ESTIMATING THE CONCENTRATION OF SEDIMENT-LADEN RUNOFF FROM HILLSLOPES

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ABSTRACT

Key Words: Sediment, Runoff, Rolled Erosion Control Product, BMPs, Hillslope

Sediment is only one of the many polluntants that can be carried by storm runoff. The United States Environmental Protection Agency (EPA) reports that sediment is the largest polluntant of our Nation's water bodies on a volume basis (EPA, 2003). Sediment causes many deleterious effects on waterways; it clogs the gills of fish, hinders photosynthesis by clouding the water column, eliminates precious spawning areas, smothers the eggs of many water organisms, and increases heat absorption (Dodson, 1999). In addition, sediment commonly transports various nutrients, insecticides, and herbicides, which all impair receiving water bodies when concentrated.

Phase II of the National Pollutant Discharge Elimination System (NPDES) recognized the detrimental effects of sediment-laden runoff, and thus placed more emphasis on the water quality exiting disturbed sites. An understanding of the sediment concentration of discharging waters from hillslopes is critical to meeting NPDES Phase II litigations.

Estimated sediment concentrations from various sized rainfall events can be used during the design phase of an erosion and sediment control plan. This paper explains a

method for estimating sediment concentrations of rainfall-induced runoff from hillslopes. The Rainfall Erosivity Factor (R factor from the Revised Universal Soil Loss Equation) is first calculated for the design storm. After the Rainfall Erosivity Factor is determined, linear regression of simulated rainfall data sets is utilized to produce an equation that can be used to predict sediment concentrations from various rainfall events. Four rolled erosion control products (RECPs) were tested for this study, and bare soil plots where used as the control. The procedure indirectly yields the filtering ability of commonly used RECPs, while providing expected sediment concentrations. Planners can select the appropriate product(s) for their erosion and sediment plan based on the estimated sediment concentrations.

Predicting sediment concentrations from hillslopes before land-disturbing activities occur is another tool for project owners, engineers, and developers to help comply with NPDES Phase II guidelines.

INTRODUCTION

Sediment-laden runoff may originate from any landscape where soil particles are subjected to detachment and entrainment. Pimetal et. al. (1995) estimates that six billion tons of soil erode in the United States annually and this rate will most likely continue to rise with increasing land development activities. More than 607,027 ha (1.5 million acres) of land are developed each year in the United States (Kassulke, 2003). Historically, agricultural lands have been labeled as the main culprit to the problem of sediment-laden runoff; however, sediment runoff rates from construction sites are typically 10 to 20 times those of agricultural lands (Dodson, 1999). Construction activities are considered to be one of the most severe modifications to the landscape and small construction activities can contribute large amounts of sediment to receiving water bodies (Goldman et. al., 1986). The importance of controlling storm water discharges from construction activities has been recognized and is being addressed through Phase II of the NPDES, which became law in March 2003.

Phase II of the NPDES resulted from prior amendments made to the Clean Water Act, which is the regulatory backbone protecting the water resources of the United States. Construction sites as small as 0.4 ha (1 acre) are required to apply for NPDES permit coverage under Phase II litigations. These permits require the owners and operators of the construction sites to implement practices to control polluted storm water runoff (EPA, 2003). RECPs are a best management practice (BMP) that can be utilized to reduce the concentration of sediment-laden runoff from construction sites.

The “acceptable” amount and concentration of storm water-induced runoff is unclear. United States Environmental Protection Agency (U.S. EPA) NPDES Phase II guidelines do not require a numeric performance level for RECPs on construction site hillslopes. Individual states are beginning to implement numerical runoff limits structured around Phase II laws. For example, the goal of the state of Wisconsin is to require an erosion and sediment control plan to reduce sediment by 80% during construction activities (WI DNR, 2003).

OBJECTIVE

The objective of this study is to devise a method that accurately predicts sediment concentrations from hillslopes protected by RECPs.

