PREDICTING SEDIMENTATION FROM FOREST ROADS

The water erosion prediction project (WEPP) model was run to predict sedimentation from forest roads for more than 50,000 combinations of distance between cross drains, road gradient, soil texture, distance from stream, steepness of the buffer between the road and the stream, and climate. The results of these WEPP runs can be viewed through computer interfaces developed for both Windows and the Internet. They offer natural resource managers a way to estimate road sediment yields quickly for a wide range of conditions. The programs are fast, simple to use, and a significant improvement over most current methods that estimate road sediment yields to streams.

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Most sedimentation in forest watersheds is caused primarily by roads and consequent surface erosion and mass failure. Practices to control sedimentation from roads are well known and have been incorporated into road designs for many years (for example, see Packer and Christensen 1977). Such guidelines, however, merely provide estimates of percentage of sediment reduction at best, and their application is limited to the soil and climate for which each was developed. Forest planners often want to know the sediment yield from a given length of road but have had no acceptable way to estimate the amount. In some cases, planned forest activities were halted because managers could not predict off-site sedimentation. Now a new computer program, written for nationwide application, can help road and watershed managers quickly and easily predict the amount of sediment entering a stream from a given road segment.

A primary practice in controlling erosion on forest roads is to divert runoff from the road surface or eroding ditch into the forest. A variety of methods can achieve this, including surface cross drains, broad-based dips, and ditch relief culverts. Diversion of overland flow reduces road surface or ditch erosion. Sometimes, these methods are meant to reduce sediment delivery to nearby streams. The runoff from the cross drain is routed over the fill slope and across a buffer area to the stream *(fig. 1).*

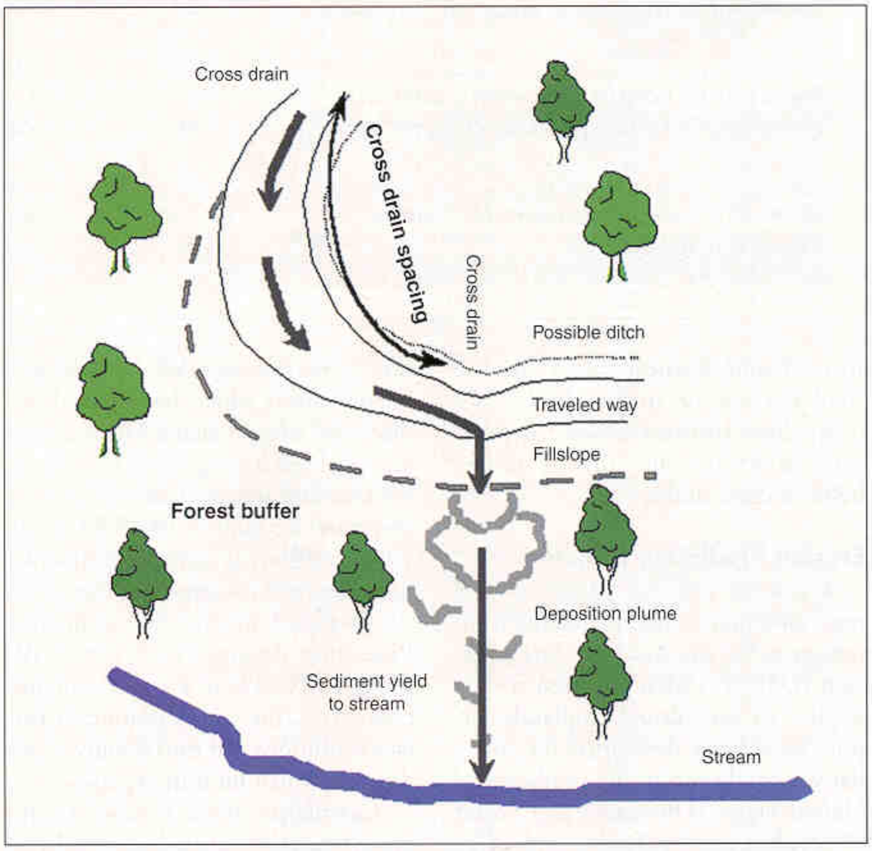

***Figure 1.* Typical forest conditions associated with stream sedimentation caused by road erosion.**

Table 1. Observed and predicted erosion rates and sediment plume lengths below forest roads using the WEPP model (Elliot in prep.).

