NASHVILLE STORMWATER MANAGEMENT MANUAL

VOLUME 3—THEORY

CHAPTER 9
Erosion and Sediment Control

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Chapter 9
EROSION AND SEDIMENT CONTROL

SYNOPSIS

Soil erosion is caused primarily by the forces of water and wind. Because wind erosion is not a concern for most stormwater management projects, theoretical aspects are not presented. Fundamentals of soil detachment and transport are discussed along with the Universal Soil Loss Equation (USLE) and sediment delivery ratios.

This chapter classifies control practices into sediment control and erosion control measures. Sediment control measures are generally structural in nature and are intended to prevent detached soil particles from leaving a particular project site. Erosion control measures can be either structural or non-structural and are intended to prevent soil particles from becoming detached. Key references include Wischmeier and Smith (1978), Schwab et al. (1981), the Transportation Research Board (1980), Gray and Leiser (1982), Graf (1971), and Goldman et al. (1986).

9.1 FUNDAMENTALS

The soil erosion process can be broken into two parts: (1) detachment and (2) transport. Qualitative descriptions of soil detachment and transport processes are given below.

9.1.1 DETACHMENT

Soil detachment is caused by raindrop impact and by sheet, rill, gully, and stream runoff. Each of these processes also acts to transport soil away from the point of detachment. In general, soil detachability increases as soil particle size increases, and the potential for soil transport increases with a decrease in particle size. For example, clay particles are initially more difficult to detach than sand, but are more easily transported. Cohesive soils are also less erodible than noncohesive soils.

Raindrop erosion is soil detachment resulting from the impact of raindrops on soil particles or shallow water surfaces, such as puddles or sheet flow. From an energy standpoint, raindrop erosion is more important than runoff erosion, because raindrop velocities typically range from 20 to 30 feet per second, while runoff velocities typically range from 1 to 6 feet per second.

Factors affecting the magnitude of soil detachment include slope, wind, soil particle size and aggregation, and soil cover. Mulch or vegetative cover reduces soil detachment from rainfall by absorbing erosive energy. Raindrop impact on bare soil not only causes detachment, but also decreases aggradation and causes deterioration of soil structure. Raindrop erosion becomes more serious as the land slope increases.

Runoff erosion can occur as a result of sheet, rill, gully, or stream flow. The eroding and transporting capability of sheet flow are functions of the depth and velocity of runoff for a given size, shape, and density of soil particle or aggregate. Erosion from sheet flow rapidly converts to rill erosion as small but well-defined channels, or streamlets, are formed. In practice, rills are defined as small channels that can be removed by normal earth-working operations. Rill erosion can become a significant source of soil loss if runoff control measures are not installed.

Gully erosion is an advanced stage of rill erosion, just as rill erosion is an advanced stage of sheet erosion. The rate of gully erosion depends primarily on the runoff-producing characteristics of the watershed; the drainage area; soil characteristics; the alignment, size, and shape of the gully; and the slope of the channel. Evaluation and prediction of gully erosion is difficult, because contributing factors are not well-defined and field records are generally inadequate. As gullies work upstream, the most severe erosion occurs at the upper end or gully head. This is often referred to as head cutting. The most stable section of the gully is generally at the lower end below the area of active head cutting.

The distinction between stream channel and gully erosion is generally based on location within the watershed and duration of flow. Stream channel erosion is generally a result of continuous flow occurring in the relatively flat lower end of a watershed, while gully erosion generally occurs in intermittent channels located in the steeper upstream reaches of a watershed.

Two types of erosion are associated with stream channels. Bank erosion occurs when runoff flows over the side of stream banks and erodes the stream bank itself (also called sloughing). This type of erosion can be increased by the removal of vegetation or by performing earthwork too near the stream banks. Scour erosion, which is generally more significant than bank erosion, occurs below the water surface and is influenced by the velocity and direction of flow, depth and width of the channel, and soil texture. Improper alignment of channel encroachments and the presence of obstructions to flow can increase meandering, which is generally caused by scour erosion. Scour erosion can also be aggravated by the improper placement and protection of pipe outlet facilities.

