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Forest Erosion Probability Analysis with the WEPP Model

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Summary:

This paper presents an analytical tool to evaluate the probability that a given annual erosion rate occurs during the short period of forest disturbance from fire or harvesting, as common in forest ecosystems. The paper provides an overview of the WEPP model and how it is applied to complex forest conditions. It then gives a review of hydrologic probability analysis methods and builds the case to support a non-parametric method. It describes a new WEPP interface which allows users to easily combine the erosion prediction strength of the WEPP model, the database of forest erodibility properties developed by our research unit, the stochastic features of the CLIGEN climate generator, and a non-parametric probability analysis of the results.

Keywords:

Forest hydrology, Erosion models, Climate

Abstract

This paper presents an analytical tool to evaluate the probability that a given annual erosion rate occurs during the short period of forest disturbance from fire or harvesting, as common in forest ecosystems. The paper provides an overview of the WEPP model and how it is applied to complex forest conditions. It then gives a review of hydrologic probability analysis methods and builds the case to support a non-parametric method. It describes a new WEPP interface which allows users to easily combine the erosion prediction strength of the WEPP model, the database of forest erodibility properties developed by our research unit, the stochastic features of the CLIGEN climate generator, and a non-parametric probability analysis of the results.

Introduction

Soil erosion is a major problem for natural resource managers. Soil erosion can reduce productivity of croplands, rangelands, and forests. It also leads to sedimentation and related pollution of surface water. Predicting soil erosion, and the impacts of management on soil erosion have been topics of considerable research within the U.S. and elsewhere for over 50 years.

Current soil erosion prediction technology such as the USLE (Wischmeier and Smith 1978), RUSLE (Renard, 1991), WEPP (Laflen et al. 1997) and WATSED (USDA Forest Service 1990) estimate average annual soil erosion rates. Other models, such as AGNPS (Young et al. 1989) and CREAMS (Foster et al. 1981), predict erosion for single events.

In forests, there is seldom significant soil erosion unless the forest is disturbed by roads, fire or logging. In most cases, erosion may occur only after a severe wildfire (Elliot et al. 1999). In the years following a severe disturbance, vegetation can rapidly regrow with increased availability of nutrients, and less competition for water from mature trees. When trying to estimate the erosion rate following a severe disturbance, managers are unsure of what type of technology to use. Average annual values are inappropriate because the forest is in a severely disturbed condition for one or two years only. Also, with the inherent variability in the weather, there is never an “average” year, only years above or below average in precipitation or temperature.

Single storm models have limitations because there is a shortage of data to determine design storms, and in many forests, erosion is more likely to result from rapid snowmelt than from rainfall. With single storm models, the user needs to know the soil water conditions when the storm occurs. In many cases, it is difficult to determine whether the soil is going to be wet or dry. A low intensity storm on a wet soil is likely to cause more runoff and erosion than a high intensity storm on a dry forest soil.

We have developed input files for the WEPP model to describe roads and other disturbed forest conditions (Elliot and Hall 1997). To address erosion with regenerating vegetation, we programmed WEPP to predict soil erosion from a vegetation sequence of a mature forest in year 1, a burned or harvested forest in year 2, and a sequence of regenerating vegetation for the next 30 years. With this template, we have observed that for most weather sequences, the only time erosion was predicted was in year 2, the year of disturbance. If the weather in year 2 was highly erosive, then a high erosion rate was predicted, if it was not erosive, then frequently no erosion was predicted. Such a prediction did not provide managers with the ability to assess the likelihood of or variation in potential erosion the year of the disturbance.

A new approach to erosion prediction after forest disturbance is needed which allows managers to determine the likelihood of erosion from undisturbed and disturbed conditions for a number of possible weather sequences. This paper discusses an approach to develop such a predictive technology.

The WEPP Model

The Water Erosion Prediction Project (WEPP) model is a physically based soil erosion model (Flanagan and Livingston 1995) developed by the USDA ARS to replace the USLE (Foster and Lane 1987). The WEPP model can be run either for a single storm, or for a number of years with daily weather input. WEPP requires values for hundreds of input variables including descriptions of the soil, topography, vegetation, and daily climate.

