RES#2016-20: Performance Base Testing for Erosion Prevention and Sediment Control (EPSC) Devices

FINAL REPORT

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May 2021

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Technical Report Documentation Page

1. Report No. RES2016-20	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle *Performance Base Testing for Erosion Prevention and Sediment Control (EPSC) Devices*		5. Report Date May 2021 6. Performing Organization Code
7. Author(s) Christopher Wilson		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Tennessee – Knoxville 851 Neyland Dr Knoxville, TN 37996		10. Work Unit No. (TRAIS) 11. Contract or Grant No. RES2016-20
12. Sponsoring Agency Name and Address Tennessee Department of Transportation James K. Polk Bldg., Suite 700 505 Deaderick Street, Suite 900 Nashville, TN 37243		13. Type of Report and Period Covered Final Report October 2015 – March 2021 14. Sponsoring Agency Code
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

To address excessive soil loss from roadway and other construction sites, several erosion prevention and sediment control practices exist. However, there is still a need for systematic performance evaluation methods that provide sound efficiency values for the different practices under a range of conditions. There is also the need for a transparent means to determine a suitable practice for specific site parameters. Three objectives were developed to help resolve these needs: (1) identify a systematic protocol for testing sediment control practices that considers the range of soil, climate, and topographic conditions in Tennessee; (2) quantify the efficiencies of different sediment retention practices using this methodology; and (3) develop a simple model for choosing proper practices for sites in Tennessee. A physical model of a fill slope below a highway shoulder leading to a drainage ditch was constructed that was similar to, but a scaled-down version of, the large platform studies used in AASHTO's National Transportation Product Evaluation Program. A step-by-step methodology for testing sediment control practices was developed using this structure. Simulated rainfall events were conducted initially with no sediment retention practice and then with a silt fence, straw-filled tube, and mulch-filled tube. The results showed that runoff was better correlated with soil loss than other examined rainfall factors (e.g., intensity), and hence, a better erosivity index. Power functions were fit to the soil loss – runoff coefficient data pairs from the simulated events to provide "floating" baseline soil loss values for quantifying Practice Management Factors, or P-factors. Since these empirical equations use runoff coefficients, which are functions of the soil, slope, weather, and management, they essentially provide "site specific" values. The P-factor values for silt fences, mulch-filled sediment tubes, and straw-filled sediment tubes exhibited a wide range (0.03 – 0.76) strongly related to the runoff coefficient. An erosion calculator was developed that incorporates the Modified Universal Soil Loss Equation and simple nomographs to determine the P-factors for common conditions in the state. A system dynamics framework was used because it is highly visual, easy-to-follow, and transparently depicts the causal links between the pedologic, topographic, hydrologic, hydraulic, and management-related components of any site-system. The calculator is web-based and can be accessed by anyone without any special software.

17. Key Words **Soil erosion, Silt fence, Straw-filled sediment tube, Mulch-filled sediment tube, Runoff Coefficient, Practice Management Factor, Erosion calculator, System dynamics model**	18. Distribution Statement No restriction. This document is available to the public from the sponsoring agency at the website https://www.tn.gov/.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

ACKNOWLEDGEMENTS

This research was sponsored by the Tennessee Department of Transportation. The author is indebted to Ali Hangul for serving as the Technical Advisor and providing productive input to improve this project. The author would also like to thank Dr. Thanos Papanicolaou for his help with this project, as well as the following students and post-docs from the University of Tennessee: Matthew Davis, Mohammad Ghaneeizad, and Christian Mooneyham, and Kaity Patterson.

Knoxville, TN
May 2021

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Executive Summary

Exorbitant soil erosion rates at roadway and other construction sites result in higher costs from having to either replace the lost soil or clean-up the expelled sediment. Project managers have available numerous literature and web-based sources that describe Best Management Practices (BMP) for abating the soil loss, but little guidance is available on which practices will be effective under the conditions for which they are planning. Recent reviews suggest that these available sources lack both short-term and long-term BMP efficiency values. Those studies that do provide efficiency values often report a wide range, which has been attributed to a lack of rigorous and quantitative performance testing procedures.

This study was developed to address the need for systematic performance evaluation methods to quantify the effectiveness of different practices under a wide range of conditions. Three objectives were established that define this study. The first objective was to identify a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee. The second objective was to quantify the efficiencies of commonly used sediment retention practices in Tennessee using this methodology. The third objective was to develop a simple model for choosing the proper erosion control or sediment retention practice for sites in Tennessee.

For addressing Objective 1, the American Association of State Highway Transportation Officials' (AASHTO's) National Transportation Product Evaluation Program (NTPEP) offers structured evaluations for erosion prevention and sediment control practices using large-scale slope/ channel platforms and following standard test methods of ASTM International. Due to the platforms' large size, it is almost a necessity to have them outside. This presents several logistical concerns. It may be difficult to designate a large piece of land or the financial resources to support such a facility. The level of infrastructure and support needed to replace and rework the soil on the platforms thoroughly is substantial.

The NTPEP evaluations do provide a common ground for the comparison of practice efficiencies by using approved, standard protocols. Essentially, all practices are tested under a singular condition. This approach does provide a common basepoint for practice comparisons. However, that common basepoint may not be applicable for certain regions or conditions outside of the bounds of the testing procedure.

In this study, a scaled-down physical model of a fill slope below a highway shoulder leading to a drainage ditch was constructed in the Hydraulics & Sedimentation Lab of the University of Tennessee – Knoxville (UTK). The structure consisted of a soil box that was 1.83 m long x 1.98 m wide x 0.30 m deep. The box was sloped to a 3:1 (Horizontal: Vertical) grade and was filled with 10 cm of soil that was compacted to approximately 90% of the Proctor density.

One outcome of this effort was a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee. A step-by-step methodology is provided. An important feature of this protocol is the use of measured runoff coefficients that result from weather and soil conditions found in Tennessee. Thus, the results from this protocol are designed to be more applicable for the Tennessee Department of Transportation (TDOT).

To resolve Objective 2, this protocol was followed providing Tennessee-relevant efficiency values for silt fences, as well as mulch-filled and straw-filled sediment tubes. Simulated rainfall events over the physical model of the fill slope were conducted initially with no sediment retention practice being used. These bare soil tests provided baseline erosion rates. The soil loss data from the bare soil tests were compared to those of the tests with the installed practices to determine the Practice Management Factor, or P-factor. The P-factor is considered as the ratio the soil loss for the practice-protected condition divided by the sediment loss from the control bare-soil condition.

However, in this study, the results from the simulated events were different than those typically found using the NTPEP methodology which show a strong correlation between rainfall intensity and soil loss. In summary, the experimental results have shown that rainfall intensity was a poor predictor of runoff and soil loss for the silt fence, straw-filled tube, and mulch-filled tube. Since rainfall intensity is the key variable that is correlated with soil loss in the NTPEP standard methods, a new approach was needed.

A chrono-sequence of images from the experiments shows an overall coarsening of the soil texture from more uniform, fine-grained particles to a wider distribution of coarse aggregates. The coarsening was attributed to erosion preferentially removing the finer particles and aggregates. From the chrono-sequence of images and the apparent coarsening of soil over time, the relative amounts for infiltration and runoff were explored as the trigger causing the difference between expected and observed results. When the soil loss was compared with the runoff coefficient, the data collapsed to a useable relationship. Thus, the new approach was centered on using runoff coefficients as the predictor of soil loss.

In light of this finding, empirical relationships were developed to provide “floating” baseline values of soil loss. For each intensity, power functions were fit to the soil loss – runoff coefficient data pairs following similar hydraulic geometry concepts characterizing sediment loads with discharge. Runoff is more correlated with soil loss than other examined rainfall factors such as intensity, total storm kinetic energy, and other combined factors. Moreover, sediment concentrations of major storm events are independent of all examined rainfall factors. Hence, the runoff coefficient should be the best erosivity index at scales from plots to watersheds.

Because these empirical equations were developed using the runoff coefficients, which are functions of the soil, slope, weather, and management, they essentially provide “site specific” values. Thus, the derived P-factors for the three practices are specific for Tennessee. The determined soil loss reduction values should then be better representative of the site.

These equations are incorporated into an erosion calculator tool that can be used by TDOT engineers when developing an erosion plan for a roadway construction site (i.e., Objective 3). The erosion calculator incorporates the Modified Universal Soil Loss Equation (MUSLE) implemented through a system dynamics framework. The system dynamics framework was chosen because it transparently depicts the causal links between the pedologic, topographic, hydrologic, hydraulic, and management-related components of any site-system. The highly visual nature is also easy to follow.

The *Tennessee Erosion Model* was developed in a web-based software provided by *InsightMaker*. With *InsightMaker*, the model is compiled in your browser and the address can be shared with whomever. The benefit of this is that TDOT engineers do not need a special software to calculate soil loss and the reductions of select sediment reduction practices. Another advantage of the *InsightMaker* software is it automatically creates a storyboard for the developed model. The story describes what inputs are needed and then walks the user through the functionalities included in the model. The created story can be placed side-by-side with the model structure and while a simulation is run, the action on the screen can be recorded or videotaped for inclusion in a training video.

Key Findings

- There is a lack of rigorous and quantitative performance testing procedures for sediment reduction practices that consider a wide range of conditions.
- Intermediate-size physical models of roadway construction sites can provide consistent and reasonable erosion estimates with less overhead than large-scale platform studies.
- Evaluations following structured, standardized testing methodologies provide a common basepoint for comparison of different practices. However, that common basepoint may not be applicable for certain regions or conditions outside of the bounds of the testing procedure.
- Experimental results showed that rainfall intensity was a poor predictor of runoff and soil loss. Runoff is more correlated with soil loss than rainfall factors such as intensity, total storm kinetic energy, and other combined factors. Moreover, sediment concentrations of major storm events are independent of all examined rainfall factors. The runoff coefficient should be the best erosivity index.

- Over repeated simulated rainfall events, there was a coarsening of the sediment which was attributed to preferential erosion of finer particles and aggregates. This coarsening of soil over time alters the partitioning of rainfall to infiltration and runoff.
- Runoff and soil loss vary with runoff coefficient, but they do so within a single rainfall intensity.
- P-factor values for silt fences, mulch-filled sediment tubes, and straw-filled sediment tubes exhibited a wide range of values (0.03 – 0.76) strongly related to the runoff coefficient during the event.

Key Recommendations

- One outcome of this study is a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee. An important feature of this protocol is the use of measured runoff coefficients that result from weather and soil conditions in Tennessee. Thus, the results from this protocol are designed to be more applicable for TDOT.
- Power functions were fit to soil loss – runoff coefficient data pairs following similar hydraulic geometry concepts characterizing sediment loads with discharge. These empirical relationships provide "floating" baseline values of soil loss.
- Using empirical equations that relate P-factor values with runoff coefficients can provide more site representative values. Runoff coefficients are functions of the soil, slope, weather, and management, so they are "site specific" parameters.
- An erosion calculator tool was developed that incorporates the Modified Universal Soil Loss Equation (MUSLE). Runoff was more correlated with soil loss than examined rainfall factors.
- The model is implemented through a system dynamics framework, which transparently depicts the causal links between the pedologic, topographic, hydrologic, hydraulic, and management-related components of any site-system. The highly visual nature makes it easy to follow.

Introduction

Problem Statement

Excessive sediment persists as the predominant pollutant to local waterways throughout the U.S. despite a plethora of erosion prevention and sediment control practices (e.g., Sprague et al., 2014). At roadway and other construction sites (Figure 1), where soil erosion rates can exceed those in agricultural areas by a hundred-fold (e.g., Faucette et al., 2006), the exorbitant loads result in higher construction costs from having to either replace the lost soil or clean-up the expelled sediment (Ledermann et al., 2010).

Project managers have available numerous literature and web-based sources that describe Best Management Practices, or BMPs, for limiting the loss of sediment (e.g., Muste et al., 2002). In addition, the companies which design, sell, and implement these practices are continuously providing new products.

Figure 1. Excessive rilling and erosion near a roadway construction site.

Rolled erosion control practices and hydraulically applied amendments have been historically highlighted in the literature with sediment retention devices recently receiving their due attention (Garcia et al., 2015). Sediment retention practices reduce the exported loads by slowing runoff, promoting infiltration, and trapping sediment before it exits the construction sites. Despite the obvious benefits of sediment retention practices, rigorous and quantitative performance testing procedures have been slow to develop (Bugg et al., 2017).

