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Modeling Vegetative Filter Performance with VFSMOD

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Abstract. *The model VFSMOD was used to investigate the effect of varying watershed characteristics and buffer dimensions on the sediment trapping efficiency of vegetative filters. This investigation allows for a better understanding of how watershed characteristics, buffer dimensions, and storm characteristics impact the performance of vegetative filters. Using VFSMOD, relationships that estimate sediment trapping efficiency from the ratio of filter area and field area were developed for different sites. These relationships have been applied for field assessment of concentrated flow.*

Keywords. Buffers, sediment trapping, surface runoff, watershed characteristics, and buffer dimensions

Introduction

Vegetative filter systems are being used nationwide as a management practice for controlling sediment delivery to water bodies, especially in agricultural settings. The installation of vegetative filter systems has increased in agricultural areas in part because of the National Conservation Buffer Initiative implemented by the USDA Natural Resources Conservation Service. Vegetative filters have the effect of retarding the velocity and reducing the sediment transport capacity of water flow (Tollner et al., 1982). As a result, a portion of the sediment in the water flowing through the filter will be deposited thus decreasing the movement of sediment to water bodies.

There has been a significant amount of research performed on plot-scale vegetative filters in the field and simulated vegetation in the laboratory to investigate the sediment trapping efficiency of vegetative filters. These studies have shown the positive impact vegetative filters can have on reducing the amount of sediment exiting the filter. However, little information is available on water flow and sediment transport in field-scale vegetative filters. While there is a need for experimental studies investigating the performance of field-scale filters, modeling affords one the ability to investigate different scenarios relative to filter and watershed characteristics and to evaluate the impact of these characteristics on filter performance. Munoz-Carpena et al. (1999) developed and field-tested a single-event model, VFSMOD, for simulating hydrology and sediment filtration. VFSMOD can be used to investigate the performance of vegetative filters.

The Natural Resources Conservation Service (NRCS, 1999) has guidelines for filter installation. From these guidelines, the minimum flow length for reducing sediment, particulate organics and sediment-absorbed contaminants is 6.1 m. Guidelines for the ratio of drainage area to filter strip area are also provided: the ratio of the drainage area to the filter strip area shall be less than 70:1 in regions with RUSLE-R factors values of 0-35, 60:1 in regions with RUSLE-R factor values of 35-175, and 50:1 in regions with RUSLE-R factor values greater than 175. This relates to filter-area-to-source-area ratios of 0.014, 0.017, and 0.02, respectively. The RUSLE-R factors reported above are in English units.

The objectives of this study were to use the field-tested vegetative filter strip model, VFSMOD, to investigate the performance of the filter under a variety of conditions, especially varying watershed characteristics. The results should provide a better understanding of the impact of various factors on the performance of filters under field conditions, where there is a relatively large contributing area to the filter. The performance of the filter is reported as sediment trapping efficiency where sediment trapping efficiency is the percent of incoming sediment that is trapped in the filter.

Description of VFSMOD and UH

In simulating the performance of vegetative filters, the surface runoff and soil erosion from the contributing area to the filter must be simulated along with the flow through the vegetative filter. To simulate filter performance using the vegetative filter strip model, VFSMOD, the user must supply the inflow hydrograph and sedimentograph from the source area. A front-end program (UH) was developed by Suwandono et al. (1999) for use in generating the source area inputs for VFSMOD.

The program UH was developed and is used to develop the inputs for VFSMOD. The program generates a hyetograph, hydrograph, and computes soil loss for the storm. The program is detailed in Suwandono et al. (1999) and summarized within. The synthetic rainfall hyetographs are generated using equations presented by Haan et al. (1994) and the specific use of these equations in UH is described by Munoz-Carpena and Parsons (2000). The hydrograph for the source area is generated using the NRCS (SCS) Curve Number method to determine the volume of runoff. The TR55 method (USDA NRCS, 1986) is used to compute the design peak flow rate. The Modified Universal Soil Loss Equation (MUSLE) is used to compute the soil loss from a single event (Williams, 1977 and Williams and Brendt, 1972). The input parameters for the UH component are provided in Table 1.

VFSMOD is a field-scale, mechanistic, storm-based model that routes an incoming hydrograph and sedimentograph through a vegetative filter. VFSMOD is discussed in detail by Munoz-Carpena et al. (1999) and briefly described within. The model calculates the outflow, infiltration, and sediment trapping efficiency of the filter. The hydrology component of the model consists of a Petrov-Galerkin finite-element overland-flow model that uses the kinematic wave approximation. The infiltration component of the model uses a modification of the Green-Ampt equation that accounts for unsteady rainfall. To describe sediment filtration within the vegetation, VFSMOD uses the University of Kentucky sediment filtration model (Barfield et al., 1978, 1979; Hayes, 1979; Hayes et al., 1982, 1984; Tollner et al., 1976, 1977). The three components of the model are linked together to form VFSMOD.

The parameters used in VFSMOD are described by Munoz-Carpena et al. (1999). A portion of the input parameters used in this investigation were based on recommended values provided with VFSMOD (Munoz-Carpena and Parsons, 2000), specifically roughness, media height, porosity of deposited sediment, and sediment weight density. For our analysis, these parameters were held constant. Other input parameters for VFSMOD – buffer dimension, soil type, and site conditions relative to slope – were varied along with the soil hydraulic parameters estimated from Rawls et al. (1993) based on soil texture.

Application of VFSMOD and UH

Previous studies have shown the effect of the variation of properties within the filter on the overall performance of the filter using VFSMOD (Munoz-Carpena et al., 1999, and Abu-Zreig et al., 2000). Abu-Zreig et al. (2000) concluded that the length of the filter had the greatest effect on sediment trapping efficiency, followed by the type of incoming sediments from the source area. They also concluded the slope of the filter and the soil type in the filter had little effect on sediment trapping. Munoz-Carpena et al. (1999) showed the major factor controlling the hydrology outputs in VFSMOD were soil hydraulic conductivity and initial water content. Their testing showed that the main parameters controlling sediment outflow from the filter were the media spacing and particle diameter. While this information provides insight into the in-filter factors that affect sediment trapping, there is less information about the impact of source-area variation on sediment trapping efficiency and the overall performance of filters under a variety of conditions.

We applied the models UH and VFSMOD to study the effect of varying watershed characteristics and buffer dimensions on the performance of the filter, specifically the sediment trapping efficiency of the filter. The source-area parameters investigated are as shown in Table 2. Note that in the simulations the slope of the filter and the soil type in the filter were the same as for the source area. The length of the buffer was varied to achieve filter-area-to-source-area ratios (filter area ratios) of 0.02, 0.06, 0.1, and 0.15. The precipitation amounts associated with the different simulated events are provided in Table 3 and are based on Hershfield (1961). These values were determined to approximate rainfall in eastern Nebraska but would be applicable to many areas in the Mid-Central region of the United States. A summary of input parameters for the filter used in VFSMOD are shown in Table 4. The soil hydraulic parameters are from Rawls et al. (1993) and the parameters for vegetation and roughness are from Munoz-Carpena and Parsons (2000).