WEPP allows users to divide the hillslope into up to ten overland flow elements (OFEs) where each OFE is a unique combination of soil and vegetation. To be able to mix elements that may have been mechanically disturbed, such as a skid trail or a road, with other elements, we have used the cropland file format. Elliot and Hall (1997) provide details of the management and soil properties associated with different forest conditions, and documentation is under development to extend that database to other forest disturbances and rangelands.

Outputs from WEPP include details of average annual runoff, soil detachment and deposition. Annual runoff and erosion rates for 1 to 999 years also can be obtained, as can similar values for each runoff event from the entire length of simulation. We have developed methods for interpreting the information in these large output files in terms of likelihood of erosion.

The CLIGEN Climate Generator

The CLIGEN Climate Generator is distributed with the WEPP model. CLIGEN generates a weather sequence from 1 to 999 years from a database of monthly climate statistics for over 1000 sites in the U.S. (Flanagan and Livingston 1995). The statistics of the generated weather sequences are similar to the observed climate. They contain occasional severe storms and sequences of storms that are not different from the observed climate (Arnold and Elliot 1996). The CLIGEN weather generator also can be run outside of the WEPP model, which allowed us to incorporate CLIGEN into our interface development.

Parametric and non-parametric distributions

Linsley, Kohler, and Paulhus (1982) report that there is no theoretical distribution of floods and that there is no best distribution for floods. The three parametric distributions often used are the normal, log-normal, and log Pearson type III.

A normal distribution fits data that are not bounded on either side of the mean and have a skew of zero. Skew is a measure of the asymetry of a distribution. A skew of zero means a distribution is centered around the mean. A positive skew has a distribution centered to the left of the mean. Conversely, a negative skew has a distribution centered to the right of the mean. The log-normal distribution fits data that span several orders of magnitude by using the logarithm of the data. It also has a skew of zero. A log Pearson type III distribution also fits data that span several orders of magnitude by using the logarithm of the data, and has the ability to compensate for both positive and negative skew by including a factor to account for non-zero skew values. Because of the use of the skew, results from log Pearson type III distributions are sensitive to changes in the skew. Several US federal agencies use log Pearson type III distribution for flood flow analysis.

An alternative to parametric methods would be to use the values generated by the simulation program directly rather than determining statistical characteristics from the data. In the non-parametric method, the largest annual value from a 100-year simulation would be the 100-year event. Similarly, the 50-year event would be the second largest annual event. The simplicity of this method is that there are no skew values to impact the prediction of a return period. However, sufficiently long simulation periods have to be run to obtain realistic results.

Number of years to simulate

Baffaut, et al. (1996) reported on using the WEPP model to determine average annual soil loss from croplands in six states in the US. They concluded that 30 years of simulation were insufficient to determine a stable soil loss value. Their definition of stable was when the average soil loss reported by WEPP from a simulation of *x* years was within 10 percent of the value reported for a 200-year simulation. The 10 percent criterion came from the WEPP User Requirements (Foster and Lane 1987). The 200-year criterion was based on their belief that 200 years was adequate to predict a long-term average annual soil loss. They reported that lengths of simulation of 20 to 120 years were required with the lower values from more erosive climates. Their recommendation was to determine the required number of years to achieve a stable average annual soil loss for each location —or alternatively, to simply use a 200-year simulation.

In the forest situation we are not trying to estimate the average annual soil loss, however. The WEPP results we believe would be useful for forest management are the distributions of annual precipitation and hillside runoff, the amount of erosion from a disturbed upland surface such as a road, and the erosion entering the stream below a forested buffer.

