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Determining Design Criteria for Land and Flow Characteristics That Produce Non-Erosive Sheet Flow

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To address this issue, this study conducted a series of computer modeling simulations to understand how key properties of a hillslope affect sediment export. The properties investigated were slope, hillslope length, soil hydraulic conductivity, and surface roughness. The Kinematic Runoff and Erosion Model, Version 2, developed by the U.S. Department of Agriculture, was used for the simulations. Simulations were conducted for 24-hour design storms with total rainfall depths from 2 to 7 in. These design storms represent 2-year to 10-year return period storms for counties and cities across Virginia. To validate the modeling results and relate them to real-world hillslopes, 18 sites proposed by VDOT engineers were investigated to measure their properties and to observe the presence or absence of erosive flow at the sites.

The results of the study documented how slope, hillslope length, soil hydraulic conductivity, and surface roughness affect sediment transport from a computer-simulated hillslope. Slope and hillslope length were the most important variables, each having a linear relationship with total sediment yield and peak sediment discharge. Hydraulic conductivity and surface roughness, measured using Manning's roughness, showed a negative correlation with total sediment yield and peak sediment discharge. A regression analysis resulted in a simple equation to estimate peak sediment discharge based on the properties of a hillslope and the total amount of rainfall received over the 24-hour design storm. Applying the regression model to the field sites showed that the model generally matched what was found in the field, although each site had unique complexities that had to be considered. The study concluded that it is possible to use a regression equation with only a few easily obtained hillslope characteristics to estimate peak sediment discharge. Further, a peak sediment value of 5 g/s per width of hillslope for a 2-year, 24-hour design storm is a reasonable threshold for determining if a hillslope is at risk of producing erosive flows.

The study recommends that VDOT disseminate the outcomes of this study to designers so that they can better understand when hillslopes will generate erosive sheet flow. Further, VDOT should continue to identify and record locations in the field where efforts to establish sheet flow resulted in erosive flows so that the peak sediment threshold values proposed in this study can be further tested and refined. If VDOT implements these recommendations, it will allow designers to better ensure that hillslopes will result in non-erosive sheet flow, thereby avoiding the need for more expensive stormwater control measures while at the same time protecting the environment and water quality from harmful erosion.

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FINAL REPORT

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and the University of Virginia since 1948)

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ABSTRACT

If a design engineer can show that a project site will produce non-erosive sheet flow, the cost and complexity of stormwater control measures that must be built for that site can be significantly reduced. However, the criteria for establishing non-erosive sheet flow are not well defined in the Virginia Department of Transportation (VDOT) *Drainage Manual*. This lack of a clear definition can result in uncertainty for projects when establishing non-erosive sheet flow through natural grading at sites or using stormwater control measures such as level spreaders.

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INTRODUCTION

Demonstrating that a project site will produce sheet flow can significantly reduce the cost and complexity of stormwater control measures that must be built on-site. However, the criteria for establishing that a hillslope will produce non-erosive sheet flow are not well defined in the Virginia Department of Transportation (VDOT) *Drainage Manual*.[1] This missing information can result in uncertainty for projects when establishing sheet flow through natural grading at sites or using stormwater control measures such as level spreaders. A level spreader is designed to produce sheet flow for a receiving hillslope (or riparian buffer) along the entire length of that hillslope until it reaches a receiving stream. By doing so, the level spreader prevents concentrated flow and the erosion and flooding risks that can be associated with it.

Models for estimating erosion from a hillslope are well established in the literature. A recent review of these models grouped them into categories including empirical models, physical models, conceptual models, and hybrid models.[2] Perhaps the most common model used to quantify erosion rates is the empirically based Revised Universal Soil Loss Equation available through the U.S. Department of Agriculture.[3] There are also more than a dozen physically based models using one- or two-dimensional landscapes, hydraulic principles, and soil physics to simulate erosion.[2] These physical models include both freely available software from governmental sources and commercial software from private hydrology and hydraulic modeling software companies.

Little is reported in the literature on the efficacy of level spreaders for achieving sheet flow. Hathaway and Hunt conducted a field survey of 20 level spreaders installed in North Carolina.[4] They found that none of the installed level spreaders was able to maintain diffuse flow for a variety of reasons, including poor design, installation, and maintenance. The study concluded that revisions were needed to better ensure properly functioning level spreaders in the state. This study, however, was limited to 20 installations in North Carolina and was conducted more than 10 years ago.

Research is needed to establish appropriate, well-defined, and implementable standards for ascertaining when it is appropriate to assume that a site, with or without an installed level spreader, will result in sheet flow given a set of simple and easily established site conditions (slope, slope length, surface roughness, and soil hydraulic conductivity). The results of such research can inform changes to the VDOT *Drainage Manual* and, ultimately, allow designers and regulators to have confidence that project designs using sheet flow will not result in harmful erosion.

PURPOSE AND SCOPE

This study addressed the problem of limited information for determining site characteristics needed to establish sheet flow. There were three objectives.

1. *Modeling Simulations*. Complete computer-based modeling simulations of a variety of hypothetical hillslope conditions to determine the conditions under which sheet flow can be established from diffusive runoff (whether from a level spreader or some other source) without causing excessive sedimentation.

2. *Field Studies.* Conduct field surveys evaluating a number of VDOT-owned sites that use sheet flow as a stormwater best management practice to determine how slope, soil, and land use conditions affect the ability to obtain sheet flow.

3. *Implementation.* Synthesize the information obtained through the field surveys to evaluate and refine the computer model–based simulations and, from the simulation results, establish an easily implementable method for determining the site characteristics needed for establishing sheet flow.

METHODS AND DATA

Modeling Simulations

Computer simulations were used to test different hypothetical conditions of four key variable characteristics: (1) downhill slope of the hillslope, (2) length of the hillslope, (3) hydraulic conductivity of the hillslope soil, and (4) Manning's roughness of the hillslope surface. These criteria can be easily obtained or estimated for a site and, therefore, can be used in site design to estimate erosion potential for a hillslope.

