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Filter Fence Design Aid for Sediment Control at Construction Sites

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Notice

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Foreword

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Lawrence W. Reiter, Acting Director
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Abstract

The focus of environmental policy and regulation is increasing on water quality issues. Particularly, there is a more widespread awareness that sediment is one of the most prevalent pollutants and that the impacts of excess sediment released into lakes and rivers can be as damaging as those caused by agricultural or industrial chemicals. Due to their nature, construction sites are typically principal sources of undesirable sediment releases. To make construction activity easier, sites are generally cleared of all vegetation. The exposed soil is then made further susceptible to erosion by being disturbed by grading and vehicle traffic. Frequently, the only action taken to attempt to control sediment releases is the installation of a filter/silt fence. This approach is not generally successful, for several reasons:

- The fence is not installed as recommended by existing guidelines.
- The fence is not adequately maintained over time.
- The fence is not located for effective control of sediment.
- The site is not suitable for a silt fence.

The first two items can best be addressed through public education along with adoption and enforcement of regulations. The third and fourth items can be addressed through development of a design aid, which was the objective of this research.

Development of the design aid required the ability to mathematically model the delivery of runoff and sediment to a silt fence from the drainage area, erosion along the toe, and the behavior of water impounded behind the fence. Many of the functions in the design aid were adopted from well-known, established modeling practices. However, existing relationships describing sediment delivery and concentrated flow erosion are not applicable to the highly disturbed construction site environment, particularly since it is likely that the soil at these sites is typically excavated and replaced. Accordingly, these relationships either required adjustment or new relationships had to be developed. In addition, the hydraulics of flow through and along the silt fences had to be modeled as there were still gaps in understanding these mechanics.

To develop the additional information needed to complete a silt fence model, a limited series of flume experiments was completed and a comprehensive series of field-scale tests was conducted. Sufficient information was obtained for a first-generation model. The purpose of the field tests was to study erosion along the toe and quantify the amounts of water and sediment delivered to the fence, flowing along the toe, and flowing through the fence. Primarily, the field data were used in the model development. In some cases, the existing relationships merely required an adjustment.

Observations made during a series of construction site visits and during the field experiments were summarized into a series of recommendations for silt fence siting, installation, and maintenance. The design algorithms were incorporated into a spreadsheet model wherein the user can enter site, rainfall, and fabric information, run a hydrologic/hydraulic computation, and then assess the likelihood of failure and the performance (in terms of sediment trapped) of the silt fence. The user can vary parameters and see the impact on performance and thereby make the best possible use of the silt fence on a particular construction site. Finally, the model can also assist the user in determining when maintenance may be required.

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Chapter 1
Introduction

Project Description

This report covers the activities completed under Contract # 3C-R023-NTEX, Filter Fence Design Aid for Sediment Control at Construction Sites. Filter fence and silt fence are used interchangeably in this report. The objective of the project was to better understand and model the failure mode of a silt fence as a result of flow along the toe of the fence. Such flow can result in erosion of the soil that holds the fence's toe in the ground, resulting in eventual undercutting.

The project was divided into three phases as follows:

Phase I:

- Create, test, and revise a preliminary design model to assess silt fence installations and guide the planning of the field testing.
- Conduct field assessments of existing silt fence sites.

Phase II:

- Evaluate the preliminary design model using data from the site visits.
- Use the preliminary design model to determine final design of filter fence and protocol for field testing.
- Develop final procedures for field testing.

Phase III:

- Conduct field testing under a range of conditions to clarify the hydraulics, sediment transport, conditions leading to failure, and overall performance of silt fences.
- Combine information from the field testing with previously developed hydrology, hydraulic, and sedimentation models to develop a model of silt fence performance.
- Develop practice recommendations and a design aid based on the model.

Background

Sediment is a pollutant of concern because it is one of the leading causes of stream impairment across the United States and results in degradation of aquatic life. At a recent EPA invitation-only conference on sediment control in Cincinnati, OH (EPA, 2002), the lack of effective and economic technologies for sediment control was identified as a major issue. This paucity of technologies is a significant problem for all construction and maintenance operations in residential, commercial, and industrial development, the petroleum industry, highway and other infrastructure construction, and other activities requiring earth moving.

Currently, a silt fence is the most frequently used structural best management practice (BMP) technology that does not cause disruption of additional off-site space. As currently constructed, filter fences consist of a geotextile filter fabric supported by posts and (ideally) anchored along the toe. Its purpose is to retain sediment from small-disturbed areas by providing a detention time to allow for sediment deposition (Smolen et al., 1998). Sediment ponds, for example, are also used, but require the use and disruption of additional land. Although silt fences are widely used, it has been found, in a recent national study (EPA, 2002), that they are usually ineffective. Further, on some construction operations, silt fences have been found to cause a concentration of overland flow, creating worse problems than having no BMP at all.

Although several laboratory studies have proposed that a silt fence can be effective in trapping a high percentage of sediment, the very few limited field evaluations that have been conducted indicate that field installations of silt fences trap a very low percentage of sediment (Barrett et al., 1995). Field inspections (Barfield and Hayes, 1992; 1997) have also found that silt fences were seldom installed according to standards and specifications, and when actually installed according to the best current standards, they were still not effective in controlling sediment. Further, overland flow concentrated by the silt fence can seek the weakest spot on the fence and undercut the fence or flow through cuts in the fabric. The result is that shallow overland flow coming into the site is transformed into concentrated flow downslope from the fence, actually increasing the amount of erosion.

Studies have shown that by removing the surface cover and disturbing the parent soil material, construction operations increase sediment yield by as much as 10,000 times that of undisturbed sites (Haan et al., 1994). As this excess sediment moves into streams and waterways it not only increases the cost of water treatment and reduces reservoir storage capacity through deposition, but also modifies the stream systems and destroys the habitat of many of our desirable aquatic species (Smith et al., 1992; EPA, 2001). Ongoing research by the Agricultural Research Service (ARS) showed that the reduction in species diversity is strongly related to the number of hours sediment load exceeds 1,000 mg/L, a sediment concentration that is frequently two orders of magnitude below that in runoff from most construction sites (EPA, 2002). Clearly, methodologies are needed to reduce sediment loads to levels that maintain habitat and species diversity. The only method currently available that does not disturb large amounts of additional landscape is a silt fence, which has not proven to be effective, as will be discussed below.

Laboratory studies of the performance of silt fences using carefully controlled conditions have cited trapping efficiencies in the range of 40 to 100%, depending on the type of fabric, overflow rate, and detention time (Barrett et al., 1995; Wyant, 1980; Wishowski et al., 1998; Britton et al., 2001). Based on these data, the EPA reported in 1993 (EPA, 1993) that a silt fence can have trapping efficiencies for total suspended solids of 70%, for sand of 80 to 90%, for silt loam of 50 to 80%, and for silty clay loam of 0 to 20%. A recent evaluation of sediment control technologies conducted by the EPA has not substantiated these claims (EPA, 2002). The results cited in this study show that field-trapping efficiencies are very low. In fact, Barrett et al. (1995) obtained a value of 0% trapping, averaged over several samples with a standard error of 26%. Barrett et al. (1995) speculate that the field tests do not show results similar to lab tests because of: 1) inadequate fabric splices; 2) sustained failure to correct fence damage resulting from overtopping; 3) large holes in the fabric; 4) under-runs or under-cutting due to erosion of the toe ditch; and 5) silt fence damage and partially covered by the temporary placement of stockpiles of materials.

Field inspections conducted by Barfield and Hayes (1992; 1997) in which more than 50 construction sites were visited in South Carolina and Kentucky revealed that silt fences were frequently not installed according to standards and specifications, and further, were frequently ineffective when actually installed according to standards. In those areas where installations did meet standards and specifications, lateral flow often occurred along the toe of the fence until finding the weakest spot on the fence. At that point, it either undercuts the fence, flowed through cuts in the fabric, or overtopped. Thus, the fence converted shallow-overland flow into downslope concentrated flow, frequently causing significant, concentrated-flow (gully) erosion.

One recent long-term study has shown promise for the use of silt fences. The US Forest Service at their Rocky Mountain Research Station (Robichaud and Brown, 2002; Robichaud et al., 2000) investigated the use of a silt fence as a tool to measure erosion. In this study, they placed the silt fence across the slope and curled the ends uphill to prevent flow from going around the ends of the fence. In addition, they buried the toe of the fence upslope from the location of the fabric and wrapped the fabric around the toe trench to prevent flow over the exposed toe. An average trapping efficiency of 93% was measured over the season. They cited cleanout and maintenance as requirements to make the silt fence perform reliably.

Reasons for the poor performance of a traditional silt fence include:

1. Erosion and failure of the toe of the fence from concentrated flow caused by cross contour installations.
2. Failure to trap fines due to inadequate detention time.
3. Structural problems, including;
   a. inadequate strength of the fence fabric resulting in failure from excessive stretching in the downstream direction, and
   b. breaking and overturning of the support post due to inadequate strength and stability of the footing.
4. Post-installation problems, such as;
   a. vandalism as well as destruction by construction equipment, and
   b. lack of maintenance.

Problems 1 to 3 can be solved by more effective design as can parts of problem 4. Complete solution of problem 4 will also require more effective regulation and inspection.

Although current silt fences have a high frequency of failure, their continued use has some positive aspects, such as being relatively inexpensive, adaptable to a wide variety of sites, and suitable for implementation without major additional disturbances to the landscape beyond those required for construction. Thus it seems prudent to evaluate the performance of a silt fence under a range of controlled conditions leading to procedures for the user community to:

- Assess the conditions under which a silt fence can be applied to a particular site.
- Develop a design that is specific to that site.

Development of such procedures was the ultimate objective of this project. In the development of the procedures, the following steps were taken:

- A preliminary model was selected and used to design a test facility where rainfall could be generated on an erosive surface and flow directed toward a silt fence oriented at varying angles to the contour.

- The test facility was constructed and calibrated.
- Data were collected on three silt fence fabrics with varying cross contour angles using three different textured soils.
- A final model was developed and tested on data generated at the test facility.
- The model was incorporated into a spreadsheet computer program that is available as a design aid.
- Recommendations were made for improvements to silt fence design and installation.

Each of these items will be covered in this report.

Chapter 2
Findings/Conclusions

Findings/Conclusions from Field Visits

The field visits were very informative in pointing out the problems with silt fence usage. Unfortunately, during the period of this study construction activity was at a low; however, there were opportunities to observe several of sites with different drainage areas, terrains, ages of installation, and level of on-going construction activity.

Several of the problems observed can be addressed through better design guidance, such as better positioning of the fence. On several sites, there was bare soil between the fence and the location it was supposed to protect. On one site, a fence was placed across a roadside ditch, creating the potential for street flooding if the fence stands and the water in the ditch back up. On another site, short lengths of fence were erected on a hillside in locations where they would not provide additional protection, and could potentially worsen erosion by concentrating flows.

Existing guidance documents address the issue of where to position the fence for best protection and to avoid increasing off-site damage (Smolen et al., 1988). However, it appears that problems with positioning a silt fence result from a lack of knowledge in the user community about the guidance available. Better efforts on the part of regulating agencies to inform users about the guidance available should lead to more effective use of silt fences. A complete solution to the problem of poor positioning will also require a thorough review of erosion control plans submitted with applications for building permits and more aggressive inspection and enforcement once a site is in operation.

Follow-up inspection and enforcement is equally important as a complement to good designs. For example, one problem consistently observed was failure to anchor the toe in the manner recommended in almost every set of guidelines evaluated, including the EPA's menu of BMPs (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/site_30.cfm). A silt fence is frequently sold pre-attached to the posts, and a practice of taking the loose end (that is supposed to be buried in a toe trench) and simply laying it flat along the ground and covering it with a thin layer of soil was observed on a number of sites. While there were locations where this method of installation had not failed, it is obvious that a heavy rain shortly after installation could easily wash away the piled up soil and result in no anchoring of the toe. Again, guidance and standards are available, but it appears that the user community is either unaware or unwilling to use proper methods and inspection and enforcement of regulations is frequently not pursued. In this case, a lack of willingness to follow the recommended method is understandable, since it is clearly more costly to dig a trench, line the trench with the toe, and cover and tamp the backfill than it is to throw soil on a flap of fabric. For now, better education, inspection, and enforcement will improve this problem. Ultimately, however, contractors will only be willing to anchor the toe correctly if there is a mechanized or otherwise quick and cost-effective means of doing so. Supporting development of such a system and promoting its use should be a priority for regulatory agencies.

Fence failures due to damaged posts and fabric were also observed, which is largely a maintenance issue. However, use of the design aid developed as part of this project can help users to determine if their fence will be subjected to depths or volumes of water that are likely to be damaging. In general, a freeboard of 0.5 ft of fence above the predicted depth of flow or impounding is recommended, and the design aid can be used to predict the peak depth.

Many of the problems observed during the site visits, particularly failure to repair broken or overturned posts or damaged fence, are primarily solved through better inspection and enforcement. For remote areas that may not be visited too often, the design aid can be used to estimate the accumulated depth of sediment resulting from a typical storm and provide an indication as to how often the site should be checked for problems. If there is a nearby national weather service rain gage or some local weather station to provide inches of rainfall, each storm can be inputted into the design aid after it occurs and a running tabulation of the predicted sediment accumulation created.

Findings/Conclusions from Simulated Field Testing

Failure of the toe trench was observed in eight simulations. The erodibility of the soil was a major factor in this, with six of the eight failures occurring with the loam soil. The secondary factor was the slope, with the other two failures occurring with red clay at a 13.5% slope. The volume of soil in the toe trench was approximately 10 ft^3. Almost all the failures occurred when the net erosion, i.e., discharge from the toe trench in excess of the incoming sediment load, reached 25% of that toe trench volume.

Half of the simulations had net erosion and half had net deposition. Again, the soil type and slope along the toe were the controlling factors. Net deposition occurred for all soil types at the 1% slope. Net deposition is beneficial in that it helps protect against toe failure due to scour and represents sediment that is prevented from leaving the site.

Regardless of whether there was net erosion or deposition, there was always significant sediment discharge at the downstream end of the toe. This sediment needs to be prevented from flowing off-site. One way to contain this sediment is to extend the silt fence upslope at the ends of the toe. It is desirable to have an extension at both ends, unless the slope along the toe is relatively steep. Based on several design aid simulations, it appears that an extension of 10 to 20 ft will be sufficient in most cases. The actual length required is determined from the peak depth and the slopes along the toe and toward the fence.

Soil type was also a factor in net deposition. With the very erosion-resistant black clay, there was net deposition in five or six tests, with a small amount (about 0.25 ft^3) of net erosion during one steep slope test. For sandy loam and loam, there was net erosion for both the moderate and steep slopes.

In almost all the simulations, a first-flush effect of concentration peaking during the first 15 to 20 min of runoff was observed. Therefore, the most downstream damage is apt to occur immediately following the initiation of runoff. This points out again the importance of not discharging the flow along the toe trench directly into a stream or other sensitive area. If the area for an impoundment or sediment trap is limited, means of capturing, at a minimum, the first 15 to 20 min of discharge should be developed.

The accumulation of sediment in sags in the fence can be beneficial up to a point by creating flat areas where more deposition is likely. The accumulation of sediment will eventually become a problem either by causing collapse of the fence under the loading or reducing the height so the overtopping becomes likely. The design aid can help in determining when there is too much sediment and when clean-out is needed. During the field tests, an apparent equilibrium was observed with incoming and discharged sediment loads approaching each other. The design aid can be used to determine if the soil/slope combination is one that will result in equilibrium under a given rainfall, thereby making the duration of rainfall much less of an issue.

The field test site usually became saturated and depressions filled in a short time – typically less than 15 min - giving a constant rate of runoff, usually slightly less than the rate of rainfall. This indicates that the National Resources Conservation Service (NRCS) curve number method for generating runoff is valid for construction sites, as the volume of runoff converges to a constant value under an input of steady rainfall.

In summary, a number of the observations and results from the construction site visits and simulated field studies confirmed the validity of the recommendations contained in the numerous guidance documents.

Chapter 3
Recommendations

Observations made at field visits, plus the data and observations collected in the field and flume testing have contributed greatly to our understanding of how silt fences functions under different conditions. That data, combined with information gleaned from literature and personal contacts with other researchers and agencies indicate that a properly installed and maintained silt fence can significantly reduce the amount of sediment discharged from a disturbed area such as a construction site. However, this data and literature also indicates that a silt fence is more often than not installed in a manner that renders it ineffective. Recommendations made earlier by EPA were based on laboratory data (EPA, 1993) since field observations were not available; however, this study plus limited additional studies (Barrett et al., 1995) indicate that the laboratory studies were not representative of actual practice in the field. The results of the study in this report, plus one field study of the use of a silt fence as a technique to measure sediment yield (Robichaud and Brown, 2002), indicate that currently available silt fences can be installed in a manner to provide effective sediment control technology. To make that happen, however, it is critical that the fence be properly cited, installed, and maintained. In addition, some changes are needed in guidelines typically used by most regulatory agencies. Therefore, the following procedures with respect to siting, installation, and maintenance are recommended for addition to current guidelines.

Siting

- Restrict the drainage area so that the predicted depth of water at the fence under the design rainfall does not go above 0.5 ft. The design aid spreadsheet which is described in Chapter 7 can be used to develop the depth prediction. Since sediment is likely to accumulate behind the fence, restricting the depth will allow for some sediment build-up before overtopping becomes a problem.
- The silt fence should be located on the contour as closely as possible. Since this is frequently not possible due to site limitations, the combination of cross contour angles and length of silt fence segment should be limited to prevent erosion of the toe of the fence and undercutting. The design aid in Chapter 7 can be used to determine the length that will cause erosion on a site specific basis for a selected design storm.
- Silt fences should always be installed in a bowl shape with limits to the length of individual segments based on the ability of the installation to store the design storm without overtopping. When installed with the bottom section parallel to the contour, both ends should have an upslope distance sufficient to store the design storm without having flow discharge around the upslope end. When installed with a cross contour slope, it should be assumed that the design storm will be stored in the catchment formed by the upslope extension at the lower end of the silt fence segment. When calculating the flow through the fence, the flow rate through the fence should account for the impact of plugging. The design aid in Chapter 7 can be used to determine the length of the upslope extension and the impacts of plugging.
- The required trapping efficiency could be determined by the design aid in Chapter 7 to assure that the required trapping efficiency will be met, particularly when fine textured soils are

involved. Following design criteria will not always assure that the trapping efficiency standards will be met.