This deficiency does not dismiss those studies that describe the different practices, detail their proper installation, and determine their potential (i.e., efficiency) for reducing runoff and sediment loads (e.g., Tyner et al., 2011; Chapman et al., 2014). However, one underlying result from the studies is that a wide range of reported reductions exists, which is in part due to different experimental conditions and key site-specific parameters (Faucette et al., 2008). The natural by-product from these sources and studies spewing wide ranges of BMP efficiency values is a murky pool of practices in which states, like Tennessee, must wade through to identify and implement those that are best suited for their local conditions. *The following needs have emerged from this quagmire:*

(1) the need for systematic performance evaluation methods to quantify the effectiveness of different practices under a wide range of conditions;
(2) the need for scientifically sound efficiency values for different erosion prevention and sediment reduction practices determined with the above systematic methods; and

(3) the need for a transparent and straightforward means to determine suitable erosion prevention and sediment reduction practice for specific site parameters.

Regardless of the project size and type, the process of selecting optimal erosion control measures for the specific set of site conditions must be simplified and made more cost effective to ensure potential benefits are achieved.

Project Objectives

To address these three needs, the following objectives were established to define the study described in this report. The **first objective** was to identify a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee. Currently, practice choices are based on efficiency values for equivalent practices that were developed for agriculture (Toy et al., 1999). Minimal to no testing have been performed at actual roadway and construction sites (Schwartz and Hathaway, 2018). The National Transportation Product Evaluation Program (NTPEP; http://www.ntpep.org/Pages/default.aspx) offers some guidance for testing methods but it is unknown how applicable their methods are for use in Tennessee. The present study conducts systematic performance evaluations of common sediment retention practices using methods based on the NTPEP approach but geared to examine them under common conditions in Tennessee.

The **second objective** for this study was to quantify the efficiencies of different sediment retention practices using the above-mentioned methodology. To reiterate, these efficiency values will be applicable to conditions across Tennessee. The practices evaluated herein were selected based on the popular choices of the Tennessee Department of Transportation (TDOT). These included silt fences and sediment tubes.

The **third objective** of this study was to develop a simple model for choosing the proper erosion control or sediment retention practice for sites in Tennessee. This study provides an erosion calculator that incorporates the Modified Universal Soil Loss Equation (MUSLE) and simple nomographs that can determine the P-factors for sediment retention practices tested through the above-developed protocol under common conditions in the state. A system dynamics framework was chosen for the erosion calculator because it transparently depicts the causal links between the pedologic, topographic, hydrologic, hydraulic, and management-related components of any site-system. The highly visual nature is easy to follow. Moreover, the calculator is web-based and can be accessed by anyone without any special software.

Literature Review

Need 1: The need for systematic performance evaluation methods to quantify the effectiveness of different practices under a wide range of conditions.

To provide standardized, quantitative testing of sediment control practices, the NTPEP was begun by the American Association of State Highway and Transportation Officials (AASHTO). NTPEP provides structured evaluations of erosion prevention and sediment control practices that are designed to simulate expected field conditions (AASHTO, 2014). These tests use large-scale slope (Figure 2) and channel platforms and follow standard test methods of ASTM International (i.e., the American Society for Testing and Materials):

- ASTM D5141 - Standard Test Method for Determining Filtering Efficiency and Flow Rate of the Filtration Component of a Sediment Retention Device Using Site-Specific Soil.
- ASTM D7351 - Standard Test Method for Determination of Sediment Retention Device Effectiveness in Sheet Flow Applications.
- ASTM D7208 - Determination of Temporary Ditch Check Performance in Protecting Earthen Channels from Stormwater-Induced Erosion.
- TM11340 - Standard Test Method for Determination of Sediment Retention Device (SRDs) Performance in Reducing Sediment Loss from Rainfall-Induced Erosion during Perimeter Control Applications (Georgia Soil and Water Conservation Commission).

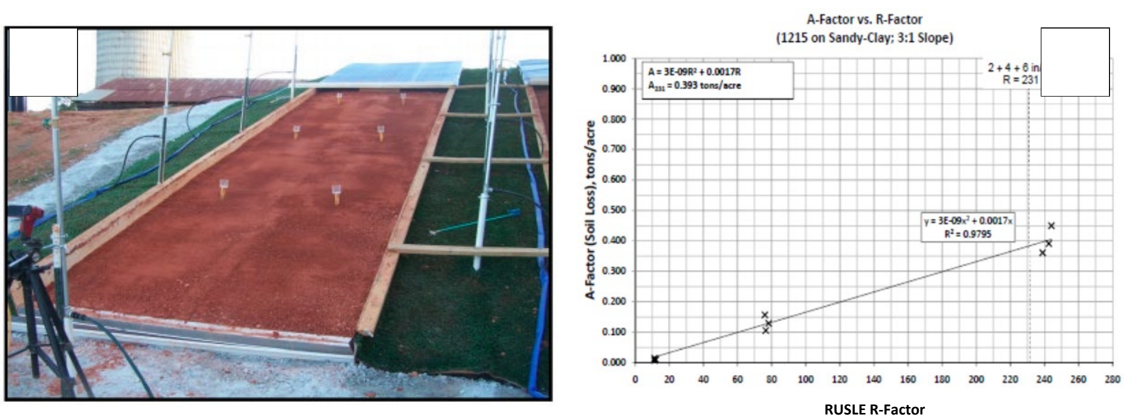

Figure 2. The standard method TM11340. (a) Example of the large-scale test structure used under the method. This is a bare soil test to provide baseline erosion rates. (b) Typical results from the TM11340 tests. It is a plot of soil loss vs. the R-factor of the USLE equation. From Sprague and Sprague (2012).

NTPEP testing provides a common ground for the comparison of practice efficiencies by using approved, standard protocols (Sprague and Sprague, 2012). Essentially, all practices are tested under a singular condition. Sediment retention practices are all evaluated on 8.23-m long x 2.44-m wide (27 ft. x 8 ft.) wide plots with 3:1 slopes and sandy clay soils. Surrounding the plots are 4.57-m (15-ft.) tall rain trees that deliver target rainfall intensities of 2, 4, and 6 in./hr. (51, 101, 152 mm/hr) for 20 minutes each. Similar tests are conducted both with the sediment retention practice present and absent. A comparison of the sediment retained during the test with the practice present and the sediment lost during the test without the practice provides the trapping efficiency which is equated to the Practice Management Factor, or P-factor, for the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997). The P-factor is determined for a characteristic K-factor (which reflects soil erodibility) and a cumulative R-factor (which reflects rainfall intensity) for the 2, 4, and 6 in./hr. rainfall simulations (Sprague and Sprague, 2012).

NTPEP allows the manufacturers of erosion control and sediment retention practices to submit their established, already commercialized products for an independent efficiency assessment (AASHTO, 2014). The results from these tests are purely objective, with no implied approval/ disapproval or AASHTO endorsement (Sprague et al., 2014). NTPEP has their DataMine website (http://data.ntpep.org) where the product descriptions and efficiencies are available. Here, various manufacturers submit an electronic Product Evaluation Form, as well as additional product literature, typical values, a quality plan, Material Safety Data Sheets information, installation instructions, and payment of testing fees.

Need 2: The need for scientifically sound efficiency values for different erosion prevention and sediment reduction practices determined with the above systematic methods.

Two primary state agencies that focus on erosion prevention and sediment control include TDOT and the Tennessee Department of Environmental Conservation (TDEC). The TDOT Drainage Manual (2012) additionally provides guidelines for the proper design of an effective erosion prevention and sediment control plan and summaries of different BMPs.

TDOT has 42 flow and sediment control practices (Figure 3) in their Drainage Manual (TDOT, 2012). These practices have been shaped considering the water quality and storm water regulations of TDEC. Standard drawings of these practices can be found online (https://www.tn.gov/tdot/roadway-design/standard-drawings-library/standard-roadway-drawings/erosion-prevention-and-sediment-control.html). Despite this valuable guidance for developing erosion control plans at roadway construction sites, many of these practices are not utilized (Schwartz and Hathaway, 2018). The commonly used practices include silt fences, rock check dams, sediment tubes, and catch basin protections (Hangul, 2017).

In addition to the TDOT source, there are multitudes of in-house manuals, websites, publications and specialized computer programs from various state/ federal government agencies and industry that provide an overview of the steps needed to implement the different practices at construction sites (Muste et al., 2002). Exhaustive reviews and surveys conducted recently (e.g., Hangul, 2017; Liu et al., 2017) suggest that these available sources lack both short-term and long-term BMP efficiency data. Those data that do exist are poorly organized and do not consider important factors, such as maintenance activities and phasing (Liu et al., 2017).

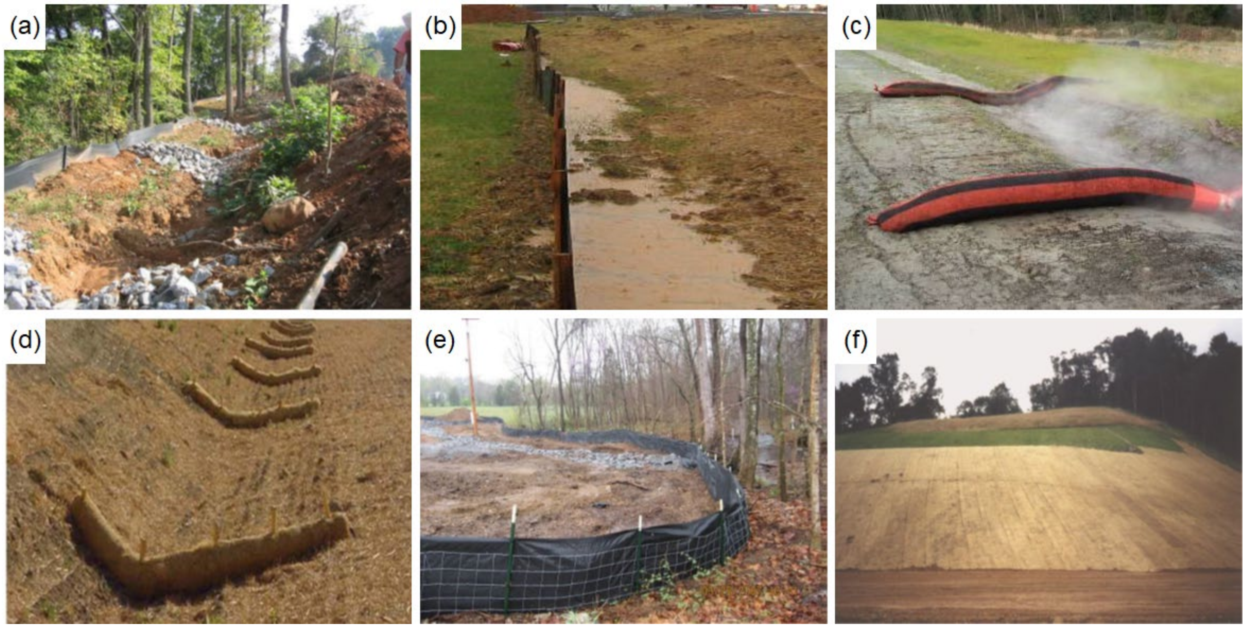

Figure 3. Examples of commonly used sediment and runoff retention devices: (a) rock check dams; (b) silt fence; (c) sediment tubes; (d) wattles; (e) enhanced silt fence; (f) rolled control erosion blankets.

In Tennessee, quantitative studies regarding sediment reduction efficiency, off-site losses, and product durability, are sparse (Schwartz and Hathaway, 2018). Table 1 lists P-factors derived for silt fences and sediment tubes conducted in the region. The wide range in values is quickly apparent with values ranging from 0 (trapping everything) to 1 (trapping nothing). Although alarming, the wide range is reasonable considering an endless number of combinations of soil, slopes, rainfall, practice design, practice implementation, and testing methodologies.

Table 1. P-factor values for silt fences and sediment tubes found in the literature.

Silt Fence	**Sediment Tubes**
0.03 (Virginia, 1992)	0.14 – 0.51 (Theisen and Spittle, 2005)
0.20 for sand; 0.5 for silt; 0.8 for clay (USEPA, 1993)	0.29 – 0.45 excelsior fiber logs (Faucette et al., 2005)
0.5 (Fitfield, 2001)	0.3 (Faucette and Tyler 2006)
0.22 – 0.68 (Theisen and Spittle, 2005)	0.66 – 0.81 for straw wattles (Kelsey et al., 2006)
0.13 – 0.46 (Faucette et al., 2008)	0.10 – 0.32 for filter socks without polymers (Faucette et al., 2008)
0.44 – 0.77 (Gogo-Abite and Chopra, 2013)	0.02 – 0.06 for filter socks without polymers (Faucette et al., 2008)
	0.03 – 0.81 (Garcia et al., 2015)

Need 3: The need for a transparent and straightforward means to determine suitable erosion prevention and sediment reduction practice for specific site parameters.