In this paper we investigate the characteristics of the results from a standard road scenario of a silt-loam road surface with a 10-year-old forest floor buffer. The road gradient was 16 percent with an outslope of 2 percent and a cross-drain spacing of 100 m. The fill slope had a gradient of 50 percent and a height of 4 m. The forest floor below the road had a length of 100 m and a slope of 60 percent. We selected four climates for our simulation runs with precipitation from 318 mm to 1282 mm. The four weather stations were Willits, CA; Lancaster, NH; Wickiup, OR; and Heber, AZ. These locations cover much of the range in precipitation across the US. Additionally, the four include snowmelt driven climates (Wickiup and Heber) and rainfall driven climates (Willits and Lancaster).

The first analysis was to determine how many years of simulation CLIGEN needed to achieve stability in the average annual precipitation. To accomplish this we looked at the results from 5, 10, 30, 60, 100, and 500 years. The results are shown in Table 1.

For each site the CLIGEN-predicted precipitation reached the reported value in 30 years. By the criteria of Baffaut et al., ±10 percent, even 5-years of simulation was sufficient. This indicates that CLIGEN generated precipitation should not be a limiting factor for developing a distribution of potential erosion rates.

Next we considered the sediment detached from the road surface. Table 2 presents the statistical characteristics of the simulated results of the amount of sediment detached from the road surface.

At all four sites the mean detachment became stable in 30 years, within 10 percent of the 500-year value. Results for the standard deviation were less clear. One site had all four standard deviations within 10 percent; one site had three values within 10 percent; and two sites had two values within 10 percent. Skew was also confusing with one site having stable skews, while the other three had no skew values within 10 percent of the 500-year value.

The amount of sediment entering the stream for the simulation results is shown in Table 3. As with the sediment detached from the road surface, the means reached stability in 30 years. Generally, neither the standard deviations nor the skews achieved stability with 500 years.

Because the standard deviation and the skew often took 500 years to achieve stability, we elected to use the non-parametric methods to determine return period events. We have chosen to estimate only up to the 100-year return period event. Many forests consider 5-year return periods when carrying out post-fire erosion prediction. We recommend using the non-parametric method with 100 years of simulation, ranking the results in decreasing order, and then estimating various return periods for annual values of precipitation, hillside runoff, upland erosion, and hillside sediment delivery.

Treatment of zeros

The runoff and the amount of sediment entering the stream could have annual values of zero. In dryer climates there may be years where there are insufficient storms for runoff or sediment to reach a stream. Regardless of the climate, a goal of forest management is to have no sediment reach a stream. How to treat these zero values is a concern.

Haan (1977) recommends using the theory of total probability to account for zero values. In this method the probability of the value being zero is multiplied by the probability of the value being non-zero after the zero values have been removed. For distributions where the number of zeros is small, this method gives results similar to ignoring the zeros.

The selected modeling results provide some insight into how often this happens for the scenario we chose. All four sites had precipitation each year in the 100-year simulation. Similarly, for all four sites there was road surface erosion in each of the 100 years. This was not true of the amount of sediment entering the stream. At Willits, CA and Lancaster, NH every year had sediment entering the stream. At Wicikup, OR, 17 years had no sediment entering the stream from a simulation of 100 years, and Heber, AZ had 6 years in which no sediment entered the stream. Because in all four examples a range of climate conditions resulted in few zeros, we choose to report the probability of zero occurrence and not to use the method suggested by Haan (1977).

Interface Development

Numerous workshops have been held on applications of the WEPP model. With hundreds of input variables, and potentially pages of output for probability analysis, users soon become discouraged.

To allow users the ability to use the WEPP model for erosion risk analysis, we are developing a new interface, "Disturbed WEPP". The interface (at http://forest.moscowfsl.wsu.edu/fswepp), can be run over the Internet with a stamdard web browser and a standalone version is under development. The interface requires the user to select a Climate, Soil, two OFE disturbances, and topography (Figure 1). Two OFEs allow users to specify a skid trail, harvest area, or prescribed burn area with a riparian buffer, or an upslope rangeland condition with a less disturbed riparian zone. The interface accesses a database that has a soil for each texture and vegetation treatment, which makes a total of 32 soil files (Table 4). Once selected, the interface software builds the WEPP soil and management input files from a database. A slope file built from data provided by the user is also prepared by the interface before it runs WEPP for the selected climate and the desired length of time. The model keeps the vegetation and soil at the disturbed conditions specified for every year of simulation, to determine the impacts of different weather sequences on annual erosion.