9.1.2 TRANSPORT

Soil that has been eroded can be transported by suspension, by saltation, and by bed load movement. The dominant action of these processes is observed in stream flows; they can also occur in runoff prior to entering a main stream channel. Important variables that control sediment transport processes include velocity of flow; turbulence; grain size and distribution, cohesiveness, and specific gravity of transported materials; channel roughness; obstructions to flow; and the availability of materials for transport.

Suspended sediment transport occurs when sediment travels without contacting the channel bottom. Most measurements of sediment transport are limited to suspended sediment, because other modes of transport are difficult to measure.

Saltation refers to the process of sediment particles bouncing or skipping along the stream bed. The height of bounce is directly proportional to the ratio of particle density to fluid density. The quantity of sediment transported by saltation is generally small when compared to total sediment transport.

Bed load refers to sediment that is rolled or pushed along the bottom by the force of flowing water. Bed load sediment is in almost continuous contact with the stream bed and, although saltation and bed load are two distinct types of transport, saltation is generally included in bed load.

9.1.3 UNIVERSAL SOIL LOSS EQUATION (USLE)

The USLE is an empirical procedure for estimating soil losses from upland slopes. Although it was developed for agricultural purposes, the USLE has been successfully adapted to construction sites. The equation contains factors that relate to rainfall, soils, runoff, and erosion control practices. The gross erosion produced by rill and inter-rill erosion from a field-sized upland area can be estimated using the USLE expressed as:

$$A = RKLSCP \tag{9-1}$$

where:

A = Soil loss, in tons per acre, for the time period selected for R

R = Rainfall factor

K = Soil erodibility factor, in tons per acre per R unit

LS = Length-slope factor, dimensionless

C = Cropping management factor, dimensionless

P = Erosion control practice factor, dimensionless

To estimate the sediment yield at some point beyond a field-sized upland area, additional erosion from gullies and stream banks must be added and deposition subtracted. The gross erosion from an upland area can be estimated for average annual, average monthly, return period annual, or return period single-storm time scales. Although it is not suitable for predicting the actual soil loss from specific design storms, a realistic estimate of the average soil loss for a number of storms with a specified return frequency can be obtained.

Numerical values for each of the parameters in the USLE must be determined for each problem considered. Guiding principles and data for determining these parameters in Nashville are presented in Volume 2.

Rainfall Factor, R

The numerical value used for the rainfall factor, R, in the USLE must quantify the effect of raindrop impact and provide relative information on the amount and rate of runoff likely to be associated with the rainfall. Higher R values indicate a higher potential for rainfall to cause erosion.

Research has indicated that the value of R can be determined directly as the product of the total storm energy, E, and the maximum 30-minute rainfall intensity, I. The relation of this product parameter, EI, to soil loss has been found to be linear, such that values determined from individual storms are additive. Thus, the quantitative measure of the erosion potential for a given period of rainfall is the sum of the product EI values within that period of rainfall.

Wischmeier and Smith (1978) have analyzed 22 years of rainfall data at various locations across the United States to determine appropriate rainfall factors for various time scales. Storm events of less than 1/2 inch and those separated from other storm events by more than 6 hours were omitted from the rainfall factor calculations unless as much as 0.25 inch fell in 15 minutes. The results of this rainfall analysis are presented for average annual, average monthly, return period annual, and return period single-storm time scales.

Soil Erodibility Factor, K

The soil erodibility factor, K, in the USLE is defined as the rate of soil loss per erosion index unit, measured on a unit plot for a given type of soil. The unit plot, which is used to determine K values experimentally, has been defined arbitrarily to match those field conditions under which erosion measurements have been made. A unit plot is 72.6 feet long, with a uniform lengthwise slope of 9 percent, in continuous fallow tilled up and down the slope. Continuous fallow, for this purpose, is land that has been tilled and kept free of vegetation for more than 2 years.