Another element lacking from the multitude of available sources is information or tools that can facilitate choosing a specific practice for the level of soil loss expected at the site. In essence, there is little guidance provided for choosing an effective practice.

To curb erosion and sediment loss, project managers must not only be familiar with the available types and operational characteristics of the different practices, but also have a comprehensive understanding of site parameters that affect erosion and impact the choice of a practice for erosion prevention or sediment control. These parameters include the following (Sonneveld and Nearing, 2003):

- Drainage area - system size directly affects the amount of runoff and sediment that can be produced;
- Climate - rainfall intensities and amounts dictate the available kinetic energy of rain splash to dislodge particles and runoff production to entrain soil particles and aggregates;
- Soil type - different soil characteristics (e.g., texture, organic matter content) will dictate different partitioning of rainfall to infiltration and runoff, as well as the degree of erodibility;
- Topograph - slope steepness and length affect the maximum rate of runoff; and
- Land use/ Land cover - the ground cover and soil roughness can protect the soil from rain splash/runoff or dictate paths for concentrated flow.

The Universal Soil Loss Equation, or USLE, first derived in the late 1970s (Wischmeier and Smith, 1978), and the models that stem from it (i.e., the Revised or Modified USLE) are some of the most widely accepted means for predicting gross soil erosion (Risse et al., 1993). The USLE intuitively captures the parameters listed above in multiplicative factors for determining the average annual soil loss, A, in tons/ acre/ year and is expressed as the following:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where R is the rainfall-runoff erosivity factor and reflects the ability of the rainfall and runoff to erode soil; K is the soil erodibility factor and represents the susceptibility of a soil to erode due to rain splash or runoff; LS is the topographic factor, which is a dimensionless term capturing the slope length and steepness; C is the cover management factor, another dimensionless term that accounts for prior land use, type of vegetative cover, quantity of residue on the surface, surface roughness and soil moisture; and P is the support practice factor, which is the focus of this study.

USLE is a common method used by several state Departments of Transportation, but it has limitations. It can be easy for users to misuse the USLE by making inappropriate input choices resulting in inaccurate soil-loss estimates as there is little guidance for mining, construction, and reclamation land applications (Toy et al., 1999). The USLE has been developed specifically for estimating soil erosion on agricultural lands. In many cases, the C- and P-factors have not yet been calibrated for use in roadway construction applications (TDOT, 2012).

In addition to the C- and P-factors, quantification of the R-factor is disputed and the hence the source of difference between USLE and its derivatives. Originally the R-factor focused on the importance of rainfall intensity to driving erosion. Although rainfall intensity does relate to runoff, especially through the peak runoff rate, intensity alone cannot capture the influence of runoff on soil entrainment and erosion (e.g., Nearing et al., 1994). Thus, the later derivatives of the USLE began to consider runoff specifically (e.g., MUSLE; Cardei, 2010; Gwapedza et al., 2018) as *runoff is more influential than rainfall when evaluating sediment export from a field or construction site*. Regardless, the USLE and its derivatives, are straightforward and intuitive. Thus, they are attractive to many needing a quick erosion value. It can be easily adopted and understood.

Results & Discussion

Objective 1: Identify a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee.

Physical Model Setup: In order to provide systematic performance evaluations of select sediment retention practices, an experimental setup is needed that has been thoroughly vetted. The large-scale platform structures used in NTPEP and the standard practice TM11340 are 8.23 m long x 2.44 m wide (27 ft. x 8 ft.). Due to this size, it is almost a necessity to have them outside. This presents several logistical concerns. It may be difficult to designate a large piece of land or the financial resources to support such a facility. Additionally, weather conditions will limit testing to certain days during certain seasons.

A scaled-down, intermediate-sized, physical model based on a typical highway cross section has been shown to provide consistent and reasonable erosion estimates (Zech et al., 2008). Scaled models that reduce typical cross section to ratios on the order of 1:7 can fit within a controllable laboratory environment.

A physical model (Figure 4) of a fill slope below a highway shoulder leading to a drainage ditch was constructed in the Hydraulics & Sedimentation Lab of the University of Tennessee – Knoxville (UTK). The structure consisted of a soil box that was 1.83 m long x 1.98 m wide x 0.30 m deep. The box was sloped to a 3:1 (Horizontal:Vertical) grade and was filled with 10 cm of soil that was compacted to approximately 90% of the Proctor density. The dimensions of this soil box can accommodate both the size of the sediment retention practices being tested and the wetted area defined by rainfall simulators that drive the erosion of the soil in the box.

A well-established, intermediate-scale, rainfall-runoff-erosion production system (Figure 4) was used for this study. The system consists of a rainfall simulator designed and developed at the U.S. Department of Agriculture National Soil Erosion Research Lab. It has been used throughout the country in both lab and field studies (e.g., Elhakeem et al., 2018; Wacha et al., 2018; Wilson et al., 2018). The system has been calibrated for the storm conditions in terms of drop size and intensity.

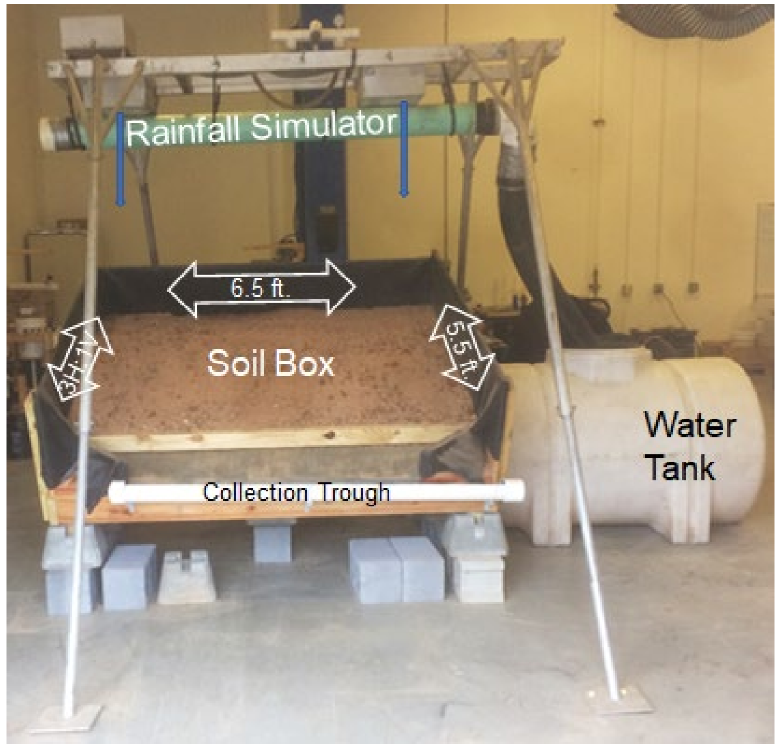

Figure 4. The intermediate-scale experimental setup used to quantify the efficiency of sediment retention practices. The main components of the setup include a soil box, water tank, rainfall simulator, and a collection trough. The experimental procedure considers Tennessee-specific characteristics of soil and rainfall intensity.

The system uses Norton Ladder Multiple Intensity Rainfall Simulators consisting of a 2.5 m long x 1.5 m wide (8.2 ft. x 4.9 ft.) aluminum frame with two nozzles spaced 1.1 m (3.6 ft.) apart, piping, an oscillating mechanism, and a drive motor. The frame has 4-telescopic legs, making the height of the unit adjustable. This feature not only provides stability, but also ensures vertical orientation of the nozzles, even over sloped surfaces. The simulators are set at least 2.7 m (8.9 ft.) above the soil surface. This height ensures the drops reach terminal velocity before hitting the soil. A flow control valve and a pressure gauge maintain a uniform operating pressure of 6 psi and the nozzles are shaped to produce spherical drops with a median drop size of 2.25 mm.

Representative Soil: With the aspiration to design a systematic performance evaluation method that considers conditions found in Tennessee, a survey of the state's soils was conducted. The soil survey maps developed for each county in Tennessee by the Natural Resources Conservation Service were reviewed (https://websoilsurvey.sc.egov.usda.gov/). There are seven major soil types in the state. Silt loam soils cover 64% of the land with loam soils covering 17% of the state. Silty clay loam and sandy loam soils both cover 8% of the land surface, while clay loam, silty clay, and clay soils each cover 1%.

With silt loams being the dominant soil texture, an effort was made to obtain sufficient amounts of this soil type from a local source. A truckload of soil was provided by the UTK Facilities Management from an on-campus construction site. Geotechnical tests were conducted for the soil that followed standard methods of ASTM International and other established/ documented methods. The tests included the use of the hydrometer to establish particle size distributions, Atterberg limit tests, and Proctor density tests (Figure 5). Multiple replicates were tested to provide a robust average. The soil had a sand content of 25.7 ± 4.6 % with silt and clay contents of 50.8 ± 7.6 % and 23.5 ± 4.0 %, respectively. The soil had median grain size of 0.076 ± 0.009 mm with a Liquid Limit of 42.9 ± 0.7 and a Plasticity Index of 20.1 ± 1.2. The maximum dry unit weight was at 1.92 g/cm^3.

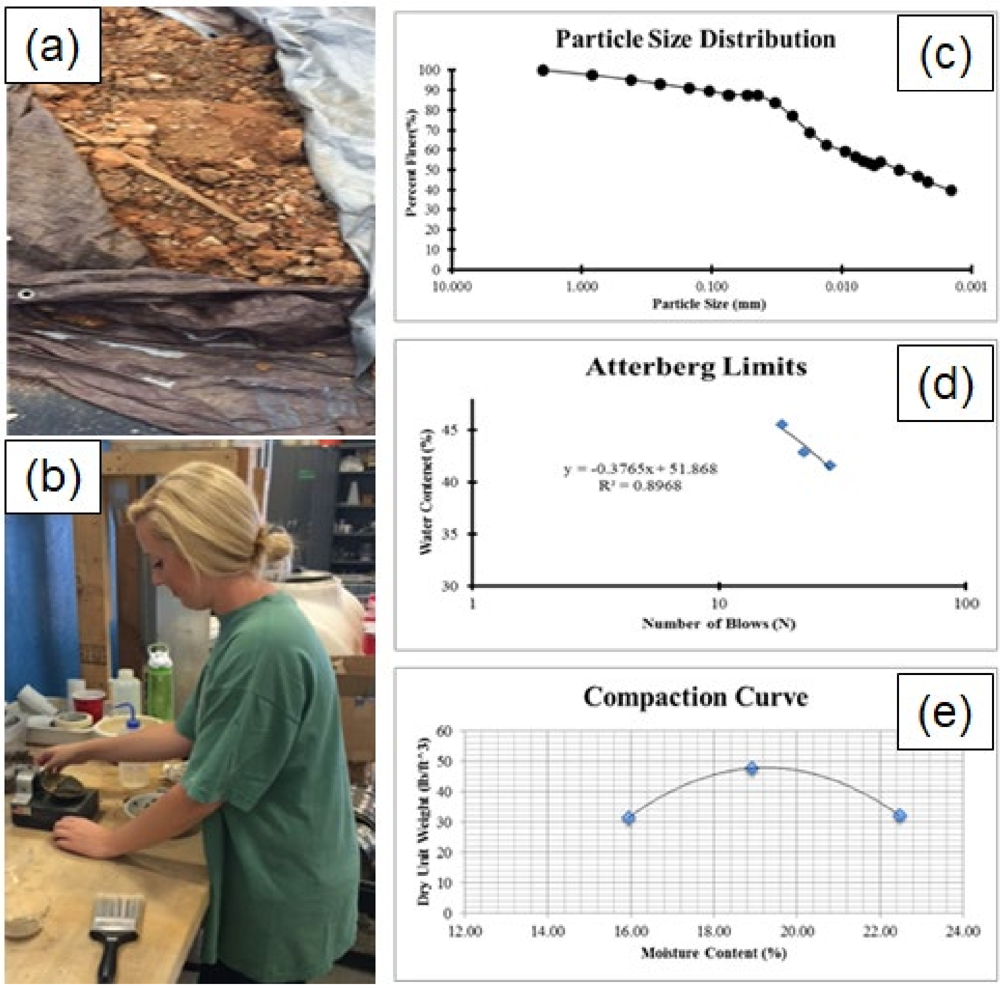

Figure 5. Geotechnical tests were used to characterize the soil used in this study. (a) The soil provided the UTK Facilities Management. (b) UTK undergraduate Kaity Patterson using the Casagrande Device for determining the Atterberg Limits. (c) An example of the particle size distribution results from the hydrometer tests. (d) An example of the Atterberg Limits results. (e) An example of the results from the proctor density tests.

