Sediment Sources

Course No: G06-006
Credit: 6 PDH

Jeelan Moghraby, Ph.D., MBA

CED engineering.com
PDH FOR THE PROFESSIONAL

Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.com

This course was adapted from the US Department of Agriculture. National Resources Conservation Service. Part 631 Geology National Engineering Handbook, Chapter 22 "Sediment Sources", which is in the public domain.

Table of Contents

List of Figures

List of Tables

Introduction

Sediments are the products of erosion caused by a series of complex and interrelated natural processes that detach, loosen, dissolve, and move earth or rock material. Erosion rates are highly variable from place to place and year to year.

The principles of geology and hydraulic engineering are used to the solution of sedimentation problems encountered in programs to reduce erosion damages and implementing sediment storage design criteria for conservation practices. This course looks at the problems affecting the evaluation of erosion and sediment storage damages, formulation of programs for reducing these damages, and sediment storage design criteria for conservation practices and systems.

The Natural Resources Conservation Service (NRCS) geologists are responsible for making field investigations and surveys concerning sediment accumulation on NRCS projects and the effect NRCS projects can be expected to have in reducing sediment yields. NRCS personnel are involved in the evaluation and documentation of sediment damages or watershed impairments.

Erosion

Introduction

Erosion produces sediment and consists of a series of complex and interrelated natural processes that detach, loosen, dissolve, and move earth or rock material. The land surface is worn away through the detachment and transport of soil and rock materials by moving water, wind, or other geologic agents. Gross erosion is the sum of all erosion occurring in a drainage area. Sediment yielded to the mouth of a watershed is a function of drainage area size, types of erosion occurring, and watershed topographic characteristics. Normally, sediment yield is only a portion of the total or gross erosion occurring in a watershed.

This course considers the different types of water erosion, mass movement, and wind erosion. It also describes various types of sediment deposits and the physical damage they cause. NRCS geologists identify recent deposits in reservoirs, channels, and flood plains. Kinds of physical damage include:

i. Burial of fertile soils by sandy or less fertile sediment.
ii. Damage to growing crops and burial of crops and pastures.
iii. Impairment of drainage and accompanying rise of the water table.
iv. Filling of channels which can increase frequency of flooding and flood heights.
v. Reducing capacity at bridges causing damage to roads, railroads, and other facilities.
vi. Damage to urban areas from sedimentation, increasing flood height.
vii. Damage to recreational facilities.
viii. Water quality degradation.
ix. Impacts on plants and animals.

Erosion can be divided into geologic and accelerated erosion categories, according to the conditions under which it occurs.

Geologic Erosion

The first category is normal (geologic) erosion, which has been occurring at variable rates, depending on climatic and terrestrial conditions.

Geologic erosion is extremely slow in most places. It is, in fact, an important process in soil formation. The underlying rock is attacked by air and water, and fragments are detached, decomposed, or dissolved. This process is termed weathering. Generally, a rough equilibrium is reached in natural environments between geologic erosion and soil formation. The rates of normal upland erosion and soil formation are determined mainly by climate, parent rocks, soil, precipitation, topography, and plant cover.

Accelerated Erosion

The second category is accelerated erosion caused by land use activities. Accelerated erosion has been defined as "erosion occurring at a rate greater than normal for the site, usually through reduction of a vegetal cover" (Roehl 1965). Deforestation, cultivation, surface mining activities, and destruction of vegetation accelerate erosion. Soil that normally would take 100 years to be eroded may vanish in one year or even in a single day. Local effects of climate change may also accelerate erosion, depending on impacts to rainfall intensity and distribution.

Upland Water Erosion

Upland erosion is accelerated erosion and is considered here separately because of the types of erosion processes and their impacts on conservation practices to control them. The types of upland water erosion are:

i. Interrill or sheet erosion
ii. Rill erosion
iii. Ephemeral gully erosion
iv. Classic gully erosion
v. Other types of erosion may occur in a watershed, including wind, floodplain scour, valley trench, streambed, streambank, landslide, roadside, wave/shoreline, urban/construction, surface mine, and ice gouging (see table 1, which also lists the erosion processes).

Sheet erosion, rill erosion, and gully erosion are caused by raindrop impact, sheet flow, and concentrated water flow. This classification is helpful in:

i. Estimating the amount of erosion and sediment yield
ii. Determining the relative importance of sediment sources
iii. Formulating treatment measures to reduce the erosion processes and to reduce sediment yield

iv. Evaluating the effectiveness of treatment measures
v. The Conservation Effects Assessment Project (CEAP) is carried out by an interagency interdisciplinary team to provide guidance on the effectiveness of watershed treatment measures, https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap/.
vi. Tools for estimating or predicting erosion and sediment yield are discussed in section "Predictive Models and Tools" at the end of the course.

In planning programs to reduce erosion and sediment yield, it is most important that the various types of erosion be thoroughly investigated as sources of sediment. Proper conservation practices and land stabilization measures can then be planned and applied. Some types of erosion that are observed on the landscape are actually combinations of sheet erosion processes, concentrated flow erosion processes, and gravitational collapse. Table 1 shows some of the more common types of erosion.

Table 1. Types of erosion by physical processes.

Erosion / Physical Process				
Erosion Type	**Sheet**	**Concentrated Flow**	**Mass Wasting (gravity)**	**Combination**
Rill and Interrill (Sheet)	✓	✓		
Rill	✓	✓		
Ephemeral Gully		✓		
Classic Gully		✓	✓	
Wind	✓	✓		
Floodplain Scour		✓		
Valley Trench		✓	✓	
Streambed		✓		
Streambank		✓	✓	✓
Landslide			✓	
Roadside				✓
Wave / Shoreline				✓
Urban / Construction				✓
Surface Mine				✓
Ice Gouging				✓

Streambank and streambed erosion may be significant sources of sediment in some watersheds. Detailed watershed analysis may be needed to identify these sources of sediment to guide watershed protection efforts to achieve the desired impacts in reducing the overall impacts of sedimentation. Guidance for identifying, quantifying, and planning for streambank erosion control and stream restoration in general can be found in the following references:

i. USDA-NRCS National Conservation Practice Standard: Streambank and Shoreline Protection, Code 580 (USDA-NRCS 2020) https://www.nrcs.usda.gov/sites/default/files/2022-10/Streambank_Shoreline_Protection_580_CPS_10_2020.pdf.
ii. USDA-NRCS National Engineering Handbook (Title 210), Part 650 – Engineering Field Handbook, Chapter 16, "Soil Bioengineering for Streambank and Shoreline Protection." Washington, D.C. https://directives.sc.egov.usda.gov.
iii. 210-NEH 653 – "Federal Stream Corridor Restoration Handbook: Principles, Processes, and Practices" (FISRWG 1988, Revised 2001). https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=34804.w ba
iv. 210-NEH 654 – Stream Restoration Design (USDA-NRCS 2007) https://directives.sc.egov.usda.gov/viewerFS.aspx?hid=21433.

Raindrop Impact

The term interrill erosion is now preferred over the term sheet erosion because erosion rarely takes place in sheets. Interrill erosion is the beginning of the erosion process, and it is caused by raindrops striking the soil surface, splashing soil particles into the air, and causing shallow overland flow that begins the sediment transport process. The raindrops that strike shallow overland flow enhance the flow's turbulence, increasing its ability to transport detached sediment.

The force of falling raindrops may initiate erosion due to the energy expended on the land's surface by the direct force of each raindrop (Figure 1). With impacts of over 20 mph, raindrops can splash unprotected grains of soil into the air and may wash out seeds.

Preventing erosion from this source is a function of providing enough shear resistance to the soil to withstand the total impact energy. Simply put, appropriate cover or soil amendments will minimize erosion from direct raindrop impact.

Figure 1. The energy of rain falling on unprotected soil begins the water erosion process.

Rill and Interrill Erosion (Sheet Erosion)

Rill and interrill erosion are the removal of soil or earth material from the land surface by the forces of rainfall and runoff. Rill erosion is the detachment of soil particles in small, concentrated flow channels that are no more than four inches deep.

Erosion begins with the impact of raindrops, detaching soil particles, and runoff moving them across the surface. This process causes interrill erosion (sometimes called sheet erosion). Runoff from interrill erosion collects and forms rills across the slope. Sediment from rill and interrill erosion is transported down slope where it slows enough to be deposited on the land surface or to be deposited directly into concentrated flow channels.

Although erosion occurs on all land surfaces, rill and interrill erosion are particularly active on cultivated areas of mild slopes where the runoff is not concentrated in well-defined channels but consists largely of overland flow. The numerous small rills caused by minor concentration of runoff are obliterated by normal field cultivation. This type of erosion occurs gradually over large areas as though the soil were removed in sheets.

Materials derived from sheet erosion are fine grained because overland flow, which is usually laminar, seldom exceeds a velocity of two or three feet per second (ft/s). Flow of this low velocity can transport only the fine particles detached by raindrop impact.

Rill and interrill erosion are a function of rainfall, soil properties, slope length, slope gradient, and kind and condition of land use and cover. The amount, duration, and intensity of precipitation events provide much of the energy that can cause sheet erosion. Additionally, snowmelt runoff either alone or in conjunction with rainfall events has a significant effect on sheet erosion in many areas of the country. Several tools incorporate these factors and can be used to estimate the amount of soil material moved by sheet erosion. These equations, originally developed for the humid areas east of the Rocky Mountains, are particularly well suited for determining the effects of land treatment measures on erosion. Natural and installed drainage practices also affect sheet erosion. Improved subsurface drainage, for example, reduces the amount and duration of runoff, which in turn affects the processes of sheet erosion.

Estimating Erosion: Tools for Conservation Planning

Introduction

Early in the history of soil erosion control programs during the 1930s, simplified tools were needed to estimate erosion rates and to predict their changes with applied conservation cover and treatments. Because continuous simulation models were not available then, practical research was conducted on small plots by research scientists to develop simplified equations that were consistent with the research plot results.

Development of Soil Loss Equations

One of the first soil loss equations was the Musgrave Equation (Musgrave 1947), which was used from the late 1940s through 1960s. As research continued, with more results in more areas of the country, and as measurement techniques and analytical capabilities advanced, the Universal Soil Loss Equation (USLE) was developed and replaced the Musgrave Equation in 1972.

The need to accurately assess existing erosion rates in a watershed was largely driven by the programs of the Soil Conservation Service (USDA-SCS) now Natural Resources Conservation Service (USDA-NRCS). One comprehensive Congressionally funded and mandated program was the Small Watershed Protection Program (PL-566). Suddenly, the need was to not only reduce soil erosion on agricultural lands, but to reduce sediment yield from watershed drainage areas to support the design of floodwater retarding structures and floodwater conveyance channels. The impetus was to design these structures economically to reduce soil erosion and reduce rates of runoff and sediment yield, allowing structures to be built smaller, to operate efficiently in series, and to last longer.

Both the Musgrave Equation and the USLE are empirical formulas in which sediment yield from sub-acre test plots is defined as “erosion” or “soil loss.” The computed soil loss from large areas is usually greater than the sediment yield from the same area: the larger the drainage area, the greater the difference between computed soil loss and sediment yield. Neither equation accounts for deposition on upland areas. Computed soil loss, however, is a valuable tool for comparing the soil loss from different areas or the effects of different land treatments on a given area. Please refer to section ‘Sediment Yield’ later in this course for further information on sediment delivery.

Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation is a simple lumped parameter empirical equation as shown below, but each variable has had much research and development. The equation was simplified in order for field conservationists to be able to make rapid estimates for planning purposes, using only simplified charts and lookup tables.

The Universal Soil Loss Equation is:

$$A = RKLSCP$$

where:

A = Computed average annual soil loss (rill and interrill erosion) in tons per acre. "A" is not the sediment yield.
R = Rainfall factor: the number of erosion index units in a normal year's rain.
K = Relative soil erodibility factor, based on soil texture, organic-matter content, permeability, and other factors inherent to soil type.
L = Slope length factor: the ratio of the soil loss from the field slope length to that from a 72.6 foot length on the same soil type and gradient.
S = Slope gradient factor: the ratio of the soil loss from the field gradient to that from a 9 percent slope on the same soil type and slope length.
C = Cropping management factor: the ratio of the soil loss from a field with specified cropping and management to that from the fallow condition from which the K factor is evaluated.
P = Erosion control practice factor: the ratio of the soil loss with contouring, contour strip cropping, or contour-irrigated furrows to that with straight-row farming, upslope and downslope.

Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) was developed to significantly update the USLE, with development work beginning in the late 1980s. RUSLE was designed to operate in the DOS operating system as both researchers and conservationists began to have access to computers.

The need for a USLE update became apparent as users demanded more flexibility in modeling erosion for new conditions, which clearly did not work well within the standard USLE (Wischmeier 1976). In addition, new research and analyses provided scientists with the power to improve the USLE's performance for both new and old land management schemes (Renard et al. 1991, Renard et al. 1994, Renard et al. 1997). The development of improved factors and the conservationists' application of the technology advanced, and RUSLE blossomed into a soil erosion prediction *model*, rather than just a simplified equation.

RUSLE was expanded to include estimates of the impact of slope shape and land use changes along the slope on sediment deposition. The model now provides estimates of deposition on the toe-slope areas of concave slopes or complex slopes and of the decreased sediment transport in other depositional areas, such as in buffer strips, filter strips, silt fences, etc. In addition, the model includes routines to estimate the sediment-catching capabilities of terraces and sedimentation basins. This means that in addition to the estimates of long-term average annual soil loss on the slope, RUSLE also provided estimates of long-term average annual sediment yield from complex slope shapes and land uses. The deposition information, however, provided no particle-size breakdown of the delivered sediment. Table 2 shows some of the significant improvements of RUSLE compared to USLE.

Table 2. Summary of the differences between the USLE and RUSLE.

Factor	Universal Soil Loss Equation (USLE)	Revised Universal Soil Loss Equation (RUSLE)
R	Based on long-term average rainfall conditions for specific geographic areas in the U.S.	Generally, the same as USLE in the Eastern US. Values for Western States (Montana to New Mexico and west) are based on data from more weather stations and thus are more precise for any given location. RUSLE computes a correction to R to reflect the effect of raindrop impact for flat slopes striking water ponded on the surface.
K	Based on soil texture, organic matter content, permeability, and other factors inherent to soil type.	Same as USLE but adjusted to account for seasonal changes such as freezing and thawing, soil moisture, and soil consolidation.
LS	Based on length and steepness of slope, regardless of land use.	Refines USLE by assigning new equations based on the ratio of rill to interrill erosion and accommodates complex slopes.
C	Based on cropping sequence, surface residue, surface roughness, and canopy cover, which are weighted by the percentage of erosive rainfall during the six crop stages and lumps these factors into a table of soil loss ratios, by crop and tillage scheme.	Uses the subfactors of prior land use, canopy cover, surface cover, surface roughness, and soil moisture. Refines USLE by dividing each year in the rotation into 15-day intervals, calculating the soil loss ratio for each period. Recalculates a new soil loss ratio each time a tillage operation changes one of the subfactors. RUSLE provides improved estimates of soil loss changes as they occur throughout the year, especially relating to surface and near-surface residue and the effects of climate on residue decomposition.
P	Based on installation of practices that slow runoff and thus reduce soil movement. P factor values change according to slope ranges with some distinction for various ridge heights.	P factor values are based on hydrologic soil groups, slope, row grade, ridge height, and the 10-year single storm erosion index value. RUSLE computes the effect of strip cropping based on the transport capacity of flow in dense strips, relative to the amount of sediment reaching the strip. The P factor for conservation planning considers the amount and location of deposition.

RUSLE2

The original RUSLE model is sometimes referred to as RUSLE1. The major change in RUSLE2 is its new, modern graphical user interface that operates in the Windows operating system (USDA-NRCS 2016).

