Predicting Sediment Delivery from Forest Roads with the XDRAIN program

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Abstract

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. Computer interfaces were developed to access the results of these runs either in Windows or over the Internet. Methods are presented to apply these results to road planning and environmental analysis.

Key Words

WEPP Roads Erosion prediction Interface

Introduction

Roads are the major source of sediment in most forest watersheds due to surface erosion or 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 site-specific soils and climates for which each was developed. Forest planners often have wanted to know the sediment yield from a given length of road but have had no acceptable means to estimate the amount. In some cases, planned forest activities were halted because managers could not predict offsite sedimentation. The purpose of this paper is to describe a new computer program that was written for nation-wide application to assist road

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and watershed mangers to quickly and easily predict the amount of sediment that is entering a stream from a given road segment.

A primary practice for controlling erosion on forest roads is to divert runoff from the road surface or eroding ditch to 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 (figure 1). 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

USLE—The most common erosion prediction technology is the universal soil loss equation (USLE). This technology has been widely applied to agricultural cropland conditions. Inputs for the USLE also have been developed for forest harvest conditions in the Southeastern U.S. (Dissmeyer and Foster 1981). Input parameters have not, however, been developed for forest roads. A major disadvantage of the USLE for road conditions is that it was developed to predict erosion from the eroding part of the hillside, and is not intended to serve as a sediment delivery model where downslope deposition is a major factor in the sediment delivery process. Developers have attempted to improve the ability of the USLE to predict sediment delivery by considering surface runoff. The Modified USLE (MUSLE) was developed to meet this need (Barfield et al. 1983). The sediment delivery principles have been incorporated into models such as those proposed by the Environmental Protection Agency (EPA 1992). Although MUSLE is a

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significant improvement, the wide variation in surface conditions and the inability of the USLE technology to address snowmelt limit its accuracy.

Cumulative Effects Models—An approach to estimating sediment delivery from forest roads was developed in the Northwestern U.S. with a series of watershed cumulative effects models. The variation in erosion and sediment delivery predicted by these models was determined initally from limited field research but often modified for a specific locality by consensus from a group of agency specialists. The WATSED model (USDA Forest Service 1990) is one of the best known of the cumulative effects models. The most comprehensive cumulative effects method to date was developed by the Washington Forest Practices Board (1995). These methods guide the user to estimate a road erosion rate for a 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 geologic and climate region for which they were developed, but they lose accuracy rapidly for other climates or geologic areas.

WEPP—The Water Erosion Prediction Project (WEPP) model (Flanagan and Livingston 1995, Laflen and others 1997) is a physically-based soil erosion model that can estimate soil erosion and sediment yield considering the specific soil, climate, ground cover, and topographic conditions of a site. WEPP simulates the daily conditions that impact erosion including the amount of vegetation canopy, the surface residue, and the soil water content. For each day that has a precipitation or snowmelt event, 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 hillslope. The model has been validated for numerous conditions including forest roads (Elliot and others 1994, Elliot and others 1995, Tysdal and others 1997). Table 1 presents a number of comparisons of WEPP predictions to observed road erosion rates for sites throughout the U.S.

Included in the WEPP technology is the CLIGEN stochastic weather generator. CLIGEN generates a daily climate for any length of simulation from 1 to 999 years, based on the statistics from the selected weather station. CLIGEN has a database of over 1000 climates spaced at a grid of approximately 60 miles for the entire U.S. (Flanagan and Livingston 1995).

Forest Service Applications of WEPP

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. Forest Service scientists have offered to assist these potential users in applying WEPP to local problems, and in numerous consultations the authors have assisted forest managers in such a way (Laflen and others 1997). In spite of these efforts, fewer than 10 percent of the workshop participants have attempted to apply the WEPP 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.

Despite of the modeling difficulties, the Forest Service and other agencies need to predict sediment yield from roads. WEPP can provide the predictions, but the current interface is too complex for the time available. Other prediction methods are limited in scope. To meet this challenge, we need a new technology that can address site-specific sediment risks, and which can 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.

Methods and Results

To exploit the ability of WEPP to predict sedimentation from roads, and to make the results available for field application, more than 50,000 runs of the WEPP model were made. 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 and others 1998) and a version to run over the Forest Service intranet or the internet via the World Wide Web (XDS 1997).