Once WEPP has been run, the interface parses the WEPP annual detailed output file to determine the first, second, fifth, tenth, and twentieth greatest values for annual precipitation, runoff, upland erosion, and sediment yield. The average values and the number of years when there were no events are also collected, and the results are presented on an output screen (Figure 2). For example, figure 2 shows that once in 50 years, the precipitation will exceed 1187 mm, the runoff will exceed 107 mm, the upland erosion rate will exceed 8.3 kg m^{-2}, and the sediment yield will exceed 1615 kg m^{-1} width of hillslope. The output also shows an "average" upland erosion rate of 2.8 kg m^{-2} and a probability of 0.06 that there will be no erosion occurring the year following the disturbance.

Discussion

The current interface is limited to two OFEs only. Within disturbed forests, spatial variation is a major feature (Robichaud 1996), and future versions of the interface may require additional OFEs to address the spatial variability.

The rangeland component of the database requires further work. Scientists have found that rangeland erosion processes are dominated not only by the percent cover, but also by the type of cover. For example, there is greater runoff from short sod-forming grasses than from shrubs for the same amount of cover (Franks et al. 1998). A feature of shrub-dominated rangeland erosion is that rill spacing is wider than on other conditions (3 to 4 m versus 1 m). Our current database does not include variable rill spacing. Also, rangelands may be more appropriately modeled as subwatersheds rather than hillslopes. Much rangeland erosion is due to increased runoff and channel erosion following disturbances, rather than the rill and interrill erosion modeled in the Hillslope Version of WEPP.

The combination of an easy to use interface and a probability distribution for an output now provides forest managers with a new tool to aid in determining erosion risk the first year following a watershed disturbance. Figure 2, for example, shows that there is a 6 percent chance that there will be no erosion for the conditions described, a ten percent chance that the erosion rate will exceed 5.9 kg m^{-2}, and a ninety percent chance that the erosion rate will be under 5.9 kg m^{-2}. This information will likely be more useful than determining that on the average, the first year erosion rate will be 2.8 kg m^{-2}, but it could be much more depending on the weather, or that the average erosion rate over a 30-year period with a regrowing forest is about 0.1 kg m^{-2}.

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Table 1 – Average annual precipitation simulated by CLIGEN for various years of simulation

Years	Willits, CA	Lancaster, NH	Wickiup, OR	Heber, AZ
5	**1333** *	**897**	**569**	**317**
10	**1294**	**872**	**552**	**331**
30	**1282**	**880**	**554**	**318**
60	**1263**	**887**	**533**	**323**
100	**1258**	**883**	**533**	**319**
500	**1232**	**872**	**528**	**321**
Observed Average	1282	880	554	318

* Values in bold are ±10% of the average annual value

Table 2 - Characteristics of sediment detachment from road surface

	Number of Years of Simulated Data							
	30	60	100	500	30	60	100	500
	Willits, CA				Lancaster, NH			
Mean	**7.68** *	**7.54**	**7.63**	**7.46**	**3.33**	**3.26**	**3.26**	**3.28**
STD	4.12	**3.39**	3.61	**3.27**	**1.48**	**1.63**	**1.49**	**1.58**
Skew	**1.94**	**1.87**	**1.91**	**1.79**	0.99	1.45	1.43	**3.07**
	Wickiup, OR				Heber, AZ			
Mean	**3.17**	**2.78**	**2.83**	**3.04**	**2.44**	**2.46**	**2.45**	**2.51**
STD	**1.58**	1.44	1.52	**1.76**	1.93	**2.29**	**2.15**	**2.32**
Skew	1.49	1.49	1.59	**1.79**	3.34	3.24	3.07	**4.70**