The Kinematic Runoff and Erosion Model, Version 2 (KINEROS2), freely available from the U.S. Department of Agriculture, was used for the simulations.[5] KINEROS2 is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion. The model is often applied for small urban and agricultural watersheds, and the model outputs include both water quantity variables (flow and velocity) and sediment variables (total sediment yield and peak sediment discharge). KINEROS2 can simulate flow over a hillslope in the model as a plane. Properties of the hillslope plane can be easily varied in the model by adjusting model input parameters.[6]

By strategically varying key model parameters and variables, it is possible to estimate relationships among the four site characteristic variables, rainfall, and sediment output. This information can be used to estimate the sediment yield given a site's characteristics and a rainfall hyetograph. It can also be used to estimate, for example, what slope and slope length are expected to result in an unacceptable amount of erosion for a given surface roughness and soil hydraulic conductivity combination.

The model setup included two plane elements in KINEROS2 (Figure 1). The uphill plane represented a road lane and shoulder that produced runoff delivered to the downhill plane. This plane was fixed at 3 m (9.8 ft) in length to represent a single lane and shoulder. In addition, it was defined as an impervious surface with a mild (0.5%) slope toward the downhill plane element. The downhill plane element represented the permeable hillslope where erosion could occur. Many other properties of the slopes were set in KINEROS2 including length, slope, Manning's roughness, and saturated hydraulic conductivity. It was assumed that both planes had a unit width (1 m / 3.2 8 ft), so all results were per unit width of hillslope. Rainfall was applied to both planes in the model simulations using a Soil Conservation Service Type II rainfall distribution.[7] The total depth of rainfall used in the simulations ranged from 50.8 mm (2 in) to 177.8 mm (7 in) with a 25.4 mm (1 in) step. This range represented the range of rainfall depths across Virginia for a 2-year to 10-year return period storm of 24-hour duration.[1]

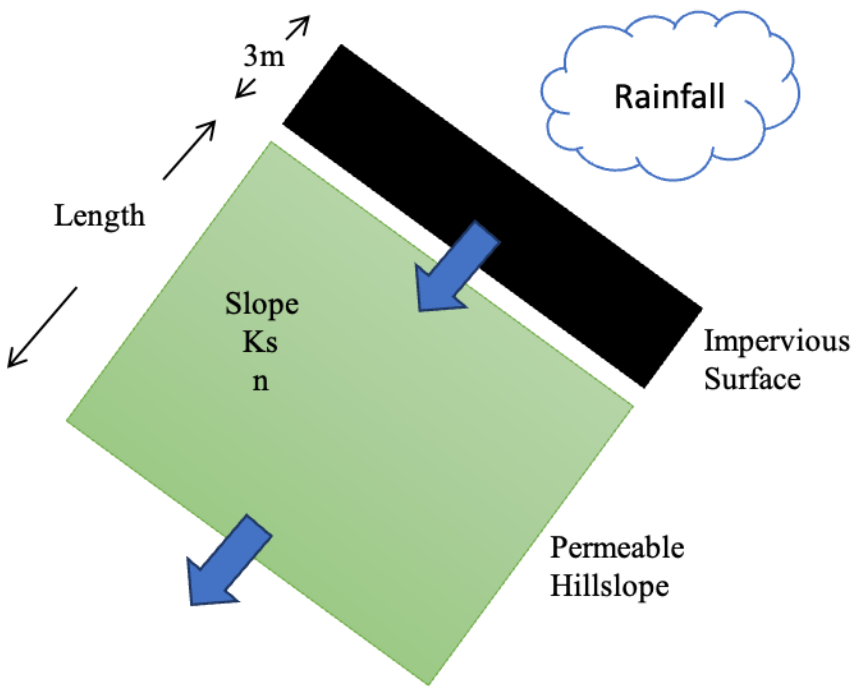

Figure 1. KINEROS2 Setup Used for Hillslope Erosion Simulations

A total of 1,152 unique simulations were run by varying hillslope length, slope, Manning's roughness, hydraulic conductivity, and rainfall depth. Values used in the model are shown in Table 1 and were selected to represent ranges of values seen in the field data. The model simulations used a 1-min time step, and the simulation output included a time series for flow, velocity, and sediment discharge. The total sediment yield (tons/ha) and peak sediment discharge (kg/s) output from KINEROS2 runs were extracted and saved in a summary output file. A Python program was written to automate the model runs by iteratively changing the input files for KINEROS2 to process all combinations of input variable values and extract the key sediment output variables after each KINEROS2 run. This code and the resulting output are available from the researchers upon request.

Table 1. Variables Used in Model Runs

Variable	Values Used In Model
Length (m)	5, 10, 15, 20
Slope (%)	20, 30, 40, 50
Manning's Roughness, n (-)	0.1, 0.2, 0.3, 0.4
Saturated Hydraulic Conductivity, K_s (mm/hr)	0.1, 1.0, 10.0
Rainfall (mm)[a]	50.8, 76.2, 101.6, 127.0, 152.4, 177.8

[a] Rainfall values are equal to 2, … 7 in.

Field Studies

A total of 30 sites were visited to collect quantitative and qualitative data pertaining to the conditions of VDOT-owned sites designed to produce non-erosive sheet flow. Figure 2 shows the location of these sites, and Table A1 in the Appendix lists the site attributes. These sites were recommended by the Virginia Transportation Research Council; Henrico County and Chesterfield County representatives; and VDOT's Culpeper, Richmond, and Fredericksburg districts. Of these sites, 11 locations had existing level spreaders and 19 were hillslopes without level spreaders. Twelve of the 30 sites were inaccessible or excluded from later analysis because they were not relevant to the study objectives (see Table A1 in the Appendix for further details). Therefore, of the 30 sites visited, 18 were surveyed and used in the subsequent analyses.

Categorical and quantitative data were collected at the 18 sites used in the analysis. Categorical data included descriptions of vegetative cover (used to estimate Manning's roughness using Table 2), observed quality of soils, and other notable observations such as the presence or absence of erosion. Quantitative data, specifically, slope length and azimuth angle, were collected and recorded using a total station. The corresponding percent slope was subsequently calculated using trigonometric relationships. Table A2, in the Appendix, includes the calculations performed to find the percent slope for a subset of the sites as examples.