Design Storms: Similarly to the soil material, the precipitation patterns in Tennessee were also examined. The NTPEP and TM11340 procedures use set intensities of 2, 4, and 6 in/hr (51, 101, 152 mm/hr). A review of the design storms in the different regions of Tennessee was conducted to see if these intensities are representative for the state. The TDOT

Drainage Manual (TDOT, 2012) contains the Intensity Duration Frequency Curves from the National Weather Service
(National Oceanic and Atmospheric Administration, 2004). Table 2 lists the corresponding recurrence intervals that match the NTPEP testing intensities of 2, 4, and 6 in/hr. The 6 in/hr rainfall corresponds to 100-yr events, which seems a bit much for evaluating BMPs, especially when most practices are designed for the 25-yr event. For the purposes of this study, the following intensities were selected: 89, 84, and 104 mm/hr (2.31, 3.29, and 4.10 in./hr.). The values correspond to the 2yr-6hr, 10yr-6hr, 25yr-6hr design storms for the Memphis region. These values are not only more representative of the state but also correspond to the capacity of the rainfall simulators.

Table 2. Corresponding recurrence intervals to NTPEP testing intensities.

Region	2 in/ hr	4 in / hr	6 in/hr
Knoxville	10 yr - 60 min	50 yr - 30 min	100 yr - 15 min
Chattanooga	5 yr - 60 min	25 yr - 30 min	100 yr - 15 min
Nashville	7 yr - 60 min	40 yr - 30 min	100 yr - 15 min
Memphis	5 yr - 60 min	25 yr - 30 min	100 yr - 15 min

Bare Soil Tests: In this study, an initial set of simulated rainfall events was conducted over the soil box that included all three rainfall intensities. However, no sediment retention practice was used. These experimental runs are referred to as the bare soil experiments herein. The bare soil tests are for providing baseline erosion rates, which are then compared to the soil loss rates from the tests with the installed practices to determine the P-factor. The P-factor is considered as the ratio the soil loss for the practice-protected condition divided by the sediment loss from the control bare-soil condition.

A summary of the procedure for quantifying soil loss under the bare soil conditions is provided here. The details can be found in the Methodology section. Before each test, the soil was mixed thoroughly and compacted to approximately 90% of the Proctor density. A 20-min rain event was then applied to the soil box using one of the three constant intensities (i.e., 59, 84, and 104 mm/hr). All water and eroded sediment generated from the soil box was delivered to a trough at the bottom of the plot and collected.

The total amount of water and sediment was collected in gallon jugs and initially weighed. Aluminum sulfate was added to induce flocculation and settling. The water was then decanted, while the sediment was dried and weighed. Thus, the total mass of sediment and volume of water were determined as the key results from each experiment (Table 3).

For the 59-mm/hr intensity events, the amount of collected runoff and eroded sediment averaged 21.7 ± 9.9 L and 0.459 ± 0.377 kg, respectively. The 84-mm/hr intensity events produced a similar amount of runoff (21.4 ± 11.1 L) and lower amount of eroded sediment (0.388 ± 0.294 kg). Finally, the 104-mm/hr events produced on average 28.3 ± 15.4 L of runoff and 0.317 ± 0.162 kg of sediment. The runoff and sediment loss for each intensity were considered similar based on an Analysis of Variance (ANOVA; $p>0.05$).

Table 3. Experimental runs for the bare soil tests.

Date	Intensity (mm/hr)	Replicate	Runoff (L)	Runoff Coefficient	Erosion (kg)	P-Value
Bare Soil						
7/11/2017	59	1	21.6	0.37	0.502	n/a
7/12/2017	59	2	30.9	0.52	0.885	n/a
7/14/2017	59	3	32.3	0.55	0.757	n/a
9/18/2017	59	4	11.2	0.19	0.081	n/a
9/22/2017	59	5	12.4	0.21	0.068	n/a
7/19/2017	84	1	33.5	0.40	0.725	n/a
8/14/2017	84	2	11.7	0.14	0.251	n/a
8/16/2017	84	3	19.1	0.23	0.187	n/a
8/25/2017	104	1	12.6	0.12	0.220	n/a
9/5/2017	104	2	43.4	0.41	0.504	n/a
9/26/2017	104	3	28.9	0.28	0.226	n/a

Clearly these results were unexpected. The expected results were to be similar to those in Figure 2b. There was presumed to be an increase in erosion with increasing R-factor. For the TM11340, the R-factor is determined strictly as a function of rainfall intensity:

R-Factor = [total kinetic energy of the storm (E)] x [the max 30-minute Intensity (I)] (2)

As can be seen in Figure 6, which displays the runoff and soil loss from the bare soil experiments, the variability of the data points at each intensity is quite large. Moreover, the runoff variability increases with the higher intensities, while the soil loss variability decreases with higher intensities. The degree of variability complicates the determination of a single baseline erosion value from which the P-factors could be calculated in the later simulated events

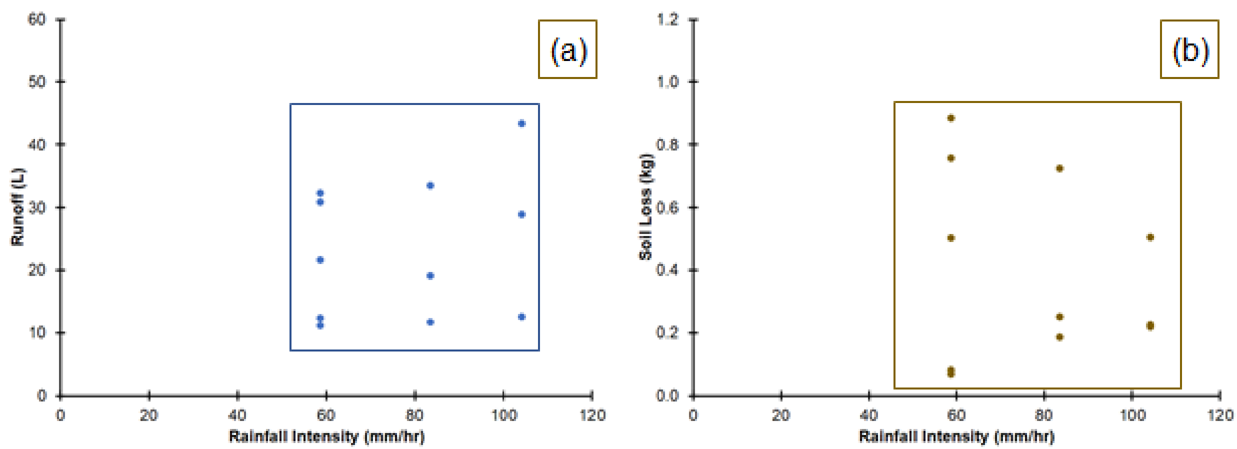

Figure 6. Relationships between runoff and soil loss with rainfall intensity for the bare soil experiments. (a) Runoff volume collected from the soil box during each bare soil experiment. (b) Soil loss collected from the soil box during each bare soil experiment. The boxes encapsulate the full range of variabilities for both runoff and soil loss.

with the sediment retention practices. As a reminder, P-factors are to be determined as the ratio of soil loss during the experiments with sediment retention practices to the soil loss during the bare soil simulations.

To explain this unexpected variability, a chrono-sequence of images (Figure 7) from the experiments shows an overall coarsening of the soil texture from more uniform, fine-grained particles to a wider distribution of coarse aggregates. The coarsening was attributed to erosion preferentially removing the finer particles and aggregates. The coarsening occurred despite replacing the exported sediment with fresh material and mixing it with the in-situ soil in between tests following the procedure outlined in NTPEP.

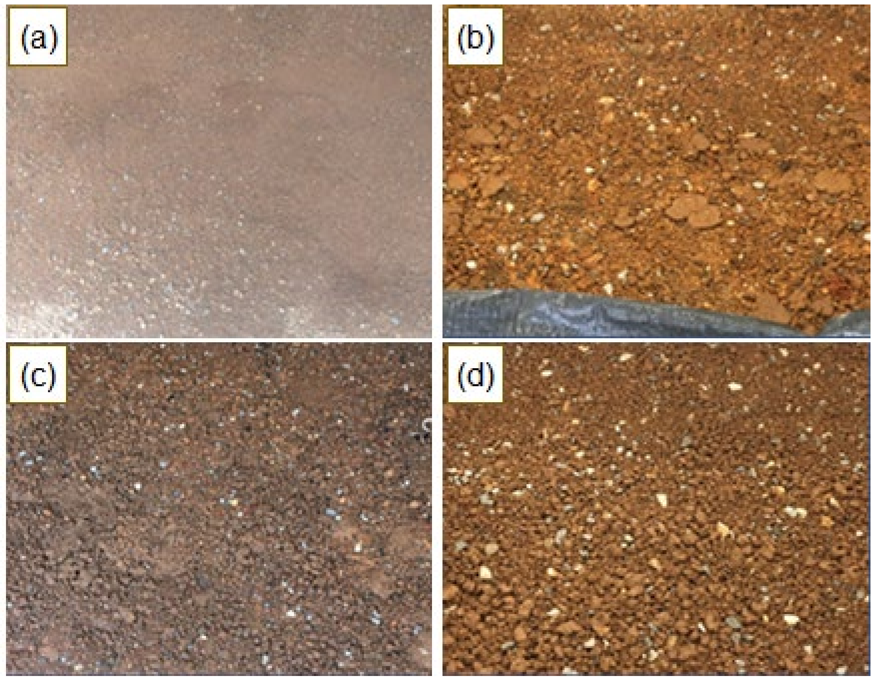

Figure 7. Images of the soil in the soil box following a chrono-sequence moving from (a) – (d). There was an overall coarsening of the soil as the test proceeded.

From the chrono-sequence of images and the apparent coarsening of soil over time, the relative amounts for infiltration and runoff were explored as the trigger causing the variability. The runoff coefficient, which is the ratio of the amount of runoff to the delivered precipitation, was used as the metric examining the relative runoff - infiltration partitioning. Table 3 contains the calculated runoff coefficient for each bare soil simulation. The range of runoff coefficients is from 0.12 to 0.55 which spans the range of expected potential values (Knox County, 2018).

Further, the expected erosion rates were calculated using MUSLE (Cardei, 2010). However, in this case R-factor was determined as the weighted sum of the rainfall influence and runoff influence. The rainfall component was determined using the product of the total kinetic energy and the peak 30-minute intensity (i.e., the EI product from eq. (2)). The influence of the runoff includes the runoff volume and the unit peak runoff rate. The relative partitioning between the rainfall influence and the runoff influence was adjusted until the calculated erosion rate matched the measured value. Table 4 contains the measured and calculated erosion values, as well as the partitioning between runoff and rainfall.

Table 4. Measured and calculated sediment yields during bare soil tests.

Intensity (in/hr)	Measured sediment (kg)	Estimated sediment (kg)	Relative amount of rainfall	Relative amount of runoff
59	0.459 ± 0.377	0.498	60%	40%
84	0.388 ± 0.294	0.369	25%	75%
104	0.317 ± 0.162	0.307	5%	95%

The importance of runoff relative to that of rainfall is highlighted by these bare soil experiments especially with the higher intensities. The runoff influence greatly outweighs the rainfall influence. In fact, when runoff and soil loss are plotted as functions of the runoff coefficient the data collapse (Figure 8). The expected increase of runoff and soil loss in relation to an increasing runoff coefficient is apparent.

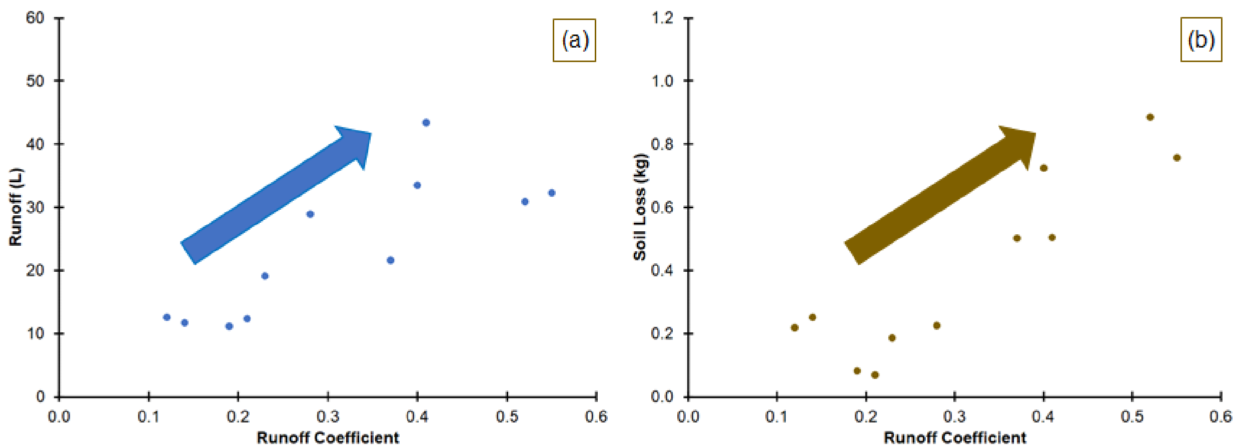

Figure 8. The relationships between (a) runoff volume and (b) soil loss with the runoff coefficient. The bold arrows show the general increasing trend.

