VISIOSED- A RAINFALL-SOIL LOSS MODEL FOR APPLICATION TO HIGHWAY CONSTRUCTION SITES

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Abstract

A model VISIOSED was developed to predict the total sediment yield from a watershed as a result of highway construction. The model is based on Universal Soil Loss Equation for calculation of sediment loads entering into water streams. Highway construction site at NASA road 1 was used for calibration of the model. The EPA Storm Water Management Model (SWMM) was used to calculate the total runoff from the site that is transported to the streams through a storm sewer system. Sediment yield was also simulated using the SWMM and compared with the sediments predicted by VISIOSED model. 10 rainfall events were selected for model simulations. Sediment yields using our model and SWMM are presented and discussed.

Introduction

Construction of highways adversely affects the quality of surface water due to the discharge of eroded sediments. Construction of highways and associated pavements and parking lots are initiated with a clearing and grubbing process in which natural vegetation is removed from the construction site. During the construction phase the area to be paved and constructed is excavated thus disturbing its naturally occurring strata. These disturbed areas of soil are exposed to the erosive forces of wind and rain. The purpose of this study is to develop a computer model to calculate the quantities of sediments produced as a result of the highway construction activities that enters the receiving streams. In this study, the VISIOSED model was developed based on the Universal Soil Loss Equation approach that calculates the total erosion resulting from the excavation and disturbance of the soil strata during a storm event.

Study Area

The highway construction site at NASA road 1 in Houston was selected for model development and calibration purposes. Water from this construction site enters either

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Cow Bayou or Clear Lake. A detailed analysis of the subdrainage areas including the construction area that goes into these two water streams was conducted. Soil type in this area is fine clay silt. The nearest established U.S.G.S rainfall gauging station is Station # 08077540 at Clear Creek, Freindswood, which is a few miles away from the site. This station is designated as station #120 by Harris County Flood Control District (HCFCD). The layout of the construction site at NASA Road 1 (Harris County), Houston, Texas, is shown in Figure 1.

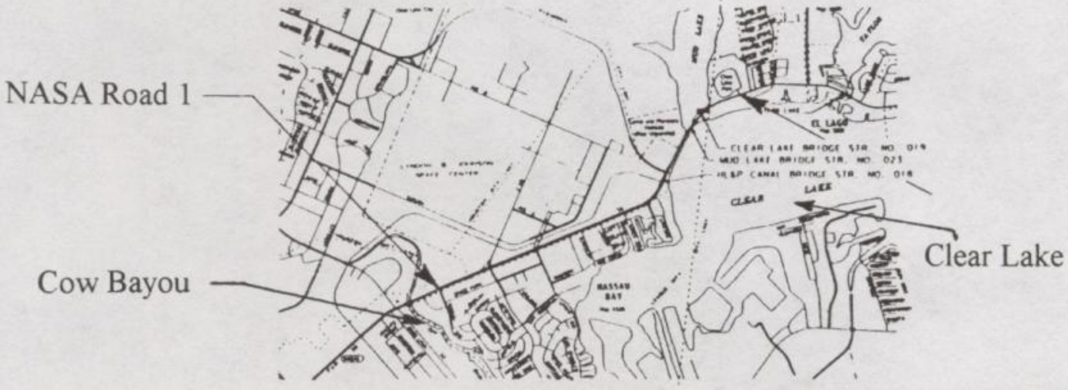

Fig.1. Site Map of NASA Road 1.

Hourly rainfall data for the above mentioned gauging station was used in the SWMM and VISIOSED models for the estimation of runoff and sediments entering the water streams. Ten different rainfall events namely Event # 0, #2, # 3, # 5, #6, # 7, #8, #9, #10 & #11 were selected and analyzed for calculating the flows and sediments that enter Cow Bayou and Clear Lake. The western 55.69 acres of the drainage area drains into Cow Bayou out of which the erosion area was about 27 acres. Different kind of control techniques were used like rock filter dams and silt fences to control the sediments from entering the water streams. In a previous study done by Center For Research in Water Resources, Bureau of Engineering Research, (University of Texas at Austin, 1996) the silt fences are found out to be treating 22 to 23 % of the construction area while the rock dams are proved to be treating 53% of the construction area. The drainage basin for Cow Bayou comprise of 36 subdrainage areas with a total area of 55.69 acres. % imperviousness of the area was calculated by adding up all the paved areas example the parking lots and paved walkways surrounding the construction areas and taking it as a percentage of the total area including the construction area (undergoing excavation), the grassy areas and the paved area. The average slope of the area was calculated using the topographic map which is about 0.000799 ft/ft. Pipe sizes, their slopes and shapes used as input in the transport Block of SWMM were taken from the storm sewer drawings available for the area. Pipe sizes used in the scheme are 24 inch, 30 inch, 36 inch and 48 inch circular pipes along with 4 ft and 5 ft square culverts.