Installation

- To avoid failure of the silt fence, measures should be taken such that the toe does not erode to a level that causes undercutting. To assist in preventing erosion of the toe, the fence should be installed so that the fabric lines the ditch excavated for the toe and the ditch is filled with soil and compacted to a density necessary to prevent erosion of the toe. In order to further protect the toe trench, the fence fabric that becomes the vertical portion of the fence should exit the trench upslope and be wrapped over the toe trench before being attached to the posts which are installed at the downslope edge of the trench.
- The depth of the toe trench should be sufficient to prevent undercutting from the design storm; in general, guidelines and experience indicate a minimum of 6 in. burial depth. When trenching machines are used, tests should be run with the equipment to ensure that the fence will not be pulled from the ground when soil is saturated, under full impoundment volume of stored water, and post spacing equal to or greater than specified in the installation plans. Also, tests should show that the fence will not fail due to undercutting with the machine installed systems when used on slopes equal to or greater than those in the installation plans.
- Posts should be installed with sufficient strength to resist breaking from the forces of impounded water and deposited soil during the design storm. Although the fence may be designed for trapping efficiency in a given design storm, when storms greater than the design storm occur, more water may be impounded than would occur in the design storm; therefore, the posts should be designed with sufficient strength to withstand full impoundment. In addition, field observations of silt fence installations indicate that construction operations often result in damage to the small posts that are commonly pre-attached to fabric in the manufacturing process.
- To be effective under the high moisture conditions that occur during stormwater events, the posts should have sufficient bearing surface to remain erect when the soil is saturated and the storage volume behind the fence is full. In cases where the bearing strength of soil is insufficient, additional bearing surface should be included by the use of fins, or a different post geometry and burial depth.
- Excessive stretching of fence fabric can lead to failure; therefore, a combination of small spacing between posts and reinforcing of fence with either a high strength geotextile grid or metal web fence backing should be used at all installations.

Maintenance

- Fences should be inspected after significant rainfall events (typically 0.5 in. or more) for significant deposition of sediment behind the fence, undercutting, damaged posts, areas where the fence has overtopped, and downslope damage from locations of fence failure. The design aid can be used to predict the amount of deposition expected for specific rainfall events, giving an indication of the amount of storm activity that can occur before maintenance is needed. Cleaning out of accumulated sediment is recommended whenever the height of fence above the deposition is less than 0.75 ft. This assumes that the area/depth recommendation in the section on siting is followed.
- In sandy or loamy soils, failure by toe erosion is also likely. The toe should be inspected after heavy rains. The design aid can be used to predict if a specific level of rainfall intensity will cause failure of the toe.

- Preventive maintenance checks should also be made on a regular basis during periods without significant rainfall events (at least weekly) for damage from construction operations and vandalism. Repairs should be made as necessary, including but not limited to replacing fence segments, patching tears and cuts, reinstalling posts that are damaged, reburial of fabric in the toe trench, and cleanout of deposited sediment.

Chapter 4
Experimental Methods - Investigations and Simulated Field Experiments

Techniques and protocols for the construction site visits and the simulated field experiments are summarized in this chapter. Information included in this chapter will provide end-users with a basis for determining if the technique or recommendation presented is applicable to a specific design situation. Details and development of the mathematical model and design aid are given in Chapter 6.

Site Investigations

Construction sites in Oklahoma and South Carolina were visited to obtain information about how silt fence installation practices were actually followed, to observe any problems, and to determine from visual inspection, if possible, whether the silt fence resulted in a decrease in the sediment leaving the site. Data from selected sites were used to evaluate the ability of the routines in the preliminary design model to route the water and sediment and predict erosion and deposition in the context of flow toward and along a silt fence.

The sites in Oklahoma were chosen to represent the widest variety of conditions possible in terms of size, terrain, soil, and age and condition of installation. A mixture of well and poorly performing installations was also considered desirable. Unfortunately, construction activity in the Stillwater area was down during the original period allotted for the visits, April to June 2003, and only three appropriate sites were identified. It was necessary to wait until late 2003 to complete the visits, and the number of active sites where a silt fence was in use was still very limited. Three additional suitable sites in varying stages of activity were located: a newly-installed fence on a recently graded area, a site with intense building activity, and a mature site where the fence was ready for removal.

For each site, as much history as possible was obtained from the owner or contractor. During site visits, to the extent possible, a prescribed series of observations and measurements was made. At times, climate, terrain, or vegetation conditions made it necessary to skip some observations or measurements.

The observations planned for each site included: type of fabric and properties; anchoring of both toe and posts; fraction of vegetative cover on contributing area, type of vegetation, and fraction of paved surface; and location of failure points with estimates of causes of failure. To generate the data needed to evaluate the preliminary design model, a survey was completed to determine contributing drainage area and slope, slope of the toe of the fence, and angle between contour and toe of fence. The height of the fence, and spacing of posts were also recorded. Soil samples were gathered for grain size analysis, and digital photographs were taken at each site.

During visits in late 2003, the measurements required only for the preliminary design model assessment were skipped, since that assessment was complete and the field plot had been constructed by that time. Table 4-1 gives a description of the construction activity and features of the sites.

Table 4-1. Sites visited in the vicinity of Stillwater, OK

Site Number	Description	Location	Visit Date
1	Construction of a walking trail – very long length of fence	Stillwater, OK – near Albertson's	03/21/03
2	Construction of a walking trail – large, steep drainage area	Stillwater, OK – near Fazoli's	03/26/03
3	New high school – steep drainage area with sandy soil	Perkins, OK	04/09/03
4	Same as site 2 – revisited because heavy rains caused failure	Stillwater, OK – near Fazoli's	04/20/03
5	Single commercial building – newly installed fence	Stillwater, OK – Miller and Main	10/07/03
6	Commercial office complex – very active site	Stillwater, OK – Western Rd.	12/30/03
7	Residential subdivision – construction nearly completed	Stillwater, OK – Lakeview Rd.	12/30/03

Simulated Field Testing

Objectives

A series of tests with controlled conditions was conducted at a specially-designed silt fence testing site located at the USDA-ARS Hydraulic Laboratory. The purposes of the tests were to (1) supplement the information obtained from the field visits and the literature search with an in-depth examination of silt fence performance; and (2) obtain numerical data to develop and validate the final mathematical model.

Parameters that were varied from test to test are summarized in Table 4-2. Factorial experimental design was used, with all combinations being tested. Dates and parameters for all simulations are given in Table 4-3.

Table 4-2. Grid of parameters varied over the simulations

Soil Type	Slope Along Toe	Fabric
Silty clay (sand-15%, silt-44%, clay-41%)	Steep – approx 13.5 %	Nilex 2127 (Fabric A)
Loam (sand-53%, silt-32%, clay-15%)	Moderate – approx 7 %	Nilex 2130 (Fabric C)
Sandy loam (sand-64%, silt-17%, clay-20%)	Flat – approx 1%	

Table 4-3. List of simulation dates and parameters

Simulation Date	Soil Type	Fabric Type	Slope Along Toe %
12/18/2003	Loam	C	Flat
1/15/2004	Loam	A	Flat
3/2/2004	Loam	C	Moderate
3/10/2004	Loam	A	Moderate
3/19/2004	Loam	A	Steep
3/24/2004	Loam	C	Steep
4/20/2004	Sandy loam	C	Steep
4/22/2004	Sandy loam	A	Steep
4/28/2004	Sandy loam	A	Flat
5/4/2004	Sandy loam	C	Flat
5/7/2004	Sandy loam	C	Moderate
5/11/2004	Sandy loam	A	Moderate
5/18/2004	Silty clay	A	Moderate
5/21/2004	Silty clay	C	Moderate
5/25/2004	Silty clay	C	Steep
5/27/2004	Silty clay	A	Steep
6/2/2004	Silty clay	A	Flat
6/4/2004	Silty clay	C	Flat

Monitoring had to be accommodated in the field plot design in order to determine runoff rates and sediment yield (1) at the edge of the silt fence's source area, (2) at the downstream end of the toe of the silt fence, and (3) flow passing through the fence. The experimental methods had to include provision for obtaining sufficient data to validate the mathematical model.

This section provides an overview of the field plot design and experimental methods and results are discussed in Chapter 5.

Field Plot Design

In order to provide access to a wide variety of test conditions, a Silt Fence Test Site (SFTS) was constructed at the USDA-ARS Water Conservation Structures Laboratory in Stillwater, OK. The need for access to water and electricity was the primary constraint in site selection. A secondary consideration was to have a terrain that was compatible with the proposed field plot configuration, as shown in the original conceptual drawing (Figure 4-1). Accordingly, a hillslope near the large concrete flume was selected.

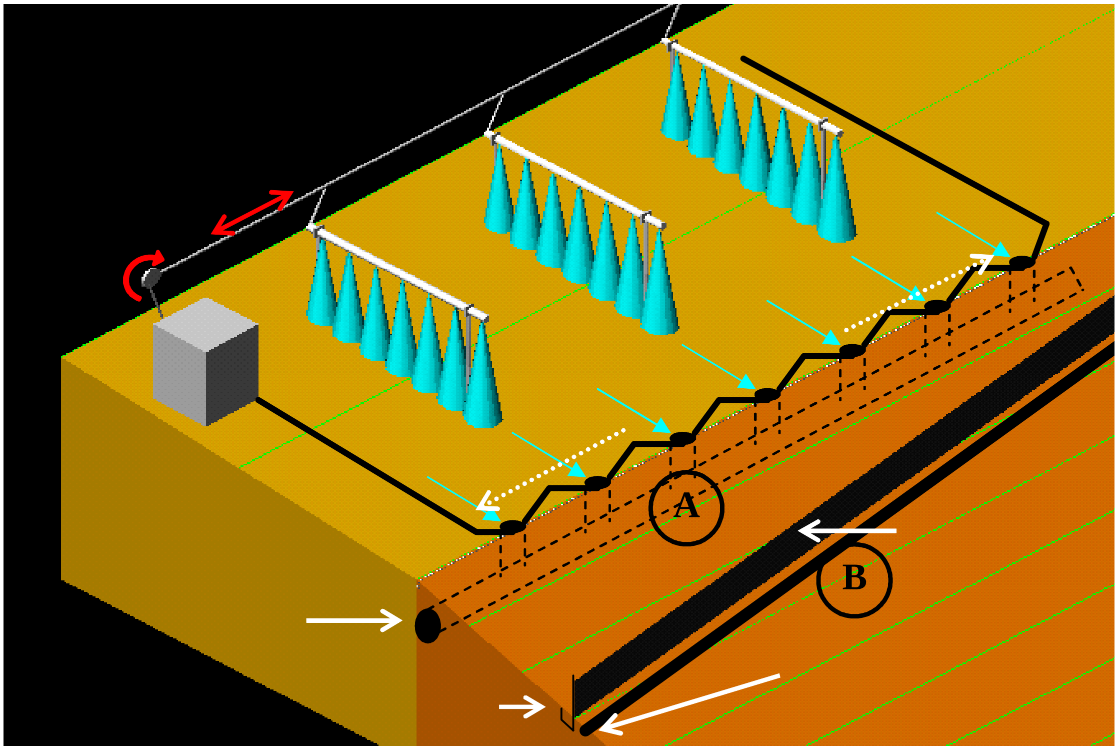


Figure 4-1. Conceptual drawing of the Silt Fence Test Site (SFTS).

Note: Runoff and sediment from the source plot sampled at A, and discharge through the fence is sampled at B.

Since a rainfall simulator would have to be constructed, limitations to the size of the source area for sediment and runoff had to be imposed. An area of 20 ft upslope by 40 ft along the fence was selected as being small enough to be manageable for purposes of constructing a rainfall simulator yet large enough to represent a large number of field conditions. A 5% slope was selected for the source area. The covered, sloped area between the samplers and fence (Figure 4-2) needed to be as steep as possible so that the slope along the toe could vary. However, it also needed to be flat enough that personnel and equipment could work safely. Balancing these concerns and the need to minimize the amount of fill required, a 20 ft long, 3:1 slope was selected. This would allow slopes along the toe to vary from zero to almost 14%.

Source area runoff samplers were installed as shown in Figure 4-3 to briefly sample runoff water and sediment from the source area and create minimal disturbance to the flow as it progressed toward the silt fence. To further minimize disruption of the flow, the samplers would operate in alternating groups, with only half of the samplers open at any one time.

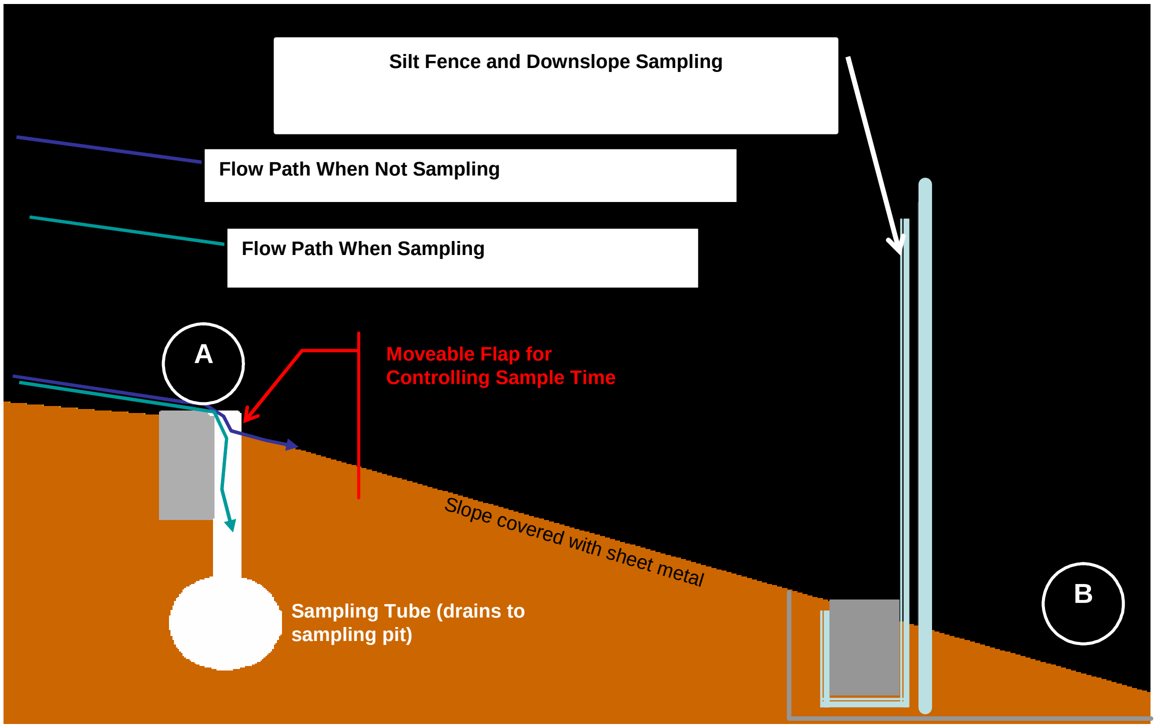


Figure 4-2. Covered sloped area between samplers and test section of silt fence

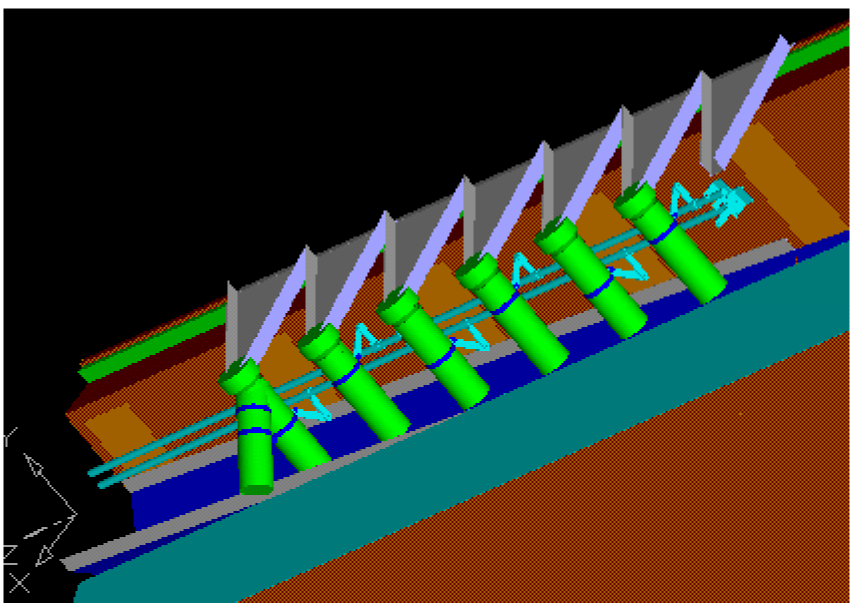


Figure 4-3. Source area runoff samplers

For the rainfall simulator to adequately cover the 20 by 40 ft area, it required four rows of nozzles, seven per row. A central main supply line provided water to the four rows, with three nozzles per row on one side of the main and four nozzles on the other side of the main. Since the runoff plot had a 5% slope, the simulator had to be built on a slant, to make all rows of nozzles 10 ft off the ground. Plan and profile of the simulator are shown in Figure 4-4.

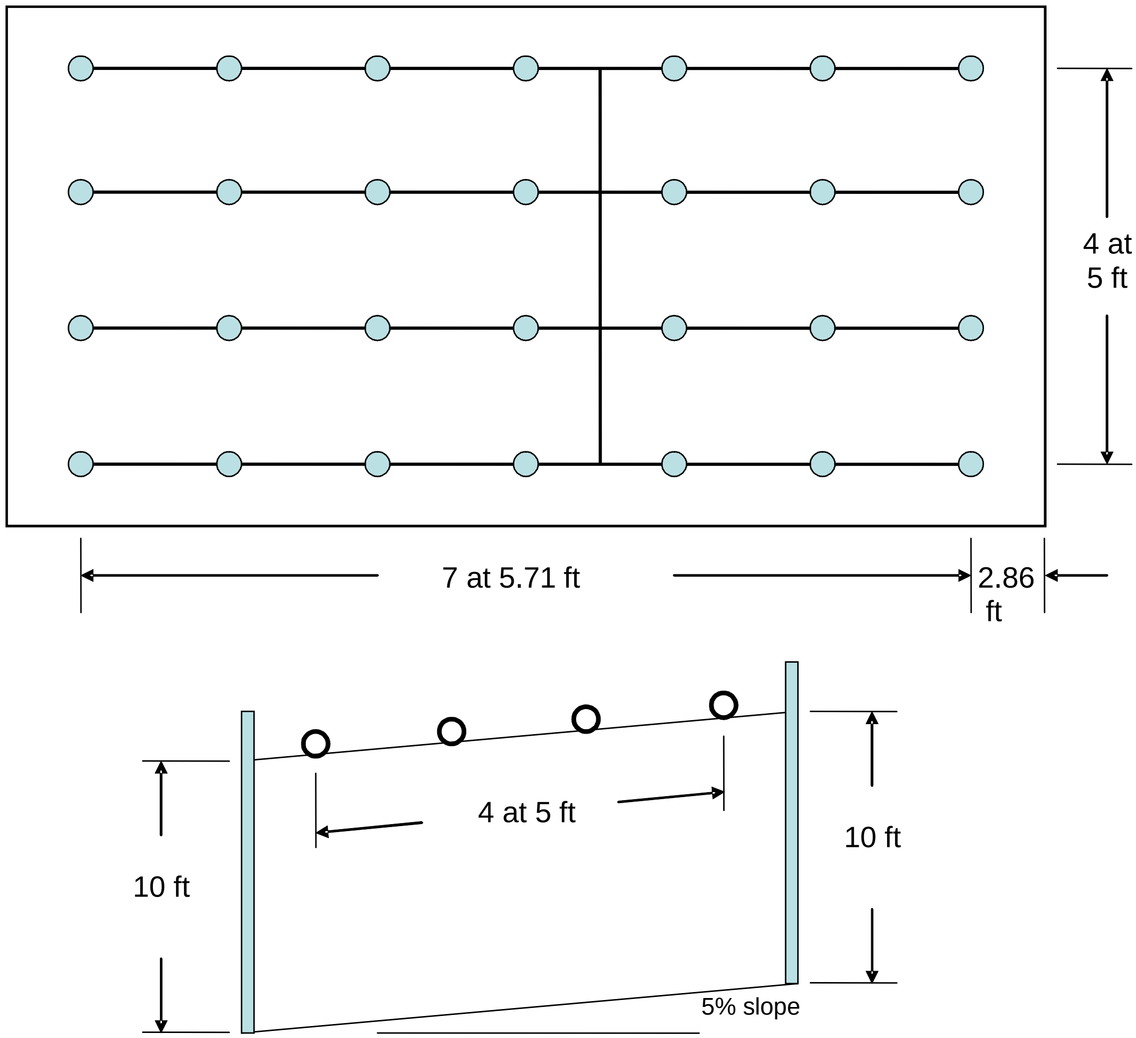


Figure 4-4. Plan and profile of the rainfall simulators

It was desirable to have a simulator that could be programmed to deliver between 1 and 3 in./h. The nozzles were grouped in rows, with the first row (row closest to the samplers) and third row operating together and the second and fourth rows also operating together. A controller was programmed to pulse the nozzle groups at intervals to achieve the desired rainfall intensity. The final rainfall simulator design parameters are summarized in Table 4-4.