In addition to the simulations described above, VFSMOD was used to develop relationships between filter-area ratio and sediment trapping efficiency for four sites in southeast Nebraska. These relationships were applied to the four sites: Rogers, Burr, ARDC, and Hamilton. The ARDC and Hamilton sites are in the plains topographic region of Nebraska, and the Burr and Rogers sites are in the rolling hills topographic region of Nebraska. The topographic region designation is based on site location and the topographic region map of Nebraska (CSD, 1973). Two of those sites had the same input parameters but different application of the relationship. These relationships were described and used by Dosskey et al. (2001) to investigate the trapping efficiency for riparian buffers on each of the four sites. The key inputs used in the model are provided in Table 5. The soil hydraulic parameters were obtained from handbook values (Rawls et al., 1993) based on the soil texture identified at the sites from the county soil survey. For these simulations, the ratio of buffer area to source area was varied by changing the flow length in the filter. A total of 12 different ratio values, from 0.01 to 0.2, were simulated. A 10-year-return-period design storm was chosen for these simulations as suggested by Larson et al. (1997).

Results and Discussion

Abu-Zreig et al. (2000) concluded that the flow length through the filter has the greatest effect on sediment trapping efficiency, and Overcash et al. (1981), Mander et al. (1997), and Bren (1998, 2000) proposed that buffer design be based on a ratio of upslope contributing area to buffer area. Since both the source area and the filter length were varied in this investigation, a comparison is made between the performance of the filter relative to filter length and filter area ratio. Figures 1a and 2a show the trapping efficiency for the fine sandy loam and silty clay loam soils as a function of filter length for different field lengths and storm characteristics. Figures 1b and 2b show the trapping efficiency as a function of the filter area ratio for the fine sandy loam and silty clay loam soils respectively. From parts a in Figures 1 and 2, the lower return period storms and the lower curve number values have trapping efficiencies of nearly 100% independent of filter length. However, for the longer duration, higher return period storms with a higher curve number shown in parts a of Figures 1 and 2, it is clear the trapping efficiency is dependent on the field length and the filter length. While filter length is an important variable in filter performance, Figures 1 and 2 reveal that the source area should also be considered when estimating the performance. Thus, the filter area ratio may be a more appropriate criterion for design of vegetative filters. It is logical that the size of the source area is important in the performance of the filter since the sediment loading rate and the water flow introduced at the upstream end of the filter will be a function of the source area size. Much of the variation in trapping efficiency caused by field length and filter length can be explained by the filter area ratio, as illustrated in parts b of Figures 1 and 2. The data for the 200 m and 400 m field lengths nearly fall on the same curve.

Another characteristic of the source area that was investigated was the effect of the variation in slope on the performance of the filter. In our analysis, the slope of the filter was the same as the slope in the source area. Figures 3 and 4 show the effect of slope for the silty clay loam soil and the fine sandy loam soil, respectively. The simulation results used in Figures 3 and 4 are for the higher curve numbers for both soil types. These results show that slope has a significant impact on the sediment trapping efficiency of the filter. While a portion of the sediment was retained in all the filter situations simulated, the trapping efficiency of the filters with filter area ratios in the 0.01 to 0.04 range for a 10% slope are less than about 10% for the silty clay loam soil and less than about 50% for the fine sandy loam soil. Figures 3 and 4 show that there can be a dramatic reduction in filter performance relative to sediment trapping as the slope increases.

The curve number value is another important parameter to consider in characterizing a watershed. Two curve numbers were chosen, one to represent a high curve number and one to represent a low curve number for the soil types (poor and good hydrologic conditions). Figures 5 and 6 show the curve number effect for soil types of fine sandy loam and silty clay loam respectively, with a 10% slope. In Figure 5, only the simulation results from the 10-year-return-period storm are shown since the simulations for the 2-year-return-period storm resulted in sediment trapping efficiencies of nearly 100% for both curve numbers. Additionally, for the fine sandy loam soil, the simulations with a 2% slope resulted in trapping efficiencies near 100% for the different combinations of curve number, return period, and storm duration; these results are not shown graphically. Figure 7 shows the curve number effect for the silty clay loam soil with a 2% slope. Figures 5, 6, and 7, reveal that in most cases increasing the curve number dramatically decreases the trapping efficiency of the filter strip. The case where there seems to be less difference in trapping efficiency with a change in curve number is for the silty clay loam soil, 10% slope, and 10-year-return-period storm, as shown in Figure 6. Figure 6 shows that there is less impact on the trapping efficiency when changing the curve number for the larger precipitation event (10-year-return-period storm). This is likely due in part to the filter being at a relatively high loading rate for the larger storm event even at the lower curve number. For the smaller storm, the curve number had a large effect on trapping efficiency. For the low curve number and smaller storm, the loading on the filter was much lower thus significantly increasing the trapping efficiency. Based on Figures 5, 6, and 7, the curve number can have a significant effect on the performance of the filter and the results indicate the importance of maintaining the source area to maximize infiltration and reduce runoff and soil erosion.

As presented previously, two storm durations and two return periods were used for this investigation. For the fine sandy loam soil and the silty clay loam soil, the effect of storm duration and return period is shown in Figures 8 and 9, respectively. Reviewing the solid symbols together and the open symbols together in Figures 8 and 9, the effect of storm duration can be compared. Except for the 10-year-return-period storms shown in Figure 9 for the silty clay loam, there is a pronounced difference in the trapping efficiency for the different storm durations. As the storm duration increases, the trapping efficiency decreases. Reviewing the circle symbols together and triangle symbols together in Figures 8 and 9, the effect of storm duration can be examined. As expected, since the amount of precipitation is increased, the trapping efficiency decreases as the return period for the storm increases. The results for the simulations presented in Figures 8 and 9 are for 10% slope conditions. For the fine sandy loam soil results shown in Figure 8 with filter area ratios less than about 0.10, the maximum trapping efficiency for the 10-year-return-period storm is about 60%; for the silty clay loam soil the results shown in Figure 9 with filter area ratios less than about 0.10, the maximum trapping efficiency for the 10-year-return-period storm is about 25%.

Two different soil types were used in the investigation, with the fine sandy loam being a coarser textured soil than the silty clay loam. Although different curve numbers were used for the different soils (since the hydrologic group for the soils is different for the curve number method), the open circle symbols (1-hr, 10-yr storm) in Figures 8 and 9 show that the trapping efficiency is greater for the fine sandy loam soil than the silty clay loam even when the curve number is greater for the fine sandy loam soil. This is expected since as the velocity of water flow decreases in the filter, the larger particles are the first to be deposited within the vegetative filter.