X-DRAIN Screens

The X-DRAIN programs have two main screens: an input screen (figure 2) and an output display screen (figure 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 ft and 100 ft is also specified. Both programs can be run with either metric or English units.

On the output screen (figure 3), the input selections are presented along with a table of sediment yield values, in lbs/ft or kg/m 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 lb/ft for a 200-ft cross drain spacing at a road gradient of 4 percent. The average annual total sediment delivery from the 200-ft of road between cross drains would be 0.1 lb/ft x 200 ft = 20 lbs.

For conditions between the points modeled, interpolation between results appears to be valid. It is not advisable, however, to extrapolate outside the region modeled, as 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 the 30 years of climate, there would be a number of large erosion-causing events, either from precipitation only, snowmelt, or the 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 of the maximum values (Elliot and others 1989, Elliot and others 1994, Elliot and others 1995, Tysdal and others 1997). Differences from one year to the next can be much greater. For example, Foltz (1996) reported erosion rates of 96, 2892, and 2544 lbs delivered in consecutive years from the same 0.06-acre road segment in the Oregon Cascades. These differences are likely due 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 1999, Elliot and others 1994, Elliot and others 1995, Tysdal and others 1997). 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 range rather than a single number to reflect the variability inherent in erosion prediction science, with an expression like 25 to 75 lbs rather than 50 lbs.

The X-DRAIN program only predicts 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 road surface erosion rates, and for 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 only 33 climates (table 3). In the central and eastern U.S., there are only small variations in climate over relatively long distances so the nearest station will likely provide reasonable predictions of sediment yield. In the western U.S., however, there can be a major variation in climate with elevation and aspect over a short distance. Although X-DRAIN has more climates in the western U.S., users may be limited in good predictions from lower elevations only where the data were collected. Higher elevation climates will likely have higher amounts of precipitation, but more of it will fall as snow, which is less erosive. The net effect of the different climate 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. When modeling forest 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 (figure 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 m (Foltz 1996), but this figure soon 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 and others 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 evaluate the impact of spacings of cross drains on any road (including skid trails) on 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 for mitigation measures. One mitigation measure is the application of gravel to a clay or silt loam, which can be evaluated by selecting a gravelly loam soil. The application of gravel to a sandy loam road can be evaluated by selecting the gravelly sand soil.

Other applications of the model are to determine erosion from footpaths or bike trails—by specifying a narrow width, like 4 ft—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 ft.

On the Horizon

A second version of X-DRAIN is under development which will include a zero-length buffer, to provide an estimate of 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 provide the user with the opportunity to 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 interpolating 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 WEPP climate database of over 1000 climates. Additional help from the input screens and more information in the outputs will be part of the interface.

Conclusions

The X-DRAIN and XDS programs offer natural resource managers a method 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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Tables

Table 1. Observed and predicted erosion rates and sediment plume lengths below forest roads using the WEPP model (Elliot 1999).

Site	Erosion Rate (t/acre/yr)	Comment
Observed at Zena Creek, ID	7.9	Included entire new road prism
Predicted for Zena Creek by WEPP:Road	4.5 and 5.4	Assumed 10 percent road gradient and Warren, ID climate for road traveled way and ditch
Observed bare and graveled road in Southern Appalachians	5.0 to 68	
Predicted for Southern Appalachians by WEPP:Road	6.8 to 83	Road dimensions from publications and Cullowee, NC climate
Observed for Alum Creek, AR	6.8 – 33.7	Vegetated fill slope and ditch
Predicted for Alum Creek, AR	19 - 49	Assumed crowned road and two ditches
Observed bare and gravelled road for Fernow NF, WV	6.0 – 52.5	
Predicted for Fernow NF, WV	16 – 37	Road dimensions from publication, used Clarksburg,WV climate
	Sediment Plume Length (feet)	
Observed on Silver Creek Watershed, ID		
Cross drain	35 – 602 (mean = 163)	
Below fill	1.3 – 217 (Mean = 12.5)	
Observed in Nez Perce NF, Central ID Below culverts	80 percent less than Mean of 78	
Predicted for Silvercreek		Average dimensions in publication
Cross drain	101	Used Deadwood Dam, ID climate, assumed road
Below fill	0	gradient was 10 percent
Local model for Wine Springs Watershed, NC	L = 5.1 + 0.00197 M If M = 9979 kg Then L = 74 ft	Length in meters and M is predicted sediment yield from road Length with a WEPP-Road predicted yield of 9979 kg
Recommended forest filter strip width in SE U.S.	43 + 1.4 x percent slope = 85 ft	
Predicted for Wine Springs Watershed, NC	118	For Cullowhee, NC climate and a 330-ft road length, 10 percent gradient, 30 percent buffer gradient
Observed in Tuskegee NF, Alabama	164 - 197	Occurred Aug '97 – Jan '98
Predicted for Tuskegee Site	131	Assumed Opelika Climate, 200 ft road, 5 percent gradient, 9 percent buffer gradient

