Elliot et al., 1994).

Forest roads may be categorized as outsloping versus insloping. On outsloping roads, water flows across the road surface and along the hillslope without concentrating, whereas on insloping roads, water concentrates in a ditch and then across the road in a surface cross drain (also called a dip) or through an underlain culvert by way of an impoundment (Tysdal et al., 1997). It may be intuitively perceived that, compared to a culvert drainage system, a cross drain structure is a more economically feasible design. For a cross drain, costs are solely required on earthwork, i.e., earth excavation, and no cost on maintenance is needed. For a culvert, costs are required not only on culvert materials and installation, but also on the subsequent regular maintenance, such as excavation of the impoundment system when it is filled in with sediment.

The health and viability of fish stocks in the northwest US is becoming a critical issue for the government and the general public. The recent listing of additional salmon species as threatened or endangered by the National Marine Fisheries Service signifies the urgent need for fish habitat protection. Improvement of our understanding of forest soil erosion in order to adequately assess its environmental impacts is an imperative and pressing task. The main purpose of this study is to evaluate forest road erosion processes using a modeling approach. WEPP (Water Erosion Prediction Project), a computer-implemented, physically-based, distributed-parameter erosion prediction model (Nearing et al., 1989; Laflen et al., 1991, 1997), was chosen as the foundation for the modeling effort.

With both a hillslope and watershed version, WEPP builds on the fundamentals of infiltration theories, plant science, open-channel and impoundment hydraulics, and erosion mechanics. It can be used for routing overland flow and sediment across land surfaces, and for estimating spatial and temporal distributions of soil detachment or deposition on an event, daily, monthly, or annual basis (Flanagan et al., 1995). While the hillslope version of WEPP may be suitable for modeling an outsloping road (Elliot and Hall, 1997), the watershed version of WEPP is needed to better describe the complex topography of an insloping road (Tysdal et al., 1997). Efforts have been made to use the watershed version of the WEPP model in assessment of water erosion from an insloping forest road with culvert and impoundment structures (Tysdal et al., 1997). However, due to several vital flaws in modeling the impoundment structure hydraulics by WEPP, these authors could not successfully execute the WEPP model's impoundment routines. Instead, a culvert channel was replaced by an open channel with negligible erodibility.

The specific objectives of this study are to: (i) apply the watershed version of the WEPP model after refinement to simulate soil erosion from insloping forest roads with culvert or cross drain structures; (ii) compare the erosion predictions for different road system designs in terms of the drainage structure type, density of the drainage structures along a road, and road slope under climate and soil conditions for a representative forest watershed in the northwestern US; and, (iii) perform cost analyses based on standard information about material and labor cost in order to identify road drainage structure designs that can lead to minimized soil erosion and sediment delivery, while proving economically justifiable.

MATERIALS AND METHODS

Refined WEPP Model

Refinement of the impoundment structure hydraulic routines of the WEPP model (watershed version 98.4) has been accomplished by the authors. In the refined WEPP model, a new routine has been added to predict the time when the impoundment structure is filled with sediment, determined by a preset sediment fill-up stage flag. The routine also calculates the total number of times of cleaning and the total sediment volume cleaned out from the impoundment during the entire simulation period.

Road Designs

The Elk Creek Watershed, Elk River, ID, a representative forest watershed in the northwestern US, was identified as the reference site for road design in this study. A field survey was conducted in May, 1999, in the Elk Creek Watershed to obtain information on physical dimensions of road prism components. Based on the field observation and measurements as well as previous studies (Tysdal et al., 1997), a "standard" road design was formed. Fig. 1 illustrates the "standard" road segment conceptualized and modeled as a watershed by the WEPP model. For a road segment with a cross drain, the culvert will be replaced by a cross drain open channel and the impoundment component will not be present. Dimensions of a typical cross drain were determined by referring to an road engineering manual (US Department of Agriculture, Forest Service, 1996). The crucial physical property parameters of the watershed components are listed in Table 1. Note that, for the cutslope, the actual flow length is 4.23 m, and the width of the flow path is 100 m. Additional road designs were then formed by changing road segment length and downslope road gradient, both being important factors affecting forest road erosion (Tysdal et al., 1997).