It is believed that the strong relationship between rainfall intensity (i.e., R-factor) and soil loss can be achieved only with very stringent control of the soil conditions and experimental parameters. The level of infrastructure and support needed to replace and rework the soil platform thoroughly is substantial requiring high investments, which may be unavailable. In addition, the standardization of a method like TM11340, which is designed to provide a single value is good to provide a common basepoint for comparison. However, that common basepoint may not be applicable for certain regions or conditions outside of the bounds of the testing procedure.

In light of this finding, empirical relationships were developed to provide “floating” baselines that span the conditions that exist in the field. Runoff coefficients vary based on soil, weather, slope, and management conditions both within and across sites. For each intensity, power functions were fit to the soil loss (E) - runoff coefficient (RC) data pairs following similar hydraulic geometry concepts characterizing sediment loads with discharge (e.g., Leopold and Maddock, 1953). The empirical equations are as follows:

$$For\ 59\frac{mm}{hr}:\quad E = 4.136\ \times RC^{2.449}\quad (r^2 = 0.91) \tag{3}$$

$$For\ 84\frac{mm}{hr}:\quad E = 1.460\ \times RC^{1.0378}\quad (r^2 = 0.81) \tag{4}$$

$$For\ 104\frac{mm}{hr}:\quad E = 0.6584\ \times RC^{0.5677}\quad (r^2 = 0.65) \tag{5}$$

These equations will be applied in the simulated rainfall events that have sediment retention practices present. The determined runoff coefficients for those studies will be entered in the derived empirical equations to estimate the expected baseline soil loss for that intensity and that runoff coefficient.

The outcome from objective 1 is a systematic protocol for testing sediment control practices that considers the wide range of soil, climate, and topographic conditions found in Tennessee. This protocol is found in the Appendix of this report. It includes a step-by-step protocol for the methods summarized above and detailed in the methodology. One important feature of this protocol is the use of measured runoff coefficients that result from weather and soil conditions found in Tennessee making it mor applicable for TDOT.

Objective 2: Quantify the efficiencies of different sediment retention practices using the above-mentioned methodology.

The second objective for this study was to quantify the efficiencies of different sediment retention practices using the above-mentioned methodology (see also *Methodology* section and *Appendix*). There were no differences between the procedure used in the bare soil simulated events and the procedure used for the simulated events involving the practices (Tables 5-7).

The practices evaluated herein were selected by TDOT based on commonly used choices (Hangul, 2017). The practices (Figure 9) include a silt fence, a straw-filled sediment tube, and a mulch-filled sediment tube. The silt fences and sediment tubes are often considered as perimeter devices around construction sites to intercept the sediment-laden runoff (Sprague et al., 2014).

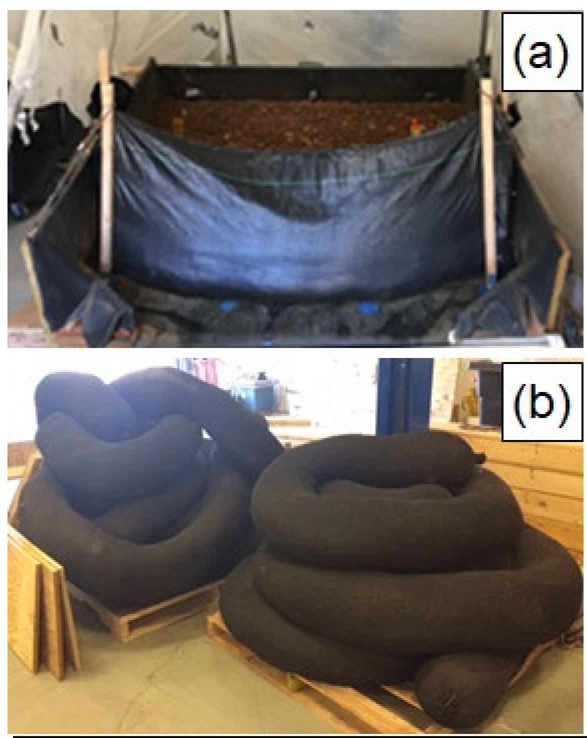

Figure 9. The sediment retention practices used in this study: (a) silt fence; (b) straw-filled and mulch-filled sediment tubes.

Table 5. Results of the simulated rainfall events using the silt fence.

Date	Intensity (mm/hr)	Replicate	Runoff (L)	Runoff Coefficient	Erosion (kg)	P-Value
Silt Fence						
4/25/2018	59	1	19.8	0.33	0.035	0.43
4/28/2018	59	2	20.5	0.35	0.044	0.50
4/30/2018	59	3	25.4	0.43	0.046	0.57
12/18/2017	84	1	28.6	0.34	0.074	0.34
12/22/2017	84	2	32.8	0.39	0.102	0.47
1/15/2018	84	3	11.1	0.13	0.021	0.10
1/19/2018	84	4	5.1	0.06	0.006	0.03
1/24/2018	84	5	8.8	0.10	0.010	0.05
1/26/2018	84	6	15.8	0.19	0.024	0.11
1/31/2016	84	7	12.0	0.14	0.023	0.11
2/2/2018	84	8	18.9	0.22	0.028	0.13
2/5/2018	84	9	10.6	0.13	0.012	0.05
5/2/2018	84	10	35.8	0.43	0.083	0.38
11/20/2017	104	1	27.9	0.27	0.123	0.39
11/22/2017	104	2	32.0	0.30	0.095	0.30
11/29/2017	104	3	30.9	0.29	0.117	0.37
12/8/2017	59	4	32.0	0.31	0.096	0.30
12/13/2017	59	5	32.7	0.31	0.116	0.37
5/4/2018	59	6	48.3	0.46	0.101	0.32

Table 6. Results of the simulated rainfall events using the mulch-filled sediment tube.

Date	Intensity (mm/hr)	Replicate	Runoff (L)	Runoff Coefficient	Erosion (kg)	P-Value
Mulch Tube						
5/11/2018	59	1	23.3	0.40	0.041	0.51
5/14/2018	59	2	22.7	0.38	0.036	0.45
5/16/2018	59	3	23.2	0.39	0.037	0.46
5/18/2018	59	4	24.1	0.41	0.044	0.54
5/29/2018	84	1	34.9	0.42	0.092	0.42
5/30/2018	84	2	37.4	0.44	0.084	0.38
5/31/2018	84	3	35.2	0.42	0.072	0.33
5/21/2018	104	1	44.4	0.42	0.099	0.31
5/22/2018	104	2	45.2	0.43	0.105	0.33
5/23/2018	104	3	45.4	0.43	0.101	0.32

Table 7. Results of the simulated rainfall events using the straw-filled sediment tube.

Date	Intensity (mm/hr)	Replicate	Runoff (L)	Runoff Coefficient	Erosion (kg)	P-Value
Straw Tube						
11/16/2018	59	1	24.2	0.41	0.054	0.66
11/6/2018	84	1	33.6	0.40	0.103	0.47
11/9/2018	84	2	33.2	0.40	0.083	0.38
11/16/2018	84	3	35.7	0.42	0.070	0.32
10/24/2018	104	1	33.6	0.32	0.188	0.59
10/30/2018	104	2	32.4	0.31	0.191	0.60
11/2/2018	104	3	42.7	0.41	0.180	0.57
12/5/2018	104	4	42.9	0.41	0.199	0.63
12/14/2018	104	5	45.3	0.43	0.242	0.76

For the silt fence, it was installed following the state guidelines. At the toe of the soil box, it was placed in a U-shape, with the posts 1.67 m (5.5 ft.) apart. The test plot was constructed so that water and soil could not escape around the silt fence. The water could only go through or under the silt fence.

During the 19 simulated events using the silt fence, the runoff would begin to accumulate at the base of the soil box. As the runoff began to pond behind the silt fence (Figure 10), the increasing force would push the water into the soil and through the silt fence. Beads of sediment-laden water could be seen popping through the silt fence, as well as streaming from underneath it (Figure 10).

As with the bare soil tests, the runoff and soil loss values exhibited a wide range, even under the same rainfall intensity (Table 5). For example, under the 84-mm/hr intensity, the runoff ranged from 5.1 L to 35.8 L and the soil loss from 0.006 to 0.102 kg. The average values for the 84-mm/hr simulated events were also the lowest amongst the three intensities, but they had the widest variability (18.0 ± 10.8 L and 0.038 ± 0.034 kg compared to 21.9 ± 3.1 L and 0.042 ± 0.006 kg for the 59-mm/hr events and 34.0 ± 7.2 L and 0.108 ± 0.012 kg for the 104-mm/hr events). With regards to the runoff coefficient, the range was 0.06 to 0.46 for all intensities. The P-factor values also exhibited a wide range averaging 0.28 ± 0.16. Incidentally, the lowest intensity events had the poorest efficiencies with an average p-value of 0.50 ± 0.07, which would seem counter-intuitive, if one did not consider the runoff coefficients (more on this later).

For the straw-filled and mulch-filled sediment tubes, the simulated events progressed similarly as those of the silt fence. The runoff began to pond behind the tubes (Figure 11) and the increasing force pushed the water into the soil, through and under the tubes. The ponded water was never large enough to overtop the tubes.

The runoff and soil loss values for the mulch tube followed the expected pattern where the average values increased with increasing intensity. This is attributed to a closer range of values across the intensities. This is seen prominently with the runoff coefficient values, which ranged from 0.38 to 0.43 across the tests. With such a tight range, it is not surprising that there was no statistical difference using an ANOVA ($p>0.05$).

Despite the tight range with the runoff, there was a significant difference between the P-factor values at each intensity level. However, the pattern was contrary to what was expected. The 59-mm/hr intensity had the worst efficiency with a P-factor of 0.49 ± 0.04. This is compared to P-factors for the 84- and 104-mm/hr intensities, which were 0.38 ± 0.05 and 0.32 ± 0.01, respectively.

For the straw-filled tubes, the patterns were similar to those of the mulch-filled tubes. There was as increasing trend in runoff volumes with increasing rainfall intensities. There was also a tight average for the runoff coefficients with them being between 0.32 and 0.42. However, the straw filled tubes had the worst efficiency of the three practices with an average P-factor 0.55 ± 0.14. No clear-cut reason was identified for this. Possible explanations being examined include the pore spacing and the absorptive capacity of the materials. For example, the mulch will adsorb more water and hence swell, to trap more soil particles. More studies are needed to confirm this hypothesis.

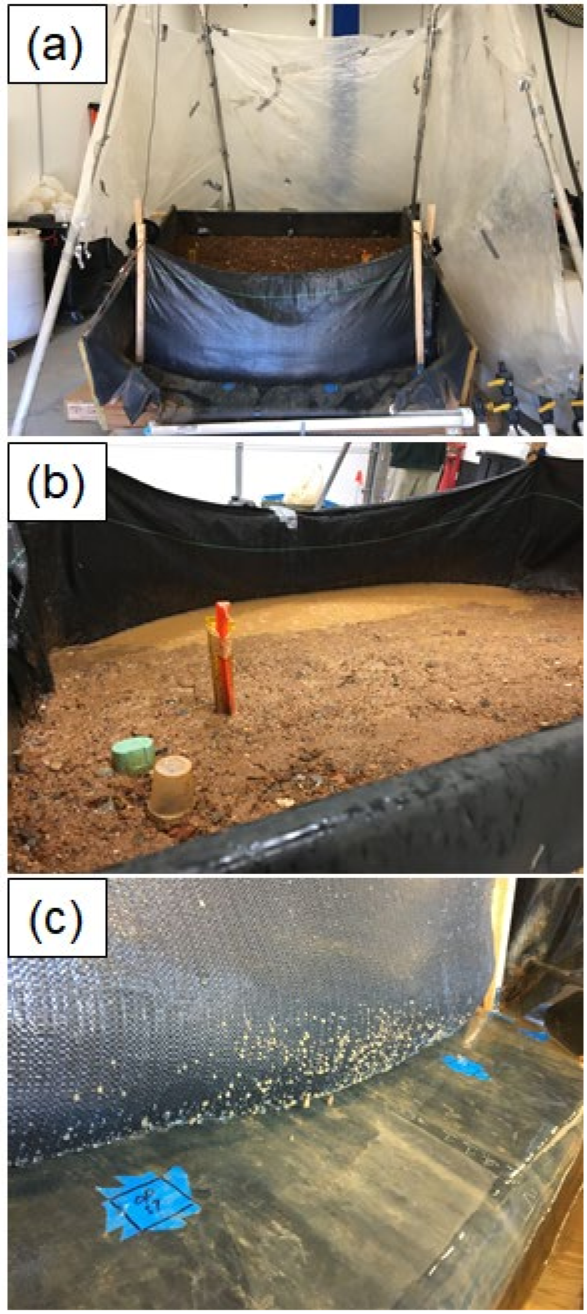

Figure 10. Images from the simulated events using the silt fence. (a) The installed silt fence shows the posts were 1.67 m (5.5 ft.) apart. (b) Runoff begins to pond behind the silt fence. (c) Sediment-laden runoff seeps through and under the silt fence.