More than 25 characteristics of a soil affect its response to water erosion. A few of the most important characteristics include the texture and organic matter of the surface layer, size and stability of structural aggregates in the surface layer, permeability of the subsoil, and depth to slowly permeable layers. Several K factors may be determined for a soil series depending on the profile characteristics.

Length-Slope Factor, LS

Theoretically, the effect of slope length and steepness on soil loss are considered separately. However, in practice, these two factors are combined in a single length-slope topographic factor, LS. The LS value is defined as the ratio of soil loss per unit area from a given site to that from a site with a 72.6-foot length and uniform slope of 9 percent under otherwise identical conditions. A site-specific value of LS can be estimated using the following empirical relationship presented by Wischmeier and Smith (1978):

$$LS = \left(\frac{\lambda}{72.6}\right)^{m} (65.41 \sin^2\theta + 4.56 \sin\theta + 0.065) \qquad (9\text{-}2)$$

where:

LS = Length-slope factor, dimensionless

λ = Slope length, in feet

θ = Angle of slope

m = 0.5 if the percent slope is 5 or more; 0.4 on slopes of 3.5 to 4.5 percent; 0.3 on slopes of 1 to 3 percent; and 0.2 on slopes less than 1 percent

Equation 9-2 will underestimate the soil loss to the foot of a convex slope and overestimate the soil loss from a concave slope. Although concave and convex slopes may have the same average slope and length, soil losses will be different. Other factors being equal, the convex slope will have the higher sediment production, because the steepest slope is closer to the receiving water.

Control Practice Factor, CP

Wischmeier and Smith (1978) originally defined two factors for evaluating erosion in agricultural applications. The cover factor, C, was defined as the ratio of soil loss from an area with specified cover and crop management conditions to the soil loss of an identical area in tilled continuous fallow. The support practice factor, P, was defined as the ratio of soil loss from an area with a support practice such as contouring, stripcropping, or terracing, to that of an area with straight-row farming up and down the slope.

Since conditions of a cleared construction site are similar to those of a tilled field with no vegetation, a combination of these two factors, known as the control practice factor, CP, can be used to evaluate construction erosion control practices. Standard control practices include surface stabilization, runoff control, and exposure scheduling. Since sediment trapping devices act to control sediment loss downstream from the point of erosion, sediment retained by these devices is generally accounted for by developing a sediment delivery ratio.

Unprotected soil has a CP value of 1.0. If the conditions being considered vary significantly from unprotected soil conditions, a CP value other than 1.0 must be determined to establish baseline conditions for developing an erosion and sediment control plan. Having established a baseline, the USLE can be used to evaluate various control alternatives.

9.1.4 SEDIMENT DELIVERY RATIOS

The USLE provides a practical method for estimating the gross soil loss from a field-sized upland area. Many natural or manmade opportunities for sediment deposition can exist from the point of origin to the design point in question. It is also possible that additional soil may be eroded from the gullies or stream banks that transport stormwater from the point of origin to the design point in question. Therefore, the sediment yield at a particular point in a stormwater conveyance system can be greater or smaller than the gross soil loss estimated using the USLE. A sediment delivery ratio is usually used to quantify the sediment transported to a particular design point. The sediment delivery ratio is defined as:

$$D = \frac{Y}{A_T} \tag{9-3}$$

where:

D = Sediment delivery ratio without manmade controls

Y = Sediment yield from a watershed without manmade controls, in tons/acre for the specified time period

A_T = Total gross erosion from the watershed, which includes upland sheet and rill erosion, gully erosion, and stream erosion, in tons/acre for the specified time period

The total gross erosion, A_T, includes additional erosion that is not accounted for by the USLE. The sediment yield, Y, is the total gross erosion minus deposition that occurs in the watershed. Very limited information is available to quantify sediment delivery ratios without actual field data.