Table 1. Important physical property parameters of the watershed components in a "standard" road segment.

Parameter	Value
Total area of the watershed (m^2)	1,064
Average annual precipitation (mm)	750.7
Road prism component	
Insloping road hillslope length and width (m)	100; 5
Insloping road hillslope cross and downslope gradients (%)	3; 6
Cutslope hillslope width and length (m)	100; 4.23
Roadside ditch channel length and width (m)	100; 1
Waterway channel length and width (m)	50; 2
Culvert:	
Impoundment depth (m) and volume (m^3)	1; 1.57
Culvert length and diameter (m)	12; 0.31
Cross drain:	
Cross drain channel width (m)	20
Cross drain channel length (m)	5.77
Cross drain channel maximum depth (m)	1

Major WEPP Input Data

Major WEPP input data include watershed structure, climate, soil, management, channel, impoundment, and slope data. To evaluate the long-term effect of different road designs on surface runoff and water erosion from insloping forest roads in the northwest US, a 30-yr climate record was created with CLIGEN, a stochastic climate generator imbedded as a sub-model of WEPP. The climate record was generated for St. Maries, ID (a CLIGEN weather station), approximately 100 km from the Elk Creek Watershed. Fig. 2 shows a 10-year time series of the generated daily precipitation and average temperature. Soil