The models VFSMOD and UH were used to simulate the response of four different sites in southeast Nebraska. Key inputs for the UH component are shown in Table 5. The slopes and soil types of the filter and the source area were assumed to be equal. The results of the simulations are shown in Figure 10. Comparing the results from the ARDC and Burr farms, where the only difference is the slope (3.8% for Burr and 2.3% for ARDC) it is evident that the change in slope from 2.3% to 3.8% has an effect on the trapping efficiency. For instance, at a filter area ratio of 0.05, increasing the slope from 2.3% to 3.8% decreases the sediment trapping efficiency from 61% to 48%. Shown on Figure 10 is the NRCS guideline for filter area ratio of 0.017 for southeast Nebraska, where the RUSLE-R factor is in the range of 150. For the guidelines shown in Figure 10, it can be seen that for filter area ratios in this range the sediment trapping efficiency is less than 50%. Based on the curves shown in Figure 10 it is evident that although the filter traps a portion of the incoming sediment, the percentage trapped could be relatively low for filter area ratios for which many filters may be designed. However, the curves in Figure 10 are for a 10-year-return-period storm, which might be on the extreme end for which one would expect the filter to perform well. The relationships of sediment trapping efficiency versus filter area ratio shown in Figure 10 were used by Dosskey et al. (2001) to estimate the trapping efficiency for riparian buffer areas on each of the four sites. Specifically, the effect of reducing the area of filter contacted by the surface water flow was investigated. This situation was used to simulate concentration of flow within a filter and assess the impact of concentration of flow on filter performance. Dosskey et al. (2001) found that using the total filter area for the filter area ratio resulted in average sediment trapping efficiencies on the order of 99%, 67%, 59%, and 41% for the Rogers, Burr, ARDC, and Hamilton farms respectively. In that study, field observation reveals that water concentrates within the filter, thus reducing the effect filter area. When the filter area was reduced to account for the actual filter area that surface water would contact, the average sediment trapping efficiencies were 43%, 15%, 23%, and 34% for the Rogers, Burr, ARDC, and Hamilton farms respectively. Thus, if surface water encounters only a portion of the vegetative filter because of flow concentration the sediment trapping efficiency of the system can be greatly reduced.

Summary and Conclusions

Both filter area and source area should be considered when evaluating or estimating performance of a vegetative filter. The models UH and VFSMOD were applied to study the effect of varying watershed characteristics and buffer dimensions on the performance of the filter, specifically the sediment trapping efficiency of the filter. The results of the simulations using UH and VFSMOD showed that slope, curve number, storm duration, and storm return period can significantly impact the performance of the vegetative filter. Also, the soil texture impacts the performance of the filter. The coarser the soil texture the greater the percentage of sediment that is trapped in the filter. Many simulation results were as expected since one would expect that as flow increases or sediment size decreases the performance of the filter would be reduced. However, the impact of watershed characteristics, storm characteristics, and filter dimensions on the filter performance were very dramatic in some cases. These factors are important to consider in the design of vegetative filters and specifically in understanding that the performance of vegetative filters is reduced as the storm size increases.

The curves in Figure 10 show the predicted sediment trapping efficiency for different sites in southeast Nebraska. These relationships show that for some filter area ratios the trapping efficiency may be relatively low for the design storm (10-year return period). These types of relationships provide information that may be useful in designing a filter for a specific design storm and desired trapping efficiency.

The analyses revealed that watershed characteristics and storm characteristics have a major effect on the performance of vegetative filters, and these factors should be considered in the design of vegetative filters. A future progression of this research might be to determine if empirical relationships could be developed from modeled results that could be used to predict filter performance. It is anticipated the empirical relationships would include parameters that could be determined based on the watershed, filter, and storm characteristics. This technique might produce a simple and efficient method to use in a broad-scale assessment of filter performance when site-specific modeling of filters may not be warranted.

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Table 1: Input parameters for UH component

Input Variable	*Description*	*Input Variable*	*Description*
Rainfall (mm)	Total rainfall for the storm	Storm Type	Type of rainfall event (I, IA, II, or III)
Curve Number	NRCS curve number for the source area	Soil Erodibility Factor, K	USLE erodibility factor
Length (m)	Length of the source area	C Factor	USLE cover and management factor
Area (hectares)	Source area	P Factor	USLE practice factor
Slope	Slope of the source area as a fraction (%/100)	Soil Type	Soil texture for the surface layer
Strom Duration (hr)	Time of the storm used to compute hyetograph and hydrograph	Rainfall Factor	Rainfall factor for the modified storm version of USLE

Table 2: Summary of source area input parameters

Input Variable	*Variation in Parameter*
Field Length	200 m and 400 m
Slope	2% and 10%
Soil Texture	Silty Clay Loam and Fine Sandy Loam
Curve Number	70 and 90 for Silty Clay Loam and 60 and 75 for Fine Sandy Loam
Storm Duration	1-hour and 6-hour
Return Period	2-year and 10-year

Table 3: Precipitation amounts for four events

Duration and Return Period of Event	*Rainfall (mm)*
1-hour duration, 2-year return period	41
1-hour duration, 10-year return period	61
6-hour duration, 2-year return period	57
6-hour duration, 10-year return period	89

Table 4: Summary of key parameters used in VFSMOD

Soil Texture	*Silty clay loam*	*Fine sandy loam*
Porosity	0.471	0.453
Green-Ampt wetting front soil suction head (cm)	27.3	11.01
Green-Ampt hydraulic conductivity (cm/hr)	0.20	2.18
Initial water content	0.169	0.064
Grass spacing (cm)	1.6	1.6
Filter mean Manning's coefficient (s-m$^{-1/3}$)	0.4	0.4
Grass modified Manning's coefficient (s-cm$^{-1/3}$)	0.012	0.012
Bare soil Manning's coefficient (s-m$^{-1/3}$)	0.04	0.04

Table 5: Field conditions and precipitation events used in VFSMOD simulations for four case study sites in southeast Nebraska

Condition	*Rogers*	*Burr*	*ARDC*	*Hamilton*
Land Slope (%)	2.0	3.8	2.3	2.0
Soil Texture	Silt loam	Silty clay loam	Silty clay loam	Silt loam
Precipitation Amount (mm)	63.5	63.5	63.5	63.5
Precipitation Duration (hr)	1	1	1	1
Precipitation Return Frequency	10	10	10	10