Discharge along the upslope side of the toe of the fence was collected at the end of the fence into a sheet metal trough with a spout as shown in Figure 4-5. A similar trough with spout was attached to the end of a triangular trough mounted on the downslope side of the fence, also shown in Figure 4-5. A sample pit, deep and wide enough for a technician to maneuver a bucket under a spout and deep enough to hold the bucket in place at the end of the spout, was excavated at the edge of the plot. The walls of the sample pit, which were approximately 3 ft deep, were supported with metal plates.

Table 4-4. Design parameters for rainfall simulator

Parameter	Unit
Nozzle type	Spray Systems Fulljet: ½ HH-SS 30WSQ
Height above ground	10 ft
Minimum spacing	6 ft
Operating pressure	4 lb/in.^{2}
Operating discharge	2 gal/min

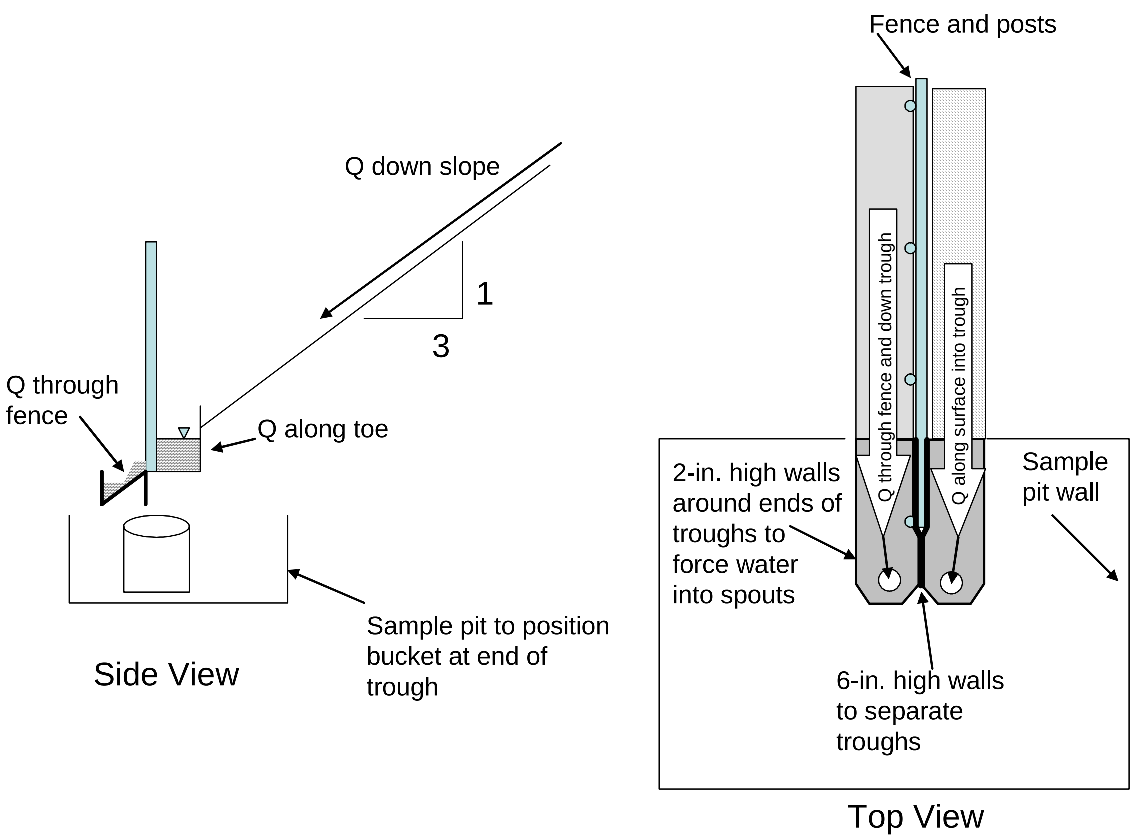


Figure 4-5. Sampling locations upslope and downslope of the silt fence

A portable pump mounted on a skid was selected to deliver the water to the simulator. The pump intake was connected to the water source with a 2.5-in. hose, and the pump discharged into a 2.5-in. hose connected to the simulator main. The pump motor was electric and could be plugged into the outlet on the power pole at the site. A back-up pump was available if the pump should break down during a simulation. Figure 4-6 shows the pump connection to the simulator. To monitor the pressure, a pressure gage was mounted on the main next to the front row of nozzles.

Figure 4-6. Pump connection to the simulator

Light-gauge sheet metal with ribs spaced at 1-ft intervals was used to cover the soil between the front plot wall and the silt fence. The ribs would function to keep the flow distributed along the plot and also minimize warping and deforming of the sheet metal under extreme temperatures.

The toe of the silt fence was buried in the manner recommended in the EPA menu of BMPs (http://cfpub.epa.gov/npdes/stormwater/menuofbmps/site_30.cfm). A trench 0.5 ft deep by 0.5 ft wide was excavated and lined with the toe of the fence. The trench was then backfilled with the same material as was present on the source area and compacted by hand tamping. This method of compaction was considered the most representative of what occurs at construction sites. Figure 4-7 is a schematic of the installation.

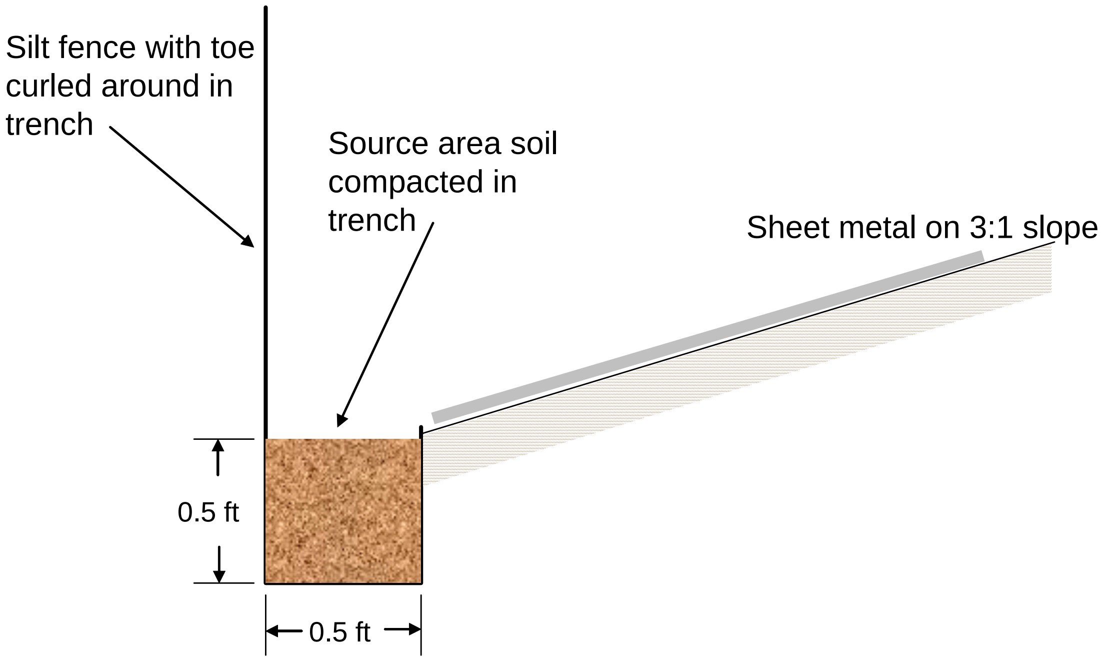


Figure 4-7. Schematic silt fence installation

Simulated Field Experimental Methods

The following sections describe the data collection activities and information that was measured and/or derived based on the sampling. The laboratory analyses conducted and methods used are also described.

Field Data Collection

Field data collection included activities before the start of the simulation, at intervals during the simulation, and at its conclusion. Data collection activities before each rainfall consisted of collection of soil samples for bulk density and surveying a pre-test profile of the toe trench. The samples for bulk density were collected using the drive cylinder method. A total station was used to complete the survey. Elevations were tied to a benchmark located on the concrete foundation for the storm sewer grate. For each profile, an angle plus horizontal and vertical distances were recorded at the edge of the sheet metal, at the center of the toe trench, and at the silt fence. These measurements were taken at every fence post.

The following sampling and data collection activities took place while the rainfall simulator was operating:

- Samples for flow rate and sediment concentration
    - Edge of source area
    - Flow along toe of fence
    - Flow through fence
- Rainfall and wind gauge readings
- Video record of flow in toe trench
- Visual observations of flow, erosion, etc.

In each test, sampling for flow rate and sediment concentration was initiated as soon as there was sufficient runoff for an adequate sample. To compute flow rates, the time required to collect each sample was recorded. Samples were collected in pre-weighed containers – either bottles or buckets, depending on flow rate - and the samples plus containers were weighed to find the weight and volume collected. When discharge rates were relatively slow, samples were collected in 1-L bottles. These samples were taken directly to the lab for weighing and sediment concentration analysis. With higher flow rates, samples were taken in 5-gal buckets, weighed in the field, and grab samples were taken in 1-L bottles for laboratory analyses.

Two rain gauges were placed in the source area, roughly centered in each half. These were the small plastic rain gauges that are read by noting the level of the water on the scale printed on the side of the container. The rain gauges were read at intervals of 10 to 15 min (depending on other responsibilities).

A video record was made of the flow in the toe trench by means of video cameras set on tripods at each end of the trench. In addition, the field supervisor observed flow in the toe trench and through the fence and noted any significant or unusual occurrences, such as the time at which flow ceased in the collection trough downstream of the fence. Scour and deposition in the toe trench were monitored and significant events such as the times and locations of complete scour down to the silt fence were recorded. The observations are summarized in Chapter 5. In addition, many of the events of the simulation were recorded with a still (digital) camera.

Laboratory Analyses

Laboratory analysis was performed to determine the sediment concentration, soil bulk density, and particle size of the eroded sediments. Total suspended solids (TSS) testing was performed using a Syringe Filter Method based on EPA method 160.2, "Standard Procedure to Determine TSS." The procedure given in ASTM D3977 – 97 was followed to perform the suspended sediment concentration (SSC) test. Soil bulk density was determined using the Drive Cylinder Method (ASTM D2937). For particle size, the larger size fractions were determined using a wet sieve apparatus. The small size fractions passing the wet sieve were analyzed using a Microscan II x-ray particle analyzer. Laboratory analysis results are discussed in Chapter 5.

Data Reduction

Field measurements and laboratory analyses were used to generate a variety of hydrologic and sediment results to support the conclusions and aid in the modeling effort.

Flow hydrographs

Sample collection times and volumes obtained were used to develop the time series of discharge at the edge of the source area, along the toe of the fence, and passing through the fence. Linear interpolation was used to estimate the discharges between the discrete data points.

Rainfall data

Rain gauge readings were used to determine the cumulative depth vs. time relationship for each simulation. Because the simulator was programmed for a constant intensity, these relationships were all very close to linear. Least squares linear regression was used to estimate the rainfall depths between the discrete data points.

Cumulative flow volumes and average flow rates

The volume discharged between two sample collection times was estimated by finding the area under the flow hydrograph between those two times and a cumulative volume vs. time relationship was developed. This relationship was also very close to linear because the runoff rate converged to a constant value soon after the source area was saturated. The slope of that linear relationship (estimated by least squares regression) was used to estimate the average discharge rate. These volumes and discharge rates were computed for all three sampling points.

Curve number

The cumulative rainfall and flow volume estimates were used to estimate the NRCS curve number for each simulation. The runoff volume from the source area was expressed in units of inches of depth and a value of curve number that minimized the sum of squared errors between predicted and estimated values of runoff depth was determined.

Sedigraph or sediment flow rate in lb/s vs. time

Each flow rate sample had an associated sediment sample, which was analyzed for concentration. The sedigraph ordinates were obtained as the product of the concentration (converted to lb/ft^3) times the flow rate (ft^3/s). The sedigraph was then used in the same way as the hydrograph to estimate the weight of sediment discharged between sampling intervals. Sedigraphs were computed for all three sampling points.

Cumulative weight of sediment

A cumulative weight of sediment discharged vs. time relationship was developed for all three sampling points. The average sediment flow rate over the simulation (lb/s) was estimated by finding the slope of that relationship.

Average sediment concentration

Average sediment concentration over the simulation period was computed by dividing the estimated total weight of sediment by the estimated total volume of water and converting to mg/L. This was computed for all three sampling points.

Chapter 5
Results and Discussion – Investigations and Simulated Field Experiments

Results from the construction site visits and the simulated field experiments are summarized and discussed in this chapter. These results, along with information obtained from the literature, were used in development of the mathematical model, design aid, and BMP recommendations. The majority of the literature citations were included in Chapter 1 and details of the development of the mathematical model and design aid along with testing the model with field laboratory data are given in Chapter 6.

Construction Site Investigation Results

Several problems were observed on a number of construction sites visited. One was a failure to anchor the toe in the recommended manner, particularly where it appeared that the fabric was purchased pre-attached to the posts. In several cases, the loose fabric that was supposed to be anchored in the toe trench was simply stretched out flat upslope of the fence and covered with soil. At those sites visited, the main problem observed with this method of installation was bulging of the fence from placing the soil against the fabric. In some locations, there was excess soil behind the fence, reducing the vertical extent of the fabric and making overtopping by water or accelerated filling with sediment more likely.

Significant sediment accumulation was observed at Site 2 (refer to Table 4-1), where at one location there was less than 0.5 ft of fabric above the accumulated sediment. The site was re-visited after about 2.5 in. of rain occurred; the silt fence was completely covered with deposited sediment.

Lack of maintenance was another observation. The extent of this ranged from failure to repair localized damage from broken posts or tears in the fabric to failure to repair the total collapse of the fence to failure to remove deposited sediment.

Improper placement was also observed at some sites. At several sites, disturbed soil was located between the fence and the area that was supposed to be protected. At one site, a fence was placed across a drainage swale.

There was also evidence at some of the sites that the silt fence did function to reduce the amount of sediment transported off-site, although the magnitude of this reduction could not be estimated from the observations and measurements. Evidence to support that the silt fence was functional included observation of deposited sediment upslope of the fence, absence of rills or other evidence of concentrated flow downslope of the fence, and whether or not the fence was intact and erect.

Simulated Field Testing Results

The series of 18 tests conducted showed that the silt fence test site yielded a wide range of useful information about silt fence hydraulics and overall performance. Each test was a controlled-conditions test, under simulated rainfall, of commonly-used commercial grades of silt fence installed to emulate construction site conditions. Field-scale data including runoff rate, sediment yield, flow and sediment transport along the toe, and sediment transport through the fence were collected. The tests were structured so that the impact of changes in slope along the toe, soil type, and fabric type could be assessed.

Insight and data regarding the performance of a silt fence was obtained through visual observation and photography and through field measurements and laboratory analyses of water and sediment samples. The following sections discuss the results and present an analysis of variance and trends.

Results Obtained by Observation

Although informal, a very informative component of the field testing was the record of visual observations made by the field supervisor and crew. Several interesting phenomena were observed through this process.

The "first-flush" effect

Once runoff was established, it appeared that the discharge exiting the toe trench at the downstream end had greater turbidity during the initial phase of the simulation. This was considered reasonable and was attributed to the fact that there was loose material in the trench that would be easily dislodged.

This observation is confirmed by analysis of water samples taken from the toe trench. For practically all simulations, the concentration would peak early in the simulation and then decrease and level off. There were a couple of exceptions to this, and the observations made at the time do not suggest a reason.

Accumulation of sediment behind the fence

For tests where there was no erosion, sediment accumulated along the toe, and significant deformation of the fence occurred. This was similar to the upslope deposition observed during construction site visits.

Two impacts were associated with this deposition. One was that it created a location where flow along the toe would tend to slow down, leading to additional deposition occurring. In the short run, this would help the fence to be more effective at trapping sediment. In the long run, the accumulated sediment itself can be a source of failure, particularly if the fence is not maintained regularly.

The other impact of this had more to do with how measurements were made rather than with how the silt fence functions in the field. The collection trough on the downstream side of the fence was mounted along the toe of the fence and flush with the ground surface. When bulging of the fence occurred, it could partially or completely block the trough. For that reason, it appears that the sampled flow passing through the fence in these cases may not represent the discharge that would be seen under field conditions. However, the concentrations recorded should be representative, since the flows that did traverse the trough would not likely pick up additional sediment. Also, when flow was not blocked in the trough, it appeared to be free-running with no unusual deposition that would distort the concentration data.

Attainment of equilibrium

After a period of time, typically in the range of 20 to 30 min, the scour and deposition appeared to reach equilibrium. This was observed by noting the depth of scour along the walls of the toe trench and the presence and movement of bed features such as head cuts, and by probing the soil in the toe trench with a pointed stake painted with alternating 0.1-ft rings to observe the depth to the silt fence lining the toe trench.

When equilibrium was observed, the discharge in the toe trench was obviously continuing to transport sediment, but it appeared that a point had been reached where the amount of sediment coming in from the source area was equal to the amount of sediment exiting. This was confirmed by examination of plots of cumulative weight of sediment leaving the source area and exiting the toe trench at the downstream end. In a number of simulations, there would be a point after which the plots of cumulative sediment yields were parallel with each other, indicating that mass flow rates of sediment into and out of the toe trench were roughly equal.

After the first two or three simulations, it was confirmed by looking at the data that the equilibrium condition was, in fact, occurring so attainment of equilibrium was used as a criterion for stopping the rainfall. Typically, once equilibrium was observed, the simulation would continue for 15 to 20 min. and then shut down.

An equilibrium condition was not attained in all simulations, depending on the soil type and slope. With the highly erodible sandy loam soil, the toe trench failed at all slopes. The simulation was stopped once there was significant progression of failure. However, it appeared the toe trench would continue to scour until the silt fence was exposed for its entire length. The same was true with loam when the slope along the toe was steep (approximately 13.5%).