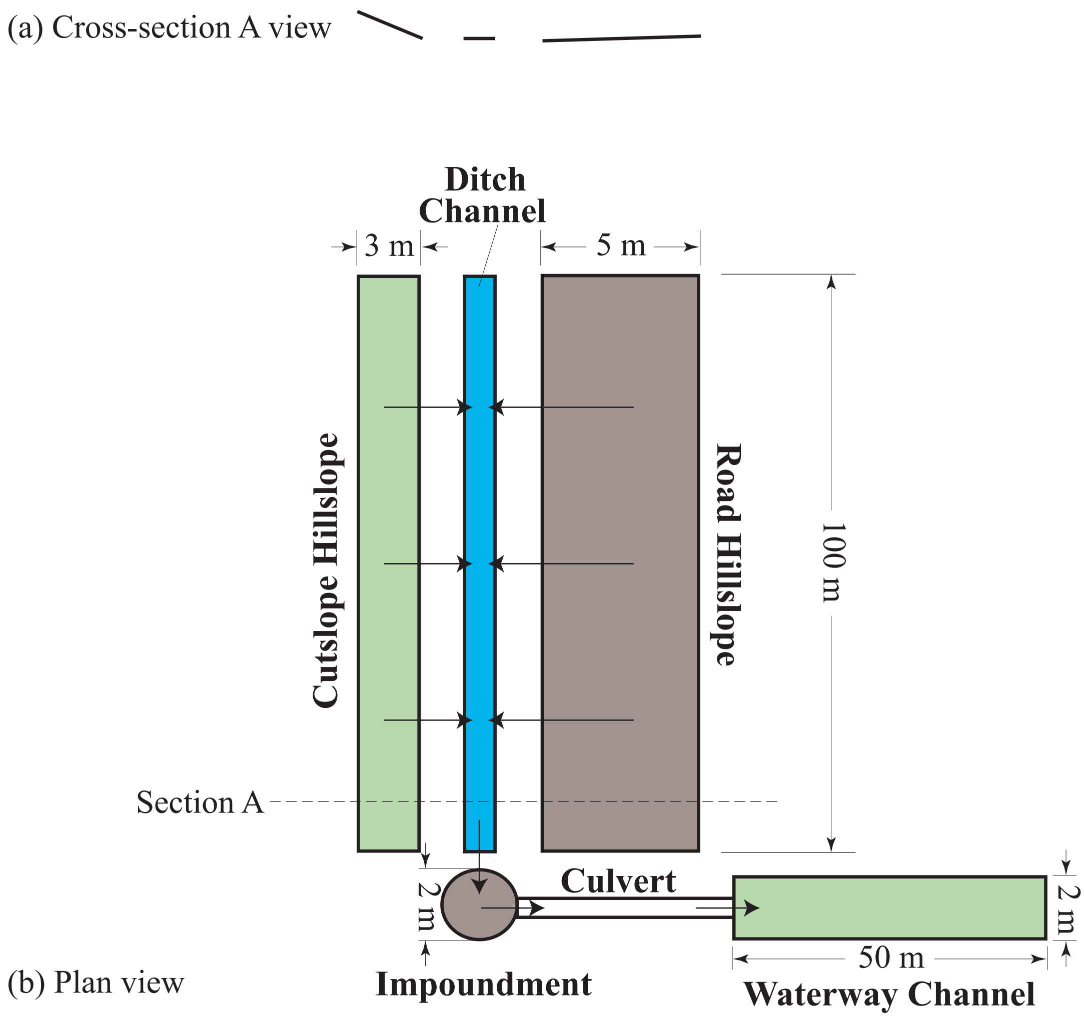

Fig. 1. Diagrams showing the conceptual watershed structure of an insloping forest road segment with an impoundment structure modeled with the watershed version of WEPP. (a) Cross-section view. (b) Plan view. Ditch width of 1 m and culvert diameter of 0.31 m are not shown. For a road segment with a cross drain, the culvert will be replaced by a cross drain channel and the impoundment will not be present.