RUSLE2 was developed primarily to guide conservation planning, inventory erosion rates, and estimate sediment delivery. Values computed by RUSLE2 are supported by accepted scientific knowledge and technical judgment, are consistent with sound principles of conservation planning, and result in effective conservation plans. RUSLE2 is also based on additional analyses and knowledge that were not available when RUSLE1 was developed. RUSLE2 is based on science and judgment that is superior to that of RUSLE1.

RUSLE2 computes erosion on a daily basis, rather than average annual. Other improvements include improved cover-management subfactor relationships, new relationships for handling crop residue, and a new ridge subfactor. The deposition equations now include sediment deposition characteristics.

RUSLE1 and RUSLE2 are used by government agencies around the world to assess and inventory erosion to assist public policy development. Government agencies use RUSLE1 and RUSLE2 as regulatory and conservation planning tools. Private consultants use RUSLE1 and RUSLE2 to select erosion control plans to ensure cost effective, environmental protection. Both RUSLE1 and RUSLE2 are land use independent and can be used on cropland, disturbed forestland, rangeland, construction sites, mined land, reclaimed land, military training grounds, landfills, waste disposal sites, and other lands where rainfall and its associated overland flow cause soil erosion. Table 3 is a comparison and illustrates some of the major improvements of RUSLE2 over the USLE.

Table 3. Summary of the differences between the USLE and RUSLE2.

Feature	Description
Climate	The most important climatic variable used by RUSLE2 is rainfall erosivity, which is related to rainfall amount (how much it rains) and intensity (how hard it rains). Another important climatic variable is temperature because temperature and precipitation together determine the longevity of biological materials like crop residue and applied mulch used to control erosion. Climate varies by location, and choosing a location in RUSLE2 chooses the erosivity, precipitation, and temperature values needed to apply RUSLE2 at a particular site.
Soils	Soils vary in their inherent erodibility as measured in a standard test involving a "unit plot." A unit plot is 72.6 ft (22.1 m) long on a 9% slope and is maintained in continuous tilled fallow (no vegetation) using periodic tillage up and down slope to leave a "seedbed-like" soil condition. The USDA-NRCS has assigned soil erodibility values for most cropland and similar soils across the U.S. RUSLE2 includes a procedure for estimating soil erodibility for highly disturbed soils at construction sites and reclaimed mined land. The RUSLE2 user typically selects a soil by soil-map unit name from a list of soils in the RUSLE2 database.
Topography	Slope length, steepness, and shape are the topographic characteristics that most affect rill and interrill erosion. Site-specific values are entered for these variables.
Land Use	Land use is the single most important factor affecting rill and interrill erosion because type of land use and land use condition are features that can be most easily changed to reduce excessive erosion. RUSLE2 uses the combination of cover-management (cultural) practices and support practices to describe land use.
Cover management	Practices affect both the forces applied to the soil by erosive agents and the susceptibility of the soil to detachment. For a given land use like cropland, important features include the crops that are grown, yield level, and the type of tillage system, such as clean, reduced, or no till. Important features on a construction site include whether or not the land is bare, the soil material is a cut or fill, mulch has been applied, or the slope has been recently reseeded. Important features on range and reclaimed land include the native or seeded vegetation, production level, and degree of ecological maturity. The description of any cover-management practice is created, named, and stored in the RUSLE2 database. When RUSLE2 is run, the cover management practice that fits the site-specific field condition is selected from the menu of choices. Changes can be made in key variables such as production (yield) level or mulch application rate, so that the practice fits the local climate, soil, and other conditions.
Support practices	Practices include ridging (e.g., contouring), vegetative strips and barriers (e.g., buffer strips, strip cropping, fabric fence, gravel bags), runoff interceptors (e.g., terraces, diversions), and small impoundments (e.g., sediment basins, impoundment terraces). These practices reduce erosion primarily by reducing the erosivity of surface runoff and by causing deposition. Support practices are selected from a list of practices in the

	RUSLE2 database. Site-specific information, such as the location of a diversion on the hillslope, is entered as required for each practice.

Water Erosion Prediction Project (WEPP)

WEPP is a new erosion prediction technology that predicts soil loss and sediment deposition from overland flow on hillslopes, soil loss and sediment deposition from concentrated flow, and sediment deposition in impoundments (USDA-ARS 2014). The WEPP erosion model is developed for application on small watersheds and hillslope profiles.

The WEPP model is a physically based soil erosion model that can provide estimates of soil erosion and sediment yield, considering the specific soil, climate, ground cover, and topographic conditions. It was developed by an interagency group of scientists including the USDA's Agricultural Research Service (ARS), Forest Service (FS), and NRCS, and the U.S. Department of Interior's Bureau of Land Management and U.S. Geological Survey.

WEPP simulates the conditions that impact erosion, such as the amount of vegetation canopy, surface residue, and soil-water content for every day in a multiple-year run. For each day that has a precipitation event, WEPP determines whether the event is rain or snow and calculates the infiltration and runoff. If runoff occurs, WEPP routes the runoff over the surface, calculating erosion or deposition rates for at least 100 points on the hillslope. It then calculates the average sediment yield from the hillslope. Table 4 is a comparison of the improvements of WEPP over RUSLE2.

In 2013, NRCS made the decision to replace RUSLE2 with the Water Erosion Prediction Project (WEPP) for predicting sheet and rill erosion. NRCS and ARS are continuing model evaluation, development, testing, and updating. A current version of WEPP can be downloaded at: https://www.ars.usda.gov/midwest-area/westlafayette-in/national-soil-erosion-research/docs/wepp/wepp-downloads/.

Table 4. Overview of the differences between WEPP and RUSLE2.

Features	WEPP	RUSLE2
Model Structure	Web-based model using a common browser (i.e., Microsoft Edge, Google Chrome, etc.) that accesses a national cloud-based database. Model or database updates or downloads are not necessary by users (automated).	Software is maintained and updated nationally and downloaded on NRCS computers. Databases need to be imported, managed locally, and require downloading/importing by users based on desired location(s).
	Incorporates GIS layers, browser functionality, and Windows graphical tie-in. Can use PRISM data (USDANRCS 2022c) to adjust input weather based on location.	Version 2.6.11.1 with GIS layers is in development stage.
	Process-based, continuous simulation, deterministic model that has seven process-based sub models including: Climate, Management, Hydrology, Plant Growth, Residue Decomposition, Soil conditions, and Erosion rates. These vary throughout the simulation period.	Lumped process, deterministic empirical model

Table 4. Overview of the differences between WEPP and RUSLE2 (continued).

Features	WEPP	RUSLE2
Climate - average weather data over many years	CLIGEN (stochastic weather generator)(USDA-ARS 2007) creates 100 years of daily weather input to WEPP, based on statistics from a 40-yr observed data from 3,000+ weather stations (1974–2013), which includes: Min/Max Temperatures Precipitation (rainfall and snow) Dew point temperature Wind speed and direction Solar radiation No validated weather data are excluded Unlike other climate generators, CLIGEN produces individual storm parameter estimates, including time to peak, peak intensity, and storm duration, which are required to run the WEPP and the WEPS soil erosion models (USDA-NRCS 2022g). Additionally, PRISM cell adjustments to precipitation and temperatures can also be utilized. Climate data are automatically adjusted to the actual latitude and longitude of the site. Climate Updates: CLIGEN weather data can be updated to the current year through an automatic process.	Uses County Wide or Sub-County Rainfall (R) Factors that are manually updated nationally. R factors have not been updated to current climate data. Equivalent R values (REQ maps) are used to account for increased erosion on thawing soils in the Pacific Northwest and precipitation maps to identify large spatial differences in R factors within counties. These maps can be manually interpreted by the user to determine the appropriate R factor to use for a site within a given county. Storm erosivity values are computed from rainfall data collected at more than 3,700 U.S. weather stations over a 30-yr period (1961 – 1990). The storm erosivity data are used to compute monthly erosivity density values (erosivity/precipitation). Storms having a return period greater than 50 years are discarded. Erosivity density values are mapped across the U.S. then spatially and temporally smoothed across the country. Erosivity table values based on weather station data that include actual storm events, including multiple events and rainfall intensities. Climate Updates Updates for R factors and erosivity intensity values are not automated.

Table 4. Overview of the differences between WEPP and RUSLE2 (continued).

Features	WEPP	RUSLE2
Plant (Crop) Growth	Plant (crop) growth is based on the Environmental Policy Integrated Climate (EPIC) cropping systems model (Texas A&M University 2022). Crop growth incorporates response to changing environmental conditions such as soil moisture, rainfall, temperature, irrigation, and solar radiation.	NRCS uses predetermined crop tables (data files) for each crop. Multiple tables are necessary for each crop to replicate growth in different climate areas.
	When crop parameters such as canopy do not match the desired temporal variation, NRCS users can request changes or new crop files in both models.	
Land Management Database	Uses Conservation Resources Land Management (Texas A&M U. 2021) Database for managements, operations, crops, residues that is consistent with WEPP (USDA-NRCS 2022h), WEPS (USDA-NRCS 2022h), IET2 (USDA-NRCS 2022a), Field to Market Platform, and utilized by several other models and tools. NRCS has developed a Stewardship Management Application that will publish the updated database on the web, making it available for modelers and others.	Uses its own unique land management database for managements, residues, crops, and operations. A conversion routine is necessary to match WEPS operations, residues, and crops.
Crop Yield	Crop yields are calibrated based on the EPIC growth model (EPIC 2022) which accounts for local climate and site conditions that adjust target yield that is input by user.	Crop target yield is manually input by the user.
Plant (Crop) Residue and Manure	Decomposition is modeled daily using 100 years of generated climate based on: Precipitation and temperature variations at the location. Rate validated from field data Rate is determined by process-based decomposition sub model.	Decomposition table values for each residue and manure type are based on: Precipitation and temperature variations at the location. Rate validated from field data

Table 4. Overview of the differences between WEPP and RUSLE2 (continued).

Features	WEPP	RUSLE2
Irrigation	Can be used for estimating erosion from surface irrigation systems. However, the main function of the irrigation monitoring feature is to provide sufficient water for crop growth. Irrigation water use is estimated based on crop water use, available water capacity of soil, and soil water deficit.	Does not directly estimate erosion from surface irrigation systems but can estimate rainfall erosion due to changes in soil moisture, which affects erodibility.
Soil Data	Soil properties are based on fixed data and extracted from soil survey data (SSURGO) (USDA-NRCS 2022f). User does not need to update soils data since it is automatically completed on the cloud-based database.	Soil properties are fixed data and are extracted from soil survey data (SSURGO) (USDA-NRCS 2022f). User must import updated soils data from desired locations.
	Soil properties such as bulk density, soil moisture and erodibility are adjusted daily during a simulation, and reflect tillage disturbance, rainfall, irrigation, and soil consolidation, using process-based soil sub-model.	Year-to-year variation in soil moisture is not reflected, although erodibility adjusts with precipitation variation throughout the year.
Winter Hydrology	Runoff from snowmelt and frozen soil conditions is modeled using the soil and hydrology sub models.	Does not have this feature.
Additional Features	Strips and Barriers	Contouring
Water Balance	Water Balance includes rainfall, infiltration, soil evaporation, plant transpiration, runoff, water drainage, irrigation, and soil water balance/hydrologic status.	Does not have this feature.
Erosion Estimates	Provides erosion estimates for specific hillslope profiles.	
Results - Sedimentation (accumulation of soil particles)	Sediment transport (detachment and soil particles suspended in water runoff). Sediment deposition (accumulation) within, and at the end of, the hillslope profile.	Estimates sediment enrichment in fine particles.
Additional Results	Irrigation Water Use	Does not have irrigation water use feature
	Fuel Consumption Soil Tillage Index Rating (STIR) (USDANRCS 2022e)	Soil Conditioning Index (SCI), (USDANRCS 2022d)

Table 4. Overview of the differences between WEPP and RUSLE2 (continued).

Features	WEPP	RUSLE2
Statistical reports	Provides a 100-year statistical analysis of Rainfall, Erosion, Irrigation, Runoff, Crop Transpiration, Evaporation, and Sediment Delivery to use for risk based conservation planning.	Does not have this feature.
Validation	WEPP has been tested and validated in numerous studies, and results published in peer-reviewed journal articles. These include validation with USLE plot data, and the model has overall shown acceptable runoff and soil loss predictions.	Product of the evolution of erosion prediction technology that began in the 1940s. This erosion prediction technology has proven itself over a half century as a conservation planning tool across the US for a wide variety of land uses.
P -Indexes and State Water Quality tools	P-indexes will need to be updated to use output from WEPP or incorporate it into them. Provides additional utility to use runoff and risk assessment statistics and more options on assessing Phosphorus and water quality risk assessments during high rainfall years. Several states have already begun the process of converting tools to use WEPP because of these benefits.	RUSLE2 output, or RUSLE2 templates built directly into existing P-Indexes are used. Erosion outputs used in current P-Indexes are typically placed in erosion rate categories (high, medium, low, etc.). Manure management planner no longer embeds RUSLE2 in its software and is being edited to allow for manual entry of erosion rates.
Sediment Delivery and Ephemeral Gully Erosion	Sediment transport and deposition within the hillslope can be estimated. Vegetative buffer strips can be placed in different locations to estimate sediment deposition. Current work on small watershed enhancement will allow for estimating sediment delivery within small field sized sub-watersheds including channel erosion. This enhancement will also provide gridded soil loss and ephemeral erosion estimates within the current interface (USDA 2009).	Sediment transport and deposition within the hillslope can be estimated. Vegetative buffer strips can be placed in different locations to estimate sediment deposition.

Table 4. Overview of the differences between WEPP and RUSLE2 (continued).

Features	WEPP	RUSLE2
Other	Allows conservation planners to quickly assess questionable CART sheet and rill resource inventory estimations, as well as create producer's conservation practice implementation requirements, within the same browser environment (USDA-NRCS 2022b). Overwhelmingly positive feedback from new conservation planners, especially surrounding the intuitive interface and ease of use. Possibility of issues in low bandwidth rural areas of US.	Technology is familiar to more experienced conservation planners. Offers users, with appropriate access, extensive control over all parameters within the model. Although grazing system development options are more extensive in RUSLE2, most grazing evaluations are conducted using other tools described in NRCS Planning Criteria.

Concentrated Flow Erosion

Channel Erosion

Concentrated flow erosion, also called channel erosion, consists of the removal of soil and rock by a concentrated flow of water. Concentrated flow exerts a more concerted local attack on the soil and associated materials. Channel erosion includes ephemeral gully erosion, classic gully erosion, streambank erosion, streambed degradation, floodplain scour, valley trenching, and road bank erosion.

Figure 2 illustrates a severely eroded farm in Iowa, with well-developed concentrated flow channels (ephemeral gullies). These erosion scars may reappear each year without application of needed conservation cropping systems and support practices. Ephemeral gullies also reappear in the same locations from year to year.

Gullies usually follow sheet erosion. They begin in a slight surface depression into which, in time, the concentrated flow cuts a channel a foot or more deep. The shape of the channel is usually determined by the relative resistance of the soil, the depth of tillage, and the shape of the topography.

Streambank erosion and bed degradation are affected primarily by the bank materials and the resistance of the channel bottom to the character and direction of flow. Removal of the natural vegetation from streambanks increases bank erosion.

Bank erosion is a natural process and occurs on streams that tend to maintain a long-term constant width. On these streams, bank erosion is offset by less obvious deposition and accretion. Therefore, streams of this type are not primary sources of sediment.

Streambed erosion is not a significant long-term sediment source because the material subject to this type of erosion is limited in both extent and volume. Compared with other potential sources of sediment, streambed erosion usually is minor.