Results of Hydrologic Analysis

Computations described in Chapter 4 were completed for each simulation, and the results are summarized in Table 5-1. Once the flow data were all processed and assembled, several phenomena which were not observable during the simulation became apparent.

The rainfall gauge readings indicated that the simulator was operating at more than 2 in./h, to up to about 2.5 in./h. This was not considered a problem since the 2 in./h rate was an arbitrary selection and the hydraulic components of the test plot (samplers, collection troughs, etc.) were sized for rainfall rates of at least 3 in./h.

Runoff from the source area was more variable than rainfall, particularly early in the simulation. This is partly due to the disturbed nature of the source area, which would not achieve saturation uniformly over the area. Also, irregularities in the surface lead to minor ponding and then release from the ponding. Since this is what would be expected from a field construction site, it was not considered a problem. Typically, the runoff rate converged to a constant value once the plot was fully saturated, all depressions were filled, and all areas of the plot were contributing to runoff.

Table 5-1. Hydrologic parameters calculated from flow data

Simulation date	Soil type	Fabric type	Slope %	Curve No	Rf avg in./h	RO avg in./h	RO start time, s	EP[2] avg ft^3/s	UF[3] avg ft^3/s	DF[4] avg ft^3/s	DF[5] start s	DF[5] end s	Ratio[6] UF/EP
12/18/2003	Loam	2130	1	NA[1]	1.64	2.19	245	.040	.022	.0003	354	5610	.54
1/15/2004	Loam	2127	1	NA[1]	1.85	3.07	978	.056	.026	.0005	1606	4059	.46
3/2/2004	Loam	2130	7.5	99.2	2.85	2.43	500.21	0.045	0.027	0.001	1624	4109	0.61
3/10/2004	Loam	2127	7.5	97.0	2.13	1.78	1072.05	0.033	0.019	0.001	1313	2729.5	0.57
3/19/2004	Loam	2127	13.5	95.4	2.51	2.09	90.42	0.039	0.027	0.002	276	4372.5	0.69
3/24/2004	Loam	2130	13.5	99.2	2.85	2.43	509.07	0.027	0.025	0.000	930.5	3011.5	0.94
4/20/2004	Sandy loam	2130	13.5	96.8	2.41	2.13	53.74	0.039	0.030	0.000	652	1037	0.76
4/22/2004	Sandy loam	2127	13.5	99.3	2.21	1.79	645.37	0.033	0.033	0.006	681	1113	0.99
4/28/2004	Sandy loam	2127	1	93.6	2.76	2.11	377.84	0.039	0.012	0.001	766	2500.5	0.30
5/4/2004	Sandy loam	2130	1	94.2	2.64	1.99	345.12	0.037	0.027	0.000	683.5	3708.5	0.72
5/7/2004	Sandy loam	2130	7.5	91.9	2.42	1.79	178.98	0.033	0.032	0.001	611	886.5	0.95
5/11/2004	Sandy loam	2127	7.5	89.1	2.52	1.43	453.58	0.026	0.029	0.002	635	1457.5	1.09
5/18/2004	Silty clay	2127	7.5	86.1	2.45	1.86	665.67	0.034	0.007	0.008	1091	6974	0.21
5/21/2004	Silty clay	2130	7.5	87.3	2.43	1.60	940.31	0.030	0.018	0.001	3362	3919.5	0.61
5/25/2004	Silty clay	2130	13.5	85.4	2.62	1.52	394.55	0.028	0.022	0.006	1018	4894	0.78
5/27/2004	Silty clay	2127	13.5	89.2	2.55	1.62	400.08	0.030	0.018	0.009	526	5422.5	0.61
6/2/2004	Silty clay	2127	1	88.2	2.28	1.17	439.27	0.022	0.015	0.003	1278	4299.5	0.71
6/4/2004	Silty clay	2130	1	92.9	2.62	1.60	1852.29	0.030	0.024	0.002	2079	2459	0.81

[1] There was more runoff than rainfall measured during this simulation
[2] Average runoff rate from source area (EP), ft^3/s
[3] Average runoff rate along the toe upslope of the fence (UF), ft^3/s
[4] Average flow rate through the fence (DF), ft^3/s
[5] Start and end times of flow through the fence
[6] Ratio of volume discharged at end of toe trench (UF) to volume discharged from source area (EP)

After the flow data were collected and reduced, it was observed that discharge from the downstream end of the toe trench was almost always significantly less than the runoff rate from the source area. Once this was discovered, the system was examined carefully during the next simulation, but there were no apparent locations where runoff that had been sampled could escape prior to reaching the fence. In fact, it was considered more likely that extra water not factored into the runoff rate could reach the fence. This was observed to happen during the very first simulation when there was a strong north wind which blew an observable amount of water directly onto the sheet metal. Fortunately, north winds are rare in Oklahoma and that was the only simulation with that problem.

Even given the bulging of the fence and occasional blockage of the downstream collection trough and lack of reliable data about flow rates through the fence, it was clear from visual observation that the flow through the fence was not sufficient to account for the differences. Therefore, it was concluded that the difference was due to seepage into the walls and bottom of the toe trench.

Results Based on Sediment Analysis

The first observation that should be noted regarding the sediment data is that there is a very strong natural randomness to the processes that control sediment detachment and movement. For example, since the slope and area of the runoff plot were constant over all the simulations and the rate of rainfall only deviated slightly, very similar rates of sediment production would be expected over all tests involving a particular soil. Such was not the case, even once rates of sediment production were normalized into tons/area/unit of time/inches of rain.

However, the sediment data did reveal some trends which both supported and challenged the existing theory and understanding of sediment movement. Table 5-2 summarizes the average or representative sediment results for each simulation at the source area and Table 5-3 gives the sediment results for the toe trench and through the fence.

When normalized to account for differences in length of simulation, sediment production from the source area was greatest for sandy loam, then loam, with silty clay having the lowest. All other things being equal, it was expected that sediment production would follow Wischmeier's soil erodibility value, K, but sandy loam had the lowest K-value and silty clay had the highest. This apparent anomaly was attributed to the fact that the soil was placed onto the source area from stockpiles, making it even more disturbed than the soil on a field construction site. In addition, the non-cohesive sandy loam soil would experience a more thorough destruction of the soil matrix in this process than would the cohesive clays.

The concentration of sediment in the toe trench discharge also followed the same order, with sandy loam having the highest, followed by loam, then silty clay. This is expected since the rill erodibility factor follows that order, and more detachment of sandy loam would be expected. However, the sandy loam also has a much higher settling velocity so there should be more deposition. The size of the data set did not permit a statistically-based evaluation of how these offsetting factors influenced sediment flow in the trench. The fact that the trench was filled with stockpiled soil would make a transport capacity assessment based on theory developed for natural streams invalid. So this issue had to be left unresolved for now.

One observation of the data that clearly followed established theory was that the concentration of sediment in the toe trench discharge increased as slope increased. This trend occurred for all three soils.

Table 5-2. Sediment results for source area

Simulation date	Soil type	Total discharge lb	Average concentration mg/L	Peak concentration mg/L	Average sed flow rates lb/s
12/18/2003	Loam	107	14899	42499	0.060
1/15/2004	Loam	284	19171	46509	0.048
3/2/2004	Loam	433	40461	122929	0.078
3/10/2004	Loam	187	19244	29000	0.041
3/19/2004	Loam	305	28540	47203	0.068
3/24/2004	Loam	151	30759	39017	0.052
4/20/2004	Sandy loam	107	26871	42536	0.058
4/22/2004	Sandy loam	34	9212	15284	0.019
4/28/2004	Sandy loam	425	66110	98682	0.143
5/4/2004	Sandy loam	256	24302	55576	0.059
5/7/2004	Sandy loam	159	30162	48786	0.057
5/11/2004	Sandy loam	156	36568	190540	0.054
5/18/2004	Silty clay	198	14621	55255	0.036
5/21/2004	Silty clay	130	12549	23778	0.023
5/25/2004	Silty clay	220	27900	49829	0.053
5/27/2004	Silty clay	61	6395	11035	0.011
6/2/2004	Silty clay	134	21066	36702	0.027
6/4/2004	Silty clay	60	16414	39600	0.021

Occurrence of failure through erosion of the toe trench also occurred as expected. The sandy loam soil, clearly the most erodible, was always scoured completely away at one or more points. For the loam, complete scour only occurred with the steep slope, and complete scour never occurred with the very still silty clay. An additional observation was that, in general, failure occurred if the net erosion was at least 25% of the original volume of the toe trench.

The average concentration passing through the fence followed the same order given previously, with sandy loam being highest and silty clay being lowest. This is hard to assess, since the main impact of the fence is through detention and settling. Much less settling of the clays was expected, but the sandy loam started out at a higher concentration. The fence did cause a reduction in concentration for all soil types. The greatest magnitude in terms of reduced mg/L was for sandy loam, but the highest percent reduction occurred for loam. Sandy loam also had the highest ratio of concentration through the fence to concentration along the fence.

The fabric type was also a factor in the concentration passing through the fence. Overall, the concentrations passing Nilex 2127 were about 50% higher. This was expected since 2127 had an observably looser weave and a higher coefficient of discharge, giving a lower detention time and less settling. The fabric type did not appear to be a factor for silty clay. Since it was extremely fine, almost no settling would occur, and the fence would have no “filtering” affect whatsoever on the particles in suspension.

Table 5-3. Sediment results for toe trench and passing through the fence

Simulation Date	Soil type	Toe trench						Through fence		
		Total mass discharge lb	Average concentration mg/L	Peak concentration mg/L	Average sed flow rates lb/s	Net erosion lb	Net deposition lb	Total discharge lb	Average concentration mg/L	Peak concentration mg/L
12/18/2003	Loam	61	8564	40065	0.011	0.0	45.3	0.9	4838	12744
1/15/2004	Loam	104	15198	22779	0.026	0.0	179.7	0.7	6505	13648
3/2/2004	Loam	446	75260	203479	0.108	12.6	0.0	0.4	13102	19262
3/10/2004	Loam	218	42764	113386	0.044	31.5	0.0	3.8	31639	44548
3/19/2004	Loam	594	116298	259380	0.146	289.1[1]	0.0	52.5	103201	140986
3/24/2004	Loam	511	122042	246513	0.172	359.6[1]	0.0	3.2	63218	74437
4/20/2004	Sandy loam	531	195635	396115	0.389	424.8[1]	0.0	2.1	79305	96544
4/22/2004	Sandy loam	969	174206	311127	0.167	935.4[1]	0.0	34.5	181813	197841
4/28/2004	Sandy loam	122	83722	106455	0.070	0.0[1]	303.2	0.7	3728	7053
5/4/2004	Sandy loam	204	27693	101908	0.035	0.0[1]	52.1	0.3	3860	10768
5/7/2004	Sandy loam	591	120681	279870	0.216	432.2[1]	0.0	6.6	93409	122045
5/11/2004	Sandy loam	426	95282	176253	0.184	270.2[1]	0.0	22.8	134009	158815
5/18/2004	Silty clay	23	8495	26506	0.003	0.0	175.2	20.2	6651	11971
5/21/2004	Silty clay	112	19593	51358	0.022	0.0	18.4	1.0	10805	11443
5/25/2004	Silty clay	262	47863	71155	0.068	42.8	0.0	19.5	15943	47101
5/27/2004	Silty clay	52	9052	14367	0.011	0.0	9.6	25.3	8744	16673
6/2/2004	Silty clay	43	15178	20882	0.015	0.0	91.7	4.4	6819	8133
6/4/2004	Silty clay	44	12114	25626	0.012	0.0	16.2	0.4	3386	3524

[1] Toe trench failed

Analysis of Variance and Trends

To the extent that trends in the results responded to changes in quantifiable input parameters, i.e., soil properties, site geometric properties such as slope along the toe, or fabric properties, analysis of variance (ANOVA) was performed to determine if the trends were statistically significant. The data analysis add-in to the Excel spreadsheet was used for this purpose, with an alpha level of 5%. The ANOVA results are in Table 5-4.

The trends – statistically significant or not – were also evaluated as to whether or not they followed expectations. This assessment is shown in Table 5-5. For Table 5-5, three generic inputs were defined – fabric type, slope along toe, and soil type. The results shown in the table are averaged over all simulations with that generic input. With slope, trends were assessed simply as to whether they increased or decreased as slope increased. With soil type, trends were assessed for correlation with the most relevant soil property: d_{50} (mm), Wischmeier's soil erodibility K, or rill erodibility factor (s/m). For reference, these properties are also included in the table.

This analysis had two purposes. One was to either bolster support for established assumptions about hydrology, sedimentation, and silt fence performance or to point out assumptions that may require further investigation. The other was to determine qualitative trends that could be used as part of the assessment of the design aid.

Generally, the trends observed in the field data followed what was expected. Specific comments on each individual item are given in the table.

Table 5-4. Analysis of Variance (ANOVA) results

Result	Variable	F statistic	P value	F critical	Conclusion
Ratio of runoff to rainfall	Soil type	6.31	0.01	3.89	Significant
Average runoff rate from source area, in./h	Soil type	3.79	0.047	3.68	Significant
Average sediment discharge rate from source area, ton/acre/h	Soil type	2.57	0.11	3.68	Not significant
Average sediment discharge rate from source area, ton/acre/h per in. of rain	Soil type	4.78	0.02	3.68	Significant
Average concentration at source area, mg/L	Soil type	2.22	0.14	3.68	Not significant
Discharge in toe trench, ft^3/s	Soil type	4.14	0.04	3.68	Significant
Discharge in toe trench, ft^3/s	Slope	0.76	0.49	3.68	Not significant
Ratio of discharge from source to discharge at toe	Soil type	1.19	0.33	3.68	Not significant
Ratio of discharge from source to discharge at toe	Slope	1.22	0.32	3.68	Not significant
Sediment discharge in toe trench, lb/s	Soil type	5.32	0.02	3.68	Significant
Sediment discharge in toe trench, lb/s	Slope	3.06	0.08	3.68	Not significant
Average concentration in toe trench, mg/L	Soil type	6.64	0.01	3.68	Significant
Average concentration in toe trench, mg/L	Slope	0.43	0.66	3.68	Not significant
Concentration passing through fence, mg/L	Soil type	3.83	0.05	3.68	Significant
Concentration passing through fence, mg/L	Slope	3.32	0.06	3.68	Not significant
Concentration passing through fence, mg/L	Fabric	0.72	0.41	4.49	Not significant
Ratio of concentration through the fence to concentration along the fence	Soil type	0.09	0.91	3.68	Not significant
Ratio of concentration through the fence to along the fence	Slope	3.24	0.07	3.68	Not significant

Table 5-5. Summary of trends assessment

Result by fabric type	2127	2130		
Concentration passing through fence, mg/L	53679	31985		Reasonable - 2130 has a tighter weave and a lower coefficient of discharge.
Result by slope	Low	Moderate	Steep	
Discharge in toe trench, ft^3/s	0.021	0.022	0.026	All other things being equal, discharge in a channel increases as slope increases. Here, however, discharge is also controlled by the amount of discharge from the source and the amount of seepage. Since there should be a lower travel time with a higher slope, and therefore less opportunity for seepage, this result is reasonable.
Ratio of discharge from source to discharge at toe	0.592	0.673	0.794	Reasonable - the higher slope would give a shorter travel time and less opportunity for seepage.
Sediment discharge in toe trench, lb/s	0.028	0.096	0.159	The higher slopes lead to higher velocities with more potential for scour.
Average concentration in toe trench, mg/L	80266	70282	47726	This result does not agree with what would be expected.
Concentration passing through fence, mg/L	4856	48269	75371	Not sure, slope might be a factor in this.
Ratio of concentration through the fence to concentration along the fence	0.318	0.738	0.692	Not sure, slope might be a factor in this.
Result by soil type	Loam	Sandy loam	Silty clay	
Ratio of runoff to rainfall	0.83	0.74	0.62	This agrees with visual observation of the soil structure. The loam formed a very tight surface, the sandy loam was more granular, and the silty clay was very clumpy with numerous macro pores that had to be filled before runoff occurred.
Estimated Curve Number	97.7	94.1	88.2	Reasonable for same reason as above.
Average runoff rate from source area, in./h	2.33	1.87	1.56	Reasonable for same reason as above.
Wischmeier's K values	0.32	0.14	0.31	Measured of computed property – included for reference.
d_{50} of soil, mm	0.0555	0.1482	0.0051	Measured of computed property – included for reference.
Result by soil type	Loam	Sandy loam	Silty clay	
Average sediment discharge rate from source area, ton/acre/h	5.70	5.66	2.65	Observation of the soils indicated that the sandy loam was the most easily erodible, loam was moderately erodible, and silty clay was erosion resistant. This result does not follow the Wischmeier's

				K values which were computed from the soil texture.
Average sediment discharge rate from source area, ton/acre/h per in. of rain	2.44	4.12	1.55	Result agrees with visual observation of the soil, but does not follow the K-value. This result does correlate with the d_{50} of the soil.
Average concentration at source area, mg/L	25512	32204	16491	Result agrees with visual observation of the soil, but does not follow the K-value. This result does correlate with the d_{50} of the soil.
Discharge in toe trench, ft^3/s	0.024	0.027	0.017	Soil type is a factor in this in grain roughness and in losses due to seepage. This result does not follow what we would expect with grain roughness, since the coarser grained sandy loam would provide more resistance to flow. However, the sandy loam also appeared to have a lower loss due to seepage since its non-cohesive structure provided fewer macro pores for significant seepage.
Ratio of discharge from source to discharge at toe	0.64	0.80	0.62	Reasonable because the sandy loam appeared to have less loss due to seepage.
Rill erodibility factor, Kr, s/m	0.00283	0.00361	0.00111	Measured of computed property – included for reference.
Sediment discharge in toe trench, lb/s	0.085	0.177	0.022	Reasonable, follows rill erodibility.
Average concentration in toe trench, mg/L	18716	116203	63354	Reasonable, follows rill erodibility.
Concentration passing through fence, mg/L	8725	82688	37084	To the limited extent that the fabric acts as a strainer, we would expect less of the coarser material to pass through, which did not occur. Plugging of the openings in the fabric is another way that the soil can affect the flow through. Here, we would expect the coarser material to plug the openings more than the clays, which would pass through easily. This supports observations made in the flume testing that plugging is not a significant factor when the flow is parallel to the fence.
Result by soil type	Loam	Sandy loam	Silty clay	
Ratio of concentration through the fence to concentration along the fence	0.56	0.64	0.55	

Chapter 6
Modeling Silt Fence Performance

Background

A key element of this project was development of a mathematical model of silt fence performance. The purpose of the model development was to provide a means of predicting silt fence performance under a wider range of site and hydrologic/hydraulic conditions that could be simulated during the field laboratory tests. The mathematical model also forms the basis of the design aid.

Ideally, a model of silt fence performance will contain the following components. However, limitations in available data for validation and a need for simplicity for the user community made some of these elements impractical.

- Hydrology. Predict runoff volume and rate, sediment yield, and sediment size distribution of flow arriving at the silt fence as a function of soil type and cover characteristics of the source area, along with rainfall characteristics.
- Hydraulics. Predict flow through the fence and along the fence as a function of the type of fabric, incoming flow rate, and slope along and toward the toe of the fence.
- Sediment transport. Predict sediment transport along the toe and through the fence; predict lateral flow erosion along the fence as a function of flow characteristics, soil properties, and slope.
- Sediment trapping. Predict the total sediment loading to the fence, total weight that is discharged at the downstream end of the toe of the fence, and total weight passing through the fence. If a simple impoundment is created by extending a length of silt fence up the slope at the downstream end, predict the trapping efficiency of the impoundment.