To evaluate the need for erosion and sediment control practices at a construction site, the sediment delivery ratio with controls can be estimated as:

$$D_C = \frac{A - T}{A_T} \tag{9-4}$$

where:

D_C = Sediment delivery ratio with controls

A = Sediment yield with controls, in tons/acre/year (from USLE, Equation 9-1)

A_T = Target total erosion from a project site, in tons/acre/year

T = Sediment trapped onsite, in tons/acre/year

By selecting a desirable value for A_T, a proposed erosion plan should be designed to keep D_C at or below 1.0.

9.2 EROSION CONTROL

The control practices considered in this chapter are classified as either erosion control or sediment control measures. In general, erosion control practices are designed to prevent soil particles from being detached, whereas sediment control practices prevent the detached particles from leaving the site or from entering a receiving water. Sediment control measures are generally structural in nature, while erosion control measures can be either structural (such as diversions) or non-structural (such as mulches).

Three general classifications of erosion control measures are presented in this section: (1) surface stabilization, (2) exposure scheduling, and (3) runoff control. Appropriate control measures for each classification are defined in sufficient detail to identify applicable conditions for employing each of these measures. Quantitative performance data for use with the USLE are presented in Volume 2, along with general information related to design considerations.

Construction erosion control measures are usually temporary, i.e., intended to function for only the duration of construction. However, the long-term or permanent stabilization of a site should be considered concurrently with the development of a temporary plan to best use the resources available for a project.

9.2.1 SURFACE STABILIZATION

Surface stabilization control measures include mulches, seeding and vegetation, chemical binders or tacks, coats, and other materials.

Mulches (Temporary)

A mulch is a layer of material applied to the soil surface for temporary soil stabilization and to help establish plant cover by holding in moisture and preventing the loss of seed. The major types of mulching material include straw or hay and wood chips. Mulches are practical on graded or cleared areas for 6 months or less where seedings may not have a suitable growing season to produce an erosion-resistant cover. Final grading is not required prior to mulching; however, mulch may be applied after final grade is reached. Whenever structural erosion control features are used, they should be installed prior to mulching.

Seeding and Vegetation (Temporary and Permanent)

Surface stabilization by vegetation includes temporary seeding, permanent seeding, sod, vines, shrubs, and trees. The types of seeding and vegetation, application rates, site preparation, and fertilizer and water requirements are discussed in Volume 2.

Chemical Binders and Tacks (Temporary)

Synthetic binders and tacks are sprayed on bare soils or mulches to bind soil particles or mulch material, reduce moisture loss, and enhance plant growth. A chemical binder or tack is a temporary erosion control measure and may be applied with seed, lime, and fertilizers. Chemical binders and tacks provide a viable alternative to seeding if construction occurs at a time when seeding is not feasible.

Other Materials

Other stabilization materials include nettings and plastic filter sheets for temporary control, and dumped-riprap for permanent control. Nettings of fiberglass, plastic, and paper yarn can be used to anchor straw, hay, wood chips, or grass and sod in drainageways and in other areas subject to concentrated runoff. Plastic filter sheets consist of porous fabric woven from polypropylene monofilament yarns. They are lightweight, porous, strong, abrasion-resistant, and unaffected by saltwater. Dumped-riprap is stone or broken concrete dumped in place on a filter blanket or prepared slope to form a well-graded mass with minimum voids.

9.2.2 EXPOSURE SCHEDULING

The sequence and duration of exposure of cleared land to the erosive forces of rainfall can have a significant effect on the gross soil loss from a site. The impact of exposure scheduling can be evaluated with the USLE by using the monthly distribution of the rainfall factor, R, which can be obtained from data presented in Volume 2.

Exposure scheduling can be evaluated by determining the appropriate surface stabilization factors for the sequence of land covers being considered. For example, a site may begin the year as an undisturbed woodland, followed by clearing for construction, temporary seeding, and then permanent seeding. Using the length of time and season during which each of these land cover types will exist, a weighted surface stabilization factor can be calculated using the monthly distribution of the rainfall factor, R.