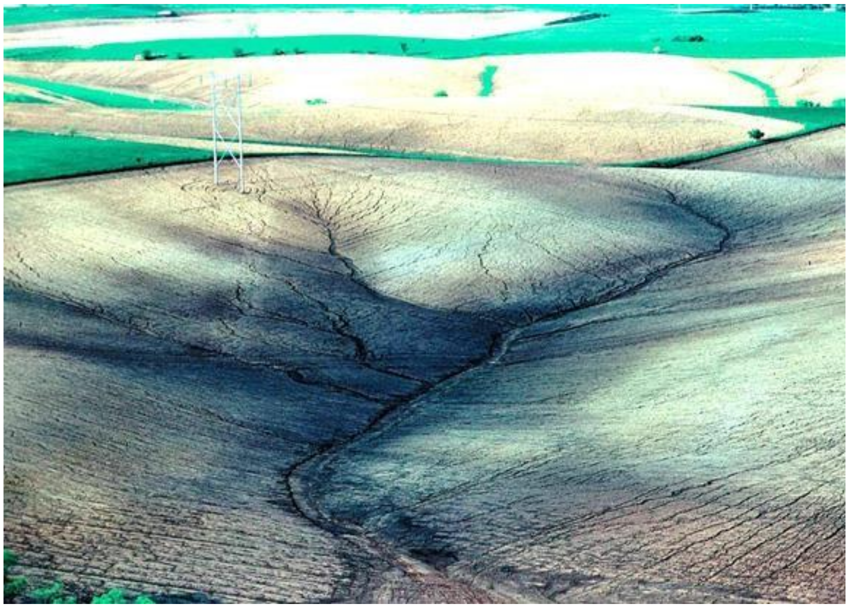


Figure 2. Crop field in Iowa showing severe sheet and rill erosion, along with concentrated flow erosion (ephemeral gullies).

Flood-plain Scour

Flood-plain scour is the removal of flood-plain soil by flows sweeping across the flood plain. It may occur in the form of channelization or sheet removal of the surface soil. This form of sheet erosion cannot be computed by the USLE, RUSLE or similar equations.

Erosion from scour channels can be computed in a somewhat similar manner to that used for other channels. The length, width, and depth of the scour channel is measured. An estimate of the average annual rate of erosion is then made in feet or tenths of a foot, either by lateral erosion or incision, in terms of volume per unit length of channel, and then converted to tons. Sheet scour should also be estimated in feet or tenths of feet per year for the area affected. Aerial photographs taken years apart may reveal occurrence of flood plain scour.

Estimating Concentrated Flow Erosion

Concentrated flow erosion includes gully, streambank, streambed degradation, floodplain scour, valley trenching, and road bank erosion. Methods of determining soil loss by the various types of channel erosion are:

i. Comparing aerial photographs of different dates to determine the annual growth rate of channels.
ii. Rerunning existing cross sections to determine the difference in total channel cross-sectional area.
iii. Assembling historical data to determine the average age of channels and their average annual growth.

Gully Erosion – Permanent, Incised, "Classic"

Classic Gullies

Large, permanent concentrated flow channels are known as gullies. They are also termed "classic gullies" only to differentiate them from ephemeral gullies. Classic gullies are too large and deep for normal farm equipment to traverse, so that farming is done around these erosion scars (figure 3). They are characterized by incision, sidewall collapse, and enlargement by headward-advance. Ephemeral gullies are smaller and capable of being temporarily filled in and farmed through by normal farm equipment.

Figure 3. Classic gully erosion, Missouri.

Estimating Classic Gully Erosion

Gully erosion can be computed by physically measuring the volumetric change in the gully over time, or a rate of recession can be applied to predict future gully erosion. Physical changes can be detected through the setting of steel pins driven into the ground and measured periodically, through aerial photographs of different dates, or through other remote sensing means, such as LiDAR (Light Distancing And Ranging).

A simple formula and example follow:

$$E = \frac{LPDVR}{2000}$$

where:

E = Gully erosion in tons/year
L = Total length of bank, each side of channel; e.g., 11,800 feet
P = Percent of total length eroding; e.g., 70%
D = Average depth of channel, in feet; e.g., 5 feet
V = Volume weight of soil in pounds per cubic foot; e.g., 81 lbs/ft3 (from sampling)
R = Annual rate of bank recession, in feet; e.g., 0.1 foot/year

then:

$$E = \frac{\left(11{,}800\text{ft x } 0.70 \text{ x } 5\text{ft x } 81\,\frac{\text{lbs}}{\text{ft}^3} \text{ x } 0.1\,\frac{\text{ft}}{\text{yr}}\right)}{2000\,\frac{\text{lbs}}{\text{ton}}}$$

$$= 167 \text{ tons/yr}$$

Ephemeral Gully Erosion

Definition

Ephemeral gullies are small channels, eroded by concentrated flow, that can be easily filled by normal tillage, only to reform again in the same location by additional runoff events (Soil Science Society of America 2008). These erosion features are often neglected due to the complex problems associated with predicting the timing of their appearance and position on the landscape (figure 4).

Figure 4. Severe sheet and rill erosion with an ephemeral gully in Iowa crop field.

Their complex genesis usually involves an inter-relationship between:

- The volume, velocity, and type of runoff
- The susceptibility of the materials to erosion
- Type and depth of tillage
- Changes in cover caused by land use and conservation practices

Development is associated with concentrated surface or subsurface flow, generally attributed to topographic variations, soil stratigraphy, tillage marks, or random irregularities affecting flow patterns.

Recent studies indicate that ephemeral gully erosion may be a significant form of erosion and source of sediment on cropland in the U.S. Soil loss from ephemeral gully erosion can vary from 10 to 100 percent of the total soil loss on a site (Capra and Sciolone 2004).

Processes that produce ephemeral gullies in crop fields and in some pastures include tractive stress of flowing water, in combination with tension cracking, sidewall collapse due to gravity, and headward advance. Ephemeral gullies may also form as the result of seepage pressures, triggering sapping and piping Normal field preparation operations temporarily fill in and mask the erosion scars, including the gully, until it reappears in the fall or spring after the crop has been harvested and following subsequent runoff events.

Models for Estimating Ephemeral Gully Erosion.
This is not a complete list, and other models are available (details are available in section entitled 'Predictive Models and Tools' at the end of this course):

- AnnAGNPS is the Annualized version of the AGricultural Non-Point Source Pollution Model.
- RUSLE2 is an erosion model predicting longtime average annual soil loss.
- The Revised EGEM (REGEM) as a stand-alone program that replaced EGEM.
- The Water Erosion Prediction Project (WEPP) is a web-based erosion prediction model for the NRCS. The NRCS version of the watershed model is currently under development by the USDA-ARS (USDA-NRCS 1992).

Streambank Erosion

Streambank erosion occurs as lateral cutting, bank caving or incision of the bed on developed drainageways in alluvial valleys (figure 5). Undercutting and subsequent gravitational slumping are the primary causative factors.

Figure 5. Streambank erosion occurring along major stream. Note missing rows of corn where the bank has eroded.

Estimating Streambank Erosion with a simple formula:

$$E = \frac{HLBV}{2000}$$

where:

E = Annual erosion from streambank erosion, in tons
H = Average bank height in feet; e.g., 10 feet
L = Length of channel bank being eroded, in feet; e.g., 1,500 feet
B = Estimated rate of bank erosion, in feet per year; e.g., 0.5 foot
V = Volume weight of bank material, in lbs/ft3.; e.g., 90 lbs/ft3
2,000 = Pounds per ton

then:

$$E = \frac{10\text{ft x } 1500\text{ft x} \frac{0.5\text{ft}}{\text{yr}} \text{x } 90 \text{ lbs/ft}^3}{2000} = 338 \text{ tons/yr}$$

Estimating Streambed erosion

Streambed erosion is not a significant long-term sediment source because the material subject to this type of erosion is limited in both extent and volume. Compared to other potential sources of sediment, streambed erosion usually is minor. For bed incision or degradation, the following formula can be used:

$$E = \frac{WLRV}{2000}$$

where:

E = Annual erosion from channel degradation, in tons
W = Average width of channel in feet; e.g., 30 feet
L = Length of channel bed being eroded, in feet; e.g., 1,200 feet
R = Estimated rate of degradation, in feet per year; e.g., 0.2 foot
V = Volume weight of bed material, in lbs/ft3.; e.g., 90 lbs/ft3
2,000 = Pounds per ton

then:

$$E = \frac{30\text{ft x } 1200\text{ft x } 0.2\text{ft x } 90 \text{ lbs/ft}^3}{2000} = 324 \text{ tons/yr}$$

Valley Trenching

Definition

Valley trenching occurs as a result of headward cutting on alluvial streams as nick points or overfalls migrate upstream. Annual rates of erosion are determined by measuring or estimating the area voided by headcutting or trenching. Figure 6 shows the valley trenching response to a lowering of the base level or bed in the stream traversed by the road bridge. Such valley trenches may also extend into crop fields and along any tributaries to the degrading main channel.

Figure 7 shows a stream that is actively downcutting, incising, or degrading. The bed is eroding and is characterized by nickpoints, overfalls, or waterfalls that may move (erode) rapidly upstream. Some overfalls may persist in a location for a period of time before becoming active again and moving upstream. Other overfalls may be initiated downstream and move up through the same reach. As the nickpoint progresses upstream, incision is triggered in the tributaries promoting further channel erosion and valley trenching.

Figure 6. Bed incision in the main channel has triggered a valley trench gully up the side of this road, Alabama. Note exposed utility pipeline.

Figure 7. Streambed erosion results in "nick point" or overfall.

Estimating Valley Trenching Erosion

For example, comparison of aerial photographs taken five years apart shows that a valley trench has migrated upstream by headcutting a distance of 800 feet. The average depth of the trench is seven feet, and its average width is 15 feet. The volume weight of the soil material is estimated at 90 pounds per cubic foot.

Using the formula:

$$E = \frac{LDWV}{2000 \text{ x } Y}$$

where:

E = erosion in tons/year
L = Length of headcut in feet; e.g., 800 feet
D = Average depth of channel in feet; e.g., 7 feet
W = Width of trench in feet; e.g., 15 feet
V = Volume weight of soil in pounds per cubic foot; e.g., 90 lbs/ft3 (from sampling)
Y = Years of valley trench growth; e.g., 5 years

then:

$$E = \frac{800\text{ft x } 7\text{ft x } 15\text{ft x } 90\ \frac{\text{lbs}}{\text{ft}^3}}{2000 \text{ x } 5\text{yrs}} = 756 \text{ tons/year}$$

Wind Erosion

Introduction

Wind erosion is the detachment and transport of soil material by wind. The process is called deflation, and the resultant deposits are classified as eolian. The rate of erosion depends on the intensity and persistence of the wind, size and availability of soil particles, and amount of protective cover (figure 8).

Figure 8. Wind erosion damaging corn crop and soil, Kansas.

In the United States, the conditions generally most favorable for wind erosion are in semiarid or arid areas west of the 100th meridian, although wind erosion does occur elsewhere. Although water erosion is dominant even in arid areas, wind erosion can approach it in amount in deserts and during periods of intensive drought in other areas.

Eolian deposits are characterized by highly sorted particles, by cross-bedded or lenticular structures, and by dunes oriented by the prevailing winds. A hummocky surface develops when wind-blown sediment lodges around isolated bushes or grass. Fence-line deposits are confined to the area alongside the fence and can be several feet thick. Wind erosion processes involve a combination of sheet flow and concentrated flow of air.

Deflation

Deflation areas contain scoured-out depressions or pock-marked surfaces. Such features are usually in exposed places and are not associated with water drainage rills or channels. Remnants of grass or even single pebbles may rest on small pedestals in the eroded zone. Some shrubs or bunches of grass may persist with the root system exposed above ground. In gravelly sands, selective removal of the smaller particles can produce a gravel pavement on the surface. The amount of deflation can be determined by comparing the voided area with the original ground surface. Measure enough cross sections to delineate an average-sized depression and determine the number of depressions on recent aerial photographs or count the number per unit area.

Deposition

Wind-deposited materials may come from outside a watershed. Conversely, a watershed under study may lose much soil to distant areas. Windblown sediment moves progressively in the direction of the prevailing winds rather than downslope.

The most important aspect of wind erosion to be considered in studies of sediment yield is the deposition of windblown sediment in channels, from which it is easily flushed and added to the sediment yield of the watershed. Channels act as natural traps for airborne sediment, whether they contain water or not. If eolian deposition in channels is a factor in the watershed being studied, measure the annual volume of deposition. A sampling process will usually be adequate. Unless channel capacity is decreasing because of these deposits, add the volume of these sediments to the sediment yield. The sediment delivery ratio depends on the texture of the eroded material.

Wind erosion does not occur every year in most areas. Annual sediment yield rates are adjusted downward to account for years when wind erosion does not occur. In some areas a significant amount of windblown soil may be deposited on snow. During snowmelt the soil is carried by water into streams or drainage ditches. This snow-caught sediment can be measured by pushing metal tubes into the snow and weighing the contents after the snow in the sample melts.

Estimating Wind Erosion

Many factors affect the amount of soil moved by wind erosion. An equation has been developed (Chepil and Woodruff 1963) to predict the average annual soil loss from wind erosion. A simple formula can be used to estimate wind erosion:

$$E = f(I, C, K, L, V)$$

where:

E = average annual soil loss (tons/acre)
I = annual soil erodibility (tons/acre)
C = local wind-erosion climatic factor (percent)
K = soil surface roughness (ratio)
L = equivalent width of field (feet)
V = equivalent quantity of vegetal cover (proportionate factor).

- Soil erodibility (I) is determined from the percentage of the non-erodible soil fraction greater than 0.84 mm in diameter.
- The local wind-erosion climatic factor (C) is estimated from a wind-erosion climatic map developed by Chepil, Siddoway, and Armbrust (1962).

- Surface soil roughness (K) is measured in terms of the height of standard ridges spaced at right angles to the wind, with a height-spacing ratio of 1 to 4.
- The equivalent width of the field (L) is the unsheltered distance along the prevailing wind-erosion direction.
- The equivalent quantity of vegetation (V) is a proportionate factor determined by the quantity, type, and orientation of the vegetal cover.

Instructions for use of these factors, as well as maps, charts, and tables, are in Agricultural Handbook 346 (USDA-NRCS 1968).

Wind Erosion Prediction System (WEPS)

The Wind Erosion Prediction System (WEPS) is a tool for predicting the effects of management (practices and cropping rotations) on the wind erosion potential for a selected field site (USDA-NRCS 2022h). WEPS simulates daily wind erosion processes based on weather, management crop rotations, and soil conditions. WEPS is a process-based, daily time-step model that simulates weather, field conditions, and erosion. As such, it simulates not only the basic wind erosion processes, but also the field processes that modify a soil's susceptibility to wind erosion.

WEPS is designed to provide the user with a simple tool for inputting initial field conditions, calculating soil loss, and displaying either simple or detailed outputs for conservation planning and designing erosion control systems. WEPS NRCS release 1.5.52 (2016-11-30) can be downloaded from the USDA-ARS at https://www.ars.usda.gov/research/software/download/?softwareid=416 (USDA-ARS 1968).

Mass Movement

Introduction

Mass movement includes slumps, mud flows, soil and rock falls, rotational and planar slides, avalanches, and soil creep. The generic term for these mass movements is also “landslides” (see figure 9 for example). Unlike wind and water, mass movement does not carry soil or rock out of the general region in which it formed, but mass movement is often an important factor in soil removal. It can increase or decrease erosion from one source, change a stream channel regime, and alter the drainage area of a watershed.

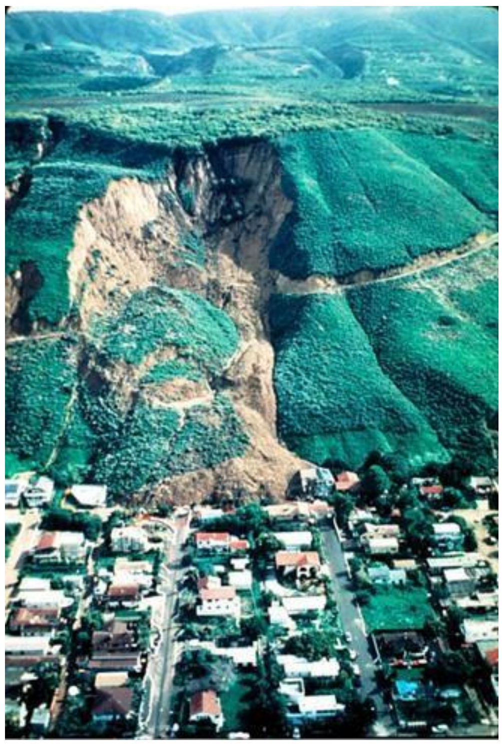


Figure 9. Landslide, California.