As a first step in model development, the functionality of several existing water and sediment routing models was reviewed to determine if there was one that might be easily adapted for this project. Models considered included WEPP (Lindley et al., 1998), SEDIMOT II (Wilson et al., 1984), and SEDIMOT III (Barfield et al., 1996). SEDIMOT III was selected because in addition to the required hydrology and overland erosion components, it also included a concentrated flow channel erosion component and a component that routes a hydrograph and sedigraph through an impoundment and generates effluent concentrations along with trapping efficiency.

To create a preliminary model, some minor modifications to SEDIMOT III were made, primarily modifying the channel flow component to account for flow through the fence (in order to use the channel erosion routine to simulate the flow along the toe of a silt fence) and modifying the output to print out the erosion calculations for each time step. Data from the first three construction site visits was used as input data to see if this preliminary model performed in a reasonable manner, and concluded that it did an adequate job of predicting runoff and sediment yield from the contributing drainage area. However, the predicted channel erosion did not agree with what was observed in the field.

From this, it was concluded that the channel erosion routines based on equilibrium channel geometry and excess shear concepts (Storm, 1991) and developed for natural streams were not applicable. This was considered due to the differences between natural soil and the excavated/re-emplaced soil in a silt fence toe trench. The preliminary model was used to design some of the details of the field laboratory test plot, specifically, to size the source area samplers and conveyance system and as an aid in planning sample collection intervals.

Since there was no off-the-shelf model to use, the mathematical model was programmed to operate within an Excel spreadsheet in order to make it adaptable to a simple design aid format. This also simplified coding and de-bugging.

This document is intended for the user community, therefore the inputs and outputs for the design aid described in Chapter 7 are those normally used by engineers and other practitioners in the erosion control profession. This is also followed in the model development described in this chapter.

Development of Model Components

In general, the model was constructed as a quasi steady-state model. While it does do computations in time steps, the inputs to each time step are identical, so the model converges to a steady state solution. For example, a uniform intensity of rainfall is assumed over the duration, so the depth of rainfall is equal for all time steps. The steady state approach was considered reasonable because an equilibrium or steady state condition to develop very quickly in most of the field laboratory tests was observed.

Hydrology Component

Elements of the hydrology component were adopted almost entirely from Sedimot III, and are also included in many other widely-used hydrology models. The following paragraphs describe the hydrology component.

Runoff Volume

Runoff volume as a function of rainfall and land cover is computed using the NRCS curve number equation (NRCS, 1969). The cumulative rainfall in each time step is the precipitation input. Since steady-state conditions were almost always observed to happen within 1 h during the field testing, a storm duration of 3 h with 0.1 h time steps was selected. This is a storm of sufficient length to create equilibrium in the flow through silt fence, as discussed later. Incremental rainfall in each time step is obtained by dividing the 3-h storm depth by 30. Cumulative depth is then obtained by summing.

The NRCS has developed standard precipitation distributions which are commonly used for hydrologic investigations. These storms require a 24-h return period precipitation and then can generate a distribution for any duration less than 24 h with the same return period. To simplify user inputs, the model works from a standard 24-h return period storm as a user input. The model then determines the 3 h storm with the same return period and uses that for runoff and peak discharge calculations.

Cumulative runoff, Q_p (in.) in each time step is determined from the cumulative rainfall, P (in.), and curve number (CN), which is a parameter that reflects soil type and land use, as:

$$Q_P = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{6.1}$$

Where, S (in.) is potential abstraction from rainfall which is defined by the curve number as

$$S = \frac{1000}{CN} - 10 \tag{6.2}$$

The quantity $0.2S$ is commonly used as the initial abstraction before start of runoff, so Q_P is equal to zero for values of P where $P < 0.2S$. The value of Q_P represents the inches of rainfall that are converted to runoff from the source area. Total volume of runoff is obtained by converting the inches to feet and multiplying by the land area. Computing with area in acres gives runoff volume in acre-feet and computing with area in square feet gives runoff volume in cubic feet. Both are determined for use in different components of the model. The incremental volume in cubic feet is determined for each time step by subtraction.

Since the land areas are small, runoff can be assumed to be instantaneous, as opposed to being routed overland using a unit hydrograph or kinematic model. Therefore, the runoff rate from the source area, q_p (ft^3/s), at any point in time is the rate of change of runoff volume, or:

$$q_p = \frac{dQ_P}{dt} \tag{6.3}$$

and the maximum runoff rate will be

$$q_{p,max} = \left[\frac{dQ_P}{dt}\right]_{max} \tag{6.4}$$

Sediment Yield
Sediment yield from overland erosion is computed with the modified universal soil loss equation (MUSLE) (Williams and Brendt, 1972), or:

$$Y = 95\left[Q_p q_{p,max}\right]^{0.56} K[LS][CP] \tag{6.5}$$

where K is an empirical soil erodibility, LS is the dimensionless length slope factor which is determined from slope and slope length (Haan et al., 1994) and CP is a dimensionless cover and practice factor that accounts for the impact of cover and compaction on sediment yield. This equation uses the computed values of peak runoff rate and runoff volume, the length and slope toward the fence, and a soil loss parameter, Wischmeier's K (Wischmeier et al., 1971), that is input by the user. Recently published NRCS county soil surveys have tabulated values of K. Otherwise, K can be determined from soil texture by using the Wischmeier et al. (1971) nomograph (Figure 6-1).

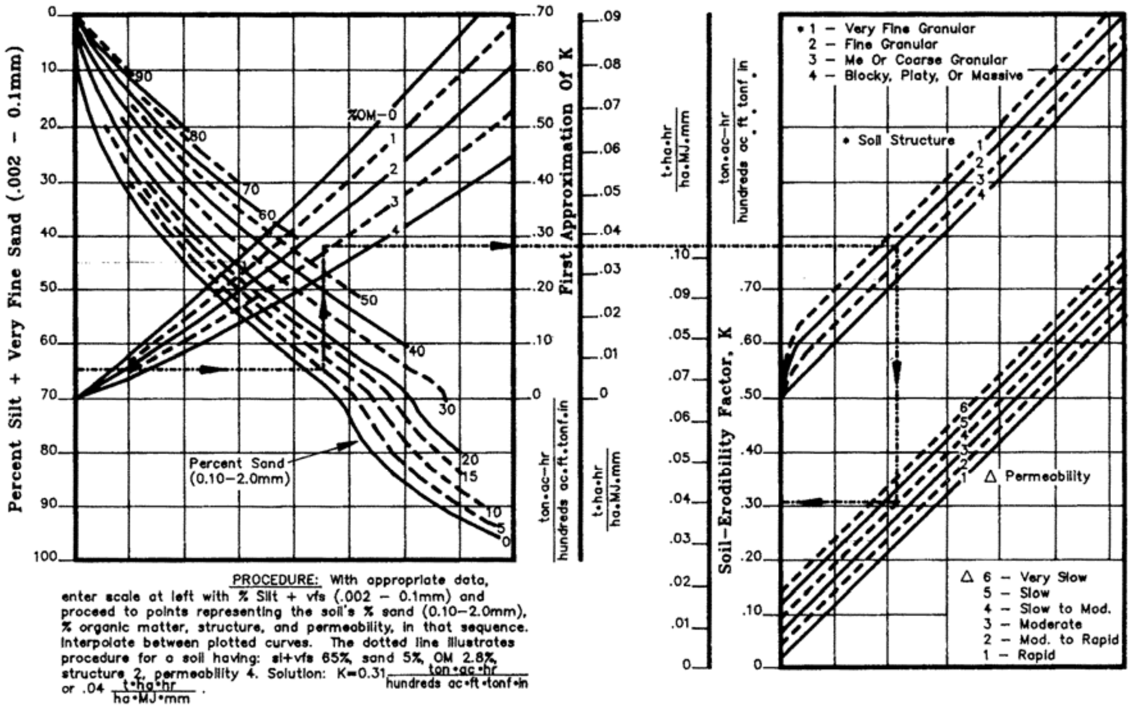


Figure 6-1. Wischmeier et al. (1971) nomograph for determining K factor

The final MUSLE parameter, a cover factor, is also input by the user. The recommended range for "bare soil, undisturbed except scraped" is 0.66 to 1.3 (Transportation Research Board, 1980). If the site cover is soil that has been recently placed from a stockpile, use of Figure 6-2 to determine cover factor is recommended (Haan et al., 1994). This accounts for the fact that, over time, soil that has been placed from a stockpile will become less erodible.

For calculation of sediment transport, an average particle diameter, d_{50} *(mm)* is needed to calculate sediment transport. Since the drainage areas contributing to a silt fence are typically small, soil was described by a single representative diameter, d_{50} *(mm)*, determined by the eroded size distribution. Also, to predict trapping in the impoundment at the end of the silt fence, particle size classes are needed. This can be based on actual measurements of eroded size distribution (Haan et al., 1994, Chapter 7) or estimated by the CREAMS model that is widely used to estimate eroded size distribution. Although the CREAMS equations are not as accurate as might be desired for eroded size distribution from construction activities (Barfield et al., 1988) it is the only predictive technology currently available. A study of eroded size distribution from construction sites is needed to fill this information gap. Developing such a model was beyond the scope of this project and not possible with the relatively small number of field trials conducted, therefore the CREAMS model will be used with a user option to input a measured eroded size distribution.

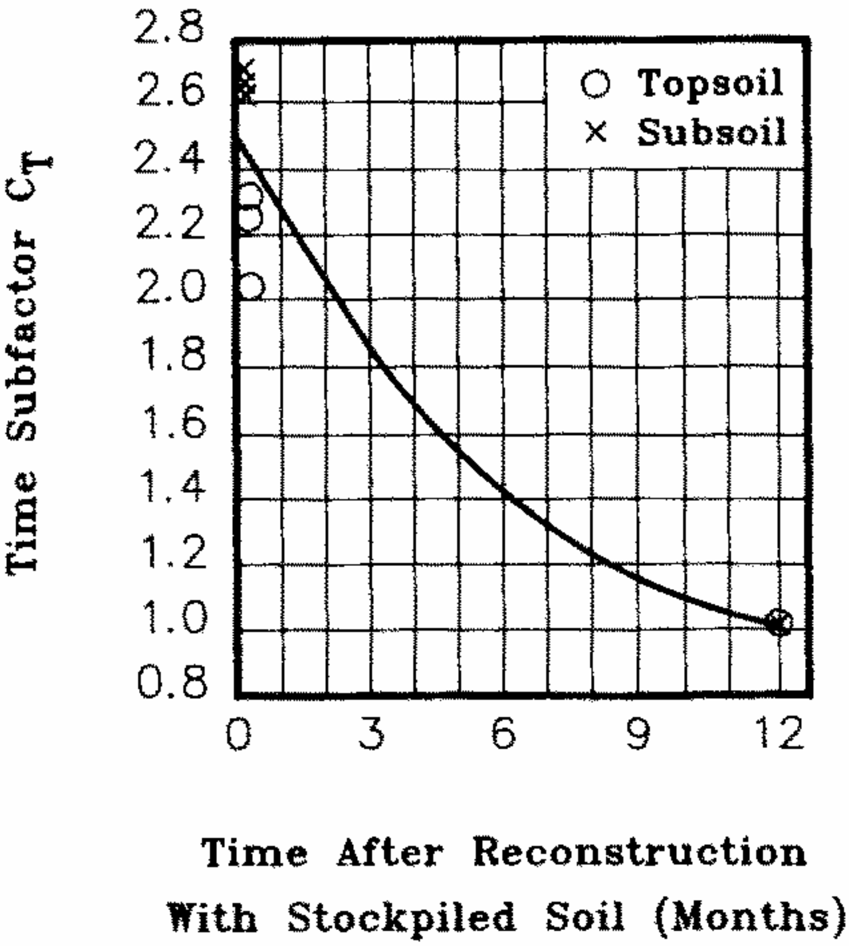


Figure 6-2. Cover factor for use of stockpiled soil

Hydraulic Component

Flow along the toe is computed based on Manning's equation (Haan et al., 1994). A triangular channel geometry, wherein the vertical silt fence is one leg of the triangle and the overland slope is the other leg (see Figure 6-3) is used to compute area and hydraulic radius. A typical bare soil value of 0.025 is used for roughness factor (Manning's *n*).

To do the routing calculations along the silt fence toe, it is convenient to have a simple relationship giving discharge along the toe as a function of head. Using Manning's equation and the triangular geometry shown in Figure 6.3 the flow rate along the toe of the fence, *q* (ft^3/s), can be expressed as:

$$q = K_q H^{8/3} \tag{6.6}$$

Where, K_q is a constant for a given combination of Manning's *n*, slope along the toe, and slope leading to the fence and *H* is the depth at the fence as shown in Figure 6.3. To compute K_q, the model includes a subroutine which finds *q* for values of *H* ranging from 0 to 1 ft and then uses linear regression to find the slope of the line formed by the *q* vs. $H^{8/3}$ data points.

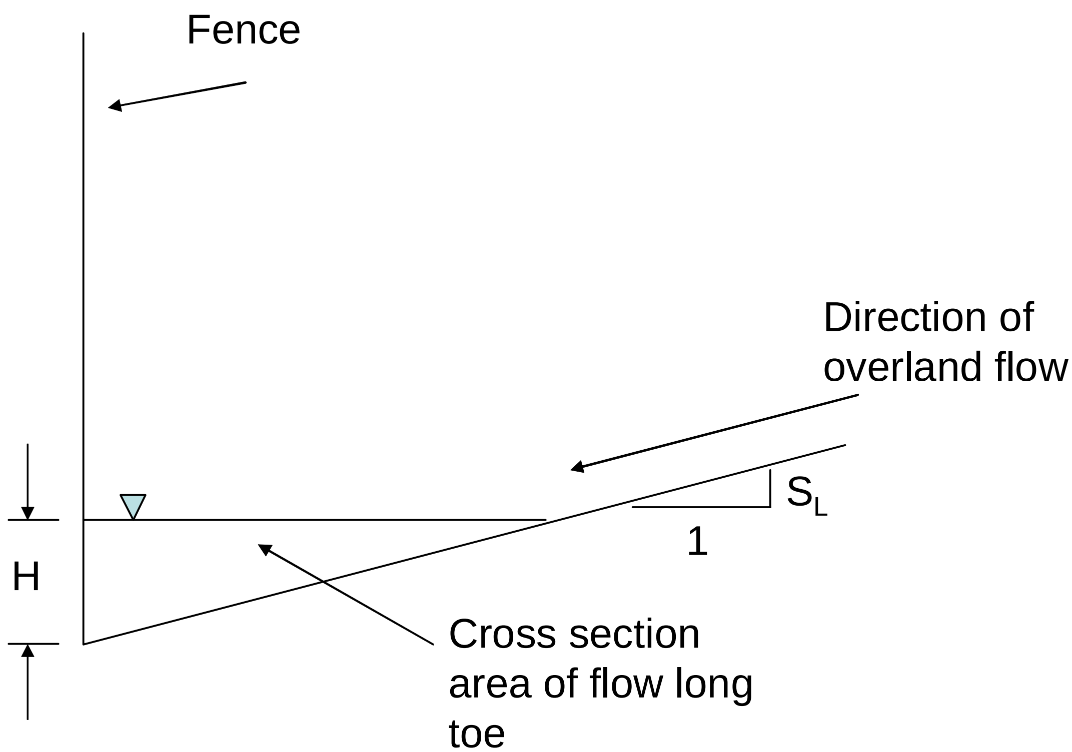


Figure 6-3. Triangular channel geometry

Flow routing along the toe is based on a mass balance wherein the basic continuity relationship is:

$$Vol_{in} - Vol_{out} = \Delta S_t \tag{6.7}$$

Where, Vol_{in} and Vol_{out} (ft^3) are inflow and outflow volumes in a time step and ΔS_t is the change in storage along the toe of the fence in the time step. Vol_{in} is the sum of the volume exiting the upstream section plus the overland runoff. Essentially, a four-point finite difference grid is used for the computations, as shown in Figure 6-4. The current version of the model is implemented using an Excel spreadsheet. To compute flow along the toe, the flow length along the toe is divided into two reaches, giving three nodes along the fence. The model solves for the head at each node in each time step. The boundary conditions are $H = 0$ for all x at $t = 0$ and $H = 0$ for all t at $x = 0$.

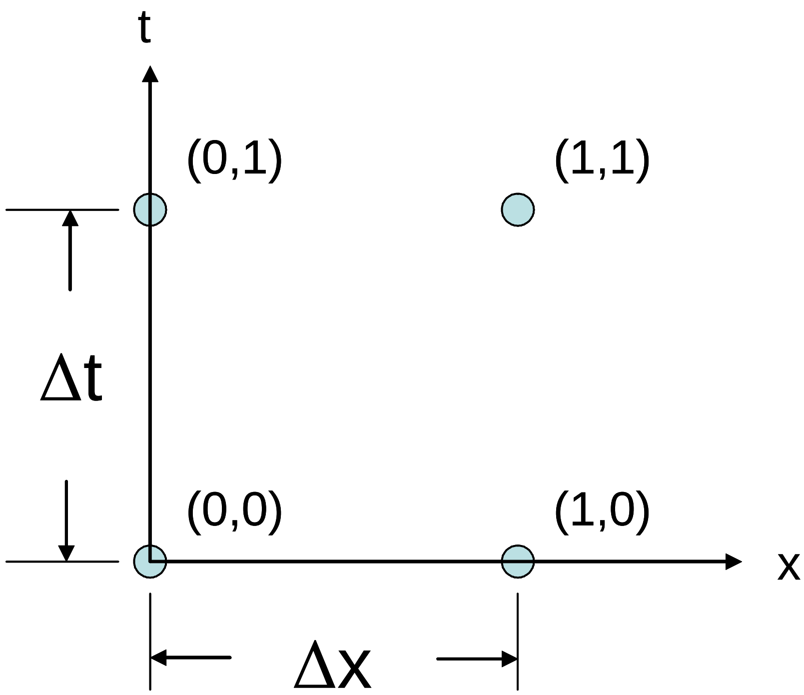


Figure 6-4. Schematic for four point grid solution matrix

The model is actually an explicit system of nonlinear equations, i.e., the solution for any property such as Vol_{In}, Vol_{Out}, or ΔS_t at Node (1,1) (see Figure 6.4) can be explicitly calculated from known values at Nodes (0,0), (0,1), and (1,0), all defined as boundary conditions. Once $H_{(1,1)}$ and the other values at (1,1) are computed, then the values at (1,2) and (2,1) are functions of known values. It is therefore possible to go through the grid sequentially and solve for each cell. Using cell (1,1) as an example, the nonlinear equations solved are:

$$Vol_{In(1,1)} = \tfrac{1}{2} K_q \left(H_{(0,0)}^{8/3} + H_{(0,1)}^{8/3} \right) \Delta t + q_{of,1} \Delta t \quad (6.8)$$

Where, $q_{of,1}$ is the overland runoff rate for one-half of the total area during time step 1. The computation for Vol_{Out} includes the discharge exiting at the downstream node, flow through the fence and losses from seepage:

$$Vol_{Out(1,1)} = \tfrac{1}{2} K_q \left(H_{(1,0)}^{8/3} + H_{(1,1)}^{8/3} \right) \Delta t + q_F \Delta t + V_{seep} \quad (6.9)$$

Where, K_q was defined earlier as the constant relating flow velocity, channel roughness, and channel geometry for flow along the fence, V_{seep} (ft^3) is the volume of flow that seeps under the fence, and q_F (ft^3/s) is the flow rate through the fence, or:

$$q_F = K_F C_S \left(H_{0,0}^{3/2} + H_{0,1}^{3/2} + H_{1,0}^{3/2} + H_{1,1}^{3/2} \right) \Delta x \quad (6.10)$$

Where, K_F is the fence constant which relates flow through the fence to the depth of impounded water for the static condition and C_s is a dimensionless parameter which accounts for the impact of parallel flow along the fence on the flow through the fence, or:

$$C_S = K_C S_C^{P1}\left[\frac{V^2}{2g}\right]^{P2} \tag{6.11}$$

Where, V (ft/sec) is the velocity in the toe trench, S_c is the slope of the toe trench, and K_c, $P1$ and $P2$ are empirical coefficients. Values for C_s, K_c, K_F, $P1$ and $P2$ are all parameters that are functions of the fence material and require calibration with laboratory or field data. For Nilex 2130 or 2127, the following values have been determined based on flume studies:

K_F = 0.0659 for Nilex 2127; 0.0306 for Nilex 2130.
K_c = 1.906
$P1$ = 0.6171
$P2$ = 0.6224

The volume of seepage loss, V_{seep} (ft^3), is a function of the overland runoff volume and is computed as:

$$V_{seep} = (1 - K_A)V_{OL} \tag{6.12}$$

Where, K_A is the adjustment factor for the ratio of volume discharged along the toe to overland runoff volume, V_{OL} (ft^3). This parameter was estimated using the field data as 0.6863. At this point, the best estimate is the average of all the adjustment factors that were backed out of the computation using the field data. This will be a user input parameter for the model.