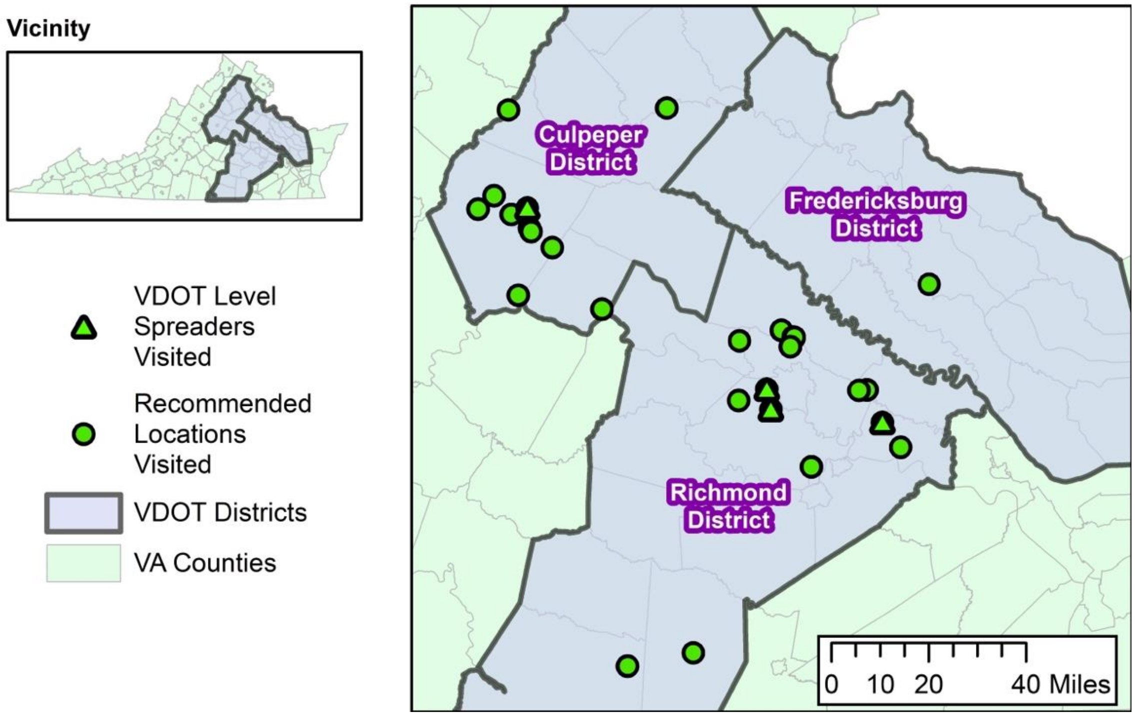

Figure 2. Locations of Sites Visted to Observe Hillslopes That Might Have Erosive Flows

Table 2. Manning's Roughness Coefficent for Shallow Sheet Flow

Surface Description	**n[a]**
Smooth surfaces – concrete, asphalt, gravel, or bare soil (compacted)	0.011
Fallow – no residue (non-compacted bare, plowed soil)	0.05
Cultivated soils	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Grasses	
Short grass prairie	0.15
Dense grasses[b]	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods[c]	
Light underbrush	0.4
Dense underbrush	0.8

[a] The n values are a composite of information compiled by Engman.[9]
[b] Includes species such as weeping lovegrass, bluegrass, buffalo grass, blue grama grass, and native grass mixtures.
[c] When selecting n, soil cover to a height of about 1 inch was considered. This is the only part of the plant cover that will obstruct sheet flow.
Source: VDOT *Drainage Manual*, Appendix 6D-2, adapted from the AASHTO 2005 Model Drainage Manual (text shown in parentheses is VDOT's addition to the original chart, which was included to simplify interpretation and application).

For some sites with and without level spreaders, a single slope measurement was taken with a total station, which was representative of the entire slope. In other locations, multiple measurements were taken to capture changes in upstream and downstream slopes or dramatic changes in slopes from the receiving bay and downstream from the weir for various level spreader sites. In a later analysis, a single slope and slope length were used for each site. In the case where multiple slope and slope lengths were measured at a single site, the slope / slope length pair with the longest slope length and that was more representative of the hillslope was used in subsequent analyses.

A dataset summarizing the key properties of each field site was produced to be used in implementation of the study recommendations. Quantitative data representing measured percent slope and slope length were included as separate attributes. Soil classification names were added from the Soil Survey Geographic Database dataset. A saturated conductivity (K_s) was then estimated based on the site's soil class name.[8] A representative Manning's roughness coefficient was assigned to each project based on the observed vegetation conditions described in Table 2. Figure 3 shows images of four field study locations with representative Manning's roughness coefficients. For sites with vegetative conditions observed to be in between the conditions described in Table 2, an adjusted coefficient was assigned to the site. A summary of the completed dataset is provided in Table A1 of the Appendix.

Figure 3. Typical Representative Land Covers and Corresponding Manning's Roughness Coefficients Associated With Sites Visited in Virginia: 1, Hildridge site in Albemarle County found to have non-compacted soils with residue covering less than 20% of the surface; 2, Broad Street site in Richmond observed to have natural range conditions; 3, LS20194, in Chesterfield County observed to have dense grasses; 4, Lawrenceville site in Lawrenceville, observed to have very dense grasses.

Implementation

The computer simulation modeling and field study outcomes were synthesized so that they could be more easily implemented into practice. Model outputs were compared to the field data for both model validation and determination of sediment export thresholds that result in field-observed erosion. Establishing this threshold and relating it to key site characteristics will make it possible to create clear and implementable guidelines for designers to determine if site conditions may result in erosion. By summarizing the outcomes of the first two study objectives, the goal of the implementation objective was to create a simple approach that could be included in the VDOT *Drainage Manual* to provide improved guidance on producing sheet flow at a site based on its characteristics.