Factors Involved

Mass movement occurs when shear stress exceeds shear strength. A high shear stress may develop through removal of lateral support; added weight through rain, snow, or accumulation of talus; or through construction or other activities of man; transitory earth stresses, as earthquakes, removal of underlying support; or lateral pressure from water in cracks and caverns, freezing of water, or swelling of clay or anhydrite. Low shear strength may be caused by:

i. Composition, as inherently weak materials
ii. Texture, as a loose arrangement of particles or roundness of grains
iii. Density
iv. Gross structure, such as:

- Discontinuities from faults, bedding planes, or joints
- Massive beds over weak or plastic materials
- Strata inclined toward a free face
- An alternation of permeable beds, such as sandstone, and weak impermeable beds, such as shale or clay

v. Changes due to weathering and other physio-chemical reactions
vi. Changes in intergranular forces due to pore water
vii. Changes in internal structure, as fissuring in clays or the effect of disturbance or remolding on sensitive materials

Gravity is the prime driver of mass movements and is assisted by the conditions listed above. Often, several types of influences affect the development of a landslide, perhaps in different parts of it or at different times in its development. No movement can occur unless topographic conditions exist that help to create the instability. No standard procedures have been developed for use in calculating erosion by mass movement. Erosion from this source, therefore, must be estimated. Hazard of debris flows may be estimated on the basis of slope. Such flows tend to originate when the slope is in excess of 30 percent and reach a terminal slope of somewhere between seven and 10 percent.

Estimating Erosion by Mass Movement

No standard procedures for calculating erosion by mass movement have been developed; it must therefore be estimated. Comparison of before and after imagery can be used to determine approximate volumes of earth materials that moved. LiDAR surveys may yield more detailed measurements and estimates.

Numerous measurements have been made in the semiarid West to determine the maximum angles at which slopes stand, with and without vegetal cover. Non-vegetated talus material stands at gradients between 68 and 80 percent (angles of about 34 to 38 degrees). Vegetated slopes underlain by fine-textured soils derived from the same parent material as the barren talus stand at gradients of as much as 173 percent (angle of 60 degrees). Without vegetation, slopes of fine material would not stand, even at gradients as high as those of coarse talus (Bailey 1941).

A procedure for calculating erosion from mass movement would require measuring the volume of materials moved. For large masses, comparing the findings of a topographic survey of the mass with the original topography (from standard quadrangle sheets if available) provides an estimate of the volume of materials moved. For smaller masses, a grid of hand-auger borings extending into the original soil profile can provide a basis for estimating the volume.

Other Sources of Sediment

Introduction

Other types of erosion not described above may contribute sediment in the study area and must be evaluated. These sediment source areas include:

i. Wave or shoreline erosion
ii. Ice erosion
iii. Road erosion
iv. Critical sediment source areas
v. Construction areas and surface mines

Wave or Shoreline Erosion

Caused by wind and water, wave erosion is an important source of sediment along shorelines of oceans, lakes, and rivers. Wave erosion can change shorelines markedly and can be measured in many places. The rate of erosion from wave action can be measured by comparing two sets of aerial photographs taken on different dates, as in estimating channel erosion. Figure 10 shows active shoreline erosion occurring on an unprotected bank.

Figure 10. Wave erosion on Cheney Lake, KS.

Historical data form another basis for estimating wave erosion rates. Unless the shoreline was mechanically shaped during reservoir construction, wave erosion along a reservoir shore can also be determined by comparing the present shore profile with an extrapolation of the slope of the profile above the influence of wave action (Figure 11).

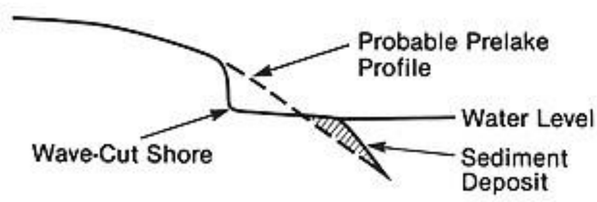


Figure 11. Projecting lines of undisturbed shoreline to determine probably pre-lake bank profile.

Ice Erosion

In watersheds likely to be studied in the NRCS small watershed program, erosion by ice falls into the following categories: glacial gouging around the margin of mountain glaciers, erosion by ice along river channels during spring freshets, and erosion by ice shoved along the shores of northern lakes. Ice erosion usually is not an important source of sediment.

Road Erosion

Erosion from roads can occur as soil loss from the surface of dirt roads and erosion of road banks and ditches. If the approximate age of the road can be determined, then erosion can be computed by the formula:

$$E = \frac{\frac{D}{Y} \text{ x W x L x V}}{2000}$$

where:

E = Annual erosion, in tons
D = Depth of road surface removal; e.g., 6 feet
Y = No. of years road has been in use; e.g., 40 years
W = Width of road surface; e.g., 30 feet
L = Length of eroded road; e.g., 2500 feet
V = Volume weight of soil material; e.g., 80 lb/ft.^{3}
2,000 = Pounds per ton

then:

$$E = \frac{\frac{6\text{ft}}{40\text{yrs.}} \text{ x 30ft x 2500ft x 80 lb/ft}^3}{2000} = 450 \text{ tons/yr}$$

Where roadside ditches or banks are undergoing erosion, the annual soil loss can be computed in the same manner as for gully erosion. Judgment is essential in making these computations. Consider original road construction and maintenance, which influences erosion estimates.

Critical Sediment Source Area

Critical areas can be defined as active gullies or other seriously eroding lands which are sources of excessive runoff or sediment contributing directly to downstream damages, or which would, if left untreated, adversely affect structural works of improvement included in the project. Erosion from these areas is often a combination of both severe sheet erosion with intermixed active gullies. Both sheet and gully erosion can be computed using methods for these sources as previously described. Rates of erosion are usually much higher than for average amounts of soil loss from these sources. Construction sites often fall into the “critical sediment source” category.

Construction Erosion and Surface Mines

Strip mining or excavating operations and construction of highways, industrial areas, public buildings, housing, shopping centers, and related areas greatly accelerate erosion of exposures and spoil banks. Sediment yield from construction sites (Figure 12) and strip-mined areas can be estimated from the computed erosion and a sediment delivery ratio. Consider projected erosion-control measures realistically when determining the sediment delivery ratio.

Figure 12. Severe sheet and rill and gully erosion resulting from recent construction.

Soil loss from construction areas can be estimated by using the procedures for both sheet, channel, and other types of erosion previously outlined. Other methods may be used if they are considered more applicable. Predictions of soil loss in areas to be developed will influence the degree of planning and treatment required for proper control of erosion and sediment yield. Predicted soil losses may also create an awareness among developers, local government agencies, and others of the urgent need to install conservation measures concurrent with construction.

Soil losses on construction sites can be estimated for an entire year, part of a year, a period of years, or based on probability storms and magnitudes of single storms. The average percent of exposure per year can be estimated using such factors as population curves, building permits, or area development plans to determine annual trends.

Construction sites are also subject to rill and gully erosion. Because of the high probability of severe to very severe sheet erosion, rilling is more likely to occur at construction sites than on agricultural land that is cultivated. The losses from severe rilling and gullying are in addition to losses from sheet erosion and must be considered for determining total losses at a given site. The traditional method for measuring soil loss from rill erosion uses a portable rill meter and ruler (McCool et al. 1981). Rill meters can be used after rainfall events on construction sites, croplands, mine spoil banks, and remote rangeland trails and logging roads. Photographing the rill meter recording is a valuable tool for documenting field conditions. This method, however, is time consuming and is invasive because of direct contact with the soil surface that modifies the rill area. Gully erosion can be estimated by procedures previously outlined.

Laser profilers have been used as a non-destructive measurement technique because of no mechanical contact between the laser sensor and the soil surface (Bertuzzi 1988). The laser profilometer is quick and records data directly to a computer. Drone-based technology has been developed as a fast and non-invasive method to measure rill erosion (Carollo et al. 2015). Quadcopters are used to survey the relief to produce a Digital Elevation Map (DEM).

Sediment Yield

Introduction

Sources of sediment must be identified to plan an adequate program for reducing downstream sediment yield and related damages. Sediment sources include agricultural land, range and forest land, road banks and ditches, stream channels and banks, flood plains, spoil banks, and gullies.

In planning a program to reduce sediment yield and sediment damages, the relative importance of the various sources and the methods for treating them must be determined before the physical and economic feasibility of the program can be determined. Sediment derived from sheet erosion can usually be reduced by land treatment measures, whereas that derived from channel-type erosion usually requires structural works. A sediment source study is made to determine:

i. The origin of the sediment.
ii. The rate of erosion from each source.
iii. The proportion of the sediment derived from each source.
iv. For program planning or structure design, the kinds of treatment that should be recommended for reducing sediment yield.
v. The relative effect that reducing erosion from the various sources will have on reducing sediment yield and damage.

The relative importance of each sediment source may differ at different locations in a watershed. Therefore, the treatment measures may also vary, depending on the location in the watershed where a reduction in sediment yield is desired. Watershed planning balances erosion reduction measures with measures that are designed to trap sediment downslope or downstream from where erosion is occurring.

Interrelationship of Erosion and Sediment Transport Processes

This section presents several procedures for determining sediment sources, sediment yields, and sediment delivery ratios.

Sediment yield depends on gross erosion in the watershed and on the transport of eroded material out of the watershed. Only part of the material eroded from upland areas in a watershed is carried out of the watershed. Variation in the proportion of the eroded material deposited as colluvium at the base of slopes and in swales, as alluvium on flood plains and in channels, and as lacustrine deposits in natural or artificial lakes usually results in variation in the yield rate for different parts of a watershed.

Field determination of sediment yield may require long-term sampling and measuring procedures. A short-term procedure is to extrapolate (and adjust as appropriate) known sediment yield from measured similar watershed in the same physiographic section.

Watershed sediment yield rates depend on the erosion processes at the sediment source and on the efficiency of the system that transports the sediment to the point of measurement. The sediment yield usually differs at different locations in a stream system.

Many interrelated factors affect sediment yield. Knowledge of each of these factors is important in:

i. Evaluating downstream sediment damages.
ii. Determining the location and extent of sediment sources so that effective controls can be planned and installed.
iii. Recognizing the relative contribution of the various sources to present and future sediment yield.
iv. Determining the sediment storage requirements for designing proposed structural works of improvement for the life of the project.

Water Quality and Sediment Yield

The computed soil loss for large areas is not sediment yield, and it is not directly related to water quality. Overland sediment transport is a complex process of transport and deposition. The USLE estimates the in-field transport component and specifically excludes the deposition component. For example, only five percent of the computed soil loss may appear as sediment yield in a drainage area of 500 mi^2. The remaining 95 percent is redistributed and deposited on uplands or flood plains and is not a net soil loss from the area. Sediment in transit, temporarily detained, or permanently trapped in the landscape may cause damages to soil and water resources.

Sediment is a mixture of primary particles and aggregates. Soil texture plays the major role in determining the sediment characteristics at the point of detachment. The effect of soil texture on sediment characteristics at the point of detachment is considered by RUSLE2. High quality soil management that improves soil aggregates also affects sediment characteristics at the point of detachment, but that effect is not considered by RUSLE2. The model computes how deposition enriches the sediment in fines.

Determining the Relative Importance of Sediment Sources

Several items must be considered in the early stages of any study made to determine the location, extent, and relative importance of sediment sources.

Maps and Aerial Photographs

Careful review of aerial photographs often reveals where erosion is severe and which channels appear to be carrying the heaviest loads of sediment. See figure 13 which illustrates stream channels with sediment loads. The information on soil surveys not only includes soil types, but slopes, land use, and erosion conditions recorded on the maps (Web Soil Survey) (USDA-NRCS 2022g). Using all such information as fully as possible saves considerable time in locating the most obvious sources of sediment.

Figure 13. Accelerated sediment transport in the Betsiboka River, Madagascar (NASA imagery).

Distinctive Minerals

The presence of distinctive minerals in modern sediment deposits helps in identifying and evaluating sediment sources. Because a watershed may contain contrasting rock formations, the distinctive erosion products of these rock formations may clearly indicate the location of the sediment sources. These distinctive minerals are quartz, micas, feldspar, chert, and calcite. Some minerals in sediment can be easily identified and traced to their original source. Other watersheds may lack geologic variety and hence may not provide such specific clues to the location of significant erosion.

Sediment "Fingerprinting"

Naturally occurring elements, isotopes, and rare earth materials can be identified in deposited sediment and traced back to erosion sources. Methodology used depends on the element(s) used:

- Radionuclides (Cs, Pb)
- Cosmogenic isotopes (10Be, 7Be)
- Stable Isotopes (C-13, N-15)
- Total carbon, nitrogen, phosphorous
- Clay mineralogy
- Magnetic susceptibility

The USGS and ARS have conducted research on the use and suitability of various fingerprinting approaches. An example of these results may be found in Banks et al. (2010).

Colluviation

Another aid in evaluating the sediment sources is the extent and location of colluvial deposition. If a coarse-grained material such as sand or gravel is being actively eroded, it may produce large volumes of sediment, little of which moves very far from the site of erosion. Substantial deposits may form at the foot of the first slope. Fans and valley deposits may form in small tributary valleys or in the next lower valleys downstream.

Procedure

Any procedure requires study of the various types of erosion apparently producing sediment. Sorting the types of erosion according to the treatments that could be recommended to reduce erosion and sediment yield makes the effectiveness of the various treatments much easier to evaluate. Several procedures can be used to determine the relative importance of the various sediment sources. A recommended procedure is to gather information on that part of the sediment yield which can be attributed to each of the various sources. Erosion rates and the watershed sediment delivery ratio should be estimated above each reach or other point of interest for the drainage area.

The sediment yield at the point of interest must be allocated to the recognized sources. Analyzing the available data, studying the watershed drainage characteristics, and considering the sediment delivery ratios and erosion estimates enable the preparation of a table, such as table 5, that indicates the relative importance of the sediment sources.

Table 5. Example of variation in watershed sediment yield.

Sediment Yield (%) [1/]			
Sediment yield source	**Reach**		
	a	b	c
Sheet Erosion	78	54	41
Classic Gullies	5	12	31
Ephemeral Gullies	9	22	11
Roadbanks	2	1	3
Streambanks	5	10	13
Scour	1	1	1
Total	100	100	100

Note: [1/] The watershed drainage area is specified by the mouth or sediment yield point.

Sediment Yield

Sediment yield is the gross (total) erosion minus the sediment deposited en route to the point of concern. Gross erosion is the sum of all the water erosion occurring in the drainage area. It includes sheet and rill erosion plus channel-type erosion (gullies, valley trenches, streambank erosion, etc.).

Measurements or estimates of the watershed sediment yield are needed to evaluate sediment damage and its reduction and to determine the sediment storage requirements for proposed structures. The yield of a given area varies with changes over time in precipitation, cover, and land use patterns. For projection into the future, the present sediment yield must be adjusted to allow for expected changes in these factors.

Climatic Factors Affecting Sediment Yield

The effect of climatic factors such as precipitation, temperature, and wind on sediment yields varies in different parts of the country. Rainfall and runoff are the primary erosion drivers throughout the country. The erosive power of rainfall depends on its intensity, duration, and frequency. Seasonal distribution of rainfall is of prime importance in cropland areas because of the condition of the cover at the time of erosion-producing rainfall. Prolonged low-intensity rainfalls are less erosive than brief intense storms. Wind erosion is serious in some sections of the country but is not as widespread as water erosion.