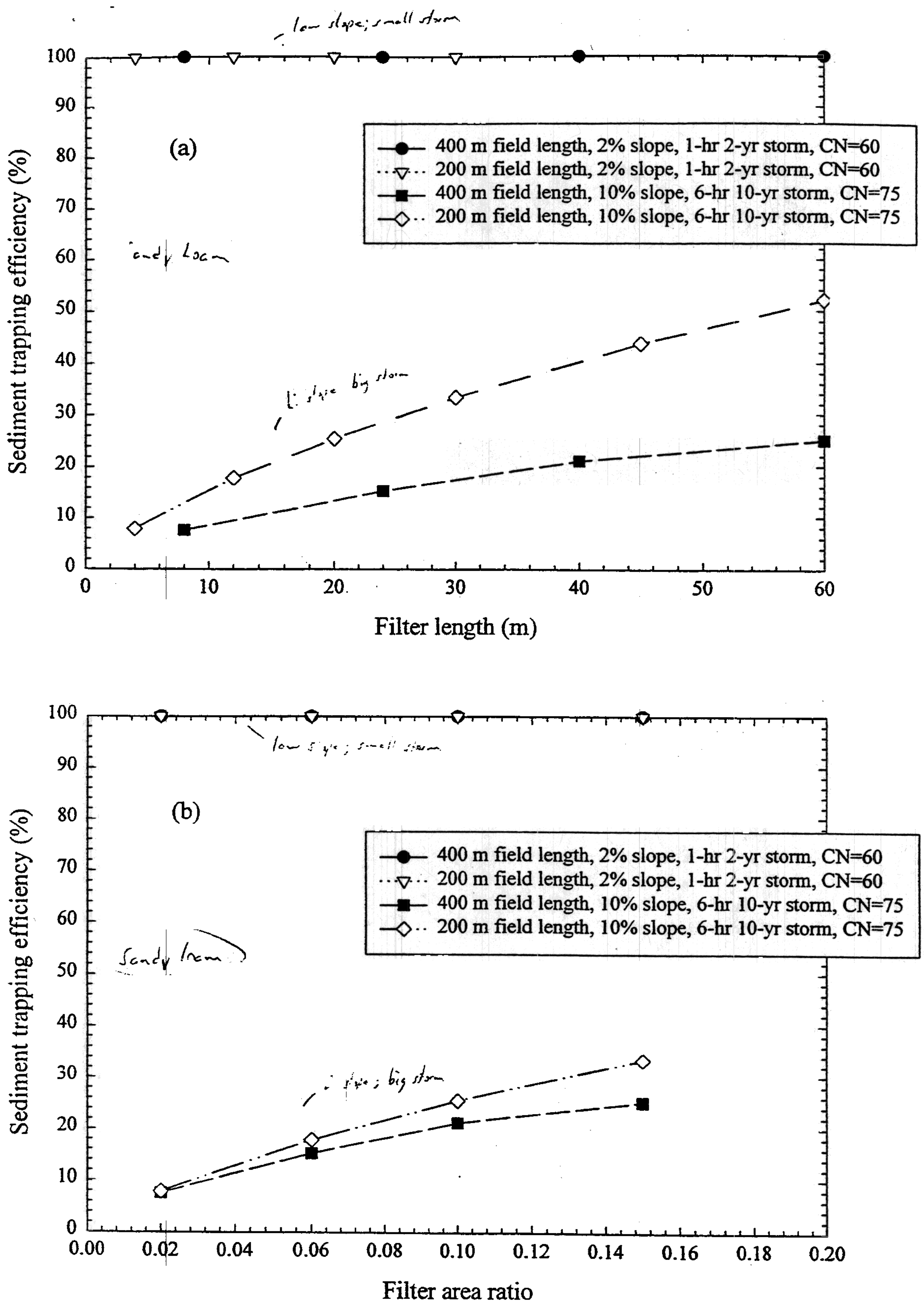
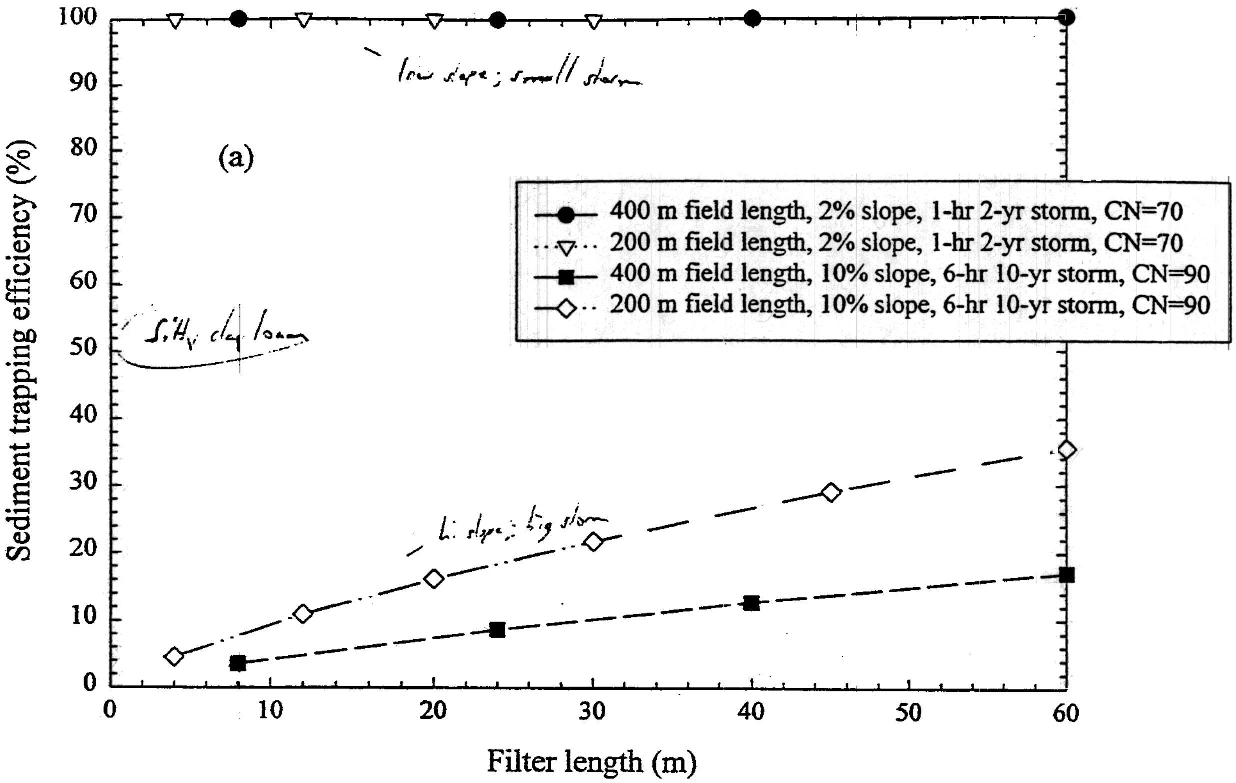


Figure 1: Trapping efficiency for fine sandy loam (a) as a function of filter length and (b) as a function of filter area ratio