Site	Erosion rate (tons/acre/year)	Comments
Observed at Zena Creek, Idaho	7.9	Entirely new road cross section.
Predicted for Zena Creek by WEPP:Road	4.5 and 5.4	Assumed 10 percent road gradient; Warren, Idaho, climate.
Observed bare and graveled road in southern Appalachians	5.0–68	
Predicted for southern Appalachians by WEPP:Road	6.8–83	Road dimensions from publications; Cullowhee, North Carolina, climate.
Observed for Alum Creek, Arkansas	6.8–33.7	Vegetated fill slope and ditch.
Predicted for Alum Creek, Arkansas	19–49	Assumed crowned road and two ditches.
Observed bare and gravelled road for Fernow National Forest, West Virginia	6.0–52.5	
Predicted for Fernow National Forest, West Virginia	16–37	Road dimensions from publication; Clarksburg, West Virginia, climate.

Site	Sediment plume length (feet)	Comments
Observed on Silver Creek watershed, Idaho		
Cross drain	35–602	Mean = 163
Below fill	1.3–217	Mean = 12.5
Observed in Nez Perce National Forest, Idaho		
Below culverts	<78	80 percent of sediment plumes were less than mean of 78 feet.
Predicted for Silver Creek		
Cross drain	101	Assumed road gradient of 10 percent;
Below fill	0	Deadwood Dam, Idaho, climate.
Local model for Wine Springs watershed, North Carolina	74	Published model: $L = 5.1 + 0.00197 M$, where L = length in meters and M = predicted sediment yield from road (9,979 kilograms).
Recommended forest filter strip width in Southeast	85	Published model: 43 + 1.4 × percent slope.
Predicted for Wine Springs watershed, North Carolina	118	Cullowhee, North Carolina, climate; 330-foot road length, 10 percent gradient, 30 percent buffer gradient.
Observed in Tuskegee National Forest, Alabama	164–197	August 1997–January 1998.
Predicted for Tuskegee site	131	Opelika, Alabama, climate; 200-foot road, 5 percent gradient, 9 percent buffer gradient.

Runoff and erosion occur on the road surface or inside ditch, and downslope infiltration and deposition occur on the hillside buffer below a cross drain.

Erosion Prediction Models

Universal soil loss equation. The most common erosion prediction technology is the universal soil loss equation (USLE), which has been widely applied to agricultural croplands. Inputs have been developed for forest harvest conditions in the southeastern United States (Dissmeyer and Foster 1981), but not for forest roads. The equation was developed to predict erosion from the eroding part of the hillside; it was not intended to model sediment delivery where downslope deposition was a major factor. The modified universal soil loss equation (MUSLE), which considers surface runoff, was therefore developed (Barfield et al. 1983). Sediment delivery principles have also been incorporated into models proposed by the Environmental Protection Agency (EPA 1992). Although MUSLE is a significant improvement, the wide variation in surface conditions and the inability to address snowmelt limit its accuracy.

Cumulative effects models. An approach to estimating sediment delivery from forest roads was developed in the northwestern United States with a series of watershed cumulative effects models. The variation in erosion and sediment delivery predicted by these models was determined initially from limited field research but often modified for a specific locality by consensus of a group of agency specialists. The WATSED model (USDA-FS 1990) is one of the best known of the cumulative effects models. The most comprehensive cumulative effects method was developed by the Washington Forest Practices Board (1995). These methods help the user estimate a road erosion rate for part or all of a given watershed road network, based on geology, age of road, and factors related to road use. The erosion rate is then adjusted for delivery, and the resulting sediment yield is calculated. Results from these methods are generally reasonable and have been validated for the geology and climate for which they were developed, but they lose accuracy rapidly for other locations.

WEPP. The water erosion prediction project (WEPP) model (Flanagan and Livingston 1995; Laflen et al. 1997) is a physically based soil erosion model that can estimate soil erosion and sediment yield considering the soil, climate, ground cover, and topographic conditions of a site. WEPP simulates the daily conditions that affect erosion, including the amount of vegetation canopy, the surface residue, and the soil water content. For each day of precipitation or snowmelt, WEPP determines whether it is rain or snow and calculates the appropriate infiltration and runoff. If there is runoff, WEPP routes it over the surface, calculating erosion or deposition rates for at least 100 points on the hillslope. It then calculates the average annual sediment yield from the slope. The model has been validated for numerous conditions, including forest roads (Elliot et al. 1994, 1995; Tysdal et al. 1997). *Table 1* compares WEPP predictions with observed road erosion rates for sites throughout the United States.