Watershed Factors Affecting Sediment Yield

Important watershed factors affecting sediment yield are size of drainage area, topography, channel density, soils, and cover conditions.

i *Watershed Drainage Area Size*

In a given physiographic area, the larger the drainage area, the larger the sediment yield, but generally the sediment yield per unit of area (sediment yield rate) decreases as the size of drainage area increases. In mountainous areas, however, the size of the drainage area often makes no difference in the sediment yield rate.

Where active channel-type erosion increases downstream, as from bank cutting on the mainstream channel, the sediment yield rate may increase as the size of the drainage area increases. The relationship between size of drainage area and the sediment yield rate must therefore be considered carefully.

In a small watershed, sediment is carried shorter distances, and areas of high and low sediment production are less likely to counterbalance each other than in a large watershed. There are fewer types of land use or other watershed variables in a small watershed than in a large watershed. In a small watershed the yield rate is higher and varies more than in a large watershed. In a small watershed in which the land is used according to its capability, both the erosion rate and the sediment yield rate are low. Conversely, a high erosion rate is sharply reflected in a high sediment-yield rate. Larger watersheds tend to have lower average slopes and less efficient sediment transport than smaller watersheds. Size of the drainage area is therefore an important factor in both the total sediment yield and the sediment yield rate.

The relationship between size of drainage area and sediment yield is complicated by many other factors, such as rainfall, plant cover, texture of the sediment, and land use. All of these factors must therefore be evaluated to estimate the volume of sediment from an erosion source, the rate of deposition in a proposed reservoir, or the rate of sediment contribution to any downstream location.

ii *Watershed Topography*

Shape of the land surface is an inherent feature of the physiographic area in which a watershed is located. Many of the problems of soil and water conservation result from the topography of an individual watershed, especially the proportions of uplands, valley slopes, flood plains, or features such as escarpments, canyons, or alluvial fans. Slope is a major factor affecting the rate of onsite erosion, and topography is important in the delivery of upland erosion products to the stream system.

iii *Watershed Channel Density*

The efficiency of a stream system in transporting sediment out of a watershed is affected by the degree of channelization. A watershed with a high channel density (total length of channel per unit area) has the highest rates of sediment yield. Channel density can be measured on aerial photographs with the aid of a stereoscope. Channel density can also be determined from topographic maps.

iv *Watershed Soil and Cover Conditions*

In general, the more erodible the soil and the sparser the vegetation, the higher the sediment yield. Estimating the average annual sediment yield from a watershed having many kinds of soil and mixed cover is complex and requires a procedure such as use of a soil-loss equation to determine erosion for the various soil-slope cover combinations in the watershed.

v *Watershed Land Use*

According to the 2017 NRCS National Resources Inventory (NRI), about 25 percent of the 1,487 million acres of non-Federal land in the United States is cropland; 35 percent is grassland, pasture, and range; 28 percent is forest; eight percent is in residential, industrial, transportation, and other urban and built-up areas; three percent is in other uses; and one percent is in the conservation reserve program (CRP). In comparison, the 1977 NRCS NRI, about 28 percent of the 1,500 million acres of non-Federal land in the United States was cropland; 36 percent was grassland, pasture, and range; 25 percent was forest; six percent was in residential, industrial, transportation, and other urban and built-up areas; and five percent was in other uses.

Land use is determined to some extent by the kind of soil. In turn, land use largely determines the type of cover. If a watershed is primarily agricultural, and the annual precipitation is more than 20 in., most of the sediment yield usually is from sheet erosion. In most forest and range country and in areas with less than 20 inches of annual precipitation, channel-type erosion usually produces most of the sediment (Brown 1960). According to the USDA, conversion of forest land to continuous cultivation of row crops increases erosion 100- to 10,000-fold. Plowing grassland for continuous cultivation of row crops increases erosion 20- to 100-fold (Brown 1960). In the United States, cultivated farm fields that annually lose more than 200 tons/acre from water erosion are not uncommon. Small, intensively cultivated watersheds in western Iowa have had annual soil losses as high as 127,000 tons/mi^2 (Gottschalk and Brune 1950).

Methods for Estimating or Predicting Watershed Sediment Yield

Depending on the environment and the data available, the average annual sediment yield in a watershed can be determined from:

i. Gross erosion and applying a watershed sediment delivery ratio
ii. Measured sediment accumulations
iii. Sediment load records
iv. Predictive equations

Gross Erosion and the Sediment Delivery Ratio

NRCS has used this method extensively for many years with success, particularly in humid sections of the country. It is well suited for estimating current watershed sediment yield and for predicting the effects of land treatment and land use changes on future sediment yield (See CEAP). The following equation can be used to estimate sediment yield for a watershed:

$$Y = E(DR)$$

where:

Y = annual sediment yield (tons/unit area).
E = annual gross erosion (tons/unit area).
DR = sediment delivery ratio (less than 1.00).

The gross (total) erosion in a drainage area is the sum of all the water erosion taking place. The watershed sediment delivery ratio is estimated from relationships discussed later in this course. The sediment delivery ratio is the computed fraction of gross erosion that is yielded as sediment to the mouth of a watershed, or it is the estimated ratio that is applied to estimated sources of erosion.

Measured Sediment Accumulation

The measured sediment accumulation in reservoirs of known age and history is an excellent source of data for establishing sediment yield, but deposition in reservoirs and sediment yield are not synonymous. For sediment yield, the amount of accumulated sediment must be divided by the trap efficiency of the reservoir. The amount of sediment that has passed through the reservoir plus the amount deposited in the reservoir equals the sediment yield.

Rates of sediment deposition in a reservoir can be computed if surveys of the volume of sediment deposits are performed over multiple years (RESSID). Existing reservoir sedimentation survey data can be found on historic data collection sheets (such as NRCS-ENG-034), or in the Reservoir Sedimentation Survey Database (RESSED https://water.usgs.gov/osw/ressed/). Larger reservoirs may have sediment survey data available such as from the U.S. Department of Interior - Bureau of Reclamation and the U.S. Army Corps of Engineers.

The sediment yield of a watershed can be estimated from measured sediment yield from another watershed in the same major land resource area if the topography, soils, and land use of the two watersheds are similar. The annual sediment yield can be adjusted on the basis of the ratio of the drainage area to the 0.8 power:

$$Y_e = Y_m \left(\frac{A_e}{A_m}\right)^{0.8}$$

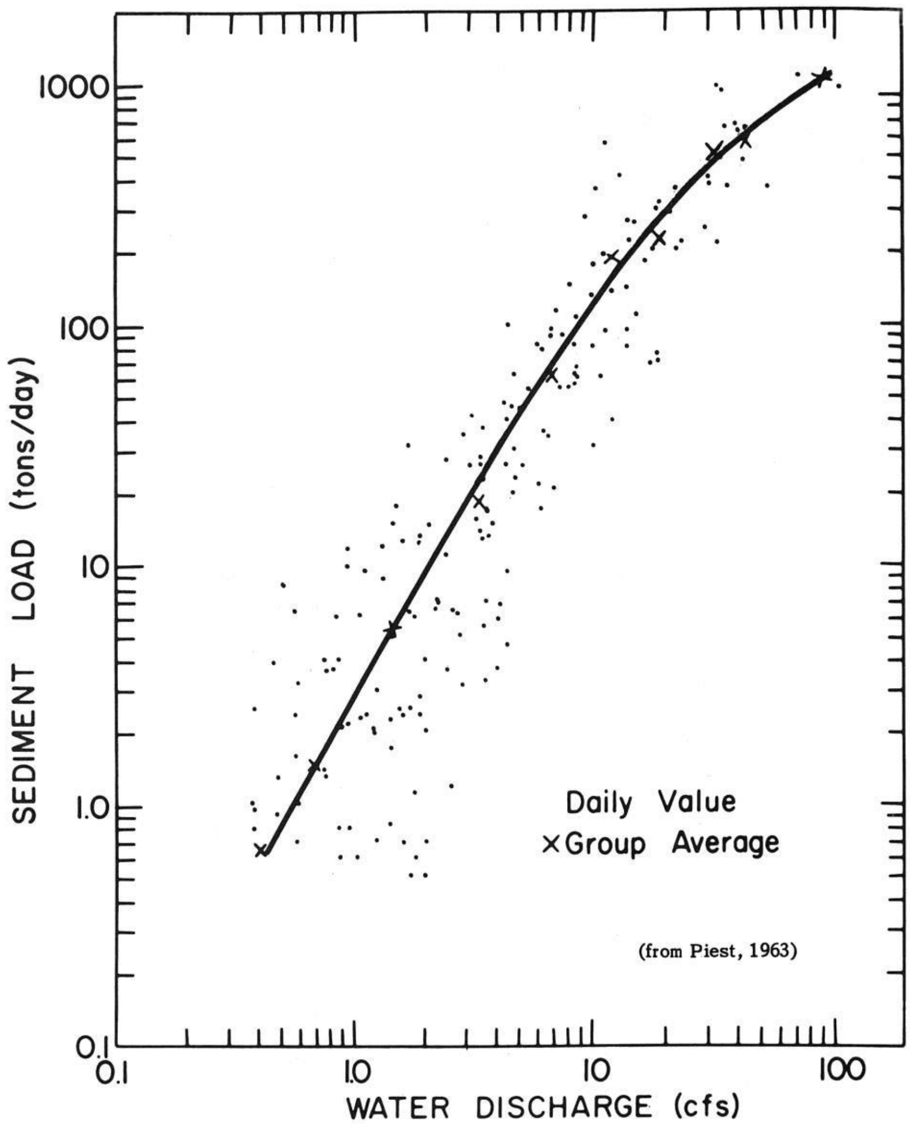
where:

Ye = sediment yield of unmeasured watershed in tons per year.
Ym = sediment yield of measured watershed in tons per year (measured annual sediment deposition divided by trap efficiency of surveyed reservoir).
Ae = drainage area of unmeasured watershed.
Am = drainage area of measured watershed.

This relationship must be used with judgment and be confined generally to the humid areas east of the Rocky Mountains. The amount of sediment accumulated on fans and flood plains over a known period of time can sometimes be used to estimate sediment yield but generally only to verify yield determined by other methods.

Suspended-Sediment Load Records

Suspended sediment can be measured by sampling, and water discharge can be determined by gaging at stream cross sections. Sediment yield can be estimated from these data. Such records may be available from the USGS for gauges in or near a target watershed. Sediment concentration in milligrams per liter or parts per million is converted to tons per day by multiplying the average concentration by the volume of water discharged on the day of record and a conversion factor (usually 0.0027). Tons of sediment per day plotted against water discharge in cubic feet per second is a sediment rating curve. The data plotted on log-log paper often approximate a straight line through at least a major part of the range of discharge (see figure 14).



Direct runoff versus sediment discharge, by day, Pigeon Roost Creek Watershed 5, January 1957–December 1960

Figure 14. A sediment rating curve showing the relationship between sediment load and water discharge for a specific period of data collection for a gauged stream.

If discharge and concentration data are available, the average annual sediment yield can be estimated by using a flow-duration curve or equivalent tabulations. Usually, the length of time required to collect a range of suspended-load data large enough to prepare a sediment rating curve prohibits the establishment of a suspended-load station for the small watersheds in NRCS programs. If such suspended-load records are available from nearby similar watersheds, however, the sediment yield rate can be derived and transposed in the same manner as reservoir sedimentation-survey data. The bedload portion of the sediment load is not measured in this method; it must be estimated. It can range from practically none to 50 percent or more of the total load.

Predictive Equations and Models

Predictive equations based on watershed characteristics have been developed in some areas to estimate sediment yield. These equations express sediment yield as a function of a combination of several measurable independent variables. The variables include size of the drainage area, annual runoff, watershed shape, relief-length ratio, average slope, an expression of the particle size of the surface soil, and others.

Information Sources

Reservoir Sedimentation Survey information can be obtained from NRCS reports and reports of other federal, state, and private agencies, and from web-based databases (RESSED). Surveys of reservoir sediment volumes repeated at the same site over time provide a relative rate of sediment accumulation. Properly executed surveys not only measure the volume and distribution of sediment deposits in a reservoir, but also provide forensic information about land use and cover changes during the survey period to document the conditions that produced the sediment volume measured.

Urbanization, transportation developments, changes in crops and cropping management systems, and mineral extraction activities may have significant short-term impacts on the amount of sediment yielded from a watershed and deposited in water bodies. Figure 15 shows a typical small floodwater retarding structure with sediment-laden water. The structure detains the floodwater, slowing releasing it safely downstream. Suspended sediment colors the water brown, and as the water remains in the reservoir, the particles may have time to settle to the bottom. Accelerated watershed erosion may result in rapid sedimentation of such reservoirs, leading to their filling and lack of effectiveness in storing and releasing floodwaters. The National Inventory of Dams (https://nid.sec.usace.army.mil/#/) indicates that about 27,000 of these reservoirs exist.

Figure 15. Small floodwater retarding structure in Iowa after severe rains.

Stream Gage Data are available on the USGS website. Suspended-load data for a wide range of watershed sizes, geographic areas, and streamflow quantities are available from water-supply papers, special reports of the U. S. Geological Survey, and from USGS stream gage data.

Other Sources of Sedimentation Information include Many project reports of the Bureau of Reclamation and U. S. Army Corps of Engineers contain sediment yield data for particular drainage basins. Reports of the Inter-Agency Committee on Water Resources should be consulted, as well as river basin reports such as those for the Missouri River and the Arkansas-White-Red Rivers. United Nations flood-control series bulletins contain some sediment-yield data. Sediment yield to bottom lands, fans, bays, deltas, and other features is evaluated in many of these reports. Sediment yield information is sometimes published in scientific and engineering journals, manuals, or conference proceedings. The USDA-Agricultural Research Service's National Sedimentation Laboratory is also an important source of a wide variety of information and research on sedimentation. SEDHYD, Inc. houses proceedings of sedimentation conferences since the 1940s (https://www.sedhyd.org/).

Sediment Delivery Ratio (SDR)

Estimating SDR

Determining the SDR is of primary importance to geologists if they are to make realistic estimates of sediment yield on the basis of computed gross erosion. No characteristic relationship is known to exist between sediment yield and erosion alone. Many factors influence the SDR, and because these are not uniform from watershed to watershed, the relationship between sediment yield and erosion varies considerably. The availability of long-term measurements of sediment loads and physical erosion also affect the reliability of SDR estimates.

The following are some of the factors that can influence the SDR:

i *Sediment Source*: The sediment source affects the SDR. Sediment produced by channel-type erosion is immediately available to the transport system. Much of it remains in motion as suspended sediment or bedload. Materials derived from sheet erosion, however, often move only a short distance and may lodge in areas remote from the transport system. These materials may remain in the fields in which they originated or may be deposited as colluvium on more level slopes.

ii *Proximity of sediment sources* is another factor that affects the SDR. For example, although a large amount of material may be produced by severe erosion in an area remote from a stream, the SDR and sediment yield may be less than those from a smaller amount of material produced by moderate erosion close to that stream.

iii *Transport System*: Runoff resulting from rainfall and snowmelt is the chief transport agent for eroded material. The ability to transport sediment depends on the velocity and volume of water discharge as well as on the amount and character of the material supplied to it. If the amount of sediment in transit exceeds the transport capacity of the system, sediment is deposited, and the SDR is decreased. The frequency and duration of discharges affect the total volume of sediment delivered. The extent and condition of the transport system have considerable bearing on the amount of sediment the system can transport. A transport system with high channel density has the greatest chance of moving materials from the uplands and should have a high SDR. The condition of the channels (clogged or open, meandering or straight) affects flow velocity and, consequently, transport capacity. A high-gradient stream, usually associated with steep slopes and high relief, transports eroded material efficiently. The converse is true of a low-gradient stream.

iv *Texture of Eroded Material*: The texture of the eroded material also affects the SDR. Transport of sand requires a relatively high velocity. Much of the sand is deposited in upstream areas wherever velocity drops significantly. Sand usually becomes part of the sediment load only if its source areas are adjacent to an efficient transport system. Eroded silt and clay are likely to stay in suspension if the water is moving, and most of such material is delivered downstream. Some of the coarser particles may be deposited as colluvium before they reach the transport system. Sands and larger grain-size materials are usually produced by channel erosion, and the silts and clays are common products of sheet erosion. Some low gradient streams may transport silts and clays in an aggregated form, decreasing their SDR.

v *Depositional Area*: Some sediment is deposited at the foot of upland slopes, along the edges of valleys, in valley flats, in and along mainstream channels, and at the heads of and in reservoirs, lakes, and ponds. Such deposition within a watershed decreases the amount of sediment delivered to points downstream.

vi *Watershed Characteristics*: The topography of a watershed affects the SDR. Slope is a major factor affecting the rate of erosion. High relief often indicates both a high erosion rate and a high SDR. The relief/length ratio (R/L ratio) often corresponds closely to the SDR. For use in the R/L ratio, relief (measured in feet) is defined as the difference between the average elevation of the watershed divide at the headwaters of the main-stem drainage and the elevation of the streambed at the point of sediment yield. Length is defined as the maximum valley length (in feet) parallel to the main-stem drainage from the point of sediment yield to the watershed divide. The shape of a watershed can affect the SDR. Channel density also affects the SDR. Channel density and topography are closely related. The size of the drainage area is also important. Size can be considered a composite variable that incorporates and averages out the individual effects of variability in topography, geology, and climate.

vii There may be additional factors not yet identified.