METHODS

Study Site

Field work for this study was completed at American Excelsior Company's ErosionLab™. The Lab is an outdoor erosion control research and development facility located near Rice Lake, Wisconsin. This study used the Rainfall Erosion Facility (REF), which is the simulated rainfall portion of the Lab. Figure 1 shows the rainfall simulator during the 102 mm/hr (4 in/hr) target intensity segment of a test. The erosion test plots used in this study were 12.2 m (40 ft) long by 2.4 m (8 ft) wide at a 3H:1V gradient. The test plots are separated from one another by a 4.9 m (16 ft) wide buffer of vegetated soil. Each plot contains either a 379 L (100 gallon) or 844 L (223 gallon) collection tank buried at the toe of the slope. V-shaped metal flashing directs all materials leaving the plot into the collection tanks. The RECPs tested for this study were tested following the procedures provided in ASTM D-6459 (2001), "Standard Test Method for Determination of Erosion Control Blanket (ECB) Performance in Protecting Hillslopes from Rainfall-Induced Erosion."

Figure 1. Collection of runoff during a RECP rainfall test.

Rainfall Testing Series

Each bare and protected plot was subjected to sequential rainfall events of approximately 51 mm/hr (2 in/hr), 102 mm/hr (4 in/hr), and 152 mm/hr (6 in/hr) on loam test plots. Each of the three test segments lasted 20 minutes. The test series were replicated three times for each surface cover tested. Six rain gauges were randomly placed throughout the plots during each test segment to measure the amount of rainfall applied. Simulated rainfall testing was performed when winds were less than or equal to 8 km/hr (5 mph) to ensure uniform plot coverage.

Erosion Plot Preparation

Each plot tested over the course of the study was prepared the same way. Plots were tilled up and down slope with a walk-behind roto-tiller. The plots were hand-raked to a uniform surface after tillage. Following raking, a 31.75 kg (70 lb) turf roller was used to lightly compact the material. If surface cover BMPs were to be tested, they were then installed on the plots according to manufacturer guidelines. The plots were not manipulated between storm increments. All plots were reconditioned following the last 20 minute storm increment.

Surface Conditions Tested

Four surface cover BMPs and bare soil conditions were tested over the course of the study. A series of bare soil tests where no surface cover was added to the plots was used as the control in the study. The BMPs tested were single net wood fiber blankets, double net wood fiber blankets, single net straw blankets, and double net straw blankets.

Data Collection

Once runoff commenced, grab samples were collected every three minutes to monitor runoff rates. All runoff from the plots was routed into the collection tank at the toe of the slope. Water was decanted and measured from the collection tanks after settling occurred. The soil slurry was transferred from the collection tanks into pre-weighed pails. The pails were then weighed to determine soil loss on a wet basis. A homogeneous sample of the soil slurry was taken to determine soil moisture content so the equivalent dry basis soil loss could be determined. The samples were analyzed following procedures outlined in ASTM D4643, “Determination of Water (Moisture) Content of Soil by the Microwave Oven Method” (ASTM, 2000). The six rain gauges were also recorded after each 20 minute increment to determine the average depth of rainfall applied to the test plot. Figure 2 shows runoff from a protected plot during the 152 mm/hr (6 in/hr) segment of the test series.

Figure 2. Runoff exiting plot during the 152 mm/hr (6 in/hr) rainfall test segment.

DATA ANLAYSIS

The average sediment concentration for each 20 minute test segment was calculated by dividing the equivalent dry mass of soil collected by the total volume of water collected.

The Rainfall Erosivity Factor (R factor) was calculated based on the rain gauge readings and test durations. The R factor, from the Revised Universal Soil Loss Equation (RUSLE), can be determined for any storm where the intensities and durations of the storm segments and total storm duration are known. Agriculture Handbook 703 (1997) provides complete background on all RUSLE parameters and also contains all equations required to calculate the R factor based on rain gauge measurements. All surface covers were tested to a minimum of 300 R factor units (U.S. Customary Units).

Least Squares linear regression was applied to the data sets. Sediment concentration was plotted vs. cumulative rainfall erosivity (see Figure 3). The resulting equation of the regression line provides a tool to determine sediment concentrations at various R factors.