Figure 11. Images from the simulated events using the straw sediment tube. (a) The installed tube shows the posts were ~0.61 m (2.5 ft.) apart. (b) Sediment-laden runoff begins to pond behind the silt fence.

Following from the bare soil simulated rainfall events, the relationships between runoff and soil loss with the runoff coefficient were examined. Figure 12 shows the runoff – runoff coefficient relationship. There are no surprises with the overall trends depicted in the two graphs. There should be a close relationship between these parameters.

The noteworthy observations in these graphs are how the data collapse along three specific trends. The original thought was to plot the data grouped by practice, as is done in Figure 12a. The data for each practice fall on all the lines signifying that the trends are not shaped by the practice. Since soil and slope are similar, the data were then grouped by rainfall intensity as in Figure 12b. This graph shows that the results vary by runoff coefficient, but they do so within each intensity.

Figure 13 shows how soil loss varies with runoff coefficient. With regards to practice, there are two specific trends (Figure 13a). One trend follows that of the bare soil simulated rainfall events, while the other trend contains the results from the simulated events with the practices. When examining the soil loss – runoff coefficient relationship with the data grouped by intensity the data for the 59-mm/r and 84-mm/hr events follow more of a linear trend while the data for the 104-mm/hr events appear to be grouped in two specific areas. Runoff is more correlated with soil loss than other examined rainfall factors such as intensity, total storm kinetic energy and other combined factors. Moreover, sediment concentrations of major storm events are independent of all examined rainfall-runoff factors. Hence, runoff coefficient should be the best erosivity index at scales from plots to watersheds (Zheng and Chen, 2015).

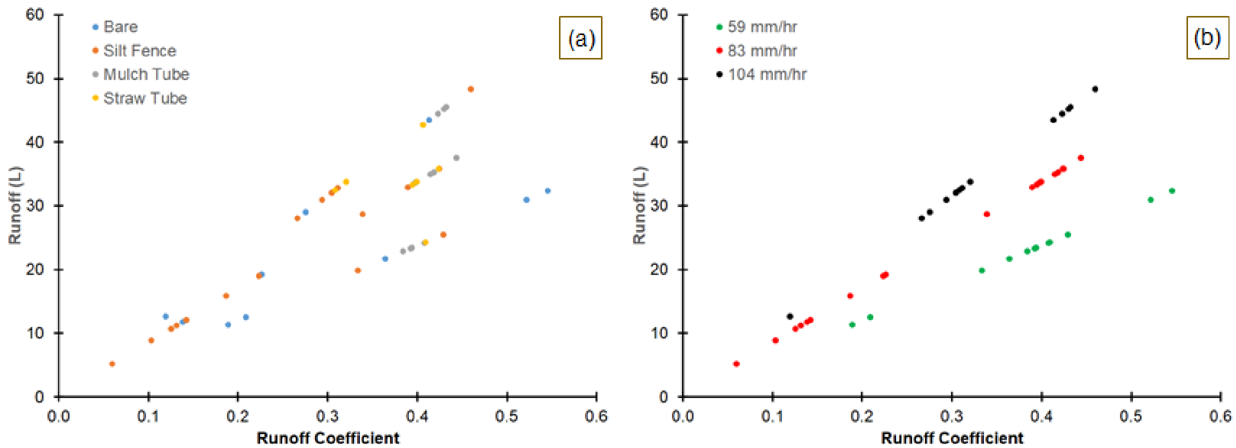

Figure 12. Comparison of runoff to runoff coefficient with the data grouped by (a) practice and (b) intensity.

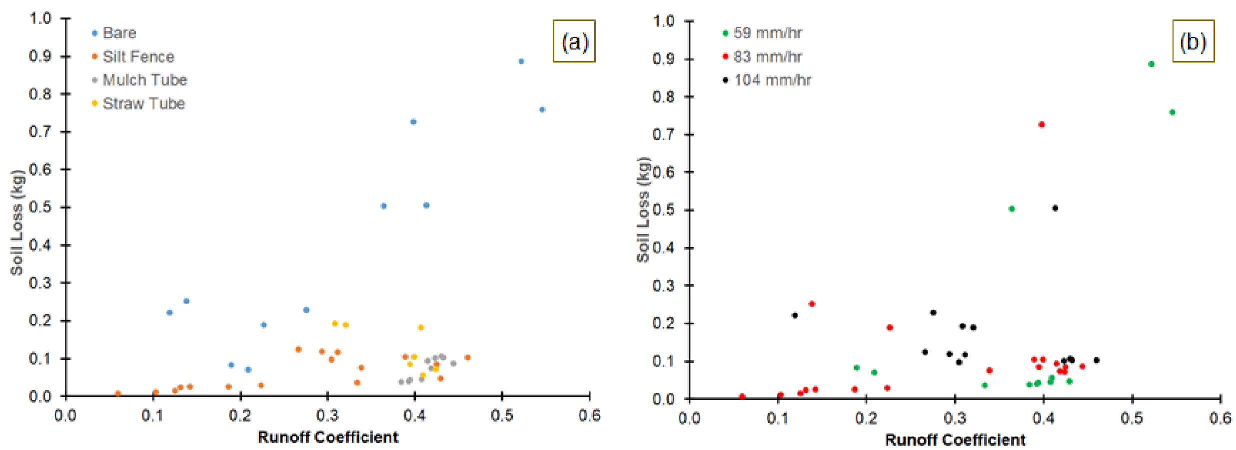

Figure 13. Comparison of soil loss to runoff coefficient with the data grouped by (a) practice and (b) intensity.

Using the P-factors values determined above and their relationship with runoff coefficient, empirical relationships were developed for each practice.

$$Silt\ Fence\ P - factor = 0.5818 \times RC - 0.0363 \quad (6)$$

$$Mulch\ Tube\ P - factor = 5.8699 \times RC - 2.2226 \quad (7)$$

$$Straw\ Tube\ P - factor = 1.5715 \times RC - 0.1304 \quad (8)$$

Because these equations were developed using the runoff coefficients, which are functions of the soil, slope, weather, and management, they essentially provide "site specific" parameters. Thus, the derived P-factors for the three practices are specific for Tennessee. These equations will be incorporated into an erosion calculator tool that can be used by TDOT engineers when developing an erosion plan for a roadway construction site. The determined soil loss reduction values should thus be better representative of the site.

Objective 3: Develop a simple model for choosing the proper erosion control or sediment retention practice for sites in Tennessee.

The multitudes of literature and internet sources detailing erosion prevention and sediment control practices can be too overwhelming for many practitioners as there is little guidance on which practices will be effective under the conditions for which they are planning. As a final outcome for this project, a transparent, simple, and interactive modeling tool was developed to aid the decision-making process.

The tool uses the Modified USLE to quantify erosion and exported loads from a site. The USLE and its derivatives are widely used because they intuitively consider key site parameters pertinent to erosion (i.e., soil, rainfall, topography, and management). The USLE is also easy to use because those key site parameters are represented with multiplicative factors. Factoring in these facts, the *Tennessee Erosion Model* was developed (Figure 14). With this model, certain sediment retention practices can be applied to the site and the trapping efficiencies of those

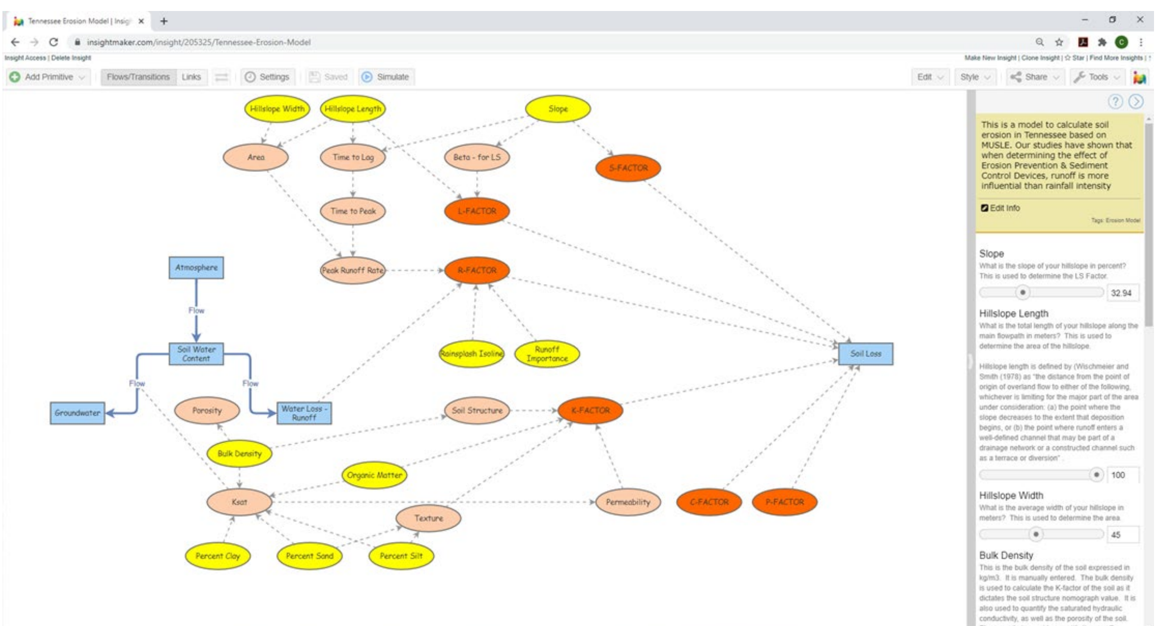

Figure 14. Screen shot of the Tennessee Erosion Model input webpage. The system dynamics framework allows user to visualize the causal connections between different site parameters. The site parameters are input through slide bars on the right side of the page.

practices are determined using the empirical equations developed from the simulated rainfall events described under Objective 2 that followed the protocol established in Objective 1. The use of these equations makes this model relevant for sites in Tennessee as the simulated rainfall experiments considered soil and rainfall characteristics in the state.

Also building from the above simulated rainfall experiments, MUSLE was chosen for the *Tennessee Erosion Model* because it was shown that runoff was more influential for evaluating sediment export from a site. The MUSLE derivative uses the storm runoff volume and peak runoff rate to determine the R-factor, while the K-factor and LS-factor are determined similarly to all other USLE derivatives.

A system dynamics framework was used for the *Tennessee Erosion Model* because it provides a simple and transparent means for project managers to determine those sediment retention practices that best fit their site. The system dynamics framework considers the feedbacks that occur between different parameters such as texture, bulk density, and infiltration, as well as surface roughness and runoff.

This framework was developed by connecting the key site parameters through functionalities. The system dynamics model consists of stocks, flows, and variables to represent the drivers, processes, and responses at a site. A stock stores a material or a resource. The amount of soil lost through erosion is a stock in the model. Stocks have an initial value that changes as materials flow in or out of the stock. Flows represent the transfer of materials from one stock to another. For example, runoff is a flow in the model. Flows are characterized by a rate (e.g., gallons per minute). A variable is a dynamically updated object in the model that synthesizes available data or provides a constant value for use in the functionalities. Key variables in this system dynamics model include the factors of MUSLE (e.g., K-factor; R-factor; LS-factor).

The model begins with you entering the dimensions of your site, assuming the site is rectangular. The slide bars are used to enter the width (ft), length (ft), and slope (%) of the site. The model calculates the area of the site using the length and width. It also converts the percent slope into an angle with the arc-tangent function.