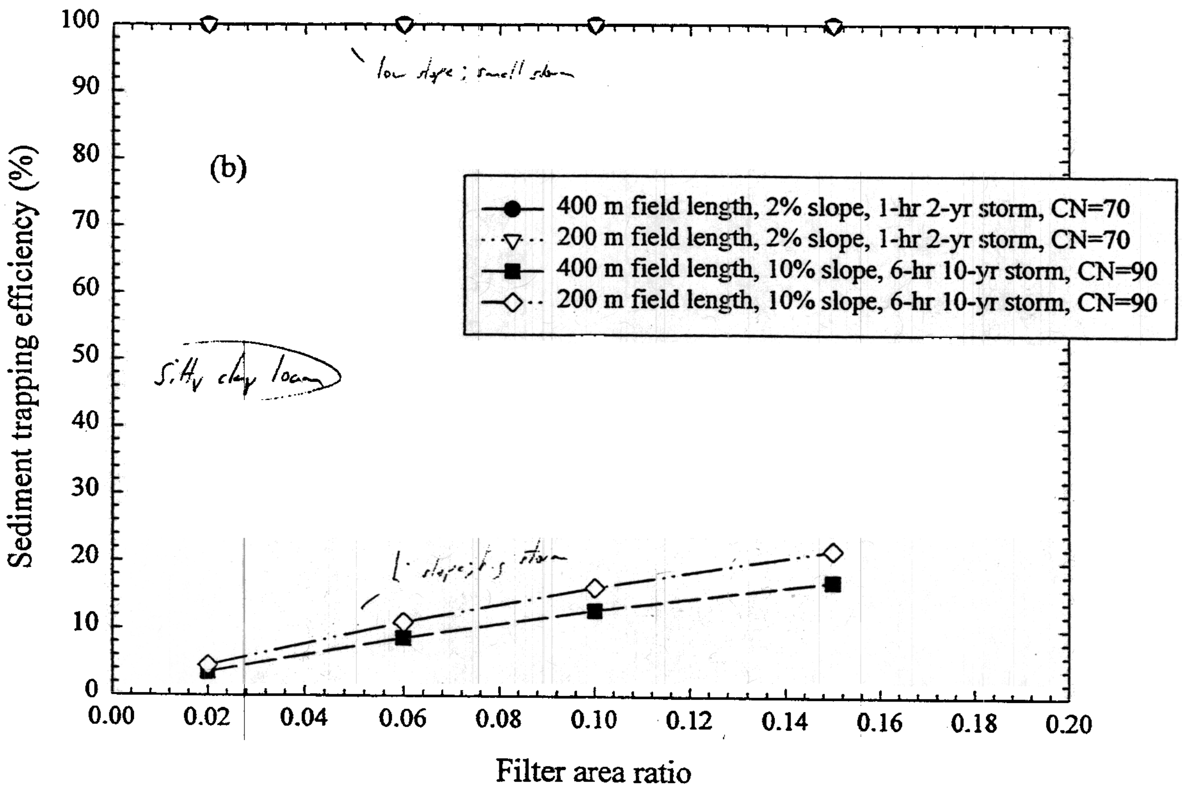


Figure 2: Trapping efficiency for silty clay loam (a) as a function of filter length and (b) as a function of filter area ratio

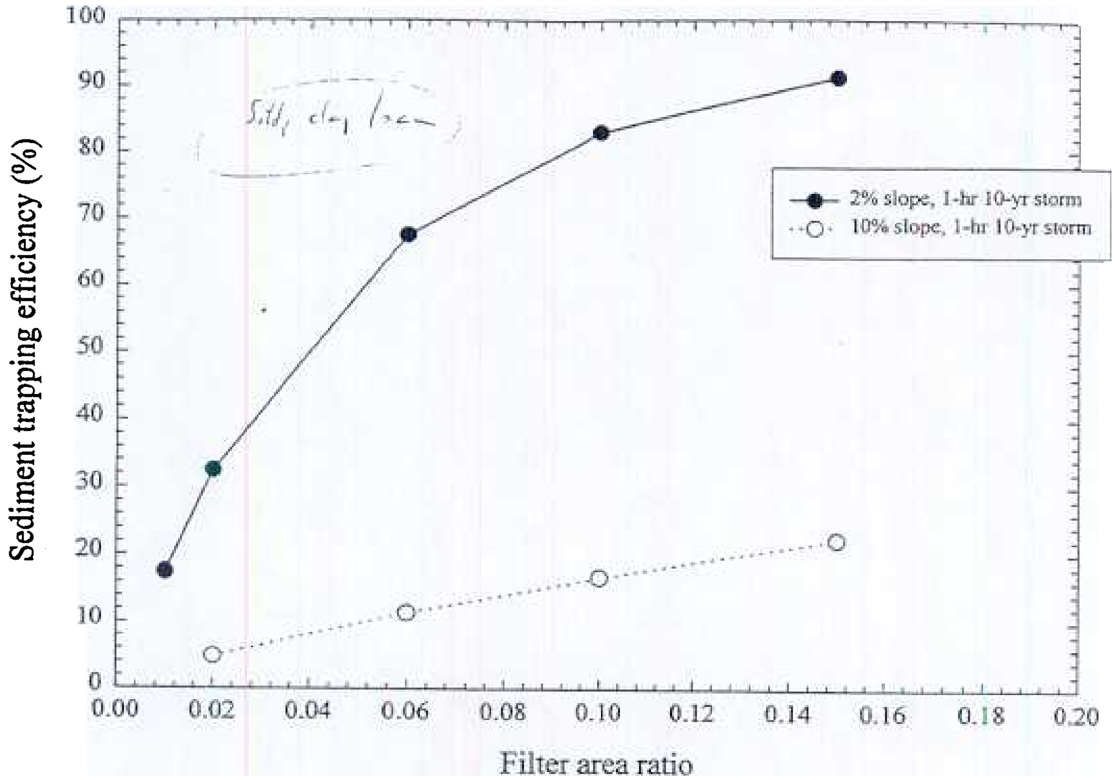


Figure 3: Effect of slope on trapping efficiency for silty clay loam, curve number = 90