RESULTS AND DISCUSSION

Model Simulations

Each of the 1,152 model runs produced time series of the flow rate, velocity, and total sediment rate for each scenario. Figure 4 shows an example of this output for one modeling scenario where total rainfall depth was 50.8 mm (or 2 in); slope was 50%; hillslope length was 10 m (32.8 ft); Manning's roughness (n) was 0.3; and saturated hydraulic conductivity (K_s) was 10.0 mm/hr (0.393 in/hr). Outflow as a flow rate (m^3/s) and as a velocity (mm/hr) and rainfall (mm/hr) are given on the left y-axis. The total sediment output (g/s) is given on the right y-axis. The peak sediment discharge value for this scenario was approximately 12 g/s (0.026 lb/s) and occurred after approximately 750 min (12.5 hr). The total sediment yield (tons/ha) is not shown on the plot but would be the area under the sediment curve divided by the area of the plane.

When the 1,152 model runs were averaged for the various slope, slope length, Manning's roughness, and saturated hydraulic conductivity values, it was possible to see how each of these variables was related to peak sediment discharge and sediment yield (Figure 5).

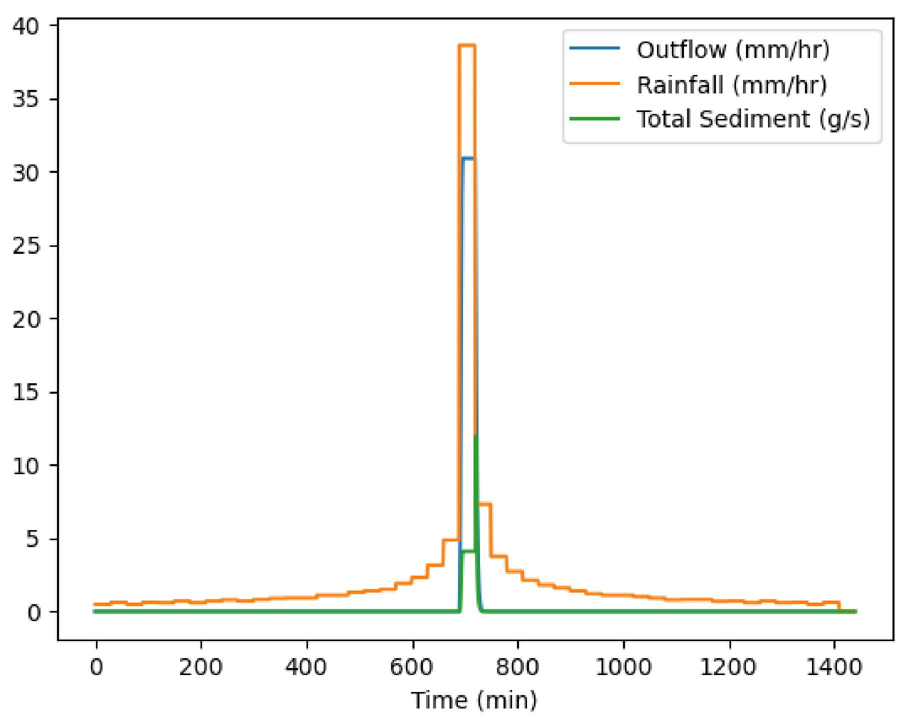

Figure 4. Example of Output Resulting From a Single Model Run

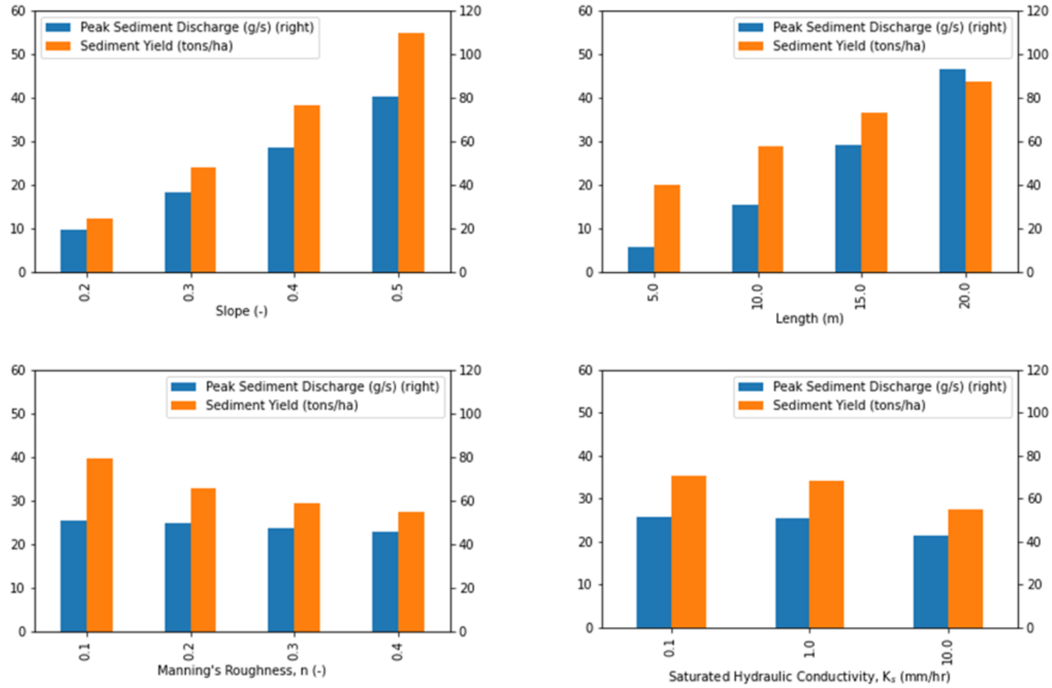

Figure 5. Relationship of Slope (Fraction), Slope Length (m), Manning's Roughness (Unitless), and Saturated Hydraulic Conductivity (mm/hr) to Peak Sediment Discharge (kg/s per meter width of hillslope) and Total Sediment Yield (tons/ha per meter width of hillslope) Across All 1,152 Model Simulations

Slope and slope length were both linearly related and positively correlated to peak sediment discharge and sediment yield. Manning's roughness and saturated hydraulic conductivity both showed a negative linear correlation to peak sediment discharge and sediment yield. Peak sediment yield was more strongly correlated to slope and slope length than to Manning's roughness and saturated hydraulic conductivity over the range of values considered in this analysis.