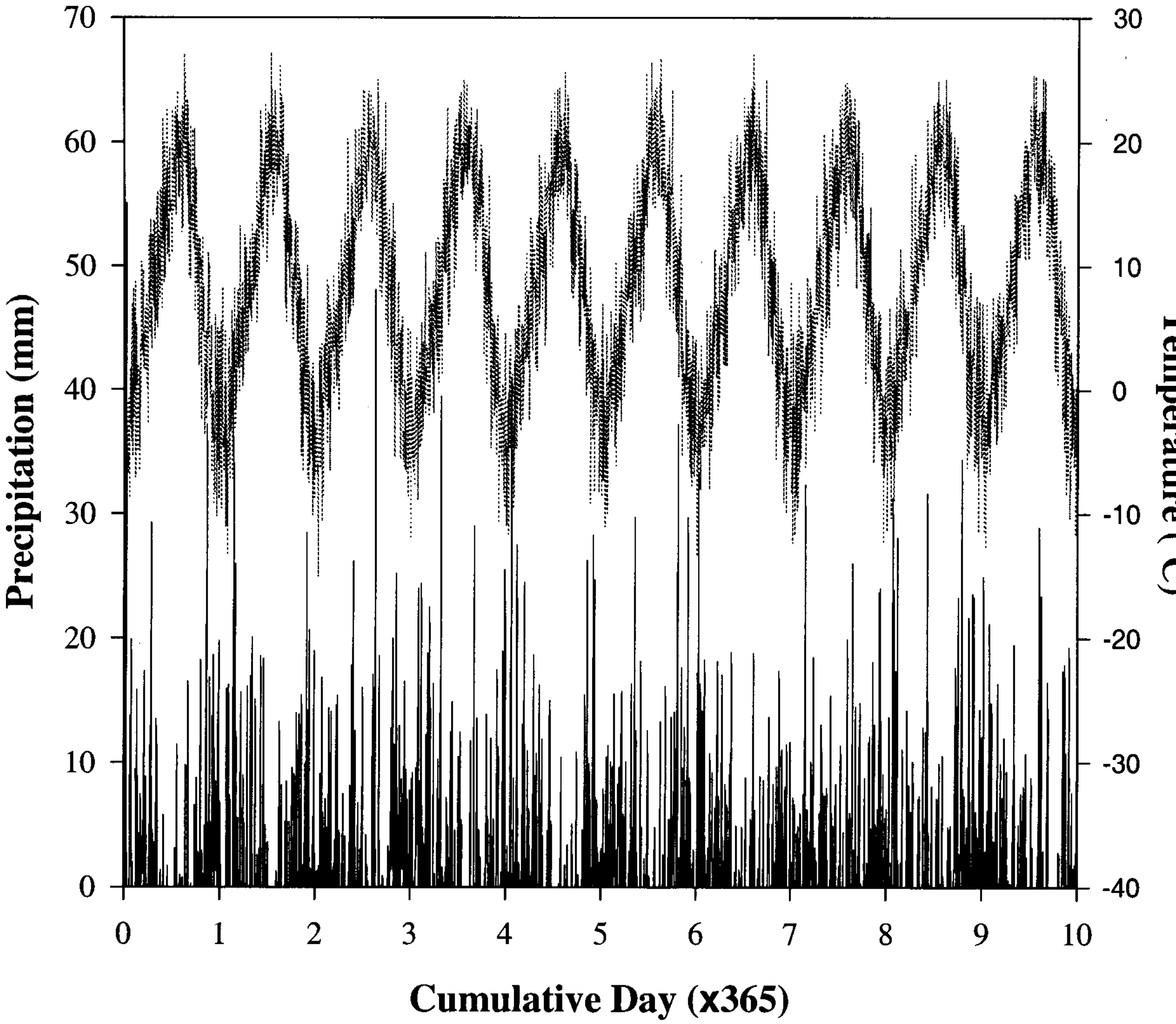

Fig. 2. Stochastically generated time series of daily precipitation and average temperature. The solid lines represent precipitation, and the dotted lines denote temperature.

information for the different road components was extracted from the Forest Soil Database developed by the Rocky Mountain Research Station (RMRS), US Forest Service at Moscow, ID. Management data were determined by referring to previous forest road erosion studies (e.g., Tysdal et al., 1997). Channel, impoundment, and hillslope topographic inputs were created primarily based on the information obtained through the field survey.

WEPP Simulations

A base run using the input files for the "standard" road segment was run for a road segment with a cross drain and culvert, respectively. Additional runs for the various designed road scenarios were then performed. In all these runs, a "graded", instead of "natural", roadside ditch channel condition was assumed to mimic the utmost erosion-pruning conditions. For the simulations with a culvert structure, the bottom stage of the culvert was set to be slightly higher (by 0.001 m) than the bottom stage of the impoundment based on field observation. The sediment stage flag was set as three-quarters of the culvert diameter, and when this sediment level was reached, WEPP was signaled that a cleaning event must take place for the impoundment system. Major outputs from the WEPP simulations included surface runoff, erosion indices, and impoundment cleaning information for the cases with a culvert structure. As the current impoundment routine computes the total volume of sediment removed from only the impoundment throughout the entire simulation period, the volume of sediment accumulated within and removed from the culvert was calculated manually for each case.

Cost Analysis

Basic cost analyses of the insloping forest road drainage designs with impoundment or cross drain structures were performed based on standard information on the costs of materials, installation, and maintenance of the two structures (US Department of Agriculture, Forest Service, 1998). A 1,000-m long road configured as in the 30-year base simulation case (with ten impoundment or nine cross drain structures) was taken as an example. Corrugated metal, most commonly used in practice, was selected as the culvert material. Culverts may also be constructed using plastic or cement materials. The former is less expensive than metal while the latter more expensive. Excavation cost of approximately $2 per cubic meter was determined by considering the reduction in labor cost for Idaho. The cost analysis results were then used, together with the WEPP predicted soil erosion results for the various scenarios, to identify the drainage designs that can minimize the adverse environmental impact while proving economically justifiable.