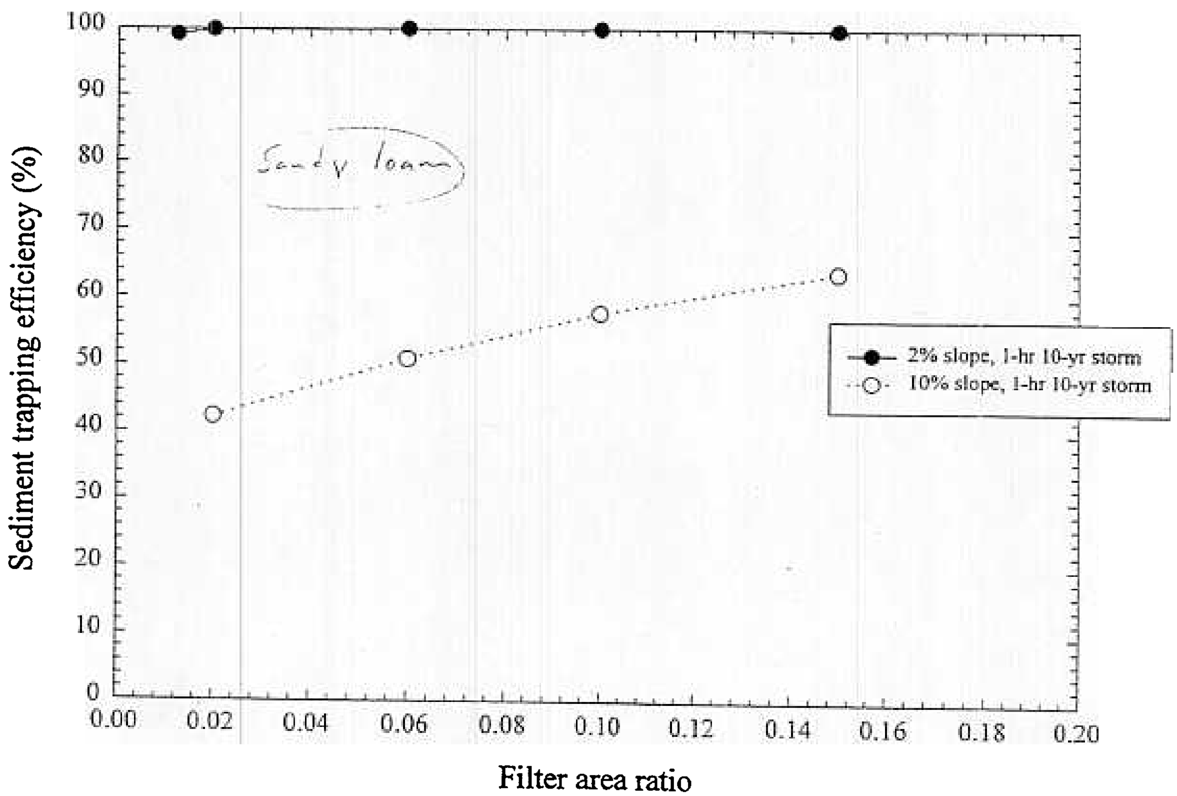


Figure 4: Effect of slope on trapping efficiency for fine sandy loam, curve number = 75

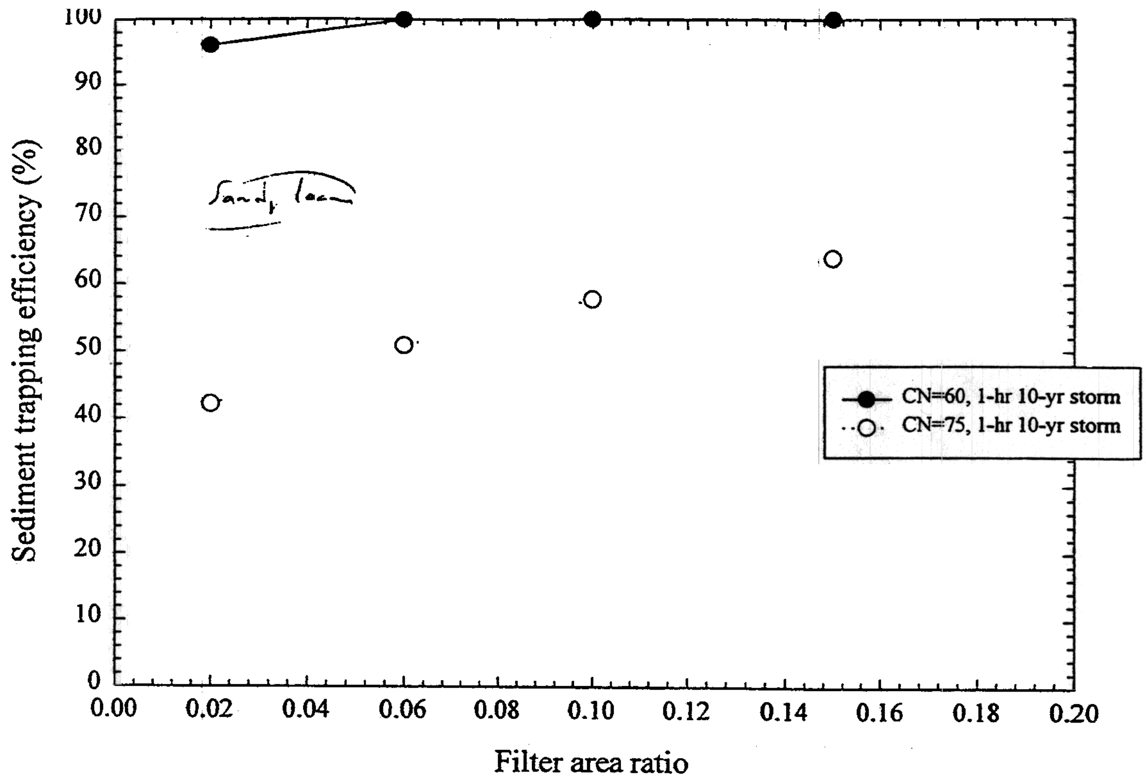


Figure 5: Effect of curve number on trapping efficiency for fine sandy loam, 10% slope