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

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 and 5 for details)	Clay loam, silt loam, sandy loam, gravelly loam, and gravelly sand

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

State	Location	Precip (mm)	Latitude °N	Longitude °W	Elevation (m)	Record (yrs)
AK	JUNEAU	1336.1	58.37	134.58	3	43
AL	BIRMINGHAM	1391.8	33.57	86.75	185	62
AR	CLARKSVILLE	1239.1	35.47	93.47	134	39
AZ	HEBER	318.4	34.38	110.58	2029	42
CA	ALTURAS	306.8	41.50	120.53	1359	61
CA	GLENVILLE	494.0	35.72	118.70	954	41
CA	WILLITS	1282.2	39.42	123.33	411	32
CO	EAGLE	282.4	39.63	106.92	1981	44
ID	DEADWOOD DAM	822.7	44.32	115.63	1639	47
ID	WALLACE	922.7	47.50	115.88	899	44
KY	HEIDELBERG	1165.2	37.55	83.77	201	60
LA	RUSTON	1391.8	32.52	92.68	85	62
MI	WATERSMEET	758.8	46.28	89.17	490	44
MO	SALEM	1108.4	37.63	91.55	365	74
MT	LIBBY	454.6	48.40	115.53	633	84
MT	SEELEY	544.9	47.22	113.52	1228	44
NC	CULLOWHEE	1279.6	35.32	83.18	640	44
NH	LANCASTER	879.9	44.46	71.57	268	42
NM	TAOS	327.1	36.42	105.57	2127	44
NV	TUSCARORA	301.8	41.42	116.23	185	33
OH	NEW LEXINGTON	1009.6	39.73	82.22	271	50
OR	AUSTIN	517.5	44.58	118.50	1283	44
OR	NORTH BEND	1611.3	43.42	124.25	3	61
OR	WICKIUP	553.9	43.68	121.70	1319	41
PA	RIDGWAY	1053.7	41.43	78.73	417	66
SD	FORT MEADE	497.1	44.40	103.47	1005	43
TX	LUFKIN	1141.4	31.47	94.72	88	85
UT	HEBER	418.8	40.50	111.42	1703	64
WA	COLVILLE	470.2	48.53	117.87	566	40
WA	PACKWOOD	1351.3	46.62	121.67	323	42
WA	SAPPHO	1935.1	48.07	124.12	231	44
WV	LEWISBURG	934.7	37.80	80.43	685	44
WY	LAKE YELLOWSTONE	415.5	44.57	110.40	2356	64

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

Condition	Cross drain application
Insloping Roads	
With no ditch treatment and no ruts	Enter width of traveled way plus inside ditch in width box
With rocked or graveled ditch and no ruts	Enter width of traveled way in width box and select 30 ft for spacing of cross drains
With ruts and stable ditch	Enter width of traveled way in width box and read output for the spacing of cross drains
With ruts and eroding ditch	Enter width of traveled way plus ditch in width box, and read output for spacing of cross drains
Outsloping Roads	
Without ruts	Enter width of traveled way in width box and select 30 ft for spacing of cross drains
With 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 will decline rapidly as vegetation is reestablished on the skid trail, to near zero by year 5.
More complex conditions	Run the WEPP model for the specific conditions

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

Cross drain soil	Typical field soils	Unified Soil Classification
Clay loam	Native-surface roads on shales and similar decomposing sedimentary rock	MH CH
Silt loam	Ash cap native-surface road. Alluvial loess native-surface road	ML CL
Sandy loam	Glacial outwash areas. Finer-grained granitics	SW SP SM SC
Gravelly loam	Cobbly loam soils. Clay or silt loam surfaces that have been graveled	GC
Gravelly sand	Coarse-grained granitics, and fine-grained granitics that have been graveled	GM