From geometry, the change in storage is computed as:

$$\Delta S_t = 0.5\left[\frac{1}{2S_L}\left(H_{(1,1)}{}^2 - H_{(1,0)}{}^2\right) + \frac{1}{2S_L}\left(H_{(0,1)}{}^2 - H_{(0,0)}{}^2\right)\right]\Delta x \tag{6.13}$$

Where, S_L is the slope perpendicular to the fence. The model uses a solver in the spreadsheet to find the head at each node that minimizes the squared error in the continuity equation written as:

$$Vol_{In} - Vol_{Out} - \Delta S_t = 0 \tag{6.14}$$

Equations (6.6) through (6.13) are used to define Vol_{in}, Vol_{out} and ΔS_t. Once $H_{(1,1)}$ is known, based on the solver routine, values of $q_{f(1,1)}$ and $q_{(1,1)}$, are determined and a new routing time step generated.

Sediment Component

In order to solve the equations that define sediment load into the impoundment at the end of the silt fence, it is necessary to define the inter-relationships between incoming sediment load, detachment potential, and deposition. Typically, this is done with a process based sediment transport equation combined with a detachment/deposition routine. This was tried initially in this project, however, as noted earlier, relationships based on traditional channel erosion and transport theory did not perform well in making predictions of sediment transport along the toe of the silt fence. Therefore it was necessary to develop these relationships using the field data. Based on an analysis of the data collected, the parameter least influenced by the scale of the tests was the average concentration of sediment in the toe trench discharge.

Concentration of sediment in the toe trench

Both an Analysis of Variance and visual observations noted during the field trials indicated that the average concentration of sediment in the toe trench discharge was a function of slope and d_{50} (mm), so a relationship of the form shown in equation (6.15) was estimated using the field data, or:

$$C_{Tavg} = 3.254(100S_c)^{2.440}(1000d_{50})^{1.335} \qquad (6.15)$$

Where, C_{Tavg} (mg/L) is the average concentration in flow along the toe and S_c and d_{50} are as previously defined. With more data it should be possible to develop a more processed-based model using channel erosion and transport capacity theory with adjustments for the fact that the toe trench bed was backfilled material, as opposed to being natural stream bed. However, there just was not enough data to attempt that at this point. Figures 6-5 and 6-6 show the predicted vs. observed values and a comparison of individual simulations. The value for d_{50} can come from a measured eroded size distribution or can be estimated from the CREAMS relationships (Knisel, 1980).

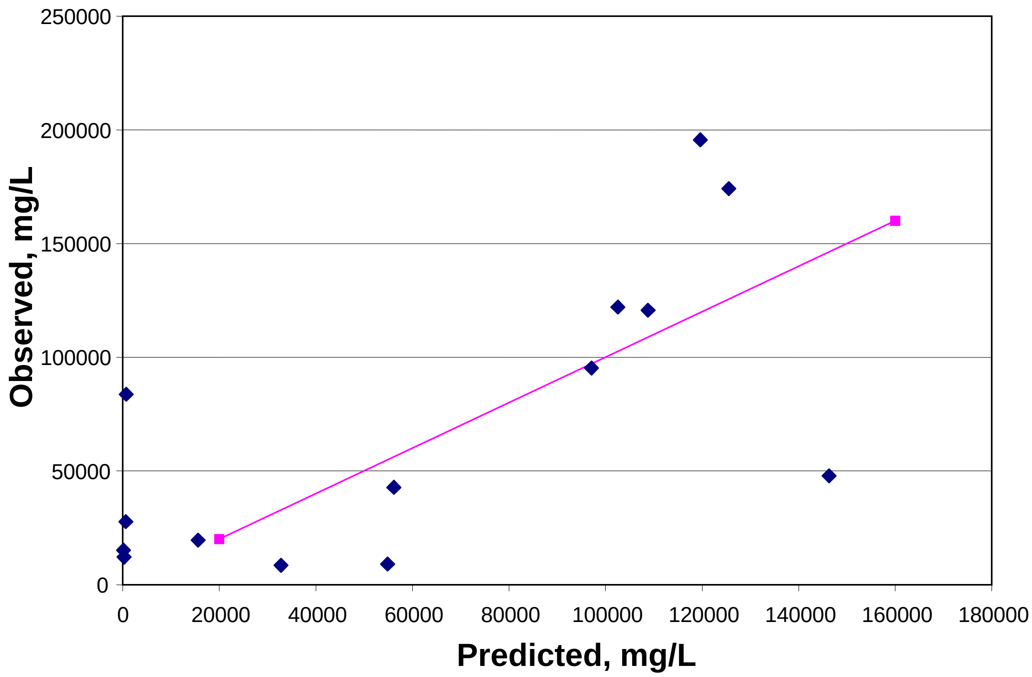


Figure 6-5. Comparison of observed and predicted concentrations in toe trench using equation (6.15)

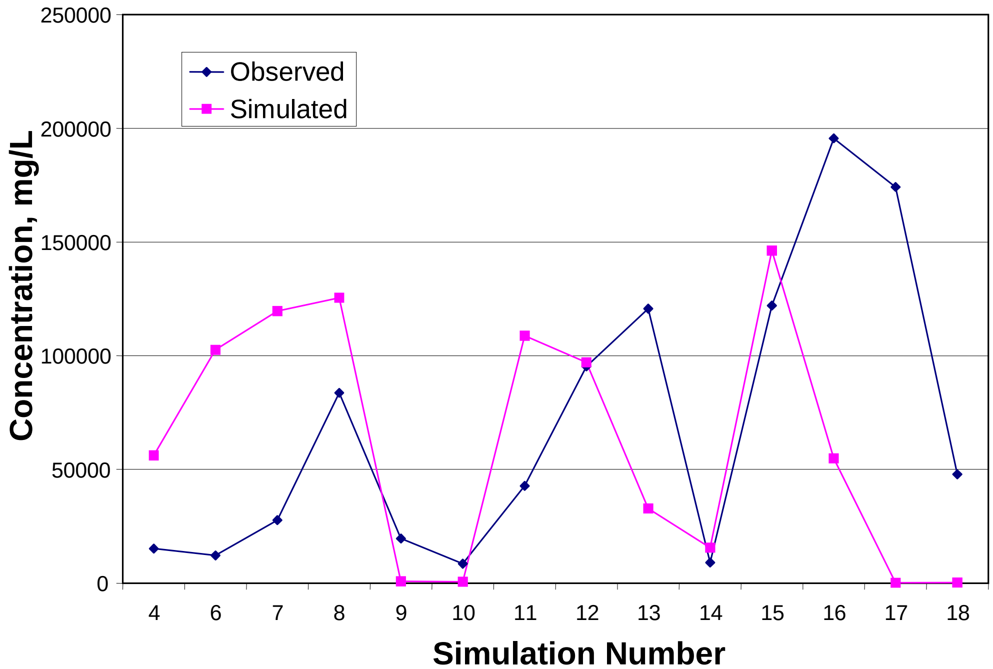


Figure 6-6. Comparison of observed and predicted concentrations by simulation number (given in Table 4-2)

Equation (6.15) actually is intended as a method to predict transport capacity. If it is assumed that the flow exiting the toe strip is operating at the sediment transport capacity, the error would not be great, based on our observations. Based on this assumption, the deposition or scour in the toe trench can be estimated from the difference in source area sediment yield and flow from the toe trench into the impoundment.

Sediment discharge in the toe trench

Using equation (6.15) for sediment yield, sediment discharge rate in the toe trench is then computed by multiplying the concentration expressed as lb/ft^3 by the toe trench discharge in ft^3/s. The total mass of sediment transported along the toe to the outlet, W_{St} (lb) during a time step is computed as:

$$W_{St} = \tfrac{1}{2}\left(q_{St1} + q_{St2}\right)\Delta t \qquad (6.16)$$

Where, q_{St1} and q_{St2} (lb/s) are the sediment discharge rates in sequential time steps.

Sediment discharge through the silt fence

Flow through the fence, q_F is obtained from the hydraulic routing. To convert this to a sediment discharge, the flow rate must be multiplied by sediment concentration. In general, one would expect the concentration flowing through the fence to be approximately equal to the suspended load concentration. Unfortunately, there are no well documented suspended load equations for soil erosion. In the absence of such a relationship, a user input is put into the model to allow user selection for the parameter. For the field studies conducted, the average concentration through the fence based on the field data was found to be a fraction of the concentration in the toe trench.

This fraction (F_c) was a function of the fabric type, with the fractions for Nilex 2130 and 2127 being 0.415 and 0.749, respectively. As with the toe trench concentration, it is hoped that if more field data becomes available, then a more process-based model can be developed to define this parameter. The weight of sediment discharged through the fence is then computed in the same manner as for the toe trench, or:

$$q_{sf} = \beta C_T q_F \tag{6.17}$$

C_T (mg/L) is concentration in the toe trench as defined by equation (6.15), q_F (ft/s) is flow through the filter fence as defined by equation (6.10) and β is the input correlation coefficient between concentration of sediment in the toe trench and concentration of sediment in the flow through the filter fence. For each time step, the model computes the weight of sediment from the source area and the weight of sediment discharged at the downstream end of the toe trench. The net erosion along the toe is the difference between the total weight of sediment over all the time steps discharged at the end of the toe and the total weight of sediment coming into the fence from the source area. If there is more sediment incoming from the source area than is discharged from the toe trench, then there is net deposition. From the field tests, it was observed that failure generally occurred if net erosion was greater than 25% of the soil volume in the toe trench. The model tracks the volume of net erosion and when net erosion exceeds 25% of the trench volume, that time step is flagged as the predicted failure time.

Sediment size distribution at the impoundment

When flow gets to the impoundment at the end of the silt fence section, it is important to have sediment divided into size classifications. For this purpose, an eroded size distribution is needed and the user has two options, both described in Haan et al. (1994, chapter 7):

1. Input the eroded particle size distribution based on measured values
2. Use the CREAMS equations to predict the size distribution wherein sediment is divided into five particle classes.

Option 1 requires the user to input the percent of particles in 5 particle classes using empirically measured eroded size distribution. This requires the use of wet sieving and some type of particle size analysis that does not require dispersion. Examples of the particle size analysis include the pipette method and particle size analyzer. It is important that the soil particles not be dispersed. Option 2 is to use the CREAMS equations. CREAMS divides the particles into 5 classes: primary sand, primary silt, primary clay, large aggregates, and small aggregates. The fraction of soil in each size range, the specific gravity in each size range, and the average diameter in each size range is either specifically defined for the size range or determined based on the percent of primary sand, silt, and clay in a dispersed sample of soil (all aggregates broken down into their primary particles). These equations are programmed into the spreadsheet as user option No 2.

The original size distribution information must be adjusted for deposition or detachment in the toe trench. This will give a corrected size distribution to use in trapping in the impoundment.

Case I: Net deposition along toe trench

If the sediment load at the end of the toe trench, calculated by equation (6.16), is less than that coming from the source area, the difference is equal to that deposited along the toe trench. The fraction trapped is the difference between that coming from the source area and that reaching the impoundment, or:

$$TE_T = \frac{M_{SP} - M_{ST}}{M_{SP}} \tag{6.18}$$

Where, TE_T *(fraction)* is the total trapping efficiency measured over the runoff event, M_{SP} and M_{ST} (lb) refer to the mass of sediment discharged from the source area and mass of sediment moving from the toe trench to the impoundment. The assumption can be made, as shown by Hayes et al. (1984) that the deposited material will be the largest particles, therefore the size distribution must be adjusted accordingly. The new fraction finer for each size class, $PF_{I,i}$, at the exit to the impoundment is given by:

$$\begin{aligned}
PF_{I,1} &= Max\left[\left(PF_{P,1} - TE_T\right), 0.0\right] \\
PF_{I,2} &= Max\left\{PF_{P,2} - Min\left[\left(PF_{P,1} - TE_T\right), 0.0\right], 0.0\right\} \\
PF_{I,3} &= Max\left(PF_{P,3} - Max\left\{PF_{P,2} - Min\left[\left(PF_{P,1} - TE_T\right), 0.0\right], 0.0\right\}\right) \\
PF_{I,4} &= Max\left\langle PF_{P,4} - Max\left(PF_{P,3} - Max\left\{PF_{P,2} - Min\left[\left(PF_{P,1} - TE_T\right), 0.0\right], 0.0\right\}\right)\right\rangle \\
PF_{I,5} &= Max\left|PF_{P,5} - Max\left\langle PF_{P,4} - Max\left(PF_{P,3} - Max\left\{PF_{P,2} - Min\left[\left(PF_{P,1} - TE_T\right), 0.0\right], 0.0\right\}\right)\right\rangle\right|
\end{aligned} \tag{6.19}$$

Impoundment Component

The geometry of the impoundment included in the model represents what is created by extending a length of silt fence upslope at the downstream end of the toe. The area relationships are based on the assumption of a uniform slope along the toe and a uniform overland slope. Therefore, the impoundment bottom can be modeled as a plane with the corner being the lowest point. Figure 6-7 is a schematic showing that *H* now refers to the maximum depth of water at the lowest point in the impoundment.

To develop the impoundment computations required development of depth vs. area and depth vs. outflow relationships, along with a trapping efficiency function. The equation for surface area as a function of the maximum impoundment depth, H_{IM} (ft) in the lower corner is:

$$A(H_{IM}) = H_{IM}^2 \left[\frac{\tan\theta}{2S_c(-S_c + S_L \tan\theta)}\right] \tag{6.20}$$

Where, θ is the angle between a line along the bottom of the silt fence and the extension, S_c, is the slope along the toe of the silt fence, and S_L is the slope perpendicular to the silt as shown in the schematic in Figure 6-7. The volume is then found by integrating $A(h)dh$ from $h = 0$ to $h = H_{IM}$, or

$$V\left(H_{IM}\right) = \frac{H_{IM}^3}{3}\left[\frac{\tan\theta}{2S_c(-S_c + S_L \tan\theta)}\right] \tag{6.21}$$

To account for the fact that the head on the silt fence varies from a maximum of H_{IM} in the corner to zero where the water surface intersects the ground (see Figure 6-8), the equation for flow through the fence was integrated as:

$$Q_{FT} = \int_0^L K_F\left[h(x)\right]^{3/2} dx = K_F \int_0^L \left[\frac{H_{IM}x}{L}\right]^{3/2} dx = \frac{K_F H_{IM}^{3/2}}{L^{3/2}} \int_0^L x^{3/2} dx = \tfrac{2}{5} K_F H_{IM}^{3/2} L \tag{6.22}$$

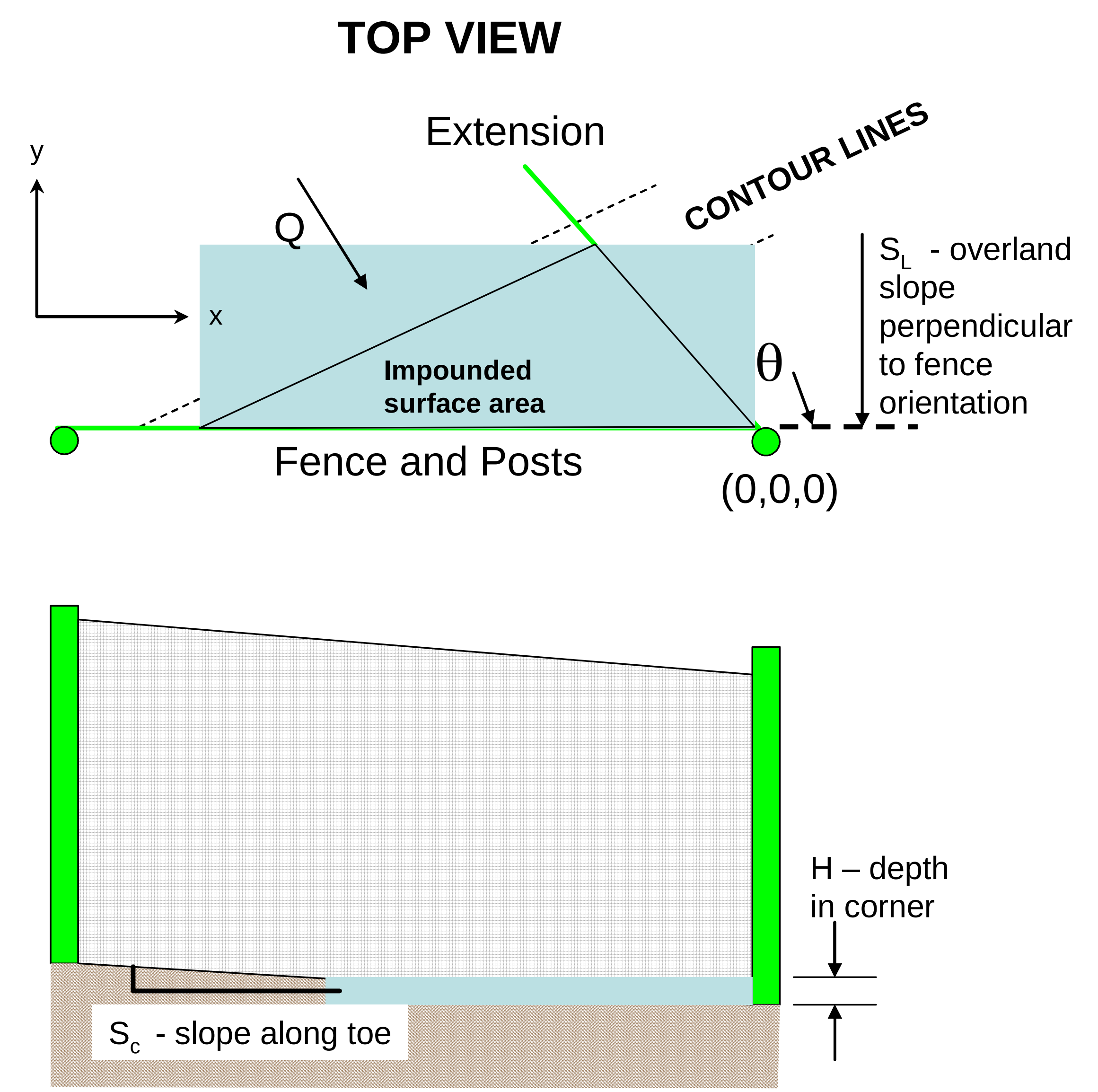


Figure 6-7. Impoundment geometry

Where, Q_{FT} is the total flow through the fence panel (ft^3/s, not $ft^3/s/ft$), K_F is the discharge coefficient for the fabric type, and H_{IM} and L are as shown in the figure. For the main silt fence, L is equal to H_{IM}/S_c. For the extension, L is equal to

$$L = H_{IM}\sqrt{\frac{1+\tan^2\theta}{(-S_c + S_L\tan\theta)^2}} \tag{6.23}$$

The final equation for the impounded flow through the silt fence is therefore

$$Q_{FT} = \tfrac{2}{5}K_F H_{IM}^{5/2}\left[\frac{1}{S_c} + \sqrt{\frac{1+\tan^2\theta}{(-S_c + S_L\tan\theta)^2}}\right] \tag{6.24}$$

Note that for the extension to actually create an impoundment, $\tan\theta/(-S_c + S_L \tan\theta)$ has to be greater than zero.