To quantify the LS-factors, the model uses the appropriate equations from the RUSLE Handbook, AH-703 (Renard et al., 1997), which are reproduced below. In order to determine the L-factor, the β-term is provided as a function of the slope angle (θ):

$$\beta = \frac{\sin\theta}{0.0896} / [3.0 \times (\sin\theta)^{0.8} + 0.56] \tag{9}$$

The β-term reflects the relationship of rill to interrill erosion. It is used to provide the exponent (*m*) in the equation for the L-factor.

$$m = \frac{\beta}{1 + \beta} \tag{10}$$

The equation for the L-factor also considers the slope length (λ) which is the horizontal projection of the slope, not the distance parallel to the soil surface which you entered with the slide bar. Simple trigonometry provides λ by multiplying the length and the slope angle. The L-factor is then determined as follows

$$L - factor = \left(\frac{\lambda}{72.6}\right)^{m} \quad (11)$$

For the S-factor, the slope angle is also used. Two empirical equations in the RUSLE Handbook AH-703 are provided. If the site slope is less than 9%, then the following equation is used:

$$S - factor = 10.8 \times \sin\theta + 0.03 \quad (12)$$

If the site slope is greater than 9%, then the following equation is used:

$$S - factor = 16.8 \times \sin\theta - 0.50 \quad (13)$$

If the site slope is less than 15 ft., then it is assumed that rill erosion is insignificant, and water drains freely from the end of the slope. In these cases, then the following equation is used:

$$S - factor = 3.0 \times (\sin\theta)^{0.8} + 0.56 \quad (14)$$

which comes from the denominator in the β-term equation (9).

For quantifying the K-factor, the nomograph in the RUSLE Handbook AH-703 is used which requires you to provide the sand, silt, and clay percentages for the soil at the site, as well as the organic matter content. The nomograph is resolved with the following equation:

$$K - factor = \frac{\left(0.00021 \times (12 - OM) \times T^{1.14}\right) + \left(3.25 \times (s-2)\right) + \left(2.5 \times (p-3)\right)}{100} \quad (15)$$

where *OM* is the organic matter content; *T* is the product of the percent silt and the sum of the present sand and percent silt; *s* is the structure code; and *p* is the permeability code. Most simply, the structure code and permeability code are provided by the texture. The table below correlates these codes with the appropriate textures.

The R-factor is partly based on the soil type and site slope, which can be used to identify the Hydrologic Soil Group and corresponding Runoff Coefficients (RC), as seen in the Table 8. In addition, the design storm is needed to provide the rainfall total (P), duration (D), and intensity (I). These values are needed to quantify the runoff volume (Q) and peak runoff rate (q_{peak}). The storm erosivity (EI) is also used.

$$Q = P \times RC \quad (16)$$

$$q_{peak} = RC \times I \times Area \quad (17)$$

$$R - factor = (0.5 \times EI) + (0.349 \times Q \times \left(q_{peak}\right)^{0.333} \quad (18)$$

The practices considered in the current version of the model include only silt fences, straw-filled sediment tubes (i.e., wattles), and mulch-filled sediment tubes. Thus C-factors are set at 1. The P-factors for the practices have been determined through experimentation following the protocol from Objective 1. The P-factors are considered as functions of the runoff coefficients determined from Objective 2.

Table 8: K-factor Subterms and Other Hydrological Variables for Different Soils

Texture	Structure Code	Permeability Code	Hydrologic Soil Group	Runoff Coefficient <2%	2-6%	>6%
Sand	1	1	A	0.14	0.18	0.22
Loamy Sand	1	2	A	0.14	0.18	0.22
Sandy Loam	2	2	A	0.14	0.18	0.22
Loam	2	3	B	0.16	0.21	0.28
Silt Loam	3	3	B	0.16	0.21	0.28
Silt	4	3	B	0.16	0.21	0.28
Sandy Clay Loam	4	4	C	0.20	0.25	0.34
Clay Loam	4	4	C	0.20	0.25	0.34
Silty Clay Loam	4	5	C	0.20	0.25	0.34
Sandy Clay	4	5	C	0.20	0.25	0.34
Silty Clay	4	6	D	0.24	0.29	0.41
Clay	4	6	D	0.24	0.29	0.41

Structure codes from the National Soils Handbook No. 430; Permeability codes from the RUSLE Handbook AH-703; Runoff Coefficients from the 2018 Knoxville BMP Manual.

The system dynamics model was developed in a web-based software provided by *InsightMaker*. With *InsightMaker*, the model is compiled in your browser and the address can be shared with whomever. The benefit of this is that TDOT engineers do not need a special software to calculate soil loss and the reductions of select practices. Moreover, it can be run on-site and at any time. The model requires minimal inputs, namely the length, width, and slope of your site, as well as texture, organic matter content and bulk density of the soil. These inputs are added with a simple slide bar (Figure 14). The model then calculates soil loss using the Modified USLE with the results appearing on the screen (Figure 15). The website is https://insightmaker.com/insight/205325/Tennessee-Erosion-Model.

Another advantage of the InsightMaker website is it automatically creates a storyboard for the developed model. The story describes what inputs are needed are then steps the user through the functionalities included in the model. The created story can be placed side-by-side with the model structure and while a simulation is run, the action on the screen can be recorded or videotaped for inclusion in a training video.

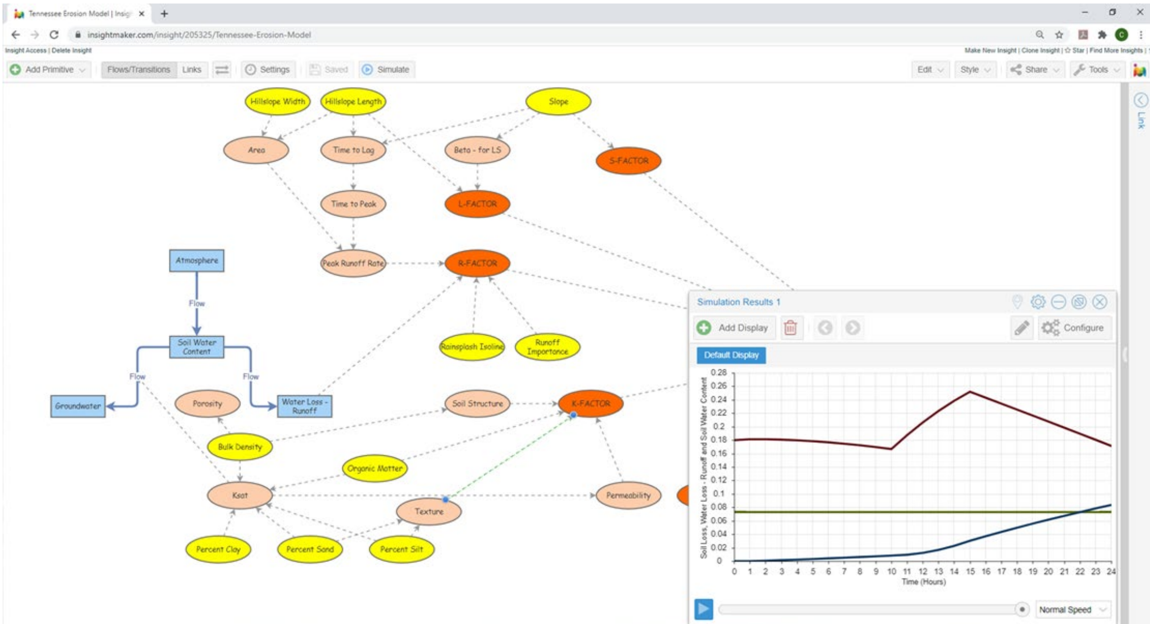

Figure 15. Screen shot of the Tennessee Erosion Model results webpage. A graph of the erosion rates, as well as any of the input parameters will pop-up on the screen.

Methodology

Experimental set-up

To complete the first objective of this study, identifying a systematic protocol for evaluating sediment control practices while considering the wide variability found in Tennessee, the established NTPEP methodology was examined. NTPEP uses standardized, quantitative testing procedures for sediment retention practices, including TM11340 - *the Standard Test Method for Determination of Sediment Retention Device Performance in Reducing Sediment Loss from Rainfall-Induced Erosion during Perimeter Control Applications*.

TM11340 was designed by the Georgia Soil and Water Conservation Commission to follow select standard test methods from ASTM International. The procedure uses large-scale platforms (Figure 2) that are 27 ft. long x 8 ft. wide with 3:1 slopes of sandy clay soil. The platforms have ten, 15-ft tall rain trees around their perimeters. The rain trees have four sprinkler heads that deliver rainfall intensities of 2, 4, and 6 in/hr for 20 minutes each. Sediment retention efficiency is obtained by comparing the erosion rates for simulated events where protective practices are present to erosion rates of simulated events where no practice is used.

The standardization of these tests establishes a common base point from which one can compare/contrast BMPs of similar types (i.e., wattles vs. wattles). However, caution must be used when comparing BMPs of different types (such as silt fences vs. sediment tubes). Over the range of available storm magnitudes, slopes, and soil types, the different practices may respond differently. The massive platforms are difficult to adjust.

As an alternative, intermediate-sized testing structures (Zech et al., 2008) are suited to simulate soil erosion and sediment transport along the right-of-way of a typical embankment cross-section along linear highway construction projects. The intermediate-sized testing structure was adopted herein. To conduct the efficiency testing of the sediment retention practices, a soil box (Figure 16) was built that was 1.83 m long x 1.98 m wide x 0.30 m deep to accommodate both the size of the sediment control practices and the wetted footprint of the rainfall simulators. The box has a 3:1 (Horizontal:Vertical) slope. The box was filled with 10 cm of soil compacted to approximately 90% of the Proctor density.

Rainfall simulators were used to generate runoff and erosion. The simulators were Norton Ladder Multiple Intensity Rainfall Simulators (Figure 16) manufactured by the U.S. Department of Agriculture – Agricultural Research Service National Soil Erosion Research Laboratory in West Lafayette, IN. The basic unit of each simulator consisted of a 2.5 m (l) x 1.5 m (w) aluminum frame that includes 2-nozzles spaced 1.1 m apart, piping, an oscillating mechanism, and a drive motor. The frame had 4-telescopic legs, making the height of the unit adjustable. This feature not only provided stability, but also ensured the vertical orientation of the nozzles, even over sloped surfaces. A flow control valve and a pressure gauge maintain a uniform operating pressure of 6 psi and the nozzles can produce spherical drops with a median drop size of 2.25 mm and an exit velocity of 6.8 m/s, leading to maximum rainfall intensity of 15 cm/hr.

The simulators were calibrated against natural rainfall using a M300-disdrometer by Parsivel (Elhakeem and Papanicolaou, 2009). The calibration considered drop size distribution and fall velocities. The drop size distribution compared favorably with the Marshall-Palmer distribution (Marshall and Palmer, 1948), which is a commonly accepted distribution for natural raindrop sizes (Frasson, 2007). The terminal velocities of the drops from the Veejet nozzle were similar to the terminal velocities of natural rainstorms when the nozzle was at least 2.7 m above the soil surface. Thus, the rainfall simulators are able to simulate natural rainfall.

A fixed procedure was developed for these tests (Figure 16). Before each test, the soil was mixed thoroughly. The plot was raked smooth, and any rills or depressions were filled with new sediment as the collected sediment from the previous tests was discarded. The soil in the box was compacted to approximately 90% of the Proctor density. The sediment retention practices were then installed following installation guides provided by TDOT. For example, the silt fence was installed at the toe of the soil box in a U-shape, with the posts 5.5 ft apart. The test plot was constructed such that water and soil cannot escape around the product ends but must go over, under or through the practice.

Following this preparation, a 20-min rain event was initiated using one of three constant intensities (59, 84, and 104 mm/hr). All water and eroded sediment generated from the soil box that passed the silt fence/ sediment tube flowed into a trough and was collected at the downstream end of the trough. Flow-weighted samples were collected until runoff ceased. Each collected sample was approximately 3.78 L and was transferred into a milk jug.

The total amount of water and sediment in each jug was initially weighed before aluminum sulfate (10 mL of a 30% alum solution/ 1 L of sample) was added to induce flocculation and settling. The water was then decanted and the sediment dried. The total mass of sediment and volume of water were determined for each experiment.