* Values in bold are ±10% of the 500-year value

Table 3 - Characteristics of sediment reaching stream below the road

	Number of Years of Simulated Data							
	30	60	100	500	30	60	100	500
	Willits, CA				Lancaster, NH			
Mean	**749.5** *	**743.2**	**747.0**	**717.3**	**292.4**	**279.7**	**285.1**	**284.6**
STD	443.9	264.8	358.0	**305.4**	148.9	135.8	**122.5**	**117.2**
Skew	2.47	2.24	1.95	**1.66**	1.91	**1.56**	**1.48**	**1.54**
	Wickiup, OR				Heber, AZ			
Mean	**161.9**	**179.6**	**167.1**	**165.6**	**243.3**	**248.3**	**245.2**	**250.2**
STD	**138.4**	167.8	**139.1**	**134.8**	199.4	247.7	232.5	**261.5**
Skew	1.70	**1.49**	1.70	**1.43**	3.01	2.99	2.82	**4.64**

* Values in bold are ±10% of the 500-year value

Table 4 - Vegetation treatments and soils in current Disturbed WEPP database

Vegetation Treatments	Soils
20-year-old forest	Clay loam
5-year-old forest	Silt loam
Shrub rangeland	Sandy loam
Tall grass rangeland	Loam
Short grass rangeland	
Low severity fire	
High severity fire	
Skid trail	