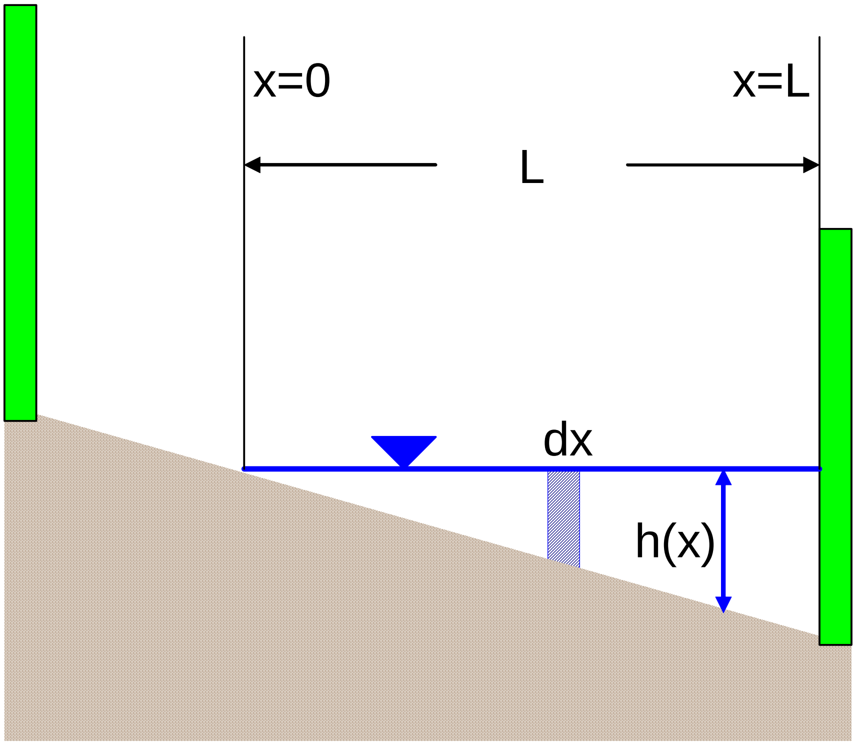


Figure 6-8. Schematic of flow through silt fence around impoundment

After running a series of full impoundment simulations, it was observed that the depth in the impoundment reached steady state, i.e. inflow equal to outflow, within a very short time, always in less than 10 min. The impoundment hydraulics was therefore modeled with steady-state conditions, as follows:

1. The peak discharge at the downstream node of the toe trench was the constant inflow rate.
2. The depth (H_{IM}) was computed using equation (6.24), surface area and volume were then computed based on H_{IM}.
3. The overflow rate velocity, V_C, was then computed as peak discharge divided by surface area at H_{IM}.

Item 3 introduces the concept of an overflow rate, a parameter that is used in calculations of trapping efficiency. The overflow rate is a settling velocity that will just allow the particle to settle from the top to the bottom of a rectangular basin with steady quiescent flow. The concept has been extended to non-rectangular channels and referred to as dynamic removal efficiency (Driscoll et al., 1986). The Driscoll et al. model was used to compute the trapping efficiency. This model requires a parameter, β, which is a performance factor, as follows:

- β = 1, very poor performance
- β = 2, average performance
- β = 3, good performance

- β >5, very good performance

The user inputs β and the model computes trapping efficiency for each particle class, TE_i as:

$$TE_i = \left(1 - \left[1 + \frac{1}{\beta}\frac{V_{s,i}}{V_c}\right]^{-\beta}\right) \times 100\% \qquad (6.25)$$

Where, $Vs_{,i}$ is the settling velocity for particle class *i*. The total trapping efficiency over all particle size classes is:

$$TE_{TOT} = \sum_{i=1}^{5} (TE)_i (PF)_i \qquad (6.26)$$

Finally, the model also warns the user if the water surface is above the end of the extension, the water discharges around the silt fence.

Validation of Model

Model validation included both a qualitative and quantitative component. For the qualitative assessment, the model responses to changes in input values were compared to the trends reported in Chapter 5. To complete the quantitative component, the conditions present for the field testing were inputted into the model and model outputs were compared to the observed results.

Qualitative Assessment

The model output was averaged according to the generic inputs described in Chapter 5, and the averages were compared to the actual field averages to see if the trends were preserved. Table 6.1 gives the results for selected comparable outputs. The outputs selected for comparison were chosen because in the model they are functions of those generic input values.

Table 6-1. Assessment of trends in model output

Result by fabric type	
Concentration passing through fence (mg/L)	Field Lab - increased as discharge coefficient increased *Model – increased as discharge coefficient increased*
Result by slope	
Discharge in toe trench, (cfs)	Field Lab – increased as slope increased *Model – increased as slope increased*
Average concentration in toe trench (mg/L)	Field Lab – decreased as slope increased *Model – increased as slope increased*
Concentration passing through fence (mg/L)	Field Lab – increased as slope increased *Model – increased as slope increased*
Result by soil type	
Average concentration in toe trench (mg/L)	Field Lab – ascending order - red clay, black clay, loam *Model – ascending order - black clay, red clay, loam*
Concentration passing through fence (mg/L)	Field Lab – ascending order - red clay, black clay, loam *Model – ascending order - black clay, red clay, loam*

The concentration through the fence as a function of fabric type preserved the trend in the field data. This is due to the way the model was developed. The computed discharge in the toe trench as a function of slope also followed the trend in the field data. However, the average concentration did not follow the results seen in the field. Those field results were not as expected (see Table 5-4), and the trend shown here does follow what we would expect to see. The model trend in concentration passing through the fence as a function of slope followed the field-observed trend. The model prediction is a function of fabric type and concentration in the toe trench.

The results as a function of soil type were not as consistent as the results by slope or fabric type. For both concentrations along the toe and through the fence, the loam soil produced the highest value, both by model and in the field. However, the trends for the other two soils were reversed. The model predictions followed the trend in the d_{50}; the field observations did not. The model observations are also explicitly a function of slope which may explain why the trends in the averages do not agree.

In general, the model did a reasonable job of following the trends in the field data, with three comparisons in complete agreement and two with peaks in agreement. For the one that completely reversed the trend, it was noted earlier that the field observed trend was not as expected.

Quantitative Assessment

The predictive ability of the model was also assessed through a comparison of model output and field-observed values, using the 14 simulations that had measured eroded d_{50} values. The outputs displayed in the design aid were selected for this comparison. Depth of water and accumulated sediment along the toe were not compared because this information was not collected as part of the field studies. Also, since the observed discharge through the fence was not considered representative of what would be seen at a field site (see discussion in Section 5), no comparisons requiring observed flow through the fence were made. Also, since it was not a part of this project to collect impoundment data, the impoundment functions could not be checked.

In general, the hydrology functions performed well, particularly at predicting runoff rate and volume. Figure 6-9 is a plot of observed vs. predicted runoff rate. The root mean square error (RMSE) in runoff rate was 0.0045 ft^3/s, the average observed value was 0.032 ft^3/s and the average predicted value was 0.035 ft^3/s.

For sediment yield, using a cover factor of 1.0 resulted in highly under-predicted values. The calibrated value of cover factor (over all the simulations) was 1.7, which is in line with the value in Figure 6-2 for emplacement of stockpiled soil. The soil for the field tests was placed from stockpiles, and the tests were run anywhere from almost immediately to about three months after the soil was placed. Figure 6-10 shows the predicted vs. observed values. The average observed and predicted values were 0.081 and 0.088 tons, respectively. Further calibration of the model with the field data was not deemed advisable because as is, the model predicts in the correct order of magnitude and responds in changes to source area slope and soil type in line with accepted theory of overland soil erosion.

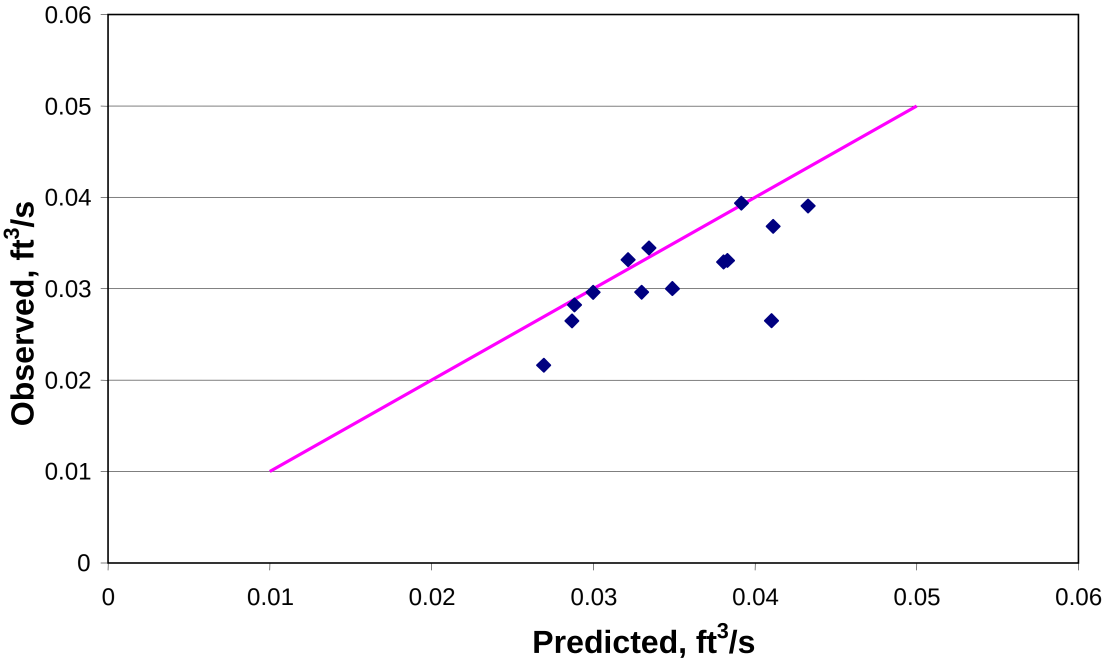


Figure 6-9. Model validation – observed vs. predicted average runoff rate from source (ft^3/s)

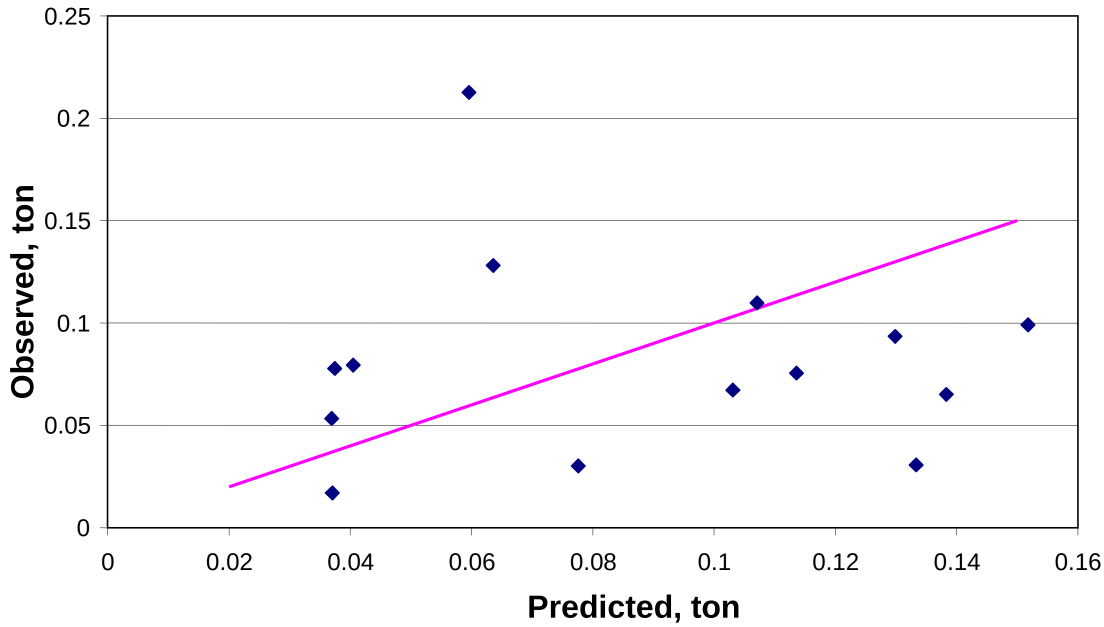


Figure 6-10. Model validation – observed vs. predicted average sediment yield from source (ton)

The average discharge in the toe trench was generally under-predicted, with an average observed value of 0.022 and a predicted value of 0.015. Figure 6-11 is a plot of the data. It was previously noted that the seepage model was based on limited data, and there is no additional data for further calibration. The model was determined acceptable since the actual errors were small and it responded to changes in input values the way it was expected.

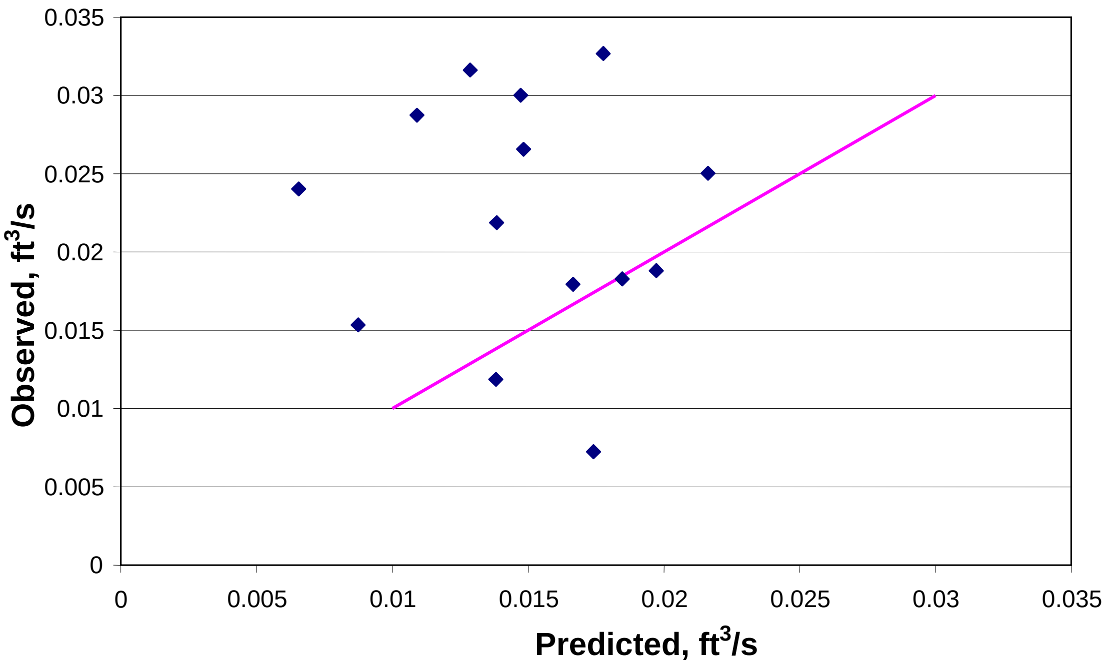


Figure 6-11. Model validation – observed vs. predicted average discharge in toe trench (ft^3/s)

The model produced reasonable results for average concentration in the toe trench. Figure 6-12 shows observed vs. predicted. The average observed value was 69,594 mg/L and the average predicted value was 58,049 mg/L. Predicted total weight of sediment discharged downstream was predicted fairly well, with a few outliers as shown in Figure 6-13. The average observed and predicted values were 293 and 185 lb, respectively.