Using regression analysis, it was possible to build a relationship among the hillslope properties, rainfall, and peak sediment discharge. This relationship showed that peak sediment discharge can be expressed as shown in Equation 1

$$S_p = 0.120 \times L \times SL \times R - 6.21 \times n \times K_s \qquad \text{(Eq. 1)}$$

where S_p = peak sediment discharge (g/s per meter width of hillslope); L = slope length (m); SL = slope (fraction); R = rainfall depth (mm); n = Manning's roughness (unitless); and K_s = hydraulic conductivity (mm/hr). Using U.S. customary units for the regression results in Equation 2 with the appropriate coefficients

$$S_p = 9.99\times10^{-3} \times L \times SL \times R - 1.67 \times n \times K_s \qquad \text{(Eq. 2)}$$

where S_p = peak sediment discharge (oz/s per foot width of hillslope); L = slope length (ft); SL = slope (fraction); R = rainfall depth (in); n = Manning's roughness (unitless); and K_s = hydraulic conductivity (in/hr).

Applying this relationship to the output across the 1,152 model runs resulted in predictions of peak sediment discharge that matched the KINEROS2-modeled sediment discharge with an R^2 value of 0.954 (Figure 6). The relationship did tend to under-predict peak sediment discharge for high values of peak sediment discharge, starting around 150 g/s/m (0.10 lb/s/ft), yet it maintained a strong overall predictive value despite its simple function of just four relatively easily observable hillslope conditions. It should be noted that none of the field sites visited had peak sediment discharge values in this upper range, suggesting that such hillslopes in practice may be rare. The regression equation can result in negative values for some combinations of hillslope attributes where erosion is not likely a risk. If a negative value is obtained, it should be set instead to zero peak sediment discharge.

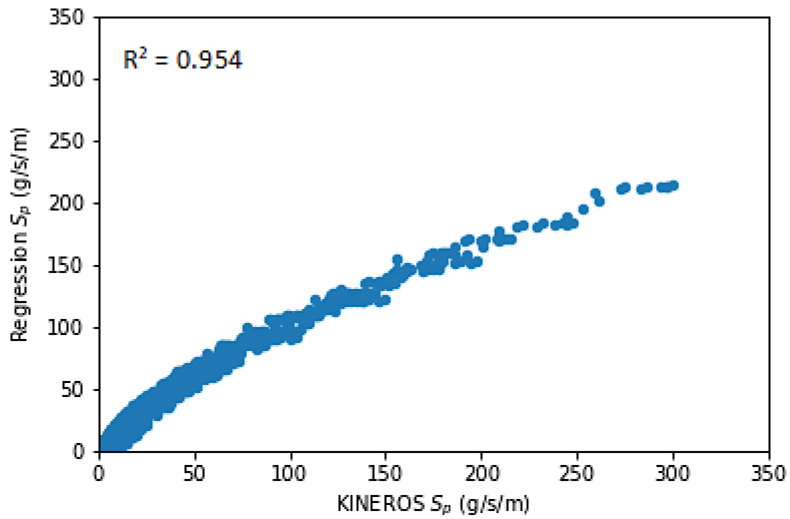

Figure 6. Relationship of Slope, Slope Length, Manning's Roughness, and Saturated Hydraulic Conductivity to Peak Sediment Discharge and Sediment Yield Across All 1,152 Model Simulations

Field Studies

Results of the field studies showed that for the seven sites without level spreaders (not containing structures designed to induce sheet flow) visited and deemed most applicable to the objectives of this study, the average slope was 32.7% and the range of slopes was 4.2% to 55.5%. The average slope length measured for these sites was 14.5 m, with slope lengths ranging from 5.8 m to 30.1 m. Erosion for these sites was generally observed as channelized erosion along the downslope adjacent to the edge of road pavement. For sites with steeper slopes (greater than 19%), thick vegetation was generally observed along with loosely compacted soils. For example, these conditions were observed at the Lawrenceville site. Sites with more shallow slopes (less than 19%) often corresponded to locations in the median of roads or highways. In particular, this was observed along the median of I-64 near the overpass of New Kent Highway. Soils in these locations were very compacted, and vegetation was sparse. In some locations with steep slopes, the placement of riprap along the hillside was observed, which was likely related to slope stabilization and erosion control. Erosion was generally not observed at sites with added riprap.

There were 11 level spreader sites, each with similar infrastructure design components, including a discharge pipe connected to a receiving bay and permeable rock with a solid, level weir at the end of the bay. The exception to this was LS02019, which had no formal discharge pipe or bay, with the weir composed of a linear row of stacked rocks with no flat top. In general, level spreaders visited were well maintained with thick vegetation in the receiving bay and along the downslope from the weir. Some level spreaders appeared to discharge stormwater as sheet flow to nearby streams and wetland areas, such as the Emerson Mills 2 site, whereas other sites, such as LS20194, discharged stormwater as sheet flow from the level spreader to wooded areas without known or visible streams. The average slope measured for level spreader sites was 6.5%, with slopes ranging between 1.2% and 10.3%. The average slope length measured was 14.3 m, with slope length ranging from 7.5 m to 18.6 m.

Although the majority of level spreaders observed were in working condition and well maintained, there was one location, UPC 97688, where major erosion due to channelization was observed downstream from the weir of the level spreader. This level spreader had a corresponding slope of 4.3% and a measured slope length of 15.8 m. Sparse vegetation was observed along the downslope from the weir. In addition, it should be noted that early signs of channelization were present at the corner of the weir of the level spreader at the River Mill 2 site. This may be attributed to possible uneven slopes in the receiving bay, which could cause the water to flow to and drain out of one corner of the bay.

Implementation

By use of the combined results of the modeling work and the field work, values of hillslope characteristics for hillslopes that may be at risk of erosion compared to those that are not likely at risk can be determined. Equation 1 was used to estimate the peak sediment discharge (g/s) for the 18 sites deemed to be relevant to the study objectives and where slope and slope length could be measured in the field. A 2-year, 24-hour rainfall depth was used as this is the most common return period used for erosion control calculations. A summary of the estimated peak sediment discharge for each of the 18 sites is presented in Table 3.