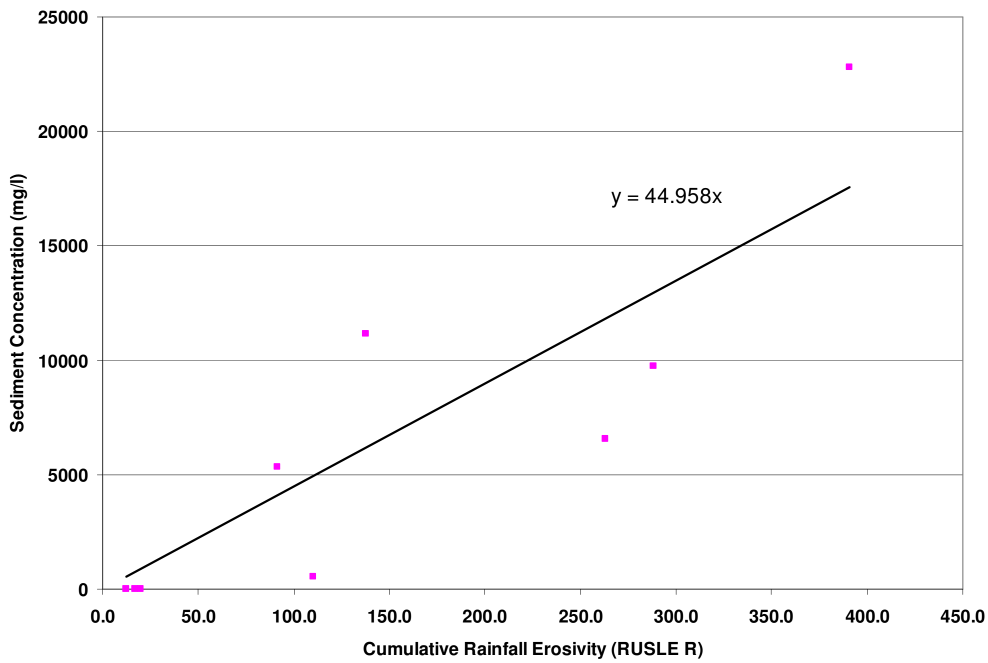

Figure 3. Average sediment concentration vs. cumulative rainfall erosivity from simulated rainfall testing on double net wood fiber blankets.

RESULTS

Table 1 provides the anticipated sediment concentrations at various RUSLE R factors from hillslopes with specified surface cover treatments. Because the data cannot be interpolated outside the limits to which they were tested, Table 1 only provides values up to an R of 300.

Table 1. Estimated sediment concentrations (mg/l) using different surface covers at various RUSLE R Factors (U.S. Customary Units).

RUSLE R Factor	*Bare Soil Control*	*Double Net Wood Fiber Blanket*	*Single Net Wood Fiber Blanket*	*Double Net Straw Blanket*	*Single Net Straw Blanket*
10	13,717	450	832	1,046	974
20	27,434	899	1,664	2,091	1,948
30	41,151	1,349	2,497	3,137	2,922
40	54,868	1,799	3,329	4,182	3,896
50	68,585	2,249	4,161	5,228	4,869
60	82,302	2,698	4,993	6,273	5,843
70	96,019	3,148	5,825	7,319	6,817
80	109,736	3,598	6,658	8,364	7,791
90	123,453	4,047	7,490	9,410	8,765
100	137,170	4,497	8,322	10,455	9,739
110	150,887	4,947	9,154	11,501	10,713
120	164,604	5,397	9,986	12,546	11,687
130	178,321	5,846	10,819	13,592	12,660
140	192,038	6,296	11,651	14,637	13,634
150	205,755	6,746	12,483	15,683	14,608
160	219,472	7,196	13,315	16,728	15,582
170	233,189	7,645	14,147	17,774	16,556
180	246,906	8,095	14,980	18,819	17,530
190	260,623	8,545	15,812	19,865	18,504
200	274,340	8,994	16,644	20,910	19,478
210	288,057	9,444	17,476	21,956	20,451
220	301,774	9,894	18,308	23,001	21,425
230	315,491	10,344	19,141	24,047	22,399
240	329,208	10,793	19,973	25,092	23,373
250	342,925	11,243	20,805	26,138	24,347
260	356,642	11,693	21,637	27,183	25,321
270	370,359	12,142	22,469	28,229	26,295
280	384,076	12,592	23,302	29,274	27,269
290	397,793	13,042	24,134	30,320	28,243
300	411,510	13,492	24,966	31,365	29,216