VISIOSED Sediment Yield Model

VISIOSED is a user friendly model programmed in Visual Basic 4.0 (the windows programming language), compatible with window 95 that will calculate the sediments entering into the streams from the highway construction sites depending on the rainfall intensities, land slopes, type of soils, type of control practices used, and type of vegetation cover used to control erosion. The model is developed based on the Universal Soil Loss Equation (USLE) (Wischmeir and Smith 1978). This equation is given as

$$L = R \cdot K \cdot Ls \cdot C \cdot P \qquad (1)$$

where L = average annual soil loss in tons/acre/year, R = the rainfall factor, K = soil erodability factor, C= cropping management factor or cover index factor and P = erosion control practice factor. Ls = slope length gradient ratio is calculated as

$$Ls = l^{0.5} \cdot (0.0076 + 0.53S + 7.6S^2) \qquad (2)$$

where l = the length in feet from the point of origin of the overland flow to the point where the runoff enters a defined channel and S = the overland slope. The rainfall factor R is formulated as

$$R = E \cdot I_{max} \qquad (3)$$

where $E = \sum[9.16 + 3.31 \cdot \log(Ij)] \cdot (Ij) \cdot T$ and E = total rainfall energy for time period of summation. Ij = rainfall intensity (in/hr) at time interval j , T = time interval (hr) and I_{max} = the maximum rainfall intensity (in/hr).

In our model the summation is performed for a single storm in two ways:

1. On a time step basis ; that is, E is evaluated at each time step using the rainfall intensity at that time step (no summation) to get the sediment values at each time step.
2. Energy summation is done for a single storm event to get the total value of the resulting sediments for that event.

Another approximation adopted in our model is using the added up erosion area and erosion lengths for all the subdrainage areas and using them in the equation. Soil factor K depending upon the soil type and texture is assumed to be uniform all over the watershed. Cropping management factor C is also assumed to be the same based on the assumption that same type of cropping is used all over the water shed to control erosion. Control practice factor is averaged out for different type of control practices like rock filter dams and silt fences used to control the sediments from the construction areas entering into the streams.

SWMM- Storm Water Management Model

The EPA's Storm Water Management Model (SWMM) was also applied to simulate the stormwater runoff and sediment for comparison. SWMM is capable of simulating all aspects of urban hydrological and quality cycles, including surface runoff, transport through the drainage network, storage and receiving water effects (Huber and Dickinson 1988). SWMM consist of several different Blocks (subroutines) which can be simulated separately. Blocks used for this study were RUNOFF block for runoff simulation and TRANSPORT block for routing of the runoff and the sediments.

The RUNOFF block generates surface runoff and sediment loads by inputting weather data (rainfall and evaporation) and a set of runoff parameters. These parameters describe the physical (area, width and slope) and hydrologic (percent impervious, depression storage, Manning's roughness coefficient and infiltration parameters) characteristics of the basin.

For the simulation purposes the watershed is divided into subwatersheds with uniform characteristics. Each subbasin is then further divided into its pervious and impervious area and modeled as a non linear reservoir, with rainfall as input. The first governing equation used by the RUNOFF block to compute the runoff from a subwatershed subsequent to a rainfall event is given by the equation of continuity.

$$\frac{dV}{dt} = \frac{d(A \cdot d)}{dt} = (A \cdot i_e) - Q \quad (4)$$

where Q = runoff flow rate from the subwatershed (m^3 / sec or ft^3/sec), V = $A \cdot d$ = volume of water in the sub-watershed (m^3 or ft^3), A = area of the subwatershed , d= depth of water over the subwatershed (ft or m), t = time (sec), and i_e = rainfall excess, which is the rainfall intensity less the evaporation and infiltration rate (ft/sec or m/s). The outflow rate is calculated based on Manning's equation as a product of velocity, runoff depth and width.

The output from the RUNOFF block is used as input for the subsequent TRANSPORT block, which models the sewer system as a series of geometrical elements. The model is based on the continuity and momentum equations given below.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \quad (5)$$

$$\frac{\partial h}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = S_o - S_f \quad (6)$$

Where h= water depth (m or ft), v = average flow velocity (m/sec or ft/sec), x = distance along the conduit (m or ft), g = acceleration due to gravity, S_o = invert slope of the conduit, S_f = energy slope, and A= cross-sectional area of flow.

Results

The results of simulation of flows and sediments for 10 different rainfall events for Cow Bayou and Clear Lake during construction of NASA road 1 show similar variation in the sediment load rate as the flow. The rainfall event #10 is shown in Figure 2. Figure 3 shows the flow variation in Cow Bayou with time. It can be seen in Figure 3 that three peaks occurred in the flow: the first one at hour 9, at which the flow reaches a value of 6.1 cfs after a cumulative rainfall of 0.43 inches; the second and third peak flows occur at hour 21 and hour 23 where the flow values are 14.3 cfs and 13.6 cfs, respectively, due to the subsequent rainfall event occurs between hour 16 and hour 21. Figure 4 shows a similar variation in the sediment load rate as the flow . At the first peak the sediment load rate is about 5198 mg/sec. The second and third peaks occur between hour 21 and hour 23 where the sediment load rate reaches values of 10000 and 9200 mg/sec. The highest value of suspended sediments reached during this simulation was 2972 mg/l.