Field data for sites that did and did not experience erosion in Equation 1 showed that the equation consistently, with some exceptions discussed later, predicted high peak sediment discharge values for sites that did experience erosion compared to those that did not (Table 3). This validated the equation and showed that it can be used for estimating potential erosion based on measurable site characteristics.

Table 3. Summary of Field Survey Results and Predicted Peak Sediment Discharge (S_p) Calculated From Equation 1 Resulting From the Modeling Simulations

Site Name	2-Year Rainfall (mm)	Measured Slope (%)	Slope Length (m)	Manning's Roughness (-)	K_s (mm/hr)	Predicted S_p (g/s/m)	Observed Erosion (Yes/No)
Spotswood	93.2	9.12	10.1	0.10	6.5	6.3	Yes
Garth	98.3[a]	14.0	19.9	0.24	3.4	27.8	Yes
Rivanna Bridge	82.6	42.4	12.3	0.30	10.9	31.4	No[b]
Cloverleaf	98.3[a]	40.2	5.84	0.2	10.9	14.2	Yes
Hildridge	98.3[a]	23.5	30.9	0.10	6.5	81.6	Yes
LS02019	98.3	10.3	10.4	0.30	10.9	0.0	No
LS20117	85.1	7.4	17.5	0.24	10.9	0.0	No
LS20194	85.1	9.6	7.51	0.24	10.9	0.0	No
Broad Street	83.3	4.2	23.0	0.13	10.9	0.9	Yes
UPC 97688	86.6	4.3	15.8	0.05	10.9	3.7	Yes[c]
Emerson Mills	84.3	1.2	18.6	0.24	10.9	0.0	No
River Mill 2	84.3	6.81	16.1	0.20	10.9	0.0	No
La Crosse	82.0	54.0	15.2	0.3	10.9	60.5	Yes[d]
Lawrenceville	85.9	51.9	8.6	0.3	10.9	25.7	Yes[d]
Freeway Med 1	85.6	15.4	7.5	0.1	10.9	5.1	Yes
Freeway Med 3	84.3	16.4	7.3	0.1	10.9	5.3	Yes
Freeway Med 4	85.1	6.7	7.7	0.1	10.9	0.0	Yes[e]
Miller's Tavern	84.1	55.5	11.4	0.30	10.9	43.5	Yes[f]

[a] This represents the average rainfall across the two zones in Albemarle County.
[b] Multiple slope and slope length measurements taken to confirm the occurrence of erosion since sites with similar characteristics may experience erosion. In addition, riprap added to portion of hillslope.
[c] Level spreader bay was filled with frozen water when observed, reducing the capacity and potentially leading to erosion.
[d] Erosion resulting from sheet flow not observed. Sites with similar characteristics may experience erosion resulting from sheet flow.
[e] The roughness coefficient may be slightly overestimated.
[f] Site had evidence of past erosion and had recently installed riprap.

Comparing the field data to the model-predicted peak sediment discharge showed the complexity of predicting erosive flows. Generally, sites with a predicted peak sediment discharge below 5 g/s/m (i.e., per meter width of hillslope) (3.2 oz/min/ft) had no observable erosion (e.g., LS02019, LS20117, LS20194, and Emerson Mills), whereas sites with a predicted peak sediment discharge near or above this threshold value had observable erosion (e.g., Spotswood, Garth, Miller's Tavern, and Broad Street).

Some sites did not follow this pattern, however. Rivanna Bridge was predicted to have erosion, but no erosion was observed. Some portion of the hillslope had riprap, which reduces the risk of erosive flows on hillslopes and likely explains why no erosion was observed. UPC97688 had observable erosion, but the peak sediment discharge was predicted to be only 3.6 g/s/m below the threshold value. The threshold value is somewhat arbitrary and perhaps should be reduced so that it includes UPC 97688. That said, this site was a level spreader location where water pooled in the bay; frozen pooled water was observed in the bay during the site visit. This effectively reduced the capacity of the bay and may have resulted in erosive flows at the level spreader outlet. The Freeway Med 4 site had observable erosion similar to that of the other freeway sites (Freeway Med 1 and Freeway Med 3), which was most likely due to compacted soils with limited vegetation. From observation, the Freeway Med 4 site appeared to be an edge case where a slight modification to the model parameters, such as adding 0.5 ft to the slope length and reducing the roughness coefficient from 0.1 to 0.08, would result in model-predicted sediment discharge. It is possible that the roughness coefficient for this site was slightly overestimated. These edge cases highlight the need for designers to continue to use their best engineering judgment when accounting for sediment discharge.

Based on this result, a peak sediment discharge of 5 g/s/m could be used as a threshold value for determining if erosive flows might result at a given site. This peak sediment discharge can be easily calculated for a site design using Equation 1 for metric units or Equation 2 for U.S. customary units. However, as evidenced by the field visits, this is not a definite threshold value. Some sites, if vegetation is established and the site has good soils (e.g., soils with a larger median particle size) so that the Manning's roughness value increases, could be safe from erosive flows with higher peak sediment discharge values. Other sites with lower peak sediment discharge values might still experience erosive flows. Thus, engineering judgment is still important for the process.

Using Equation 1 and the threshold of 5 g/s/m peak sediment discharge, designers could vary slope, slope length, saturated hydraulic conductivity, and Manning's roughness to determine values that would result in flow that is likely non-erosive. It is not possible to make broad claims that certain slopes or slope lengths will never be at risk of erosive flows. This was verified by the field data that showed even sites such as Broad Street, with a slope of just over 4%, a sufficiently long slope length, and bare soils (resulting in a low Manning's roughness), still produced erosive flows. Given this, a best practice would include checking the peak sediment discharge value using Equation 1 for a particular design to determine if the value is near or above the 5 g/s/m threshold. If it is found to be near the threshold and the design can be altered, then an effort should be made to do so. If the peak sediment discharge is clearly above the threshold, the design should be altered to reduce the risk of flow-causing erosion. Last, it should be noted that the model-predicted sediment discharge assumes homogenous conditions for the hillslope being analyzed. For hillslopes with long slope lengths and noticeable changes in vegetation or soil conditions, Equation 1 should be applied to each relatively homogenous segment of the hillslope to estimate the peak sediment discharge. An average peak sediment discharge for the hillslope could then be estimated using a weighted average of these peak sediment discharge values based on slope length.