9.2.3 RUNOFF CONTROL

Runoff control measures include diversions, down drains, level spreaders, and check dams.

Diversions (Temporary or Permanent)

Any structure that slows runoff or diverts runoff away from downslope areas can reduce erosion. Types of diversion structures include dikes, swales, and channels, which can function as temporary or permanent facilities.

A diversion dike is a ridge of compacted soil placed above, below, or around a disturbed area to intercept runoff and divert it to a stable area. Generally, a diversion dike is the least durable diversion structure and is best used to provide protection for short periods of time and when relatively small amounts of runoff must be handled. It is often used above a newly constructed cut and fill slope to prevent excessive erosion of the slope until more permanent control features are established. Where the ground slope is not steep, it is also used before graded slopes to divert sediment-laden runoff into sediment traps or basins. Once the slope is stabilized, the diversion dike is removed.

A diversion swale is an excavated, temporary drainageway used above and below disturbed areas to intercept runoff and divert it to a safe disposal area. A diversion swale can be constructed at the perimeter of a disturbed area to transport sediment-laden water to a sediment trap or sediment basin. The swale is left in place until the disturbed area is permanently stabilized. A diversion swale can be constructed in conjunction with a dike to prevent stormwater from entering a disturbed area. Although it is generally a temporary feature, with careful planning a swale could also become part of the permanent drainage system.

A diversion channel is a permanent or temporary drainageway constructed by excavating a ditch along a hillside and possibly placing a soil dike along the downhill edge of the ditch with the excavated soil. In other words, it can be a combination of a ditch and a dike. Although diversion channels can be used in place of temporary structures such as diversion dikes and swales, they are mainly used to provide more permanent runoff control on long slopes subject to heavy flow concentrations. Diversion channels can be used to intercept runoff upgradient of a roadway to prevent off-site flow from entering roadway gutter and inlet facilities.

Slope Drains and Down Drains (Temporary or Permanent)

Down drain structures (pipes) and slope drains (paved or sodded channels) can be used as temporary or permanent structures to conduct concentrated runoff safely down a slope. Such structures are often used to help dispose of water collected by diversion structures.

A paved slope drain is a channel lined with bituminous concrete, portland cement concrete, or comparable nonerodible material (such as grouted riprap), placed to extend from the top to the bottom of a slope. A paved slope drain is generally used where a concentrated flow of surface runoff must be conveyed down a slope without causing erosion. When flow is supercritical, pipe down drain should be used to prevent flow from leaving the channel.

A down drain generally consists of either corrugated metal pipe or flexible tubing, together with a prefabricated entrance section, and is temporarily placed to extend from the top to the bottom of a slope.

Level Spreaders (Permanent)

A level spreader is generally a permanent outlet constructed at zero percent grade across the slope to convert a concentrated flow of sediment-free runoff (e.g., from diversion outlets) into sheet flow and to discharge it at nonerosive velocities onto undisturbed areas stabilized by existing vegetation. The level spreader should be used only in those situations where the following conditions apply:

1. The spreader can be constructed on undisturbed soil.

2. The area directly below the level lip is stabilized by existing vegetation.

3. The drainage area above the spreader is stabilized by existing vegetation.

4. The materials used are rigid and nonerodible, such as concrete or asphalt, and a fixed grade can be maintained.

5. The water will not be reconcentrated immediately below the point of discharge.

Check Dams (Permanent)

A check dam is generally a permanent structure used to maintain subcritical flow and thus stabilize the grade or control head cutting in natural or artificial channels. Check dams are used to reduce or prevent excessive erosion by reducing velocities in watercourses or by providing partially lined channel sections or structures that can withstand high flow velocities. Check dams are used where the following conditions apply:

1. The capacity of earth and/or vegetative measures is exceeded in the safe handling of water at permissible velocities.

2. Excessive grade or overall conditions occur.

3. Water must be lowered from one elevation to another.

9.2.4 OUTLET PROTECTION

Outlet protection entails providing de-energizing devices and erosion-resistant channel sections between drainage outlets and stable downstream channels. The channel sections may be rock-lined, vegetated, paved with concrete, or otherwise made erosion-resistant. The purpose of outlet protection is to convert pipe flow to channel flow and reduce the velocity of the water consistent with the channel lining. The flow of water can then be conveyed to a stable existing downstream channel without causing erosion.