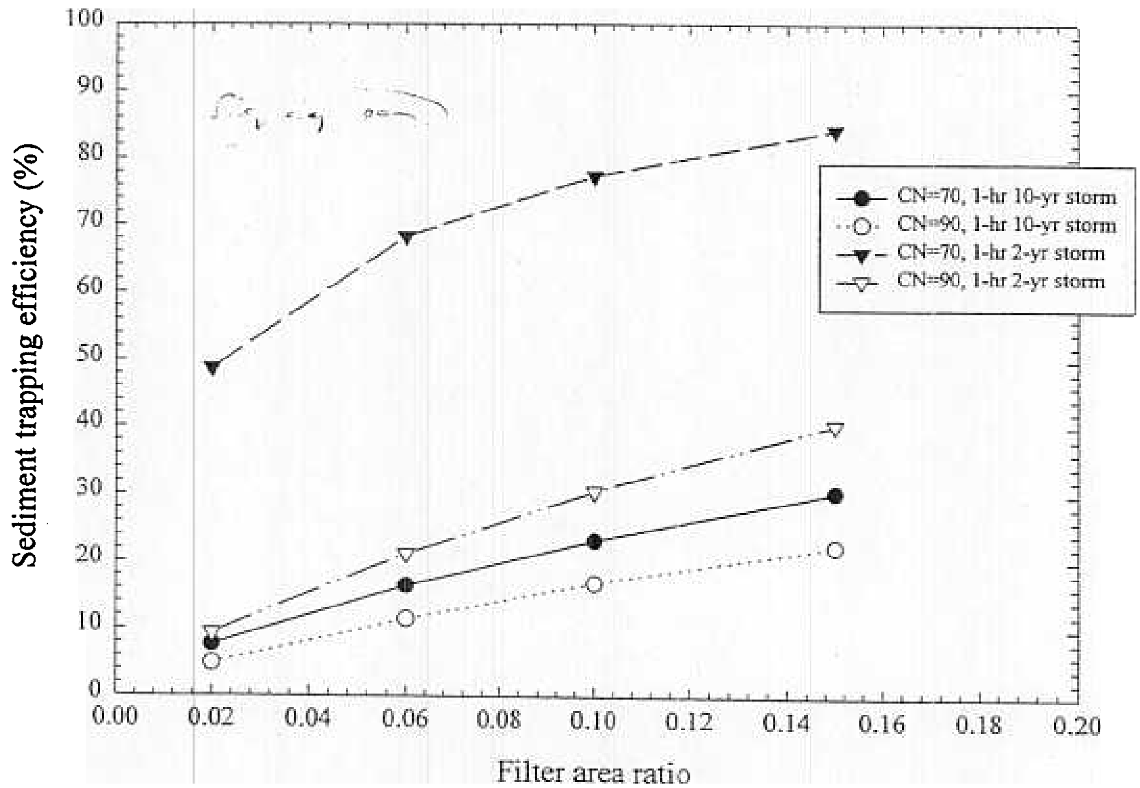


Figure 6: Effect of curve number on trapping efficiency for silty clay loam, 10% Slope

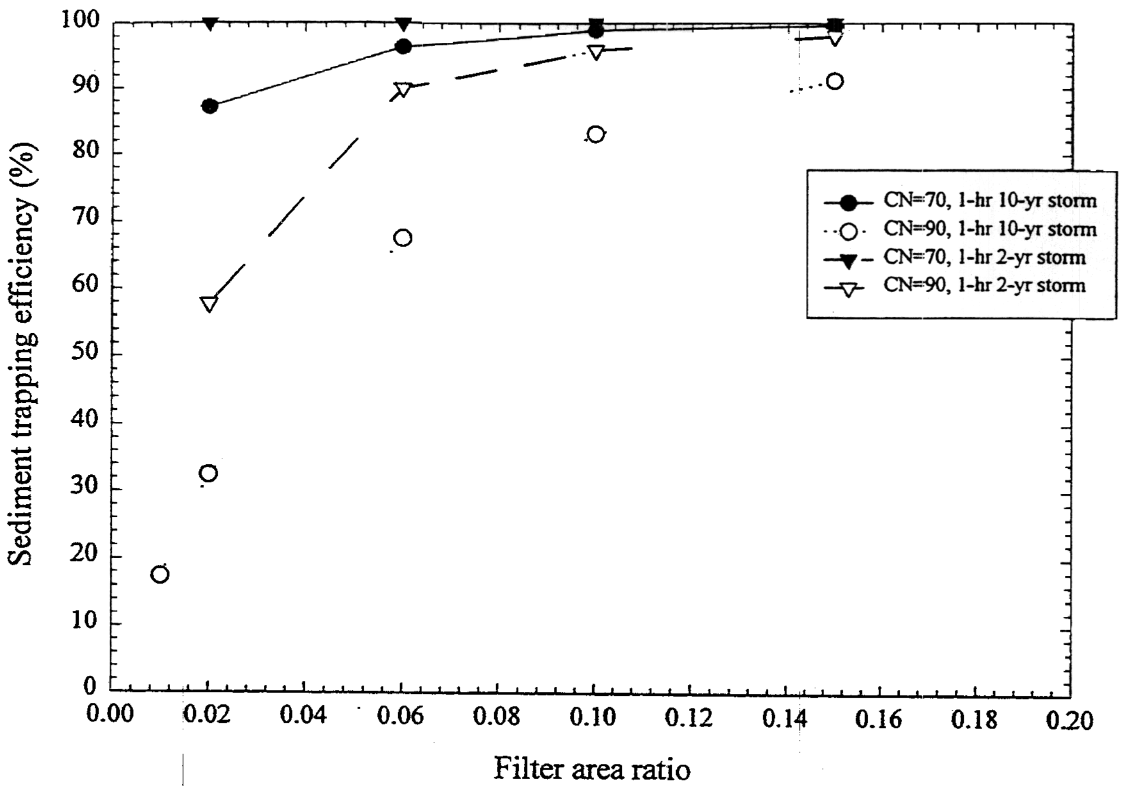


Figure 7: Effect of curve number on trapping efficiency for silty clay loam, 2% slope

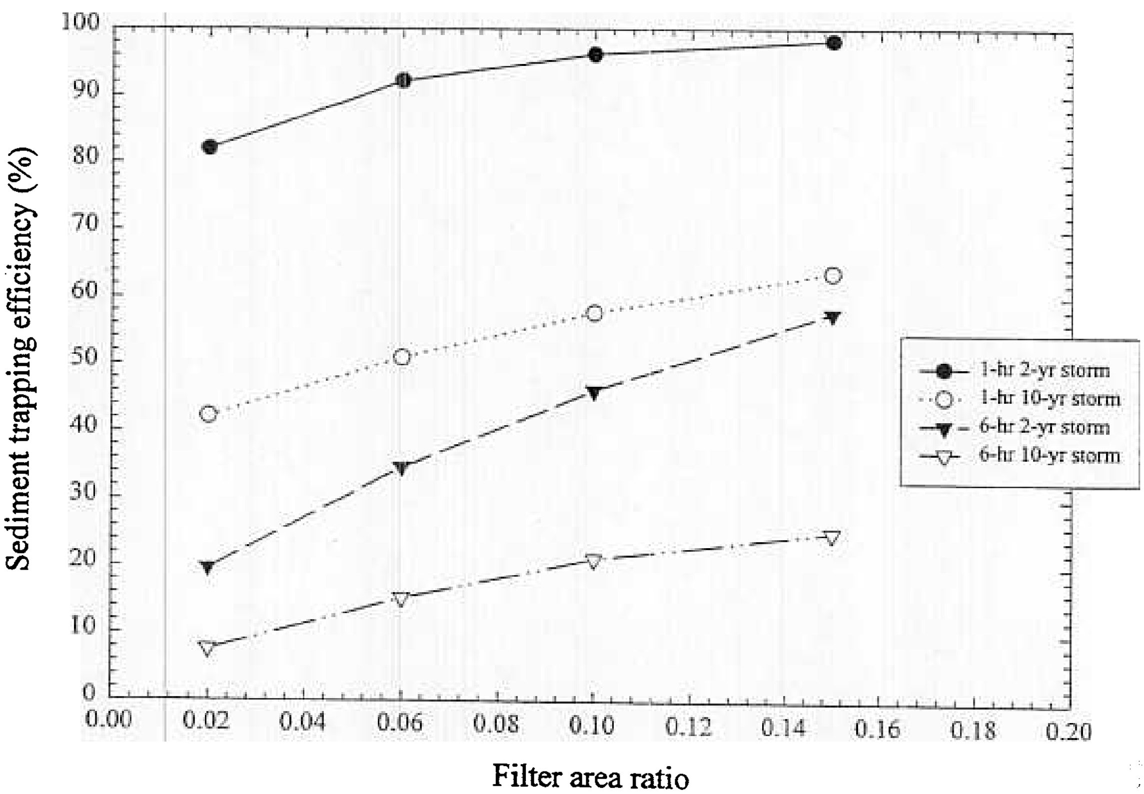


Figure 8: Effect of duration and return period on trapping efficiency for fine sandy loam, 10% slope, curve number = 75