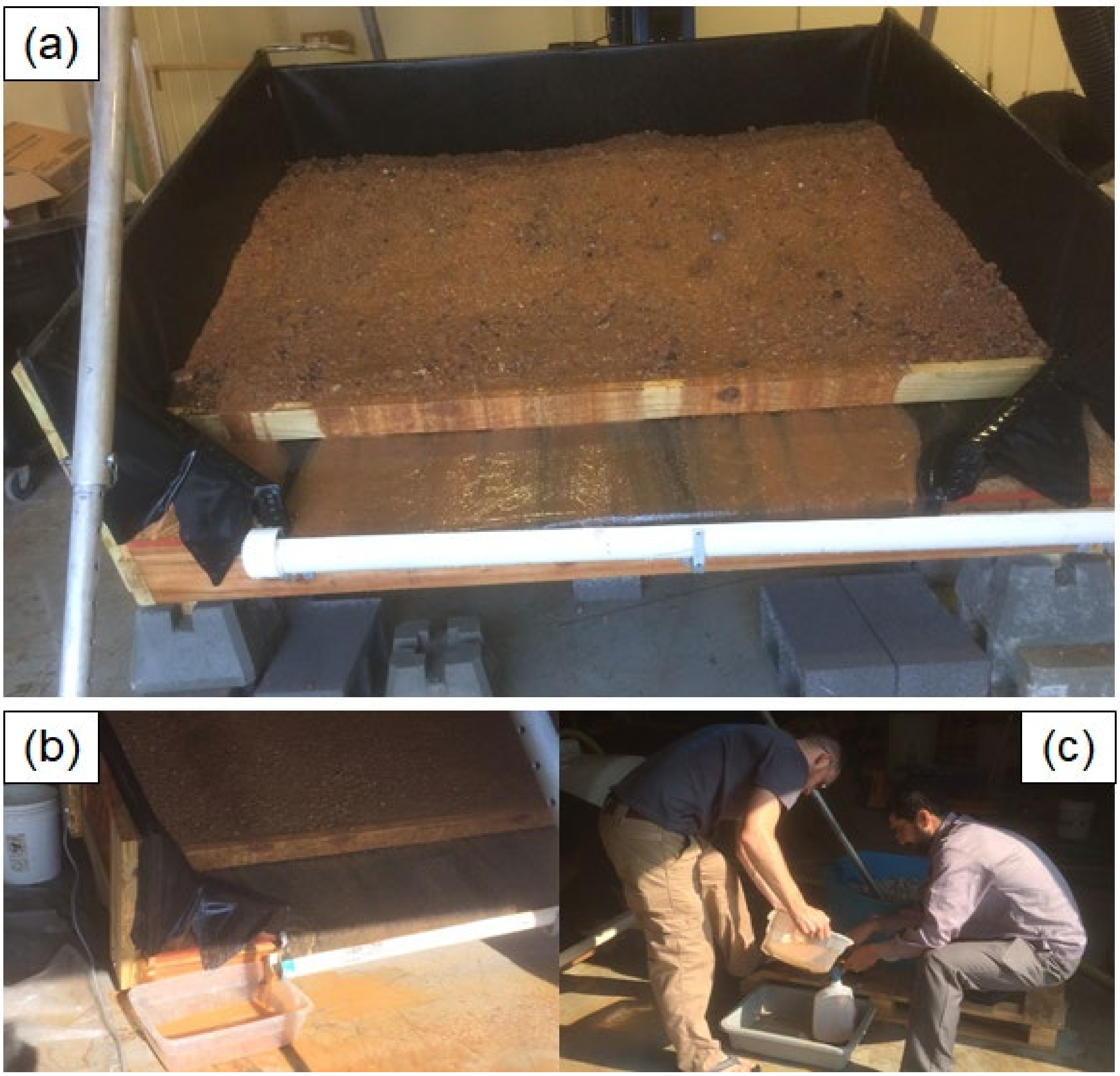

Figure 16. The experimental simulated rainfall events. (a) Runoff and eroded soil are flowing from the soil box during a bare soil test. (b) and (c) The sediment-laden runoff is collected in bins and transferred to milk jugs for storage and weighing. UTK students Christian Mooneyham and Mohammad Ghaneeizad transfer the collected sample into a milk jug for weighing.

Experimental matrix

An experimental matrix was developed based primarily on the parameters of the tested sediment retention practices and rainfall intensities (e.g., Foltz, 2012). Soil and slope were fixed for these tests. The experimental matrix shows that tests were run over a bare soil (no practice) to get the baseline condition. The tests using the sediment retention practices were compared with the baseline to quantify their efficiencies.

Through the project coordinator, Ali Hangul, the following devices were provided by Midwestern Construction Products out of Nashville, TN. These included the following: Silt fence, Straw-filled sediment tubes, and Mulch-filled sediment tubes (Figure 9).

Standard methods of ASTM International and other geotechnical methods were used to evaluate the characteristics of the soil used during the tests. The soil samples were weighed wet, air-dried at room temperature under low humidity for one week, and re-weighed to estimate water content. The bulk density for each sample was determined by dividing the dry weight with the volume of the sample (125 cm^3).

To determine texture, the dried samples were lightly crushed and passed through a nest of pre-weighed sieves (i.e., No. 10, 20, 40, 60, 100, 140, 200) to determine the sand content (ASTM D422). The silt-clay particle size distribution was determined using a standard hydrometer test (ASTM D422-63). Approximately 50-g of the soil less than 0.074 mm was dispersed in 125 mL of a 35.7 g/L mixture of sodium hexametaphosphate $(NaPO_3)_6$ for 12 hours. Hydrometer measurements were recorded at set intervals over a two-day period to determine the gradation of fine soil particles.

The Liquid Limit (*LL*) and the Plastic Limit (*PL*) of the soil samples were estimated using the Casagrande Cup method and the standard plastic limit test (ASTM D4318). In addition, the Plasticity Index, *PI*, was estimated as the difference between the *LL* and the *PL*, or $PI = LL - PL$. The organic carbon was measured using a visible near infrared spectrometer following the NRCS Rapid Carbon Assessment protocol. The pH of each sample was measured in a 1:2 mixture with distilled water.

Conclusions

There are three apparent needs when trying to choose an effective sediment reduction practice for abating soil loss at a roadway construction site. These needs include a systematic performance evaluation methodology; scientifically sound efficiency values for different erosion prevention and sediment reduction practices; and a transparent and straightforward means to determine a suitable erosion prevention and sediment reduction practice for specific site parameters. To address these needs an intermediate-size physical model of a fill slope below a highway shoulder leading to a drainage ditch was constructed in the UTK Hydraulics & Sedimentation Lab.

Forty-nine simulated rainfall events were performed over this physical model. In some of these events, one of three sediment reduction practice was implemented. These practices included silt fences, as well as mulch-filled and straw-filled sediment tubes. The runoff and soil loss collected below these plots were compared to those values of corresponding bare soil studies with no practice present. This comparison was used as the P-factor for the Modified USLE.

Building from the results of the experiments, the importance of runoff as an erosivity index was apparent. Runoff is more correlated with soil loss than all other examined rainfall factors such as intensity, total storm kinetic energy and other combined factors. It is, thus, recommended that any systematic protocol for testing sediment control practices utilize runoff coefficients, which are functions of the soil, slope, weather, and management, making them essentially "site specific" parameters. The results from this protocol are designed to be more applicable for TDOT. This study provided a step-by-step methodology that utilizes the runoff coefficient as a central parameter for determining practice efficiency values.

Empirical relationships were developed to provide "floating" baseline values of soil loss. The use of floating-baseline values is recommended over single "characteristic" baseline soil values to limit the uncertainty associated with the derived P-factors. Additionally, that singular basepoint may not be applicable for certain regions or conditions outside of the bounds of the testing procedure. Herein, power functions were fit to the soil loss – runoff coefficient data pairs for each intensity. Because these equations were developed using the runoff coefficients, the derived P-factors for the three practices are specific for Tennessee. The determined soil loss reduction values should then be better representative of the site.

To be of any practical use, these equations should be incorporated into a transparent erosion calculator that can be used by TDOT engineers when developing an erosion plan for a roadway construction site. It is recommended that this tool is transparent and straightforward so that users feel confident the results are applicable and a system dynamics framework is suited for this requirement. The erosion calculator incorporates the Modified Universal Soil Loss Equation (MUSLE) implemented through a system dynamics framework. The system dynamics framework was chosen because it transparently depicts the causal links between the pedologic, topographic, hydrologic, hydraulic, and management-related components of any site-system. The highly visual nature is easy to follow. The system dynamics model was developed in a web-based software. The model is compiled in your browser and the address can be shared with whomever making it readily available for TDOT. The website for the model is https://insightmaker.com/insight/205325/Tennessee-Erosion-Model.

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Appendix A

Performance Evaluation Method of Sediment Retention Practice

Preface: This test method establishes the procedures for evaluating the trapping efficiency of sediment-laden runoff by perimeter-located Best Management Practices (e.g., silt fence, sediment tubes). These perimeter practices can be applied to roadway and other construction sites to prevent the export of eroded sediment from the site area.

This procedure compares erosion rates from simulated rainfall events in an intermediate-sized testing structure with a fixed slope and soil under different rainfall intensities in the absence and presence of the sediment retention practices. The presented method should be considered as a representative procedure as it does not necessarily address all possible site-specific conditions. This procedure may not address all safety concerns, if any, associated with its use and the user assumes all responsibility for the safe implementation of this procedure.

Apparatus: The following list contains the base level of equipment needed to conduct this procedure. The components described below can be adapted to meet the needs of the user.

- Intermediate-sized testing platform – a soil box that is 1.83 m long x 1.98 m wide x 0.30 m deep with a 3:1 (Horizontal:Vertical) grade.
- Collection device – a trough located at the bottom of the soil box to capture the generated sediment-laden runoff and deliver it to a storage container. The storage container(s) should be sized to capture all the runoff.
- Rainfall simulators – Norton Ladder Multiple Intensity Rainfall Simulators consisting of an aluminum frame that is at least 2.5 m (l) x 1.5 m (w) x 2.7 m (h). Other characteristics include evenly spaced nozzles that can oscillate, a flow control valve with a pressure gauge to maintain a uniform operating pressure of 6 psi and the nozzles can produce spherical drops with a median drop size of 2.25 mm and an exit velocity of 6.8 m/s.
- Clean water source and pumping equipment – a source of water and associated pumping equipment to supply sufficiently and uninterruptedly water for at least 20 minutes.
- Stockpile of soil – the soil should match the dominant soil type of the site. A means to distribute the soil to the soil box is also needed.
- Dewatering mechanism and scale – the sediment must be separated from the water, dried and weighed to obtain the erosion rate. A scale is needed to weigh the sediment.

Procedure: The methodology uses at least 2 sets of simulated rainfall events conducted over the soil box subjected to three rainfall intensities. During the first set of simulated rainfall events, no sediment retention practice is present. These bare soil tests provide baseline erosion rates. The soil loss data from the bare soil tests are compared to those of the tests with the installed practices to determine the USLE P-factor. The P-factor is the sediment loss for the protected condition divided by the sediment loss from the control condition. A summary of the test procedure is provided here.

Preliminary Steps

1. Characterize the soil type from the site. At a minimum, the following parameters are needed; texture, organic matter content, proctor density.
2. Identify the rainfall amounts/ intensities that cover the range of design storms for the region that the site is located. Select three representative intensities (e.g., 2yr-6hr, 10yr-6hr, 25yr-6hr).
3. Select the practice to be tested. This test focuses on perimeter practices, such as silt fences, sediment tubes, and wattles.

Soil Box Preparation

4. Before each test, rake the plot smooth. Fill any rills or depressions with new soil. Mix the soil thoroughly and compact it to approximately 90% of the Proctor density. The soil depth should be at least 10 cm.
5. Install the sediment retention practices following approved guidelines. Make sure water and eroded soil cannot escape around the practice but must go over, under or through it.

Rainfall Simulator Preparation

6. Erect the rainfall simulator over the soil box so that the wetted footprint covers the entire soil surface. The nozzles should be high enough above the soil so that the drops reach terminal velocity (e.g., 2.7 m). Ensure the simulators have been calibrated for drop size distribution and fall velocities (see Blanquies et al., 2003; Paige et al. 2003).
7. Fill a water tank from a clean water source. There should be enough water for a 20-minute rain event for the desired intensities.

Simulated Rainfall Events

8. Initiate a 20-minute rain event using one of three intensities from step 2. The intensity should be kept constant throughout the event.
9. Collect all water and eroded sediment generated from the soil box that was delivered to a trough below the practice. Flow-weighted samples can be collected but only the total amounts of runoff and eroded soil are needed.

Sample and Data Processing

10. Weigh the total amount of water and sediment collected in the storage container(s).

11. Add an aluminum sulfate solution (10 mL of a 30% alum solution/ 1 L of sample) to induce flocculation and settling.
12. Decant the water. Dry and weigh the sediment.
13. The data produced include total mass of sediment and volume of water. The weight of the water can be converted to volume using the specific weight. The weight of the sediment is the soil loss.
14. Determine the runoff coefficient using the total volume of precipitation delivered to the soil box and the volume of runoff.
15. From all the bare soil rainfall events develop a relationship between runoff coefficient and soil loss.
16. Apply this relationship to the runoff coefficients determined for the simulated rainfall events that used sediment retention practices. This provides the baseline soil loss value for that test.
17. Determine the practice efficiency by dividing the soil loss for the simulated rainfall event that used the sediment retention practice and the corresponding baseline soil loss value.