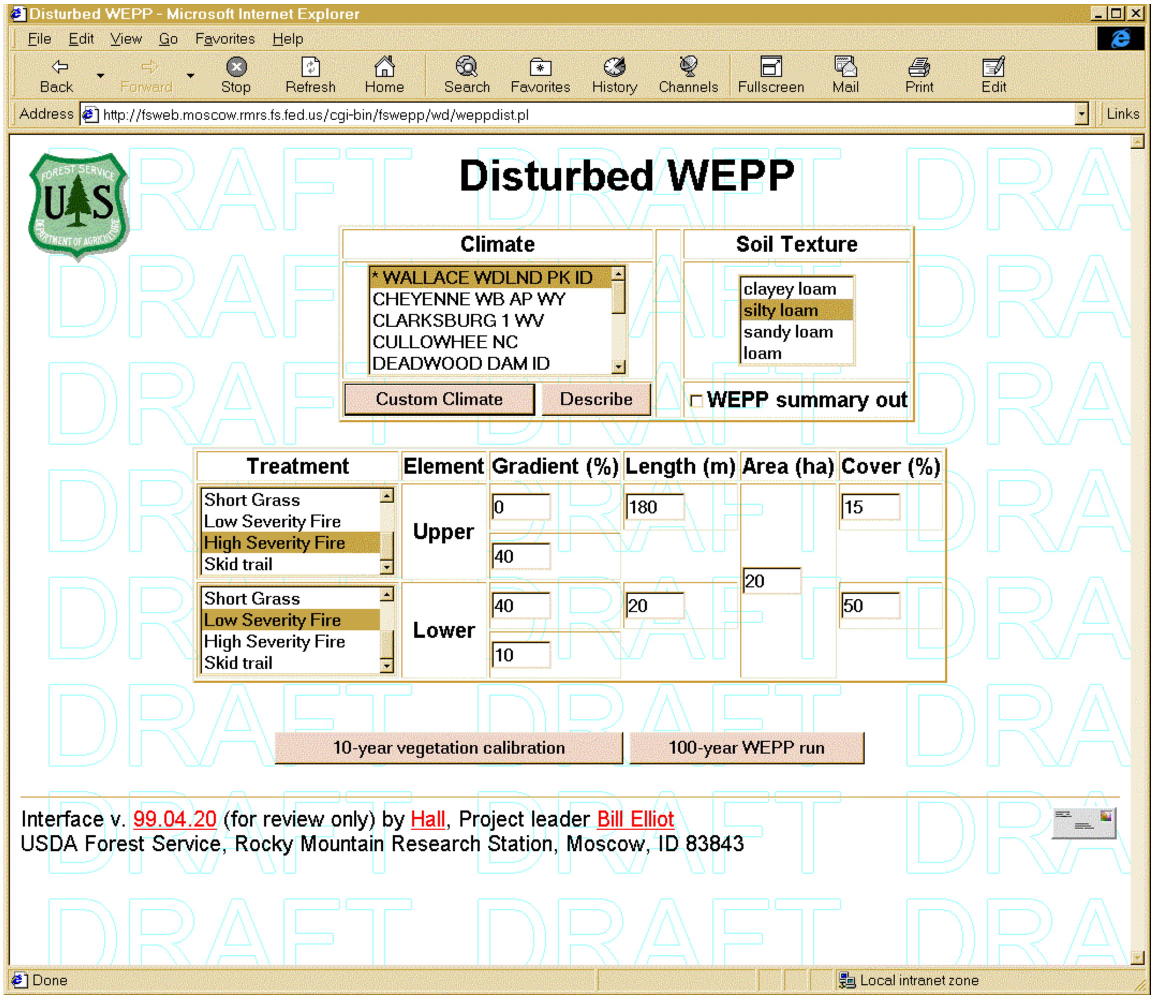
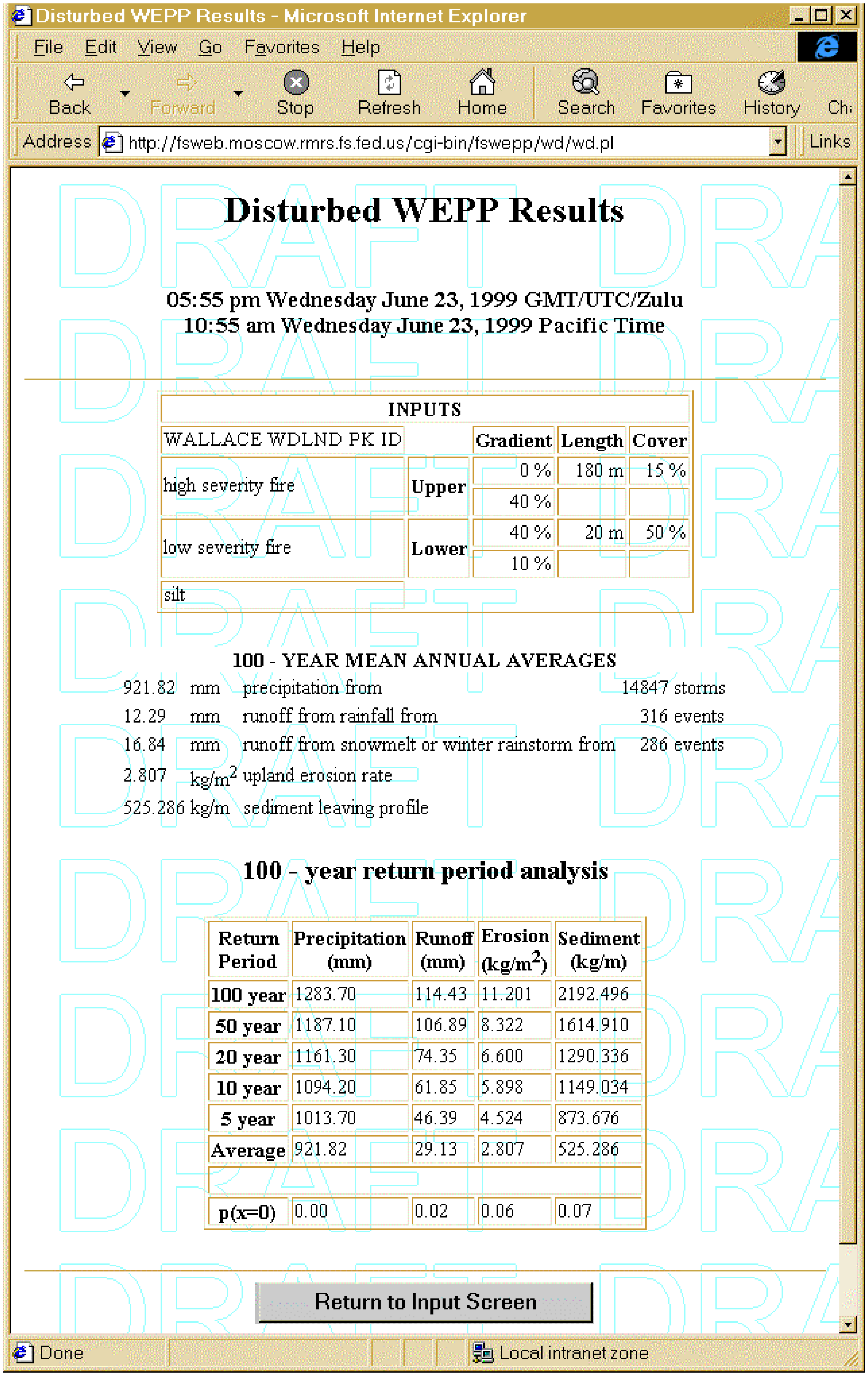