Figure 5 and Figure 6 show the analyses of linear regression between the total rainfall in inches and total runoff in cfs plotted for different rainfall events for Cow Bayou and Clear lake respectively. The slope of the regression line can be used as the indication of the % imperviousness of the area. The ratio of imperviousness for Cow Bayou from Figure 5 is about 60.7 % and the imperviousness for Clear Lake from Figure 6 is about 63 %. It should also be noted from Figures 5 and 6 that the input of hydrologic parameters is consistent with each simulated storm event. Figure 7 shows the variation in the total amount of sediments in kg as obtained from SWMM and our VISIOSED model. It can be seen from Figure 7 that sediments predicted from our model agree reasonably well with the SWMM results for small rainfall events but for large rainfall events our values are under-estimated by about 35 to 40 % in comparison with the total sediment loads obtained from SWMM.

Conclusions

A model VISIOSED was developed to predict the total sediment yield from a watershed as a result of highway construction. Total sediments were also simulated using the SWMM for comparisons. The results of simulation show similar variation in the sediment load rate as the flow. The average ratio of imperviousness for the drainage areas that drains into the Cow Bayou is about 61% and is about 63% for the drainage areas that drain into Clear lake. For small rainfall events the total sediments from our model agree well with those obtained from SWMM. For large rainfall events, however, the variation in results between the two models is up to 40%.

Acknowledgments

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Fig. 2. Rainfall Event #10.

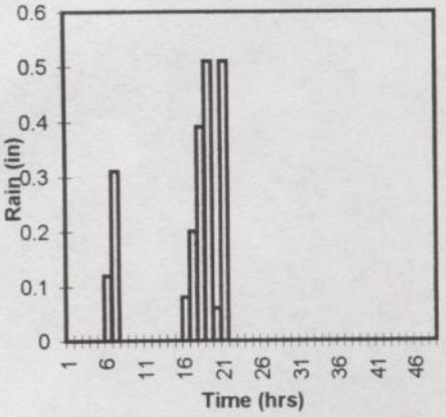

Fig. 5. Rainfall (in) and Runoff (cfs) for Cow Bayou.

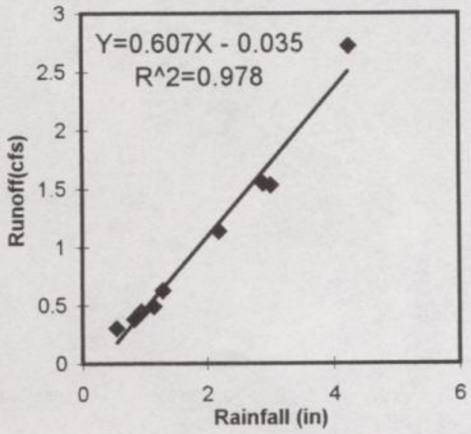

Fig. 3. Flow (cfs) in Cow Bayou for Rainfall Event #10.

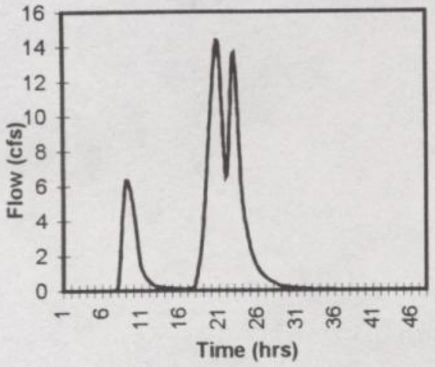

Fig. 6. Rainfall (in) and Runoff (cfs) for Clear Lake.

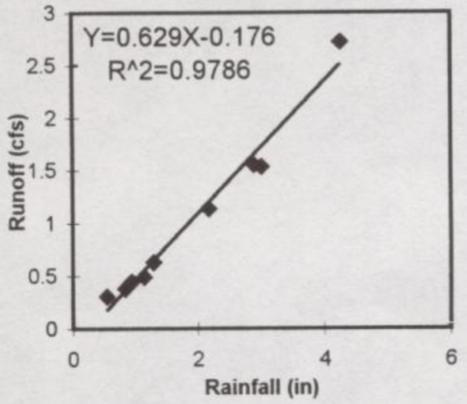

Fig. 4. Sediment Load (mg/sec) in Cow Bayou for Rainfall Event #10.

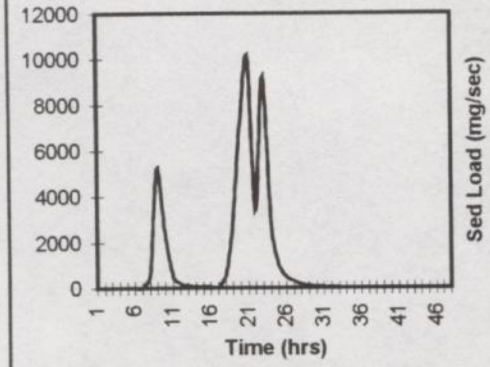

Fig. 7. Total Sediments Obtained from VISIOSED and SWMM for 10 Rainfall Events.