Procedures for Estimating the SDR

Determining the SDR requires knowledge of the sediment yield at a given point in a watershed and the total amount of erosion. If this information is available, determining the SDR is simple. Values for both of these required items, however, usually are not available for most small watersheds. Gross erosion in a watershed can be estimated by using standard procedures previously described in this chapter. Sediment yield can also be determined from reservoir sedimentation surveys or sediment-load measurements.

Many reservoirs are not located at points where measurements of sediment yield are needed, and a program of sediment-load sampling may be long and expensive. But if the ratio of known sediment yield and erosion within a homogeneous area can be analyzed, in conjunction with some measurable influencing factor, these data can be used to predict or estimate the SDR for similar areas where measurements are lacking. In each physiographic area, finding measurable factors that can be definitely related to the SDR is the goal of any delivery-ratio analysis. As already pointed out, many factors can affect the SDR. Some are more pronounced in their effect than others; some lend themselves to quantitative expression and others do not.

Statistical analysis is an effective means of developing information for estimating the SDR. The SDR is used as a dependent variable and the measurable watershed factors are used as the independent or controlling variables. For such an analysis, quantitative data on sediment yield, erosion, and measurable watershed factors must be available. Reservoir sedimentation surveys are a source of sediment yield data. Either maps or field surveys can be used to obtain the erosion information and determine the watershed factors. These data can be analyzed to develop a means for estimating the SDR for similar areas.

Size of Drainage Area and SDR

Data obtained from past studies (Gottschalk and Brune 1950, Woodburn and Roehl, Maner and Barnes 1953, Glymph 1954, Maner 1957, Roehl 1962) are plotted in figure 16. The figure indicates a wide variation in the SDR for any given size of drainage area. The shaded area represents the general range of data, and the dashed line is the median. This analysis of data from widely scattered areas does show, however, similarity in SDRs throughout the country and that they vary inversely as the 0.2 power of the size of the drainage area.

Rough estimates of the SDR can be made from figure 16, but any such estimate should be tempered with judgment and other factors such as texture, relief, type of erosion, sediment transport system, and areas of deposition within the drainage area. For example, if the texture of the upland soils is mostly silt or clay, the SDR will be higher than if the texture is sand.

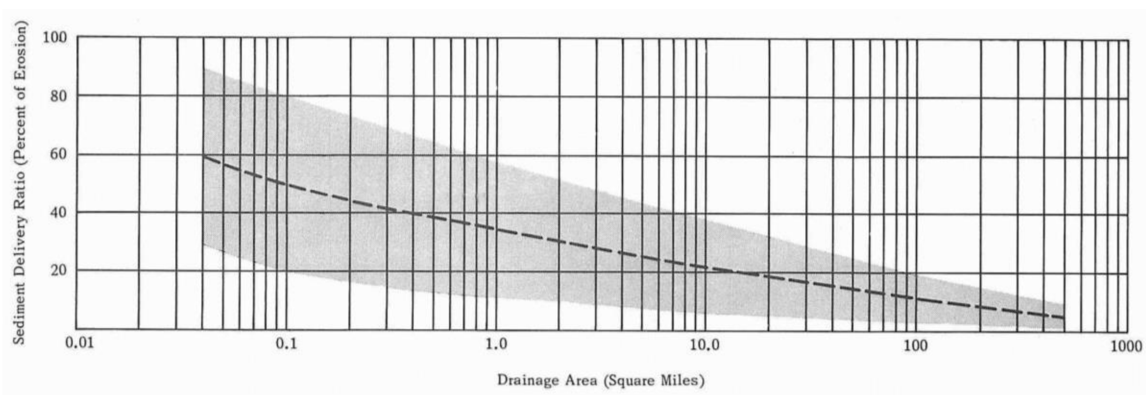


Figure 16. Relationship between drainage area and SDR (Roehle 1962).

Relief-Length Ratio

The watershed relief-length ratio (Barnes and Maner 1953, Roehl 1962) has been used as an indicator of the watershed SDR in some areas.

Source-Texture Analysis

In all the preceding discussion of methods for estimating the SDR, the delivery ratio is a percentage of total erosion. In many places the individual SDR of the component parts of the total erosion is of concern to NRCS geologists and for resource protection. Reasonable and realistic values for the delivery of component parts must be estimated from scant data. One method of obtaining these estimates is to make certain determinations or assumptions about the source of various components of a known sediment yield.

In the following example, the method of source-texture analysis is applied to a watershed in which the sediment sources are sheet erosion, gullies, roadbanks, ditches, and receding streambanks. The suspended-sediment yield (determined by sampling) consists of silt and clay, and the bedload (estimated as a percentage of the suspended-sediment yield) is sand. The streambed is in equilibrium and therefore is not considered a net source of sediment under existing conditions. Because of the texture of the sediment and the texture of the material available in the various sources, assume that all the sand is provided by gullies, roadbanks, and ditches and that the fine materials are provided by the receding streambanks and sheet erosion. Assume that 100 percent of the streambank material will be delivered to the point of measurement.

Use the following procedure to determine the SDR:

Step 1. Compute the amount of sediment produced by each source or type of erosion in tons per year.

Step 2. Determine the suspended-sediment yield of the watershed by sampling.

Step 3. Establish a delivery ratio for the gullies and roadside erosion by comparing the amount of sand being carried past the point of measurement with the volume of material provided by gullies, road banks, and ditches.

This procedure can be used to estimate the SDR in similar areas. Many broad assumptions are required in an analysis of this type, and the results will be only as good as the assumptions.

Source Deposition

Another method of determining the SDR is to make a field study of a watershed and estimate the amount of deposition that can be traced to any one source. The difference in the volume of such deposition and the volume of sediment produced by the source gives an estimate of the delivery ratio from that source. Table 6 shows estimated SDRs for various sediment sources.

Table 6. Example of Watershed Sediment Sources and SDRs.

Watershed Sediment Sources	Erosion [1/]		Sediment yield [2/]		Sediment Delivery Ratio (SDR in %)
	Sand	Fines	Sand	Fines	
	tons/yr				
Sheet erosion	-	900,000	-	300,000 [3/]	33
Ephemeral gullies	69,000	200,000	39,000	100,000	50
Classic gullies	212,000	-	170,000	-	80 [4/]
Road banks	150,000	-	120,000	-	80 [4/]
Streambanks	-	900,000	-	900,000	100
Total	431,000	2,000,000	400,000 [5/]	1,300,000 [6/]	70

Notes:

[1/]Determine by standard NRCS procedures (RUSLE2, formulas, etc).

[2/]Assume that all fines are from sheet erosion and streambanks and all sand is from gullies and road banks.

[3/]Difference between total yield of fines and yield of fines from streambanks.

[4/]Compute as ratio of total sand yield to total sand available; assume equal delivery ratio for classic gullies and road banks.

[5/]Estimate bedload as a percentage of the suspended load.

[6/]Determine from suspended-load measurement.

Predictive Models and Tools

Introduction

The following are brief descriptions of models currently used to predict erosion and sediment yield rates on fields and in watersheds (USDA 2009). The descriptions were prepared jointly by the NRCS and the ARS National Sedimentation Laboratory, Watershed Physical Processes Research Unit, Oxford, MS.

Model development continues to advance the technology and knowledge of soil erosion and sediment transport processes, so this should not be considered a complete listing. Predictive models produce a single value of erosion for a given set of land use and conservation treatments. Erosion rates are highly variable from place to place and year to year. Consult a specialist to select a model that will work for the size and location of your watershed or area.

AnnAGNPS

AnnAGNPS (the Annualized version of the AGricultural Non-Point Source Pollution Model)(Bingner and Theurer 2001) is a continuous-simulation, mixed-land use,
watershed-scale computer model designed to predict the origin and movement of water, sediment, and chemicals at any location in primarily agricultural watersheds. It distinguishes between erosion caused by sheet and rill (from RUSLE 1.06), tillageinduced ephemeral gullies (TIEG), other gully processes, and streambed and bank sources. It also predicts the amount of each pollutant (sediment and chemical loads) at any location in the watershed; i.e., how much of each pollutant comes from where and arrives at any location in the watershed. Erosion from gullies is estimated using procedures describing the depth, width, and migration rate of the headcut (Alonso et al. 2002). Sediment delivered to the mouth of the gully is estimated using the HUSLE procedure (Hydro-geomorphic Universal Soil Loss Equation) (Theurer and Clarke 1991). AnnAGNPS is available for download at https://www.ars.usda.gov/southeastarea/oxford-ms/national-sedimentation-laboratory/watershed-physical-processesresearch/docs/annagnps-pollutant-loading-model/.

TIEGEM (Tillage-Induced Ephemeral Gully Erosion Model) is a new addition to AnnAGNPS that incorporates recent ARS research (Bingner at al. 2007). Several algorithms are used to determine the minimum gully width for each event:

i. Previously determined width by a prior event.
ii. Nachtergaele et al. (2002) equation 10.
iii. The hydraulic geometry relationship for the gully's concentrated flow.
iv. Non-submerging tailwater depth at the crest of the headcut.
v. Woodward's (1999) equilibrium gully width.
vi. Woodward's (1999) ultimate gully width.

Features within AnnAGNPS can be used to determine the probability and amount of a pollutant reaching any location within the watershed, including tillage-induced ephemeral gullies (TIEGs). To include the TIEG feature in an AnnAGNPS analysis requires locating the mouth of each potential TIEG. Preliminary studies have been performed to identify the mouth of a gully headcut based on topographic analysis and have been integrated into AGNPS GIS components (Parker et al. 2007).

AGNPS with ephemeral gully erosion capabilities is currently available to quantify the magnitude and extent of tillage-induced ephemeral gully erosion, sediment yield, and sediment load in watersheds (see: http://www.ars.usda.gov/Research/docs.htm?docid=5199). These results could be correlated through land use, soils, and climate to indicate the magnitude and risk associated with pollutants originating from TIEGs.

APEX

The APEX model (Agricultural Policy Environmental eXtender) was developed by the Blacklands Research and Extension Center in Temple, Texas (Texas A&M University 2002). APEX is a flexible and dynamic tool that is capable of simulating a wide array of management practices, cropping systems, and other land uses across a broad range of agricultural landscapes, including whole farms and small watersheds. The model can be configured for novel land management strategies, such as filter strip impacts on pollutant losses from upslope crop fields, intensive rotational grazing scenarios depicting movement of cows between paddocks, impacts of vegetated grassed waterways in combination with filter strips, and land application of manure from livestock feedlots or waste storage ponds. A description and download of the APEX model are provided at https://epicapex.tamu.edu/apex/.

The APEX daily time-step model simulates weather, farming operations, crop growth, and yield, plus the movement of water, soil, carbon, nutrients, sediment, and pesticides. Weather events and their interaction with crop cover and soil properties are simulated to produce effects on the fate and transport of water and chemicals through the soil profile and over land to the watershed outlet. Soil erosion is simulated over time and includes wind erosion, sheet and rill erosion, and irrigation-induced erosion.

The APEX sediment routing component transports sediment through channels and floodplains, computing both degradation and deposition. The quantity of sediment produced by ephemeral gully erosion is calculated by using two of the runoff-based soil erosion equations available in APEX: MUSLE (Modified Universal Soil Loss Equation) and MUSS (small watershed version of MUSLE). Runoff variables increase the prediction accuracy, eliminate the need for a SDR, and enable the model to estimate sediment yield for a single storm.

MUSLE was developed to simulate sediment yield from small agricultural watersheds. Some of the watersheds used in its development contained natural channels, so the sediment yield estimate is composed of both upland and channel erosion. MUSLE uses a SDR to estimate the amount of eroded soil that actually leaves the boundary of the field. A portion of the eroded material is redistributed and deposited within the field or trapped by conservation buffers or other forms of conservation treatment that promote deposition. This is considered in the sediment delivery calculation.

A second soil erosion routine in the APEX model, MUSS, is used with MUSLE to account for the quantity of material being transported by ephemeral gully erosion. MUSS is an equation developed by fitting small watershed data where no channel erosion occurred. In APEX, the MUSS soil erosion in the small watershed is subtracted from the MUSLE erosion to estimate ephemeral gully erosion on the field.

CONCEPTS

The channel evolution computer model, CONCEPTS (CONservational Channel Evolution and Pollutant Transport System), simulates the long-term evolution of incised and restored or rehabilitated stream corridors (Langendoen 2000). The physically based model simulates the three main processes that shape incised streams: hydraulics, sediment transport, and streambed and bank adjustments. Channel cross sections are of any shape and include a main channel with left and right overbank sections. Streambed and streambank material can be composed of layers with different material properties, such as grain-size distribution, resistance to hydraulic erosion, or shear-strength parameters. Channel hydraulics is represented by the full Saint-Venant equations of gradually varying flow or its diffusion wave form in case of high Froude numbers. The equations are solved using the Preissmann (1960) scheme. A description and download of the CONCEPT model are provided at https://www.ars.usda.gov/southeast-area/oxford-ms/national-sedimentationlaboratory/watershed-physical-processes-research/research/concepts/.

CONCEPTS calculates fractional sediment transport similarly to KINEROS2 (KINematic runoff and EROSion model, see section I below). CONCEPTS adds an additional source term in the sediment mass balance that accounts for lateral inputs from streambank erosion and distinguishes between the different erosion characteristics of cohesive and cohesionless sediments (Langendoen and Alonso 2008). Sediment transport capacity for each particle size class is calculated by the SEDTRA model using optimal transport equations for each size class: Laursen (1958) for silts, Yang (1973) for sands, and Meyer-Peter and Mueller (1948) for gravels (Garbrecht et al. 1996). Deposition or erosion of sediment deposits is uniformly distributed over the wetted part of the bed. Bed erosion is limited by bed rock.

Erosion of streambanks is a combination of:

i. Lateral erosion of the bank toe by fluvial entrainment of in situ bank materials, often termed hydraulic erosion.
ii. Mass failure of the upper part of the bank due to gravity (Langendoen and Simon, 2008).

The amount of hydraulic erosion is calculated separately for each soil layer comprising the streambank by an excess shear stress equation, using an average boundary shear stress exerted by the flow on each soil layer.

CONCEPTS performs stability analyses of planar and cantilever failures, which are most widely observed in the incised stream systems of the midcontinent of the United States. The stability of the bank is determined by the bank's geometry, bank stratigraphy, soil properties, pore-water pressures, confining pressure exerted by the water in the stream, and riparian vegetation (Langendoen and Simon 2008). In case of bank failure, the failed material becomes part of the bed-material load, and the cross-sectional geometry is updated accordingly.