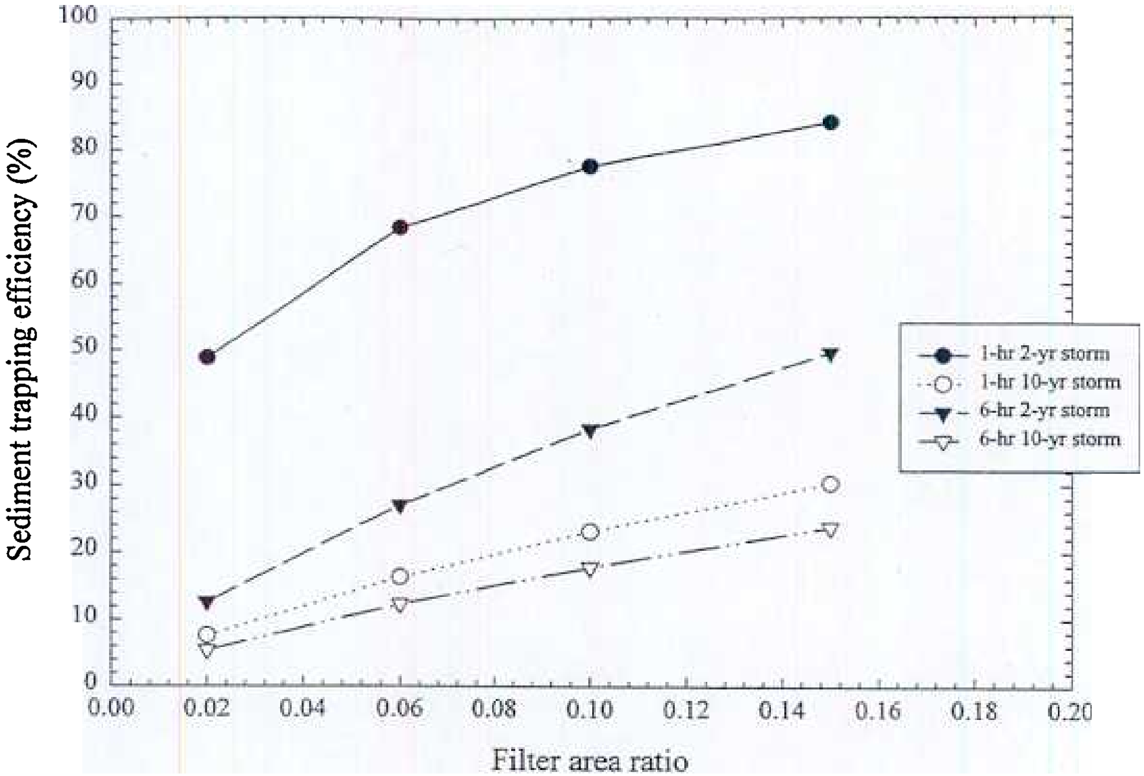


Figure 9: Effect of duration and return period for trapping efficiency for silty clay loam, 10% slope, curve number = 70

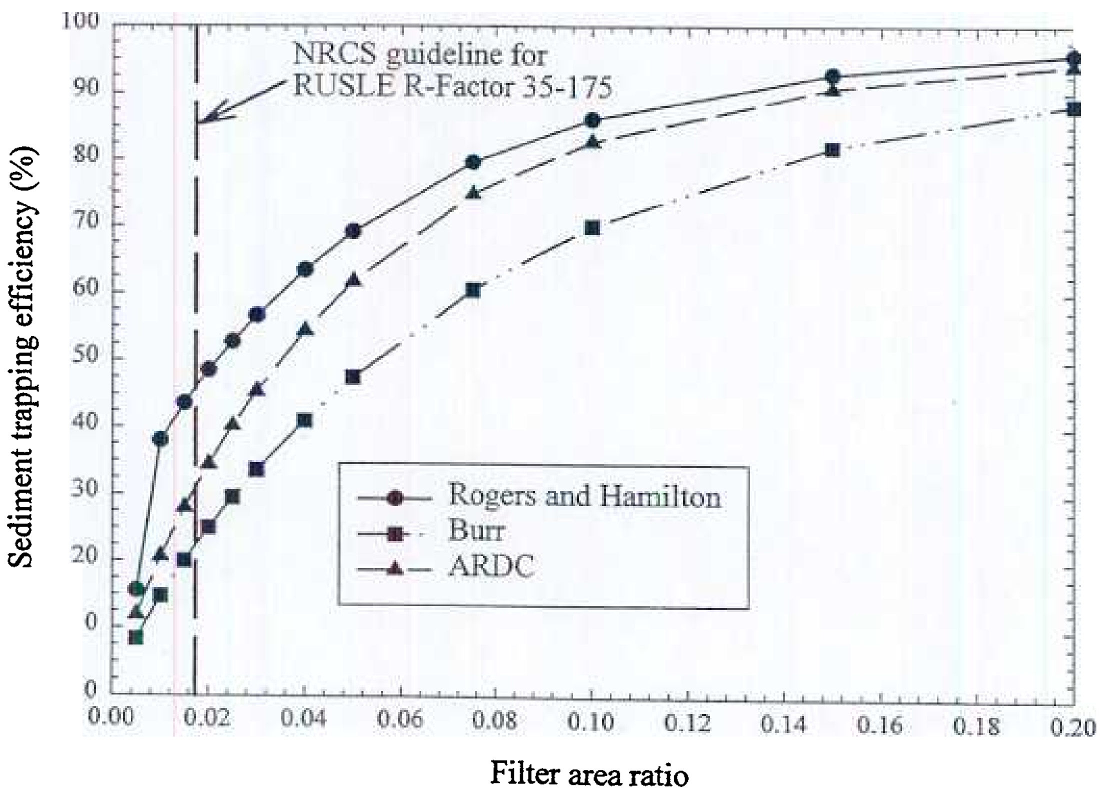


Figure 10: Relationship of sediment trapping efficiency and filter area ratio for four sites in southeast Nebraska