CONCLUSIONS

- *It is possible to create a simple regression equation to estimate peak sediment discharge from a site from only four easily obtainable site characteristics and an assumed 24-hour rainfall depth.*

- *From field data, a value of 5 g/s per meter width of hillslope seems to be a reasonable threshold for determining if a site will experience erosive flows, although good engineering judgment is still needed, especially in borderline cases. This threshold value was based on field data collected at 18 sites that were accessible and deemed appropriate for the study out of the 30 sites visited by the researchers.*

- *Using the regression equation and with knowledge of a threshold for when peak sediment discharge can result in erosive flows, designers can adjust a site's slope, slope length, vegetative cover (through the Manning's roughness), and soil type (through the soil hydraulic conductivity) to achieve a hillslope design less likely to result in non-erosive sheet flow.*

RECOMMENDATIONS

1. *VDOT's Location and Design Division should disseminate the outcomes of this study to designers through a method deemed most appropriate by the division staff (e.g., updated policy or guidance documents or a software application).* In particular, the regression equations developed in this study can be shared with designers along with a basic classification of peak sediment discharge values of low concern (perhaps less than 3 g/s/m); medium concern (perhaps from 3 g/s/m to 7 g/s/m); or large concern (above 7 g/s/m) for erosive flows. Designers will use this information along with their engineering judgment to create hillslopes that produce sheet flow and do not result in erosive flows.

2. *VDOT's Location and Design Division should continue to identify and record the condition of locations where efforts were made to establish sheet flow, i.e., did the efforts result in erosive or non-erosive flows.* Based on this continued data collection, the division can determine if it is necessary to adjust the peak sediment discharge ranges, as given in Recommendation 1, for low, medium, and large concern with regard to developing erosive flows.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With respect to Recommendation 1, dissemination of this information will be initiated by the end of 2023 and in a manner that allows this new information to be easily used by designers. If a software application to assist designers is deemed appropriate, additional time will be required to develop and disseminate that information but this should be completed within 3 years.

With respect to Recommendation 2, following the dissemination of this information, district design personnel will be surveyed to identify sites suitable for continued monitoring. The number and location of these sites will be determined based on this information. Emphasis will be placed on recently or soon to be established sites so that impacts due to variations in the establishment of vegetative cover early in the project life cycle can be fully recorded. Once selected, long-term monitoring of these sites will be conducted over a 3-year period.

Benefits

The benefits to VDOT of implementing the recommendations of this study include increased guidance for design engineers to determine if non-erosive sheet flow can be established. This guidance is currently lacking, resulting in uncertainty among designers and design reviewers. Further, implementation of these recommendations would provide VDOT with additional numerical justification to regulatory agencies in situations where increased volumes of sheet flow will be generated at a site but will not result in erosion as described in Part D of 9 VAC 25-870-66. The ability to rely on sheet flow rather than more traditional water quantity controls can provide substantial cost savings in terms of both construction costs and additional land acquisition costs required for these measures, particularly in densely populated areas.

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APPENDIX
SITE CHARACTERISTICS

Table A1. Attributes of Sites Visited in Culpeper, Richmond, and Fredericksburg Districts

District	Site Name	Measured % Slope[1]	Slope Length (ft)[1]	Erosion[2]	Soil Name[3]	K_s (mm/hr)[4]	Manning's Roughness n[5]	Site Description
Culpeper	Spotswood	9.12	33.07	Yes	Myersville and Catoctin extremely stony silt loam	6.5	0.1	Erosion observed adjacent to edge of road pavement; steep slopes and thick vegetation on site - measured upstream and downstream of observed erosion.
Culpeper	Garth	14.03	65.28	Yes	Hazel loam	3.4	0.24	Minimal erosion observed - measured overall slope and slope from existing pipe to end of mat.
Culpeper	Rt. 802	-	-	-	Toccoa fine sandy loam	-	-	Steep slope along guardrail. No measurements taken.
Culpeper	Cloverleaf*	40.24	19.17	Yes	Chester loam	10.9	0.2	Erosion observed adjacent to edge of road pavement; steep slopes and thick vegetation on site - measurement taken.
Culpeper	Monticello	-	-	No	Rabun clay loam	-	-	Appeared to be a soft shoulder of existing road. No sheet flow-induced erosion observed.
Culpeper	Loop	-	-	No	Rabun clay	-	-	No sheet flow-induced erosion observed; deemed not applicable site.
Culpeper	Hildridge	23.52	101.38	No	Manteo channery silt loam	6.5	0.1	Measurement taken – near-bare surfaces with patches of erosion observed along the slope.
Culpeper	Dollar Store	-	-	No	Manteo channery silt loam	-	-	Erosion associated with construction. No appearance of sheet flow-induced erosion; not applicable site.
Culpeper	Rivanna Bridge*	42.42	40.5	No	Congaree fine sandy loam	10.9	0.3	No erosion observed - multiple measurements taken as similar slopes may experience erosion.

Table A1 (cont.). Attributes of Sites Visited in Culpeper, Richmond, and Fredericksburg Districts

District	Site Name	Measured % Slope[1]	Slope Length (ft)[1]	Erosion[2]	Soil Name[3]	K_s (mm/hr)[4]	Manning's Roughness n[5]	Site Description
Culpeper	Raccoon Ford	-	-	Yes	Klinesville silt loam	-	-	Slope failure observed, possibly due to the type of soils or excess precipitation/river erosion; deemed not an applicable site.
Culpeper	LS02019	10.32	33.98	No	Culpeper fine sandy loam	10.9	0.3	Existing level spreader - measurements taken - no erosion observed.
Richmond	LS20117	7.36	57.53	No	Fluvaquents	10.9	0.24	Existing level spreader - measurements taken - no erosion observed.
Richmond	LS20194	9.56	24.64	No	Cecil fine sandy loam	10.9	0.24	Existing level spreader - measurements taken - no erosion observed.
Richmond	Broad St	4.18	75.57	Yes	Creedmoor fine sandy loam	10.9	0.13	Erosion observed, possibly due to lack of vegetation or compacted soils - measurements taken as similar slopes may experience erosion.
Richmond	LS18002	-	-	No	Slagle fine sandy loam	-	-	Existing level spreader - measurement not taken due to water - no erosion observed.
Richmond	UPC 97688	4.26	51.82	Yes	Nevarc-Remlik complex	3.4	0.05	Existing level spreader - erosion observed - measurements taken from concrete lip of level spreader to end of observed channelization.
Richmond	TMDL Project	-	-	-	Myatt loam	-	-	Was not able to locate this project.
Richmond	Cedar Grove (LS)	-	-	No	Chewacla and Riverview soils	-	-	Existing level spreader - measurements not taken due to inaccessibility (vegetation growth). In working condition - discharges to stream.