Included in the WEPP technology is the CLIGEN stochastic weather generator. CLIGEN generates a daily climate for any length of simulation

Table 2. Soil and topography conditions in X-DRAIN program.

Variable	Values
Spacing of cross drains	30, 70, 130, 200, and 330 feet
Road gradient	2, 4, 8, and 16 percent
Length of forest buffer between road and stream	30, 130, 260, and 660 feet
Steepness of forest buffer	4, 10, 25, and 60 percent
Soil classifications (see *tables 4, 5*)	Clay loam, silt loam, sandy loam, gravelly loam, and gravelly sand

Table 3. Details of climate stations used in the study.

State	Location	Precipitation	Latitude	Longitude	Elevation	Record
Alabama	Birmingham	1,391.8 mm	33.57°N	86.75°W	185 m	62 years
Alaska	Juneau	1,336.1	58.37	134.58	3	43
Arizona	Heber	318.4	34.38	110.58	2,029	42
Arkansas	Clarksville	1,239.1	35.47	93.47	134	39
California	Alturas	306.8	41.50	120.53	1,359	61
	Glenville	494.0	35.72	118.70	954	41
	Willits	1,282.2	39.42	123.33	411	32
Colorado	Eagle	282.4	39.63	106.92	1,981	44
Idaho	Deadwood Dam	822.7	44.32	115.63	1,639	47
	Wallace	922.7	47.50	115.88	899	44
Kentucky	Heidelberg	1,165.2	37.55	83.77	201	60
Louisiana	Ruston	1,391.8	32.52	92.68	85	62
Michigan	Watersmeet	758.8	46.28	89.17	490	44
Missouri	Salem	1,108.4	37.63	91.55	365	74
Montana	Libby	454.6	48.40	115.53	633	84
	Seeley	544.9	47.22	113.52	1,228	44
Nevada	Tuscarora	301.8	41.42	116.23	185	33
New Hampshire	Lancaster	879.9	44.46	71.57	268	42
New Mexico	Taos	327.1	36.42	105.57	2,127	44
North Carolina	Cullowhee	1,279.6	35.32	83.18	640	44
Ohio	New Lexington	1,009.6	39.73	82.22	271	50
Oregon	Austin	517.5	44.58	118.50	1,283	44
	North Bend	1,611.3	43.42	124.25	3	61
	Wickiup	553.9	43.68	121.70	1,319	41
Pennsylvania	Ridgway	1,053.7	41.43	78.73	417	66
South Dakota	Fort Meade	497.1	44.40	103.47	1,005	43
Texas	Lufkin	1,141.4	31.47	94.72	88	85
Utah	Heber	418.8	40.50	111.42	1,703	64
Washington	Colville	470.2	48.53	117.87	566	40
	Packwood	1,351.3	46.62	121.67	323	42
	Sappho	1,935.1	48.07	124.12	231	44
West Virginia	Lewisburg	934.7	37.80	80.43	685	44
Wyoming	Lake Yellowstone	415.5	44.57	110.40	2,356	44

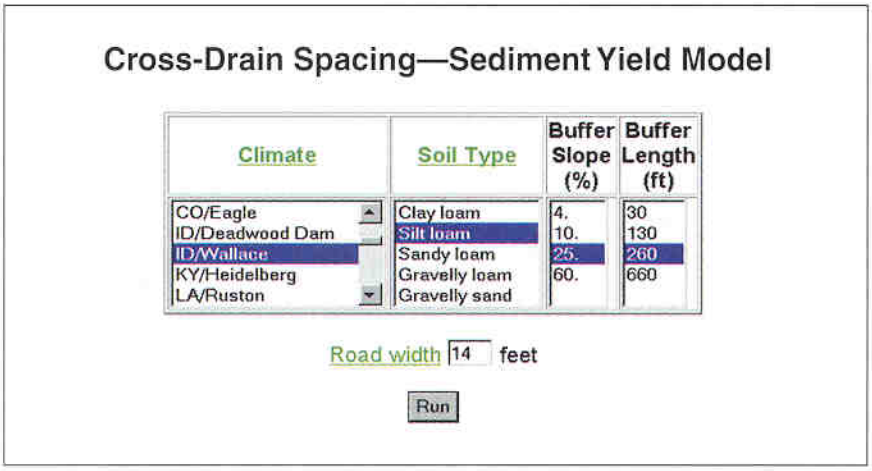

Figure 2. **X-DRAIN website input screen.**

from one to 999 years, based on the statistics from the selected weather station. CLIGEN has a database of more than 1,000 climates spaced at a grid of approximately 60 miles for the entire United States (Flanagan and Livingston 1995).