This practice is applicable to storm sewer outlets, road culverts, and paved channel outlets discharging into natural or constructed channels, which, in turn, discharge into existing streams or drainage systems. The appropriate treatment should be provided along the entire length of the flow path from the end of the conduit, channel, or structure to the point of entry into an existing stream or publicly maintained drainage system. More detailed information on outlet protection is presented in Chapter 10.

9.3 SEDIMENT CONTROL

Sediment control practices are designed to prevent detached soil particles from leaving a particular site. The three general types of sediment control measures defined and discussed in this section are straw bale dikes, sediment traps, and sediment basins. The stabilization of construction entrances to control sediment is considered as well.

9.3.1 STRAW BALE DIKES (TEMPORARY)

This temporary measure is a dike constructed of straw bales, normally installed across or at the toe of a slope, with a life expectancy of 3 months or less. A straw bale dike is used to intercept and detain small amounts of sediment from unprotected areas of limited extent; it is a stop-gap measure applicable only under the following conditions:

1. No other practice is feasible.
2. There is no concentration of water in a channel or other drainageway above the barrier.
3. Sheet and rill erosion would occur.
4. Contributing drainage area is less than 1/2 acre and the length of slope above the dike is less than 100 feet.

Straw bales should be placed in a row with ends tightly abutting adjacent bales. Each bale should be embedded a minimum of 4 inches into the soil. In addition, bales should be securely anchored in place by stakes or rebars driven through the bales.

9.3.2 TRAPS (TEMPORARY OR PERMANENT)

A sediment trap is generally a temporary basin formed by an excavation and/or an embankment to intercept sediment-laden runoff and to trap and retain the sediment. In so doing, drainageways, properties, and rights-of-way below the trap are protected from sedimentation. If maintained by periodic cleaning, traps can sometimes be used as permanent facilities.

An earth outlet sediment trap consists of a basin formed by excavation and/or an embankment. The trap has a discharge point over or cut into natural ground. A pipe outlet sediment trap consists of a basin formed by an embankment or a combination of an embankment and excavation. The outlet for the trap is through a perforated riser and a pipe through the embankment.

9.3.3 BASINS (TEMPORARY OR PERMANENT)

A sediment basin is usually a temporary facility constructed along a flow path to capture sediment carried by runoff from a cleared construction site. The basin is formed by placing an earthen dam across the watercourse, by excavating a depression, or by a combination of the two. The purpose of a sediment basin is to protect drainageways, properties, and rights-of-way below the sediment basin from sedimentation.

Sediment basins are installed below construction sites, on or adjacent to the major watercourses. They act as a last line of defense against offsite sediment damage. If maintained by periodic cleaning, they can sometimes be used as permanent facilities.

A sediment basin should be constructed only under the following conditions:

1. When failure would not result in loss of life, damage to buildings, or interruption of service from public roads or utilities

2. When it will be removed within a specified period of time or maintained at regular intervals to restore its sediment storage capabilities

9.3.4 CONSTRUCTION ENTRANCES (TEMPORARY)

All points of access to a construction site should be stabilized to reduce or eliminate the tracking or flowing of sediment onto public rights-of-way. A stabilized pad of crushed stones is to be placed at entrances of construction sites for this purpose. Maintenance of such entrances may require periodic top dressing with additional stone as conditions demand or cleanout of any facilities used to trap sediment.

In some cases, wheels of construction vehicles should be cleaned prior to leaving the construction site. When appropriate, a stabilized area (one with crushed stone) that drains into a sediment trap or basin should be washed.