RESULTS AND DISCUSSION

WEPP simulation results for various road design scenarios are summarized in Tables 2 and 3 and Fig. 3. In all these tables and figure, watershed runoff refers to the volumetric water flow exiting the watershed outlet, gross sediment yield represents the total erosion occurring within the watershed, watershed sediment discharge is the sediment that leaves the watershed, and delivery ratio is the ratio of the watershed sediment discharge to gross sediment yield.

Tables 2 and 3 present the comparison of the WEPP simulated 30-year total values of surface runoff and soil erosion for a road segment with a culvert or cross drain structure for varying road segment lengths and downslope gradients, respectively. It can be seen that, in general, increased road segment length and downslope gradient lead to more surface runoff

Table 2. WEPP simulation results for a road segment with a culvert or cross drain structure for varying road segment lengths. Reported values are the totals for the 30-year simulation period.

Simulation scenario	1		2 (base run)		3		4	
Road segment length (m)	50		100		150		200	
	Culvert	Cross drain	Culvert	Cross drain	Culvert	Cross drain	Culvert	Cross drain
Watershed area (m^2)	552	668	1,064	1,180[†]	1,576	1,692	2,089	2,204
Watershed runoff (m^3)	2.0	37.0	95.9	169.1	216.6	308.9	361.0	494.9
Gross sediment yield (kg)	2,244	2,360	4,929	5,166	7,926	8,226	11,977	12,667
Watershed sediment discharge (kg)	267	840	2,346	3,549	4,938	6,252	7,761	10,488
Delivery ratio	0.119	0.356	0.476	0.687	0.623	0.760	0.648	0.828
Sediment delivery per unit watershed area (kg/m^2)	0.5	1.3	2.2	3.0	3.1	3.7	3.7	4.8
Impoundment sediment stage flag (m)	0.23	--[‡]	0.23	--	0.23	--	0.23	--
Number of impoundment cleaning	2	--	5	--	7	--	11	--
Sediment removed from impoundment (m^3)	0.172	--	0.428	--	0.598	--	0.964	--
Sediment removed from culvert (m^3)	1.441	--	3.595	--	5.023	--	7.993	--

[†] The difference between the watershed area values for the respective culvert and cross drain cases is attributed to the additional cross drain area of $20 \times 5.77 = 116$ (m^2).
[‡] not applicable.

Table 3. WEPP simulation results for a road segment with a culvert or cross drain structure for varying downslope road gradients. Reported values are the totals for the 30-year simulation period.

Simulation scenario	1		2		3 (base run)		4		5	
Downslope road gradient (%)	3.0		4.5		6.0		7.5		9.0	
	Culvert	Cross drain	Culvert	Cross drain	Culvert	Cross drain	Culvert	Cross drain	Culvert	Cross drain
Watershed area (m^2)	1,064	1,180	1,064	1,180	1,064	1,180	1,064	1,180	1,064	1,180
Watershed runoff (m^3)	93.8	165.3	94.8	166.9	95.9	169.1	97.1	171.2	98.3	173.3
Gross sediment yield (kg)	3,091	3,311	3,948	4,142	4,929	5,166	6,000	6,193	10,196	9,157
Watershed sediment discharge (kg)	1,533	2,394	1,974	2,916	2,346	3,549	2,616	4,230	3,426	5,256
Delivery ratio	0.496	0.723	0.500	0.704	0.476	0.687	0.436	0.683	0.336	0.574
Sediment delivery per unit watershed area (kg/m^2)	1.4	2.0	1.9	2.5	2.2	3.0	2.5	3.6	3.2	4.5
Impoundment sediment stage flag (m)	0.23	--[†]	0.23	--	0.23	--	0.23	--	0.23	--
Number of impoundment cleaning	3	--	3	--	5	--	6	--	10	--
Sediment removed from impoundment (m^3)	0.263	--	0.254	--	0.428	--	0.526	--	0.879	--
Sediment removed from culvert (m^3)	2.181	--	2.142	--	3.595	--	4.361	--	7.278	--

[†] not applicable.