The Need for Field Applications

During the past four years, more than 120 people have been trained in Forest Service workshops to apply the WEPP model to forest roads and disturbed forest conditions, and Forest Service scientists have offered to help forest managers apply WEPP to local problems (Laflen et al. 1997). Despite these efforts, fewer than 10 percent of the workshop participants have attempted to apply the model. The reasons given for the low use rate have been the users' lack of time to devote to using WEPP and the complexity of the current WEPP interface. WEPP typically requires more than 400 input variables to run. Even though templates have been developed for many agriculture, range, and forest conditions (Flanagan and Livingston 1995; Elliot and Hall 1997), users become discouraged when trying to find and adjust the critical variables to describe a given site.

Regardless, the Forest Service and other agencies need to predict sediment yield from roads. Although WEPP can make the predictions, the current interface is too complex, and other prediction methods are limited in scope. To meet this challenge, we need a new technology that can address site-specific sediment risks and be readily learned and applied by field personnel. One technology that we are developing to meet this challenge is incorporated in the X-DRAIN computer programs.

To make WEPP predictions of sedimentation from roads available for field application, we ran more than 50,000 runs of the WEPP model. We sequentially ran WEPP for each combination of the soil and topography conditions described in *table 2* for a 30-year simulated climate for each location described in *table 3*. The predicted average annual delivery of road sediment from the buffer for each run was stored in a data file. Two programs were developed to access the data: a stand-alone version to run in Windows (X-DRAIN 1997; Elliot et al. 1998) and a version to run over the Forest Service intranet or the internet via the World Wide Web (http://forest.moscowfsl.wsu.edu/4702/crossdrain.html) (XDS 1997).

The X-DRAIN programs have two main screens: an input screen *(fig. 2)* and an output display screen *(fig. 3)*. On the input screen, the user can select the climate, the soil classification, the steepness of the forested buffer between the road and the nearest stream, and the length of the buffer. A road width between 3 and 100 feet is also specified. Both programs can be run with either metric or English units.

On the output screen, the input selections are presented along with a table of sediment yield values, in pounds per foot or kilograms per meter of road length between cross drains for five cross drain spacings and four road gradients. To determine the sediment yield from a road segment with a given gradient and cross drain spacing, multiply the value in the output table by the length of the spacing between cross drains. For example, the output shown in *figure 3* predicts a sediment yield of 0.1 pound per foot for a 200-foot cross drain spacing at a road gradient of 4 percent. The average annual total sediment delivery from the length of road between cross drains would be 0.1 lb/ft × 200 ft = 20 lbs.