Table A1 (cont.). Attributes of Sites Visited in Culpeper, Richmond, and Fredericksburg Districts

District	Site Name	Measured % Slope[1]	Slope Length (ft)[1]	Erosion[2]	Soil Name[3]	K_s (mm/hr)[4]	Manning's Roughness n[5]	Site Description
Richmond	Emerson Mills 1 (LS)	1.21	61.17	No	Appling fine sandy loam	10.9	0.24	Existing level spreader - measurements taken; in working condition; no erosion observed.
Richmond	Emerson Mills 2 (LS)	-	-	No	Appling fine sandy loam	-	-	Existing level spreader - no erosion observed; measurements taken at other sites with similar slopes; in working condition; discharges to creek approximately 15-20 ft downstream.
Richmond	Magnolia Ridge Road (LS)	-	-	No	Nevarc-Remlik complex	-	-	Existing level spreader - no erosion observed; measurements taken at other sites with similar slopes; discharges to creek within 5-10 ft downstream.
Richmond	River Mill 1 (LS)	-	-	No	Norfolk fine sandy loam	-	-	Existing level spreader - no erosion observed; measurements taken at other sites with similar slopes; in working condition; contains energy dissipation blocks.
Richmond	River Mill 2 (LS)	6.81	52.7	Yes	Norfolk fine sandy loam	10.9	0.20	Existing level spreader - measurements taken; in working condition; early signs of channelization observed at corner of level spreader; looks to be associated with uneven slopes.
Richmond	La Crosse	54.03	50	Yes	Worsham fine sandy loam	10.9	0.3	Slope failure observed, possibly due to poor soils; thick vegetation observed in surrounding areas; erosion resulting from sheet flow not observed; measurements taken as similar slopes may experience erosion.

Table A1 (cont.). Attributes of Sites Visited in Culpeper, Richmond, and Fredericksburg Districts

District	Site Name	Measured % Slope[1]	Slope Length (ft)[1]	Erosion[2]	Soil Name[3]	K_s (mm/hr)[4]	Manning's Roughness n[5]	Site Description
Richmond	Lawrenceville	51.86	28.92	Yes	Rion-Ashlar sandy loam	10.9	0.3	Slope failure observed, possibly due to poor soils; thick vegetation observed in surrounding areas; erosion resulting from sheet flow not observed; measurements taken as similar slopes may experience erosion.
Richmond	Freeway Med 1	15.37	24.77	Yes	Altavista fine sandy loam	10.9	0.1	Erosion observed; sandy soils and lack of vegetation appear to contribute.
Richmond	Freeway Med 2	-	-	Yes	Tomotley loam	-	-	Erosion observed; sandy soils and lack of vegetation appear to contribute; measurements taken at other sites with similar slopes.
Richmond	Freeway Med 3	16.39	24.09	Yes	Kempsville very fine sandy loam	10.9	0.1	Erosion observed; sandy soils and lack of vegetation appear to contribute.
Richmond	Freeway Med 4	6.71	25.11	Yes	Nevarc-Remlik complex	10.9	0.1	Erosion observed; sandy soils and lack of vegetation appear to contribute.
Fredericksburg	Miller's Tavern 5	55.5	37.31	Yes	Suffolk sandy loam	10.9	0.3	Not applicable site. Steep embankment slope, riprap added, but water appears to congregate at edge of pavement. Channelization observed at bottom of slope.

[1] Measured using total station.
[2] Based on judgment of researchers visiting sites.
[3] Soil information from SSURGO data.
[4] Estimated from Table 7.4.1 of Reference 8.
[5] Manning's roughness coefficients from VDOT *Drainage Manual*, Chapter 6, Appendix 6D-2.
[*] Soil attributes estimated using nearest adjacent SSURGO map unit to site location.

Table A2. Sample Calculations Based on Total Station Measurements

Site	X Coordinate	Y Coordinate	Measuring Up/Down to Prism	Slope Distance (ft)	Zenith Angle				Vertical Angle		Second Angle		Third Angle		Vertical Height (ft)	Horizontal Length (ft)	Slope (%)
					Degrees	Minutes	Seconds	Decimal Degree	Degrees	Rad	Degrees	Rad	Degrees	Rad			
Garth	38.102655	-78.590092	Down	65.28	97	59	10	97.99	82.01	1.4314	90	1.5708	7.99	0.13938	9.07	64.64	14.03
Garth (pipe to end of mat)			Down	29.74	98	50	20	98.84	81.16	1.4165	90	1.5708	8.84	0.15427	4.57	29.39	15.55
Rt. 802	38.062383	-78.650551	-														
Cloverleaf	38.046204	-78.524808	Down	19.17	111	55	10	111.92	68.08	1.1882	90	1.5708	21.92	0.38257	7.16	17.78	40.24
Monticello	38.005941	-78.45683	-														
Loop	37.995521	-78.450304	-														
Hildridge	37.947988	-78.370703	Down	101.38	103	14	10	103.24	76.76	1.3398	90	1.5708	13.24	0.23101	23.21	98.68	23.52
Dollar Store	37.806127	-78.499462	-														
Rivanna Bridge (to center of gully)	37.764225	-78.184304	Down	53.94	108	52	20	108.87	71.13	1.2414	90	1.5708	18.87	0.32938	17.45	51.04	34.18
Rivanna Bridge (to edge of gully)			Down	40.50	112	59	15	112.99	67.01	1.1696	90	1.5708	22.99	0.40121	15.82	37.28	42.42