Figure 1 - Input screen for Disturbed WEPP



Disturbed WEPP Results

05:55 pm Wednesday June 23, 1999 GMT/UTC/Zulu
10:55 am Wednesday June 23, 1999 Pacific Time

INPUTS				
WALLACE WDLND PK ID		Gradient	Length	Cover
high severity fire	Upper	0 %	180 m	15 %
		40 %		
low severity fire	Lower	40 %	20 m	50 %
		10 %		
silt				

100 - YEAR MEAN ANNUAL AVERAGES

921.82	mm	precipitation from	14847 storms
12.29	mm	runoff from rainfall from	316 events
16.84	mm	runoff from snowmelt or winter rainstorm from	286 events
2.807	kg/m^2	upland erosion rate	
525.286	kg/m	sediment leaving profile	

100 - year return period analysis

Return Period	Precipitation (mm)	Runoff (mm)	Erosion (kg/m^2)	Sediment (kg/m)
100 year	1283.70	114.43	11.201	2192.496
50 year	1187.10	106.89	8.322	1614.910
20 year	1161.30	74.35	6.600	1290.336
10 year	1094.20	61.85	5.898	1149.034
5 year	1013.70	46.39	4.524	873.676
Average	921.82	29.13	2.807	525.286
p(x=0)	0.00	0.02	0.06	0.07

Return to Input Screen

Figure 2 - Output screen for Disturbed WEPP

Appendix I - CLIGEN Results

While preparing this report we discovered some interesting aspects about the CLIGEN results. CLIGEN uses random numbers to generate weather sequences. However, it always uses the same sequence of random numbers so that each time a climate is generated, all values in the file will be the same. For example, if there is 5.8 mm of precipitation on June 8 of year 10 in one realization from CLIGEN there will be 5.8 mm of precipitation on June 8 of year 10 in a realization run the next time as well. This is so that results are repeatable between shorter and longer periods of generated climate.

The random number sequence resets each time the program is run. There is an option in CLIGEN to generate several stations in a single run of the program. For the same station, a different realization will result between files generated in the first run compared to being generated second. For example, a Heber file generated as the first climate in a run of CLIGEN is not the same as a Heber file generated as the second climate in a run of CLIGEN.

Another noteworthy aspect of the CLIGEN model is that it appears to generate of a maximum daily precipitation with a low probability of occurrence within 30 years. This means that in short length files have rare events. Table A1 illustrates this observation.

Table A1 - Maximum daily precipitation (mm) in various years of CLIGEN results.

Site	Years of Record			
	30	60	100	500
Willits, CA	318	318	318	318
Lancaster, NH	112	112	112	137
Wickiup, OR	95	95	95	119
Heber, AZ	133	198	198	443

For Willits, if one ran only 30 years, one would incorrectly conclude that the 30 year event was 318 mm when it should be the 500-year event. Similar difficulties exist for the other three sites. It appears that CLIGEN places a rare storm around year 25 that actually has a probability of occurrence of less that 1 percent.

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