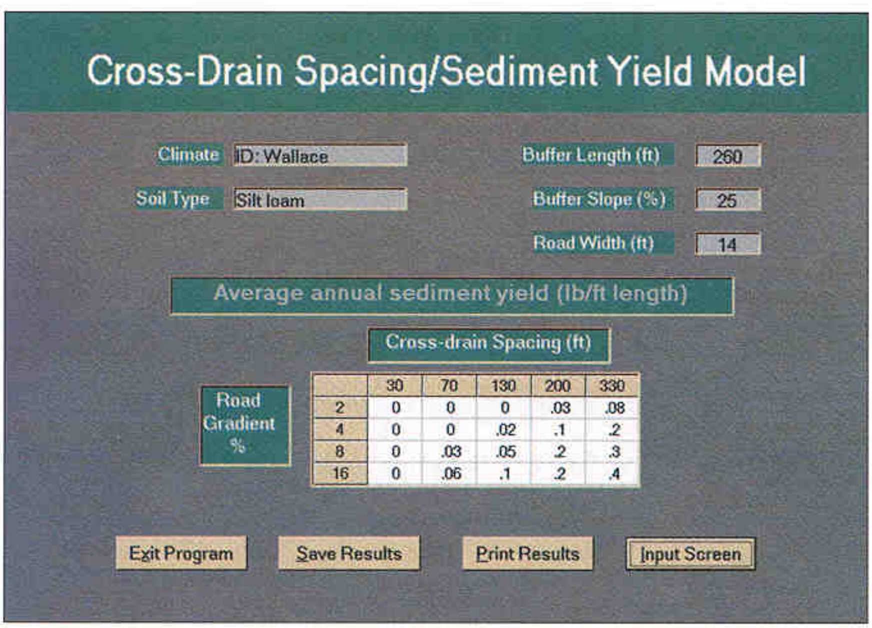

Figure 3. **X-DRAIN standalone output display screen.**

Table 4. Adapting cross drain inputs to model different conditions.

Condition	Cross drain application
Insloping roads	
No ditch treatment, no ruts	Enter width of traveled way plus inside ditch in width box.
Rocked or graveled ditch, no ruts	Enter width of traveled way in width box and select 30 feet for spacing of cross drains.
Ruts and stable ditch	Enter width of traveled way in width box and read output for the spacing of cross drains.
Ruts and eroding ditch	Enter width of traveled way plus ditch in width box, and read output for spacing of cross drains.
Outsloping roads	
No ruts	Enter width of traveled way in width box and select 30 feet for spacing of cross drains.
Ruts	Enter width of road contributing runoff to ruts. Read the results for the observed spacing of cross drains.
Other	
Road with flat traveled way	Enter width of traveled way in width box and read output directly.
Bladed and compacted skid trail	Select appropriate native surface soil and appropriate topographic variables for first year erosion. Subsequent years' sediment loss will decline rapidly as vegetation is reestablished on the skid trail, to near zero by year five.
More complex conditions	Run the WEPP model for the specific conditions.

For conditions between the points modeled, interpolation between results appears valid. It is not advisable, however, to extrapolate outside the region modeled because the relationships are not linear.

Discussion

Each sediment yield value predicted by X-DRAIN is the result of a WEPP run for 30 years of typical climate for the given site. The climate was stochastically generated with the CLIGEN climate generator distributed with the WEPP model. Within those 30 years, there would be a number of large erosion-causing events from precipitation only, snowmelt, or a combination of the two.

In our field research observations, the observed erosion rate varies from the mean by at least 30 percent of the mean within a set of replicated experiments. The minimum observed values are frequently less than half the maximum values (Elliot et al. 1989, 1994, 1995; Tysdal et al. 1997). Differences from one year to the next can be much greater. For example, Foltz (1996) reported erosion rates of 96, 2,892, and 2,544 pounds delivered in consecutive years from the same 0.06-acre road segment in the Oregon Cascades. These differences are attributable to variations in climate, soils, road use and maintenance, and microtopography. Our WEPP validation work has shown that the erosion rates predicted by WEPP generally fall within the range of observed values (Elliot et al. 1994, 1995; Tysdal et al. 1997; Elliot in prep.). Because of the magnitude of natural variability in soil erosion processes, users should not place too much emphasis on small differences between predicted values. Users may wish to present predicted sediment delivery rates as a range rather than a single number to reflect the variability inherent in erosion prediction science, with an expression like 25 to 75 pounds rather than 50 pounds.

The X-DRAIN program predicts only the sediment delivered to the bottom of a hill. *Table 1* and other validation references are generally limited to measuring road surface sediment delivery rates, or lengths of sediment plumes deposited below roads. Other studies are frequently at watershed scale, so it is difficult to distinguish between sediment from road erosion only and sediment from other sources within the watershed. We believe that if WEPP provides reasonable predictions for both road surface erosion rates and sediment plume lengths, as shown in *table 1,* then the amount of sediment delivered to a stream will also be a reasonable value.

The X-DRAIN program is limited to 33 climates *(table 3).* In the central and eastern United States climate varies only slightly over relatively long distances, so the nearest station will likely provide reasonable predictions of sediment yield. In the West, however, there can be major variations in climate with elevation and aspect over a short distance. Users may be able to make good predictions only from lower elevations, where the data were collected. Higher elevations will likely have higher amounts of precipitation, but more of it will fall as snow, which is less erosive. The net effect is not easily predicted.