EGEM

A method for estimating ephemeral gully erosion (Ephemeral Gully Erosion Model) was developed under the direction of Dr. John Laflen, USDA-ARS, which used regression equations to predict outputs of the CREAMS model (Watson et al. 1985). The computer program developed was named Ephemeral Gully Erosion Estimator (EGEE). The model is based on research on erosion from concentrated flow conducted by Foster (1982) and Franti et al. (1985). EGEE estimates the quantity of soil eroded from a single ephemeral gully (ephemeral gully). Erosion computation routines from EGEE are added to the existing NRCS Engineering Field Manual Chapter-2, EFM-2 computer program (USDA-NRCS 1989), resulting in the EGEM model (Merkel et al. 1988).

The two options within EGEM are to estimate ephemeral gully erosion from a single storm event or average annually. Various options allow for more flexibility in estimating average annual ephemeral gully erosion. The year may be divided into up to three seasons, representing such conditions as fallow, cover crop, and row crop.

Computation of average annual ephemeral gully erosion is based on four concepts:

i. The largest storm of the year causes the ephemeral gully to reach its maximum dimensions.
ii. The ephemeral gully is filled with soil once per year through a tillage operation.
iii. A single ephemeral gully is assumed with user-defined length (no dendritic pattern).
iv. The average annual ephemeral gully erosion may be computed based on a probability relationship.

REGEM

The EGEM model was revised by Gordon et al. (2007) to extend the capabilities of EGEM. REGEM is a stand-alone program that added the following features:

i. A new algorithm was added which estimates the migration rate of the headcut (Alonso et al. 2002).
ii. An algorithm was added which creates the initial headcut's knickpoint.
iii. Some of the existing EGEM components were refined.
iv. Additional components were revised and further enhanced the algorithm.

The revised ephemeral gully erosion model approach incorporates analytic formulations for plunge pool erosion and headcut retreat within single or multiple storm events in unsteady, spatially varied flow at the sub-cell scale, and addresses five soil particle-size classes to predict gully evolution, transport-capacity, and transport-limited flows, gully widening, and gully reactivation. REGEM was the basis for the ephemeral gully components within AnnAGNPS.

Hairsine and Rose

Hairsine and Rose developed a model that considered rainfall and shear driven erosion of the soil bed, overland transport of sediment and deposition of the sediment (Hairsine and Rose 1992a and 1992b). The erodibility of the original soil, the eroded material in transport, and the grain size of the transported material are considered in the model. The model incorporates a specific description of the role of cohesion, the capability to deal with a range of sediment sizes and settling velocities, and an explicit representation of the layer formed by deposition. The formation and evolution of deposited sediment has a different cohesive strength than the original uneroded soil.

The transport capacity of the flow is determined as a limiting outcome of the evolution of the deposition and erosion processes. Conditions of net erosion and net deposition are merely a change in the balance of these processes. When cohesion plays no role in limiting the transport of sediment, the expression for sediment concentration has been shown to have similarities to the sediment transport equation of Yang (1973). An examination of the data of Meyer and Harmon (1985) showed that the rill erosion extension theory provides consistent parameter values across an extensive set of experiments. Rill shape was shown not to affect the sediment concentration at the entrainment limit; however, sediment concentration at the transport limit was sensitive to rill shape.

HUMUS

The Hydrologic Unit Model for the United States (HUMUS) is a decision support system designed for making national and river basin scale resource assessments. The components of the HUMUS system include:

i. The basin-scale Soil and Water Assessment Tool model (SWAT).
ii. GIS to manage spatial inputs and outputs.
iii. Relational databases of climate, soil, crop, and management properties.

The HUMUS project was designed to provide the technical basis for conducting the appraisal of water resources for the 1997 RCA Appraisal Report. It is intended to provide detailed information about the uses of water on irrigated and non-irrigated agricultural lands and of the physical and economic effects of changing agricultural practices and cropping patterns on future water needs and supplies.

Recent advancements in computer-based natural resource simulation technologies give the opportunity to do comprehensive regional and national water resources assessments. The HUMUS system is expected to be a prototype for other national natural resources policy development forums and for uses of the technology at the regional level by natural resources agencies. HUMUS includes information about local weather, soil properties, topography, natural vegetation, cropped areas, runoff, erosion, ground water, irrigation, and agricultural practices for approximately 2,150 watershed areas (the 8-digit hydrologic accounting units delineated by the Water Resources Council in the Second National Assessment). Water flows are routed from the 2,150 watershed areas through the 18 major river basins. The system is calibrated by comparing simulated water outflows with actual stream flows derived from gauging records at 350 locations (the 6-digit hydrologic unit areas).

KINEROS2

The KINematic runoff and EROSion model (KINEROS2) is an event-oriented, physically based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds (Woolhiser et al. 1990). The watershed is represented by a cascade of planes and channels. The partial differential equations describing overland flow, channel flow, erosion, and sediment transport are solved by finite-difference techniques.

KINEROS2 routs flow and mixed-size sediments through channels with a compound cross section (trapezoidal main and overbank sections). The kinematic wave form of the Saint-Venant equations describe channel hydraulics and are solved using the Preissmann scheme. Fractional sediment transport is described by a mass balance equation for each size fraction that accounts for storage in the water column, advective transport, and exchange of sediment between bed and water column. The latter is a function of the difference between current sediment concentration and the equilibrium concentration.

Transport capacity is computed using the Engelund and Hansen (1967) total load formula. Resulting changes in channel depth and width are calculated by minimizing stream power (Chang 1982). KINEROS2 assumes a maximum erodible depth and fails banks if they become too steep. The KINEROS2 model is available for download at https://www.tucson.ars.ag.gov/kineros/Download.html.

RHEM/KINEROS

The Rangeland Hydrology and Erosion Model (RHEM) is a process-based model that was designed to model and predict runoff and erosion rates on rangelands and to assist in assessing rangeland conservation practice effects (Wei et al. 2009, Nearing at al. 2011). RHEM is designed for government agencies, land managers and conservationists who need sound, science-based technology to model, assess, and predict runoff and erosion rates on rangelands and to assist in evaluating rangeland conservation practices effects.

RHEM is an event-based model that estimates runoff, erosion, and sediment delivery rates and volumes at the spatial scale of the hillslope and the temporal scale of as single rainfall event. It represents erosion processes under normal and fire-impacted rangeland conditions. RHEM version 2.3 Update 5 is the current version and has a web-based interface. The web model was built with the following goals:

i. Simplify the use of the model
ii. Manage user sessions
iii. Centralize the model runs or scenario results
iv. Provide tabular and graphical reports

RHEM is a web-based application, and no download is available. The model is available at https://apps.tucson.ars.ag.gov/rhem.

RUSLE2

RUSLE2 currently simulates a channel at the bottom of a hillslope and estimates deposition in the channel if a low channel gradient is specified. RUSLE2 uses soil management and climatic information to estimate sediment load and runoff from a location's 10-yr 24-hr precipitation amount (P10y, 24h) to determine transport capacity and sediment yield from channels. However, RUSLE2 does not predict erosion in the channels, no matter how steep the gradient or how large the discharge.

A 2-D version of RUSLE was developed by Desmet and Govers (1996) who claimed that the extended LS factor captured the effects of ephemeral gully erosion in concentrated flow areas. This approach was incorporated and extended to include sediment deposition in the WATEM/SEDEM model (Van Rompaey et al. 2001; Verstraeten et al. 2007) where alternative sediment transport capacity formulations have been implemented.

Dabney et al. (2011) described recent enhancements to RUSLE2 that allow prediction of runoff and erosion associated with a representative sequence of events that can be derived from RUSLE2 databases. Results can be linked with a process-based ephemeral gully erosion model such as that used by CREAMS or WEPP. A distributed 2D version of RUSLE2 that will employ this approach in a GIS application is currently under development. See the USDAS-ARS website for the latest release of the RUSLE2 program at https://www.ars.usda.gov/Research/docs.htm?docid=5971.

SWAT

The Soil and Water Assessment Tool model (SWAT) (Arnold et al. 1998) was developed by the USDA-ARS as a basin-scale continuous time-scale management evaluation tool. The CREAMS (Knisel 1980), GLEAMS (Leonard et al. 1987), and EPIC (Texas A&M U. 2022 and Williams et al. 1984) models, ,) were used in developing the watershed scale components. Sediment delivery to the edge of the field is estimated from the MUSLE equation. The use of MUSLE lumps all sediment sources from the fields based on USLE parameters and flow characteristics. The SWAT model adjusts the MUSLE sediment yield by considering snow cover effects and the sediment lag in surface runoff. The SWAT model also calculates the lateral and ground water contributions to channel flow. Sediment is routed downstream through the channel system.

SWAT is an enhancement of the SWRRB model (Arnold et al., 1990) that allows simulation of water quality and quality in large, complex basins. A detailed description of the model is given in Arnold et al. (1998a). It was designed to predict the impact of topography, soils, land use, management, and weather on yields of water, sediment, nutrient (nitrogen and phosphorus), and agricultural chemicals for large ungauged watersheds. To meet these design criteria, the model:

i. Does not require calibration (which is impossible on ungauged watersheds).
ii. Uses inputs that are readily available for large areas.
iii. Is computationally efficient in order to simulate the interaction of hundreds of sub-basins, using a daily time step.
iv. Is capable of simulating hundreds of years in a continuous time mode to assess the long-term impacts of change.

The command structure is used to route water, nutrients, and chemicals through streams and reservoirs and to input measured data for point sources of water and nutrients. Basins can be subdivided into grid cells or subwatersheds to increase detail for input and output. Model sub-basin components can be divided into the following: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Simulated hydrology processes include:

i. Surface runoff estimated from daily rainfall using the NRCS runoff curve number.
ii. Percolation modeled with a layered-storage routing technique combined with a crack flow model.
iii. Lateral subsurface flow.
iv. Ground water flow to streams from shallow aquifers.
v. Potential evapotranspiration by the Hargreaves, Priestley-Taylor, and Penman Monteith methods.
vi. Snowmelt is simulated.
vii. Transmission losses from streams.
viii. Water storage and losses from ponds.

Weather variables that drive the hydrologic model include daily precipitation, maximum and minimum air temperatures, solar radiation, wind speed, and relative humidity. A weather generator can be used to simulate all or several variables based on monthly climate statistics calculated from long-term measured data. Different weather data can be associated with specific sub-basins. Sediment yield is computed for each sub-basin with the MUSLE. Soil temperature is updated daily for each soil layer as a function of air temperatures; snow, plant and residue cover; damping depth; and mean annual temperature.

Crop growth is simulated with a daily time-step using a simplification of the EPIC crop model, which estimates phenological development based on daily accumulation of heat units, harvest index for partitioning grain yield, Monteith's approach for potential biomass, and adjustments for water and temperature stress. Different crops, both annual and perennial, can be simulated by using crop-specific input parameters.

Nitrate losses in runoff, percolation and lateral subsurface flow are simulated. Organic nitrogen losses are estimated from soil losses and an enrichment ratio. A nitrogen transformation model modified from EPIC includes residue mineralization, organic matter mineralization, nitrification, denitrification, volatilization, fertilization, and plant uptake. Phosphorus processes include residue and organic matter mineralization, losses with runoff water and sediment, fertilization, fixation by soil particles, and plant uptake. Pesticide transformations are simulated with a simplification of the GLEAMS model approach and include interception by the crop canopy; volatilization; degradation in soils and from foliage; and losses in runoff, percolation, and sediment.

Simulated agricultural management practices include tillage effects on soil and residue mixing, bulk density, and residue decomposition. Irrigation may be scheduled by the user or applied automatically according to user-specified rules. Fertilization with nitrogen and phosphorus can also be scheduled by the user or applied automatically. Pesticide applications are scheduled by the user. Grazing is simulated as a daily harvest operation.

Simulated stream processes include channel flood routing, channel sediment routing, and nutrient and pesticide routing and transformations modified from the QUAL2E model. Components include algae as chlorophyll-a, dissolved oxygen, organic oxygen demand, organic nitrogen, ammonium nitrogen, nitrite nitrogen, organic phosphorus, and soluble phosphorus. In-stream pesticide transformations include reactions, volatilization, settling, diffusion, resuspension, and burial. The ponds and reservoirs component includes water balance, routing, sediment settling, and simplified nutrient and pesticide transformation routines. Water diversions into, out of, or within the basin can be simulated to represent irrigation and other withdrawals from the system.

WEPP/CREAMS

The Water Erosion Prediction Project (WEPP) model is a continuous simulation, process-based model that allows simulation of water and sediment balance in small watersheds and on hillside profiles within those watersheds. WEPP is available at https://www.ars.usda.gov/midwest-area/west-lafayette-in/national-soil-erosionresearch/docs/wepp/research/.

GeoWEPP is a geospatial (GIS-based) interface to the WEPP model and allows the user to import available digital elevation models (DEM), topography, soils, and land use data to scenario simulations. GeoWEPP ia available at https://geowepp.geog.buffalo.edu/versions/arcgis10-4/.

Haan et al. (1994) provide a clear conceptual derivation of the channel erosion theory represented by the process-based equations used in CREAMS to describe ephemeral gully erosion. Essentially the same theory is used in the watershed version of WEPP and GeoWEPP to describe channel erosion. The theory is based on several assumptions that:

i. Manning's equation applies.

ii. The shear stress distribution around the cross section of a channel can be represented by a hard-coded dimensionless distribution.
iii. The soil consists of a uniform erodibile layer with characteristic erodibility and critical shear stress values overlying a non-erodible layer at a specified depth. iv. Potential detachment rate is proportional to excess shear stress.
iv. Actual detachment is proportional to the unsatisfied transport capacity of a steadystate runoff rate.
v. Transport capacity can be determined by the set of equations proposed by Yalin (1963).
vi. Deposition occurs if sediment load exceeds transport capacity.

In application, the runoff hydrograph is converted to an effective steady-state runoff rate with corresponding duration. The shear stress is calculated from discharge using channel slope, Manning's n, and channel dimensions to determine velocity and hydraulic radius; and assuming that shear stress is proportional to the product of slope, hydraulic radius, and the unit weight of water. Application of the detachment/transport coupling relationships, together with the assumption of a rectangular channel shape, leads to the determination of an effective channel width prior to the intersection of the eroding surface with the non-erodible layer. The effective channel width depends on critical shear stress but not on soil erodibility.

The time to reach the non-erodible layer is determined (depending on available transport capacity and soil erodibility), and the total time of the event is divided into a period before reaching the non-erodible layer and a period after reaching the layer. After the non-erodible layer is reached, the channel widens, asymptotically approaching the width where shear stress at the toe of the channel bank is equal to the specified critical stress. This allows application of a rapidly solved analytical calculation of soil loss at several cross sections down the channel. Two limitations of this approach are that:
i. The non-erodible layer remains forever non-erodible.
ii. Any deposition of sediment predicted from one event is neglected in subsequent erosion calculations.

WinSRFR

WinSRFR is an integrated hydraulic analyses application for surface irrigation systems that combines a simulation engine with tools for irrigation system evaluation, design, and operational analysis (ALARC 2006). Its simulation engine, SRFR, simulates the unsteady hydraulics and morphology of trapezoidal furrows in a single soil (Strelkoff and Bjorneberg 2001).

SRFR solves the Saint-Venant equations for one-dimensional open-channel flow, either in its diffusion or kinematic form, hence neglecting the effects of inertia, while accounting for infiltration. The length of the surface stream is computed as part of the solution. The detachment, transport, and deposition of mixed-sized sediments largely follow the WEPP approach. However, SRFR uses the Laursen transport capacity equation because it was found that the Yalin transport capacity equation greatly overpredicts the transport of silt-sized sediments.

SRFR assumes a constant boundary shear stress along the wetted perimeter of each furrow section, which includes the furrow bottom and sidewalls. Therefore, the eroded or deposited sediments are distributed uniformly across the wetted perimeter.