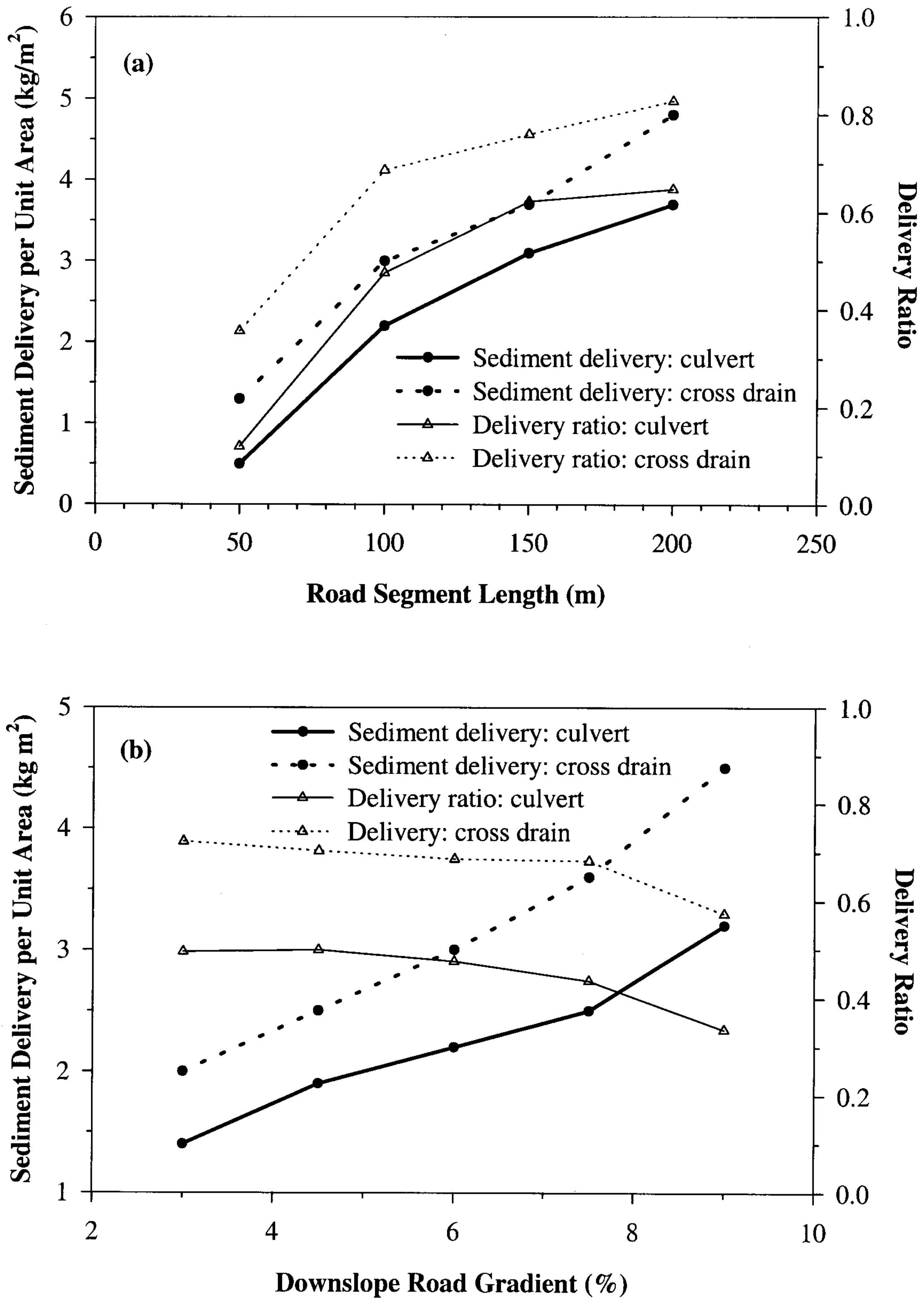

Fig. 3. WEPP simulated sediment discharge per unit watershed area and delivery ratio as affected by (a) road segment length and (b) downslope road gradient for the culvert and cross drain simulation cases, respectively.