Small differences in soil properties from those assumed in the X-DRAIN program are unlikely to cause any major differences in road erosion and sediment delivery. In models of forest

Table 5. Categories of common forest soils in relation to cross drain soils.

Cross drain soil	Typical field soils
Clay loam	Native-surface roads on shales and similar decomposing sedimentary rock.
Silt loam	Ash cap native-surface road. Alluvial loess native-surface road.
Sandy loam	Glacial outwash areas. Finer-grained granitics.
Gravelly loam	Cobbly loam soils. Clay or silt loam surfaces that have been graveled.
Gravelly sand	Coarse-grained granitics, and fine-grained granitics that have been graveled.

road erosion, soil properties are overshadowed by surface conditions. A soil of a given texture that has been compacted into a road with an infiltration rate near zero is not likely to differ from one ecoregion to another. In the same manner, the surface cover dominates the erosion properties of a forest soil. Differences due to texture may be plus or minus a factor of about 0.5, whereas differences in soil erodibility properties due to cover can vary by a factor of 25 or more (Robichaud 1996).

For this study we assumed that the runoff water followed the road from one cross drain to the next *(fig. 1)*. This template can be applied to a variety of conditions for a reasonable estimate of sediment yield *(table 4)*. Outsloping roads without wheel ruts generally have an equivalent cross drain spacing of about 7 meters (Foltz 1996), but this figure increases as traffic flattens the cross slope, so cross drains are generally recommended on outsloping roads. If the site template presented in *figure 1* is not adequate to describe the site conditions, then site-specific runs can be made with the WEPP model with the aid of the templates developed by Elliot and Hall (1997). If the road drains directly into a channel, then the cross drain template is not valid. With WEPP, this condition can be modeled as a simple rutted or insloping road, or as a small watershed (Elliot and Hall 1997; Tysdal et al. 1997).

Applications

In a typical application, a planner can estimate the average annual sediment yield from a given road system by determining the sediment yield for each road segment with X-DRAIN after consulting the road design and a site survey or contour map. The road design generally will specify the distance between cross drains, the appropriate surface shape, and the gradient of the road for each segment. The buffer slope and distance to a channel can be determined from a field survey or a contour map. With this information and an appropriate soil type and climate, the sediment yield can be determined for each road segment, and the total sediment yield for the road system can be calculated.

A second application of X-DRAIN is to determine how the spacing of cross drains on any road (including skid trails) affects sediment delivery. The necessary input information is collected, and the output table is studied to determine what spacing will give an acceptable sedimentation rate.

A third application is as an aid to identifying sections of road that are the best candidates for closure or mitigation measures. To evaluate, for example, the effects of one mitigation measure—the application of gravel to a clay or silt loam—the user selects the gravelly loam soil or the gravelly sand soil *(table 5)*.

Other applications of the model are to determine erosion from footpaths or bike trails, by specifying a narrow width, such as 4 feet, or from log landings, parking lots, or similar cleared areas if the surface is in an eroding state and the width is less than 100 feet.

On the Horizon

A forthcoming version of X-DRAIN will include a zero-length buffer to estimate sediment leaving a given road surface or the amount of sediment entering a channel at a stream crossing. An additional cross drain spacing of 660 feet will likely be added to the database.

The X-DRAIN data are being studied to see whether regression relationships can be developed to replace the look-up table, which will let the user enter any topographic value rather than being limited to those that were part of the underlying WEPP runs. If these relationships can be identified, then users may be able to enter exact dimensions rather than interpolate between values given on the output screen.

Interfaces to the WEPP model and its climate generator similar to the X-DRAIN programs are under development for roads and disturbed forests. These new interfaces will allow the user to specify any length and steepness of slope, as well as adapt a climate from the more than 1,000 in the WEPP database. Additional help from the input screens and more information in the outputs will be part of the interface.

Literature Cited

BARFIELD, B.J., R.C. WARNER, and C.T. HAAN. 1983. *Applied hydrology and sedimentology for disturbed areas.* Stillwater, OK: Oklahoma Technical Press.

DISSMEYER, G.E., and G.R. FOSTER. 1981. Estimating the cover-management factor (C) in the universal soil loss equation for forest conditions. *Journal of Soil and Water Conservation* 36(4):235–40.

ELLIOT, W.J. In prep. Roads and other corridors. In *Managing watersheds for municipal water supplies,* ed. G.E. Dissmeyer. Washington, DC: USDA Forest Service.