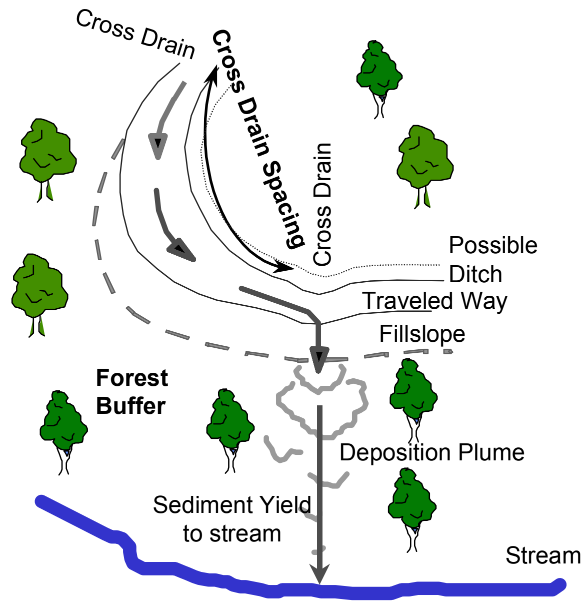

Figure 1. Typical forest conditions associated with road erosion causing stream sedimentation

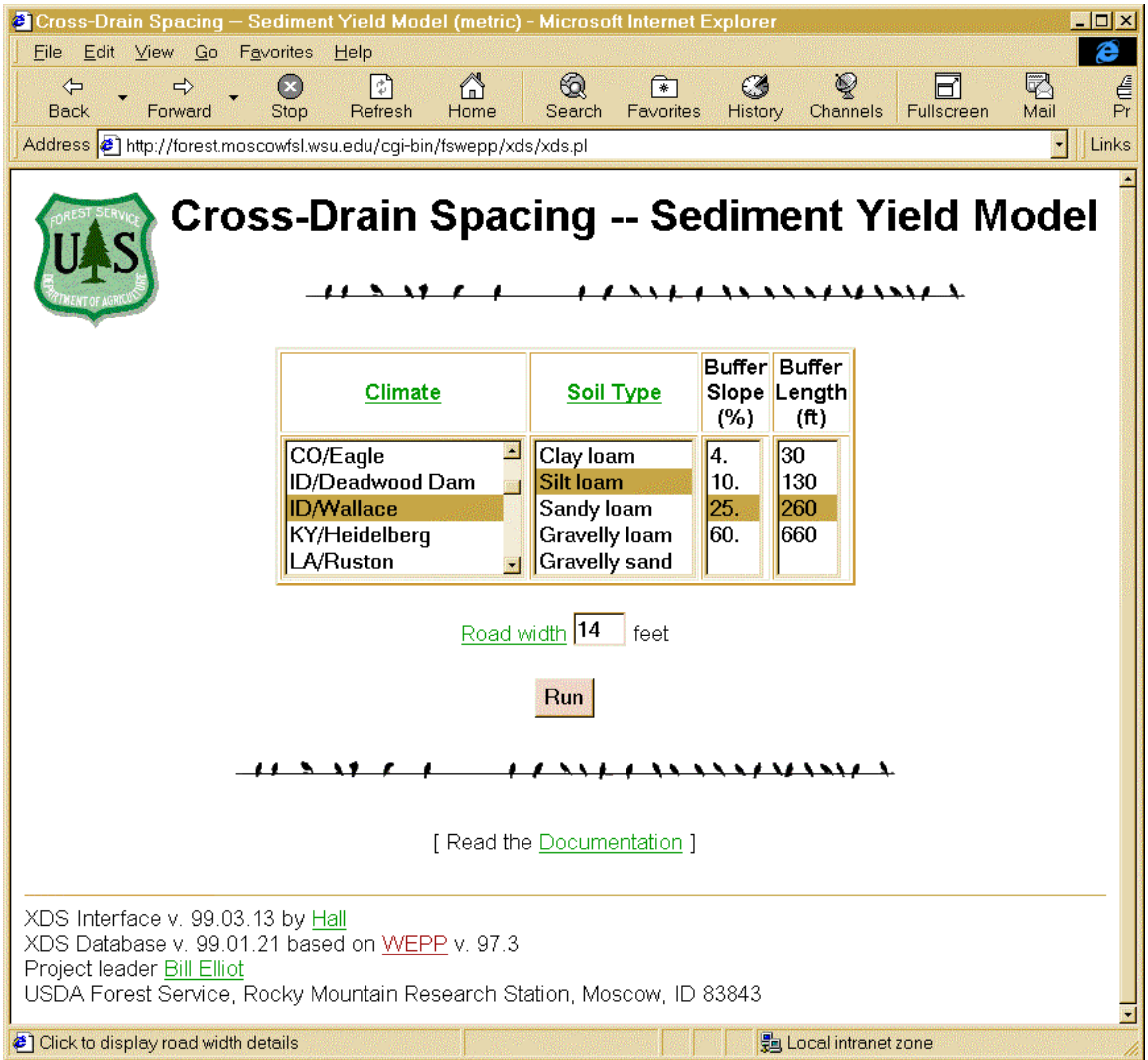