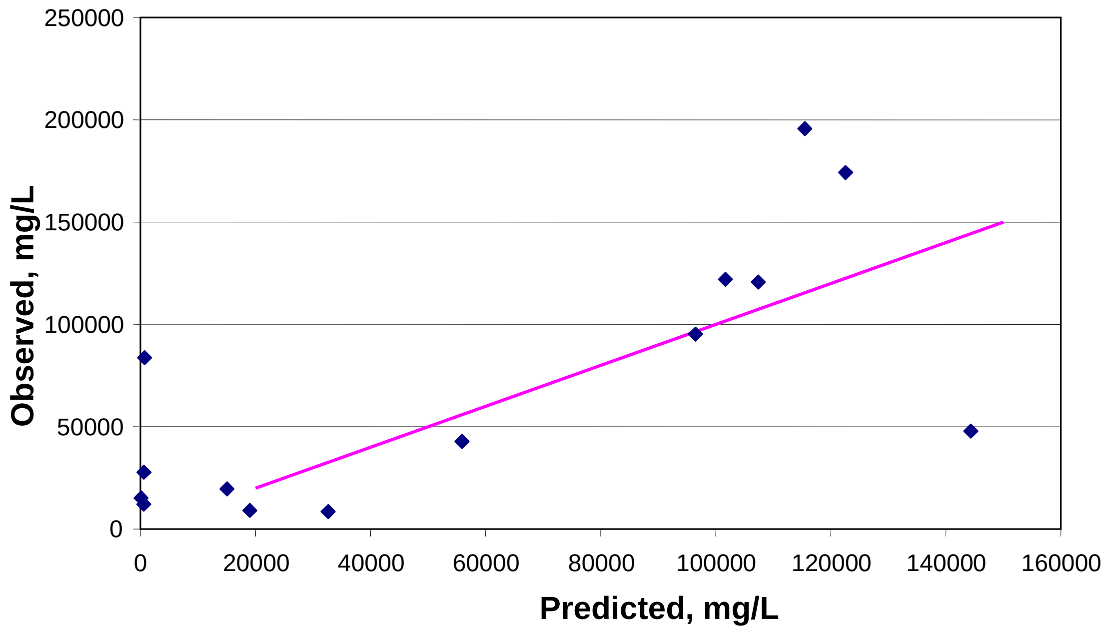


Figure 6-12. Model validation – observed vs. predicted average concentration in toe trench (mg/L)

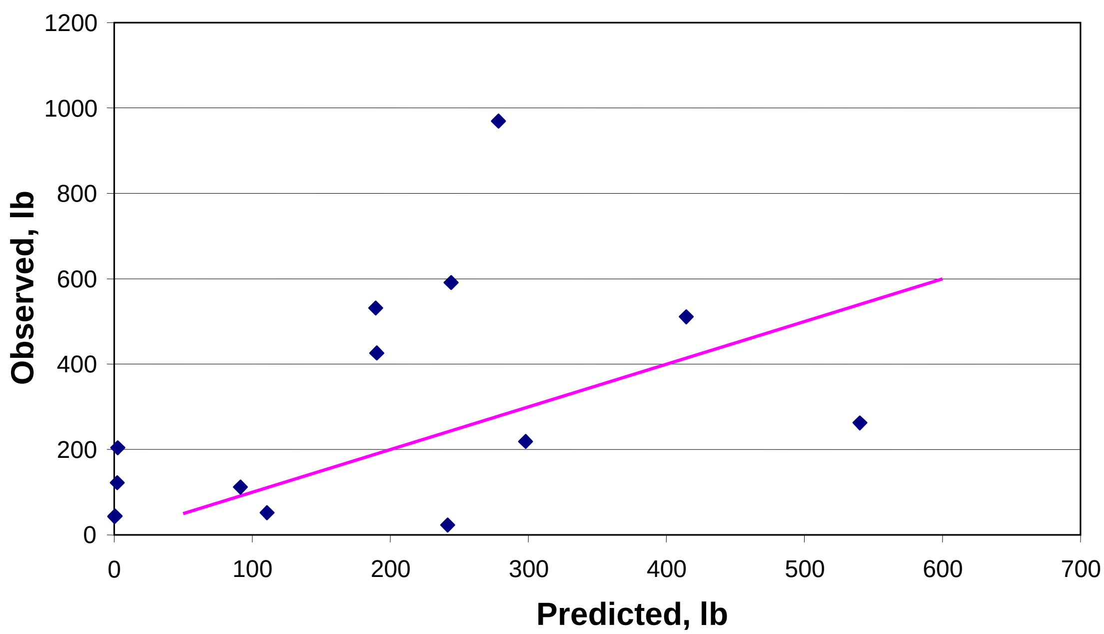


Figure 6-13. Model validation – observed vs. predicted sediment discharged at end of toe (lb)

Predictions of net erosion and deposition were fair. The correct type – erosion or deposition – was predicted correctly for all 14 simulations evaluated. Figure 6-14 shows the observed vs. predicted. Since there are zero values, comparing the averages for this output is not very informative. The model uses the net erosion as an indicator of failure by scour at the toe of the silt fence. In this respect, the model performed quite well. The correct phenomena – failure or no failure – was predicted for 11 of 14 simulations. With the three that were incorrect, for two of them failure was predicted when it did not occur. There was only one instance where failure occurred in a fence that was predicted to stay intact. This is a good attribute for a design aid in that predictions are mostly conservative and include a factor of safety.

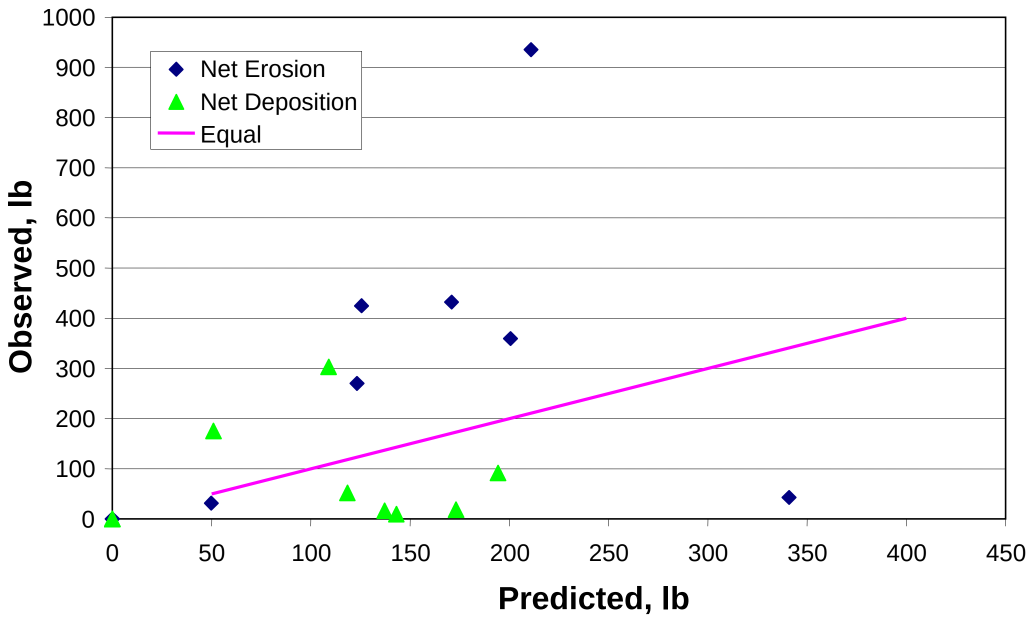


Figure 6-14. Model validation – observed vs. predicted net erosion/deposition (lb)

There was fair agreement for concentration passing through the silt fence. Observed vs. predicted values are in Figure 6-15. This computation is a function of several intermediate computations and error in this output would be compounded by even small errors in intermediate computations. Still, the overall magnitude of the results was good, with average observed and predicted concentrations of 42,832 and 42,658 mg/L, respectively.

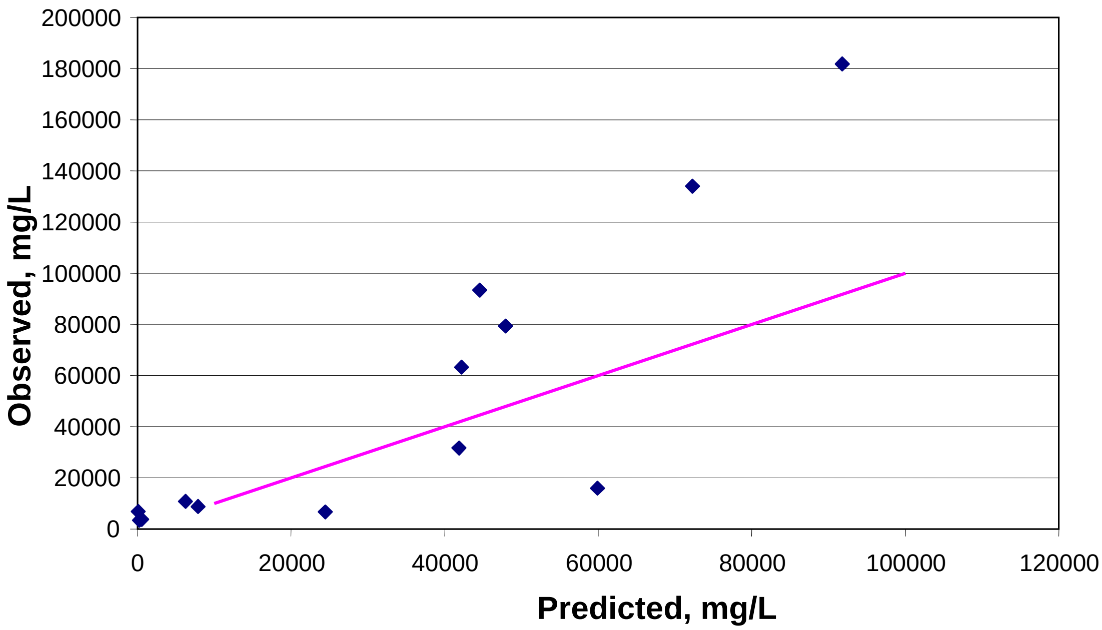


Figure 6-15. Model validation – observed vs. predicted concentration of sediment in flow through fence (mg/L)

The primary objective of the model validation/calibration was to have the model produce results with a reasonable magnitude, but not to calibrate to the point that the model responses with respect to changes in input values did not agree with accepted theory and practice. This model produces, on average, predictions that agree well with the field observations, and generally responds to changes in inputs in the appropriate manner. Therefore, it is concluded that the modeling objectives were accomplished and the model can serve as the basis for a design aid.

Chapter 7
Design Aid Spreadsheet

Background

The design aid spreadsheet (attached herewith) evaluates the following aspects of a silt fence installation:

- Duration of a specified rate of rainfall that will result in failure due to scouring of the toe, or indication that failure by scour will not occur within 3 h.
- Average depth of sediment deposition that occurs behind the fence. Since fences are installed at different heights, the designer can use this information to determine the number of storms the fence can withstand before the accumulated sediment becomes a problem and clean-out is required.
- Total pounds of sediment that will be discharged at the downslope end of the fence. Ideally, the downslope end of the fence will form an angle up the slope to create an impoundment or the flow will be directed to a suitable location, such as a sediment trap.
- Total pounds of sediment that will be discharged through the fence.
- Trapping efficiency if the toe of the downslope end of the fence is angled up-slope to create an impoundment.

To execute the design aid, the user enters the information specified in Table 7-1.

User Instructions

The user opens the tab labeled Input and Output to enter the data described in the preceding table. All of the cells highlighted in blue need to have entries. If the fence will not be extended uphill to create an impoundment, the default values can be left in the impoundment data section. Once the data are entered, the user switches to the Hyd routing page to solve the flow hydraulics component. For now, this is executed by calling up the Excel Solver using the Tools – Solver menu. The solver is programmed to do the computations. The user should click on the Solve button. The highlighted box with the word Result gives the squared error in the continuity based on the assumed head. Repeating the Solver computation will decrease the error. It is recommended that the user repeat Solver until the error is less than 0.001 or until stops doing additional iterations.

The user can then go back to the Input and Output page to view the results. The user may then adjust the input parameters to show the impact of management measures on the silt fence performance. Changing the cells highlighted in green requires repeating the Solver.

Table 7-1. Summary of user input to design aid

Parameter	Units
Hydrology information	
24-h rainfall for selected return interval	in.
Curve number	
Length up slope	ft
Width along fence	ft
Slope to fence	ft/ft
Slope along fence	ft/ft
Toe trench width	ft
Toe trench depth	ft
Soil information	
Wischmeier's K	English Units
d_{50}	mm
Cover factor	
Eroded size distribution OR	
Sand-silt-clay for CREAMS	
Fabric information	
Fabric type – Nilex 2130 or Nilex 2127	
OR discharge coefficient	
Impoundment information	
Angle that extension makes with toe	Degrees
Length of extension	ft
Performance factor	

Example

A residential subdivision includes 4 building lots along 400 ft of road frontage. The fronts of the lots slope toward the road, and the drainage divide is 20 ft from the edge of the road. A silt fence will be used to protect the road from the construction site sediment. The slope toward the road is 8% and the slope along the road (and along the fence) is 5%. Using a 3-h rainfall depth of 2.5 in./h, evaluate the suitability of using silt fence.

Additional properties required are listed in Table 7-2.

Table 7-2. Site properties for design aid model

Property	Value	Units
Curve number	96	
Toe trench width	0.5	ft
toe trench depth	0.5	ft
Fabric Data		
Put X next to type		
Fabric type - Nilex 2130		
Wischmeier's K	0.15	English units
% sand	20	
% silt	35	
% clay	45	
Cover factor	1.7	
Angle of extension upslope	90	degrees
Length of extension upslope	4	ft
Beta performance factor	2	

Figure 7-1 shows the data input screen. After executing the routing, the output can be viewed on the same page of the spreadsheet, as shown in Figure 7-1. The output shows that the fence is not only ineffective in trapping sediment, the presence of the fence and the concentrated flow along the toe results in a greater release of sediment than would occur with no fence.

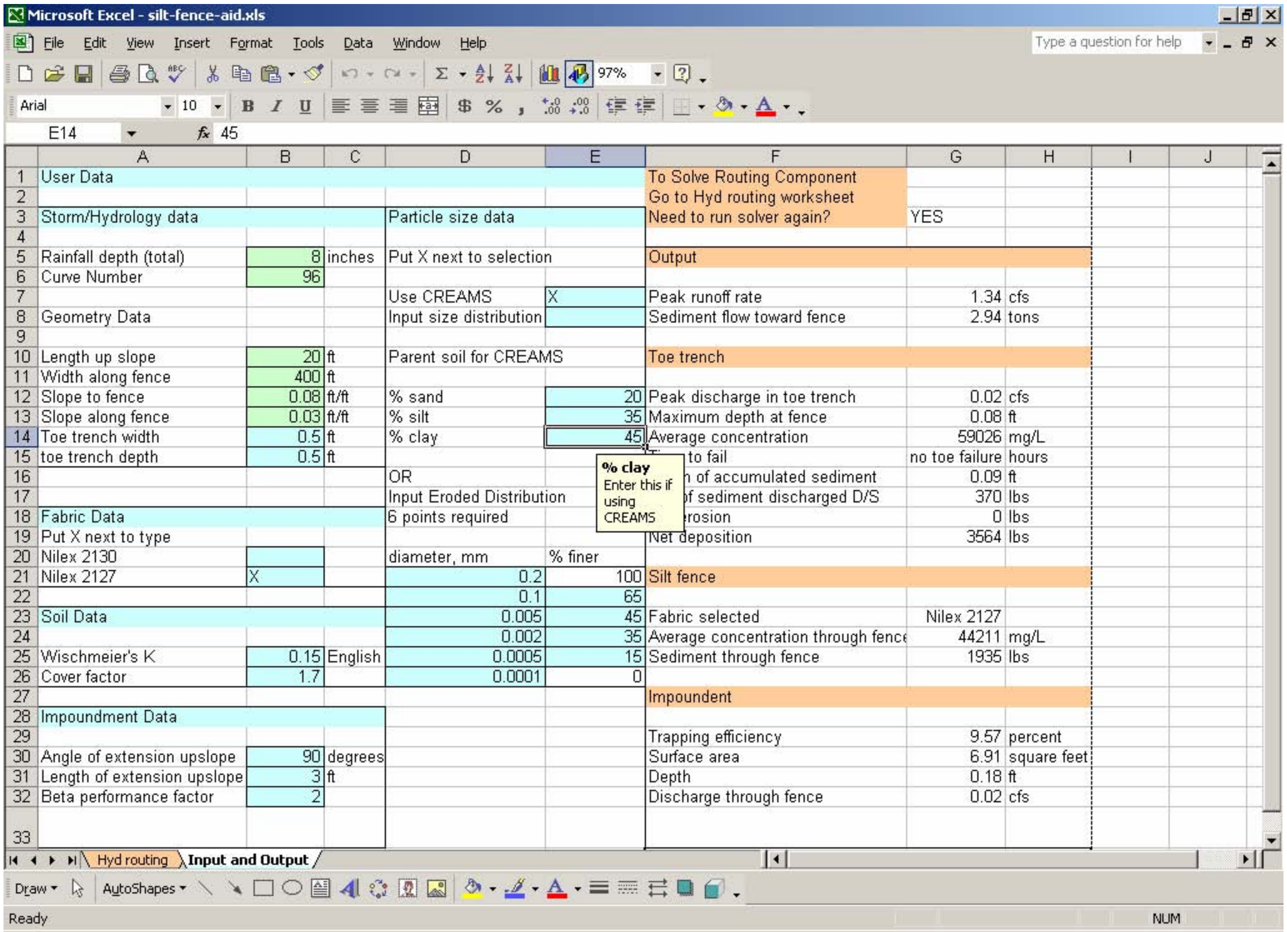
The user should also note that there is a warning that the water elevation in the impoundment is higher than the end of the extension, meaning more sediment lost as flow goes around the end of the extension. This can be corrected by increasing the length until the warning disappears. In this case, an increase from 3 to 4 ft is sufficient.

The model can be used to assess modifications to the design. For example, the fence is re-positioned to lower the slope along the fence to 3%. This increases the overall trapping efficiency to 70.3%. With the lower slope, there is less scour along the toe and a lower concentration of sediment in the flow along the toe and less sediment discharged into the impoundment. There is also less sediment discharged through the fence because the concentrations are lower.

If the looser, Nilex 2127 fabric is used, overall trapping decreases to 51%. This is due to the higher concentration and discharge through the fence and the higher rates of discharge from the impoundment.

The soil in this example is a fine-grained soil, and failure due to scour of the toe trench is not expected. For the rainfall selected, a deposition of 0.09 ft is expected. Typically, clean-out is recommended when the height of sediment reaches one-third the height of the fence. For a typical 12 to 18-in. high fence, after 3 to 5 similar storms, maintenance should be considered.

These examples illustrate the use of the design aid to assess the overall trapping efficiency of a silt fence installation and use as a management measure.



	A	B	C	D	E	F	G	H
1	User Data					To Solve Routing Component		
2						Go to Hyd routing worksheet		
3	Storm/Hydrology data			Particle size data		Need to run solver again?	YES	
4								
5	Rainfall depth (total)	8	inches	Put X next to selection		Output		
6	Curve Number	96						
7				Use CREAMS	X	Peak runoff rate	1.34	cfs
8	Geometry Data			Input size distribution		Sediment flow toward fence	2.94	tons
9								
10	Length up slope	20	ft	Parent soil for CREAMS		Toe trench		
11	Width along fence	400	ft					
12	Slope to fence	0.08	ft/ft	% sand	20	Peak discharge in toe trench	0.02	cfs
13	Slope along fence	0.03	ft/ft	% silt	35	Maximum depth at fence	0.08	ft
14	Toe trench width	0.5	ft	% clay	45	Average concentration	59026	mg/L
15	toe trench depth	0.5	ft			to fail	no toe failure	hours
16				OR		n of accumulated sediment	0.09	ft
17				Input Eroded Distribution		of sediment discharged D/S	370	lbs
18	Fabric Data			6 points required		rosion	0	lbs
19	Put X next to type					Net deposition	3564	lbs
20	Nilex 2130			diameter, mm	% finer			
21	Nilex 2127	X		0.2	100	Silt fence		
22				0.1	65			
23	Soil Data			0.005	45	Fabric selected	Nilex 2127	
24				0.002	35	Average concentration through fence	44211	mg/L
25	Wischmeier's K	0.15	English	0.0005	15	Sediment through fence	1935	lbs
26	Cover factor	1.7		0.0001	0			
27						Impoundment		
28	Impoundment Data							
29						Trapping efficiency	9.57	percent
30	Angle of extension upslope	90	degrees			Surface area	6.91	square feet
31	Length of extension upslope	3	ft			Depth	0.18	ft
32	Beta performance factor	2				Discharge through fence	0.02	cfs
33								

Figure 7-1. Screen capture of spreadsheet input and output

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