References

1. ALARC. 2006. WinSRFR 2.1 User Manual. U.S. Department of Agriculture, Agricultural Research Service, Arid-Land Agricultural Research Center, Maricopa, Arizona, 142 pp.

2. Alonso, C.V., S.J. Bennett, and O.R. Stein. 2002. Predicting headcut erosion and migration in upland flows, Water Resources Research, 38:1–15.

3. Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment part I: model development. J. American Water Resources Association 34(1):73–89.

4. Bailey, R.W. 1941. Land erosion – normal and accelerated – in the semiarid West. Am. Geophys. Union Trans. 22 (pt. 2):240–261.

5. Banks, William S.L., Allen C. Gellis, and Gregory Noe. 2010. Sources of Fine-Grained Suspended Sediment in Mill Stream Branch Watershed, Corsica River Basin, A Tributary to the Chesapeake Bay, Maryland, 2009. US Geological Survey. In Proceedings of the 2nd Joint Federal Interagency Conference on Sedimentation and Hydrologic Modeling, Las Vegas, NV.

6. Barnes, L.H., and S.B. Maner. 1953. A method for estimating the rate of soil loss by sheet erosion from individual fields or farms under various types of land treatment. USDA Soil Conserv. Serv., Western Gulf Region, Ft. Worth, Tex., 12 p.

7. Bertuzzi, P, J.M. Caussignac, 1988. Measuring in-situ soil surface roughness using a laser profilometer. Proc. Of the 4th International Colloquim on special signatures in Remote Sensing, Aussois, France, p. 19-24.

8. Bingner, R.L., and F.D. Theurer. 2001. AnnAGNPS: estimating sediment yield by particle size for sheet & rill erosion. In Proceedings of the Sedimentation: Monitoring, Modeling, and Managing, 7th Federal Interagency Sedimentation Conference, 25–29 March, Reno, NV. p. I-1 – I-7.

9. Bingner, R.L., F.D. Theurer, L.M. Gordon, S.J. Bennett, C. Parker, C. Thorne, and C.V. Alonso. 2007. AnnAGNPS Ephemeral Gully Erosion Simulation Technology. Proceedings of the IV International Symposium on Gully Erosion. Pamplona, Spain, J. Casali and R. Gimenez, eds. Public University of Navarre. 17-19 September, p. 20–21.

10. Brown, Carl B. 1960. Effects of land use and treatment on pollution. Natl. Conf. on Water Pollut. Proc, Public Health Serv., Dep. Health, Educ, and Welfare, p. 209–218.

11. Capra, A., L.M. Mazzara, and B. Sciolone, 2004, "Application of the model to predict ephemeral gully erosion in Sicily, Italy.", Catena, 59 (2), page 133–146.

12. Carollo, F.G., C. Di Stefano, V. Ferro, V. Pampalone, 2015. Measuring rill erosion at plot scale by a drone-based technology, Hydrological Processes. 29. 3802–3811, DIO: 10.1002/hyd.10479.

13. Chepil, W.S., and N.P. Woodruff. 1963. The physics of wind erosion and its control. Adv. Agron. 15:211–302.

14. Chepil. W., F.H. Siddoway, and D.V. Armbrust. 1962. Climatic factor for estimating wind erodibility of farm fields. J. Soil Water Con-serv. 17(4):162–165.

15. Colorado State University. 2021. Conservation Resources Land Management Operations Database (CRLMOD). https://alm.engr.colostate.edu/cb/dir/70416. Colorado State University, Fort Collins, CO.

16. Dabney, S.M., D.C. Yoder, D.A.N. Vieira, and R.L. Bingner. 2011. Enhancing RUSLE to include runoff-driven phenomena. Hydrol. Process. 25, 1373–1390.

17. Desmet, P.J.J. and G. Govers, 1996. A GIS procedure for automatically calculating the USLE LS factor on topographically complex landscape units. Journal of Soil and Water Conservation 51, 427–433.

18. Engelund, F., and E. Hansen. 1967. A monograph on sediment transport in alluvial streams. Teknisk Forlag, Copenhagen, 62 pp.

19. FISRWG. 1998. Stream Corridor Restoration: Principles, Processes, and Practices. By the Federal Interagency Stream Restoration Working Group (FISRWG)(15 Federal agencies of the US gov't). GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653. ISBN-0-93421359-3.

20. Foster, G.R. 1982. Modeling the Erosion Process, In: C.T. Haan, H.P. Johnson, and D.L. Brakensiek (editors), Hydrologic Modeling of Small Watersheds, Monograph Number 5, American Society of Agricultural Engineers, St. Joseph, MI, p. 305.

21. Franti, T.G., Laflen, J.M., and Watson, D.A. 1985. Soil Erodibility and Critical Shear Under Concentrated Flow, American Society of Agricultural Engineers, Paper No. 85–2033.

22. Garbrecht, J., R.A. Kuhnle, and C.V. Alonso. 1996. "A transport algorithm for variable sediment sizes: Fundamental concepts and equations." Proceedings of the Sixth Federal Interagency Sedimentation conference, Las Vegas, Nevada, VI-8_15.

23. Glymph, Louis M., Jr. 1954. Studies of sediment yields from watersheds. Int. Union of Geod. and Geophys., Int. Assoc. Hydrol. 10th Gen. Assem., Rome, Italy, Part 1, p. 178–191.

24. Gordon, L.M., S.J. Bennett, R.L. Bingner, F.D. Theurer and C.V. Alonso. 2007. Simulating ephemeral gully erosion in AnnAGNPS. Transactions of the ASABE, 50(3):857–866.

25. Gottschalk, L.C, and G.M. Brune. 1950. Sedimentation-design criteria for the Missouri Basin loess hills. USDA Soil Conserv. Serv. Tech. Publ. 97.

26. Gottschalk, L.C. 2021.USDA-Soil Conservation Service, Sediment-design criteria for the Missouri Basin loess hills. USDA-Soil Conservation Service Tech. Publ. 97. Washington, D.C.

27. Haan C.T., B.J. Barfield, J.C. Hayes. 1994. Design Hydrology and Sedimentology for Small Catchments. Academic Press: San Diego, CA.

28. Hairsine, P.B. and C.W. Rose. 1992a. Modeling water erosion due to overland flow using physical principles: 1. Sheet flow. Water Resour. Res., 28, 237–243.

29. Hairsine, P.B. and C.W. Rose. 1992b. Modeling water erosion due to overland flow using physical principles: 1. Rill flow. Water Resour. Res., 28, 245–250.

30. Knisel, W.G., ed. 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. U.S. Dept of Agric., Conservation Research Report No. 26, 640 pp.

31. Langendoen, E.J. 2000. CONCEPTS—Conservational channel evolution and pollutant transport system. Research Rep. No. 16, U.S. Dept. of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS.

32. Langendoen, E.J., and A. Simon. 2008. Modeling the evolution of incised streams: II. Streambank erosion. J. Hydr. Eng. 134(7):905–915.

33. Langendoen, E.J., and C.V. Alonso. 2008. Modeling the evolution of incised streams: I. Model formulation and validation of flow and streambed evolution components. J. Hydr. Eng. 134(6):749–762.

34. Laursen, E., 1958. The total sediment load of streams. J. Hydr. Div., 84(1):1–36.

35. Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Ground water loading effects of agricultural management systems. Transactions of the American Society of Agricultural Engineers. 30(5): 1403–1418.

36. Maner, Sam B. 1957. Factors affecting sediment delivery rates in the Red Hills physiographic area. Am. Geophys. Union Trans. 39:669–675.

37. Maner, Sam B., and L.H. Barnes. 1953. Suggested criteria for estimating gross sheet erosion and sediment delivery rates for the Blackland Prairies problem area in soil conservation. USDA Soil Conserv. Service, Ft. Worth, Tex., 17 p.

38. McCool, D.K., M.G. Dosserr, S.J. Yecha, 1981. A portable rill meter for field measurement of soil loss, Erosion and Sediment Transport Measurement (Proceeding of the Florence Symposium, June 1981). IAHS Publ. no. 133.

39. Merkel, W.H., D.E. Woodward, C.D. Clarke. 1988. Ephemeral Gully Erosion Model (EGEM), In: Modeling Agricultural, Forest, and Rangeland Hydrology, International Symposium, Publication 07-88, American Society of Agricultural Engineers, St. Joseph, MI, pp. 315–323.

40. Meyer, L.D. and W.C. Harmon. 1985. Sediment losses from cropland furrows of different gradients. Trans. ASAE, 28, 448–453.

41. Meyer-Peter, E., and R. Mueller. 1948. Formula for bed-load transport. Proc., Int. Association for Hydraulic Research, 2nd Meeting, Stockholm, Sweden.

42. Musgrave, G.W. 1947. The quantitative evaluation of factors in water erosion—a first approximation. J. Soil Water Conserv., Vol. 2, No. 3, p. 133–138.

43. Nachtergaele, J., J. Poesen, A. Sidorchuk, and D. Torri. 2002. Prediction of concentrated flow width in ephemeral gully channels. Hydrol. Process. 16:1935–1953.

44. Nearing, M.A., H. Wei, J.J. Stone, F.B. Pierson, K.E. Spaeth, M.A. Weltz, D.C. Flanagan, M. Hernandez. 2011. A rangeland hydrology and erosion model. Trans. ASABE 54(3): 901–908.

45. Parker, C., C. Thorne, R.L. Bingner, R.R. Wells, and D.L. Wilcox. 2007. Automated Mapping of Potential for Ephemeral Gully Formation in Agricultural Fields. Research Report No. 56. U.S. Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS.

46. Preissmann, A. 1960. Propagation des intumescences dans les canaux et riviers, 1er Congrès d'association Française de calcul, 433–442, Grenoble, France.

47. RESSED. 2022. Reservoir Sedimentation Survey Database (RESSED). https://water.usgs.gov/osw/ressed/.

48. Roehl, J. W. 1965. Erosion and its control on agricultural land. Fed. Inter-Agency Sediment. Conf. 1963 Proc. U.S. Dep. Agric. Misc. Publ. 970, p. 18–22.

49. Roehl, John W. 1962. Sediment source areas, delivery ratios, and influencing morphological factors. Presented at IAHS Symposium on Land Resources, Oct. 1962. Int. Assoc. Hydrol. Sci. Publ. 59.

50. SEDHYD, inc. Proceedings of Sedimentation conferences (sedhyd.org).

51. Soil Science Society of America. 2008. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI.

52. Strelkoff, T.S., and D.L. Bjorneberg. 2001. Hydraulic modeling of irrigation-induced furrow erosion. In: Sustaining the Global Farm. Selected Papers from the 10th International Soil Conservation Organization Meeting, May 24–29, 1999, Purdue University, D.E. Stott, R.H. Mohtar, and G.C. Steinhardt, Eds., 699–705.

53. Texas A&M University EPIC. 2022. Environmental Policy Integrated Climate Model. (EPIC). https://epicapex.tamu.edu/software/. Blackland Research and Extension Center, Texas A&M University.

54. Texas A&M University. APEX. 2022. Agricultural Policy Environmental eXtender, (APEX) https://epicapex.tamu.edu/software/. Blackland Research and Extension Center., Texas A&M University.

55. Theurer, F.D. and C.D. Clarke. 1991. Wash load component for sediment yield modeling. In: Proceedings of the Fifth Federal Interagency Sedimentation Conference, March 18–21, 1991, pg. 7–1 to 7–8.

56. USDA. 2009 (unpublished document). Ephemeral Gully Erosion—A National Resource Concern–Recommendations for the Development of Technology and Tools for Prediction and Treatment of Ephemeral Gully Erosion; USDA Contributors: NRCS, Jerry Bernard, Jerry Lemunyon, Bill Merkel, Fred Theurer, Norm Widman; ARS, Ron Bingner, Seth Dabney, Eddy Langendoen, Robert Wells, Glenn Wilson.

57. USDA-ARS, 1968, Agriculture Handbook 346, Wind Erosion Forces in the United States and Their Use in Predicting Soil Loss, Washington D.C.

58. USDA-ARS, 2014. Water Erosion Prediction Project (WEPP), National Soil Erosion Research: West Lafayette, IN.

59. USDA-ARS. 2007. CLIGEN. Weather generator. https://www.ars.usda.gov/midwestarea/west-lafayette-in/national-soil-erosion-research/docs/wepp/cligen/.

60. USDA-NRCS, 1992. Ephemeral Gully Erosion Model, Version 2.0 DOS, User Manual, Washington, DC.

61. USDA-NRCS, 2022b. CART. Conservation Assessment Ranking Tool, Washington, D.C.

62. USDA-NRCS, 2022e. Soil Tillage Intensity Rating. (STIR). https://alm.engr.colostate.edu/cb/issue/6448. Washington, D.C.

63. USDA-NRCS. 1988. National Engineering Handbook (Title 210), Part 650, Chapter 16, Streambank and Shoreline Protection. Washington, D.C. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=46288.wba

64. USDA-NRCS. 1989. Engineering Field Manual Chapter 2 (EFM 2), Estimating Runoff and Peak Discharge, Washington, DC.

65. USDA-NRCS. 2016. Revised Universal Soil Loss Equation 2. (RUSLE2). Purdue University, IN.

66. USDA-NRCS. 2021. National Engineering Handbook (Title 210), Part 654, Stream Restoration Design. Washington, D.C.

67. USDA-NRCS. 2022a. IET2. Integrated Erosion Tool (IET). Version 2. Colorado State University. Fort Collins, CO.

68. USDA-NRCS. 2022c. PRISM. NRCS Parameter elevation Regression on Independent Slopes Model. https://data.nal.usda.gov/dataset/prism. Washington, D.C.

69. USDA-NRCS. 2022d. Soil Conditioning Index. (SCI). Website for RUSLE2: https://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm. Purdue University, IN.

70. USDA-NRCS. 2022f. SSURGO Database.

https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053631. Washington, D.C.

71. USDA-NRCS. 2022g. Web Soil Survey. https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Washington, D.C.

72. USDA-NRCS. 2022h. Wind Erosion Prediction System, (WEPS), https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/tools/weps/?cid=stelprdb1240784.

73. Van Rompaey, A., G. Verstraeten, K. Van Oost, G. Govers, J. Poesen. 2001. Modelling mean annual sediment yield using a distributed approach. Earth Surface Processes and Landforms 26, 1221–1236.

74. Verstraeten, G., I.P. Prosser, and P. Fogarty. 2007. Predicting the spatial patterns of hillslope sediment delivery to river channels in the Murrumbidgee catchment, Australia. J. of Hydrology 334:440–454.

75. Watson, D.A., J.M. Laflen, T.G., Franti, 1985. Ephemeral Gully Erosion Estimator (Unpublished).

76. Wei, H., M.A. Nearing, J.J. Stone, D.P. Guertin, K.E. Spaeth, F.B. Pierson, M.H. Nichols, C.A. Moffett. 2009. A new Splash and Sheet Erosion Equation for Rangelands. Soil Sci. Soc. Am. J.

77. Williams, J.R., C.A. Jones, and P.T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Transactions of the American Society of Agricultural Engineers. 27: 129–144.

78. Wischmeier, W.H. 1976. Use and misuse of the universal soil loss equation. J. Soil Water Con-serv. 31:5–9.

79. Woodward, D.E. 1999. Method to predict cropland ephemeral gully erosion. Elsevier Science B.V., Catena 37: 393–399.

80. Woolhiser, D.A., R.E. Smith, and D.C. Goodrich. 1990. KINEROS, A kinematic runoff and erosion model: Documentation and user manual. U.S. Department of Agriculture, Agricultural Research Service, ARS–77, 130 pp.

81. Yalin, M.S. 1963. An expression for bed-load transportation. Proc. Am Soc. Civil Eng 89(HY3):221–250.

82. Yang, C.T. 1973. Incipient motion and sediment transport. J. Hydraul. Div. Am. Soc. Civ. Eng., 99(HY10), 1679–1704.