and higher sediment delivery rate, with the impact of the latter factor being much less significant on surface runoff, which confirms the findings from the study by Tysdal et al. (1997). For the simulations with an impoundment structure, the WEPP predicted cleaning frequency and total sediment removed range from two to eleven times and 1.61 to 8.96 m^3, for a 30-year simulation period. The extreme cleaning conditions were predicted for the cases with 50-m (shortest) and 200-m (longest) road segment lengths, respectively. In general, cleaning of once every five years is practical, and the bulk volume of cleaning of no more than 1 m^3 should pose no difficulty (William Elliot, personal communication, 1999). Following this rule, a road segment with a length no less than 100 m and a steepness smaller than 6% would be a feasible design. Compared to a road segment with an impoundment structure, a road segment with a cross drain structure produces substantially higher surface runoff, gross sediment yield, watershed sediment discharge, delivery ratio and sediment delivery per unit watershed area.

Fig. 3 depicts the values of sediment discharge per unit watershed area and watershed delivery ratio as affected by road segment length and downslope gradient. Increasing road segment length increases sediment delivery per unit watershed area as well as delivery ratio, following a nonlinear relationship. Although increasing road steepness tends to decrease delivery ratio, the resulting sediment delivery per unit area still increases, following a nearly linear relationship.

The cost analysis results are summarized in Table 4. Clearly, the use of impoundment structures for insloping forest road drainage leads to significantly higher costs than the use of cross drain structures. For a typical road with an drainage structure every 100 m, using the impoundment system will cost about $1,550. When taking into consideration both the economic and environmental impacts of the two types of forest road drainage system, we regard the following designs as acceptable, which lead to moderate erosion and acceptable cleaning frequency while proving economically justifiable: road segment length 100 m, downslope road gradient 3–6%, with impoundment structures; or, road segment length 50 m, downslope road gradient 3–6%, with cross drain structures; or road segment length 100 m, downslope road gradient less than 4.5%.

SUMMARY

The watershed version of the WEPP model after refinement was used to simulate soil erosion from insloping forest roads with impoundment or surface cross drain structures. A set of input data were prepared for a representative forest watershed in central Idaho. The simulation results show that increased road segment length and downslope gradient both tend to increase surface runoff and soil erosion, though the effect of the latter factor is much less significant on surface runoff. Compared to roads with impoundment structures, roads with cross drain systems produce substantially higher surface runoff, gross sediment yield, watershed sediment discharge, delivery ratio and sediment delivery per unit watershed area. For typical road with an impoundment structure per 100 m and with a downslope gradient of 6%, WEPP predicted cleaning frequency and total sediment removed of 5 times and about 4 cubic meters, respectively, for a 30-year simulation period, which is regarded acceptable in practice. The cost analysis of the two types of insloping forest road drainage system indicates that the use of impoundment structures leads to significantly higher costs than the use of cross drain structures. However, if both the economic and environmental impacts are taken into consideration, either impoundment or cross drain structures for insloping forest road drainage may be regarded as acceptable, under certain constraints of road conditions.

Table 4. Comparison of estimated costs for insloping forest road with impoundment or cross drain structures. Assume a 1,000-m long road configured as in the base run cases.

Cost	Impoundment structure	Cross drain structure
Materials	\$212×10=\$2,120	none
Installation	\$29×10=\$290	\$2×57.7×9=\$963
Maintenance	\$2×5×10=\$100[†]	none
Total	\$2,510	\$963

[†] Five times of impoundment system cleaning of a total volume of about 4 m^3 were predicted for a 30-year period. Assume 0.8 m^3 was cleaned each time at an excavation cost of \$2 for each cubic meter or less.

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