EXAMPLE APPLICATION

Obtaining estimated sediment concentrations from hillslopes before a rainstorm occurs is possible as described by this study. First, the rainfall erosivity factor is calculated based on the design storm. Table 2 provides the 2-hour, 100-year event data for Fort Collins, CO. These data were analyzed by grouping the storm segments into 15 minute intervals. The resulting R factor equals approximately 165 R factor units. From Table 1, the estimated sediment concentration from a storm of this size is approximately 226,330 mg/l from unprotected slopes. The expected sediment concentration from the same size storm would be reduced to approximately 7,420 mg/l if the same hillslope was protected with a double net wood fiber blanket.

Table 2. 2-hour, 100-year rainfall data for Fort Collins, CO.

Time (hr:min)	Intensity (in/hr)
12:00	0.00
12:05	1.00
12:10	1.14
12:15	1.33
12:20	2.23
12:25	2.84
12:30	5.49
12:35	9.95
12:40	4.12
12:45	2.48
12:50	1.46
12:55	1.22
13:00	1.06
13:05	1.00
13:10	0.95
13:15	0.91
13:20	0.87
13:25	0.84
13:30	0.81
13:35	0.78
13:40	0.75
13:45	0.73
13:50	0.71
13:55	0.69
14:00	0.67

DISCUSSION

Sediment control is becoming more and more important as land development rates continue to increase. Phase II of the NPDES recognized this importance, and thus produced more stringent litigations affecting disturbed sites. The method of estimating average sediment concentration from bare hillslopes or hillslopes protected by surface cover BMPs may be used as a guideline in the early planning stages of an erosion and sediment control plan. The expected rainfall erosivity (RUSLE R) can be calculated based on specific design storm criteria. Table 1 can then be used to determine the estimated sediment concentration that could be expected if the design storm occurred before vegetation was established on the hillslope. The expected sediment concentration from bare soil conditions can be compared to expected sediment concentration from hillslopes protected with RECPs. As is the goal in Wisconsin, bare soil sediment will have to be reduced by 80%. The method described in this paper provides the framework for obtaining a numeric sediment concentration value that can be used to help earth disturbing activities stay in compliance with NPDES Phase II guidelines.

If the estimated average sediment concentrations exceed the anticipated levels required to stay in compliance with NPDES permits, the problem can be addressed before any fines are issued. Various options are available in the BMP toolbox that could be used to further reduce sediment concentrations to NPDES compliance levels if a RECP cannot achieve the task alone.

The method has some potential limitations. First, the ability to perform numerous simulated rainfall tests must exist. Second, the estimated sediment concentrations are average values and the method assumes that sediment-laden runoff will occur consistently through out the rainstorm. This is not always true and concentrations produced by the initial flush will most likely exceed the estimated average value; however, having an estimate of the average sediment concentration value over the course of a single storm is valuable information that can be used in the early planning stages of a project to prevent costly NPDES Phase II non-compliance fines.

It should be noted that the study tested the RECPs and controls in a "worst case scenario". The 152 mm/hr (6 in/hr) segment of the storm series meets or exceeds the 100-year, 20-minute event for many cities in the United States (Chow, 1964). Average sediment concentrations from the rainfall-induced runoff may have been lower if less intense rainfall events were applied to the test plots.

Future studies should include additional replications on the loam soil tested for this study and the methodology should also be applied to data sets across various soil types.

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