ELLIOT, W.J., R.B. FOLTZ, and C.H. LUCE. 1995. Validation of the Water Erosion Prediction Project (WEPP) model for low-volume forest roads. In *Proceedings of the Sixth International Conference on Low-Volume Roads,* 178–86. Washington, DC: Transportation Research Board.

ELLIOT, W.J., R.B. FOLTZ, and M.D. REMBOLDT. 1994. Predicting sedimentation from roads at stream crossings with the WEPP model. Presented at the 1994 American Society of Agricultural Engineers International Winter Meeting, Paper No. 947511. St. Joseph, MI: ASAE.

ELLIOT, W. J., S.R. GRAVES, D.E. HALL, and J.E. MOLL. 1998. *The X-DRAIN cross drain spacing and sediment yield model.* Publication No. 9877 1801. San Dimas, CA: USDA Forest Service Technology and Development Center.

ELLIOT, W.J., and D.E. HALL. 1997. *Water Erosion Prediction Project (WEPP) forest applications.* General Technical Report INT-GTR-365. Ogden, UT: USDA Forest Service, Intermountain Research Station.

ELLIOT, W.J., A.M. LIEBENOW, J.M. LAFLEN, and K.D. KOHL. 1989. *A compendium of soil erodibility data from WEPP cropland soil field erodibility experiments, 1987 and 1988.* NSERL Report No. 3. Columbus, OH: Ohio State University; and West Lafayette, IN: USDA Agricultural Research Service.

ENVIRONMENTAL PROTECTION AGENCY (EPA). 1992. *An approach to water resources evaluation on non-point silvicultural sources.* Publication EPA-600/8-80-012. Washington, DC.

FLANAGAN, D.C., and S.J. LIVINGSTON. 1995. *WEPP user summary.* NSERL Report No. 11. West Lafayette, IN: USDA-ARS National Soil Erosion Research Laboratory.

FOLTZ, R.B. 1996. Traffic and no-traffic on an aggregate surfaced road: Sediment production differences. In *Proceedings of the Seminar of Environmentally Sound Forest Roads and Wood Transport,* Sinaia, Romania, June 17–22, 1996, 195–204. Rome: Food and Agriculture Organization of the United Nations.

LAFLEN, J.M., W.J. ELLIOT, D.C. FLANAGAN, C.R. MEYER, and M.A. NEARING. 1997. WEPP: Predicting water erosion using a process-based model. *Journal of the Soil and Water Conservation Society* 52(2):96–102.

PACKER, P.E., and G.F. CHRISTENSEN. 1977. *Guides for controlling sediment from secondary logging roads.* Ogden, UT: USDA Forest Service Intermountain Forest and Range Experiment Station; and Missoula, MT: USDA Forest Service Northern Region.

ROBICHAUD, P.R. 1996. Spatially varied erosion potential from harvested hillslopes after prescribed fire in the interior northwest. PhD thesis, University of Idaho, Moscow.

TYSDAL, L.M., W.J. ELLIOT, C.H. LUCE, and T. BLACK. 1997. *Modeling insloped road erosion processes with the WEPP watershed model.* Presented at the 1997 American Society of Agricultural Engineers Annual International Meeting, Paper No. 975014. St. Joseph, MI: ASAE.

USDA FOREST SERVICE (USDA-FS). 1990. *R1-WATSED Region 1 water and sediment model.* Missoula, MT: USDA Forest Service, Region 1.

WASHINGTON FOREST PRACTICES BOARD. 1995. Standard methodology for conducting watershed analysis, Version 3. Olympia, WA: Department of Natural Resources, Forest Practices Division.

WATER EROSION PREDICTION PROJECT (WEPP) v. 97.3. 1997. West Lafayette, IN: Agricultural Research Service, National Soil Erosion Research Laboratory. Available at http://topsoil.nserl.purdue.edu/weppmain/.

X-DRAIN V. 1.0. 1997. Moscow, ID: USDA Forest Service, Rocky Mountain Research Station. 16- and 32-bit Windows versions available at http://forest.moscowfsl.wsu.edu/4702/x-drain.html.

XDS. 1997. Cross drain spacing model v. 1.0. Moscow, ID: USDA Forest Service, Rocky Mountain Research Station. Available at http://forest.moscowfsl.wsu.edu/4702/crossdrain.html.

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