Figure 2. X-DRAIN web site input screen.

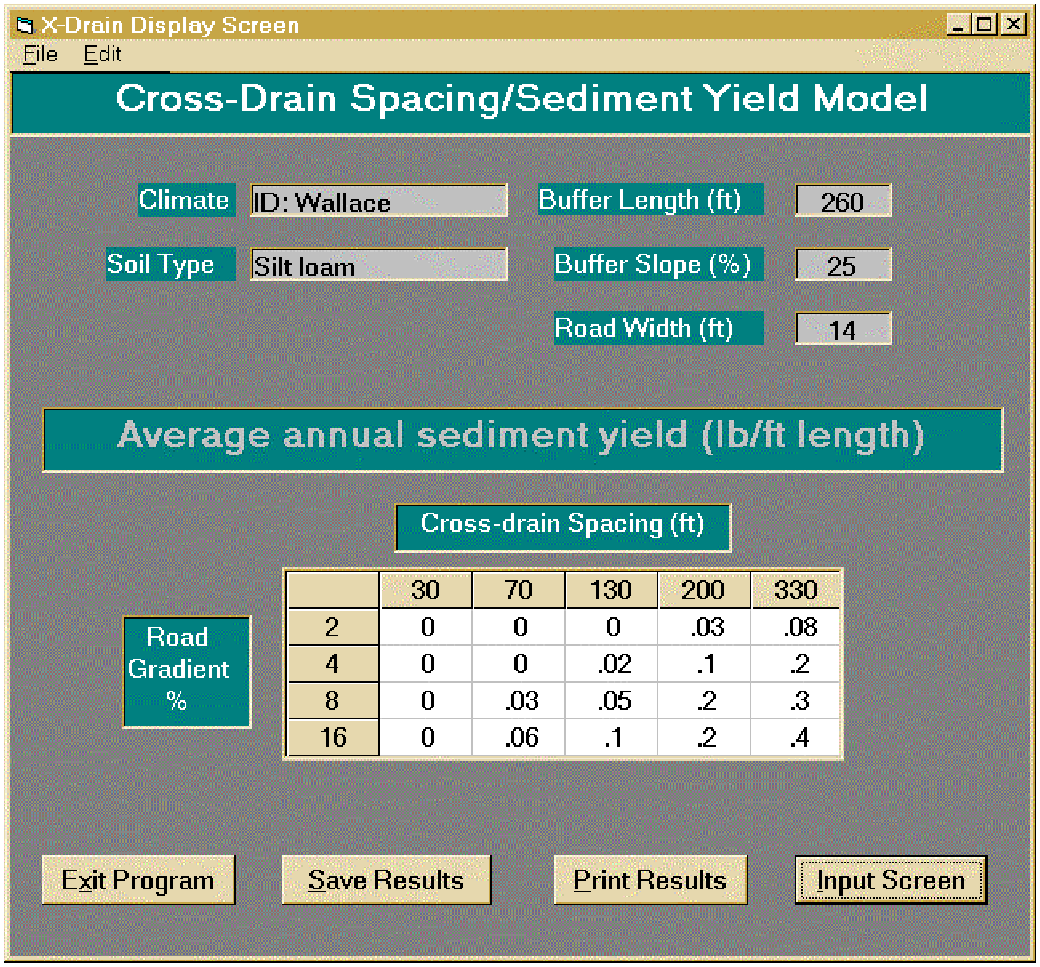

Figure 3. X-DRAIN standalone output display screen.

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